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Thermal Evaluations for Tank Cesium Removal System

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INTRODUCTION

Radioactive waste settles down into three regions, salt supernate, saltcake, and sludge. The sludge is taken to be vitrified into radioactive glass, which is an immobilized form of the waste. The saltcake and salt supernate require more processing before they can be safely stored. Both salt wastes are taken to the Salt Waste Processing Facility for radioactive cesium-137 removal. Then the radioactive material is vitrified at the Defense Waste Processing Facility. The decontaminated material is sent the Saltstone Facility to be mixed with grout and immobilized. The Tank Closure Cesium Removal (TCCR) system is a proposed system to remove cesium-137 from the salt solution. The primary objective of the work is to optimize the design of the TCCR system in terms of a thermal aspect. The column contains a Crystalline Silicotitanate (CST) material to remove the cesium-137. The CST column containing radioactive cesium releases large amounts of heat from the radioactive decay. The CST column must be engineered to handle the thermal load to preserve the integrity of the column. The CST material must not exceed 105°C for non-boiling safety purposes.

The purpose of the present work is to compare designs and scenarios for the CST column. Some of the design characteristics that were examined included varying air gap size, thermal load, and the dimensions of the columns. The modeling results show the maximum temperatures which could be achieved by the design configurations.

DESCRIPTION OF THE WORK AND RESULTS

The modeling geometry used for the thermal calculations is shown in Fig. 1. The component materials for the TCCR system are shown in Fig. 1. The material and thermal properties for the system components are shown in Table 1.

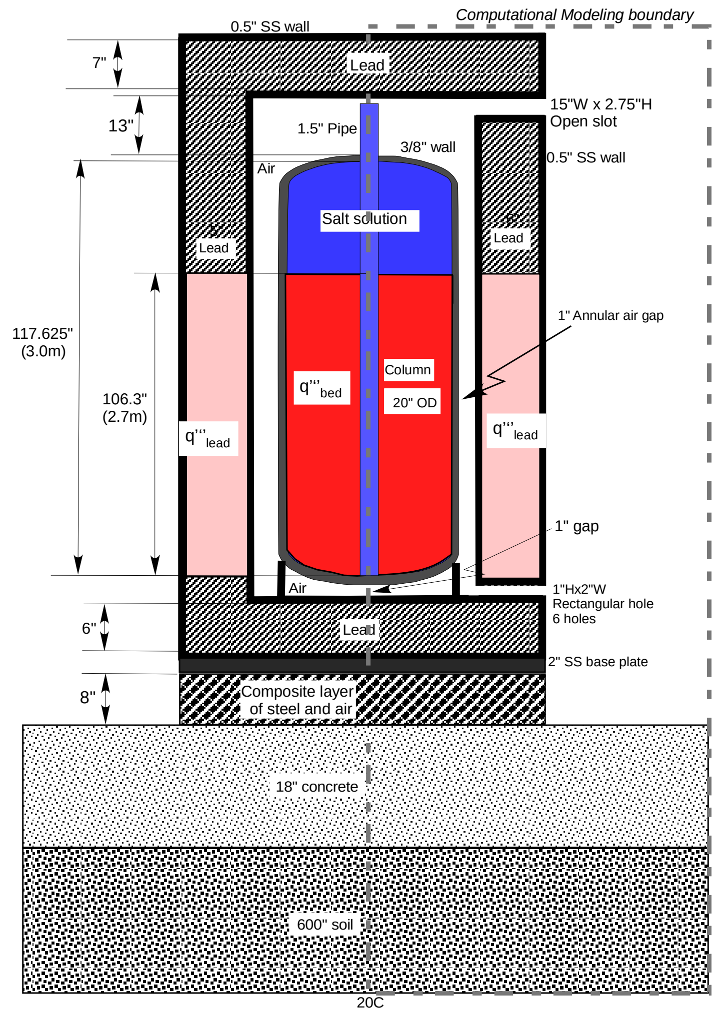


Figure 1. Modeling geometry of the TCCR system with materials and dimensions.

Table 1. Material and thermal properties used in modeling analysis

Material	Density (Kg/m^3)	Heat Capacity (J/Kg-K)	Thermal Conductivity (W/m-K)
Concrete	2400	750	1.5
CST solution	1589	2513	0.4119
Lead	11258	127	34.7
Soil	2000	1450	1.25
Salt solution	1232	3630	0.68
Stainless steel	8030	502.48	16.27
Stainless steel and air composite	79.2	998.8	0.187

Three different cases where evaluated:

- Nominal Case – 20” CST column with a center water pipe, with 1” of natural convection
- Sensitivity Case 1 – 18” CST column with a center water pipe, with 2” of natural convection
- Sensitivity Case 2 – 20” CST column with no center water pipe, with 1” of natural convection.

The total volume was kept the same for all three cases. So the height of the column for the Sensitivity Case 2 was adjusted to maintain the same volume.

A two-dimensional axisymmetric model was used for the thermal calculations of the TCCR system. The modeling boundary was shown in Fig. 1. For the analysis, the ambient temperature was set to 56°C and the bottom of the 600-inch soil was set to 20°C.

Assumptions used for the modeling calculations include the following:

- The system was at steady state
- The TCCR system geometry was assumed to be axisymmetric.
- The heat source was uniformly distributed
- Ambient temperature was 56°C for a conservative estimate of the thermal performance for the facility
- Air was assumed to follow the ideal gas behavior, considering temperature-induced natural convection

A mesh size comparison was done for the Nominal Case to find the minimum mesh size for the column region with a load of 100 Ci/L. This was done by reducing the mesh size of the column region until the results were independent of mesh size. The minimum size was found to be 0.531 inches, anything smaller than that also produced the similar solution but took more time to solve. Evaluation of the Mesh Size on the Computational Results is shown in Fig. 2.

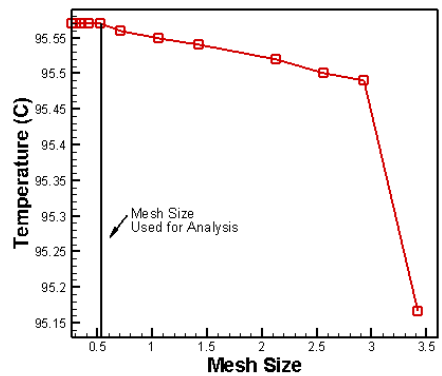


Figure 2. Evaluation of the Mesh Size on the Computational Results (Mesh size is in inch.).

Benchmarking was done to compare the theoretical results to the computational results, using a cross section of a simplified version of the TCCR system with the center water pipe removed as shown in Fig. 3.

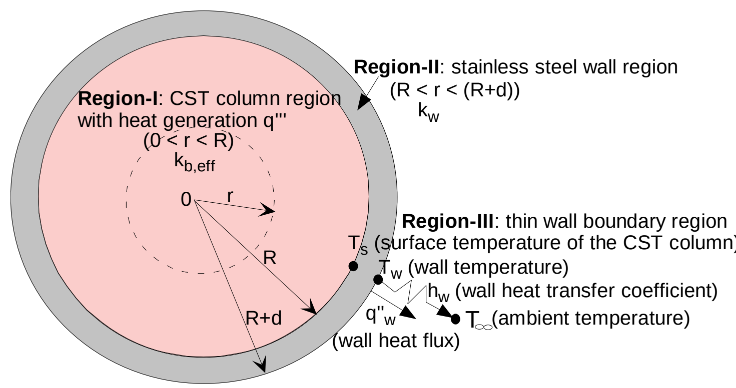


Figure 3. Illustration of the CST column model used for both the theoretical and the computation modeling.

The theoretical equation for the stainless steel outer layer, R ≤ r ≥ R+d, can be found using the following equation, the $q'''=0$, since there is no heat generation in this layer.

$$\int \frac{1}{r}\frac{d}{dr} r \frac{dT}{dr} = 0 \tag{1}$$

$$T_{ss}(r) = C_1 \ln(r) + C_2 \tag{2}$$

The boundary conditions for the stainless steel layer are

$$T_{ss}(r = R + d) = T_w \tag{3}$$

$$q''_w = -k_w \frac{dT}{dr}(r{=}R + d) = h_w (T_w - T_\infty) \tag{4}$$

$$q''_w = q'''\left(\frac{V_b}{A_w}\right) = q'''\left(\frac{\pi R^2 L}{2\pi (R+d) L}\right) = q'''\left(\frac{R^2}{2(R+d)}\right) \tag{5}$$

By using the T_{ss} equation and the boundary conditions above the CST wall region equation becomes:

$$T_{ss}(r) = T_w + \left(\frac{q'''R^2}{2k_w}\right)\ln\left(\frac{R+d}{r}\right) \qquad (6)$$

The theoretical equations for the uniform heat generation in the CST column region from $0 \leq r \geq R$, as shown in Fig. 3, was found using the equation below. The T_{col} equation then becomes

$$T_{col}(r) = \frac{q'''}{4k_{b,eff}}(R^2 - r^2) + \left(\frac{q'''R^2}{2k_w}\right)\ln\left(\frac{R+d}{R}\right) \qquad (7)$$

The CFD modeling results of the temperature distribution for a cross section of a TCCR column were compared with the theoretical results. In Fig. 4 the theoretical and computational results are compared, in which we can see that the results are very similar. This was done to show that our model was accurate by comparing the results.

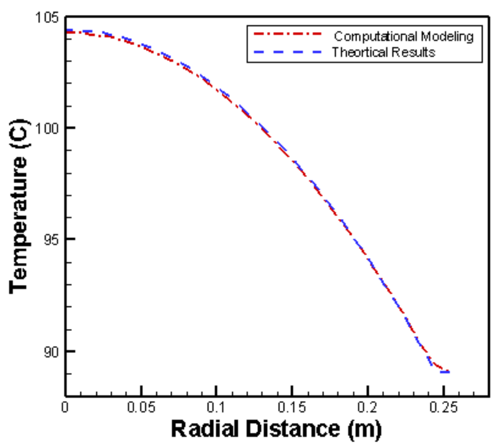


Figure 4. Comparison of the Computational Modeling Results to the Theoretical Results.

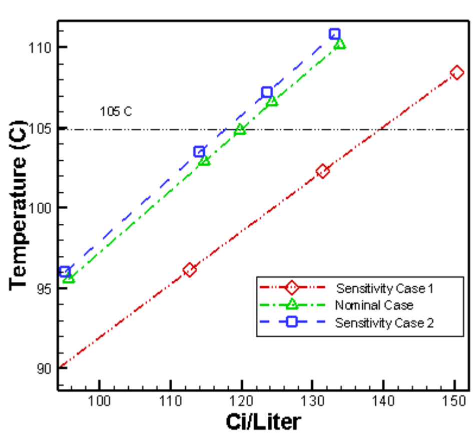


Figure 5. Evaluation of Ci/L Threshold for Modeling Cases.

The TCCR system has to be kept below 105°C for safety reasons. To find the maximum load each design case could hold the source terms were increased until 105°C was reached as shown in Fig. 5. Then using a linear equation for each line the maximum load was found. Table 2 shows the maximum amounts that each case can hold.

Table 2. Maximum Curies per liter for each case.

Design	Maximum Ci/L
Nominal Design	119.678
Sensitivity Case 1	139.785
Sensitivity Case 2	118.027

The Sensitivity Case 1 could hold the most amount of Ci/L, around 20 Ci/L more than the Nominal Case. This is most likely due to the increased surface area of the column which allowed for more natural convection to take place. The radial temperature distributions for the modeling cases along the middle plane of the TCCR system are compared in Fig. 6. With a 100 Ci/L load, the Sensitivity Case 1 had a 6 degree temperature drop from the Nominal Case as shown in the figure. The temperature difference between the Nominal Case with a water pipe and the Sensitivity Case 2 without a water pipe was less than half a degree. When looking at the temperature difference from the outer wall of the CST column and the lead shielding there was an 18°C temperature drop with the Nominal Case and the Sensitivity Case 2. Sensitivity Case 1 had a 16°C temperature drop.

In Fig. 7 temperature distributions and natural convection flow patterns for the top of the air space of the TCCR system are shown. The red indicates a high velocity for the air, since the heated air is rising while the cooler air sinks.

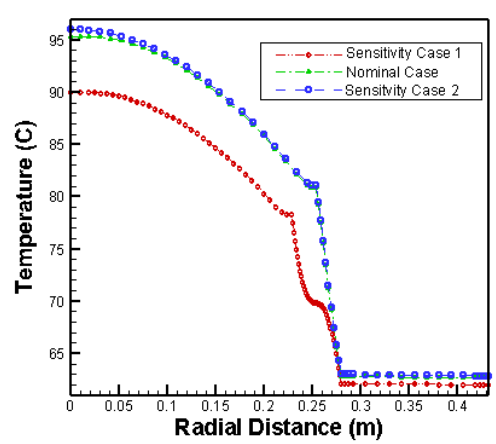
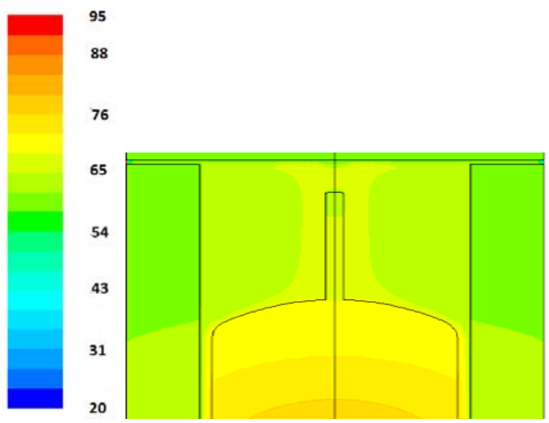
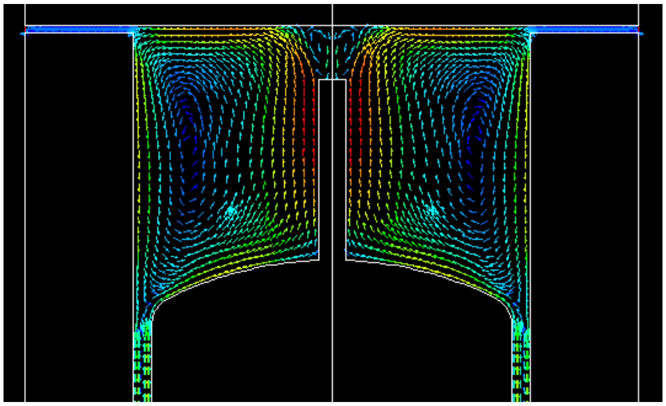


Figure 6. Evaluation of the temperature distributions in the modeling cases.



(Temperature distributions; color code in ^{o}C)



(Flow patterns in air space)

Figure 7. Temperature distributions and flow patterns in the upper air space.

DISCUSSIONS AND SUMMARY

The Sensitivity Case 1 proved to be the better design out of the three cases tested. With a 100 Ci/L load the Sensitivity Case 1 had a 6 degree temperature drop from the Nominal Case. Since, the volume of the CST column was kept the same as the nominal design but the column diameter was decreased the column was thinner and taller so more natural convection could take place, which released more heat from the column. However, the manufacturing cost would be higher for the Sensitivity Case 1 since there would be more shielding material and stainless steel used.

In addition, the effects of the water pipe were almost minimal; there was only half a degree difference between the Nominal Case and Sensitivity Case 2. A cost analysis could be done to see if the benefits of the stagnant water pipe are worth the manufacturing cost.

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