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**FFTF HORIZONTAL SODIUM STORAGE TANK
PRELIMINARY THERMAL ANALYSIS**

January 1995

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FFTF HORIZONTAL SODIUM STORAGE TANK PRELIMINARY THERMAL ANALYSIS

1.0 INTRODUCTION

In the FFTF Shutdown Program, sodium from the primary and secondary heat transport loops, Interim Decay Storage (IDS), and Fuel Storage Facility (FSF) will be transferred to four large storage tanks for temporary storage. Three of the drain tanks will be cylindrical vertical tanks having a diameter of 28 feet, height of 22 feet and fabricated from carbon steel. The vertical tanks were the subject of a previous report (WHC 1995) and are not the subject of this report. The fourth tank is a horizontal cylindrical tank 18 feet in diameter, having an overall length of 31 feet and fabricated from carbon steel. A depiction of the horizontal can be seen in Figure 1. The four storage tanks will be located near the FFTF in the 400 Area will rest on a steel-lined concrete slab in an enclosed building.

The purpose of this work is to document the thermal analyses that were performed to ensure that the FFTF horizontal sodium storage tank design is feasible from a thermal standpoint. The key criterion for this analysis is the time to heat up the storage tank containing frozen sodium at ambient temperature to 400 °F. Normal operating conditions include an ambient temperature range of 32 °F to 120 °F.

A key parameter in the evaluation of the sodium drain tank is the type of insulation. The baseline case assumed four inches of calcium silicate insulation as stipulated in WHC 1994a. An alternate case assumed refractory fiber (Cerablanket) insulation also with a thickness of four inches. Both cases assumed a total electrical trace heat load of 60 kW, evenly distributed on the tank heads and on the tank side wall (cylinder).

Figure 1. Thermal Model of the FFTF Horizontal Sodium Storage Tank Design.

2.0 SUMMARY OF RESULTS

The most important results derived from the thermal analysis for the baseline configuration (as depicted in Figure 1) include the following (these results are also summarized in Table 1):

- The calcium-silicate-insulated horizontal storage tank requires a 18.5 day period to heat up to 400 °F from an initial temperature of 32 °F. The average heat up rate was determined to be 19.1°F/day. This thermal response is depicted in Figure 2.
- The refractory-fiber-insulated horizontal storage tank requires a 17.0 day period to heat up to 400 °F from an initial temperature of 32 °F. The average heat up rate was determined to be 21.7°F/day. This thermal response is depicted in Figure 3.
- The maximum steady-state sodium temperature for the calcium-silicate-insulated horizontal storage tank was determined to be 815°F with 60 kW heater power and 32 °F ambient. The maximum outer surface temperature was determined to be 103 °F for the same conditions.
- The maximum steady-state sodium temperature for the refractory-fiber-insulated horizontal storage tank was determined to be 976 °F with 60 kW heater power and 32 °F ambient. The maximum outer surface temperature of the tank was determined to be 103°F for the same conditions.
- 16 kW of heater power is required to maintain a 400 °F sodium temperature in the horizontal storage tank while insulated with 4 inches calcium silicate insulation and with an ambient temperature of 120 °F. The maximum insulation outer surface temperature of the tank was determined to be 134 °F for the same conditions. This thermal characteristic is depicted in Figure 4.
- 11 kW of heater power is required to maintain a 400 °F sodium temperature with the horizontal storage tank insulated with 4 inches of refractory fiber and with an ambient temperature of 120 °F. The maximum insulation outer surface temperature of the tank was determined to be 134 °F for the same conditions. This thermal characteristic is depicted in Figure 5.

Figure 2. Thermal Transient for FFTF Sodium Tank
with Calcium Silicate Insulation.

Figure 3. Thermal Transient for FFTF Sodium Drain Tank
with Refractory Fiber Insulation.

Figure 4. Thermal Model Temperature vs Heater Power Plot of the FFTF Sodium Horizontal Storage Tank Design, Insulated with Calcium Silicate.

Figure 5. Thermal Model Temperature vs. Heater Power Plot of the FFTF Sodium Horizontal Storage Tank Design, Tank Insulated with Refractory Fiber.

**Table 1. Expected Heat up Times And Temperatures for
FFTF Sodium Drain Tank Designs.**

Case Number	Case Description	Time to 400 °F Days	Sodium Temperature °F	Outer Surface Temperature ⁽²⁾ °F
1	30 day Transient, Cal. Sil. Insulation	18.5	606 ⁽¹⁾	82
2	30 day Transient, Ref. Fiber Insulation	17.0	683 ⁽¹⁾	76
3	Steady-State, 32 °F Amb. 60 kW, Cal. Sil. Insulation	NA	815	104
4	Steady-State, 32 °F Amb. 60 kW, Ref. Fiber Insulation	NA	976	103
5	Steady-State, 120 °F Amb., 60 kW, Cal. Sil. Insulation	NA	845	177
6	Steady-State, 120 °F Amb., 30 kW, Cal. Sil. Insulation	NA	566	152
7	Steady-State, 120 °F Amb., 18 kW, Cal. Sil. Insulation	NA	420	140
8	Steady-State, 120 °F Amb., 12 kW, Cal. Sil. Insulation	NA	333	134
9	Steady-State, 120 °F Amb., 60 kW, Ref. Fiber Insulation	NA	997	177
10	Steady-State, 120 °F Amb., 30 kW, Ref. Fiber Insulation	NA	686	152
11	Steady-State, 120 °F Amb., 18 kW, Ref. Fiber Insulation	NA	516	140
12	Steady-State, 120 °F Amb., 12 kW, Ref. Fiber Insulation	NA	411	134

(1) Temperatures at the end of the 30 day transient or ultimate temperature for steady state cases.

3.0 DESCRIPTION OF THE FFTF HORIZONTAL SODIUM STORAGE TANK DESIGN

The FFTF horizontal sodium storage tank has been designed to contain up to 52,000 gallons of sodium. The principal physical characteristics of the horizontal sodium storage tank consists of a right circular cylindrical tank with ASME flanged and dished (F&D) heads and supported by two saddle supports attached to the tank at the cylinder section. The outer surface of the tank is covered with four inches of insulation. There is an air gap between the tank wall and the insulation. The air gap will contain trace heaters that will be utilized to heat up frozen sodium to a 400 °F operating temperature. The trace heaters are installed on the heads and the cylindrical side wall of

the tank. The inside diameter of the tank is 214.5 inches and is 370.5 inches in overall inside length. The heads and side of the tank are 0.75 inch thick. The support saddles are assumed to be insulated on its inside and outside surface with up to four inches of insulation down to within 12 inches of the floor surface. A simplified depiction of the baseline FFTF horizontal sodium storage tank is shown in Figure 1.

The horizontal sodium storage tank will contain approximately 52,000 gallons of sodium, filling the tank to 213.5 inches. There will be a nitrogen cover gas above the sodium surface within the tank. The tank shell and supports are fabricated from type SA-515 mild carbon steel. The insulations modelled in the analyses were either Calcium Silicate foam blocks or Refractory Fiber batting (Cerablanket). Both insulations have previously been used at the FFTF. The trace heaters are mineral insulated cable type heaters with magnesium oxide insulation within a incoloy sheath, the heating element is helical wound incoloy centered within the cable.

The sodium storage tanks will be installed into a newly constructed facility near the FFTF in the 400 area. The tanks will be installed onto a steel-lined reinforced concrete slab floor. The horizontal sodium storage tank is further described in WHC 1994a.

The principal operating features of the FFTF horizontal sodium storage tank for thermal analysis, for normal operating conditions, are as follows:

- a. The trace heat power contained exterior to the tank walls is transferred by thermal radiation and gas conduction through an air gap between the steel tank walls and the inner surface of the insulation.
- b. The trace heat is then transferred by thermal conduction through the tank walls to the sodium contained in the tank.
- c. A portion of the trace heat is additionally transferred by conduction through the insulation and rejected to the ambient environment.
- d. The trace heat is transferred within the sodium contained in the tank. Since the tank design capacity is near the calculated empty volume of the tank, the thermal model assumed a completely sodium filled tank with no cover gas.
- e. The outer surface of the tank dissipates the heat to the ambient environment by combined thermal radiation and convection heat transfer. The ambient temperature is assumed to remain constant at 32 °F or 120 °F. The outer surface temperature limit is specified at 140 °F (WHC 1994a).
- f. A portion of the trace heat is conducted through the support structure of the tank to the concrete floor slab. This portion of the heat rejection was not modelled. The prior analysis on the vertical tank (WHC 1995) showed that the supports have a negligible effect on the overall thermal performance of the tank system.

- h. The FFTF sodium storage tanks are stored within an enclosed structure, therefore the tanks will absorb no incident solar energy and there will be no forced convective cooling (only natural convection) due to ambient conditions.

4.0 THERMAL MODEL DESCRIPTION

Common thermal analysis models were used for all transient and steady-state evaluations of the normal conditions of operations. All of the models used for the thermal analysis were developed using the PATRAN/PTHERMAL finite element code (PDA 1991).

A thermal analysis of the final configuration of the FFTF horizontal sodium storage tank is described. The thermal model utilized a longitudinal axisymmetric segment of the sodium drain tank i.e., the circumferential conduction effects were ignored. The thermal model coincided with the longitudinal center axis of the tank.

Configurations from WHC 1994a were utilized in developing the physical model of the drain tank. The tank was assumed to be completely filled with sodium with no nitrogen cover gas. The latent heat of fusion for sodium (ORNL 1972) was assumed in the model, the effect for the phase change was assumed to occur over a temperature range of 208 to 209 °F. Thermal conduction and convection with temperature dependent properties were modelled. Thermal radiation effects with constant thermal emissivity values were utilized.

Both transient and steady state analyses were performed utilizing the PATRAN/PTHERMAL and PATRAN/PVIEWFACTOR finite element computer codes (PDA 1991). A depiction of the sodium drain tank, that formed the basis for the analysis, with the stated boundary conditions is shown in Figure 1.

4.1 HEAT TRANSFER COMPUTER CODE DESCRIPTION

The PATRAN/PTHERMAL computer code solves transient or steady-state temperature distributions using a finite difference method of solution. Multi-dimensional configurations can be analyzed using a combination of coordinates. Computations are performed with provisions for temperature-dependent material properties employing conduction, thermal radiation and convection. Boundary conditions may be time-dependent temperatures or heat fluxes. Convection may be based upon local time dependent or variable temperature difference heat transfer coefficients. The PATRAN/PVIEWFACTOR computer code solves for the thermal radiation view factors of arbitrary surfaces.

The codes have been used extensively at Hanford and have completed the software quality assurance requirements for Impact Level 2 QA applications (WHC, 1991). Configuration control requirements, as outlined in the QA Manual WHC-CM-4-2, Section QI 3.3 Rev. 1, have been met and the study complies with the engineering practice EP-2.1, Rev. 2 computer Software Configuration Management.

4.2 GENERAL MODELING TECHNIQUES

Three modes of energy transfer were used in the analysis:

- 1) Conduction heat transfer within the materials of the drain tank and the concrete support pad.
- 2) Thermal radiation including:
 - a) heat transfer from external surfaces to the environment
 - b) heat transfer across internal air gap surfaces
 - c) heat transfer across internal cover gas surfaces.
- 3) Natural convection from the external surfaces of the tank and concrete support pad to still air in the environment.

The heat from the trace heat system was modeled as internal heat generation.

4.3 SUMMARY OF THERMAL PROPERTIES OF MATERIALS

Thermal material properties used for analyses were taken from WHC, 1994b. These properties are listed in Tables 2 through 7. Quadratic interpolation and linear extrapolation techniques were used to evaluate properties at temperatures not explicitly defined in the tables.

Table 2. Material Properties of Air at 1 atm.

Temperature (°F)	Thermal Conductivity (BTU/Hr-Ft-°F)	Thermal Conductivity (BTU/Sec-Inch-°F)	Specific Heat (BTU/Lbm-°F)
-110	0.0118	0.000000273	0.2393
40	0.0143	0.000000331	0.2396
90	0.0156	0.000000361	0.2399
240	0.0191	0.000000442	0.2416
440	0.0237	0.000000549	0.2458
640	0.0280	0.000000648	0.2516
840	0.0320	0.000000741	0.2579
1040	0.0370	0.000000856	0.2642
1240	0.0410	0.000000949	0.2698
1440	0.0450	0.000001042	0.2750
1640	0.0480	0.000001111	0.2794

Density of 0.0812 lbm/cu. ft. or 0.000047 lbm/in³ at STP,
Data from WHC 1994b.

Table 3. Material Properties of Type 515 Carbon Steel.

Temperature (°F)	Thermal Conductivity (BTU/Hr-Ft-°F)	Thermal Conductivity (BTU/Sec-Inch-°F)	Specific Heat (BTU/Lbm-°F)
70	29.891	0.000692	0.09852
100	29.762	0.000689	0.10261
200	29.221	0.000676	0.11354
300	28.524	0.000660	0.12110
400	27.694	0.000641	0.12627
500	26.750	0.000619	0.13003
600	25.716	0.000595	0.13337

Density of 490 lbm/cu. ft. or 0.284 lbm/in³,
Thermal emissivity of 0.8,
Data from ORNL 1987.

Table 4. Material Properties of Sodium.

Temperature (°F)	Thermal Conductivity (BTU/Hr-Ft-°F)	Thermal Conductivity (Btu/Sec-Inch-°F)	Specific Heat (Btu/Lbm-°F)
32	78.98	0.001828	0.2865
100	75.34	0.001744	0.2959
150	72.66	0.001682	0.3074
200	69.98	0.001620	0.3229
208	50.49	0.001169	0.3307
250	49.74	0.001151	0.3281
300	48.86	0.001131	0.3250
350	47.99	0.001111	0.3222
400	47.13	0.001091	0.3195
450	46.28	0.001071	0.3170
500	45.44	0.001052	0.3146

Density of Solid 60.22 lbm/cu. ft. (100°F) or 0.03485 lbm/in³,
Density of Liquid 57.56 lbm/cu. ft. (250°F) or 0.03331 lbm/in³,
Thermal emissivity of 0.9 for Solid & 0.2 for Liquid,
Heat of Fusion 48.69 Btu/lbm at 208°F,
Data from ORNL 1987.

Table 5. Material Properties of Calcium Silicate.

Temperature (°F)	Thermal Conductivity (BTU/Hr-Ft-°F)	Thermal Conductivity (Btu/Sec-Inch-°F)	Specific Heat (Btu/Lbm-°F)
32	0.03215	0.000000744	0.23
100	0.03419	0.000000791	0.23
150	0.03607	0.000000835	0.23
200	0.03828	0.000000886	0.23
250	0.04080	0.000000945	0.23
300	0.04365	0.000001011	0.23
350	0.04683	0.000001084	0.23
400	0.05032	0.000001165	0.24
450	0.05415	0.000001253	0.24
500	0.05829	0.000001349	0.24

Density of 14 lbm/cu. ft. or 0.0081 lbm/in³,
Thermal emissivity of 0.9,
 $k = 0.0313988 + 2.14484E-005 \cdot T + 6.46826E-008 \cdot T^2$, Btu/hr-ft-°F,
Data from WHC 1976.

Table 6. Material Properties of Refractory Fiber.

Temperature (°F)	Thermal Conductivity (BTU/Hr-Ft-°F)	Thermal Conductivity (Btu/Sec-Inch-°F)	Specific Heat (Btu/Lbm-°F)
32	0.02044	0.000000473	0.23
100	0.02202	0.000000510	0.23
150	0.02352	0.000000545	0.23
200	0.02532	0.000000586	0.23
250	0.02740	0.000000634	0.23
300	0.02977	0.000000689	0.23
350	0.03243	0.000000751	0.23
400	0.03538	0.000000819	0.23
450	0.03862	0.000000894	0.23
500	0.04214	0.000000976	0.23

Density of 8 lbm/cu. ft. or 0.0046 lbm/in³,
Thermal emissivity of 0.9,
 $k = 0.019881 + 1.56547E-005*T + 5.77381E-008*T^2$, Btu/hr-ft-°F,
Data from WHC 1976.

Table 7. Material Properties of Magnesium Oxide.

Temperature (°F)	Thermal Conductivity (BTU/Hr-Ft-°F)	Thermal Conductivity (Btu/Sec-Inch-°F)	Specific Heat (Btu/Lbm-°F)
32	38.70	0.0008959	0.21
212	26.12	0.0006047	0.25
392	18.87	0.0004367	0.265
572	14.03	0.0003247	
752	11.12	0.0002575	0.285
1112	7.25	0.0001679	
1472	4.83	0.0001119	
1832	4.11	0.0000952	0.31
2372	3.63	0.0000840	
2912	4.11	0.0000952	0.34

Density of 223 lbm/cu. ft. or 0.1293 lbm/in³,
Thermal emissivity of 0.9,
Data from Bailey 1987.

4.4 Ambient Air Temperature

For this analysis, the ambient air temperature was specified in WHC 1994a to be in the range of 32 °F to 120 °F. For a conservative assessment for tank heat up, the lower ambient temperature of 32 °F was assumed. This assumption will produce the longest heat up time. For the steady-state analysis to determine maximum insulation outer surface temperatures, an ambient temperature of 120 °F was assumed. For this analyses, the ambient air temperature was assumed to be constant.

4.5 NATURAL CONVECTION

Heat is also rejected from external surfaces of the tank to the environment by natural convection heat transfer. This mode of heat transfer depends on the temperature difference between the heat rejecting surface and the ambient air, the orientation of the heat rejecting surface, the velocity of air flowing past the surface and the thermophysical properties of air. For this analysis the air is assumed to be still (zero flow velocity) in accordance with conservative practices. The tank was modelled as a horizontal right circular cylinder. The equations describing natural convection that were used in the thermal model were taken from Holman, 1972. The equations utilized were:

for a horizontal cylindrical surface;

$$h_c = 0.22\Delta T^{1/3}$$

where;

h_c = convective heat transfer coefficient, Btu/hr-sq-ft-°F,

ΔT = Temperature difference between convective surface and ambient, °F.

For the internal gas gaps at the interface between the tank and the insulation, heat is transferred by a combination of conduction and convection. This mode of heat transfer depends on the temperature difference between the heat rejecting surfaces, the orientation of the heat rejecting surfaces, the gap width and the thermophysical properties of air at the mean air temperature. Because of the small gap size and the small temperature gradient across the gap there will be no convective effect and only gas conduction was assumed.

4.6 HEAT LOAD

For the baseline case the highest internal heat generation for the total tank was specified at 60 kWatts. This heat generation was apportioned equally over the heads and cylindrical sides of the tank. This apportionment was based upon an equal surface area basis.

The trace heater elements were assigned a specific heat generation of $9.5136E-4$ Btu/sec. per cu. inch. for the tank cylindrical surface. The trace heaters were modelled as a 1/4 inch thick elements with uniformly distributed along the length of the tank cylindrical side.

4.7 THERMAL RADIATION BOUNDARY CONDITIONS

The view factor for thermal radiation to the environment was assumed to be 1 for the tank cylindrical surface. For the internal gas gaps of the tank, the effective thermal emissivity of the gap surfaces are required boundary conditions. All emissivity values were entered as constants within the PThermal model with the emissivity values for carbon steel was specified at 0.8 and the insulation surface at 0.9.

A second set of thermal radiation boundary conditions was applied to the air gap between the tank outer surface and the insulation inner surface, a gap of 1/4 inch was assumed. The view factors for the various surfaces are calculated by the PATRAN/PVIEWFACTOR computer program from the geometric description of the thermal model.

4.8 THERMAL MODEL CASE DESCRIPTIONS

The case descriptions for the thermal analysis of the sodium drain tank are as follows.

- Case 1 consisted of a transient analysis progressing for 30 days of simulated heat up. The baseline horizontal storage tank is assumed with 60 kWatts total heat, 32 °F initial and ambient temperature and 4 inches of calcium silicate insulation.
- Case 2 consisted of a transient analysis progressing for 30 days of simulated heat up. The baseline horizontal storage tank is assumed with 60 kWatts total heat, 32 °F initial and ambient temperatures and 4 inches of refractory fiber insulation.
- Case 3 consisted of a steady state analysis. The baseline horizontal storage tank is assumed with 60 kWatts total heat, 32 °F ambient temperature and 4 inches of calcium silicate insulation.
- Case 4 consisted of a steady state analysis. The baseline horizontal storage tank is assumed with 60 kWatts total heat, 32 °F ambient temperature and 4 inches of refractory fiber insulation.
- Case 5 consisted of a steady-state analysis with 60 kW of heater power, 120 °F ambient, and 4 inches calcium silicate insulation.
- Case 6 consisted of a steady-state analysis with 30 kW of heater power, 120 °F ambient, 4 inches calcium silicate insulation.
- Case 7 consisted of a steady-state analysis with 18 kW of heater power, 120 °F ambient, 4 inches calcium silicate insulation.
- Case 8 consisted of a steady-state analysis with 12 kW of heater power, 120 °F ambient, 4 inches calcium silicate insulation.
- Case 9 consisted of a steady-state analysis with 60 kW of heater

power, 120 °F ambient, and 4 inches of refractory fiber insulation.

- Case 10 consisted of a steady-state analysis with 30 kW of heater power, 120 °F ambient, and 4 inches of refractory fiber insulation.
- Case 11 consisted of a steady-state analysis with 18 kW of heater power, 120 °F ambient, and 4 inches refractory fiber insulation.
- Case 12 consisted of a steady-state analysis with 12 kW of heater power, 120 °F ambient, and 4 inches refractory fiber insulation.

Case 1 and 2 are used to determine heat up rates for the two different insulation designs, the steady state cases, case 3 and 4, is used to determine the ultimate thermal capability of the tank design. Case 5 through 12 are used to determine the amount of heater power to maintain the sodium temperature at 400 °F and the maximum insulation outer surface temperature when the sodium temperature is at 400 °F.

5.0 ANALYSIS RESULTS

5.1 MAXIMUM TEMPERATURES - NORMAL OPERATING CONDITION

Table 1 represents a set of steady-state and peak transient temperature predictions for the various tank configurations that are evaluated at the prescribed ambient temperature for normal operating conditions. The transient cases were modelled with up to 30 days of heat up from the initial ambient temperature. These cases represent the maximum normal condition temperatures for the tank. The pertinent results from the analyses are listed below.

- The calcium silicate insulated drain tank requires a 18.5 day period to heat up to 400 °F from an initial temperature of 32 °F. The average heat up rate was determined to be 19.1 °F/day. The sodium temperature at the end of the 30 day transient was determined to be 606 °F. The maximum insulation outer surface temperature (accessible by plant personnel) was determined to be 82 °F.
- The refractory fiber insulated drain tank requires a 17.0 day period to heat up to 400 °F from an initial temperature of 32 °F. The average heat up rate was determined to be 21.7 °F/day. The sodium temperature at the end of the 30 day transient was determined to be 683 °F. The maximum insulation outer surface temperature (accessible by plant personnel) was determined to be 76 °F.
- The maximum steady state sodium temperature for the calcium silicate insulated drain tank with 60 kW of heater power was determined to be 815 °F with an ambient temperature of 32 °F and 845 °F with an ambient temperature of 120 °F. The maximum insulation outer surface temperature (accessible by plant personnel) was determined to be 177 °F.
- The maximum steady state sodium temperature for the refractory fiber

insulated drain tank with 60 kW of heater power was determined to be 976 °F with an ambient temperature of 32 °F and 997 °F with an ambient temperature of 120 °F. The maximum insulation outer surface temperature (accessible by plant personnel) was determined to be 177 °F.

- Figure 4 depicts the results of the parametric study to determine the heater power required to maintain a calcium silicate insulated drain tank at various sodium temperatures. This figure shows that 16 kW of heater power is required to maintain the sodium at 400 °F with a 120 °F ambient temperature. The figure also shows that the insulation outer surface temperatures are below 140 °F for the heater power level.
- Figure 5 depicts the results of the parametric study to determine the heater power required to maintain a refractory fiber insulated drain tank at various sodium temperatures. This figure shows that 11 kW of power is required to maintain the sodium at 400 °F with a 120 °F ambient temperature. The figure also shows that the insulation outer surface temperatures are below 140 °F for the heater power level.

5.2 RECOMMENDATIONS

Either of the two insulation designs is acceptable from a thermal standpoint. The refractory fiber design has a slightly better thermal performance. The total cost between the two designs should be the deciding factor.

A detailed thermal assessment of the tank supports was not performed in this analysis, but the following guidelines are provided;

- The tank support rings (1.5 inch by 12 inch) should be enclosed with insulation with a thickness of approximately 2 inches. This will reduce the amount of heat loss from the support ring which would behave as heat rejecting fins. Insulating the support rings will also minimize the thermal gradients and thus the thermal stresses at the ring to tank attachment area.
- The temperature of the concrete area below the tank is expected to remain at ambient conditions based upon the analyses performed for the vertical storage tanks (WHC 1995).

6.0 REFERENCES

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