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TRANSIENT HEAT TRANSFER ANALYSIS FOR SRS RADIOACTIVE TANK OPERATION

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INTRODUCTION

Some of nuclear waste storage tanks at Savannah River Site (SRS) are 0.75 million-gallon, single-wall, Type-I 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 as shown in Fig. 1. 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. 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.

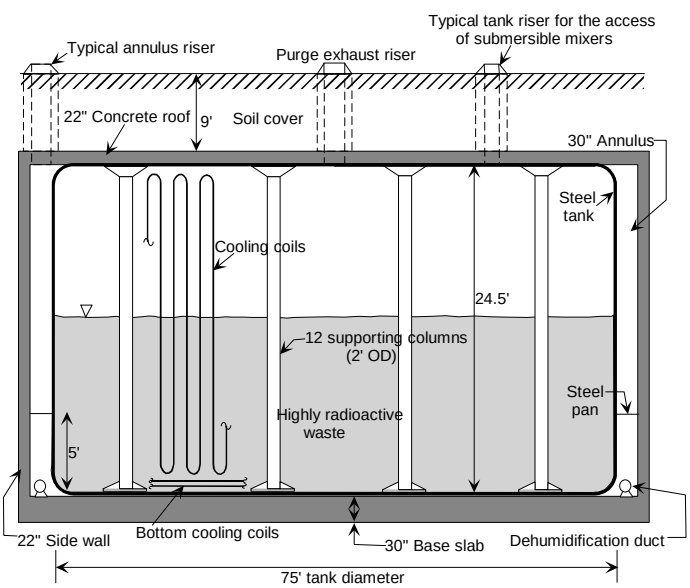

Fig. 1. Typical type-I waste tank (750,000 gallons tank) used for the present analysis

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. Previous results [4,5] 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.

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 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. Average and maximum decay heat loads of the type-I waste tanks in the F and H areas are about 22 and 43 W/m^3, respectively.

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.

DESCRIPTION OF THE WORK

A 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 SMP. The tank domain used in the present model consists of two SMP's for sludge mixing, one 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. All governing equations were established by an overall energy balance for the tank domain, and they were numerically solved.

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

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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.
- Gas above the free surface of tank liquid consists of a well mixed 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.
- 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.
- 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 becomes:

$$\rho_l C_{pl} V \frac{dT_{liq}}{dt} = \rho_l C_{pl} \dot{v}_{l,in}\left(T_{liq,in} - T_{liq}\right) + Q_{SMP} + Q_{STP} + Q_{decay} - Q_{surf} - Q_{coil} - Q_{wall} - Q_{bottom} - Q_{str} \quad (1)$$

In Eq. (1) heat source terms are Q_{SMP} for SMP, Q_{STP} for STP, and Q_{decay} for radioactive decay heat source. 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. Thus, transient temperature of bulk waste fluid, T_{liq}, is determined by the energy balance of heat sources and sinks through the tank domain boundary when sludge flow $\dot{v}_{l,in}$ of temperature $T_{liq,in}$ comes into the tank as shown in Eq. (1). Detailed discussions for the heat source and sink terms are provided below.

As discussed earlier, heat sources (Q_{SMP}, Q_{STP}, and Q_{decay}) used in Eq. (1) are due to the presence of two SMP's, one STP, and decay heat source of radioactive waste contents contained in type-I tank. Average decay load is about 22 W/m^3. For the analysis, Tank 11 decay heat is used as the referenced decay load since the tank has the highest decay source as shown in Table 1. Each SMP used in the analysis considers high pumping power in the range of 225 to 350 horse power (HP). Detailed discussions for the heat sink terms used in the overall balance equation, Eq. (1), are provided below.

In the 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}).

$$\dot{m}'' = g\left(\frac{m_{H2O,\infty} - m_{H2O}}{m_{H2O} - m_{total}}\right) = gB \quad (2)$$

In Eq. (2) 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 [1] was used to estimate the evaporative mass of fluid at the top surface of the type-I waste tank. That is,

$$g = 0.0287\, \rho_\infty u_\infty Pr^{-0.4} Re^{-0.2} \frac{ln(1+B)}{B} \quad (3)$$

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

$$Q_{sens} = h_{surf} A\left(T_{liq} - T_{gas}\right) \quad (4)$$

In Eq. (4), the transient bulk gas temperature above the free surface, T_{gas}, can be computed by an energy transport equation associated with total heat transfer at the free surface Q_{surf}. That is:

$$\rho_g V_g C_{pg} \frac{dT_{gas}}{dt} = \rho_\infty \omega_{g,\infty} C_{pg}\left(T_\infty - T_{gas}\right) + Q_{surf} \quad (5)$$

In Eq. (5) $\omega_{g,\infty}$ is the purge air flowrate at the inlet of the purge gas system. The exit gas flowrate $\omega_{g,t}$ can be estimated by the mixed flow of purge gas and evaporation flowrates. In this case, the gas temperature at the exit of purge gas system, $T_{g,out}$, is assumed to be equal to the bulk gas temperature T_{gas}. Gas density is computed using the ideal gas law. In Eq. (4), the heat transfer coefficient at the surface (h_{surf}) was estimated by the literature correlation [1] for the cooled plate facing upward. 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}.

$$Q_{evap} = \dot{m}'' A\left\{i_{fg} + C_{pl}\left(T_{liq} - T_{gas}\right)\right\} \quad (6)$$

In Eq. (6) 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, Eqs. (2) and (3), 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. (2), 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 quantitative evaluation of heat transfer through the cooling coil system with chemical deposition on the outer surface of the coil, energy balance equations for the modeling boundary of cooling coil are constructed for the normal operating conditions with forced convective coolant flow. A_{cwo} and A_{cwi} are total wetted areas of the outer and inner walls of the cooling coils, respectively. A_{cm} in Eq. (21) is logarithmic average of area for an annular chemical deposition layer of the outer coil diameter d_{co}.

Wetted surface area of the cooling coil (A_{cwo}) in Eq. (7) is dependent on transient tank level (L_{wc}). In the present analysis, nominal tank level is used as 100 inches from the tank bottom. 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. 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. After algebraic manipulations of the heat transfer equations across the cooling coil, 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.

$$Q_{coil} = (T_f - T_1)\left(\frac{1}{h_{fo}A_{cwo}} + \frac{c}{k_c A_{cm}} + \frac{1}{h_{fi}A_{cwi}} + \frac{0.5}{N_c \rho_f \dot{v}_{cf} C_p}\right)^{-1} \quad (7)$$

In Eq. (7) 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 [1,2]. Heat transfer coefficient for the inner wall surface of the cooling coil (h_{fi}) in Eq. (7) was evaluated by the literature correlation for the forced convection [2]. For the referenced conditions, Reynolds number was found to be about 10^5, corresponding to turbulent flow.

For the evaluation of heat transfer across the side wall of a 75-ft waste tank, a plane wall is assumed to be exposed to a hot waste fluid 1, T_{f1}, on one side and a cooler fluid 2, T_{f2}, on the other side for the evaluation of overall heat transfer coefficient in Eq. (7). In this case the heat transfer processes for the wall and bottom regions are represented by the resistance network.

Now, all constitutive equations associated with the transient heat balance equation, Eq. (1), are complete. In this work, transient tank boundary conditions are required to compute transient temperature for each material region of the waste tank system.

Table 1. Reference operating conditions for heat balance study

Operating parameters	Reference conditions
Tank dimension (diameter x height)	75 ft x 24.5 ft
Initial temperature of waste fluid	65 ^oC
Initial tank level	100 in
Purge gas temperature at inlet	25 ^oC
Waste fluid density	1.35 sg
Temp. and flowrate at coolant inlet	25 ^oC, 5.7 gpm per coil
Cooling coil surface condition	No chemical deposition
No.of operating coils out of total 36 cooling coils	12
Purge gas flowrate, Relative humidity	500 scfm, 97%
Number of operating pumps	2 SMP's and 1 STP
Pumping power of each SMP	250 HP
Pumping power of each STP	25 HP
Transfer pump flowrate	200 gpm
Tank refill flowrate	31 gpm
Max. decay heat of Tank 11 waste	42.58 W/m^3

Note: 1 gpm = 3.7854 liters/min

RESULTS

Overall energy balance equations for typical SRS type-I waste tank such as Tank 11 were constructed for the modeling domain. The modeling governing equations were solved numerically for the transient boundary conditions for the waste operation. In this work, the original plan is related to 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 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. SRS 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, when cooling coil system was restored from previously inactive status, was used for the model benchmarking. The reference operating conditions shown in Table 1 were used in the benchmarking. The results showed that the model predictions agreed with the test data for the waste temperature within about 10% as shown in Fig. 2.

In the calculations, 12 active cooling coils were used as one of the reference nominal operating conditions as established by the benchmarking test. When 100 inches of initial tank level and 65 ^oC of initial waste temperature were used as the

reference conditions in Table 1, 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. 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. Those heat source and sink terms are quantitatively compared in Fig. 3. Transient temperatures of waste liquid, purge gas, cooling coil exit for the reference operating conditions are shown in Fig. 4. 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. It is also shown 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. From the 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. All the analyses demonstrate that maintaining active cooling coil system provides important cooling mechanism to remove the process heat from the waste tank system.

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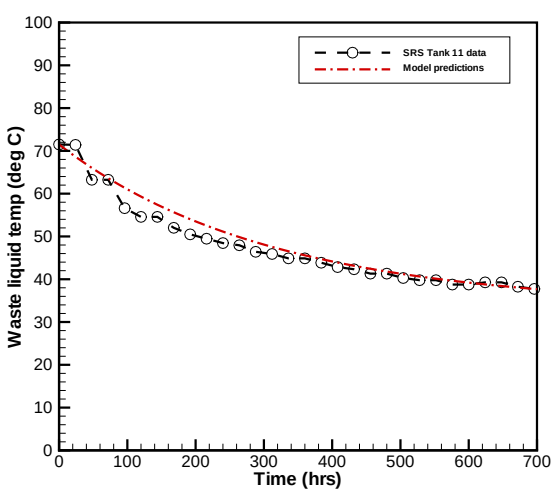

Fig 2. Comparison of waste temperatures between Tank 11 measurements and the predictions for the reference conditions.

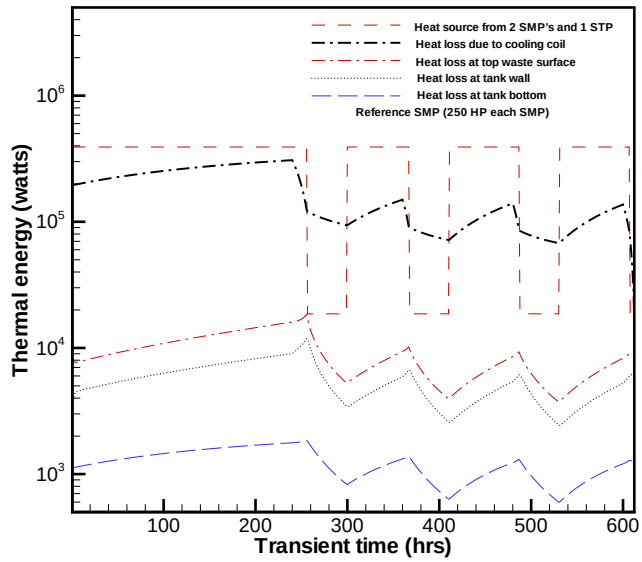

Fig. 3. Transient heat source and sink for the reference operating conditions as shown in Table 1

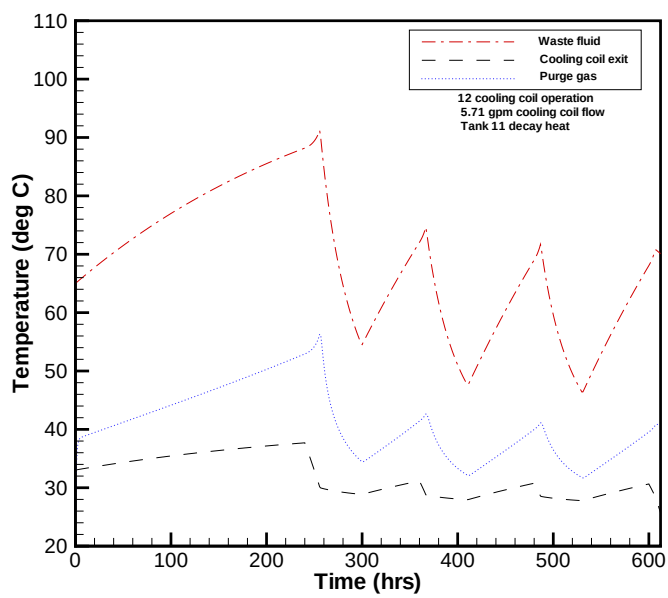

Fig 4. Transient temperatures of waste liquid, purge gas, cooling coil exit for the reference operating conditions as shown in Table 1