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Thermal Analysis of Salt Solution Receipt Tanks

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ABSTRACT

Modifications to the Savannah River Site (SRS) Saltstone Production Facility (SPF) low level waste (LLW) feed function include the installation of the Salt Solution Receipt Tanks (SSRTs). As the SSRTs contain salt solution with various species of flammable gases, there is a flammability concern when the tank solutions are heated to temperatures greater than 50°C in the summer. For winter operation, the concern is the freezing of the salt solution within the SSRTs. For this purpose, a transient thermal analysis for the SSRT and its enclosure has been developed. This analysis takes consideration of the thermal energies from the agitator, recirculating pump, nuclide decay, as well as the ambient air purge flow. Analysis results indicate that for continuous agitator and recirculating pump operation, the minimum volume salt solution temperature reaches 50°C in 31.8 hours during the summer condition. During the winter condition, the solution reaches its freezing point in 59.0 hours. Results of parametric studies have indicated that the results are primarily controlled by the agitator and the recirculating pump, and are insensitive to material properties, building characteristics, and the presence of the rain cover.

INTRODUCTION

The SSRTs are part of the Salt Disposition and Integration Project (SDI) at SRS. These two tanks receive salt solution containing low amounts of radioactive contamination to be mixed subsequently into cement (Saltstone) for permanent disposition. Each SSRT is a cylindrical tank with a capacity of 60,000 gal. The tank is constructed out of single wall 3/8-inch steel and is installed above grade with a weather shelter above and a concrete secondary containment/shielding wall around it. The liquid waste transferred to the SSRTs must be between 10°C and 40°C as required by the Waste Acceptance Criteria (WAC) [Ref. 1]. However, there is a concern for the temperature of the salt solution during summer operation. The salt solution in the SSRTs contains various species of flammable gases that may cause the formation of an explosive mixture in the vapor space of the tank if the vapor space exceeds 50°C [Ref. 2]. Another concern during winter operation is the freezing of the salt solution.

Incorporating the concept of integrating safety into the design process as stipulated in DOE-STD-1189 [Ref. 3], this analysis develops a transient heat transfer model to determine the salt solution temperature for the hottest summer and the coldest winter conditions. Parametric analyses are also performed for salt solution volume, agitator power, recirculating pump power, purge flow rate, ambient air leakage into the enclosure and the effects of the rain cover over the roof of the SSRT enclosure.

ANALYTICAL METHODS AND COMPUTATIONS

The SSRT vessel is located in a rectangular concrete enclosure with a roof of thin steel and three walls exposed to ambient conditions. The fourth wall is an interior wall that separates the SSRT vessel enclosure from the other SSRT vessel enclosure. There is a rain cover over the roof of the building. Figure 1 is a schematic showing the SSRT and the building where it resides. A thermal model of the SSRT and the enclosure in which it resides was developed to determine the solution temperature in the SSRT to support an SSRT flammability analysis (Ref. 4). For conservatism, heat transfer to the floor is ignored. The exterior concrete walls and steel roof have solar insolation as heat input to the walls. Heat transfer from the exterior walls and roof occur via convection and radiative heat transfer. Natural convection heat transfer occurs on the surfaces inside the enclosure. The SSRT building is also modeled with and without the presence of a rain cover over the building roof. When the rain cover is considered, it is modeled as a radiation shield which cuts the solar insolation by 50% [Ref. 5].

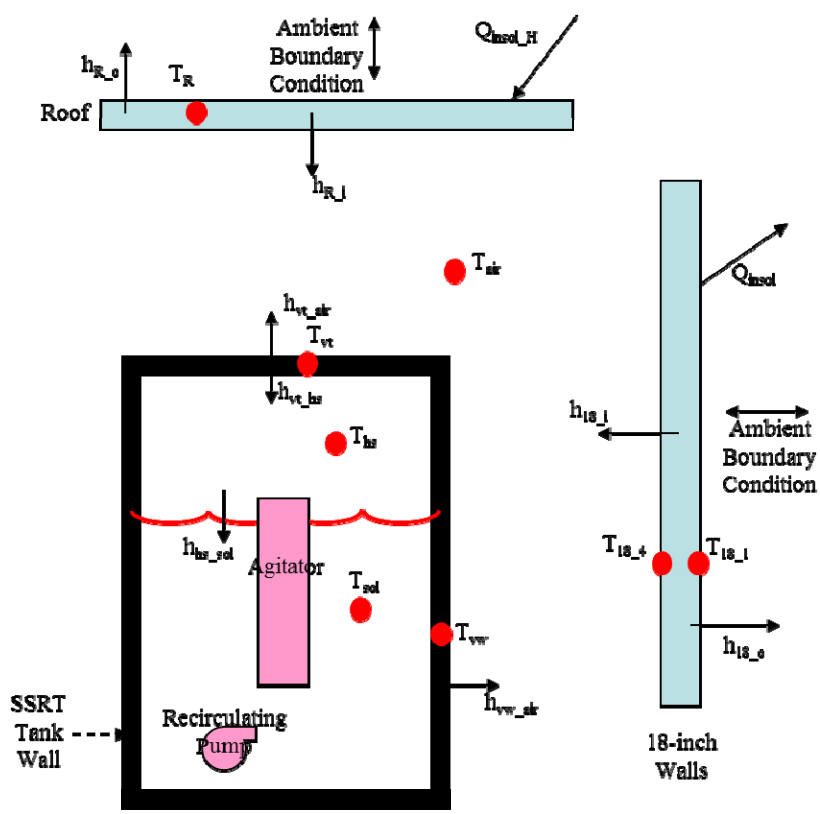

Figure 1 Heat Transfer Schematic for the SSRT Enclosure

<u>Heat Transfer in Concrete Walls</u>

The north, south, and west facing exterior concrete walls surrounding the SSRT are 18 inches thick. For this wall, the equation for conduction heat transfer is:

$$\rho_{con}\, Cp_{con} \frac{\partial T(x,t)}{\partial t} = k_{con} \frac{\partial^2 T(x,t)}{\partial x^2} \tag{1}$$

where

T = temperature in concrete, °C
ρ_{con} = density of the concrete wall, kg/m^3
Cp_{con} = specific heat of the concrete wall, J/(kg-°C)
k_{con} = thermal conductivity of the concrete wall, W/(m-°C)
t = time, sec.

Equation 1 is not valid at the edge of the wall. The general boundary condition for the edge is:

$$k_{con}\, A_w \frac{\partial T}{\partial x} = -Q_c - Q_r + Q_s \tag{2}$$

where

$$Q_c = \text{convective heat loss} = h\, A_w \left(T_{wall} - T_{amb}\right) \tag{3}$$

$$Q_r = \text{radiative heat transfer} = A_w\, \sigma\, \varepsilon \left(T_w^4 - T_{amb}^4\right) \tag{4}$$

$$Q_s = \text{solar gain} = A_w\, \alpha_{con}\, Q_{insol} \tag{5}$$

σ = Stefan-Boltzmann constant, W/(m^2-K^4)
ε = emissivity for the wall surface, unitless
T_{amb} = ambient temperature, °C
Q_{insol} = solar insolation, W/m^2
A_w = wall surface area, m^2
α_{con} = solar absorptivity for the wall surface, unitless
x = distance into the wall.

The radiative and solar insolation terms in Equation 2 are only used for the exterior surfaces of the building. For the radiative heat transfer term, the ambient air temperature was used as the sink temperature. Since the ambient air temperature is higher than the apparent temperature for radiative heat transfer, this provides a conservatively low estimate for the radiative heat loss. For summer conditions, the ambient temperature is based on the hottest day on record for a single day transient, and the temperature is available on an hourly basis. For transients longer than one day, the hourly temperatures of the hottest day are repeated recurrently but reduced by 2°C. For the winter conditions, the hourly temperatures are based on the coldest day on record for a single day transient, and these temperatures were used for all other days in the winter transient calculation.

The solar insolation is also available on an hourly basis [Ref. 6], and the day with the highest hourly value was chosen for the summer condition. These hourly values were for a horizontal surface. For walls of different orientations, Reference 7 provides the correction

to the horizontal value for other orientations. For the winter transient calculation, the solar insolation is assumed to be zero.

Energy Balance for the Salt Solution

The temperature change of the salt solution is a function of the heat transfer in/out of the control volume, potential cooling, and heat generation within the control volume. The governing differential equation is:

$$V_{sol}\,\rho_{sol}Cp_{sol}\left(\frac{dT_{sol}}{dt}\right) = Q_{hdspS} + Q_{wall} + Q_{ag} + Q_{rp} + Q_{dh} + \dot{m}_v\left(h_{in} - h_{out}\right) \qquad (6)$$

where

T_{sol} = temperature of the salt solution, ^oC
V_{sol} = volume of salt solution, m^3
ρ_{sol} = density of the solution, kg/m^3
Q_{hdspS} = heat transfer from the headspace into the solution, W
Q_{wall} = heat transfer from the air to the SSRT, W
Q_{ag} = heat generation from the agitator deposited into the solution, W
Q_{rp} = heat generation from the recirculating pump deposited into the solution, W
Q_{dh} = heat generation from Cs-137 decay heat deposited into the solution, W
$\dot{m}_v$ = salt solution flow into and out of the SSRT, kg/sec
h_i = enthalpy of the incoming salt solution, J/kg
h_e = enthalpy of the exiting salt solution, J/kg

The agitator has a rated power of 15 hp with an efficiency of 85%, while the recirculating pump has a rated power of 7.5 hp with an efficiency of 55%. In this analysis, all governing differential equations are discretized in a finite-difference form, which can be solved implicitly in time for numerical stability.

Temperatures in Vessel Wall, Headspace, and Vessel Top

The vessel walls are made of steel with a mere thickness of 3/8 inches. In the heat transfer model, the side walls and bottom of the SSRT are assumed to be in thermal equilibrium with the salt solution. This is justified because calculations have shown that these tank surface temperatures are typically only 0.1˚C cooler than the salt solution. Only the top surface of the SSRT tank, which is never wetted by the salt solution, uses a form of Equation 6 without the airflow terms to determine its temperature.

The headspace of the SSRT vessel also uses an equation similar to Equation 6 to determine its temperature except that the feed-and-bleed term, $\dot{m}_v\left(h_{in} - h_{out}\right)$, is replaced by that of the air purge. For small to zero purge airflows, the headspace temperature is nearly equal to the salt solution temperature; i.e., in thermal equilibrium. The present SSRT heat transfer model does not consider the heat transfer between the salt solution and the headspace air due to mass transfer. Temperature changes in the top surface of the SSRT

and the roof of the enclosure above the SSRT are also formulated in a similar fashion except that there is no internal heat source and no purge flow.

For the summer transient, the maximum possible Cs-137 loading in the salt solution is assumed along with the most limiting ambient temperatures. To maximize the solution temperature, purge flow into the headspace is set to be zero. For the winter transients, heat generation in the salt solution is not assumed and the ambient temperature is used for the purge airflow into the SSRT headspace. For conservatism, the agitator and the recirculation pumps are turned off. For this analysis, the freezing temperature of the salt water (sea water), -1.8°C, was used as the freezing point for the salt solution.

Heat Transfer Correlations

Heat transfer correlations are needed to determine the heat transfer coefficient for each non-adiabatic surface in the heat transfer model. The Nusselt number Nu and the heat transfer coefficient for natural convection are given in the following general functional relationship:

$$\mathrm{Nu} = \frac{h\,L}{k} = f(\mathrm{Gr} \cdot \mathrm{Pr}) \tag{7}$$

where h = heat transfer coefficient, $W/m^2\text{-}^oC$
L = characteristic length, m
k = thermal conductivity, $W/m\text{-}^oC$
Gr = Grashof number
Pr = Prandtl number

The correlations used in this analysis are listed in Table 1 (Ref. 8, Table 9 of Chapter 4), which gives Nu as a function of the Raleigh number Ra, which is a product of Gr and Pr. Depending on the geometry and orientation, the correlating parameters range as high as 10^{12}. However, a single correlation seldomly covers the entire range. In this study, a gap between correlations was covered by using a straight line to connect the endpoints of the individual correlations.

Table 1 Natural Convection Correlations

Condition for Usage	Correlation for Nusselt Number	Reference
For upper surface of a flat plate with $T_w > T_f$ and lower surface of a flat plate with $T_f > T_w$ Used for salt solution to headspace, vessel upper head to enclosure air /	$0.96 \times \mathrm{Ra}^{1/6} \quad 1 < \mathrm{Ra} < 200$ $0.59 \times \mathrm{Ra}^{0.25} \quad 200 \le \mathrm{Ra} < 10^4$ There is a gap in the range of Ra between 10^4 and 2.2×10^4. The previous correlation is extended to Ra of 2.2×10^4 to provide a bridge to the next correlation.	[8], Table 9, Chapter 4

headspace, and building roof to enclosure air inside the building	$0.54 \times Ra^{0.25} \quad 2.2 \times 10^4 < Ra < 8 \times 10^6$ $0.15 \times Ra^{0.333} \quad 8 \times 10^6 \le Ra < 1.5 \times 10^9$ This expression is extrapolated for Ra values above 1.5×10^9.	
For upper surface of a flat plate with $T_w \le T_f$ and lower surface of a flat plate with $T_f \le T_w$ Used for salt solution to headspace, vessel upper head to enclosure air / headspace, and building roof to enclosure air inside the building	$\frac{Ra}{10^4} \times 0.59 \times 10000^{0.25} \quad 10^5 \ge Ra$ Correlation is an extrapolation of the correlation below to provide a continuous range of Ra for the Excel function. $0.27 \times Ra^{0.25} \quad 10^5 < Ra < 10^{10}$ This expression is extrapolated for Ra values above 10^{10}.	[8], Table 9, Chapter 4
For vertical flat plate. Can be used for a vertical cylinder if $(D/L)_{cyl} > 35/Gr^{0.25}$ (true for this work) Used for SSRT vessel to enclosure air, exterior / interior surfaces of vertical building wall to ambient air / enclosure air	$\left[0.825 + \frac{0.387 \times Ra^{1/6}}{\left[1 + \left(\frac{0.437}{Pr}\right)^{9/16}\right]^{8/27}}\right]^2 \quad 10^{-1} < Ra < 10^{12}$ This expression is extrapolated for Ra numbers above 10^{12}.	[8], Table 9, Chapter 4

RESULTS

The three base cases considered in this analysis are:

- Case 1: Minimum solution volume (8,235 gal) in summer conditions with continuous operation of agitator at 85% agitator efficiency and recirculating pump at 55% efficiency.
- Case 2: Maximum solution volume (60,000 gal) in summer conditions with continuous operation of agitator at 85% agitator efficiency and recirculating pump at 55% efficiency.
- Case 3: Minimum solution volume (8,235 gal) in winter conditions with 107 scfm purge flow from ambient air and no agitator or recirculating operation.

The results for the three base cases are presented in Table 2.

Table 2 Results for the Three Base Cases

Case	Volume (gal)	Conditions	Solution Temperature (°C)				Notes
			3 Days	5 Days	10 Days	30 Days	
1	8,235	Summer conditions, with agitator and recirculating pump	62.1	71.9	83.4	88.0	Reaches 50°C in 31.8 hr
2	60,000	Summer conditions, with agitator and recirculating pump	43.8	46.4	52.3	69.4	Reaches 50°C in 190.5 hr
3	8,235	Winter conditions, no agitator or recirculating pump, 107 scfm purge flow	-0.9	-4.3	-8.5	-11.1	Reaches 0°C in 59.0 hr*

* Seawater, with a salinity of 35 parts per thousand, is estimated to freeze at -1.8°C. The SSRT salt solution in Case 3 of this analysis reaches -1.8°C in 79.8 hours.

The temperature transients for the three base cases are shown in Figures 2 - 4. For Cases 1 and 2, the impact of the energy from the agitator and recirculation pump is shown by the rapid temperature increase of the enclosure (building) air, head space, and solution in the SSRT.

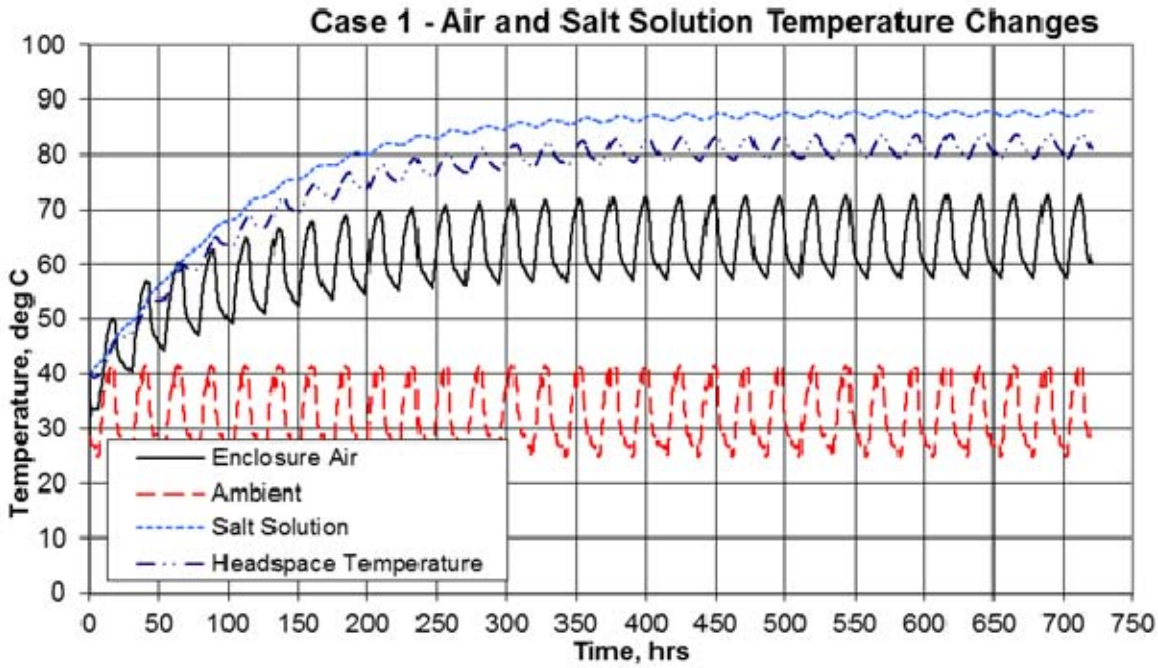

Figure 2 Air and Salt Solution Temperature History for Case 1

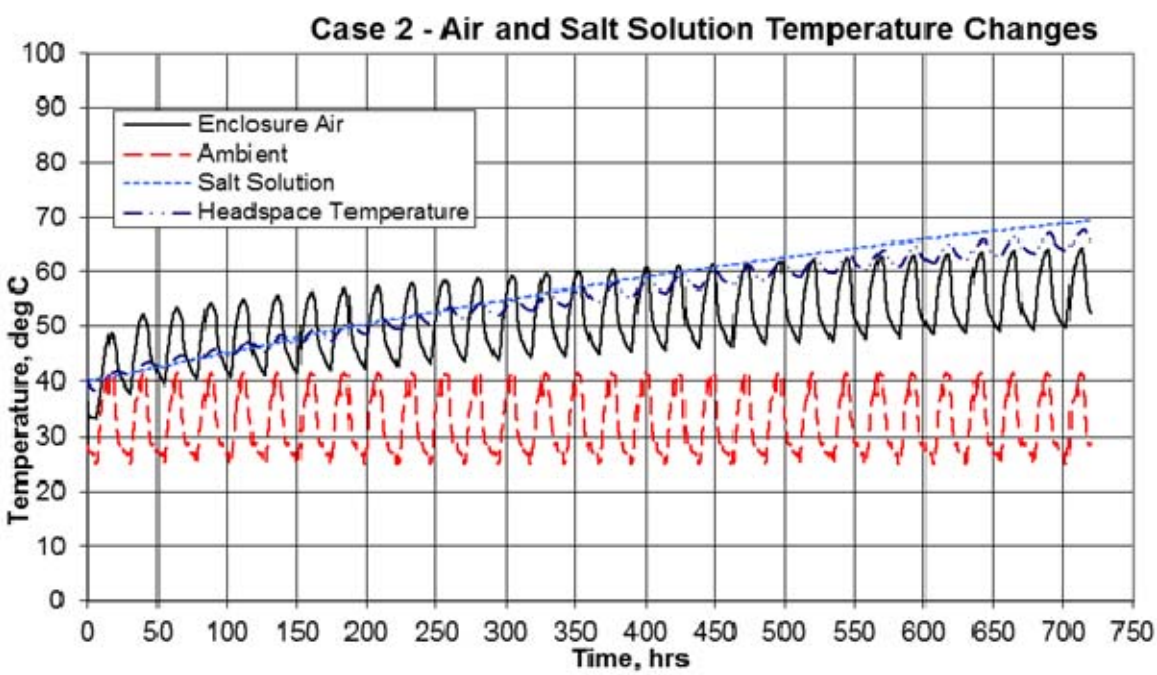

Figure 3 Air and Salt Solution Temperature History for Case 2

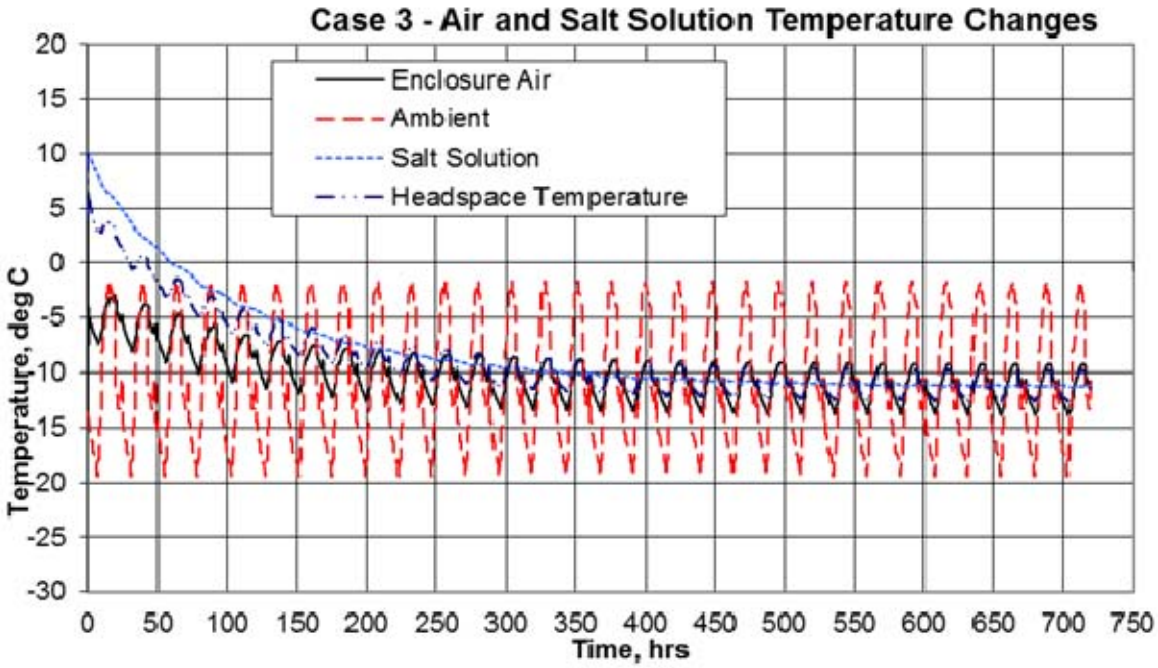

Figure 4 Air and Salt Solution Temperature History for Case 3

Additional cases were run for the summer condition with variations to the model. One variation to the model is the placement of a rain cover above the enclosure. The model for the rain cover is based on Reference 4, which indicates that a radiative heat transfer barrier would reduce heat transfer (i.e., solar insolation) by 50%. This analysis uses 40% reduction of solar insolation. Another variation to the model is the exchange of 10% of the enclosure air with ambient air each hour. Other variations are the addition of purge flow from ambient air and an increase in agitator efficiency. Table 3 presents results for the additional cases; all with solar heating and continuous mechanical input from the agitator and recirculating pump, which operates at 55% efficiency for all cases.

Table 3 Additional Summer Cases with Solar Heating and Continuous Mechanical Heat Input

Case	Volume (gal)	Agitator Efficiency	Model Modifications	Solution Temperature (°C)				Time to Reach 50°C (hrs)
				3 Days	5 Days	10 Days	30 Days	
4	8,235	100%	100% Agitator Efficiency	63.7	74.0	85.8	90.4	28.6
6	8,235	85%	Rain Cover	60.3	69.0	78.8	82.5	33.7
7	60,000	85%	Rain Cover	43.5	45.8	51.2	66.7	210.6
8	8,235	85%	107 scfm Purge Flow	60.9	69.6	79.0	82.4	33.3
9	60,000	85%	107 scfm Purge Flow	43.7	46.2	51.8	67.4	199.7
10	8,235	85%	Rain Cover & 107 scfm Purge Flow	59.2	66.9	75.1	77.8	35.4
11	60,000	85%	Rain Cover & 107 scfm Purge Flow	43.4	45.7	50.8	64.8	220.3
12	8,235	85%	10% Air Exchange per Hour	61.9	71.6	82.8	87.3	31.9
13	60,000	85%	10% Air Exchange per Hour	43.8	46.3	52.2	69.1	191.9

Conclusions

The results of the calculation show that under summer conditions with continuous agitator and recirculating pump operation, the solution temperature of the minimum tank working volume reaches the flammability temperature of 50°C after 31.8 hours. Under the same conditions, the solution temperature of the maximum working volume would reach the same flammable temperature in 190.5 hours. Also, under winter conditions with 107 scfm purge flow from ambient air and no agitator or recirculating pump operation, the minimum tank working volume solution temperature reaches 0°C (freezing temperature of water) and -1.8°C (freezing temperature of seawater) after 59.0 hours and 79.8 hours, respectively. Based on the parametric studies, the results are not very sensitive to material properties, small variations in building characteristics, or the presence of the rain cover. The results are mainly driven by the operation of the 15-hp agitator and 7.5-hp recirculating pump.

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