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HEAT BALANCE STUDY FOR SUBMERSIBLE MIXER PUMP

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Nomenclature

A = area (ft^2 or m^2)

B = mass driving force defined in eq. (7) (--)

c = wall thickness of cooling coil tube (m or ft)

C_p = specific heat (J/kg K)

d = diameter of cooling coil (ft or m)

D = tank diameter (ft or m)

g = mass transfer conductance (kg/m^2 sec)

h = heat transfer coefficient (W/m^2 sec)

H = tank liquid level (ft or m)

k = thermal conductivity (W/m K)

m = mass fraction (--)

$\dot{m}''$ = mass flux (kg/m^2 sec)

M = Molecular weight (g)

P = pressure (Pa)

Pr = Prandtl number, $\mu C_p/k$, (--)

q = heat flux (W/m^2)

Q = heat transfer rate (watts)

r = resistance (m^2 sec/W)

R = overall heat transfer resistance (sec/W)

Re = Reynolds number, $d\rho u/\mu$ or $d\rho U/\mu$

t = time (second or hour)

T = temperature (^oC or ^oF)

v_{cf} = volumetric flowrate per coolant channel

V = total volume (m^3)

x = thickness (m)

X = mole fraction of vapor component in the mixture (--)

Greek

ρ = density (kg/m^3)

ϕ = relative humidity (--)

Γ = mass diffusion coefficient (kg/m sec)

μ = dynamic viscosity (N sec/m^2)

ν = kinematic viscosity (m^2/sec)

ω = volumetric flowrate (m^3/sec)

Subscript

air = air

avg = average

c or coil = coil

decay = radioactive decay heat

evap = evaporation

f = fluid

fouling = heat transfer fouling due to chemical deposition

g or gas = gas

H2O = water

i = inner

l or liq = liquid

m = mean

mixture = gas mixture

o = outer

out = exit or outlet

ref = reference

sens = sensible

surf = surface

t or total = total

tk = tank

w = water or wall

wall = wall surface

∞ = ambient

Abstract

A transient heat balance model was developed to assess the impact of a Submersible Mixer Pump (SMP) on waste temperature during the process of waste mixing and removal for the Type-I SRS tanks. The model results will be mainly used to determine the SMP design impacts on the waste tank temperature during operations and to develop a specification for a new SMP design to replace existing long-shaft mixer pumps used during waste removal. The model will also be used to provide input to the operation planning. This planning will be used as input to pump run duration in order to maintain temperature requirements within the tank during SMP operation.

The analysis model took a lumped parameter approach. The modeling calculations have been performed using commercial software, Aspen Custom Modeler (ACM^{TM}). A series of the modeling analyses was performed to examine how submersible mixer pumps affect tank temperature during waste removal operation in the Type-I tank such as Tank 11. The model domain included radioactive decay heat load, two SMP's, and one Submersible Transfer Pump (STP) as heat source terms.

The present model was benchmarked against the test data obtained by the Tank 11 measurement to examine the quantitative thermal response of the tank and to establish the reference conditions of the operating variables under no SMP operation. The results showed that the model predictions agreed with the test data of the waste temperatures within about 10%.

Transient modeling calculations for two potential scenarios of sludge mixing and removal operations have been made to estimate transient waste temperatures within a Type-I waste tank. In this case, a primary scenario has the 40 days' continuous operation of two SMP mixers as an initial phase of sludge mixing with no sludge transfer. The calculation results demonstrate that maximum waste temperature will reach about 91 ^{o}C when two 200-HP submersible mixers and 12 active cooling coils are continuously operated in 100-in tank level and 40 ^{o}C initial temperature for 40 days since the initiation of mixing operation. In this case, waste temperature rises about 9 ^{o}C in 48 hours at a maximum.

Sensitivity studies for the key operating variables were performed. The sensitivity results showed that the chromate cooling coil system provided the primary cooling mechanism to remove process heat from the tank during operation.

1 Introduction

Tanks 1-8 in F area and Tanks 9-12 in H area are 0.75 million-gallon, single-wall, Type-I waste tanks. The tank is a 75 ft diameter, flat-bottomed, cylindrical tank with a height of about 24.5 ft. The tank consists of a primary steel tank and secondary containment. The primary tank shell is made of 0.5-in thick carbon steel, and is constructed in accordance with Section VIII of the ASME Boiler Code for Unfired Pressure Vessels. The secondary containment is a 0.5-in thick, 80-ft diameter and 5-ft high steel pan. Inside the primary tank, there are cooling coils, a valve housing to control the coolant flow of the cooling coils, and 12 structural support columns internal to the tank. A total of 36 cooling coils are supported from the roof including two horizontal coils across the tank bottom, but only about 12 coils in Tank 11 are actually functional during normal operations [3]. Each cooling coil is 2-in Sch. 40 carbon steel, and is made of seamless pipe. It is proposed to use a Submersible Mixer Pump (SMP) to suspend and mobilize the waste in typical type-I waste tanks for sludge removal operations. A schematic of the type-I waste tank is shown in Fig. 1.

The waste tank requires more than one slurry pump during sludge removal operations. Each pump has a bottom suction with two opposing discharge nozzles. The pump is normally submerged to approximately the level of the sludge, allowing a recirculating mixture of sludge and water to serve as the feed flow. The pump nozzle is placed about 30 inches above the tank bottom [1]. Previous results [9] show that the pump location is not sensitive to the mixing performance of waste sludge within the 30-in elevation. Therefore, pump location can be assumed to have negligible impact on thermal balance due to non-uniform pump dissipation inside tank. All pumps are accessible to the waste region through tank risers as shown schematically in Fig. 1.

The waste in the tank consists of salt and sludge. The salt was removed by dissolution in water and transferred to other tanks for storage. The remaining sludge layer settled near the bottom and will be hydraulically mobilized by SMP and transferred to other tanks by a Submersible Transfer Pump (STP). Waste sludge contained in the tank has high decay heat loads due to the presence of radioactive nuclides. The present work considers the heat loads of tank waste caused by the dissipation of submersible pumps and radioactive decay of waste sludge. Detailed information for the decay heat loads of the type-I waste tanks in the F and H areas is shown in Table 1 [4].

High-level Waste Engineering is currently in the process of developing a specification for a new SMP design to replace existing long-shaft mixer pumps used during waste removal [1]. Prior to releasing the specification out for bids, it was considered necessary to perform a preliminary heat balance study to determine how the SMP design impacts waste tank temperature during waste removal operations. The primary objective of the present work is to perform a heat balance study for type-I waste tank to assess the impact of using submersible mixer pumps during waste removal. The temperature results calculated by the model will be used to evaluate the temperatures of the slurry waste under various tank operating conditions.

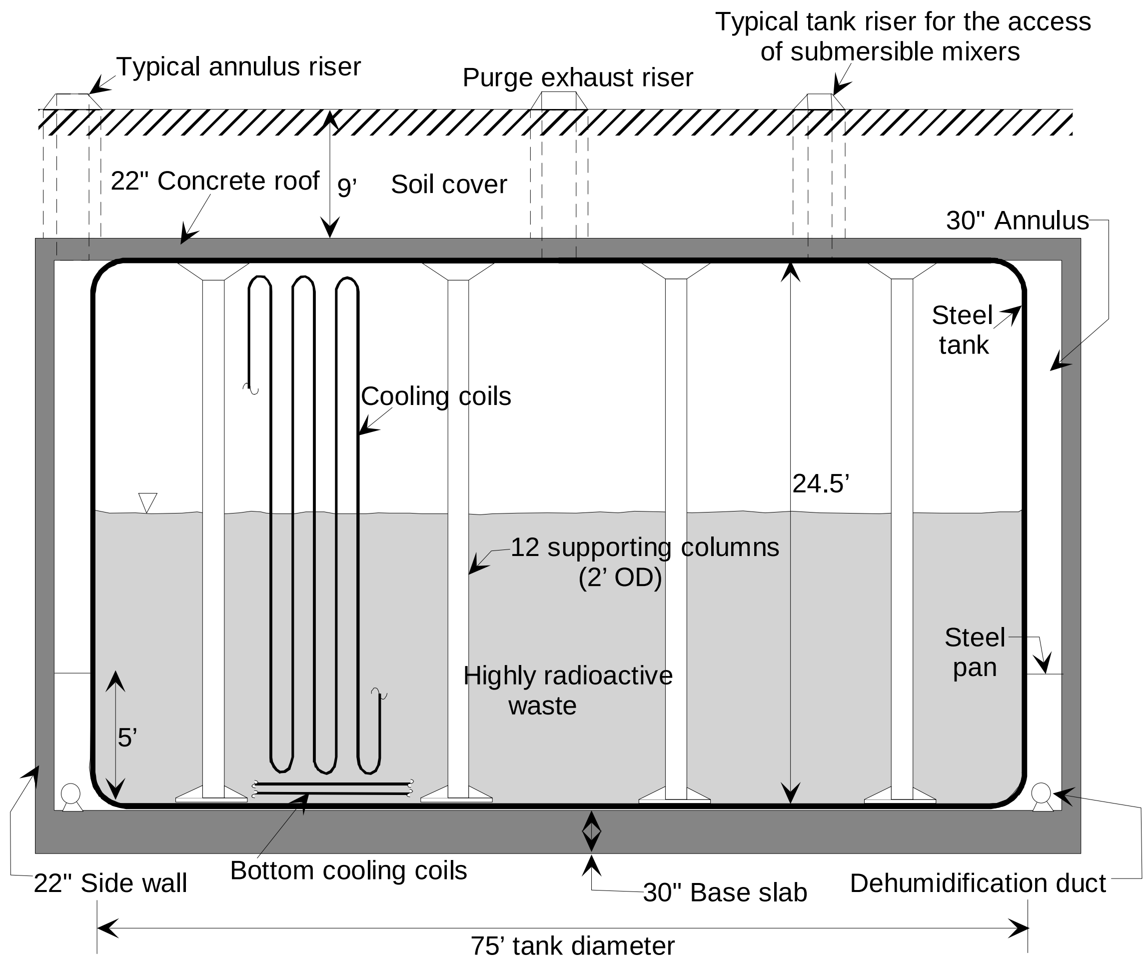


Figure 1. Typical type-I waste tank (750,000 gallons tank) used for the present analysis

2 Modeling Approach and Analysis

A lumped parametric approach was taken to develop a transient model for the heat balance study for type-I waste tanks such as Tank 11, during waste removal by Submersible Mixer Pumps (SMP). The tank domain used in the present model consists of two SMP's for sludge mixing, one Submersible Transfer Pump (STP) for the waste removal, cooling coil system with 36 coils, and purge gas system. The sludge waste contained in Tank 11 also has a decay heat load of about 43 W/m^3 mainly due to the emission of radioactive gamma rays. Thus, the tank is located below a 9-ft thick soil layer for radiation shielding as shown in Fig. 1.

All governing equations were established by an overall energy balance for the modeling domain as shown in Fig. 2, and they were solved using the Aspen Custom Modeler (ACM™) code. Detailed descriptions for the modeling assumptions and governing equations are provided below.

2.1 Model Assumptions and Overall Energy Balance

A transient heat balance model used single waste temperature model, which represents one temperature for the entire waste liquid domain contained in the tank at each transient time. Detailed descriptions for the modeling assumptions are provided below.

- Waste fluid inside 75-ft tank is always well-mixed thermally so that bulk fluid temperature and properties can be represented as volume-averaged values since submersible mixing and transfer pumps are in operation.
- Heat transfer effect from the cooling coil surface above the free surface, which is exposed to purge gas, is assumed to be negligible for conservatism.
- Structural materials such as supporting columns and pump risers are always in thermal equilibrium with slurry fluid since scoping calculations show that thermal diffusivities of structural materials are at least about 10^4 larger than that of waste fluid.
- Gas above the free surface of tank liquid consists of air-vapor mixture combined with relative humidity.
- Air and vapor of purge gas mixture obey perfect-gas behavior, and they follow the Gibbs-Dalton law for the gas mixture.
- Waste fluid follows the behavior of water evaporative cooling at the free surface.
- Soil region surrounding the tank is assumed to be infinite heat sink.

Based on the main assumptions mentioned above, an overall energy balance for the control volume of type-I SRS waste tank shown in Fig. 2 becomes

$$\rho_l C_{pl}\left(T_{liq} - T_{ref}\right)\frac{dV_l}{dt} + \rho_l C_{pl} V \frac{dT_{liq}}{dt} = \rho_l C_{pl}\, \dot{V}_{l,in}\left(T_{liq,in} - T_{ref}\right) - \rho_l C_{pl}\, \dot{V}_{l,out}\left(T_{liq} - T_{ref}\right)$$

$$+ Q_{SMP} + Q_{STP} + Q_{decay} - Q_{surf} - Q_{coil} - Q_{wall} - Q_{bottom} - Q_{str} \qquad (1)$$

In Eq. (1) heat source terms are two Submersible Mixer Pumps (SMP) Q_{SMP}, one Submersible Transfer Pump (STP) Q_{STP}, and radioactive decay heat source Q_{decay}. In the balance equation, heat sink terms are heat loss rate from the top liquid surface of waste tank Q_{surf}, heat transfer rate across the cooling coil surface due to convective coolant flow Q_{coil}, and heat loss rates from the external surfaces of the tank side and bottom walls Q_{wall} and Q_{bottom}. Q_{str} represents transient heat absorbed into the structural material, and it is assumed to be negligibly small since preliminary study shows that thermal diffusivity for tank structural material such as concrete or steel is at least 10^4 times larger than that of water. Detailed discussions for the heat source and sink terms are provided below.

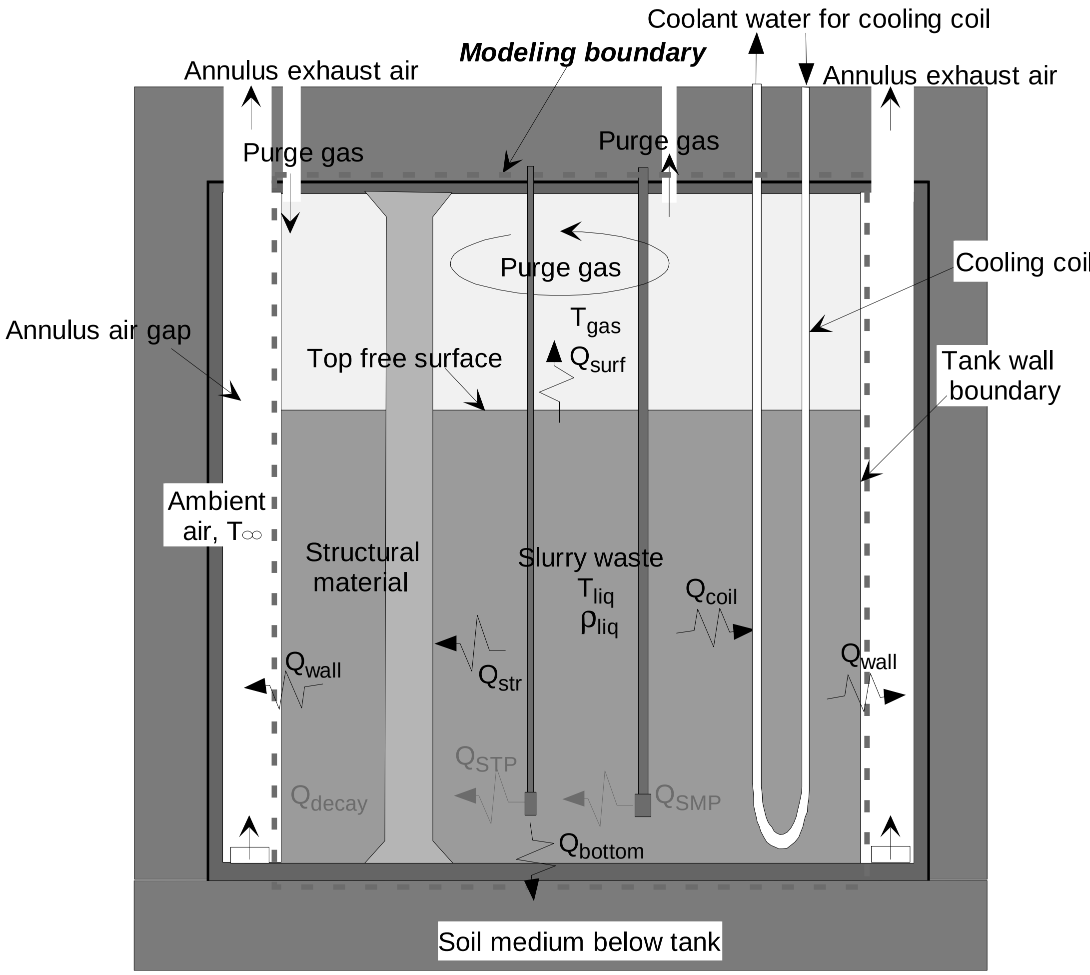


Figure 2. Modeling boundary for the heat balance study of Submersible Mixer Pump (SMP) in type-I SRS waste tank

2.2 Heat Source and Sink Terms

As discussed earlier, heat sources (Q_{SMP}, Q_{STP}, and Q_{decay}) used in Eq. (1) are due to the presence of two Submersible Mixer Pumps (SMP), one Submersible Transfer Pump (STP), and decay heat source of radioactive waste contents contained in type-I tank. Typical decay loads considered in the present work are shown in Table 1. For the present analysis, Tank 11 decay load will be used as the referenced decay heat load since the tank has the highest decay heat source in terms of overall tank heat load. Average decay heat of the tanks located in F area will be also used in the sensitivity analysis. Each SMP used in the analysis considers high pumping power in the range of 225 HP to 350 HP [1, 2]. Detailed operating conditions for the mixing pumps will be provided later.

Detailed discussions for the heat sink terms used in the overall balance equation, Eq. (1), are provided below.

Heat loss rate at the top surface of tank waste (Q_{surf})

Based on the ideal gas assumption of the purge gas mixture, mole fraction of vapor component in the mixture (X_{H2O})

$$X_{H2O} = \frac{m_{H2O} M_{mixture}}{M_{H2O}} \quad (1)$$

In Eq. (1) equivalent molecular weight of the mixture

$$M_{mixture} = X_{H2O} M_{H2O} + X_{air} M_{air} \quad (2)$$

Table 1. Decay heat loads of SRS type-I tanks for the present analysis [4]

Tank		Overall decay heat rate		Overall volumetric decay heat rate	
		(Btu/hr)	(Watts)	(Btu/hr gal)	(W/m^3)
F tank Farm	Tank 1	56,864	16,661	0.11	8.51
	Tank 2	19,747	5,786	0.04	3.09
	Tank 3	19,607	5,745	0.04	3.09
	Tank 4	151,493	44,387	0.31	23.98
	Tank 5	70,988	20,799	1.17	90.52
	Tank 6	80,442	23,570	0.26	20.11
	Tank 7	103,897	30,442	0.31	23.98
	Tank 8	4,488	1,315	0.01	0.77
	Average	63,440	18,588	0.28	21.76
H tank Farm	Tank 9	19,820	5,807	0.04	3.10
	Tank 10	3,031	888	0.02	1.55
	Tank 11*	154,371	45,231	0.55	42.58
	Average	59,074	17,309	0.20	15.73

Note:* Tank 11 decay heat was used as the reference decay heat source in the sensitivity analysis as recommended by the HLW customer.

For a perfect gas mixture, mole fraction is related to the volume and partial pressure of each component. That is,

$$X_{H2O} = \frac{V_{H2O}}{V} = \frac{P_{H2O}}{P} \tag{3}$$

In Eq. (3) V_{H2O} is the volume which substance vapor (H_2O) alone would occupy at the temperature and pressure of the mixture. P_{H2O} term of the equation is the partial pressure of the vapor in the mixed gas above the free surface inside the tank. From Eq. (2) and Eq. (3), the resulting equation becomes

$$m_{H2O} = \left(\frac{P_{H2O}}{P}\right)\left(\frac{M_{H2O}}{M_{mixture}}\right) = \left(\frac{P_{H2O}}{P}\right)\left(\frac{M_{H2O}}{\left(\frac{P_{H2O}}{P}\right)M_{H2O} + \left(\frac{P - P_{H2O}}{P}\right)M_{air}}\right) \tag{4}$$

After algebraic manipulation of Eq. (4) and use of molecular weight ratio of air to vapor gases, the relation to give the mass concentration of water vapor in the mixture is

$$m_{H2O} = \left(\frac{P_{H2O}}{1.611P - 0.611P_{H2O}}\right) \tag{5}$$

In Eq. (5), molecular weights for M_{H2O} and M_{air} are used as 18 and 29. In the present calculations, relative humidity ϕ is provided as

$$\phi = \left(\frac{P_{H2O}}{P_{H2O,sat}}\right) \tag{6}$$

In Eq. (6) $P_{H2O,sat}$ is the saturation vapor pressure of water corresponding to the transient temperature. An empirical correlation for the saturation pressure [5] in terms of absolute water temperature T is :

$$P_{H2O,sat} = exp(-38.874 + 0.29129T - 5.7014x10^{-4}T^{2} + 4.0606x10^{-7}T^{3}) \tag{6a}$$

In Eq. (6a), saturation pressure $P_{H2O,sat}$ should be in N/m^2 (or Pa), when the absolute temperature T is used in K.

In the present work, it is assumed that liquid is mainly evaporated within a boundary layer near the top surface of the tank waste. In this case, liquid mass concentrations in the boundary layer are controlled by diffusion-driven mechanism. Mass flux ($\dot{m}''$) due to evaporation across the top interfacial surface can be written in terms of water mass fraction (m_{H2O}).

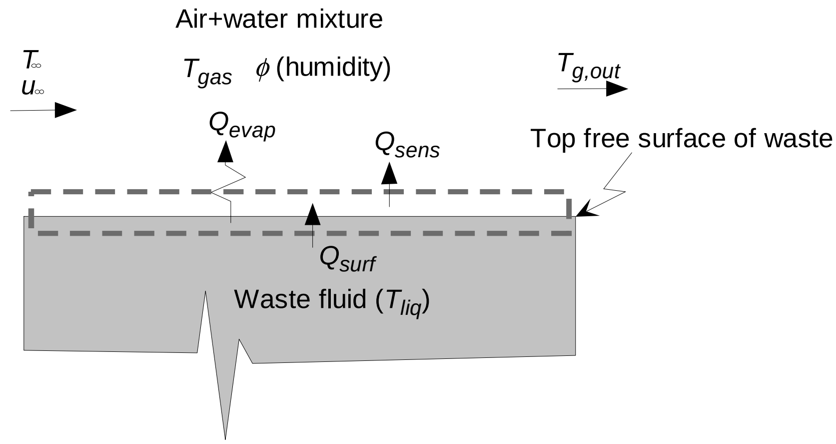


Figure 3. Control volume at the phase interface for the energy balance equation

$$\dot{m}'' = \frac{\Gamma\left(\partial m_{H2O} / \partial x\right)_i}{\left(m_{H2O} - m_{total}\right)} = g\left(\frac{m_{H2O,\infty} - m_{H2O}}{m_{H2O} - m_{total}}\right) = gB \tag{7}$$

In Eq. (7) g is the mass transfer conductance (kg/m^2 sec), corresponding to a heat transfer coefficient, and m_{total} is total concentration of water, which is equivalent to unity since water is a single-component fluid. A literature correlation for the mass transfer conductance g [6] was used to estimate the evaporative mass of fluid at the top surface of the type-I waste tank. That is,

$$g = 0.0287\,\rho_\infty u_\infty\, Pr^{-0.4}\, Re^{-0.2}\, \frac{ln(1+B)}{B} \tag{8}$$

This equation is applicable only to the fluid temperature less than its boiling temperature.

From the energy balance at the interfacial boundary of the free surface as shown in Fig. 3, total heat loss at the top surface of waste liquid Q_{surf} can be estimated in terms of sensible heat transfer Q_{sens} and evaporative cooling Q_{evap}.

$$Q_{surf} = Q_{sens} + Q_{evap} \tag{9}$$

When constitutive equations for the sensible heat loss Q_{sens} and the evaporative cooling Q_{evap} are provided, total heat loss at the surface of waste Q_{surf} can be quantified.

$$Q_{sens} = h_{surf}\, A\left(T_{liq} - T_{gas}\right) \tag{10}$$

In Eq. (10) transient bulk gas temperature above the free surface, T_{gas}, can be computed by the energy transport equation associated with total heat transfer at the free surface Q_{surf}. That is,

$$\rho_g V_g C_{pg} \frac{dT_{gas}}{dt} = \rho_\infty \omega_{g,\infty} C_{pg} \left(T_\infty - T_{ref}\right) - \rho_g \omega_{g,t} C_{pg} \left(T_{g,out} - T_{ref}\right) + Q_{surf} \quad (11)$$

In Eq. (11) $\omega_{g,\infty}$ and $\omega_{g,t}$ are purge air flowrates at the inlet and exit of the purge gas system, respectively. The flowrate $\omega_{g,t}$ can be estimated by the mixed flow of purge gas and evaporation flowrates. In this case gas temperature at the exit of purge gas system, $T_{g,out}$, is computed by the assumption that bulk gas temperature T_{gas} represents the arithmetic mean temperature of the inlet and exit temperatures. Using the notations presented in Fig. 3, gas temperature at the exit of the purge gas system becomes

$$T_{g,out} = 2T_{gas} - T_\infty \quad (12)$$

In Eq. (10), the heat transfer coefficient at the surface (h_{surf}) was estimated by the literature correlation [7] for the cooled plate facing upward. That is,

$$h_{surf} = 0.61\left({\Delta T}/{L^2} \right)^{0.2} \quad (13)$$

For a typical condition of the present analysis, h_{surf} was found to be about 0.5 W/m^2 sec.

The evaporative cooling term Q_{evap} is expressed in terms of mass flux $\dot{m}''$ and enthalpy for latent heat of evaporation i_{fg}.

$$Q_{evap} = \dot{m}'' A \left\{ i_{fg} + C_{pl} \left(T_{liq} - T_{ref}\right) \right\} \quad (14)$$

In Eq. (14) C_{pl} and T_{liq} are specific heat and temperature of liquid, respectively. In this case evaporative mass flux term can be evaluated by the constitutive equations, Eq. (5) through (8), for the estimation of total heat loss due to purge gas at the top free surface of waste tank. It should be emphasized that the empirical correlation, Eq. (8), for evaporative mass flux due to the purge gas flow is valid only for single-phase liquid. If fluid temperature exceeds its boiling temperature, the evaporative mass transfer at the free surface is assumed to be a constant value corresponding to the boiling temperature since the present work is concerned only with non-boiling situation for the evaluation of thermal impact due to operation of the SMP mixers.

Heat loss rate at the surface of cooling coil (Q_{coil})

For the quantitative evaluation of heat transfer through the cooling coil system with chemical deposition on the outer surface of the coil as shown in Fig. 4, energy balance equations for the modeling boundary of cooling coil are constructed for the normal operating conditions with forced convective coolant flow. That is,

$$\left(T_f - T_{wc1}\right) = \frac{Q_{coil}}{h_{fo} A_{cwo}} = R_{fo} Q_{coil} \tag{15}$$

$$\left(T_{wc1} - T_{wc2}\right) = \frac{c Q_{coil}}{k_c A_{cm}} = R_c Q_{coil} \tag{16}$$

$$\left(T_{wc2} - T_{cm}\right) = \frac{Q_{coil}}{h_{fi} A_{cwi}} = R_{fi} Q_{coil} \tag{17}$$

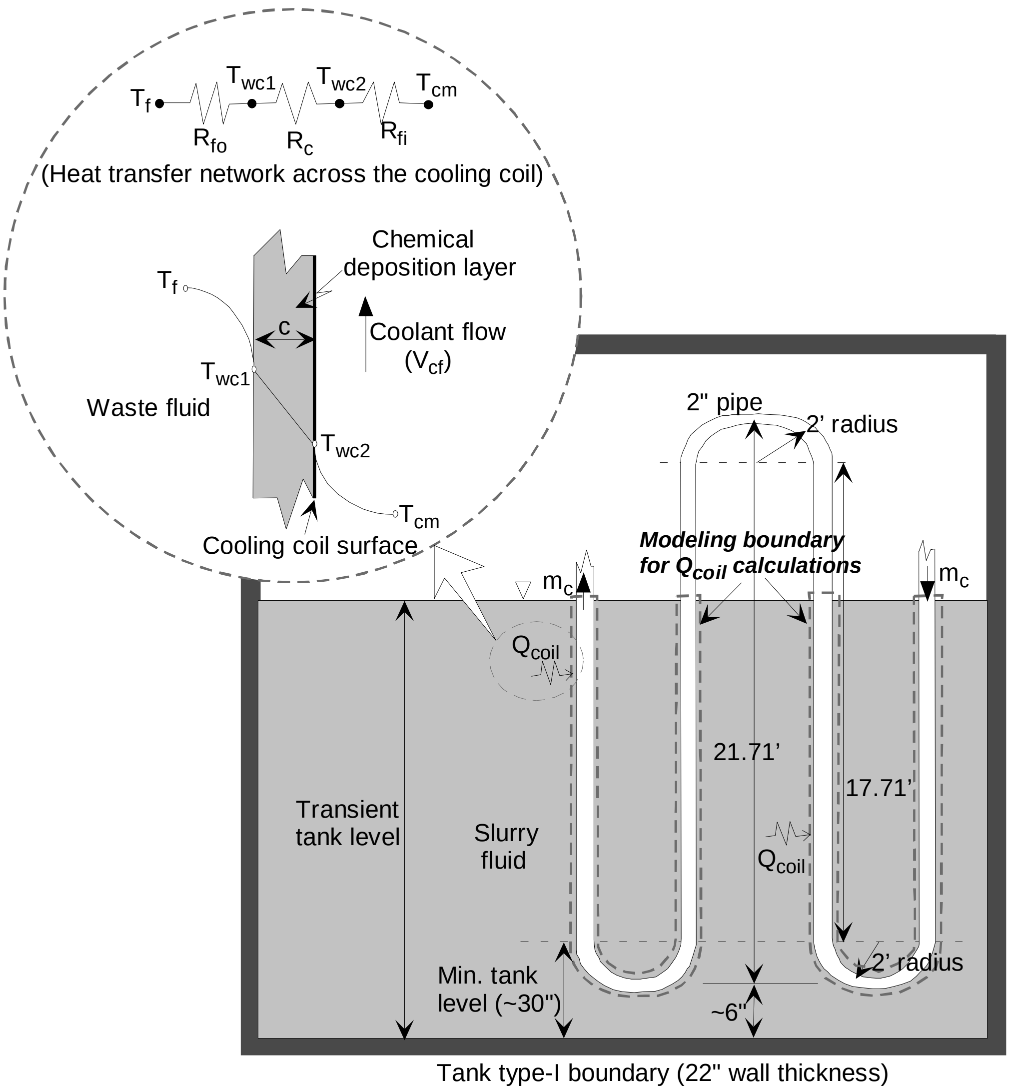


Figure 4. Modeling boundary for heat transfer calculations due to the presence of cooling coil flow (Q_{coil})

In Eqs. (15) to (17), transient energy accumulation during the heat transfer across the coil surface is assumed to be negligible. The heat transfer resistances, R_{fo}, R_c, and R_{fi}, are for thermal boundary layer external to the coil surface, for the chemical deposition layer of thickness c, and for thermal boundary layer of the inner surface of the coil, respectively. A_{cwo} and A_{cwi} are total wetted areas of the outer and inner walls of the cooling coils, respectively. A_{cm} in Eq. (16) is logarithmic average of area for an annular deposition layer of the outer coil diameter d_{co}.

$$A_{cm} = \frac{2\pi c L_{wc}}{ln\left(\frac{d_{co}+2c}{d_{co}}\right)} = \frac{2cA_{cwo}}{d_{co}\, ln\left(\frac{d_{co}+2c}{d_{co}}\right)} \tag{18}$$

Wetted surface area of the cooling coil (A_{cwo}) in Eq. (18) is dependent on transient tank level (L_{wc}). Important elevation levels for the type-I tank are shown in Fig. 6. In the present analysis, nominal tank level is used as 100 inches from the tank bottom as provided by the customer [1]. Other notations of the variables used in the equations are presented in Fig. 2. In Eq. (17), mean bulk temperature of coil coolant flow, T_{cm}, is used as an arithmetic average of the inlet and outlet temperatures, T_1 and T_2.

$$T_{cm} = \frac{1}{2}\left(T_1 + T_2\right) \tag{19}$$

In this case, when nominal coolant flow v_{cf} is given, temperature difference between the inlet and exit of the cooling coil flow is related to the convective energy transfer through the cooling coil system with N_c active cooling coils out of total 36 available cooling coils. The horizontal cooling coil located near the bottom of the tank, which is always wet regardless of the tank level, is assumed to be inactive as one of the reference operating conditions for conservative estimation. However, the sensitivity analysis for the active bottom cooling coil will be performed.

$$\left(T_2 - T_1\right) = \frac{Q_{coil}}{N_c \rho_f v_{cf} C_p} \tag{20}$$

After algebraic manipulations of the equations, Eq. (15) to Eq. (20), the resulting equation for the heat transfer rate due to the presence of the N_c cooling coils (Q_{coil}) can be obtained in terms of waste fluid temperature T_f and cooling coil inlet temperature T_1.

$$Q_{coil} = \left(T_f - T_1\right)\left(\frac{1}{h_{fo}A_{cwo}} + \frac{c}{k_c A_{cm}} + \frac{1}{h_{fi}A_{cwi}} + \frac{0.5}{N_c \rho_f \dot{v}_{cf} C_p}\right)^{-1} \tag{21}$$

In Eq. (21) heat transfer coefficient for the external surface of cooling coil (h_{fo}) was estimated by the theoretical formulation for constant heat flux with laminar flow condition found in the literature [6]. That is,

$$h_{fo} = 4.364\frac{k_f}{d_{co}} \tag{22}$$

In Eq. (22) k_f is thermal conductivity for waste fluid. In this case material and thermal properties of water were used for the estimation of the heat loss across the external surfaces of the cooling coils.

Heat transfer coefficient for the inner wall surface of the cooling coil (h_{fi}) in Eq. (21) was evaluated by the literature correlation for the forced convection [12], which is known as Dittus-Boelter equation. That is,

$$h_{fi} = 0.023\left(\frac{k_{fw}}{d_{ci}}\right) Re_d^{\,0.8}\, Pr^{\,0.4} \tag{23}$$

In Eq. (23) k_{fw} is thermal conductivity for water. Non-dimensional numbers of Reynolds number (Re_d) and Prandtl number (Pr) in the equation were defined in terms of water properties and cooling coil diameter. For the referenced nominal conditions, Reynolds number was found to be about 10^5, which corresponds to the turbulent flow regime. Thus, the empirical correlation Eq. (23) is applicable to the present work.

Heat loss rates through the side wall and bottom of tank (Q_{wall} and Q_{bottom})

For the evaluation of heat transfer across the side wall of type-I waste tank as shown in Fig. 5, a plane wall is assumed to be exposed to a hot waste fluid 1 on one side and a cooler fluid 2 on the other side for the evaluation of overall heat transfer coefficient U. In this case the heat transfer process is represented by the resistance network shown in Fig. 5.

$$Q_{1\rightarrow 2} = Q_{wall} = U\,(T_{f1} - T_{f2}) \tag{24}$$

In Eq. (24) overall heat transfer coefficient U becomes

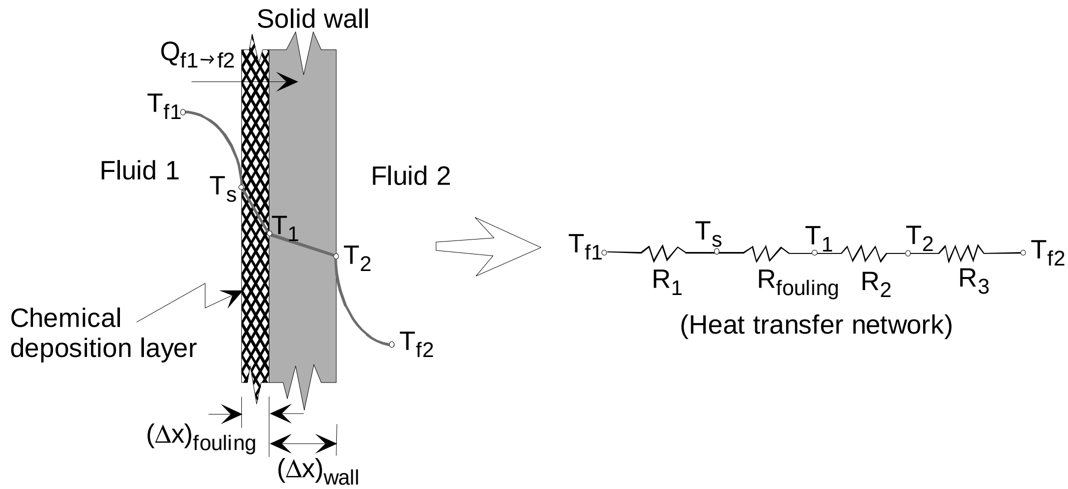
$$U = (R_1 + R_{fouling} + R_2 + R_3)^{-1} \tag{25}$$

The resistances, R_1, R_2, and R_3, are written in terms of thermal properties for the materials. That is,

$$R_1 = \frac{1}{h_{f1}A},\; R_{fouling} = \frac{(\Delta x)_{fouling}}{k_{fouling}A},\; R_2 = \frac{(\Delta x)_{wall}}{k_{wall}A},\; R_3 = \frac{1}{h_{f2}A} \tag{26}$$

Heat transfer rate through the tank bottom (Q_{bottom}) can be evaluated in the same way as that of the wall heat loss (Q_{wall}), replacing the thermal resistance of air, R_3, with that of soil material.

Now, all constitutive equations associated with the transient heat balance equation, Eq. (1), are complete. In this case, transient tank boundary conditions are required to compute transient temperature for each material region of the waste tank system. Transient responses of heat loads are dependent on initial volume of the waste stored in the tank. Waste volumes for the ranges of tank levels to be used in the analysis are shown in Table 2.



(Temperature profile across the tank wall boundary)

Figure 5. Overall heat transfer through a tank wall

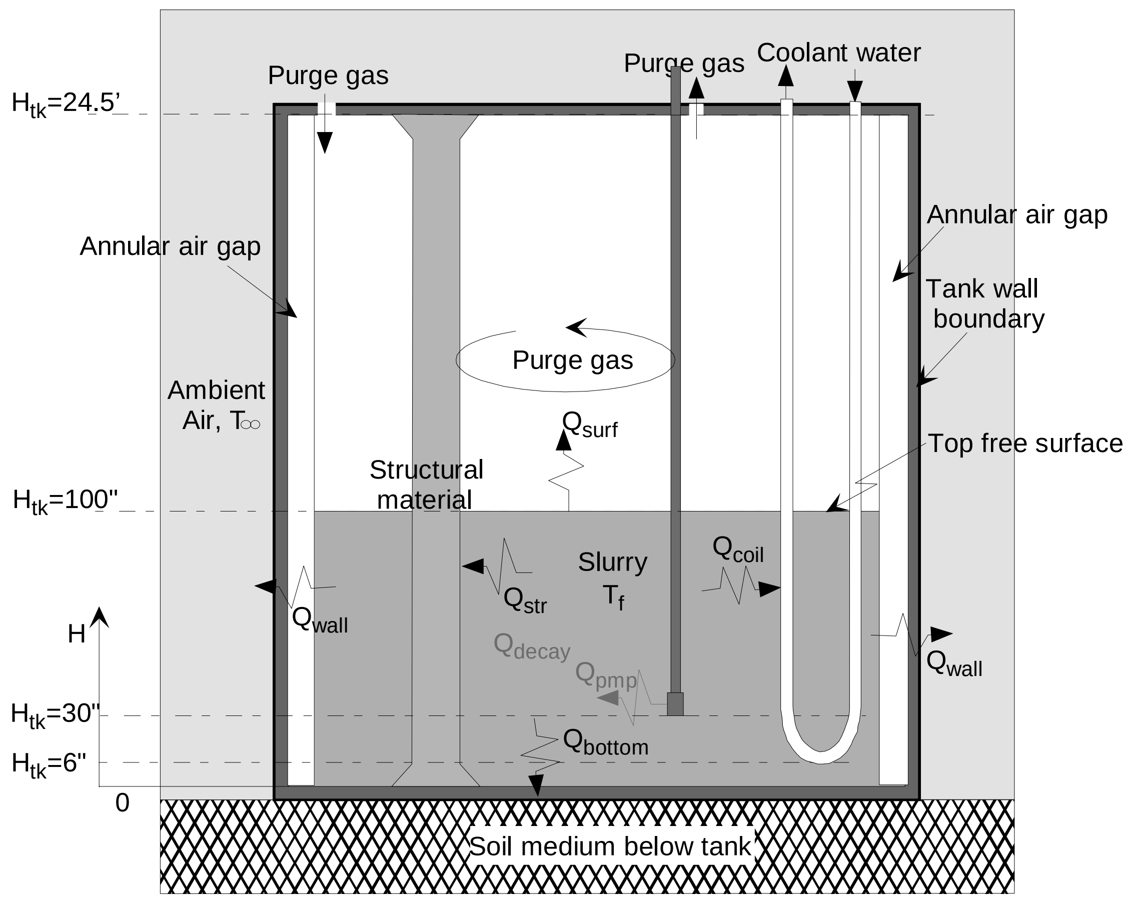


Figure 6. Tank elevations used for the energy balance equations in tank slurry mixing

3 Results and Discussions

Based on the analysis methodology and the modeling assumptions, a transient heat balance model has been developed by using a lumped parametric approach. Overall energy balance equations for typical SRS type-I waste tank such as Tank 11 were constructed for the modeling domain as shown in Fig. 2. The modeling governing equations were solved using Aspen Custom Modeler (ACM™) software for the transient boundary conditions provided by the operational procedure for the sludge mixing and removal [1, 2, 3, and 4]. List of the coding and all variables used in the model under the ACM environment are provided in Appendix 2 and Appendix 3, respectively.

For the present analysis, two scenarios of the waste tank operations are considered to estimate thermal impact of Submersible Mixer Pumps (SMP's) on waste fluid during the process of waste removal. One scenario is the original operational plan as provided by the earlier version of TTR [1]. The original plan was the 10 days' initial mixing followed by three cycles of waste removal and refilling operations as shown in Fig. A.1 in Appendix 1. The other scenario is related to the updated plan with 40 days' initial mixing with constant tank level, which was recently modified by the TTR adjustment [4]. This plan is the primary one since these changes of the updated plan are due to the proposed tank changes made and information found as part of the initial draft review on the results of the original plan.

In the present work, one scenario is related to the long period of sludge mixing (40 days' initial mixing) with continuous pump operations under fixed tank level, and the other simulates the shorter period of the initial mixing (10 days' initial mixing) with three cycles of waste removal and refilling operations (5 days' mixing for each cycle). The results for the continuous mixing with constant tank level are presented in this section since this scenario is the primary choice for the operations of the SRS type-1 tanks. All detailed sensitivity results and discussions for the second scenario are provided in Appendix 1.

The primary goal of the present work is to assess the thermal performance impact of the slurry pumps on waste fluid in the process of sludge mixing and removal in the tank and to provide the operational information and design guidance for the replacement of the existing mixer pumps. In addition, sensitivity studies for the key variables of tank operation are performed to investigate what parameters are most sensitive to the thermal response of the waste tank to the SMP operations.

3.1 Model Benchmarking

The present model was benchmarked against the test data obtained by the Tank 11 measurement to examine the quantitative thermal response of tank waste to decay heat loads under no pump operation. HLW Engineering has made continuous measurements for the sludge and supernate temperatures for Tank 11 since January 1997. The measurement data for the one-month period of December 2000 [3], when cooling coil system was restored from previously inactive status, was used for the model benchmarking. The reference operating conditions were used in the benchmarking. They are presented in Table 3. The thermal properties used in the calculations are shown in Table 4. The results showed that the model predictions agreed with the test data for the waste temperature within about 10% as shown in Fig. 7. Thus, the uncertainty of the present calculations was quantified by the benchmarking test for the reference operating conditions as defined in Table 3.

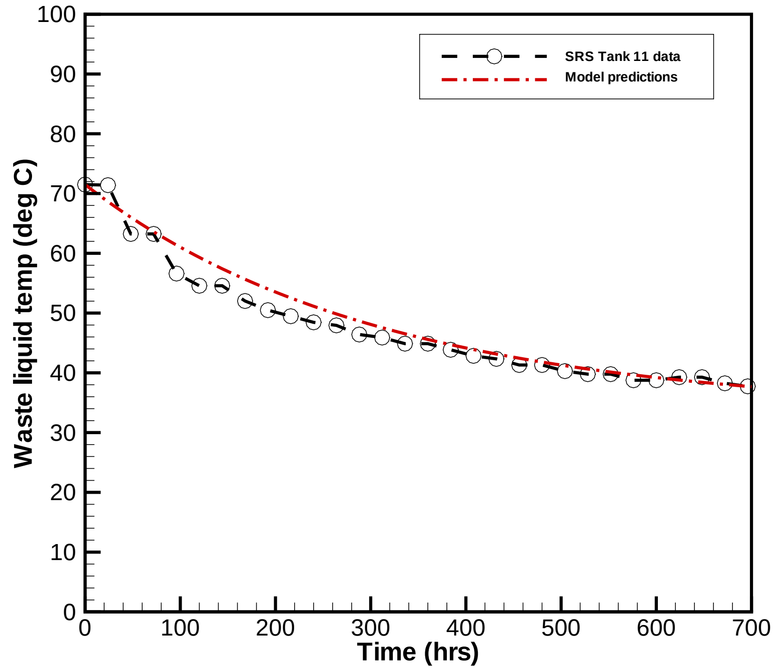


Figure 7. Comparison of transient waste temperatures between Tank 11 measurements and the model predictions for the reference conditions.

3.2 Modeling Calculations and Sensitivity Results for Constant Tank Level

Primary operation plan for the sludge mixing of the SRS tank type-1 is shown in Fig. 8. As shown in the figure, the initial sludge mixing will be performed by continuous operation of Submersible Mixer Pumps (SMP's) under fixed tank liquid level for 40 days. Waste volumes corresponding to the initial tank levels to be used in the analysis are shown in Table 2. In the present analysis, a tank level of 100 inches will be used for the mixing operation as one of the reference conditions shown in Table 3. The operational conditions and modeling results for the sludge mixing with variable tank level allowing for the waste transfer and refilling operations are provided in the Appendix.

Transient calculations have been made for the 40-day continuous operations of the sludge mixing under the fixed tank level and analyses performed to estimate transient waste temperatures within the type-I tank for various operating conditions when the tank has two SMP's during operation. As discussed earlier, it is assumed that pumping energy of the slurry mixers and decay heat loads of the sludge waste are dissipated uniformly and instantaneously through the entire fluid region of the tank.

The reference boundary and initial conditions shown in Table 3 were used to evaluate the thermal response of the tank system to decay heat loads and two SMP mixers. A series of the modeling calculations was performed to assess how submersible mixer pumps affect tank temperature during waste removal in type-I tank such as Tank 11. Table 4 shows thermal and heat transfer properties of tank components used for the present analysis. A sensitivity analysis of key operating variables with respect to their reference nominal conditions was performed in association with the cooling performance of the waste tank. The sensitivity variables used for the analysis are listed in Table 5. The calculation results show that the chromate cooling coil water system is the primary mechanism to remove the heat from the tank during operation. Detailed results for transient thermal responses of the waste tank to different SMP powers under the reference operating conditions are discussed here.

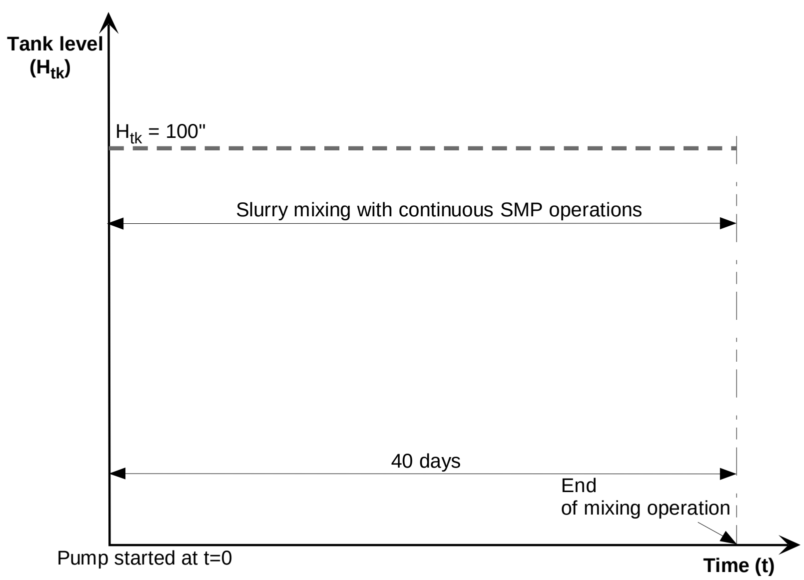


Figure 8. Sludge mixing operation curve used in the present analysis

Table 2. Waste volumes corresponding to various tank levels

Tank levels (inches)	Waste volume		
	(m^3)	(gallons)	(ft^3)
75	770.37	203,511	27,205
90	924.66	244,270	32,654
100	1,027.52	271,443	36,286
120	1,233.25	325,791	43,551
130	1,336.11	352,964	47,184

Table 3. Reference operating conditions for heat balance study of the type-1 waste tank during the initial 40 days' mixing period

Operating parameters	**Reference operating conditions**
Tank dimension (diameter x height)	75 ft x 24.5 ft
Initial temperature of waste fluid	40 ^{o}C (65 ^{o}C)*
Initial tank level	100 in (from 90 in to 130 in)*
Purge gas temperature at inlet	25 ^{o}C
Waste fluid density	1.2 sg (1.35 and 1.4 sg's)*
Coolant temperature at coil inlet	25 ^{o}C
Cooling coil surface condition	Surface with no chemical deposition**
Number of operating cooling coils out of total 36 cooling coils	12 (24 and 34)*
Bottom cooling coil availability	Not available
Flowrate per cooling coil	5.7 gpm corresponding to 200 gpm for 35 cooling coils
Purge gas flowrate	500 scfm (250, 300, 400 scfm)*
Relative humidity	97 %
Number of operating pumps	2 SMP's and 1 STP (1 SMP and 1 STP)*
Pumping power of each submersible mixing pump (SMP)	200 HP (from 150 HP to 350 HP with 25 HP increment)*
Pumping power of each submersible transfer pump (STP)	25 HP
Transfer pump flowrate	(no transfer during mixing)
Tank refill flowrate	(no refilling during mixing)
Max. decay heat of Tank 11 waste (average decay heat of type-I tanks)	42.58 W/m^3 [0.55 Btu/hr gal] (21.76 W/m^3 [0.28 Btu/hr gal])*

Note: *conditions used for the sensitivity analysis of the present model
**information provided by the customer [2]

Table 4. Thermal and heat transfer properties of tank components used for the present analysis

Region (material) [Ref.]	**Material thickness**	**Thermal conductivity or heat transfer coeff. used in the analysis**
Cooling coil (carbon steel) [Rohsenow and Choi, 1961]	0.154 in	43.24 (W/mK)
Waste fluid (slurry) [Kays and Crawford, 1980]	---	0.615 (W/mK)
Waste liquid film (water) [Kays and Crawford, 1980]	---	0.1173 (W/m^2K)*
Purge gas film layer (air) [Holman, 1969]	---	0.5 (W/m^2K)**
Tank wall (carbon steel) [Rohsenow and Choi, 1961]	0.5 in	43.24 (W/mK)
Chemical deposition layer (salt compound) [SRS-HLW]	0.5 in***	0.43 (W/mK)
Concrete [Rohsenow and Choi, 1961]	30 in	1.107 (W/mK)
Soil [Marsily, 1986]	---	1.4 (W/mK)

Note:* Heat transfer coefficient is based on constant wall heat flux correlation available in the literature.

** Heat transfer coefficient is based on natural convection correlation for flat plate available in the literature.

*** Data provided by the customer (for tank wall and bottom)

Table 5. Parameters used for the sensitivity study of the type-1 waste tank analysis

Operating or physical parameters (dimension unit)	Sensitivity study ranges of each parameter
Decay heat (W/m^3)	From 21.76 (avg.) to 42.58 (Tank 11)*
Initial temperature of waste fluid (^oC)	From 40* to 65
Cooling coil inlet temperature (^oC)	From 10 to 41.7, (25)*
Number of cooling coils operated (---)	6, 12*, 24, and 34
Bottom cooling coil availability among the active cooling coils (---)	From no bottom coil available* to one bottom coil available
Initial tank liquid level (inches)	From 90 to 130, (100)*
Number of SMP operations (---)	From 1 to 2*
SMP powers (HP)	From 150 to 350 with every 25 HP increment, (200)*
Purge gas flowrate (scfm)	From 250 to 500, (500)*
Waste fluid density (s.g.)	From 1.2 to 1.4, (1.2)*

Note: * Nominal reference operating conditions in the present analysis.

As one of the reference conditions for the thermal analysis of the type-I tank, decay heat load of Tank 11 was used in the calculations since it has the highest decay heat source among the type-I tanks located in F and H tank farm areas as shown in Table 1. When 100 inches of initial tank level and 40 ^oC of initial waste temperature were used as the reference conditions, maximum waste temperature was about 91 ^oC at the end of the first 960 hours' mixing operation, which is just before the beginning of the first waste transfer. In the calculations, the tank operation curve shown in Fig. 9 was applied to the model as the transient boundary conditions. In this case, the dominant heat load comes from the operation of two 200 HP SMP mixers. The decay heat load corresponding to the waste content of Tank 11 is about only 15 % of the heat dissipated by two SMP's. The results show that the cooling coil system is the dominant heat removal mechanism, compared to other potential heat sinks such as evaporative cooling from the top surface of the tank and convective heat transfer through the tank wall. Those heat source and sink terms for the reference operating conditions shown in Table 3 are quantitatively compared in Fig. 10. Thermal responses of waste tank to the variations of the SMP powers from 150 HP to 350 HP with every 25 HP increase have been evaluated when each SMP horsepower of two SMP's increased from 150 HP to 350 HP with every 25 HP increment. The calculation results of maximum tank temperature and temperature increase rate for each SMP power are summarized in Table 6. As one of the transient thermal responses to the reference SMP power of total 400 HP, maximum increase rate of waste temperature is about 9 ^{o}C in two days under the reference operating conditions defined by Table 3.

Transient temperatures for waste fluid, purge gas, and cooling coil water under the reference operating conditions are presented in Fig. 11. In the calculations, 12 active cooling coils were used as one of the reference nominal operating conditions as established by the benchmarking test. The results show that the purge gas temperature is more sensitive to the waste temperature at each transient time, compared to the cooling coil water since the gas specific heat is much smaller than the water.

Table 6. Calculation results of maximum waste temperatures for different SMP powers (other operating conditions used for the reference mixing conditions as defined in Table 1)

SMP powers (HP)	Max. waste temperature		Max. temperature increase rate
	^{o}C	^{o}F	^{o}C increase in 48 hrs
150	78	173	7
175	85	185	8
200*	91	196	9
225	97	206	10
250	101	213	11
275	107	224	12
300	113	236	13
325	120	248	14
350	127	260	16

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

It is noted that steady state temperature for each material region is reached in about 800 hours (corresponding to about 34 days) after initiation of tank operation under the reference operating conditions. Thus, steady-state thermal responses of the waste tank system are reached during the first 40 days' operations.

Sensitivity runs have been performed to investigate what physical variables are most sensitive to the waste temperature with respect to the reference conditions. Detailed sensitivity results for each variable are provided below.

Decay Heat

When average decay heat load (21.8 W/m^3) of the F-area tanks was used instead of the referenced decay heat (42.6 W/m^3) for the sensitivity run, maximum waste temperature was found to be about 88 ^{o}C, which is 3 ^{o}C lower than the reference case, Tank 11 decay heat. Figure 12 compares transient waste temperatures for the two different decay heat loads under the reference tank level (100 in). In this case, other operating parameters including the initial waste temperature were kept at the reference values as given by Table 3. Table 7 shows that waste temperature is not sensitive to the decay heat load since it is small fraction (about 14 %) of total heat load dissipated by the two SMP and one STP as discussed earlier. Table 8 presents the sensitivity results for the two different decay heat loads under various initial tank levels.

Table 7. Sensitivity results of maximum waste temperatures for the tank with different decay heats under various SMP powers (other operating conditions used for the reference mixing conditions as defined in Table 3)

SMP powers (number of SMP's)	**Max. waste temperature**			
	Tank 11 decay heat (0.55 Btu/hr gal)		Average decay heat (0.28 Btu/hr gal)	
	^{o}C	**^{o}F**	**^{o}C**	**^{o}F**
150 HP (2)	78	173	75	166
200 HP (2)	91*	196*	88	190
250 HP (2)	101	213	99	210
300 HP (2)	113	236	110	229
350 HP (2)	127	260	123	253

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Table 8. Sensitivity results of maximum waste temperatures for different decay heats (other operating conditions used for the reference conditions as defined in Table 3)

Physical parameter		**Decay heat loads**	
		Tank 11 decay heat (0.55 Btu/hr gal)	Average decay heat (0.28 Btu/hr gal)
Max. waste temperature (90 in tank level)	^oC	95	92
	^oF	203	198
Max. waste temperature (100 in tank level)	^oC	91	88
	^oF	196	190
Max. waste temperature (120 in tank level	^oC	85*	81
	^oF	184*	177
Max. waste temperature (130 in tank level)	^oC	82	78
	^oF	179	172

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Initial Waste Temperature

When initial waste temperature changes from the reference condition (40 ^oC) to 65 ^oC, maximum waste temperature for the 40 ^oC case is about 1 ^oC lower than the reference case near 960 hours' transient time from the beginning of operation, which is just before the first transfer of tank waste. The transient results are compared in Fig. 13. The temperature difference becomes smaller and smaller with transient time when steady-state thermal equilibrium approaches after the initial mixing operation as shown in Fig. 13. Maximum waste temperatures for the two different initial conditions are compared for various tank levels in Fig. 14. Detailed results for the two different values of initial waste temperatures are summarized in Table 9. Sensitivity results of different initial tank levels for two different initial temperatures of waste have also been performed as shown in Table 10. The results show that maximum waste temperature is decreased by about 13 ^oC when initial tank level is increased by 40 in from 90 in to 130 in.

Table 9. Sensitivity results of maximum waste temperatures for the tank with different initial waste temperatures under various SMP powers (other operating conditions used for the reference mixing conditions as defined in Table 3)

SMP powers (HP)	**Max. waste temperature**			
	40 °C initial temperature		**65 °C initial temperature**	
	°C	**°F**	**°C**	**°F**
150	78	173	79	174
200	91*	196*	92	197
250	101	213	101	214
300	113	236	114	237
350	127	260	128	262

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Table 10. Sensitivity results of maximum waste temperatures for two different initial temperatures of waste (other operating conditions used for the reference conditions as defined in Table 3)

Physical parameter		**Initial waste temperatures**	
		40 °C (104 °F)	65 °C (149 °F)
Max. waste temperature of Tank 11 (90-in tank level)	°C	95	96
	°F	203	204
Max. waste temperature of Tank 11 (100-in tank level)	°C	91*	92
	°F	196*	197
Max. waste temperature of Tank 11 (120-in tank level)	°C	85	85
	°F	184	185
Max. waste temperature of Tank 11 (130-in tank level)	°C	82	83
	°F	179	180

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Cooling Coil Inlet Temperature

Ambient temperature is assumed to be 25 °C (about 77 °F) in the reference run as shown in Table 3. The inlet temperature of the purge gas and its initial gas temperature are assumed to be equal to ambient temperatures. In this case, the inlet temperature of the cooling coil water is also assumed to be ambient temperature to estimate the thermal impact of tank waste, since the exit water of the cooling coil is indirectly cooled by ambient temperature through heat exchanger such as cooling tower.

For the sensitivity runs with respect to ambient temperature, three different ambient temperatures, 10 °C, 25 °C, and 42 °C, were considered including the reference value. For the reference tank level (100 in), maximum waste temperature during the initial 40 days' continuous SMP operation varied from 79 °C to 101 °C when ambient temperature changes from 10 °C to 42 °C. The results for the two different tank levels are shown in Table 11. As shown in the table, it is noted that when initial tank level becomes higher, maximum waste temperature is more sensitive to ambient temperature because of the increased wet surface area of the cooling coils.

Table 11. Sensitivity results of maximum waste temperatures for different ambient temperatures (other operating conditions used for the reference conditions as defined in Table 3)

Physical parameter		**Cooling coil inlet temperature (based on 12 cooling coil operation)**		
		10 °C (50 °F)	25 °C (77 °F)	41.7 °C (107 °F)
Max. waste temperature of Tank 11 (100-in tank level)	°C	79	91*	101
	°F	174	196*	214
Max. waste temperature of Tank 11 (130-in tank level)	°C	68	82	96
	°F	155	179	204

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Number of Active Cooling Coils

As mentioned earlier, 12 coils out of total 36 cooling coils available in the tank were assumed to be active as one of the reference operating conditions from the benchmarking test and the customer's information [2, 3]. In this case, the cooling coil located near the bottom of the tank was assumed to be inactive for conservative estimation of waste temperature since the entire cooling coil is spread horizontally above the bottom surface of the tank and it has 100% wetted coil surface. Another reason for this was to consider the fact that the bottom coil has poor heat transfer capability due to fouling of the coil surface as provided by the customer's information [3].

Sensitivity results of maximum waste temperatures for different number of active cooling coils have been performed under different SMP powers using the reference conditions for other operating conditions. The results showed that maximum waste temperature decreased by 26 ^{o}C when 24 cooling coils are in active operation instead of the referenced 12 coils. All the results for different numbers of active cooling coils and different powers of the mixing pumps are compared in Table 12 and Table 13. In Table 14 maximum waste temperatures for four different tank levels are compared between the two different numbers of active cooling coils. When two different numbers of active cooling coils cool down tank waste under the reference operating conditions for the other parameters as shown in Table 3, Figure 15 and Figure 16 show the results of maximum waste temperatures for the systems with the two cooling coils as a function of tank level.

When one bottom coil out of 12 total active cooling coils was assumed to be active, maximum waste temperature decreased by about 12 ^{o}C, compared to the reference case. Table 15 compares the results for the two cases for various tank levels. As the initial tank level increased, the difference of maximum waste temperatures between the two cases decreased since the cooling capability of the other 11 vertical cooling coils increased due to the increase of wetted surface area. Detailed results are presented in Figs. 17 and 18.

Table 12. Sensitivity results of maximum waste temperatures for the tank with 24 active cooling coils under different SMP powers (other operating conditions used for the reference mixing conditions as defined in Table 3)

SMP powers (HP)	**Max. waste temperature**				**Max. temperature increase rate**	
	12 coils		**24 coils**		**(^{o}C/48 hrs)**	
	^{o}C	**^{o}F**	**^{o}C**	**^{o}F**	**12 coils**	**24 coils**
150	78	173	56	133	7	4
200	91*	196*	65	148	9*	7
250	101	213	73	163	11	9
300	113	236	81	177	13	11
350	127	260	88	191	16	13

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Table 13. Sensitivity results of maximum waste temperatures for the tank with 34 active cooling coils under different SMP powers (other operating conditions used for the reference mixing conditions as defined in Table 3)

SMP powers (HP)	**Max. waste temperature**				**Max. temperature increase rate (^oC/48 hrs)**	
	12 coils		**34 coils**			
	^oC	**^oF**	**^oC**	**^oF**	**12 coils**	**34 coils**
150	78	173	49	121	7	3
200	91*	196*	56	132	9*	5
250	101	213	62	143	11	7
300	113	236	68	154	13	9
350	127	260	74	166	16	11

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Table 14. Sensitivity results of maximum waste temperatures for two different number of cooling coils operated (other operating conditions used for the reference conditions as defined in Table 3)

Max. temperatures for different initial tank levels	**Number of cooling coils operated**			
	12 cooling coils		24 cooling coils	
	^oC	^oF	^oC	^oF
90 in	95	203	67	153
100 in	91*	196*	65	148
120 in	85	184	61	141
130 in	82	179	59	138

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Table 15. Sensitivity results of maximum waste temperatures for the bottom cooling coil operated (other operating conditions used for the reference conditions as defined in Table 3)

Max. temperatures for different initial tank levels	**12 active cooling coils**			
	No active bottom coils		1 active bottom coil	
	^oC	^oF	^oC	^oF
90 in	95	203	82	179
100 in	91*	196*	79	175
120 in	85	184	75	167
130 in	82	179	74	164

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Initial Tank Level

The 100-in initial tank level was used as one of the reference operating conditions as provided by the operational procedure of waste removal [4]. Sensitivity studies of the initial tank level were performed to examine the temperature responses of the waste tank system to different tank levels for the reference operating conditions except for the tank level. When the initial tank level reduced from the reference level, 100 in, to the reduced level, 90 in, maximum waste temperature increased about 4 ^oC higher than the reference level at the end of the initial 40 days' continuous mixing. Figure 19 shows comparison of transient waste temperatures for various tank levels under the reference mixing operation conditions. Detailed results for the sensitivity study of the initial tank levels are summarized in Table 16. The results show that waste temperature is about 9 ^oC increase in two days in the maximum. Note that the increase rate of the transient waste temperature becomes higher as the initial tank level becomes lower since the wetted surface area of the active cooling coils is reduced for given heat sources including two SMP's and decay heat.

It is important to perform the sensitivity studies of the initial tank level and the SMP power to the waste temperature when the number of active cooling coils is increased from the referenced nominal conditions (12 active coils) to 24 active coils. The summary results are shown in Table 17.

Table 16. Sensitivity results of maximum waste temperatures for various tank liquid levels (other operating conditions used for the reference mixing conditions as defined in Table 1)

Tank levels (inches)	**Max. waste temperature**		**Max. temperature increase rate**
	^oC	^oF	^oC/48 hrs
90	95	203	10
100*	91	196	9
120	85	184	7
130	82	179	7

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Table 17. Sensitivity results of maximum waste temperatures for various tank liquid levels under two different numbers of active cooling coils (other operating conditions used for the reference mixing conditions as defined in Table 1)

Tank liquid levels	**Max. waste temperature**							
	2 SMP's (200 HP each)				**2 SMP's (250 HP each)**			
	12 active coils		24 active coils		12 active coils		24 active coils	
inches	^oC	^oF	^oC	^oF	^oC	^oF	^oC	^oF
90	95	203	67	153	105	221	76	168
100	91*	196*	65	148	101	213	73	163
120	85	184	61	141	95	204	68	154
130	82	179	59	138	92	198	66	151

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Powers of Submersible Mixer Pump (SMP)

Transient calculations have been made for the initial 40-day operation of the mixing with constant tank level to estimate transient waste temperatures within type-I waste tank when the tank has two Submersible Mixer Pumps (SMP's) and one Submersible Transfer Pump (STP) for sludge removal operation as the reference conditions.

As discussed earlier, the dominant heat load is from the referenced operation of two 200 HP SMP mixers, and the highest decay heat load among the type-I waste tanks, which is generated by the Tank 11 waste. This decay heat is about only 14 % of the two-SMP dissipation heat under the reference operating conditions as discussed earlier. In this case, comparisons of transient waste temperatures are made for a range of SMP powers from 150 HP to 350 HP with 12 active cooling coils as shown in Fig. 20. When each of two SMP powers is increased from the reference case (200 HP) to 250 HP, maximum waste temperature increases from 65 ^{o}C to 73 ^{o}C for 24 active cooling coils available in the tank system. The detailed results are shown in Fig. 21. Figure 22 also shows comparisons of the results for different SMP powers under three different cases of active cooling coils. When the number of the SMP units is reduced from two to one, maximum waste temperature decreased by 27 ^{o}C during the initial 40 days' mixing period under the reference tank level. The sensitivity results of the initial tank levels are shown in Table 18. The results are also compared in Fig. 23.

Table 18. Comparison of maximum waste temperatures between two SMP's and one SMP operations (other operating conditions used for the reference conditions as defined in Table 3)

Pump horse powers for each SMP	Max. waste temperature			
	2 SMP's operation		1 SMP operation	
	^{o}C	^{o}F	^{o}C	^{o}F
150 HP	78	173	57	135
200 HP	91*	196*	64	147
250 HP	101	213	71	159
300 HP	113	236	77	171
350 HP	127	260	84	183

Note: * This case corresponds to the results of the reference operating conditions.

In case of one-mixer operation instead of two-mixer tank operation, the impact of the SMP powers on maximum tank temperature was also examined. When initial tank level changed from 90 in to 130 in, maximum temperature of the waste tank changed from 67 ^{o}C to 60 ^{o}C under the reference SMP power as shown in Table 19. For instance, the maximum temperature reached 67 ^{o}C when the tank level had 90 inches using one 200 HP SMP mixer and the reference decay heat load.

Table 19. Comparison of maximum waste temperatures between 2 SMP's and 1 SMP operations (other operating conditions used for the reference conditions as defined in Table 3)

Initial tank level	**Max. waste temperature**			
	2 SMP's operation		1 SMP operation	
(inches)	^{o}C	^{o}F	^{o}C	^{o}F
90	95	203	67	153
100*	91*	196*	64	147
120	85	184	61	142
130	82	179	60	139

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Waste Fluid Density

For the reference operating conditions except for waste density, the transient calculations for three different waste densities have been performed to examine the sensitivity of waste temperature associated with the change of waste material property.

As shown in Table 3, 1.2 specific gravity (sg) of waste density was used as one of the reference operating conditions as provided by the customer [1]. For the sensitivity analysis of the waste fluid properties, different densities of 1.2, 1.35, and 1.5 sg were used for the same specific heat. When the waste density was increased from the reference value (1.2 sg) to 1.35 sg, maximum waste temperature of the waste tank system operated by two 200 HP SMP mixers was reduced by 1 ^{o}C due to the increased thermal inertia. Detailed results for the two different waste densities are compared under various SMP powers in Table 20. Transient temperatures of the 1.2 sg density waste are compared among the three different waste densities in Fig. 24.

Table 20. Comparison of maximum waste temperatures between two different waste densities for various SMP powers (other operating conditions used for the reference conditions as defined in Table 3)

SMP horse powers (number of SMP's)	**Max. waste temperature**			
	1.20 sg waste		**1.35 sg waste**	
	^{o}C	^{o}F	^{o}C	^{o}F
200 HP (2)	91*	196*	90	194
250 HP (2)	101	213	100	212
300 HP (2)	113	236	112	233
350 HP (2)	127	260	125	257

Note: * This case corresponds to the results of the reference operating conditions.

Purge Gas Flowrate

As shown in Table 3, 500 scfm purge gas flow was used as one of the reference operating conditions. Sensitivity study of the gas flow was performed to examine how gas flow affects the coolability of the waste tank system.

When the gas flow changed from the reference value (500 scfm) to 250 scfm under the reference conditions for other operating parameters as defined in Table 3, maximum temperatures of waste and coolant coil water were changed no more than 1 ^{o}C, but the gas temperature was increased by about 10 ^{o}C since specific heat capacity of gas is much smaller than that of the liquid waste. In Fig. 11, transient temperatures for waste, cooling coil water, and purge gas during 40 days' operations of initial waste mixing with 100 in tank level are shown. Table 21 compares maximum transient temperatures for the four different gas flowrates for the 200 HP and 225 HP SMP powers under the reference conditions for other parameters as shown in Table 3.

Table 21. Sensitivity results between two different SMP powers for various purge air inlet flowrates during the 40 days' initial mixing with 100 in tank level (other operating conditions used for the reference conditions as defined in Table 3)

Purge air inlet flow	**2 SMP's (200 HP each SMP)**			**2 SMP's (225 HP each SMP)**		
	Max. waste temp.	Gas temp.	Purge gas exit flow	Max. waste temp.	Gas temp.	Purge gas exit flow
250 scfm	92 °C	67 °C	254 scfm	98 °C	82 °C	258 scfm
300 scfm	92 °C	64 °C	305 scfm	98 °C	79 °C	309 scfm
400 scfm	91 °C	60 °C	406 scfm	97 °C	74 °C	411 scfm
500 scfm	91 °C*	57 °C*	507 scfm*	97 °C	70 °C	513 scfm

Note: * This case corresponds to the results of the reference operating conditions.

Summary of Sensitivity Results

Sensitivity calculations for the operating parameters were performed by the heat balance model for the SRS type-I waste tank system equipped with SMP mixers. The results show that number of active cooling coils and coil flowrate are dominant cooling mechanisms to control waste tank temperature for given SMP mixer power. As discussed earlier, the nominal reference conditions defined in Table 3 are considered the best-estimate operating values. The modeling results show that the waste temperature rises a maximum 9 °C in 48 hours under the reference operating conditions during the initial 40 days' continuous mixing with constant tank level. Figure 11 shows transient peak temperatures of waste during 40 days' operations with two 200-hp SMP. As shown in the figure, the waste fluid reaches steady temperature cycling in about 800 hours since the initiation of tank operations under the reference conditions. It is also emphasized that the power dissipated by the SMP mixers provides the dominant heat source term, compared to the radioactive decay heat load of the tank waste. Table 5 shows a summary of the sensitivity parameters performed in the present analysis.

From the heat balance analysis, it is concluded that maximum temperature of the tank type-I waste will remain below boiling temperature (100 °C) when waste removal is processed with the heat source terms of two units of 225 HP SMP mixers and Tank 11 decay heat. The analysis used the reference operating conditions listed in Table 3 and the operational procedure of waste removal shown in Fig. 8. All the sensitivity analyses demonstrate that maintaining active cooling coil system provides important cooling mechanism to remove the process heat from the waste tank system.

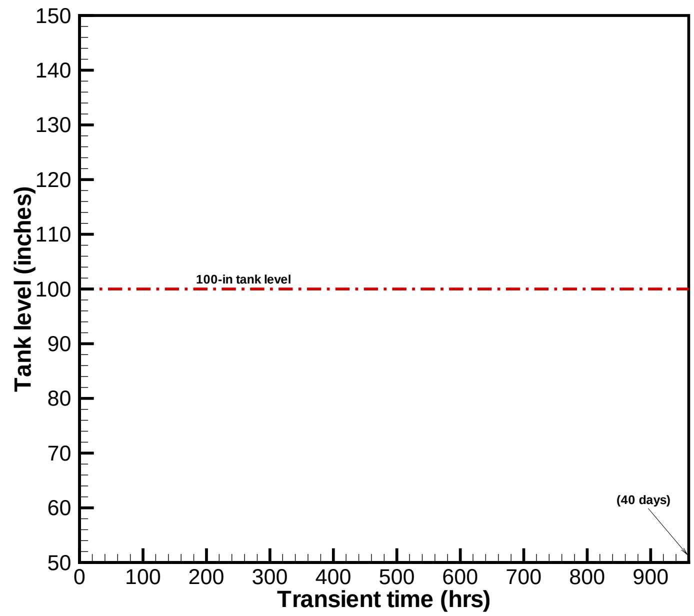


Figure 9. Transient liquid level of submersible slurry pumps (SMP) for tank type-I waste mixing

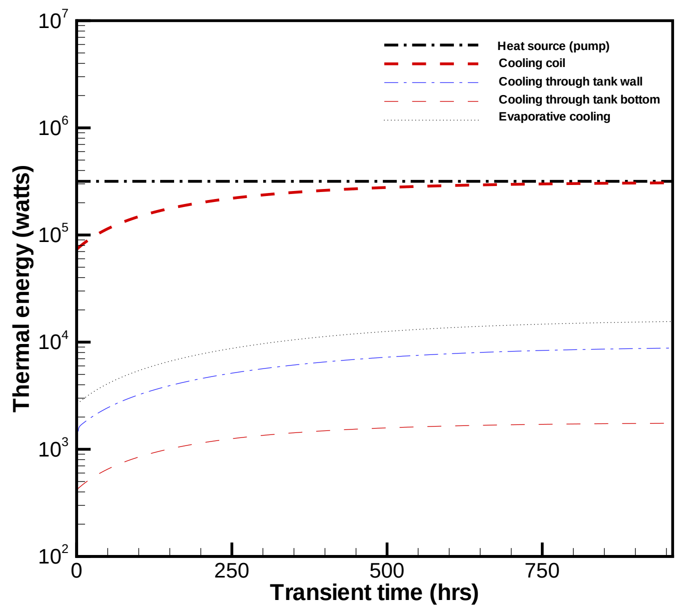


Figure 10. Transient heat source and sink for the reference operating conditions as shown in Table 3

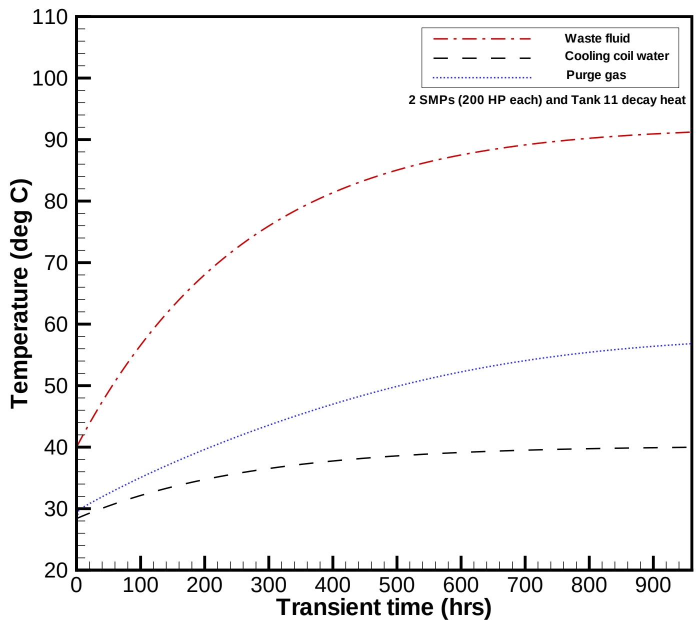


Figure 11. Transient temperatures of waste liquid, purge gas, cooling coil exit for the reference operating conditions as shown in Table 3 (showing maximum 9 ^{o}C temperature increase in 48 hours)

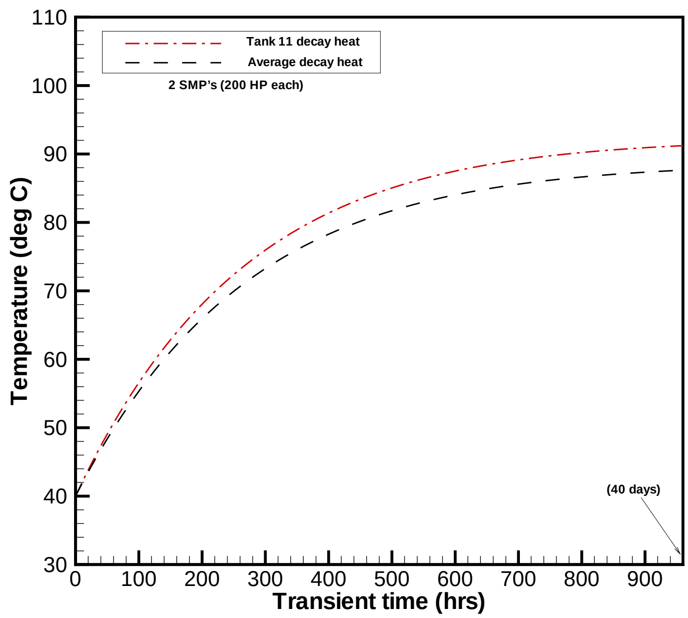


Figure 12. Comparison of transient waste temperatures for two different decay heats under the reference mixing operation conditions

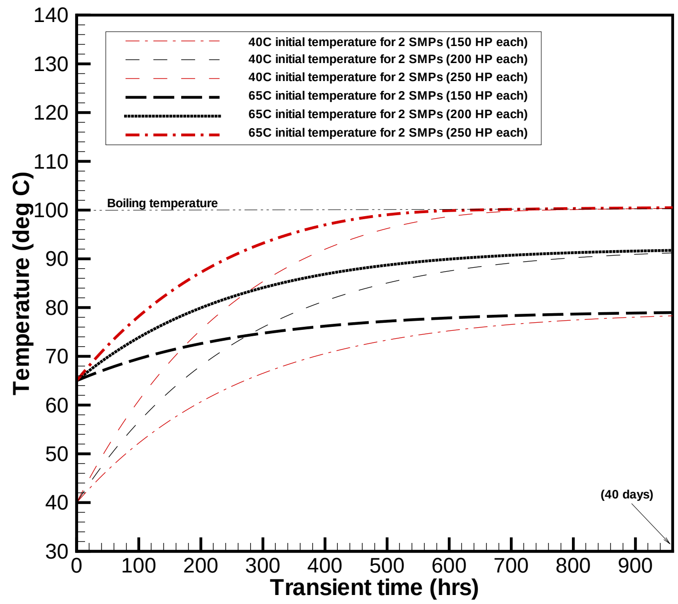


Figure 13. Comparison of transient waste temperatures for two different initial waste temperatures (40 ^{o}C and 65 ^{o}C) for the reference conditions of the other parameters as shown in Table 3

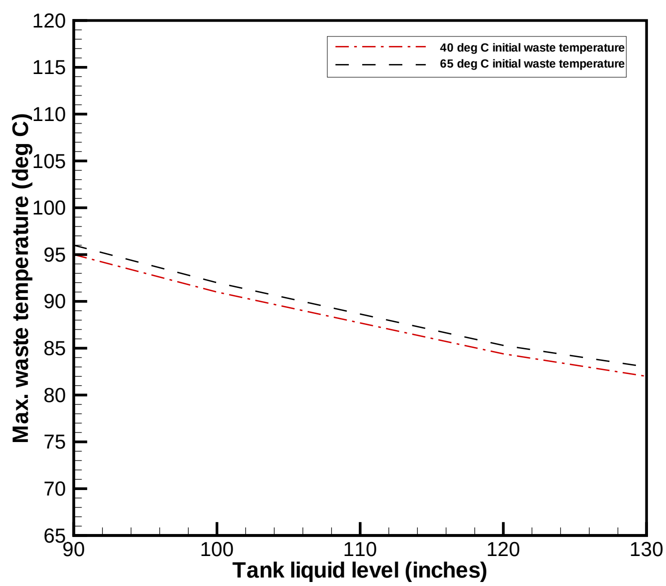


Figure 14. Comparison of maximum waste temperatures for two different initial waste temperatures (40 and 65 ^{o}C) for the reference conditions of the other parameters as shown in Table 3

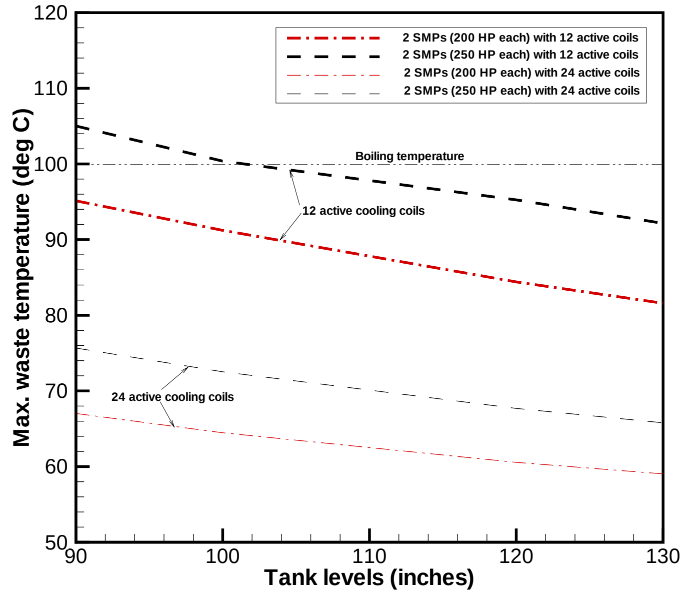


Figure 15. Comparison of maximum waste temperatures for various tank levels with two different numbers of active cooling coils under the reference mixing operation conditions of the other parameters as shown in Table 3

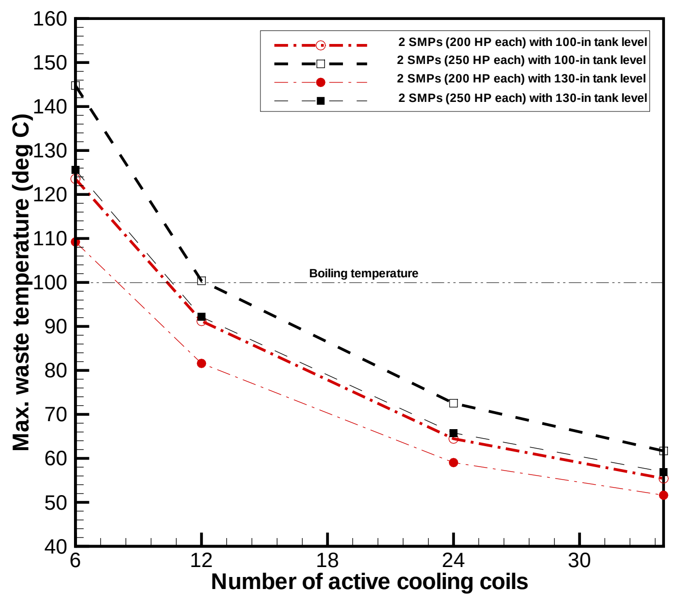


Figure 16. Comparison of maximum waste temperatures for different SMP powers as function of number of active cooling coils

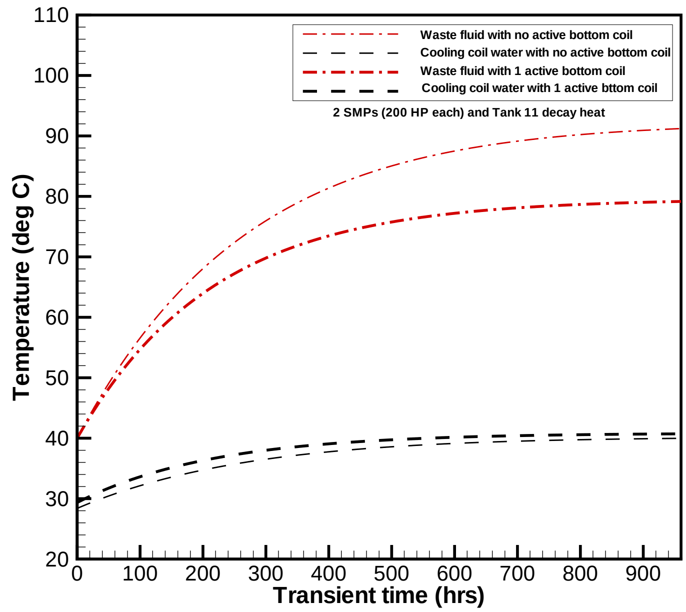


Figure 17. Comparison of transient waste temperatures between with and without active bottom cooling coil operations for the reference conditions of the other parameters as shown in Table 3

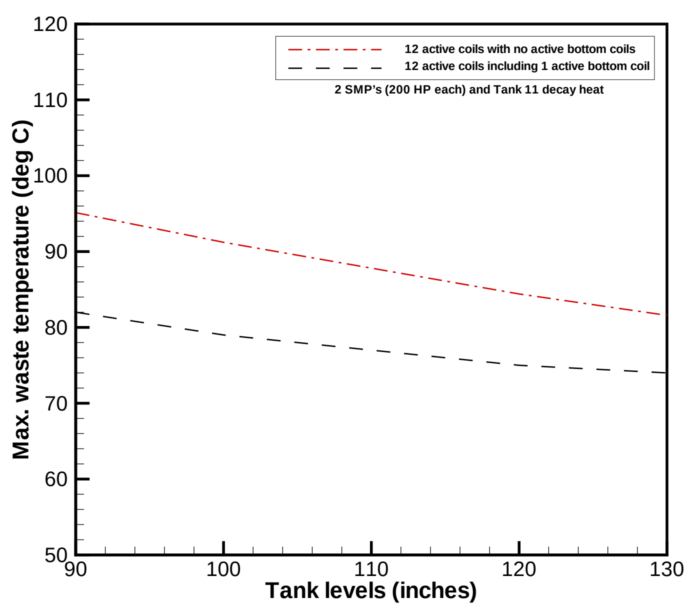


Figure 18. Comparison of transient waste temperatures for various tank levels between no active bottom coil and one active bottom coil using the reference operating conditions of the other parameters as shown in Table 3

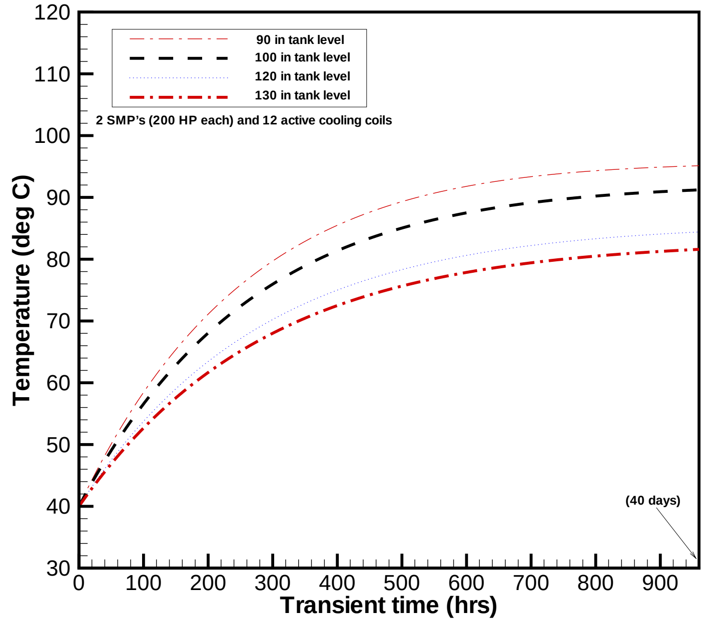


Figure 19. Comparison of transient waste temperatures for various tank levels under the reference mixing operation conditions during the initial 40 days' mixing period

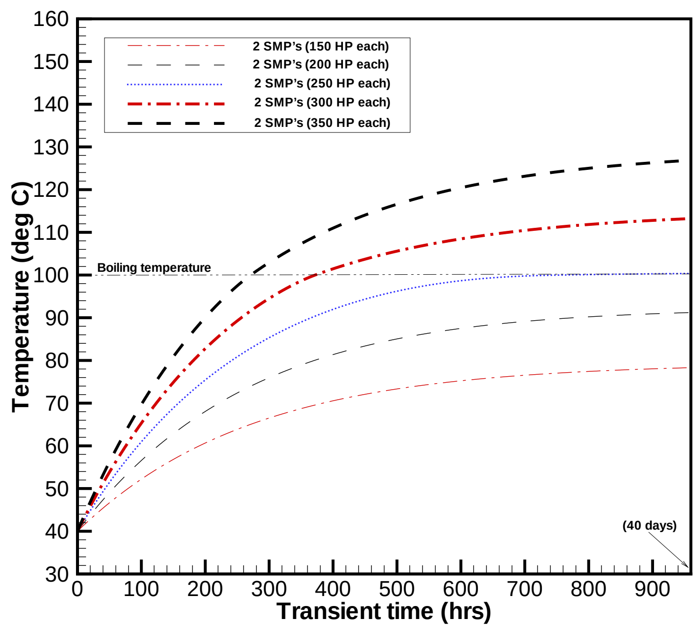


Figure 20. Comparison of transient waste temperatures for different SMP powers based on 12 active cooling coils

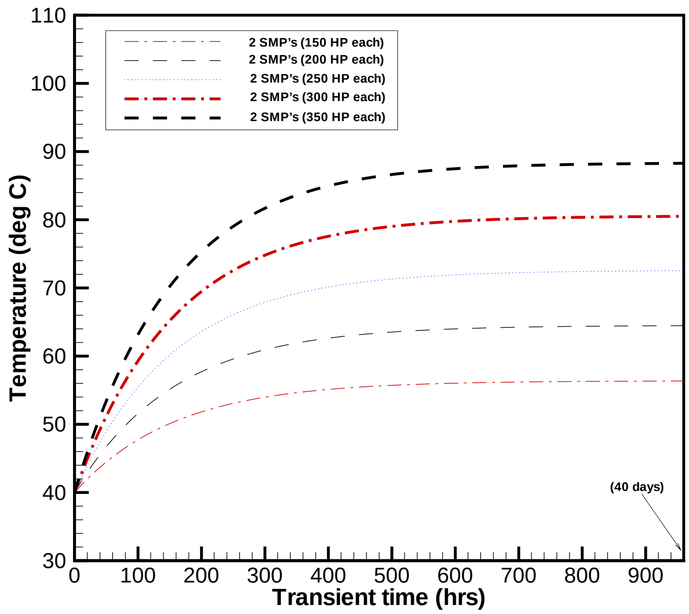


Figure 21. Comparison of transient waste temperatures for different SMP powers based on 24 active cooling coils

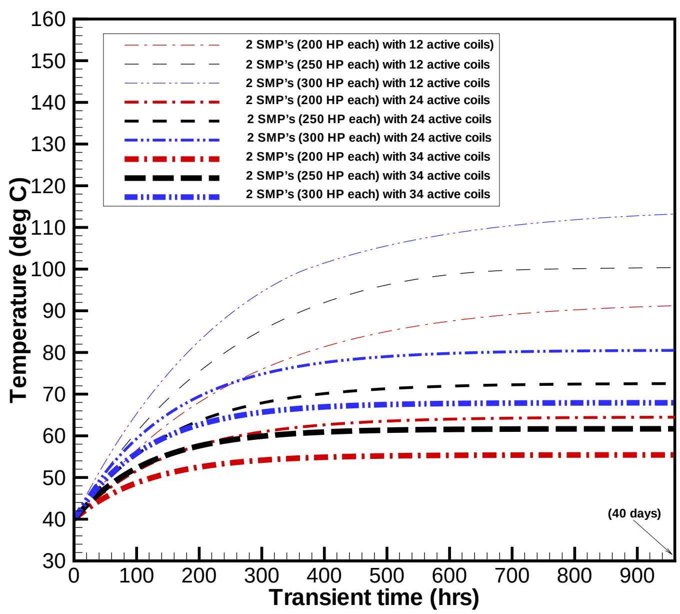


Figure 22. Comparison of transient waste temperatures for different number of active cooling coils using the reference operating conditions of the other parameters as shown in Table 3

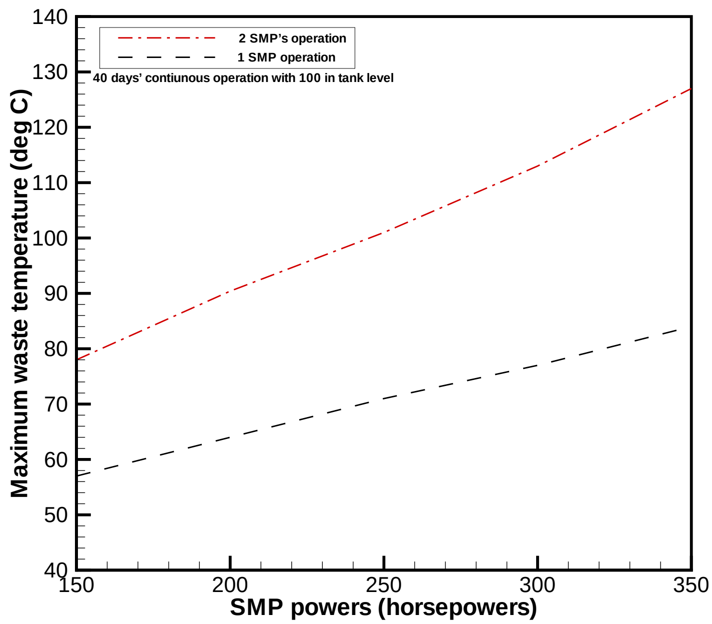


Figure 23. Comparison of maximum waste temperatures between two SMP's and one SMP operations under the reference mixing operation conditions of the other parameters as shown in Table 3

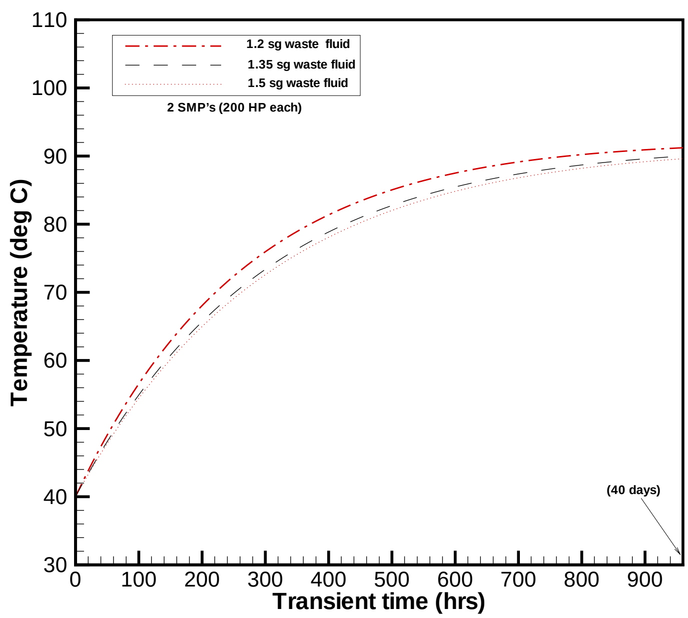


Figure 24. Comparison of transient waste temperatures for different waste fluid densities under the reference mixing operation conditions

4 Conclusions

Transient heat balance analysis for the SRS Type-I tank such as Tank 11 were performed to assess the impact of using Submersible Mixer Pump (SMP) on the coolability of the tank waste contents during waste mixing and removal operations. The reference conditions of the variables used in the balance model were established by the test data and design information provided by the customer [1,2,3,4]. The reference operating and design conditions are listed in Table 3.

For the present analysis, a lumped parametric approach was taken to develop a transient model for the heat balance study for type-I tank waste during the waste removal operated by the SMP mixers. The tank domain used in the model includes two SMP's for the sludge mixing, one Submersible Transfer Pump (STP) for the waste removal, a cooling coil system with 12 active coils as one of the reference nominal conditions, and purge gas system. Typical waste contained in Tank 11 has decay heat load of about 43 W/m^3 due to the presence of radioactive materials. All the governing equations were established by the overall energy balance for the modeling domain, and they were numerically solved using the Aspen Custom Modeler (ACM™) code. The results computed by the present model with no SMP operation were compared with test data for benchmarking. The results showed that the model predictions agreed with the test data for the waste temperature within about 10%.

In the analysis two potential operational scenarios were considered for transient modeling calculations to estimate transient waste temperature for the operational domain and to perform the sensitivity studies of key operating parameters. They are 40 days' continuous mixing with no sludge removal during the initial phase of operation as a primary updated option and 10 days' initial mixing followed by 15 days of subsequent three-cycle waste removal operation as a secondary original option. The modeling results for the original option including the detailed sensitivity analyses for all physical parameters related to the tank operations are summarized in Appendix 1.

The results for the primary option show that a maximum waste temperature is reached consistently at the end of the initial mixing of waste (40 days after the initiation of the operation) and it reaches steady-state conditions for the tank system. In this case, the purge gas temperature closely follows the waste temperature at each transient time, and it is very sensitive to the change of the waste temperature, compared to the thermal response of the cooling coil water. It is noted that steady temperature for each material region is reached in about 800 hours from the beginning of tank operations under the reference conditions.

Sensitivity studies for the key variables of tank operations were performed to investigate what physical variables are most sensitive to the waste temperatures with respect to the reference conditions. The results show that the number of active cooling coils and coil flowrate are dominant cooling mechanisms to control waste tank temperature for given SMP power and decay heat load. It is emphasized that the power dissipated by SMP provides dominant heat source term, compared to the radioactive decay heat load of the type-I tank waste.

The calculation results for the reference operating conditions including two 200-HP mixers and 12 active cooling coils show that waste temperature rises about 9 ^oC in 48 hours at a maximum during the initial 40 days' mixing operation. It is concluded that maximum temperature of tank waste will remain well below boiling temperature (100 ^{o}C) when waste removal is processed under the reference operating conditions including the heat source terms of two units of 200-HP SMP mixers and Tank 11 decay heat. All the analysis results demonstrate that the active cooling coil system provides primary heat sink to remove the process heat from the waste tank system.

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Appendix

Appendix 1: Sludge Removal Operation with 10 Days' Initial Mixing Followed by Three Cycles of Waste Removal and Refilling

As discussed earlier, two operating scenarios have been considered for the transient modeling calculations. They are the 40 days' period of initial mixing with continuous pump operations under fixed tank level as a primary option and the 10 days' period of the initial mixing with subsequent 15 days' three-cycle operations of waste removal and refilling as a secondary one. The analysis results for the secondary option shown in Fig. A.1 are provided in the Appendix since they provide the operational information and design guidance for the replacement of the existing mixer pumps. In addition, sensitivity studies for the key variables of tank operation are performed to investigate what parameters are most sensitive to the thermal response of the waste tank to the SMP operations.

As one of the reference conditions for the thermal analysis of the type-I tank, decay heat load of Tank 11 was used in the calculations since it has the highest decay heat source among the type-I tanks located in F and H tank farm areas as shown in Table A.1. When 100 inches of initial tank level and 65 ^{o}C of initial waste temperature were used as the reference conditions, maximum waste temperature was about 91 ^{o}C at the end of the first 260 hours' mixing operation, which is just before the beginning of the first tank refill. In the calculations, the tank operation curve shown in Fig. A.2 was applied to the model as the transient boundary conditions. In this case, the dominant heat load comes from the operation of two 250 HP SMP mixers. The decay heat load corresponding to the waste content of Tank 11 is about only 10 % of the heat dissipated by two SMP's. The results show that the cooling coil system is the dominant heat removal mechanism, compared to other potential heat sinks such as evaporative cooling from the top surface of the tank and convective heat transfer through the tank wall. Those heat source and sink terms are quantitatively compared in Fig. A.3.

Transient temperatures for waste fluid, purge gas, and cooling coil water are shown in Fig. A.4. In the calculations, 12 active cooling coils were used as one of the reference nominal operating conditions as established by the benchmarking test. The reference conditions for the modeling analysis are shown in Table A.1. The results show that the purge gas temperature is more sensitive to the waste temperature at each transient time, compared to the cooling coil water since the gas specific heat is much smaller than the water. It is noted that steady state temperature for each material region is reached in about 400 hours after initiation of tank operation under the reference operating conditions.

Sensitivity runs have been performed to investigate what physical variables are most sensitive to the waste temperature with respect to the reference conditions. Detailed sensitivity results for each variable are provided below.

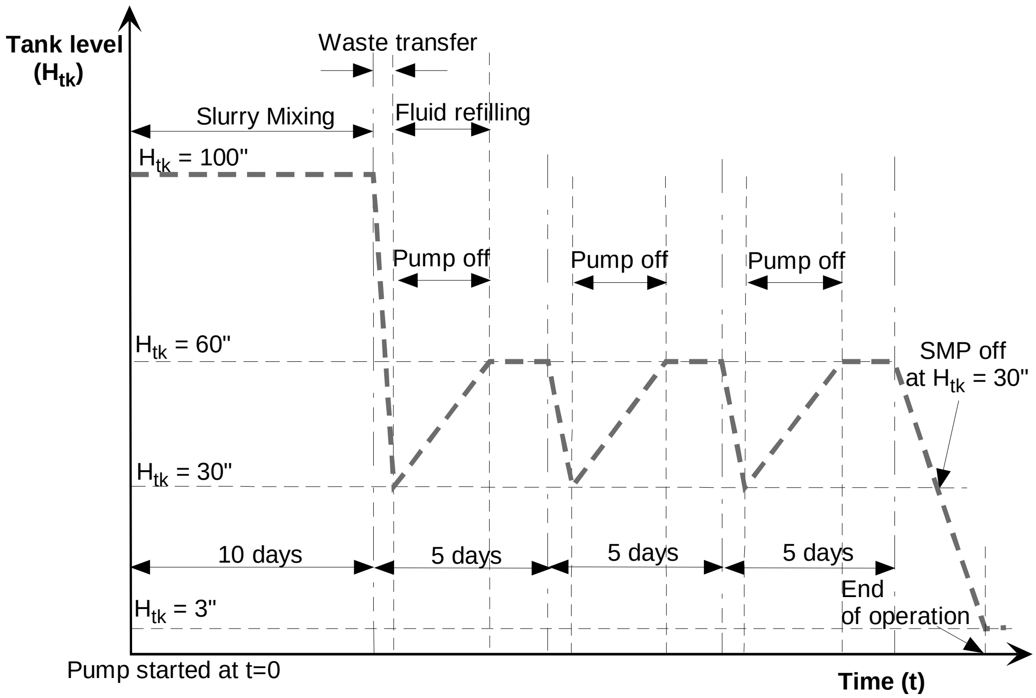

Figure A.1. Slurry removal operating curve used in the present analysis

Table A.1. Reference operating conditions for heat balance study of the type-1 waste tank

Operating parameters	Reference operating conditions
Tank dimension (diameter x height)	75 ft x 24.5 ft
Initial temperature of waste fluid	65 ^{o}C (40 and 50 ^{o}C)*
Initial tank level	100 in (from 75 to 130 in)*
Purge gas temperature at inlet	25 ^{o}C
Waste fluid density	1.35 sg (1.2, 1.3, and 1.4 sg's)*
Coolant temperature at coil inlet	25 ^{o}C
Cooling coil surface condition	Surface with no chemical deposition**
Number of operating cooling coils out of total 36 cooling coils	12 (11)*
Bottom cooling coil availability	Not available
Flowrate per cooling coil	5.7 gpm corresponding to 200 gpm for 35 cooling coils
Purge gas flowrate	500 scfm (250scfm)*
Relative humidity	97 %
Number of operating pumps	2 SMP's and 1 STP
Pumping power of each submersible mixing pump (SMP)	250 HP (350 HP, 300 HP, and 225 HP)*
Pumping power of each submersible transfer pump (STP)	25 HP
Transfer pump flowrate	200 gpm
Tank refill flowrate	31 gpm
Max. decay heat of Tank 11 waste (average decay heat of type-I tanks)	42.58 W/m [0.55 Btu/hr gal] (21.76 W/m^3 [0.28 Btu/hr gal])*

Note: *conditions used for the sensitivity analysis of the present model

**information provided by the customer [2]

Table A.2. Parameters used for the sensitivity study of the type-1 waste tank analysis

Operating or physical parameters (dimension unit)	Sensitivity study ranges of each parameter
Decay heat (W/m^3)	From 21.76 (avg.) to 42.58 (Tank 11)*
Initial temperature of waste fluid (^oC)	From 40 to 65*
Ambient temperature (^oC)	From 10 to 41.7, (25)*
Cooling coil flowrate (gpm)	From 0.0** to 7.45, (5.71)*
Number of cooling coils operated (---)	From 11 to 12*
Bottom cooling coil availability among the active cooling coils (---)	From no bottom coil available* to one bottom coil available
Purge gas flowrate (scfm)	From 250 to 500*
Max. evaporation rate (lbm/ft^2 hr)	From 0.795* to 2.140
Initial tank liquid level (inches)	From 75 to 130, (100)*
Number of SMP operations (---)	From 1 to 2*
SMP powers (HP)	From 225 to 350, (250)*
Waste fluid density (s.g.)	From 1.2 to 1.4, (1.35)*

Note: * Nominal reference operating conditions in the present analysis.

** Zero flow is equivalent to failure of all the remaining 12 operational coils.

Decay Heat

When average decay heat load (21.8 W/m^3) of the F-area tanks was used instead of the referenced decay heat (42.6 W/m^3) for the sensitivity run, maximum waste temperature was found to be about 89 ^oC, which is 2 ^oC lower than the reference case, Tank 11 decay heat. Figure A.5 compares transient waste temperatures for the two different decay heat loads under the reference tank level (100 in). In this case, other operating parameters including the initial waste temperature were kept at the reference values given in Table A.1. Waste temperature is not sensitive to the decay heat load since it is small fraction (about 10 %) of total heat load dissipated by the two SMP and one STP as discussed earlier. Table A.3 presents the sensitivity results for the two different decay heat loads under various initial tank levels.

Table A.3. Sensitivity results of maximum waste temperatures for different decay heats (other operating conditions used for the reference conditions as defined in Table A.1)

Physical parameter		**Decay heat loads**	
		Tank 11 decay heat (0.55 Btu/hr gal)	Average decay heat (0.28 Btu/hr gal)
Max. waste temperature (75 in tank level)	^oC	100	98
	^oF	212	208
Max. waste temperature (90 in tank level)	^oC	94	92
	^oF	201	197
Max. waste temperature (100 in tank level	^oC	91*	89
	^oF	196*	192
Max. waste temperature (130 in tank level)	^oC	84	82
	^oF	183	179

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Initial Waste Temperature

When initial waste temperature changes from the reference condition (65 ^oC) to 40 ^oC, maximum waste temperature for the 40 ^oC case is about 10 ^oC lower than the reference case near 260 hours' transient time from the beginning of operation, which is just before the first cycle of tank refill. The temperature difference becomes smaller and smaller with transient time after the first cycle operation as shown in Fig. A.6. Maximum waste temperatures for the three different initial conditions are compared for various tank levels in Fig. A.7. Detailed results for the three different values of initial waste temperatures are summarized in Table A.4.

Table A.4. Sensitivity results of maximum waste temperatures for three different initial temperatures of waste (other operating conditions used for the reference conditions as defined in Table A.1)

Physical parameter		**Initial waste temperatures**		
		40 °C (104 °F)	50 °C (122 °F)	65 °C (149 °F)
Max. waste temperature of Tank 11 (75-in tank level)	°C	91	95	100
	°F	196	203	212
Max. waste temperature of Tank 11 (90-in tank level)	°C	84	88	94
	°F	183	191	201
Max. waste temperature of Tank 11 (100-in tank level)	°C	81	85	91*
	°F	177	184	196*
Max. waste temperature of Tank 11 (120-in tank level)	°C	75	80	86
	°F	167	175	187
Max. waste temperature of Tank 11 (130-in tank level)	°C	73	78	84
	°F	164	172	183

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Ambient Temperature

Ambient temperature is assumed to be 25 °C (about 80 °F) in the reference run as shown in Table A.1. The inlet temperature of the purge gas and its initial gas temperature are assumed to be equal to ambient temperatures. In this case, the inlet temperature of the cooling coil water is also assumed to be ambient temperature to estimate the thermal impact of tank waste, since the exit water of the cooling coil is indirectly cooled by ambient temperature through heat exchanger such as cooling tower.

For the sensitivity runs with respect to ambient temperature, three different ambient temperatures, 10 °C, 25 °C, and 42 °C, were considered including the reference value. For the reference tank level (100 in), maximum waste temperature varied from 84 °C to 99 °C when ambient temperature changes from 10 °C to 42 °C. Transient waste temperatures are compared among the three cases of different ambient temperatures in Fig. A.8. The results for the two different tank levels are shown in Table A.5. It is noted that when initial tank level becomes higher, maximum waste temperature is more sensitive to ambient temperature because of the increased wet surface area of the cooling coils.

When only the inlet and initial temperatures of the purge gas are used as the sensitivity parameter, and other operating parameters including the inlet temperature of the cooling coil are kept as the reference values, the results show that they are not sensitive to the waste temperature. For instance, maximum waste temperature is increased by about 0.4 ^oC when ambient temperature changes from 25 ^oC to 42 ^oC.

Table A.5. Sensitivity results of maximum waste temperatures for different ambient temperatures (other operating conditions used for the reference conditions as defined in Table A.1)

Physical parameter		**Ambient temperatures (based on 12 cooling coil operation)**		
		10 ^oC (50 ^oF)	25 ^oC (77 ^oF)	41.7 ^oC (107 ^oF)
Max. waste temperature of Tank 11 (100-in tank level)	^oC	84	91*	99
	^oF	183	196*	210
Max. waste temperature of Tank 11 (130-in tank level)	^oC	76	84	93
	^oF	169	183	199

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Cooling Coil Flowrate

As discussed earlier, the calculation results for the reference conditions show that heat loss through the cooling coil system is the most dominant among the other heat sink mechanisms provided in the waste tank system. In this case, 5.71 gpm of cooling coil flow and 12 active coils out of total 36 possible cooling coils were used as the reference operating conditions since they were established by the benchmarking test and the customer's information [2, 3].

Several different cases for zero flow to 7.45 gpm flowrates were used for the sensitivity runs of the cooling coil flow. For instance, when the cooling coil flow increased from 5.71 gpm to 7.45 gpm, maximum waste temperature decreased by about 1 ^oC due to the increased convective energy transport, and maximum coolant exit temperature decreased by about 3 ^oC as shown in Fig. A.9. In this situation, the impact of cooling coil flow on the waste temperature was also assumed under different initial tank liquid levels. The results show that maximum waste temperature for the referenced cooling coil flow (5.71 gpm) is consistently about 1^{o}C higher than the case of 7.45 gpm flowrate for various tank levels as shown in Fig. A.10.

For zero flowrate of the cooling coil system, it was assumed that pumping heat and decay heat loads were cooled by natural convection [13] inside the cooling coil, which contains a stagnant water medium of about 1.257 m^3 total volume. For the present conditions, heat transfer coefficient at the inner wall of the cooling coil was found to be about 242.13 W/m^2 sec. The results showed that maximum waste temperature would increase up to about 129 ^{o}C for the referenced tank level (100 in). Detailed sensitivity results of the cooling coil flowrate are summarized in Table A.6.

Table A.6. Sensitivity results of maximum waste temperatures for different cooling coil flowrates (other operating conditions used for the reference conditions as defined in Table A.1)

Physical parameter		**Coolant flowrate per cooling coil (based on 12 cooling coil operation)**			
		No flow*	2.86 gpm	5.71 gpm***	7.45 gpm
Max. waste temperature of Tank 11 (100-in tank level)	^{o}C	129	95	91**	90
	^{o}F	264	203	196**	194
Max. waste temperature of Tank 11 (130-in tank level)	^{o}C	119	88	84	83
	^{o}F	247	190	183	181

Note:* This is based on the assumption that failure of all the 12 active cooling coils results in no flow condition.
** This case corresponds to the results of the reference operating conditions in the present analysis.
*** This corresponds to the reference case (200 gpm coolant flow for 35 cooling coils).

Number of Active Cooling Coils

As mentioned earlier, 12 coils out of total 36 cooling coils were assumed to be active as one of the reference operating conditions from the benchmarking test and the customer's information [2, 3]. In this case, the cooling coil located near the bottom of the tank was assumed to be inactive for conservative estimation of waste temperature since the entire cooling coil is spread horizontally above the bottom surface of the tank and it has 100% wetted coil surface. Another reason for this was to consider the fact that the bottom coil has poor heat transfer capability due to fouling of the coil surface as provided by the customer's information [3].

When one bottom coil out of 12 total active cooling coils was assumed to be active, maximum waste temperature decreased by about 8 ^oC, compared to the reference case. As the initial tank level increased, the difference of maximum waste temperatures between the two cases decreased since the cooling capability of the other 11 vertical cooling coils increased due to the increase of wetted surface area. Detailed results are presented in Figs. A.11 and A.12.

When the number of active cooling coils is reduced from the reference number (12 coils) to 11 coils for the 100-in reference tank level, maximum waste temperature increased by 2 ^oC with respect to the reference results. Figure A.13 shows maximum temperatures of the waste containing the decay heat load of Tank 11 for various initial tank levels. Sensitivity results are compared between the two cases in Table A.7.

Table A.7. Sensitivity results of maximum waste temperatures for two different number of cooling coils operated (other operating conditions used for the reference conditions as defined in Table A.1)

Max. temperatures for different initial tank levels	**Number of cooling coils operated**			
	11 cooling coils		12 cooling coils	
	^oC	^oF	^oC	^oF
75 in	102	216	100	212
90 in	96	205	94	201
100 in	93	199	91*	196*
120 in	88	190	86	187
130 in	86	187	84	183

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Purge Gas Flowrate

As shown in Table A.1, 500 scfm purge gas flow was used as one of the reference operating conditions. Sensitivity study of the gas flow was performed to examine how gas flow affects the coolability of the waste tank system.

When the gas flow changed from the reference value (500 scfm) to 250 scfm, maximum temperatures of waste and coolant coil water were changed less than 1 ^oC, but the gas temperature was increased by about 9 ^oC since specific heat capacity of gas is much smaller than that of the liquid waste. In Fig. A.14, transient temperatures for waste, cooling coil water, and purge gas during 25 days' operations of waste removal are shown. Maximum temperatures for the two different gas flowrates are compared in Table A.8.

Table A.8. Sensitivity results of maximum waste temperatures for two different purge gas flowrates (other operating conditions used for the reference conditions as defined in Table A.1)

Max. temperatures of component materials	**Purge gas flowrate**			
	500 scfm*		250 scfm	
	^oC	^oF	^oC	^oF
Waste	90.8	195.4	91.1	196.0
Cooling coil exit	37.8	100.0	37.9	100.2
Purge gas	55.8	132.4	64.6	148.4

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Evaporation Rate

As discussed earlier, the reference conditions were established by the benchmarking test and the customer's information [2, 3]. As one of the reference operating conditions, about 0.8 lbm/ft^2 hr of evaporation rate was used for the modeling calculations.

For the sensitivity analysis, three different values of the evaporation rate were applied to the present model. The calculation results showed that maximum temperature of the waste tank was not sensitive to different evaporation rates since more evaporation rate caused the gas temperature to be raised and then made sensible heat loss smaller for the reduced temperature difference between the gas and the waste fluid at the free surface of the tank. Transient waste temperatures for the three different evaporation rates are compared in Fig. A.15. Table A.9 also presents the sensitivity results for maximum waste temperatures.

Table A.9. Sensitivity results of maximum waste temperatures for different evaporation rates (other operating conditions used for the reference conditions as defined in Table A.1)

Physical parameter		**Max. evaporation rate at top surface of waste tank (lbm/ft^2 hr)**		
		0.795*	1.501	2.140
Max. waste temperature of Tank 11 (100-in tank level)	^oC	91	90	90
	^oF	196	194	193

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Initial Tank Level

The 100-in initial tank level was used as one of the reference operating conditions as provided by the operational procedure of waste removal [1, 2]. Sensitivity studies of the initial tank level were performed to examine the temperature responses of the waste tank system to different tank levels. When the initial tank level changed from the reference level, 100 in, to the reduced level, 75 in, maximum waste temperature increased by 9 ^oC. Figure A.16 shows detailed comparison of transient temperatures between the two cases. Sensitivity results of the initial tank levels are summarized in Table A.10.

Table A.10. Sensitivity results of maximum waste temperatures for different initial tank levels (other operating conditions used for the reference conditions as defined in Table A.1)

Initial tank level	**Max. waste temperature**	
(inches)	(^oC)	(^oF)
75	100	212
90	94	201
100*	91	196
120	86	187
130	84	183

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Powers of Submersible Mixer Pump (SMP)

Transient calculations have been made for the 25-day operation of the mixing and three-cycle sludge removal to estimate transient waste temperatures within type-I waste tank when the tank has two Submersible Mixer Pumps (SMP's) and one Submersible Transfer Pump (STP) for sludge removal operation as the reference conditions.

As discussed earlier, the dominant heat load is from the operation of two 250 HP SMP mixers, and the highest decay heat load among the type-I waste tanks, which is generated by the Tank 11 waste, is about only 10 % of the two-SMP dissipation heat. In this case, when the number of the SMP units is reduced from two to one, maximum waste temperature decreased by 18 ^{o}C under the reference tank level. The sensitivity results of the initial tank levels are shown in Table A.11. The results are also compared in Fig. A.17.

Table A.11. Comparison of maximum waste temperatures between 2 SMP's and 1 SMP operations (other operating conditions used for the reference conditions as defined in Table A.1)

Initial tank level	**Max. waste temperature**			
	2 SMP's		1 SMP	
(inches)	^{o}C	^{o}F	^{o}C	^{o}F
75	100	212	77	171
90	94	201	74	165
100*	91	196	73	163
120	86	187	71	160
130	84	183	70	158

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

In case of two mixer operation, the impact of the SMP powers on maximum tank temperature was also examined. When each power of the two SMP mixers increased from 225 to 350 horsepower, maximum temperature of the waste tank changed from 87 ^{o}C to 106 ^{o}C under the reference tank level as shown in Table A.12. For instance, the maximum temperature reached 106 ^{o}C when each SMP power has 350 horsepower. In Fig. A.18 the transient results are compared between 300 and 350 HP for the reference decay heat load.

When the tank was assumed to have average decay heat load (21.76 W/m^3 in Table 1) and each SMP increased from 300 to 350 horsepower, maximum temperature was found to be about 104 ^{o}C, which is 2 ^{o}C lower than the reference case of Tank 11 decay heat. Transient temperatures of the waste fluid with average decay heat are compared for the three different powers of SMP in Fig. A.19.

Table A.12. Sensitivity results of maximum waste temperatures for various SMP powers (other operating conditions used for the reference conditions as defined in Table A.1)

SMP horse powers (number of SMP's)	**Max. waste temperature**			
	Tank 11 decay heat		Average decay heat	
	^oC	^oF	^oC	^oF
225 HP (2)	87	188	---	---
250 HP (2)	91*	196*	89	192
300 HP (2)	98	208	96	205
350 HP (2)	106	223	104	220

Note: * This case corresponds to the results of the reference operating conditions in the present analysis.

Waste Fluid Density

As shown in Table A.1, 1.35 specific gravity (sg) of waste density was used as one of the reference operating conditions as provided by the customer [1]. For the sensitivity analysis of the waste fluid properties, different densities of 1.2 to 1.4 sg were used for the same specific heat. When the waste density was reduced from the reference value (1.35 sg) to 1.2 sg, maximum waste temperature was increased by 3 ^oC. Detailed results for the two different waste densities are compared under various SMP powers in Table A.13. Transient temperatures of the 1.2 sg density waste are compared among different SMP powers in Fig. A.20.

For the reference operating conditions except for waste density, the transient calculations for four different waste densities have been performed to examine the sensitivity of waste temperature associated with the change of waste material property. The results showed that maximum waste temperature for the density change of 1.4 to 1.2 sg was changed by about 3 ^oC. Detailed transient results for the waste temperature are compared among the four different waste densities in Fig. A.21.

Sensitivity study for the operating parameters was performed by the heat balance model for the tank type-I waste storage system with SMP operation. The results show that number of active cooling coils and coil flowrate are dominant cooling mechanisms to control waste tank temperature for given SMP mixer power. As discussed earlier, the nominal reference conditions defined in Table A.1 are considered the best-estimate operating values. The results show that the waste temperature rises a maximum 6 ^{o}C in 48 hours under the reference operating conditions. Figure A.22 shows transient peak temperatures of waste during 25 days' operations with two 250-hp SMP. As shown in the figure, the waste fluid reaches steady temperature cycling in about 400 hours since the initiation of tank operations under the reference conditions. It is also emphasized that the power dissipated by the SMP mixers provides the dominant heat source term, compared to the radioactive decay heat load of the tank waste. Table A.2 shows a summary of the sensitivity parameters performed in the present analysis.

From the heat balance analysis, it is concluded that maximum temperature of the tank type-I waste will remain below boiling temperature (100 ^{o}C) when waste removal is processed with the heat source terms of two units of 250 HP SMP mixers and Tank 11 decay heat. The analysis used the reference operating conditions listed in Table A.1 and the operational procedure of waste removal shown in Fig. A.2. All the sensitivity analyses demonstrate that maintaining active cooling coil system provides important cooling mechanism to remove the process heat from the waste tank system.

Table A.13. Comparison of maximum waste temperatures between two different waste densities for various SMP powers (other operating conditions used for the reference conditions as defined in Table A.1)

SMP horse powers (number of SMP's)	**Max. waste temperature**			
	1.20 sg waste		**1.35 sg waste**	
	^{o}C	^{o}F	^{o}C	^{o}F
225 HP (2)	90	194	87	188
250 HP (2)	94	202	91*	196*
300 HP (2)	101	215	98	208
350 HP (2)	109	229	106	223

Note: * This case corresponds to the results of the reference operating conditions.

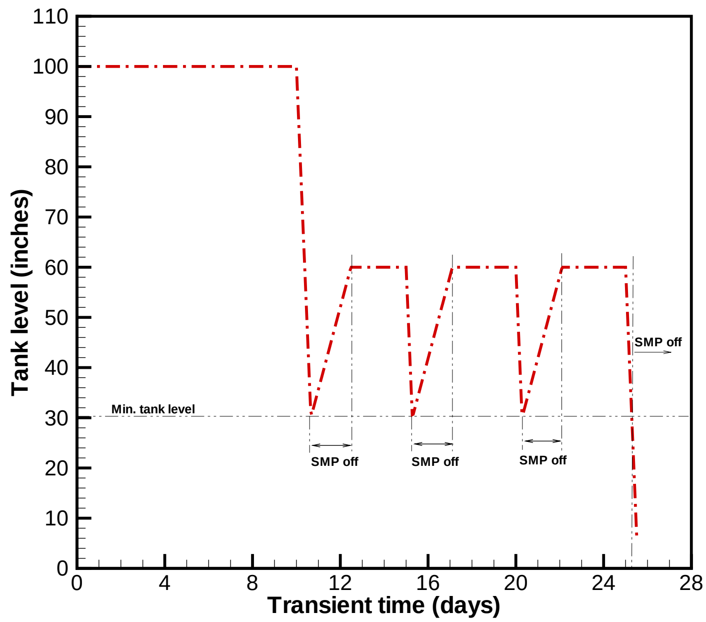

Figure A.2. Transient operating curve of submersible slurry pumps (SMP) for tank type-I waste removal

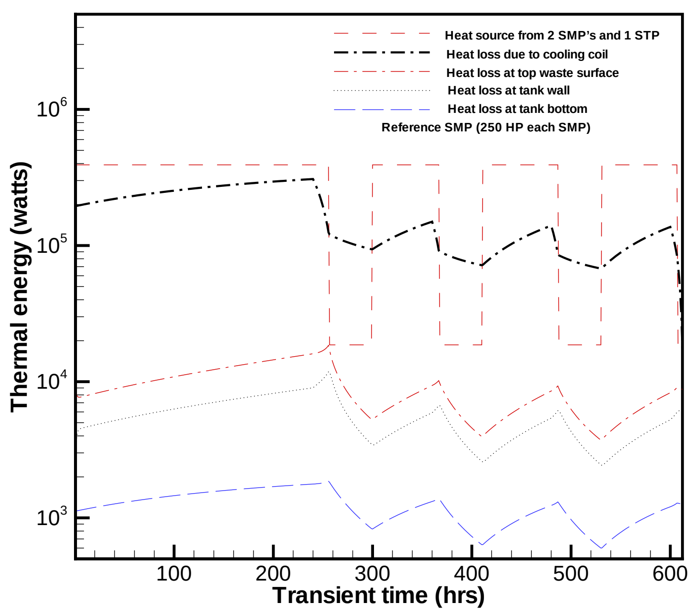

Figure A.3. Transient heat source and sink for the reference operating conditions as shown in Table A.1

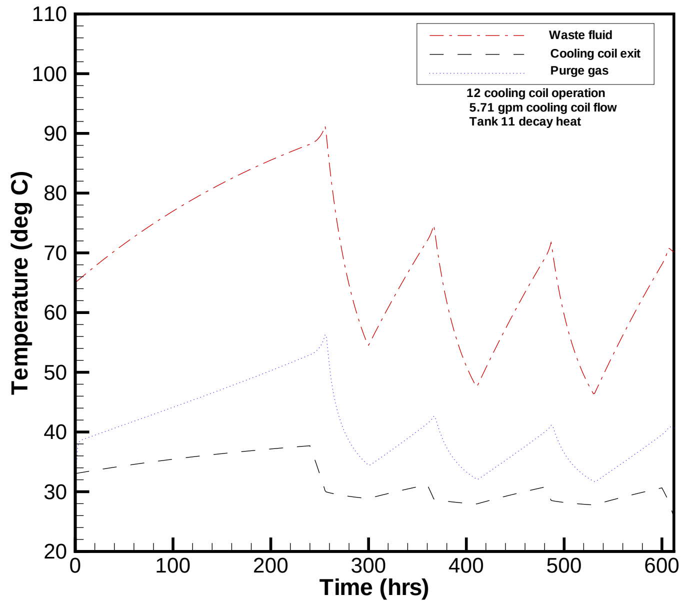

Figure A.4. Transient temperatures of waste liquid, purge gas, cooling coil exit for the reference operating conditions as shown in Table A.1

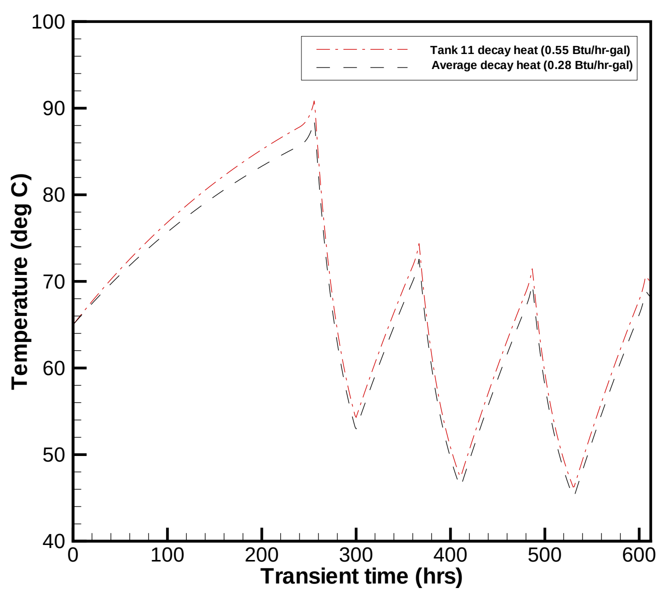

Figure A.5. Comparison of transient temperatures of waste fluid between average decay power and decay heat load of Tank 11 for the reference operating conditions of the other parameters as shown in Table A.1

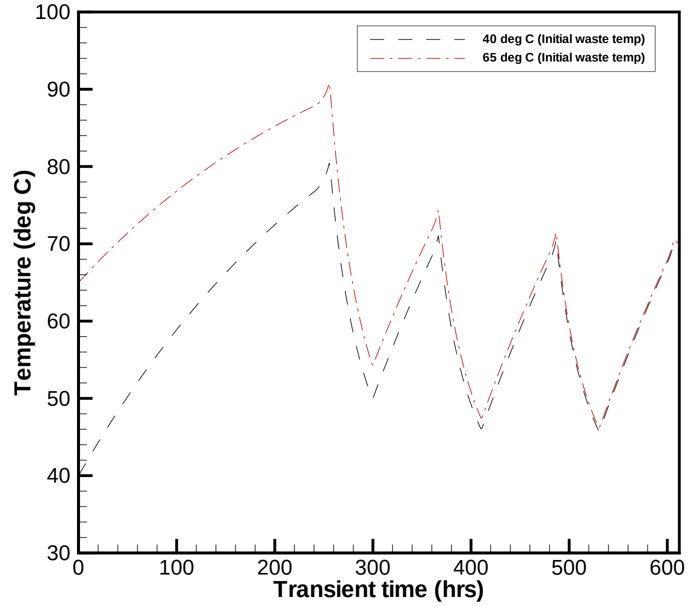

Figure A.6. Comparison of transient waste temperatures for two different initial waste temperatures (40 °C and 65 °C) for the reference conditions of the other parameters as shown in Table A.1

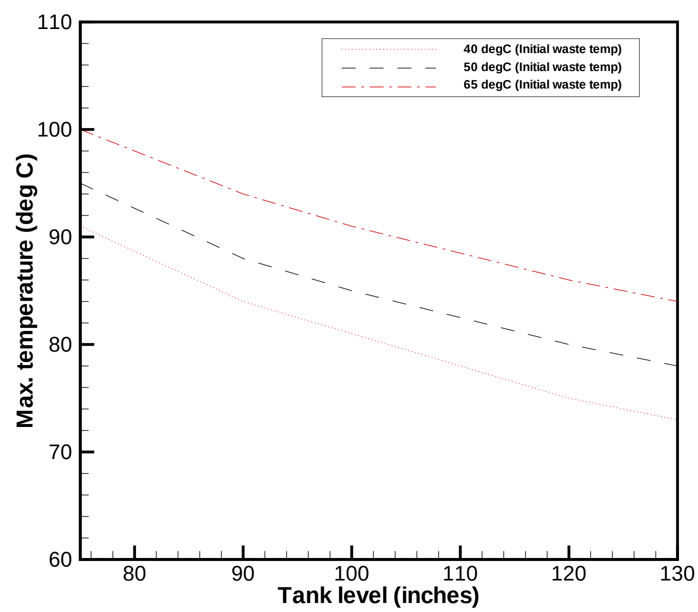

Figure A.7. Comparison of maximum waste temperatures for three different initial waste temperatures (40, 50, and 65 °C) for the reference conditions of the other parameters as shown in Table A.1

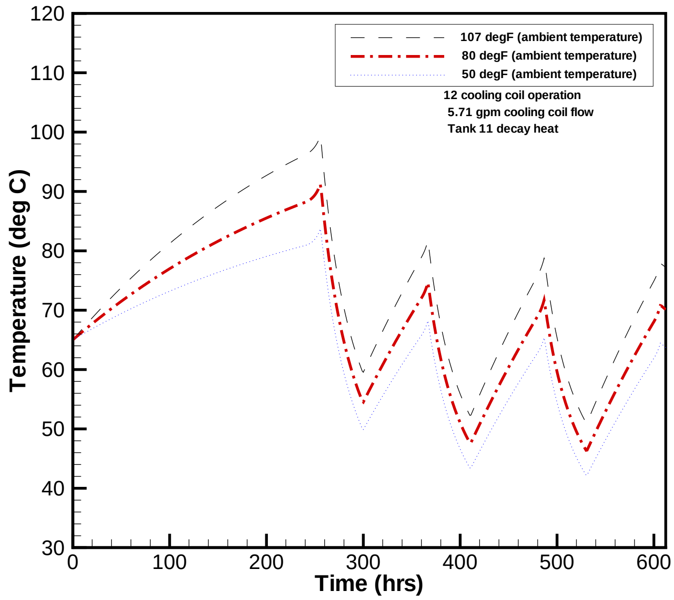

Figure A.8. Comparison of maximum temperatures of waste fluid for different ambient temperatures using the reference operating conditions of the other parameters as shown in Table A.1

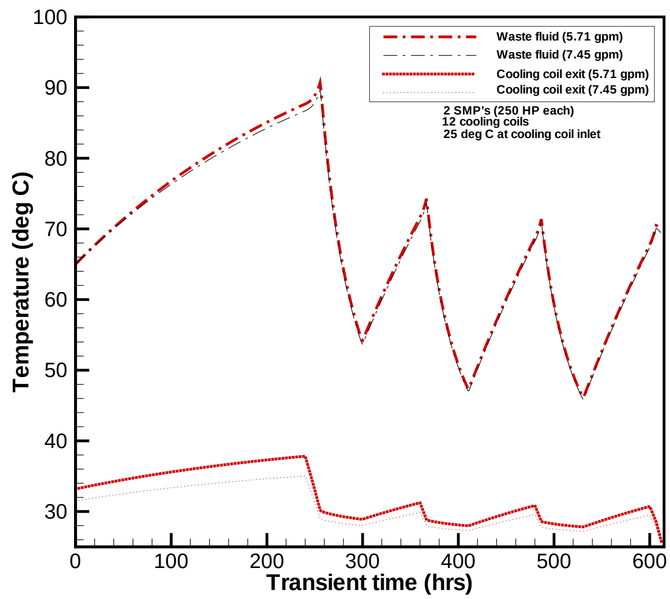

Figure A.9. Comparison of transient waste and cooling coil temperatures for two different cooling coil flowrates under the reference operating conditions of the other parameters as shown in Table A.1

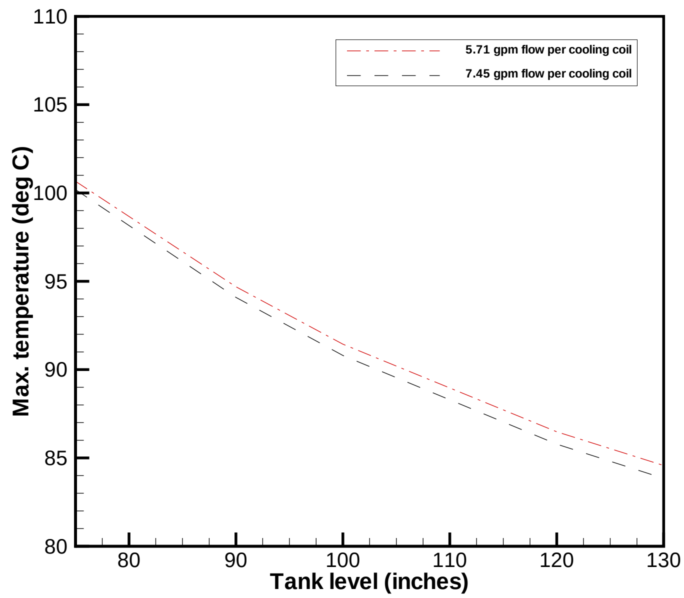

Figure A.10. Maximum temperatures of waste fluid for two different cooling coil flowrates under various tank levels using the reference conditions of the other parameters as shown in Table A.1

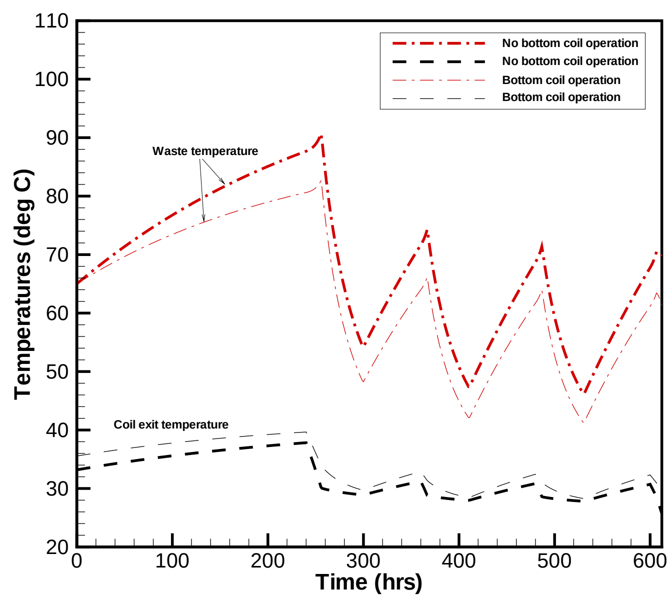

Figure A.11. Comparison of waste liquid and coil exit temperatures between with and without bottom coil operation using the reference operating conditions of the other parameters as shown in Table A.1

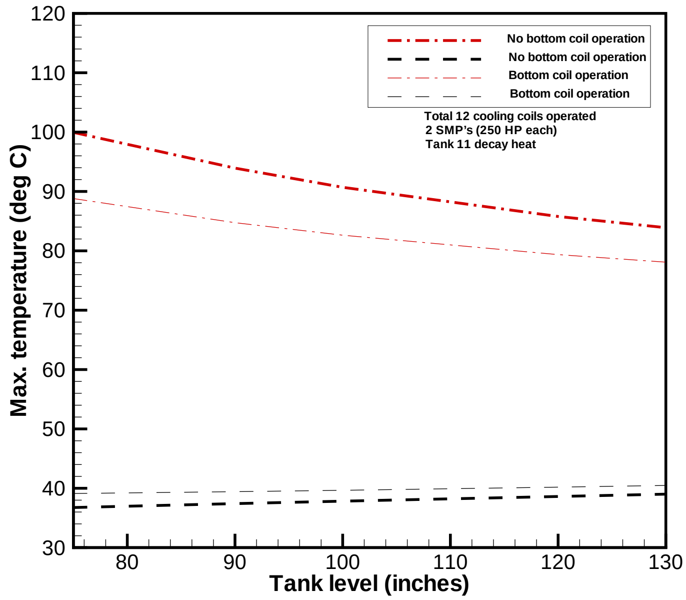

Figure A.12. Comparison of maximum temperatures of waste fluid between with and without bottom coil operation for the reference operating conditions of the other parameters as shown in Table A.1

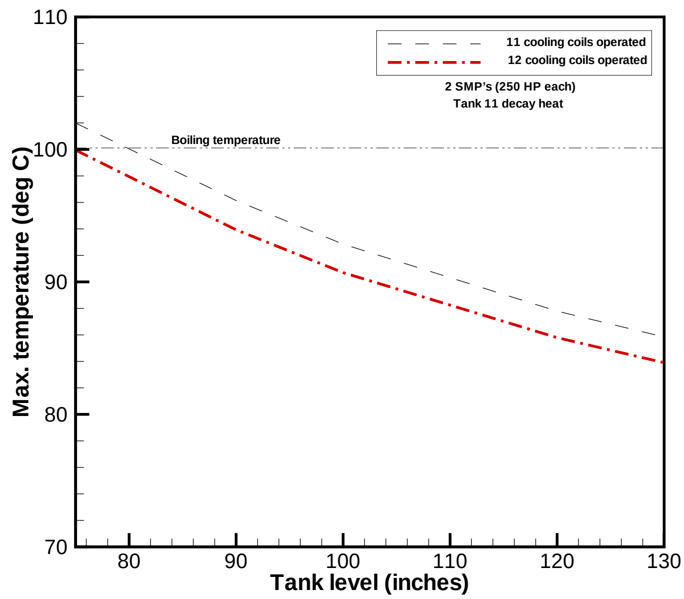

Figure A.13. Comparison of maximum temperatures of waste fluid for 11 and 12 operating cooling coils for various tank levels using the reference operating conditions of the other parameters as shown in Table A.1

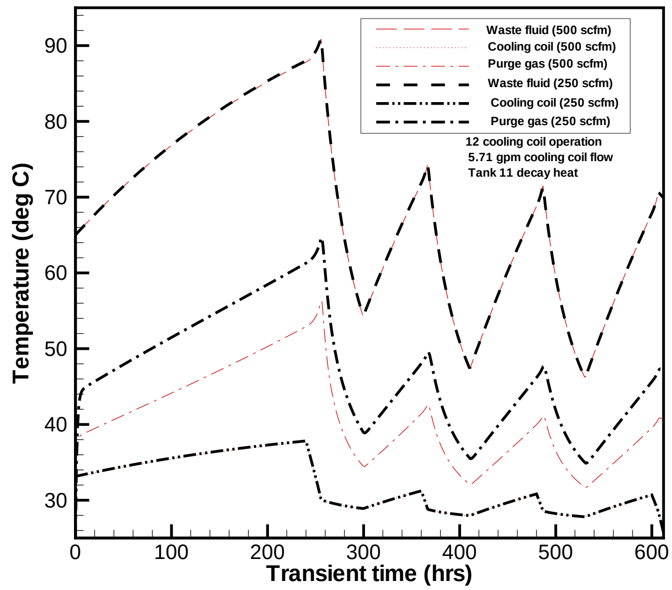

Figure A.14. Sensitivity results of transient waste temperatures for two different purge gas flowrates under the reference operating conditions of the other parameters as shown in Table A.1

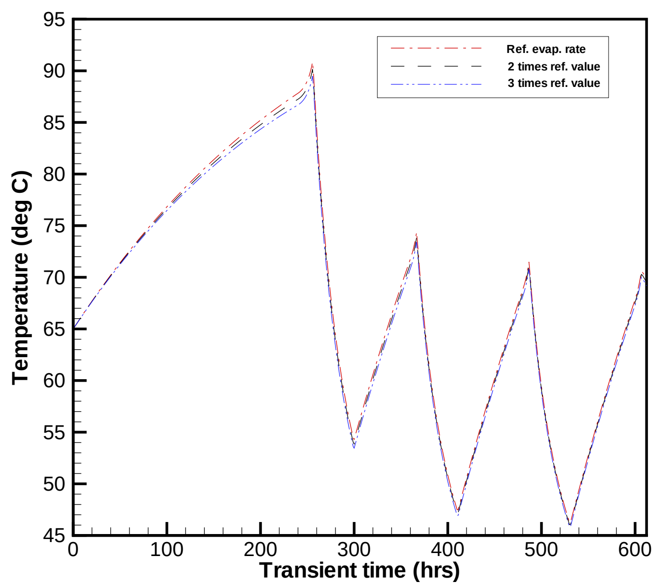

Figure A.15. Comparison of transient waste temperatures for different evaporation rate at the top surface of waste under the reference operating conditions of the other parameters as shown in Table A.1

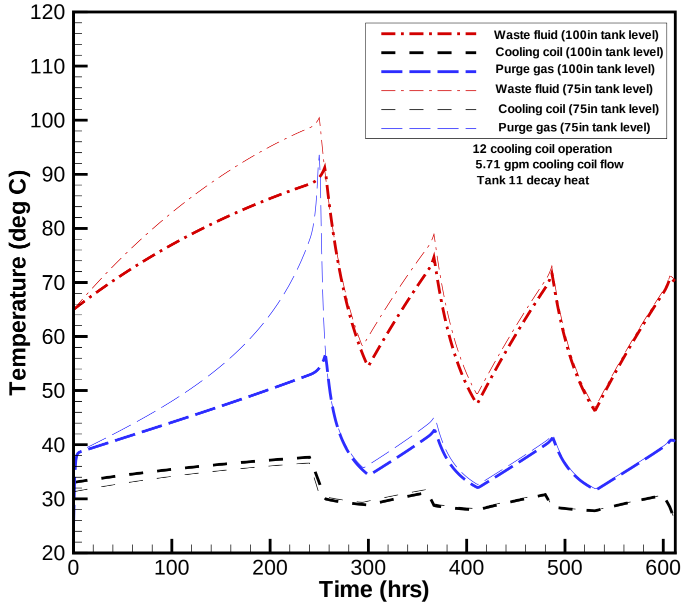

Figure A.16. Comparison of transient waste, purge gas, and cooling coil exit temperatures for two different tank levels for the reference conditions of the other parameters as shown in Table A.1

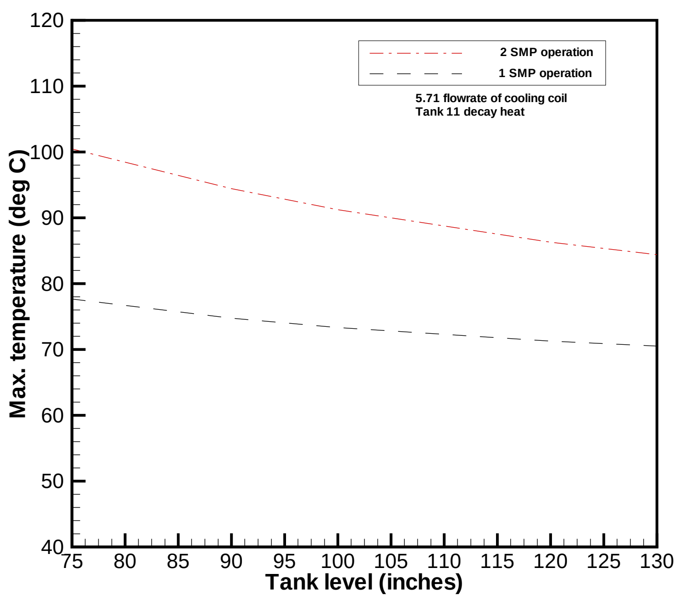

Figure A.17. Comparison of maximum temperatures of waste fluid for 2 SMP's and 1 SMP operations for various tank levels using the reference operating conditions of the other parameters as shown in Table A.1

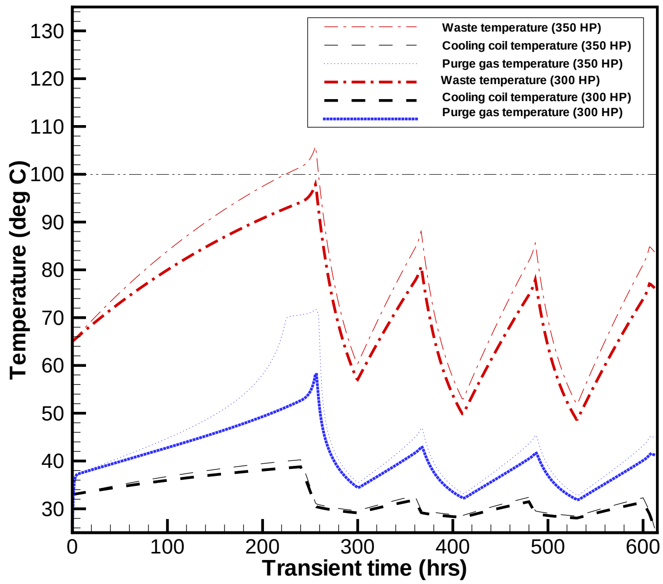

Figure A.18. Transient temperatures of waste fluid, cooling coil, and purge gas for two different SMP powers for the reference conditions of the other parameters as shown in Table A.1

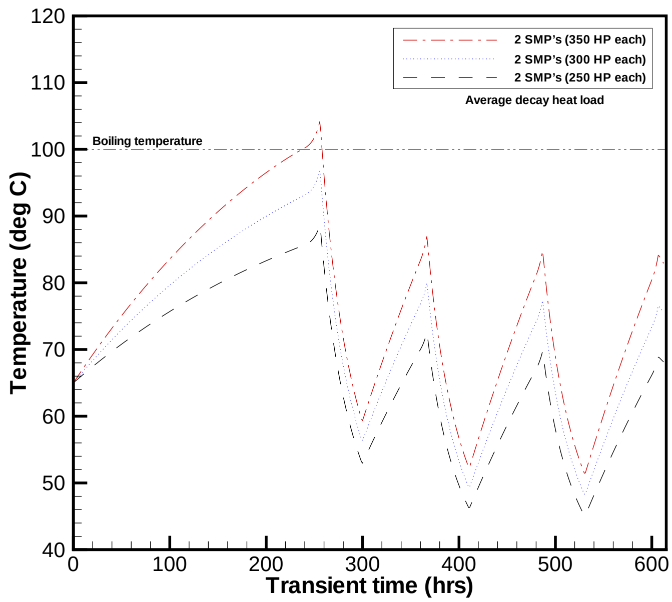

Figure A.19. Transient temperatures of waste fluid with average decay heat of type-I tanks for three different SMP powers under the reference conditions of the other parameters as shown in Table A.1

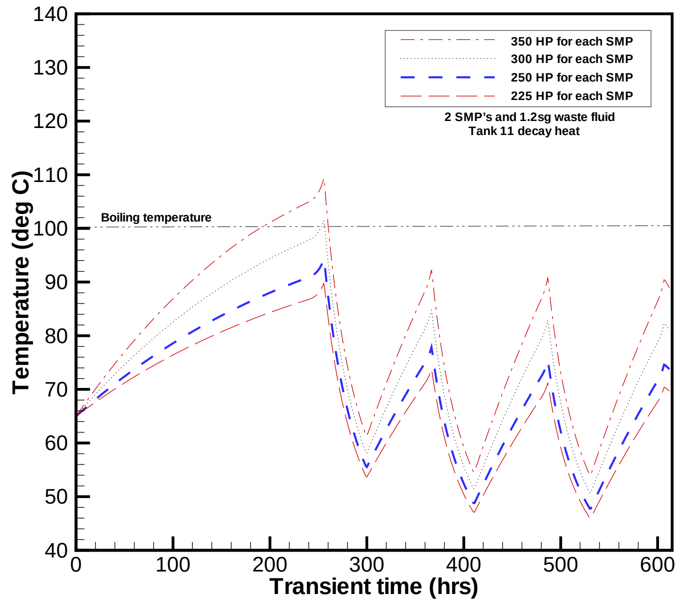

Figure A.20. Comparison of transient waste temperatures for various submersible mixing pump (SMP) powers under decay heat load of Tank 11 with 1.2S.G. and 2 SMP's operation

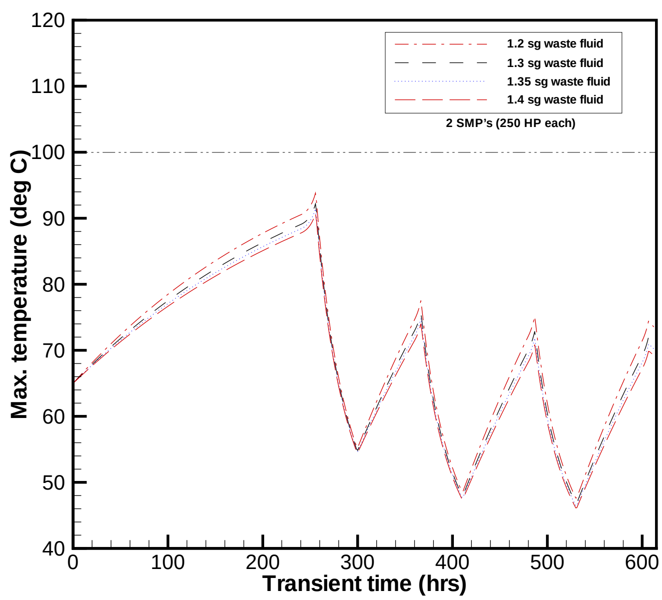

Figure A.21. Comparison of transient waste temperatures for various waste densities under the reference operating conditions of the other parameters as shown in Table A.1

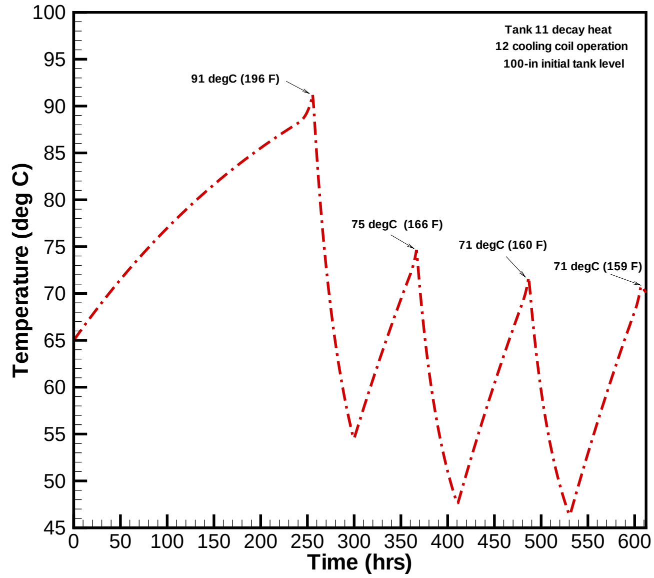

Figure A.22. Transient waste temperatures for the reference nominal operating conditions showing maximum 6 ^{o}C temperature increase in 48 hours

Appendix 2: Code Listing of the Heat Balance Model under ACM

```
Model T1_HeatBal
/*      Title: Submersible Mixing Pump Heat Balance Calculation

        Description: This module models the heat balance in a Type 1 waste tank
        under the influence of submersible mixing pumps.

        Design Inputs/Outputs:
           Input Parameters
           pump and decay heat source
           heat source, kW

           Input Streams
               None
           Output Stream
               None

        Revision History:
               Rev No       Rev. 0

*/
```

```
// PARAMETERS & VARIABLES

//      Numtubes AS Realparameter (302.);
        Numtubes AS Realparameter (106.);
        TankH    AS Realparameter (7.4676);
        pi       AS Realparameter (3.1415962);
        in2m     AS Realparameter (0.0254);
        gpm2m3hr AS Realparameter (.22712);
        gpm2m3sec AS Realparameter (0.00006309);
        Lowlevel AS Realparameter (0.762);  /* Lowlevel = 30 in.   */
        Highlevel AS Realparameter (1.905); /* Highlevel = 75 in.  */

    TIMEHr      AS timeSec;

// Tank physical parameters

    Vliq        AS  volume_SI;
    Vgas        AS  volume_SI   (Fixed, 2300.0);
    VsludIn     AS  flow_vol_SI;
    VsludOut    AS  flow_vol_SI;
    Tank_flow       AS  flow_vol_SI;

    Vol30       AS  volume_SI    (Fixed, 307.4857);
    Atop        AS  area_SI      (Fixed, 404.97);
    TankLev     AS  length_SI;
    Lcw         AS  length_SI;
    d_tank      AS  length_SI    (Fixed, 22.86);

// Pump parameters
    Qsmp        AS  power  (Fixed, 260995.0);
    Qstp        AS  power  (Fixed, 18642.5);
    Qpump       AS  power      ;
    Pump1Flag   AS  notype     ;
    Pump2Flag   AS  notype     ;

//  Heat Transfer
    Tliq        AS  tempK;
    TliqIn      AS  tempK  (Fixed, 298.15);
    Tref        AS  tempK  (Fixed, 273.16);

//  Heat transfer parameters related to evaorative cooling term

    Qevap       AS  power      ;
    Qsens       AS  power      ;
    Qsurf       AS  power      ;

    hwa         AS  htcoef (Fixed, 0.5);
    Tgas        AS  tempK        ;
    Mflux       AS  massflux    ;
    cmflux   AS  notype   (Fixed, 1.0);
    Enth_fg     AS  enthalpy_SI  (Fixed, 2503000.0);
```

```
    flowgas   AS  flow_vol_SI     (Fixed, 0.23598);
    flowmix   AS  flow_vol_SI     ;
    Tgasin       AS  tempK        (Fixed, 298.15);
    Tgasout      AS  tempK        ;
    pamb      AS  pressPa   (Fixed, 101325.0);
    Bratio    AS  notype    ;
    mwinf     AS  notype    ;
    mwf       AS  notype    ;
    rel_humid       AS  notype    (Fixed, 0.97);
    rel_humidin AS  notype (Fixed, 0.0);
    Area_gas  AS  area_SI   ;
    d_gas     AS  length_SI (Fixed, 1.0668);
    pr_gas    AS  notype    (Fixed, 0.71);
    Rex_gas   AS  notype    ;
    vis_gas   AS  viscosity (Fixed, 1.0e-5);
    rhogasin  AS  dens_mass      (Fixed, 1.18);
    psatin    AS  pressPa   ;
    psat      AS  pressPa   ;

//  Heat transfer parameters related to cooling coil
    Qcoil        AS  power        ;
    hwfout       AS  htcoef  (Fixed, 54.035);
    Acwo         AS  area_SI        ;
    Tcliqin      AS  tempK  (Fixed, 298.15);
    Vflow_coil      AS  flow_vol_SI      (Fixed, 0.00036051);
    coil_resist AS  notype              ;
    Douter    AS  length_SI (Fixed, 0.060325);
    hwfin        AS  htcoef ;
    Acwi         AS  area_SI             ;
    Dinner    AS  length_SI (Fixed, 0.0525018);
    length_bot  AS  length_SI     (Fixed, 236.12);
    Tcliqout     AS  tempK        ;
    ksalt        AS  thcond       (Fixed, 0.4324);
    kwater       AS  thcond       (Fixed, 0.615);
    cpw          AS  cp_SI        (Fixed, 4180.0);
    rhow         AS  density_SI   (Fixed, 998.0);
    vis_w     AS  viscosity (Fixed, 1.0e-3);
    c_fouling    AS  length_SI     (Fixed, 0.003716);
    Reliq        AS  notype      ;
    CoilFlag     AS  notype      ;

   Qdecay_vol    AS  power_density(Fixed, 21.7606);
    Qdecay       AS  power        ;

//  Heat transfer parameters related to tank wall
    Qwall        AS  power             ;
    hwtanka      AS  htc_SI (Fixed, 0.9933);
    hwtankw      AS  htc_SI (Fixed, 0.1106);
    Twgas        AS  tempK        ;
    Twgasin      AS  tempK      (Fixed, 298.15);
    Twgasout     AS  tempK        ;
```

```
    rhowgas     AS  density_SI        (Fixed, 1.1);
    Vwgas_in AS  flow_vol_SI          (Fixed, 0.70793);

//  Heat transfer parameters related to tank bottom
    Qbottom     AS  power           ;
//    kbot        AS  thcond       (Fixed, 1.107);
    Tsoil       AS  tempK        (Fixed, 298.15);
//    wall_slab   AS  length_SI    (Fixed, 0.762);
    hwbot       AS  htc_SI       (Fixed, 0.06809);

// Properties
    cpliq       AS  cp_SI     (Fixed, 4180.0);
    cpgas       AS  cp_SI     (Fixed, 1005.0);
//    rholiq      AS  density_SI        (Fixed, 998.0);
    rholiq      AS  density_SI        (Fixed, 1347.3);
    rhogas      AS  density_SI     (Fixed, 1.1) ;

// ASSIGNMENTS
//  z_H2O("H2O"): 1;

// EQUATIONS

Eq01:  TimeHr = time;

Eq01a:  Tank_flow = VsludIn - VsludOut;
Eq01b:  $Vliq = Tank_flow;

Eq02a:  rholiq * cpliq * ((Tliq - Tref) * Tank_flow + Vliq * $Tliq) =
                   rholiq * VsludIn * cpliq*(TliqIn - Tref)
                - rholiq * VsludOut * cpliq*(Tliq - Tref)
                 + Qpump + Qdecay - Qsurf - Qcoil - Qwall - Qbottom;

Eq03a: TankLev = (Vliq - Vol30)/Atop + 30*in2m;

Eq03b: if (TankLev >= 0.762) then
           Lcw = TankLev - 30*in2m + 0.00001;
       else
           Lcw = 0.0;
       endif;
//Eq03b: Lcw = TankLev - 30*in2m + 0.00001;

//Eq04:  Qpump = Qsmp + Qstp;
Eq04a: Qpump = Qsmp*(Pump1Flag + Pump2Flag) + Qstp;
Eq05:  Qdecay = Qdecay_vol * Vliq;

// compute Qsurf term
Eq06:  Qsurf = Qsens + Qevap;
Eq06a: Qsens = hwa * Atop * (Tliq - Tgas);
Eq06b: Qevap = Mflux * Atop * (Enth_fg + cpliq * (Tliq - Tref));

// compute Tgas and Tgasout from the arithmatic avaerage relation
//Eq07:  Qsurf = rhogas * flowmix * cpgas * (Tgasout - Tgasin);
```

```
Eq07a:  flowmix = Mflux * Atop / rhogas + flowgas;

Eq08:  Tgas = 0.5 * (Tgasin + Tgasout);

Eq08a:  rhogas * Vgas * cpgas * $Tgas =
                               rhogasin * flowgas * cpgas * (Tgasin - Tref)
                             - rhogas * flowmix * cpgas * (Tgasout - Tref)
                             + Qsurf;

// Eq09:  rhogas = pamb / (287.0 * Tgas);

//Eq10a:  Vgas = Atop * (7.4676 - TankLev);

Eq11:  mwinf = rel_humidin * psatin / (1.61 * pamb - 0.61 * rel_humid * psatin);
Eq12:  mwf = rel_humid * psat / (1.61 * pamb - 0.61 * rel_humid * psat);
Eq13:  psatin = exp(-38.874 + 0.29129 * Tgasin - 0.00057014 * Tgasin^2 +
                    0.00000040606 * Tgasin^3);
Eq14:  psat = exp(-38.874 + 0.29129 * Tliq - 0.00057014 * Tliq^2 +
                    0.00000040606 * Tliq^3);

Eq10:  if (Tliq < 373.16) then
           Bratio = (mwinf - mwf) / ((mwf - 1.0));
       else
           Bratio = 24.76131;
//             Bratio = 9.7855;
       endif;

Eq15:  if Bratio < 0.000001 then
           Mflux = 0.0;
       else
Eq15b:     Mflux = 0.0287 * rhogasin * ((2.0 * cmflux - Coilflag)
                  * flowgas / Atop) * pr_gas^(-0.4)
                  * Rex_gas^(-0.2) * loge(1 + Bratio);
//Eq15b:        Mflux  =  0.0287  *  rhogasin  *  (flowgas  /  (d_tank  *  (TankH  -
TankLev)))
//                  * pr_gas^(-0.4) * Rex_gas^(-0.2) * loge(1 + Bratio);
       endif;

Eq18:  Rex_gas = rhogas * (flowgas / Atop) * d_tank / vis_gas;
//Eq18:  Rex_gas = rhogas * (flowgas / (d_tank * (TankH - TankLev)))
//                * d_tank / vis_gas;

// compute gas viscosity at purge gas temperature Tgas
// Eq19:  vis_gas = 0.000001458 * Tgas^1.5 / (110.4 + Tgas);

// heat loss at the cooling coil with coolant flowrate Vflow_coil
// coil_resist is heat transfer resistance from inlet wall to bulk fluid

Eq20:  Qcoil = hwfout * Acwo * (Tliq - Tcliqin) / (1.0 + hwfout * Acwo *
                (0.5 / (rholiq * 12.0 * Vflow_coil * cpliq) + coil_resist));

Eq21:  coil_resist = 1.0 / (hwfin*Acwi) + (Douter / (2.0 * ksalt * Acwo))
```

```
                    * loge((Douter + 2.0 * c_fouling) / Douter);
Eq21a:  hwfin = 0.023 * (kwater / Dinner) * Reliq^0.8
               * (vis_w * cpw / kwater)^0.4;
Eq21b:  Reliq = rhow * Dinner * Vflow_coil
               / (0.25 * vis_w * pi * Dinner^2.0);

Eq22:  if (TankLev < 0.762) then
           Acwo = pi * Douter * (Numtubes - 8.0 * CoilFlag)
                 * (0.5 * pi * 48 * in2m)
                 * (TankLev / 0.762) + pi * Douter * length_bot * CoilFlag;
           Acwi = pi * Dinner * (Numtubes - 8.0 * CoilFlag)
                 * (0.5 * pi * 48 * in2m)
                 * (TankLev / 0.762) + pi * Dinner * length_bot * CoilFlag;
       else

           Acwo = pi * Douter * (Numtubes - 8.0 * CoilFlag)
                 * ( 2.0 * Lcw  + .5 * pi * 48 * in2m)
                 + pi * Douter * length_bot * CoilFlag;
           Acwi = pi * Dinner * (Numtubes - 8.0 * CoilFlag)
                 * ( 2.0 * Lcw  + .5 * pi * 48 * in2m)
                 + pi * Dinner * length_bot * CoilFlag;
       endif;


Eq25:  Tcliqout = Tcliqin + Qcoil / (12.0 * rholiq * Vflow_coil * cpliq);

// heat loss at the side wall through the annular 30-inch air gap of of type-1
// tank

Eq28:  Qwall = pi * d_tank * TankLev * hwtankw * (Tliq - Twgas)
              + pi * d_tank * (TankH - TankLev)* hwtanka * (Tgas - Twgas);
Eq29:  Twgas = 0.5 * (Twgasin + Twgasout);
Eq30:  Qwall = rhowgas * Vwgas_in * cpgas * (Twgasout - Twgasin);

// heat loss at the tank bottom through the heat sink of soil region

Eq32:  Qbottom = 0.25 * pi * d_tank * d_tank * hwbot *
                     (Tliq - Tsoil);

End
```

Appendix 3: List of All Variables Used in the Heat Balance Model

	Value	Spec
Acwi	95.6549	Free
Acwo	109.908	Free
Atop	404.97	Fixed
Bratio	0.197194	Free
c_fouling	0.0	Fixed
cmflux	1.0	Fixed
coil_resist	1.26861e-005	Free
CoilFlag	0.0	Fixed
ComponentList	Default	
cpgas	1005.0	Fixed
cpliq	4180.0	Fixed
cpw	4180.0	Fixed
d_tank	22.86	Fixed
Dinner	0.0525018	Fixed
Douter	0.060325	Fixed
Enth_fg	2.503e+006	Fixed
flowgas	0.23598	Fixed
flowmix	0.236623	Free
gpm2m3hr	0.22712	
gpm2m3sec	6.309e-005	
Highlevel	1.905	
hwa	0.5	Fixed
hwbot	0.06809	Fixed
hwfin	824.074	Free
hwfout	54.035	Fixed
hwtanka	0.9933	Fixed
hwtankw	0.1106	Fixed
in2m	0.0254	
ksalt	0.4324	Fixed
kwater	0.615	Fixed
Lcw	1.778	Free
length_bot	236.12	Fixed
Lowlevel	0.762	
Mflux	1.87554e-006	Free
mwf	0.164713	Free
mwinf	0.0	Free
Numtubes	106.0	
pamb	101325.0	Fixed
pi	3.1416	
pr_gas	0.71	Fixed
psat	25172.1	Free
psatin	3147.8	Free
Pump1Flag	1.0	Fixed
Pump2Flag	1.0	Fixed
Qbottom	1117.86	Free
Qcoil	198422.0	Free

Qdecay	43753.9	Free
Qdecay_vol	42.582	Fixed
Qevap	2107.45	Free
Qpump	391492.0	Free
Qsens	8099.4	Free
Qsmp	186425.0	Fixed
Qstp	18642.5	Fixed
Qsurf	10206.9	Free
Qwall	652.141	Free
rel_humid	0.97	Fixed
rel_humidin	0.0	Fixed
Reliq	8725.12	Free
Rex_gas	1573.26	Free
rhogas	1.18106	Fixed
rhogasin	1.18413	Fixed
rholiq	1347.3	Fixed
rhow	998.0	Fixed
rhowgas	1.1	Fixed
Tank_flow	0.0	Free
TankH	7.4676	
TankLev	2.53999	Free
Tcliqin	298.15	Fixed
Tcliqout	306.294	Free
Tgas	298.15	Initial
Tgasin	298.15	Fixed
Tgasout	298.15	Free
TIMEHr	0.0	Free
Tliq	338.15	Initial
TliqIn	298.15	Fixed
Tref	273.16	Fixed
Tsoil	298.15	Fixed
Twgas	298.567	Free
Twgasin	298.15	Fixed
Twgasout	298.983	Free
Vflow_coil	3.605e-004	Fixed
Vgas	2252.69	Fixed
vis_gas	1.e-005	Fixed
vis_w	1.e-003	Fixed
Vliq	1027.52	Initial
Vol30	307.486	Fixed
VsludIn	0.0 Fixed	
VsludOut	0.0 Fixed	
Vwgas_in	0.70793	Fixed