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Soil Mesh Optimization and Preliminary FEA Study of Tank-to-Tank Interaction for Hanford Type IV SST

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ABSTRACT

As a result of atomic weapons production, millions of gallons of radioactive waste were generated and stored in underground tanks at various U.S. Department of Energy (DOE) sites. The DOE Hanford Site in the state of Washington has the largest number of high-level waste (HLW) storage tanks in the United States. The safe storage, retrieval, treatment and disposal of 53 million gallons of HLW in these tanks is a national priority for DOE. A total of 149 underground single-shell tanks (SST) were constructed between 1943 and 1964. An SST is an underground nuclear waste storage tank with a single liner of steel within a cylindrical reinforced concrete structure. The SSTs are beyond their estimated design life and several are known to have leaked. The continued safe use and decontamination operations by the tank farm contractor are necessary until the tanks are cleaned and decommissioned by DOE. In order to assess the structural integrity of the SSTs, an analysis was recommended by the SST Integrity Expert Panel. Pacific Northwest National Laboratory (PNNL) is conducting a finite element analysis (FEA) of these structures using the commercial software ANSYS® [1]. The temperature and waste level history for Tank A-101 is fully documented and was used in this analysis. Mechanical live and dead loads including soils loads, hydrostatic loads as well as loads due to overhead equipment were considered. The thermal and structural interaction of closely spaced waste tanks was investigated to evaluate the structural integrity of the Type IV SST. A finite element sensitivity study was conducted to establish the required level of mesh refinement for multi-tank analysis using symmetry planes. The temperature profile for the soil reaches convergence for a mesh element size of 12 inches. Soil plastic strain was observed near the footing, haunch and dome for combined thermal and structural loads. Moreover, other structural factors such as soil pressure and displacement were captured accurately and are in agreement with expected results. The soil mesh was improved based on previous models and a preliminary FEA study was completed to provide a foundation for future more comprehensive models, including 90 degree wedge models used to quantify the influence of thermal and operating loads on adjacent tanks.

[1] ANSYS is a registered trademark of ANSYS, Inc., Canonsburg, Pennsylvania.

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1.0 INTRODUCTION

In response to Hanford's plutonium production, a total of 149 underground tanks were constructed between 1943 and 1964 to contain the nuclear waste in twelve separate tank farms in the 200 East and West areas of the Hanford Site. The twelve tank farms are identified as A, AX, B, BX, BY, and C in the 200 East Area and S, SX, T, TX, TY, and U in the 200 West Area of the Hanford Site north of Richland, Washington. The tanks are classified as Type I, II, III, and IV in order of increasing waste level capacity. Type I tanks have an internal diameter of 20 feet and a storage capacity of 55,000 gallon. Type II, III and IV tanks each have 75-foot internal diameters with capacities that vary by height. The Type II tanks can hold 530,000 gallons and have an internal height of 21 feet. Type III SST have a 758,000 gallon capacity and are similar to Type II in the design, except that these have thicker walls and a height of 37 feet [1]. The Type IV tanks are 1 million gallon capacity with an internal height of 44.33 feet.

Given that the SSTs are beyond their estimated design life, the DOE Office of River Protection (ORP) determined the need to analyze and understand the structural soundness of the SSTs on the Hanford Site. In order to address this matter, Pacific Northwest National Laboratory is conducting the SST Analysis of Record (AOR) for Washington River Protection Solutions (WRPS).

The objective of the SST AOR Project is to perform a thorough structural analysis for the SSTs in order to understand the current structural integrity of such tanks given the record of past usage as well as the hazards posed by natural phenomena. Both static and dynamic structural analyses are conducted. Seismic analysis is included as well in order to account for any possible earthquakes in the future. PNNL is carrying out the analysis for the thermal and static operating loads whereas M&D Professional Services, Inc. is the subcontractor who performs the seismic analysis of the SSTs.

For the purpose of this study, the analysis will be focused on the Type IV SST. There are three variations of Type IV tanks (Types IVa, IVb, and IVc). The structures are approximately the same size; however, there are some differences in the design of the liner as well as the base slab of the tank [1].

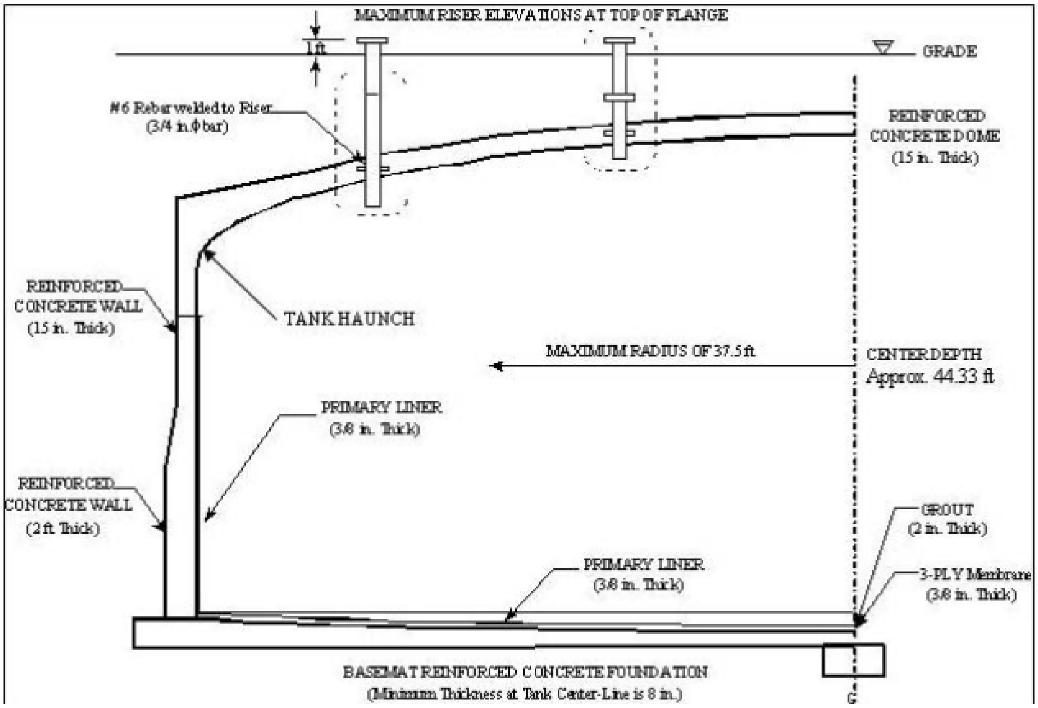

Figure 1. Typical 1 million gallon SST waste tank for the Type IVa tanks, 241SX. Note that these tanks have dish-shaped bottoms. [1]

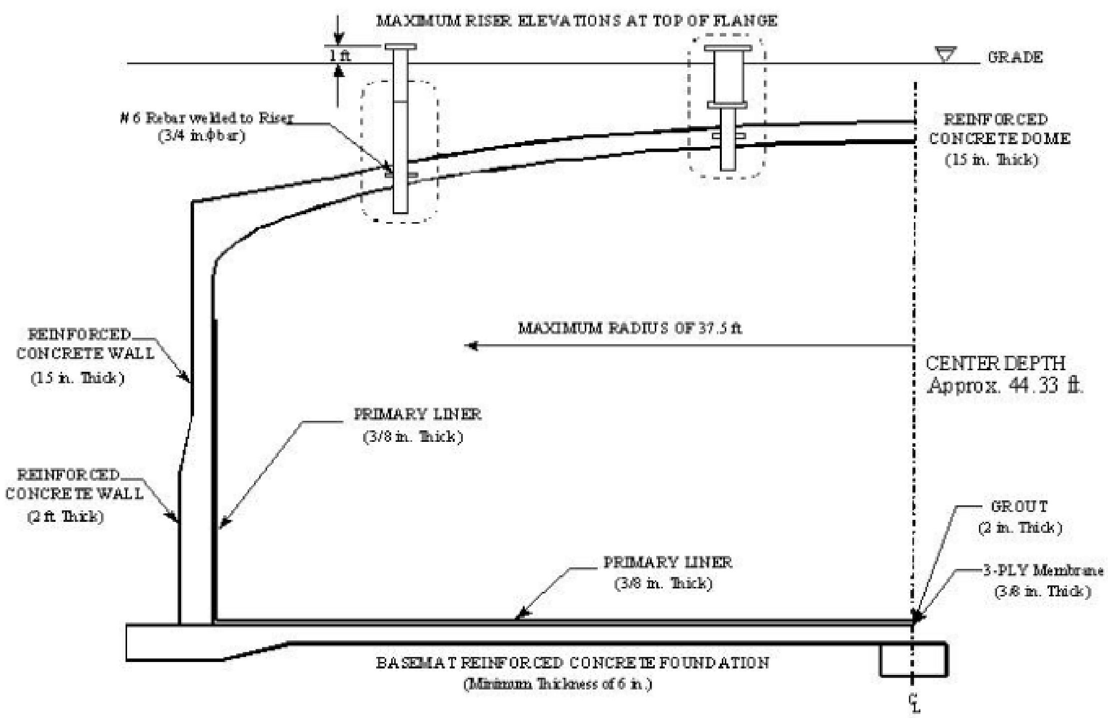

Figure 2. Typical 1 million gallon SST waste tank and riser configuration for Type IVb, 241A. These tanks have flat bottoms. [1]

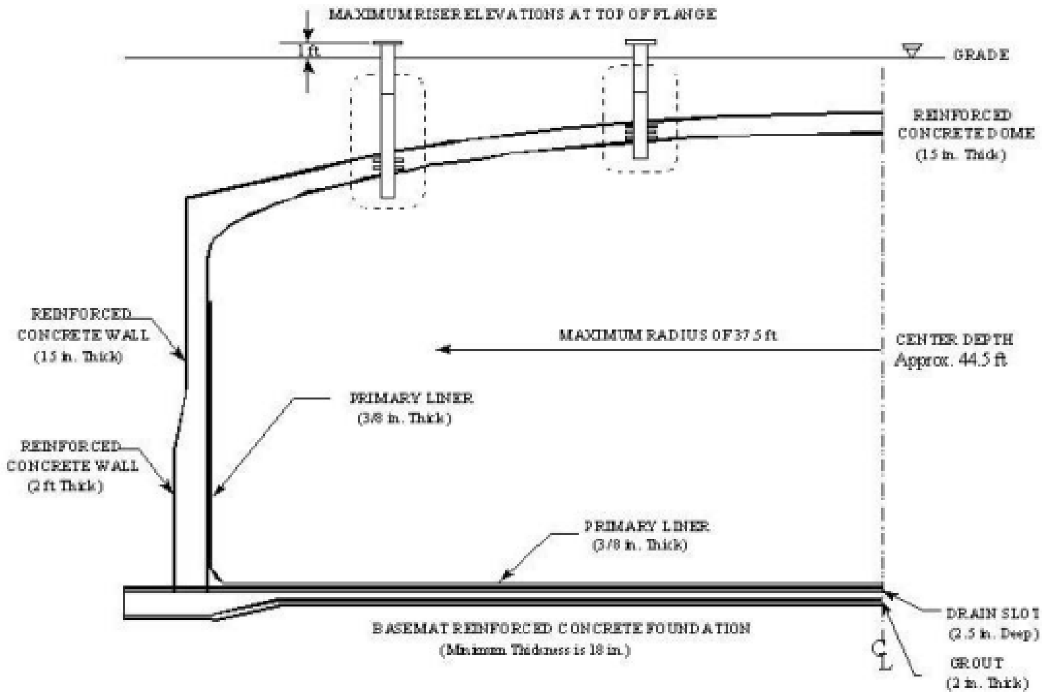

Figure 3. Typical 1 million gallon SST waste tank and riser configurations for Type IVc, 241AX. Similar to Type IVb, these have flat bottoms and include drain slots. [1]

Figures 1 through 3 show descriptive schematics for the Type IV tanks, where the differences between Types IVa, IVb and IVc can be observed. Mainly, dish-shaped or flat bottoms and drain slots are some of these differences but also Type IVc has a thicker basemat [1].

Figure 4. Typical SST basemat during construction of BX tank farm. Taken from [1]

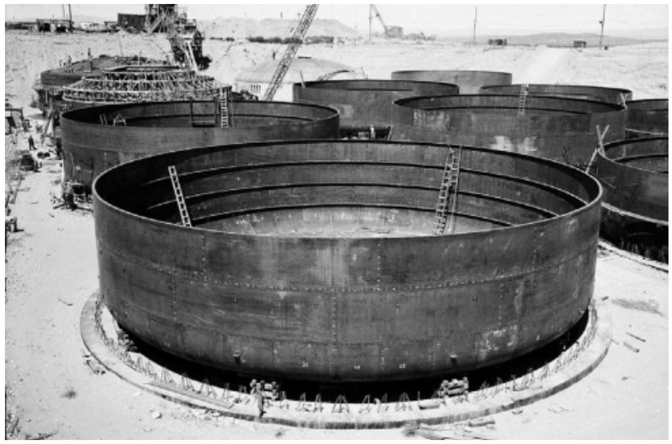

Figure 5. Construction of steel liner for tank in BX farm. Taken from [1]

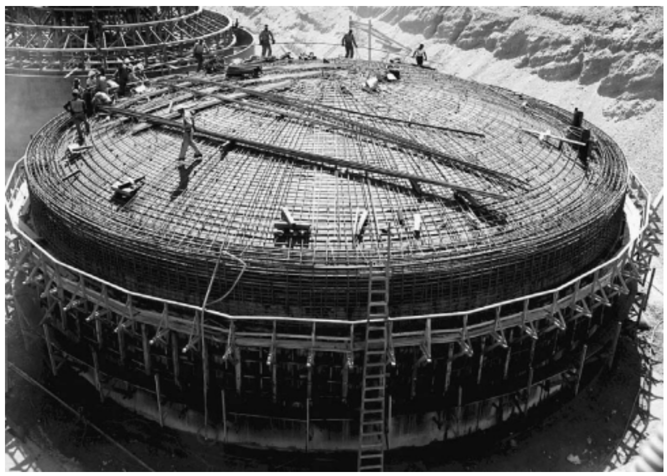

Figure 6. Construction of reinforcement bar for tank dome in BX farm. Taken from [1]

Figures 4 through 6 show photographs taken during the construction of the SSTs at the BX tank farm. This gives a better visual understanding of the structural components of the tanks, including the basemat, steel liner and reinforcement bars in hoop and meridional directions before the concrete was poured. It must be noted that the steel liner is not intended to be a structural member, but its purpose is to provide leak protection to the tank. Therefore, this component is not considered in the structural integrity analysis of the SSTs.

According to the Structural Evaluation Criteria [1], the analysis and qualification of the SSTs will be followed using several codes and standards as guidance and reference, which includes:

- BNL 52527, Guidelines for Development of Structural Integrity, Programs for DOE High-Level Waste Storage Tanks [2].
- BNL 52361, Seismic Design and Evaluation Guidelines for the Department of Energy High Level Waste Tanks and Appurtenances [3].

- American Society of Civil Engineers (ASCE) Standard 4, Seismic Analysis of Safety Related Nuclear Structures and Commentary on Standard for Seismic Analysis of Safety Related Nuclear Structures [4].
- ASCE Standard 7, Minimum Design Loads for Buildings and Other Structures [5].
- TFC-ENG-STD-06, Design Loads for Tank Farm Facilities.

Most importantly, the American Concrete Institute (ACI) code ACI 349-06, Code Requirements for Nuclear Safety Related Concrete Structures (ACI 2007), is used as the standard in the evaluation of the reinforced concrete single shell tank structures.

2. EXECUTIVE SUMMARY

This research work has been supported by the DOE-FIU Science & Technology Workforce Initiative, an innovative program developed by the US Department of Energy's Office of Environmental Management (DOE-EM) and Florida International University's Applied Research Center (FIU-ARC). During the summer of 2011, a DOE Fellow intern (Rinaldo Gonzalez Galdamez) spent 10 weeks doing a summer internship at Pacific Northwest National Laboratory (PNNL) under the supervision and guidance of Kenneth Johnson. The intern's project was initiated on June 7, 2011, and continued through August 12, 2011 with the objective of assisting in the ongoing efforts in the Single-Shell Tank Analysis of Record (AOR) conducted by PNNL.

3. RESEARCH DESCRIPTIONS

3.1 Design Considerations

The design life of the SSTs has been specified in different reports since the early construction stages [6]. Some literature stated the design life of the structures would be between 25 to 35 years. This time frame was specified only for the SX and A farms.

However, there are other sources that assume a sound structural integrity for 100 years. Being that this period of time seems high considering the waste conditions for which these tanks were subjected to, the AOR design life was assumed to be 25 to 35 years for all types of SSTs.

As it was previously specified, the analysis for this report will be focused on the Type IV SST, and specifically the Type IV-B design of tank farm A. This is the tank chosen and modeled in the Preliminary Modeling Plan report by PNNL [6].

For this tank, the geometry and waste design parameters are given in the following tables.

Table 1. Type IV-B SST Tank Geometry (Taken from [6])

Tank Farm	Tank Type	Concrete Foundation Centerline Thickness (in)	Reinforced Concrete Wall Thickness (in)	Reinforced Concrete Dome Thickness (in)	Steel Liner Height (in)	Reference (Drawings)	Steel Liner Centerline Thickness (in)
A	IV-B	6[(a)]	24 to 15[(c)]	15	388	H-2-55911[(d)]	0.375
(a) Flat bottom (b) Tapered, thicker at the bottom							

Table 2. Type IV-B Waste Design Parameters (Taken from [6])

Max Specific Gravity	Reference	Height (in)	Reference	Storage Pressure (psi)	Reference	Max Liquid Design Tempera-ture (°F)	Reference	pH	Reference
2	Smith 1955 and Stivers 1957	~363	Drawing H-2-55911[(a)]	~(-0.55) to 2.2	1996_HanFC and 1981_MercierPF	250	Stivers 1957 and Harvey 1970	8 to 10	Stivers 1957 and Harvey 1970

The design equipment loads are categorized as "live loads" according to the Evaluation Criteria report [1], and are defined in Table 3.

Table 3. Equipment Loading for SST Type IV-B [6]

Tank Farm	Tank Type	Equipment Loading	Reference
A	IV-B	2×35,000 lb tractors, 1'-3" concrete slab at 150 psf	Stivers 1955
		a 28 ton concentrated load for tank dome live load	Shefcik 1964

Moreover, details on the soil density, bearing value, and top backfill cover depth are presented in Tables 4, 5 and 6 respectively. These quantities are important and are taken into consideration when defining material properties for the soil elements in the finite element model developed in ANSYS.

Table 4. Soil Density for Type IV SST [6]

Tank Farm	Tank Type	Soil Density Specification (lb_f/ft^3)	Reference
SX, A, and AX	IVA, B and C	110	Harvey 1970 and Mercier 1981

Table 5. Soil bearing value for Type IV SST [6]

Tank Farm	Tank Type	Soil Bearing Value (lb_f/ft^2)	Reference
SX, A, and AX	IVA, B and C	6000	Harvey 1970 and Mercier 1981

Table 6. Backfill Top Soil Cover Depth [6]

Tank Farm	Tank Type	Soil Cover Depth from Top of Dome Apex to Finished Backfill Grade (in.)	Reference
A	IVB	84	Drawing H-2-55911

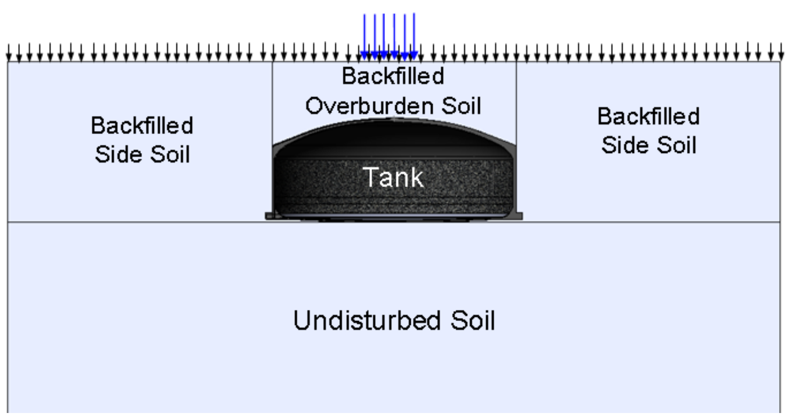

Figure 7. Schematics for application of loads and definition of soil location [7].

3.2 Temperature Histories

The main reason for which this study was conducted is related to the high temperature conditions that were observed in the Type IV tank farms. Hence, the description of the thermal consideration for Type IV SST is of importance in this report. Figures 8 through 10 show the available temperature histories for Type IV-B, tank farm A tanks A-101 and A-106. It can be observed that tank A-101 possesses a complete record of temperature history, and its values are comparable to tanks A-102, A-103 and A-105. Tank A-106 has the highest temperature recorded for all SSTs, but data prior to 1963 is not available. Therefore, A-106 was chosen as a special case for further modeling.

Given the available records, tank A-101 was chosen as a conservative Type IV SST. The proposed temperature and waste level profiles for tank A-101 are shown below, which covers the entire life of the tanks from 1956 to 2010.

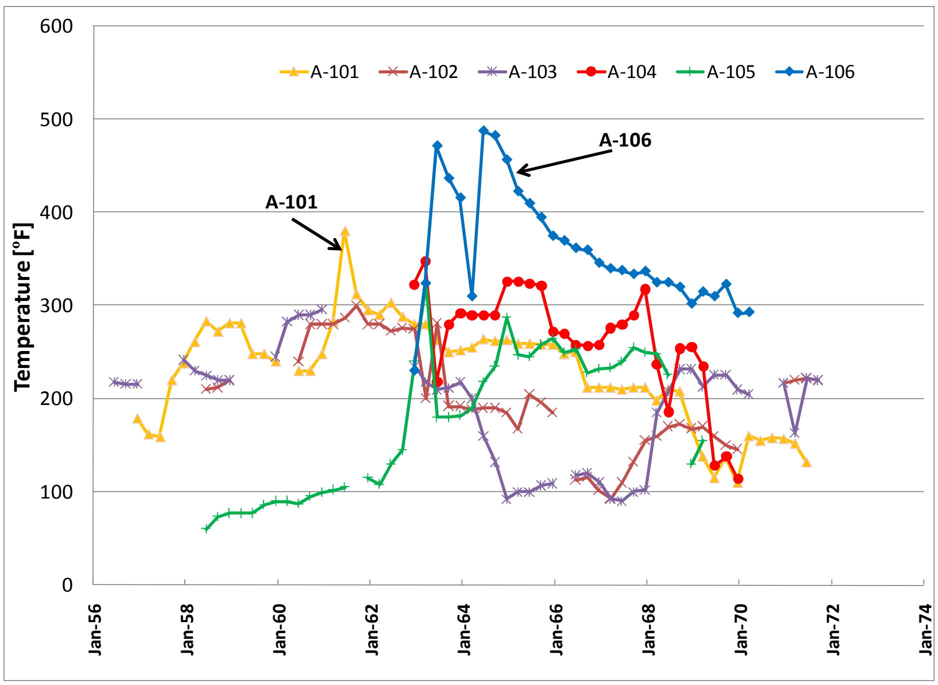

Figure 8. Temperature history of SST Type IV A series [6].

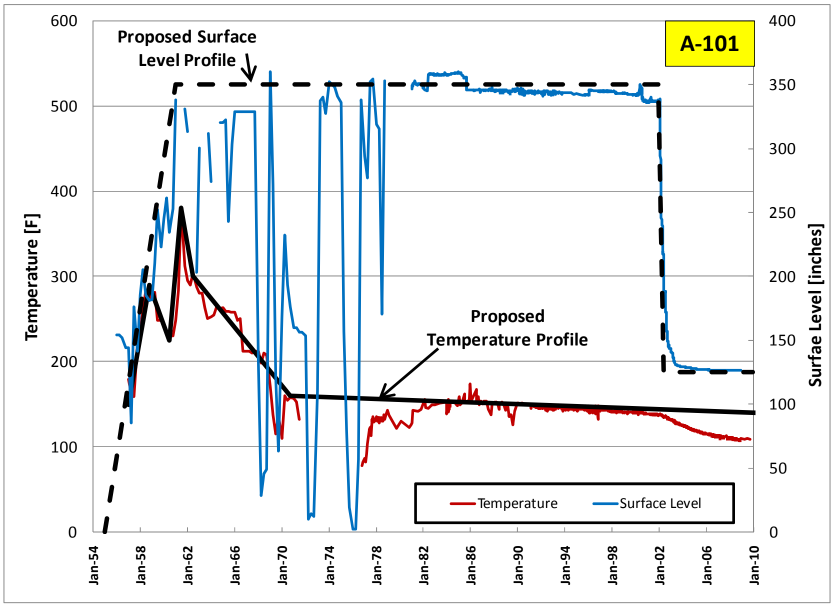

Figure 9. Temperature and waste height profiles for Tank A-101 [6].

Figure 9 shows the temperature and waste level profiles for tank A-101. It can be observed that the waste level shows great fluctuations throughout the years, which gives a degree of uncertainty regarding the actual values of the height of the liquid waste. As engineering good practice, the worst case scenario is assumed to happen; therefore, the proposed waste level profile was assumed constant at the maximum level during the period of time where the fluctuations occur.

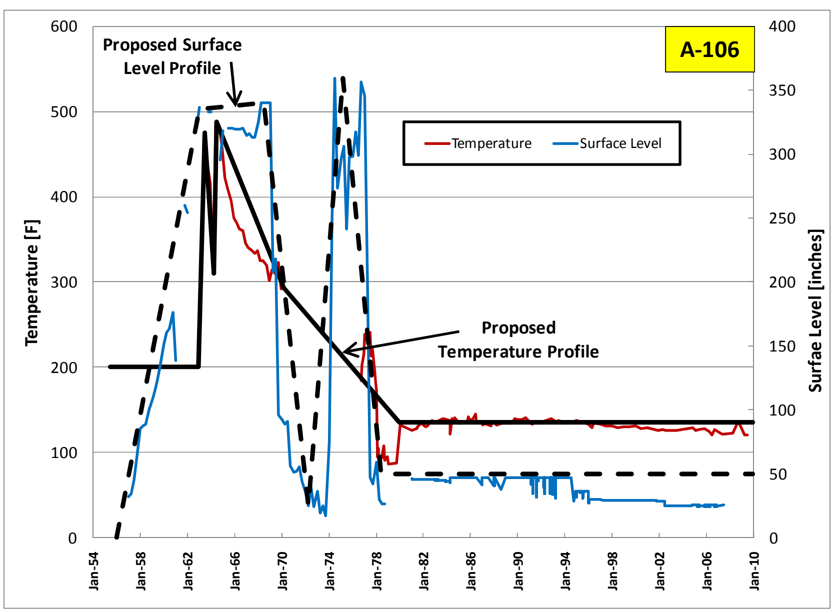

Figure 10. Temperature and waste height profiles for Tank A-106 [6].

Figure 10 shows that tank A-106 reached a higher temperature compared to tank A-101. The waste level also fluctuates significantly. The proposed level and temperature profiles for this tank are shown in the graphs with the black lines (Figure 10).

Given the high fluctuations in the data available for this tank, A-106 is considered as an atypical case that is not representative of other Type IV SSTs. Hence, the test case considered in this modeling and further efforts will be tank A-101.

3.3 Finite Element Model

The thermal analysis of the SSTs was carried out using a 2-D axi-symmetric model. The soil extent is defined as the distance separating the center of the tank to the wall of the adjacent tank (see Appendix A).

The nodal temperatures at specific locations at the end of each analysis step were extracted and recorded in a text file. These exported nodal results were then implemented as body forces in the 3-D structural model.

Figure 11 shows the schematics of the thermal boundary conditions implemented in ANSYS Mechanical Parametric Design Language (APDL). The waste surface was added to the 2-D thermal model in order to simulate radiation and lumped convection heat transfer from the waste surface to the tank dome and walls.

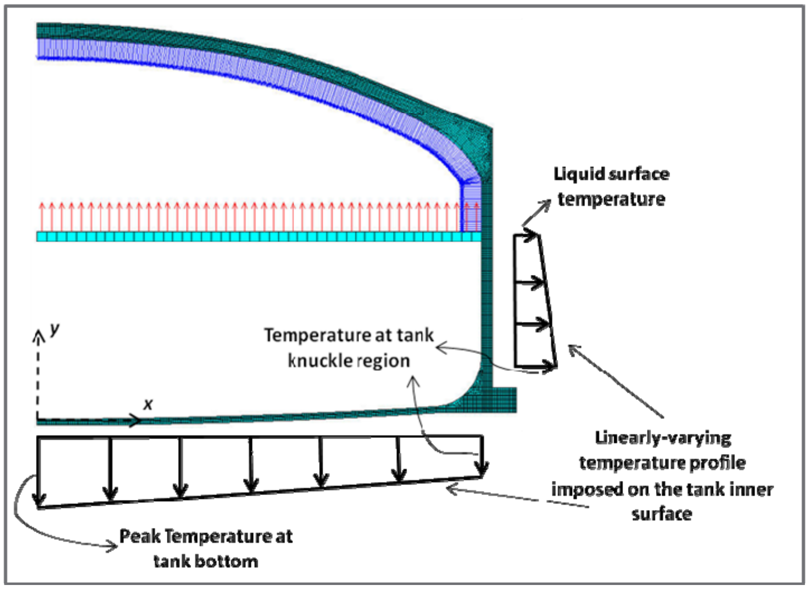

Figure 11. Thermal boundary conditions in ANSYS APDL [7].

The radiation surfaces have been identified in Figure 11 with the aid of red and blue arrows. ANSYS® calculates the radiation view factors for all element surfaces based on the axi-symmetric model.

The waste temperature is assumed to vary linearly from the bottom of the tank to the knuckle region. In a similar fashion, the temperature is assumed to vary linearly from the knuckle to the surface of the liquid waste. This representation is observed in Figure 11 by the black lines and arrows. The thermal boundary conditions on the tank inner's surface and the liquid surface are given as ramped boundary conditions. Hence, the temperature for each time step varies linearly with time.

The boundary conditions implemented in ANSYS APDL are presented in Figure 12.

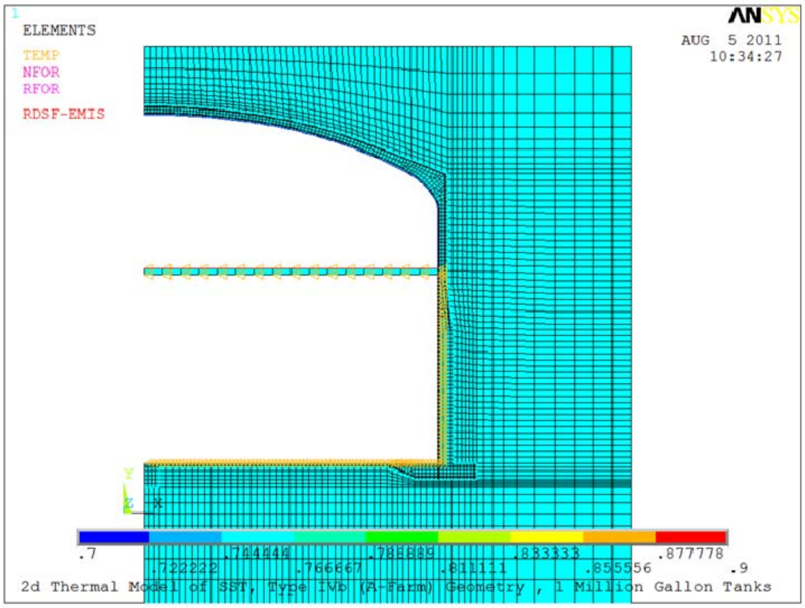

Figure 12. Boundary conditions in ANSYS APDL.

Isothermal boundary conditions were used for the top (55°F) and bottom of the soil (53°F). An adiabatic boundary condition was used on the right end of the soil model.

The structural analysis was divided into two parts. The first part was carried out with purely mechanical loads. The resulting ANSYS database file was resumed in the second part of the analysis and augmented with further analysis steps including temperature loads, as described above. Thus, the tank structural analysis in the second part contained both the mechanical and thermal loads from the waste surface to the tank dome and walls. In another note, the waste surface is not physically linked to the rest of the tank elements. Hence, there is no conduction heat transfer between the waste surface elements and the tank elements.

4. ANALYSIS AND RESULTS

4.1 Soil Mesh Improvement

A preliminary FEA study was conducted for the Type IV SST, and this included a thermal and structural loading study using a mesh built similarly to the one shown in Figure 13. The primary goal of this task was to improve and optimize the mesh that is constructed for the FEA model of the Type IV-A SST.

After careful discussion with the structural engineers at PNNL, it was decided that in order to maximize use of time and minimize corrections and convergence issues, only one mesh would be used for both thermal, structural and combined loading analysis. This helps PNNL in their task given that sometimes the mesh used in the thermal analysis is not refined enough to be used in the structural analysis.

Given the studies performed for Type II SSTs, the FEA engineers were expecting soil plasticity to occur in the highlighted areas of Figure 13. The finite element mesh must be refined in these specific areas to predict the soil plasticity. Meshing techniques such as domain partitioning and biasing/stretching were used to achieve this result [7].

Furthermore, from a thermal load point of view, the thermal gradient through the walls, dome and bottom of the tank needs to be captured with relative accuracy. This is important to capture the thermal effects of the soil on the concrete, similar to CFD analyses where mesh refinement (with biasing or inflation) is needed at the walls in order to accurately capture the formation of boundary layers.

The improved mesh gives a higher element quality and better control close to the dome, haunch and footing as well as in the rest of the soil.

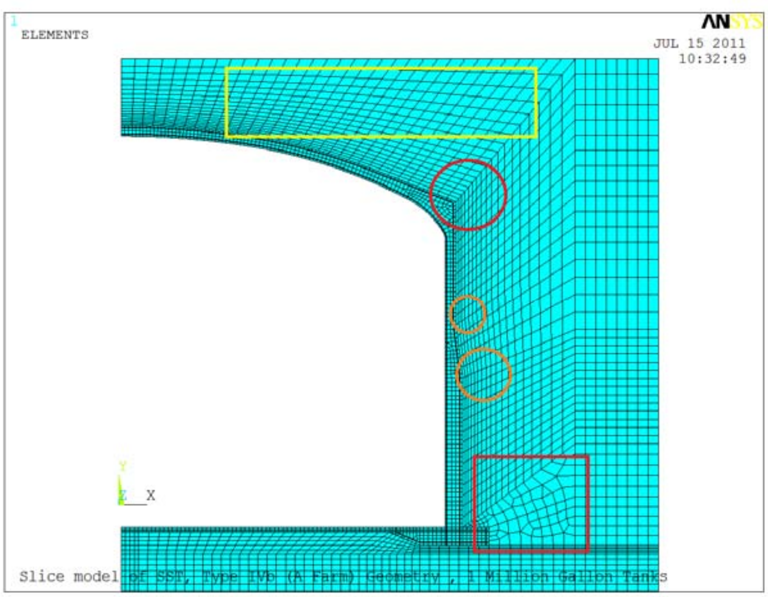

Figure 13. Mesh from Preliminary Modeling report [6] and modifications.

The red circle in Figure 13 is the region where soil plasticity is expected to occur; hence, a refinement is needed in this corner of the dome. The same level of refinement should be done in the tank walls, for the regions highlighted by the orange circles. Moreover, the elements highlighted by the yellow and orange rectangles show an irregular trapezoid shape or automatically generated quadrilateral elements. This can be improved by implementing new meshing lines and commands in the input file.

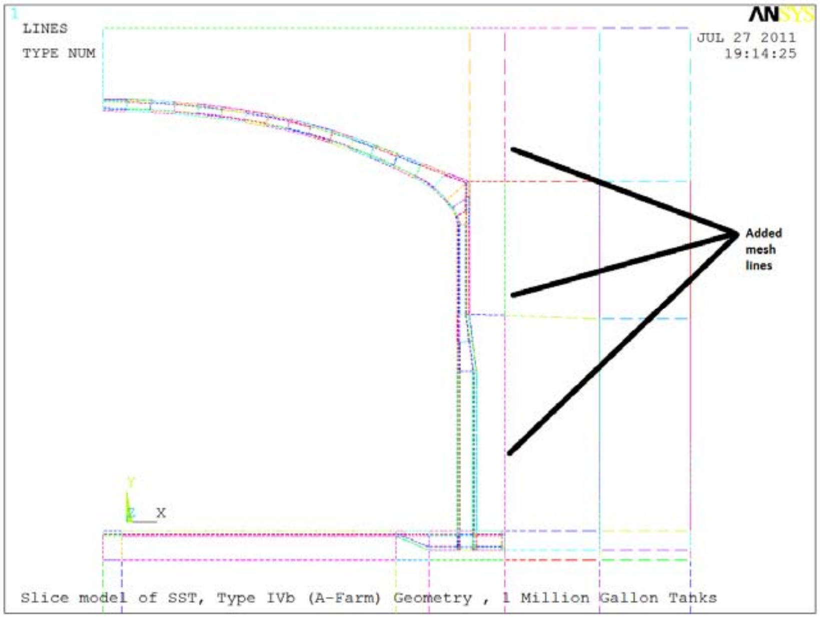

Figure 14. Modifications to mesh geometry.

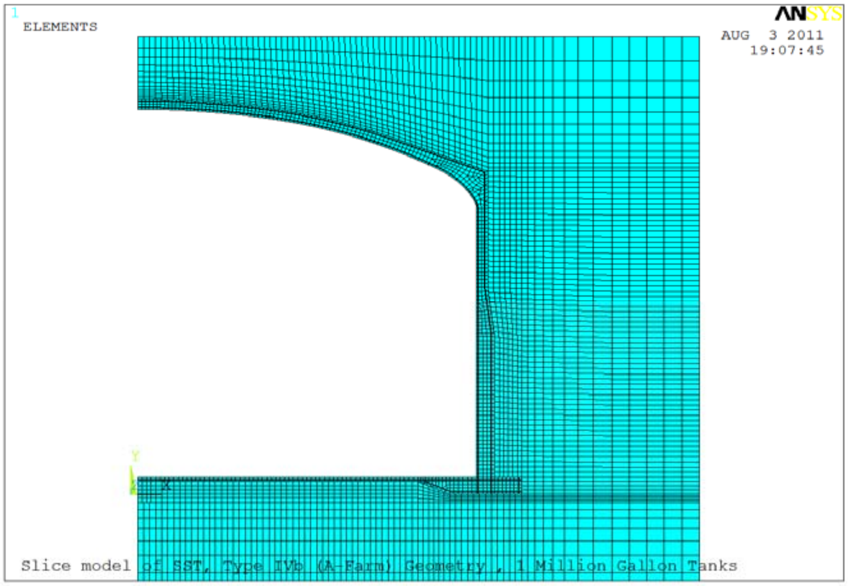

Figure 15. New geometry and finite element mesh.

Figures 14 and 15 show the modifications that were introduced in the input file for ANSYS APDL for the geometry as well as the meshing lines. It can be observed how new lines were introduced in order to accurately build a uniform quadrilateral mesh around the tank as well as for the rest of the soil that surrounds it. The stretching of the mesh can also be observed, where the grid is refined and the distance between nodes is smaller at regions of interest, in this case close to the surface of the tank. While the grid further away from the tank stretches to coarser, bigger elements. This is especially useful when measuring thermal gradients from the region in one domain close to another.

4.2 Mesh Convergence Study

As was explained in the previous section, the main goal of this study was to find the minimum mesh refinement level required to capture a converged thermal profile of the soil for the Type IV-A SST.

Given that the mesh modifications were introduced into the geometry and mesh generation input file for ANSYS APDL, the new mesh was implemented for 8 levels of refinement. The details about the mesh convergence study are provided in Table 7. The thermal gradient was measured using the temperatures for (X_1,Y_1) and (X_2,Y_2) points in the domain discretization. The values were then calculated as a temperature difference and used to measure and compare the convergence of results for each mesh refinement level.

Table 7. Mesh Statistics

Soil element size (in)	ΔT(F)	n	Normalized element size	Variation
8	53.20	1	1.00	4%
10	51.24	1.25	0.80	2%
12	50.30	1.5	0.67	17%
16	58.79	2	0.50	3%
18	60.28	2.25	0.44	4%
22	57.93	2.75	0.36	3%
28	59.42	3.5	0.29	9%
32	64.55	4	0.25	-

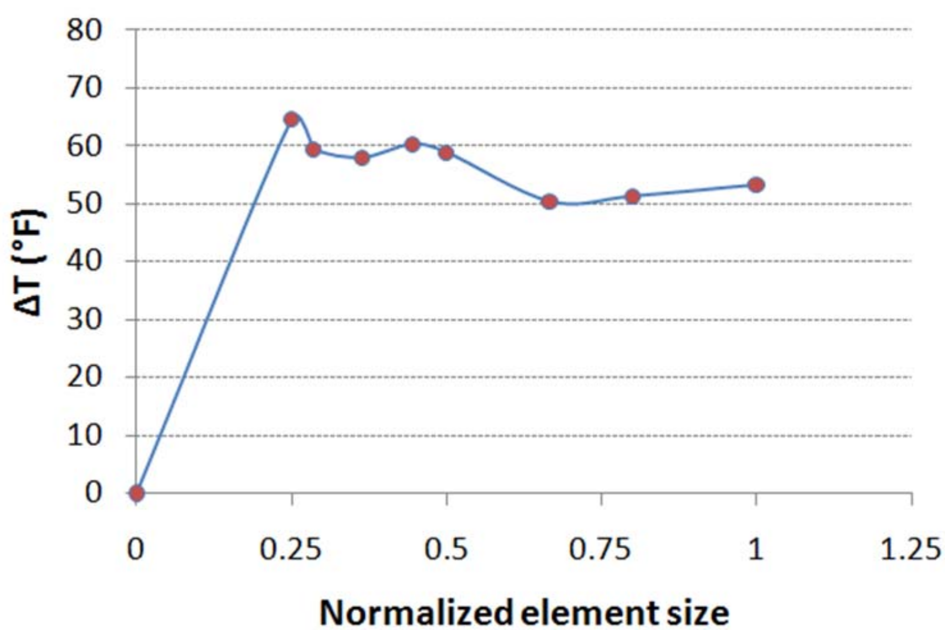

Figure 16. Plot for grid convergence study.

Figure 16 presents the convergence plot for the different grid sizes that were analyzed. It can be observed from Table 7 as well that the change of the results for meshes finer than 12 in was between 2% and 4%; hence, the change is quite minor. Graphically, it can be seen that the result is practically converged. For further detail, a mesh case at a size of 6 in can also be completed and will most probably fall within the 50 degree F vicinity. A change not larger than 5% would be expected if this is done. Therefore, it can be assumed that the thermal profile is converged at a soil mesh element size of 12 in.

No further refinement beyond 12 in is required to achieve good results. Further refinement would only increase solution time and file sizes required to complete this project.

Figures 17 through 19 present the results for the temperature profile of the tank and soil domain at different mesh sizes. Qualitatively, one can observe that the profile seems to be quite similar; however, the quantitative differences are highlighted in Table 7.

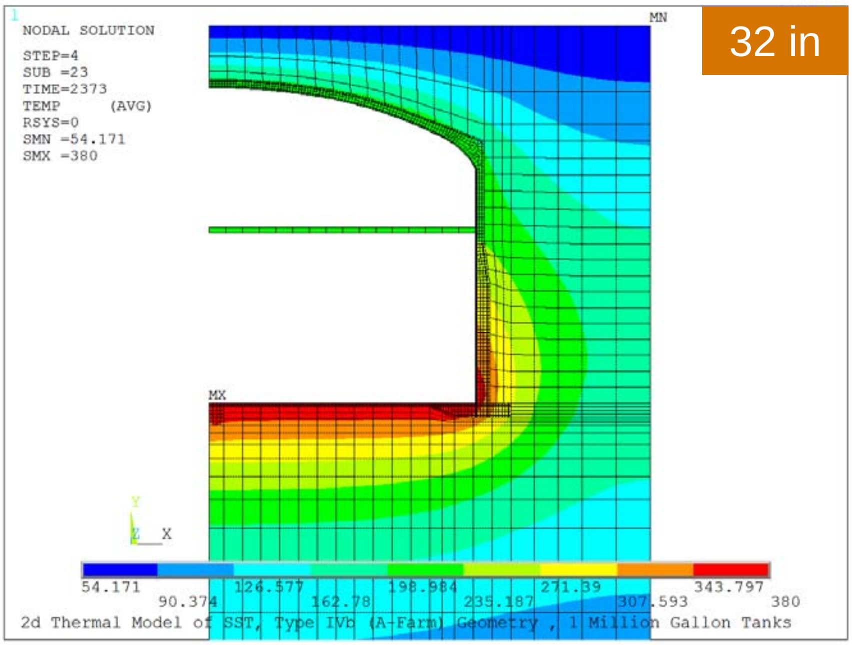

Figure 17. Temperature profile for soil mesh element size of 32 in.

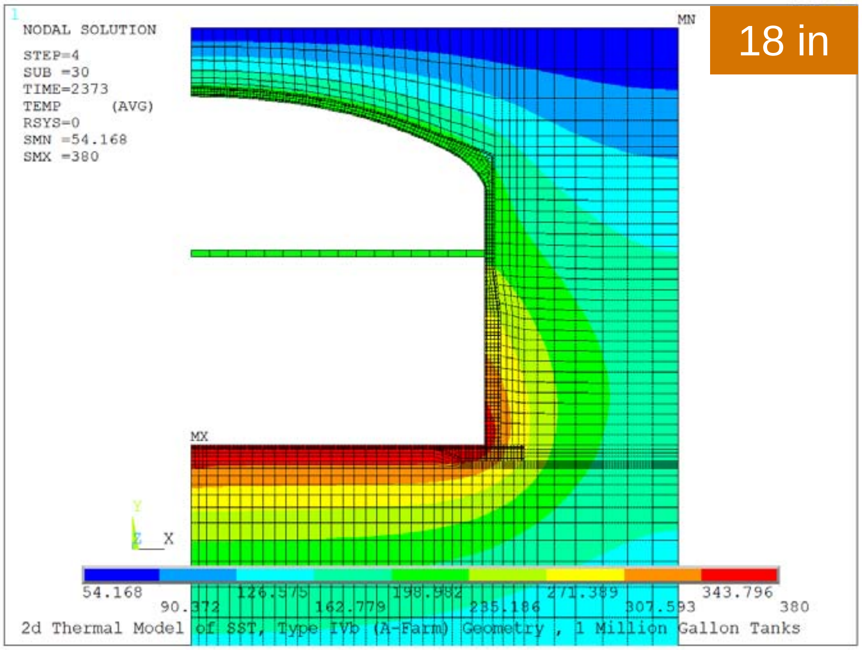

Figure 18. Temperature profile for soil mesh element size of 18 in.

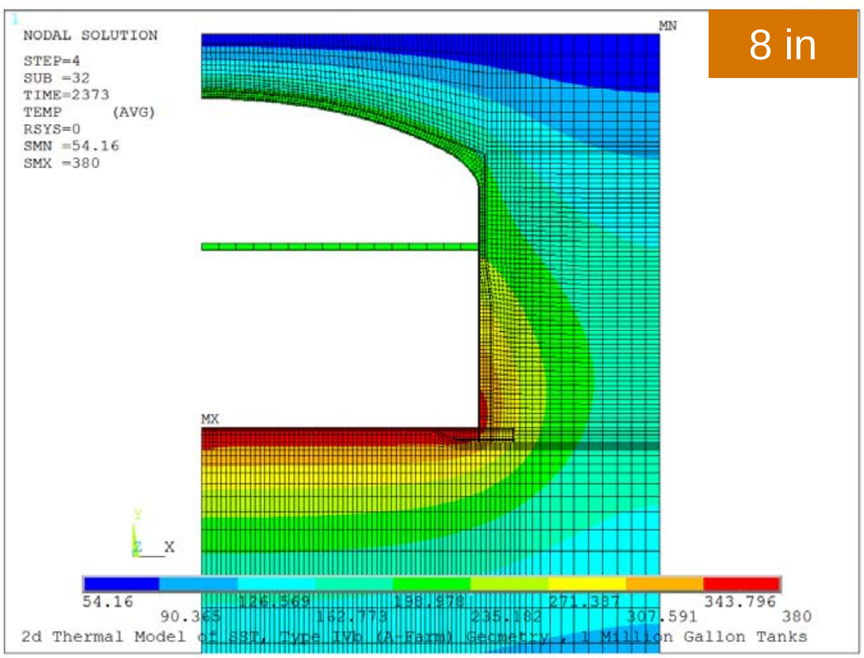

Figure 19. Temperature profile for soil mesh element size of 8 in.

4.3 Results of FEA Study

Once the adequate mesh size was chosen, the structural analysis was completed for which Figures 20, 21 and 22 present the contour plots for the Von Mises stress, soil plasticity and total displacement, respectively.

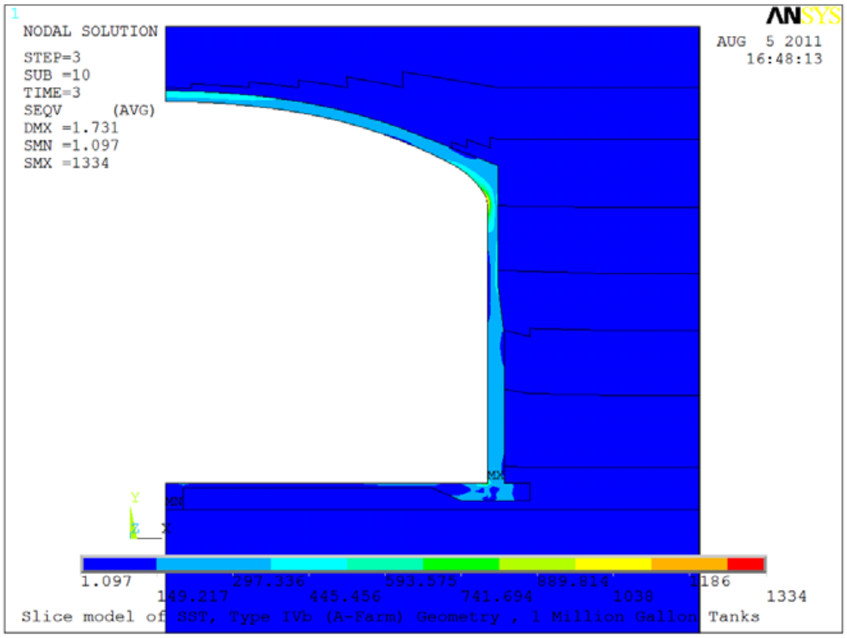

Figure 20. Plot for Von Mises stress (structural loading only).

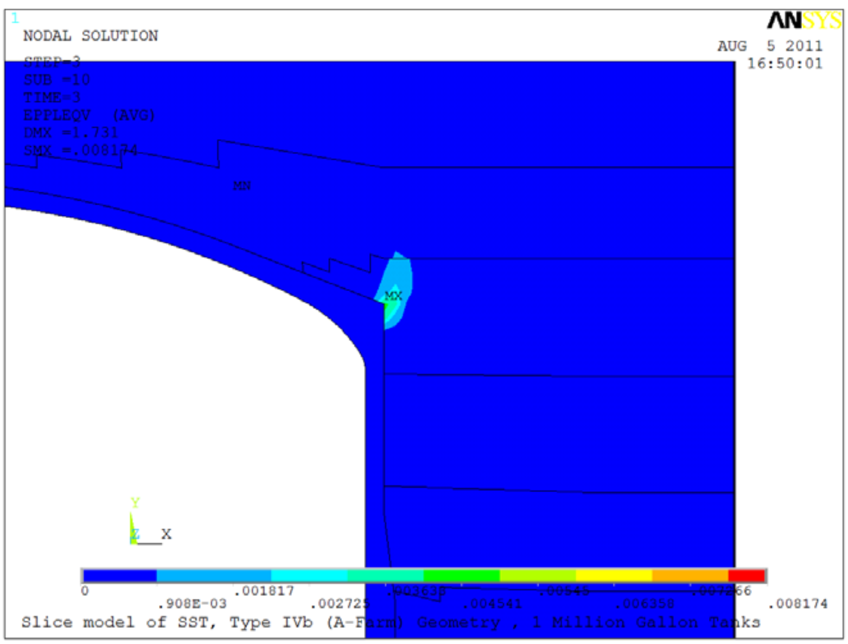

Figure 21. Soil plasticity (structural loading only).

Plasticity is shown in the haunch as was expected per discussions with PNNL structural engineers.

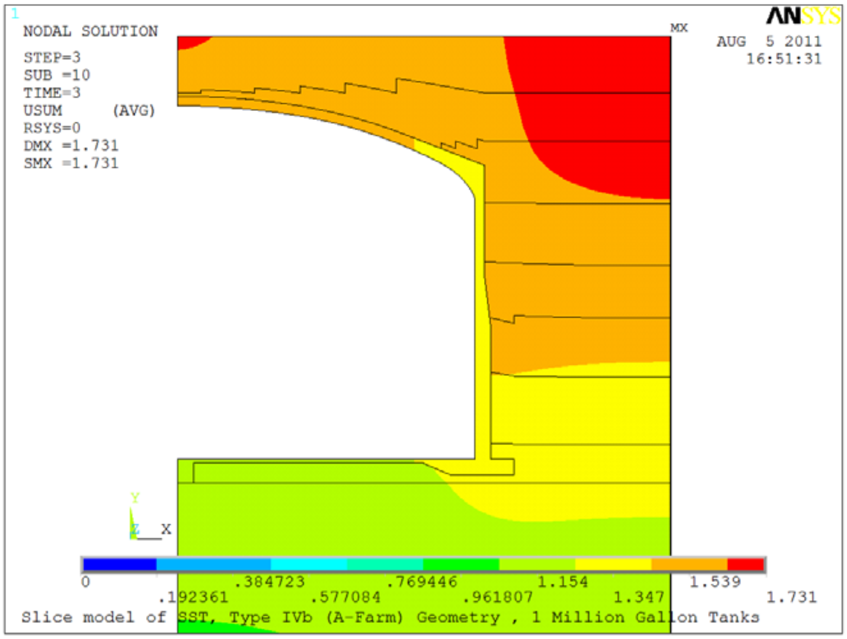

Figure 22. Total displacement (structural loading only).

Given the thermal stresses solved in the 2D model, these were loaded and mapped into the 2 degree slice model for the combined thermal and structural load analysis. Figures 23 through 25 show the contour plots for the Von Mises stress, soil plastic strain, and total displacement respectively.

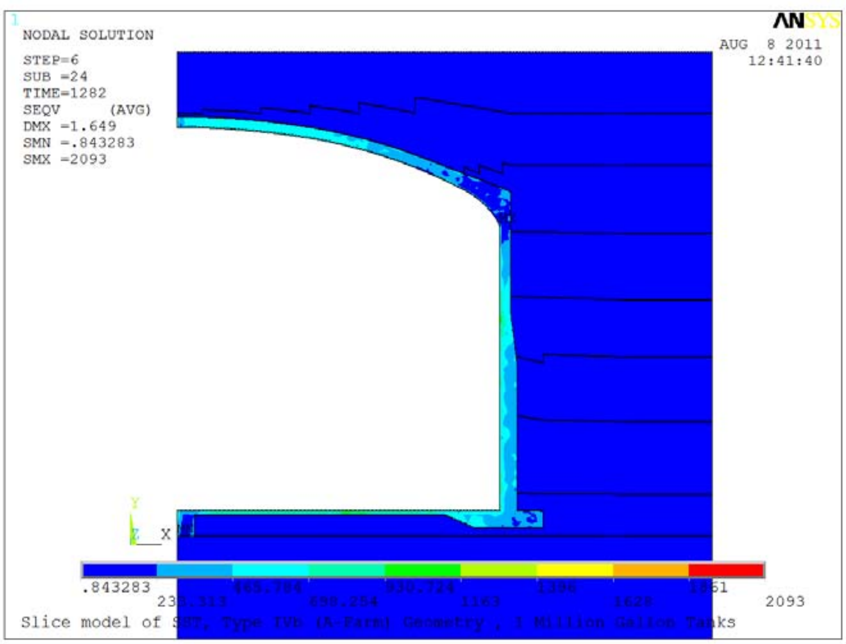

Figure 23. Von Mises stress (combined thermal and structural loading).

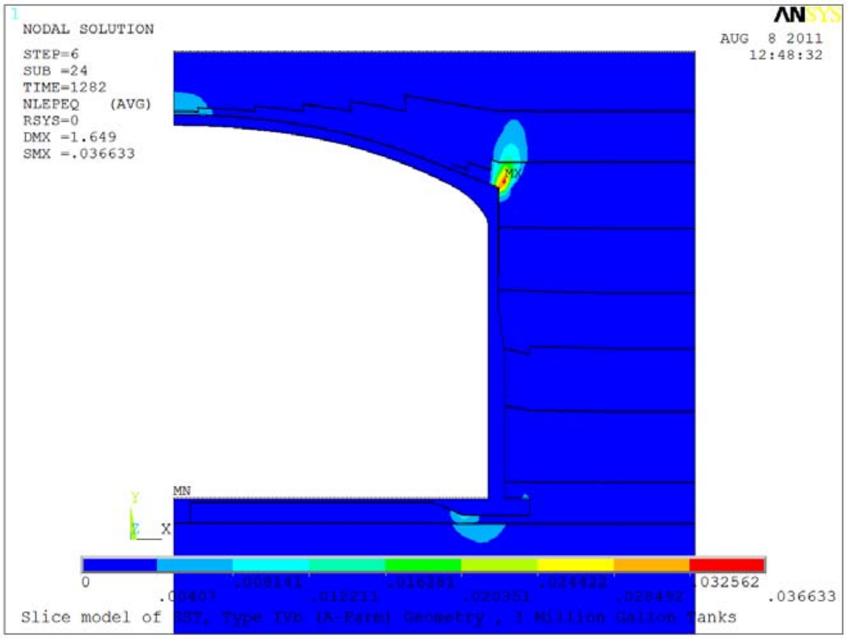

Figure 24. Soil plastic strain (combined thermal and structural loading).

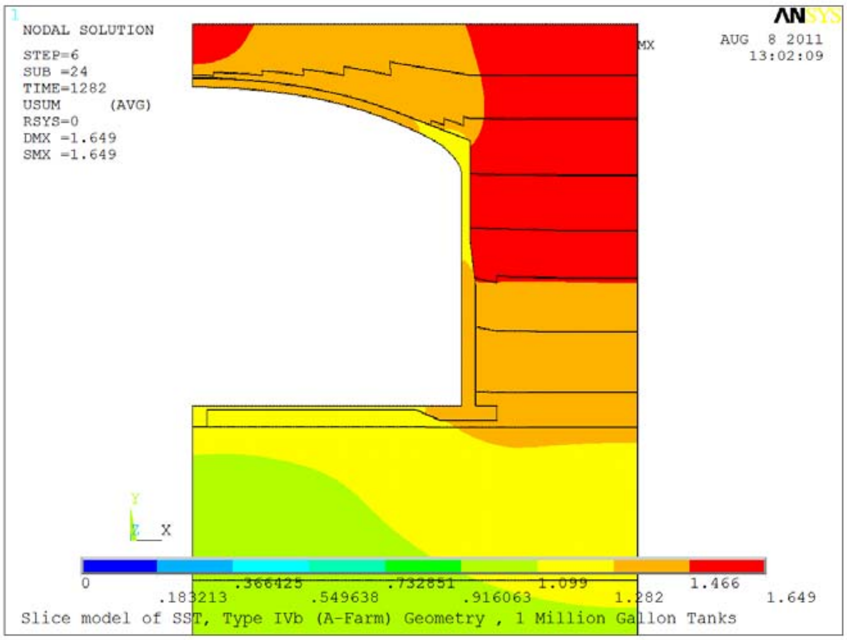

Figure 25. Total displacement (combined thermal and structural loading).

In Figure 23, it can be observed that the Von Mises stresses are higher for the combined thermal and structural loading compare to the pure structural loading (Figure 20). This is due to the thermal expansion of the concrete. The tank bottom is now withstanding stress given the thermal loads of the tank waste. Figure 24 shows plastic strains in the soil close to the haunch, dome and near the footing.

These results are important to understand the issues that will be present in the tank-to-tank interaction study to be carried out for the Type IV SST.

5. CONCLUSIONS

The temperature profile in the soil reaches convergence for a mesh element size of 12 in. Considering the analysis and results obtained for the Type II SST, soil plasticity is observed and captured in the haunch with more accuracy than previous models. Furthermore, soil plasticity is still observed in the footing, haunch and dome for combined loading [7].

Regarding the grid improvement, the current mesh with an element size of 12 in reduces size and aspect ratio issues that were observed with the grid built for the Preliminary Modeling effort [6].

It can also be concluded that this mesh size is suitable for the 90-degree wedge model that will be used to quantify the influence of thermal and operating loads on adjacent tanks. The wedge model of the Type IV SST will be built using the mesh parameters that are documented in this report. The thermal, structural and combined load analysis for a single Type IV SST will also be completed. A symmetric model in ANSYS APDL with two tanks adjacent to each other will be modeled and its complete simulation will be carried out. Moreover, the seismic analysis for the Type IV SST tank-to-tank interaction will be performed by M&D Professional Services to analyze the effects of dynamics loading on these closely spaced tanks.

6. REFERENCES

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APPENDIX A: Technical Drawing H-2-55910