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Salt Tank Testbed: a Test Site Designed to Replicate Floor Buckles Observed in Commercial TES Tanks

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Abstract. A test site has been designed and is under construction to replicate the buckling failure observed in several in-service storage tanks for nitrate salts operating up to 565°C. In commercial tanks multiple factors have been identified that influence the floors susceptibility to buckling, including: the as-manufactured shape of the floor, high compressive stresses due to thermal gradients and/or friction, fluid inventory and absolute temperature. Based on extensive modeling analysis it was determined that similar buckles can be reproduced in a scaled test tank (approximately 9x smaller than a representative commercial tank design). To buckle the scaled tank a radial thermal gradient is generated in the tank with a low fluid level, the fluid level is then increased while maintaining the thermal gradient; based on the modeling results just one of these cycles can plastically deform the tank floor. The test site which is under construction is designed to replicate this damaging cycle at lower temperatures. The goal of testing will be to reproduce this damaging cycle and buckle the scaled test tank floor, allowing proper model validation and a methodology for comparing different tank designs at a smaller (and less costly) scale.

Keywords: Thermal Energy Storage, Buckling, FEA

1. Introduction

As more renewables enter electrical grids around the world, load-shifting and long-duration energy storage (>8 hours) becomes increasingly important [1]. Thermal Energy Storage (TES) is considered one of the most mature forms of long-duration energy storage; in particular, two-tank TES systems with nitrate salts have been implemented in various Concentrated Solar Power (CSP) plants in the past decade. In a recent study that surveyed challenges in operating CSP plants, the hot nitrate salt tank in two-tank thermal energy storage systems is one of the main reliability concerns in operational molten salt tower CSP plants [2]. Recent analysis of the failures seen in salt tanks found multiple issues related to design, manufacturing and operation of the salt tanks [3], [4], [5]. The failures experienced by multiple operational plants indicate that the state-of-the-art tank design adopted in several projects around the world is not suitable for CSP applications. This manuscript describes the efforts under DOE-funded project to address the hot tank challenges experienced by the CSP industry. The main project goal is to model, design, and manufacture a test site capable of replicating the failure mode experienced by commercial tanks in a geometrically scaled test tank. The test site capabilities and modeling methodology will be validated with the state-of-the-art tank design. The model validation with test data, and demonstrating improvement of new designs with the validated test setup

2. Failure Mode Selection

Based on the authors' commercial experience and collaborations with operating CSP plants, information regarding the failures was compiled. All of the tanks evaluated by the authors were part of Gen2 CSP technology, i.e., solar towers with direct TES using a nitrate salt working fluid. The tanks are generally constructed from stainless steel 347H; the floors are thin near the center (< 10 mm) manufactured from large rectangular plates welded on-site and reinforced with thicker annular plates at the perimeter (and underneath the wall). Multiple issues have been identified in operating hot tanks including metallurgical issues, in particular SRC [3], creep [4], and buckling of the floor [5]. These failure modes are related because they can be influenced by similar pre-cursor and operating conditions; however, they should be analyzed individually to ensure that each failure mode is well understood and can be prevented for the full tank lifetime.

Of these failure modes, buckling of the tank floor, followed by cracking on the buckled regions, is considered the most appropriate for studying in a geometrically scaled test site setup. The consistent buckling observed in several commercial plants indicate a systematic design issue that can be replicated in an appropriately scaled tank. Once buckles form, the floor can be considered effectively failed because the stresses developed in the buckled regions have a projected creep life of only a few years. The thin floor in flat-bottom tanks is not considered a critical structural member in typical oil storage tank design [6]; however, the plastic deformation occurring in hot nitrate salt tanks indicates this is an incorrect assumption for CSP applications. Based on observations at commercial projects, it is clear that the forces acting on the tank floor must be better understood and the floor redesigned to accommodate these forces.

3. Modeling Analysis

Extensive modeling analysis has been completed to investigate buckling of the tank floor structure, compared to previous work from some of the authors [5] the results presented here focus on the smaller test tank geometry to ensure the buckling failure observed in commercial tanks can be replicated in a smaller test tank (about 9x scale) that can be easily instrumented and subject to controlled conditions; however, the larger modeling effort did consider the commercial tank geometry and several geometry variations and operating conditions to better understand the floor buckling failure. Based on the overall analysis of the buckling failure mode, the following factors are viewed as important contributors to the buckling failure:

- Excessive compressive forces on the floor caused by friction and thermal stress
- The effective friction coefficient has a big impact and is not necessarily well understood
- Specific operating conditions including the temperature profile and fluid inventory
- The initial shape of the floor
  - The as-designed shape of the floor, including any slope
  - Weld deformations that form during manufacturing
- Material properties
  - Variation of properties with temperature
  - Variation of material properties in base vs weld metal

3.1 Scaled Tank Model Description

In this project, two independent FE models were developed using different software packages to gain confidence in the results [7], [8], due to difficulties in achieving model validation with the available data from commercial plants, e.g., the initial shape of the floor after welding in any commercial project is unknown, and temperature measurements are taken with several meters of spacing in some cases. A thermal-fluid model of the test tank was also developed and used to predict the temperature profile within the tank. The models will eventually be validated and refined as needed with test site data. All models consider similar tank geometries with a thin floor with a 1% slope towards the perimeter, and a thicker perimeter floor section that extends under the wall, in the scaled test tank, the wall is a constant thickness from the floor to the roof structure, the geometry in described in further detail in Section 3.1. The CFD model also includes the internal tank piping as seen in **Figure 4**. The models were used to simulate the following cycle in the scaled tank to reproduce the damaging conditions that can occur in the commercial case:

1. Fill the tank to the minimum fluid level, 200 mm of water at 20°C,
2. Heat the central portion of the tank to generate a compressive thermal gradient in the tank floor,
3. Increase the fluid level in the tank to 1 - 1.5 m while maintaining the thermal gradient,
4. Drain and cool the tank

The cycle described above is representative of the conditions that can occur during preheating and initial filling of a commercial tank (and potentially during daily start-up as well). Although the cycle identified for the scaled tank occurs at room temperature, as opposed to much higher temperatures in the commercial case (290 – 565°C), the ability to carefully control the radial temperature profile while cycling the fluid level in the scaled test provides an effective and controllable method of reproducing the damaging conditions to buckle the floor. Since the temperature of the tank wall does not increase significantly, friction play a minor role in stresses developed in the cycle above; this is done on purpose to minimize the impact of the friction coefficient, which is considered highly uncertain in the commercial case. The CFD model considers buoyant flow inside the tank with the minimum fluid level (200 mm) and the flow within the internal heating and cooling pipes to determine the steady state temperature profile on the floor. The change in fluid level is similar to the minimum level up to about 60-70% capacity of a typical commercial tank when accounting for the geometrical scaling factor and the density difference between the working fluids (molten salt vs water). The FE models simulate the cycle above through a quasi-static structural analysis with bi-linear relations for stress-strain and accounting for mechanical property variations with temperature.

3.2 Model Results with Ideal Floor Geometry

Both thermal-fluid and mechanical models were developed considering the ideal scaled floor geometry with no backing plates or weld deformations. Backing plates are thin strips of metal placed underneath the gaps between plates to help achieve full penetration and prevent burn-through during the welding process in commercial tanks. There is significant uncertainty attributed with the initial weld deformations in the commercial case and the impact of backing plates on the effective friction coefficient, by considering the ideal geometry this factor and the surrounding uncertainty is neglected. The commercial case with the addition of non-uniform friction and deformations due to welding will certainly be more susceptible to buckling than this ideal case. One of the common design features in the commercial tank designs evaluated was a lightly sloped floor with the center of the tank higher than the perimeter (around 1 – 2% slope), this slope was found to increase the likelihood of buckling and is therefore included in the ideal floor model. The temperature profile in the test tank at the minimum fluid level for the ideal floor geometry with a 1% slope was resolved using the CFD model and is plotted in **Figure 1**.

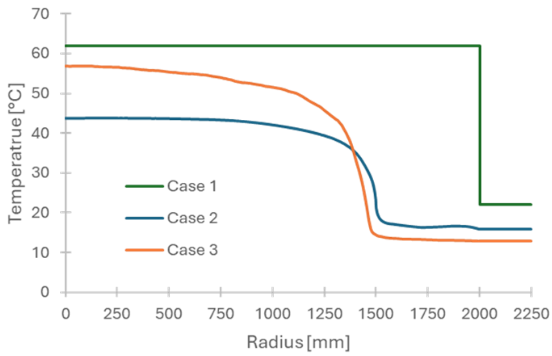

Figure 1. *Comparison of CFD model results of test tank under different conditions: Case 1 the ideal case used for preliminary design, Case 2 (ΔT=28°C) and Case 3 (ΔT=44°C) are the real test tank geometry with different heat loss assumptions for the separator between hot and cold fluid zones*

The temperature profile of the tank calculated through CFD (see **Figure 1**) was input to the FEA, the temperature profile is applied in Steps 2 and 3 of the quasi-static structural analysis of the scaled tank. Results of this FEA showing the vertical deflection of the scaled tank floor can be found in **Figure 2**. Comparing results with different floor thickness and temperature profiles it is evident how the extent of the buckling increases with larger values of dT and thinner floors. The 0.9 mm floor is a perfect geometric scaling of a representative commercial design. Although the thin floor is a contributor to the buckling failure, if the right conditions are met (i.e. higher thermal gradient in this case) the thicker floor can still buckle similar to the thinner floor. The radial temperature gradient causes buckles to form, but is not necessarily sufficient for plastic deformation; the subsequent increase in fluid level increases the level of plastic deformation resulting in a permanently buckled floor.

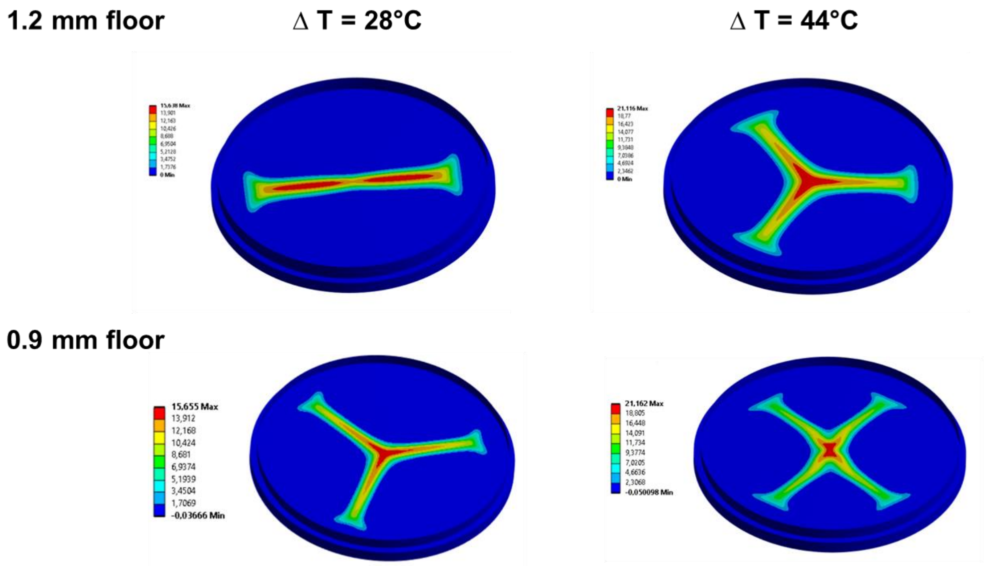

Figure 2. *FEA model results showing out-of-plane deformation on tank floor for different floor thicknesses after applying a radial temperature profile and increasing the fluid level from 0.2 to 1.5 m.*

3.3 Model Results with Deflected Floor Geometry

In commercial tanks, the central portion of the floor is manufactured from thin rectangular plates with backing plates. One of the models developed under this project looked at the influence of backing plates in the scaled geometry for a better comparison to the commercial case. The results in **Figure 3** show the initial and final deformed shapes of the floor for a scaled tank with two different floor thicknesses; in this case the buckles tend to form near welds and the location is clearly influenced by the floor plate arrangement. Comparing these results to the ideal floor model (**Figure 2**), with the ideal geometry the buckles tend to form symmetric patterns and less extensive buckling is observed at the same floor thickness and ΔT. For now a simple verification of the model is achieved by comparing the trends in **Figure 2** and **Figure 3**: both models predict plastic deformation of the tank floor after a single cycle at room temperature, and in both cases increasing the floor thickness from 0.9 to 1.2 mm reduces the extent of buckling by reducing the number of 'wrinkles' that appear on the floor. A more extensive validation is planned at the test site under construction.

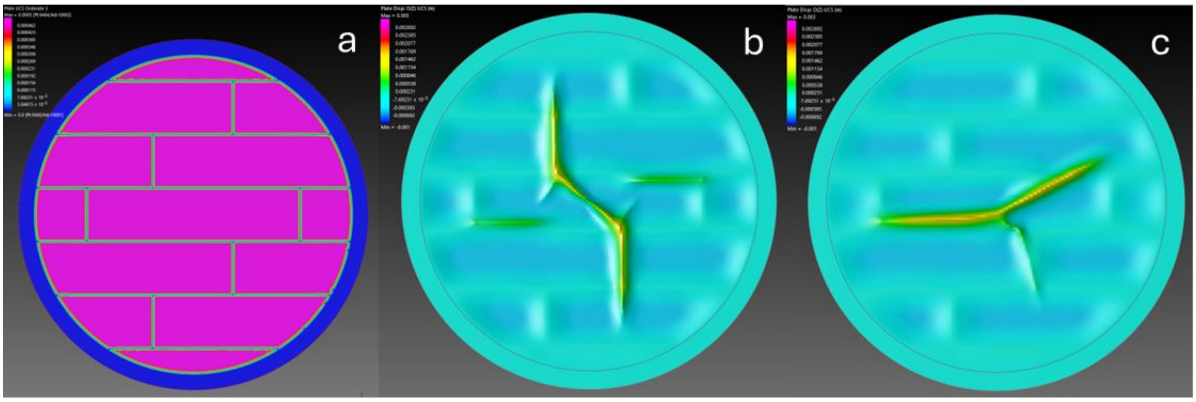

Figure 3. *FEA results for the scaled tank simulation with backing plates after a damaging cycle with radial ΔT = 28°C: a) initial deformation considered in test tank simulations, b) test tank simulation results with 0.9 mm floor, and c) test tank simulation results with 1.2 mm floor*

The simulated cycle (described in Section 2.1) occurs at significantly lower temperature compared to the commercial case (maximum T = 53°C as opposed to 500 - 565°C), still permanent buckles are formed on the floor. These results demonstrate how a single damaging cycle can be sufficient to cause permanent damage to the floor; furthermore, based on Section 2.2, even with an ideal floor geometry permanent buckles were predicted after a single cycle, suggesting that even a perfectly manufactured floor (which is not feasible in reality) is not an adequate solution. These modeling results confirm that the current tank design is very susceptible to buckling, as demonstrated by plastic deformation after a single cycle with a compressive thermal gradient and minimal friction forces. In the case of the test tank, an applied thermal gradient followed by an increase in inventory level is the mechanism that leads to buckling; however, depending on the specific design, manufacturing, and operating conditions different factors may contribute to buckling in different tanks. Given the variability in solar resources and potential for transients in CSP tower plants, it is extremely challenging to avoid buckling of the floor with the current design.

4. Test Site Design

A test site is under construction to replicate the model results in **Figure 2** and **Figure 3**. The goal is to manufacture a scaled test tank and subject it to the same damaging cycle described in Section 2.1; this data will be used to validate the model results from Section 2.2 and refine the model as needed. Successful completion of these tasks will verify the test site can reproduce the buckling failure observed in commercial tanks and pave the way for testing of novel designs with higher resistance to buckling.

4.1 Tank Design

The tank dimensions are compared to a representative commercial design in Table 1. The floor thickness and diameter were considered the key dimensions to scale, the foundation ring is significantly thicker in the scaled tank to capture a commercial design with additional reinforcement at the perimeter.. The tank will be constructed of stainless steel 304; since the test site is designed to evaluate the buckling phenomena at lower temperature all 3xx series stainless steels are expected to fail in a similar manner due to the similar mechanical properties at the test conditions (T < 100°C). The advantages of 347H (the most common material for tank manufacturing) are not evident until much higher operating temperatures and time-at-stress [9].

Table 1. *Comparison of important tank dimensions. The average commercial design is the mean value of an operating plant that provided data for this analysis and a planned commercial design.*

	Diameter [m]	Floor thickness [mm]	Outer ring thickness [mm]	Lower wall thickness [mm]
Avg. Commercial Design	34.2	7.5	22.0	48.4
Test Tank, Scaling = 8.5	4.0	0.88	3.5	5.7
Test Tank, Simulated	4.0	0.9	6.3	6.3

While the lower tank structure (floor and walls) are a scaled-down commercial design, the roof structure is designed to support the internal piping and planned instrumentation. The tank design is shown in Figure 4. For lower temperature testing the roof is constructed of carbon steel structural members and insulated metal sandwich panels. The tank has internal piping and a baffle to allow accurate control of the radial temperature differential; with this setup the tank can achieve the temperature profiles from Figure 1, based on CFD model results.

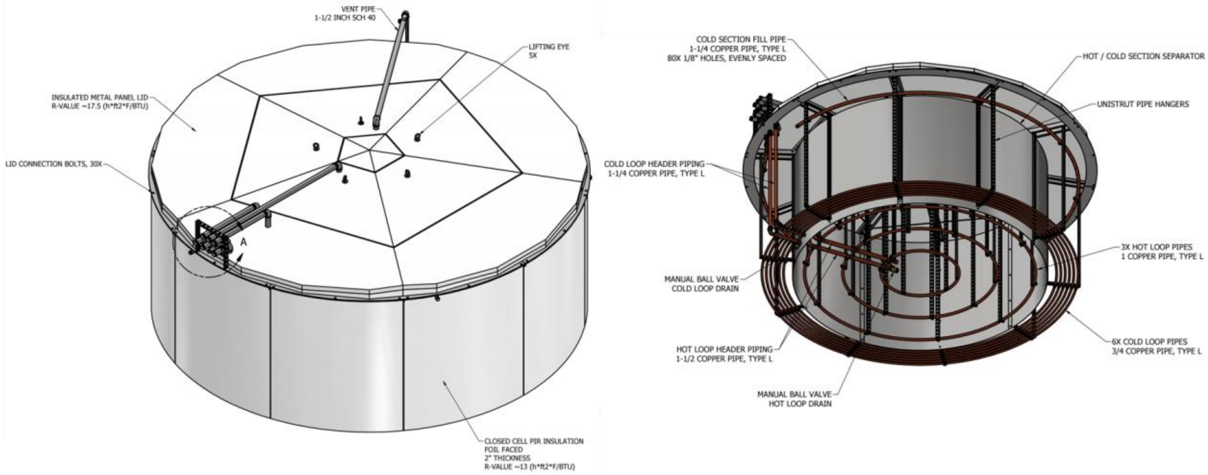

Figure 4. *CAD rendering of the insulated test tank assembly (right) and removable roof structure which supports the internal piping (left).*

4.2 Tank Foundation

As discussed in Section 2, the shape of the floor and friction can be important contributors to the buckling failure. In the commercial case the slope is achieved using a solid lubricant (e.g. sand) that can be compacted to the desired shape, the floor plates are then welded on-site on top of an already sloped foundation. In addition, the foundation stiffness and interaction with the tank floor influence the friction loading. Due to the impact of the foundation design on the initial tank floor shape and stresses due to friction, it can play an important role in the formation of buckles in the tank floor. In the commercial case, the foundation may also have embedded pipes to avoid heating of the underlying soil, although this design feature will influence the heat transfer and expected temperature profile of the tank floor, it is not considered a main contributor to the buckling failure.

For the first phase of testing the foundation for the scaled test tank will be constructed of concrete with no solid lubricant or cooling pipes. Since the test tank is planned to operate at lower temperatures (T < 100°C) there are no issues having the tank sit directly on concrete or eliminating the cooling system. Constructing the foundation from concrete will allow relatively good control of the floor shape at small scale and reduces some of the uncertainty attributed to the friction coefficient. The friction coefficient between concrete and steel is relatively well characterized, compared to the commercial case compared to the solid lubricants used in commercial plants, partly due to the uncertainty related to the solid lubricant shifting as the tank expands and contracts. Although the team considered the addition of sand as a solid lubricant, for the purposes of model validation a concrete foundation with better defined coefficient of fiction was preferred. The foundation will be poured, shaped and allowed several days to cure before placing the tank on top. The tank is manufactured with a flat floor, which will assume the shape of the foundation when placed on top. Based on a simple FEA analysis < 5 N are required to deflect the 0.9 mm tank floor to the sloped shape; therefore, this process is negligible impact on the mechanical integrity of the tank.

5. Conclusions

A test site has been designed and is under construction to replicate the buckling failure observed in several in-service storage tanks for nitrate salts operating up to 565°C. In commercial tanks multiple factors have been identified that influence the floors susceptibility to buckling, including: the as-manufactured shape of the floor, high compressive stresses due to thermal gradients and/or friction, fluid inventory and absolute temperature. Based on extensive modeling analysis it was determined that similar buckles can be reproduced in a scaled test tank (approximately 8.5x smaller than a representative commercial tank design). To buckle the scaled tank a radial thermal gradient is generated in the tank with a low fluid level, the fluid level is then increased while maintaining the thermal gradient; based on the modeling results just one of these cycles can plastically deform the tank floor. The test site which is under construction is designed to replicate this damaging cycle at lower temperatures. The goal of testing will be to reproduce this damaging cycle and buckle the scaled test tank floor, allowing proper model validation and a methodology for comparing different tank designs at a smaller (and less costly) scale.

Data availability statement

The data that guided this analysis is proprietary and protected by non-disclosure agreements. Great care was taken to publish pictures and data relevant to the topics discussed that did not reveal any sensitive information.

Author contributions

Luca Imponenti – Investigation, project admin., writing (original draft); Nathan Stegall – Formal analysis, methodology; Bruce Kelly – Conceptualization, validation; Hank Price – Supervision, project admin.; David Cubel – Supervision, methodology; Sergio Davila – Conceptualization; Ricard Fernandez – Software, methodology; Kevin Vila – Software, methodology; David Andrews – Formal analysis, software, methodology, Bruce Leslie – Conceptualization, supervision; Kurt Drewes – Conceptualization

Competing interests

The authors declare that they have no competing interests.

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