Hypothesis of Sources of Failures in Hot Salt Tanks at Central Receiver Projects

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Hot Tank Failure Hypothesis

- Floor Welding
  - The floor is fabricated from large rectangular plates. The plates are arranged on the foundation, and then butt welded along each face. Metal backing plates are used at the seams to help control the gas chemistry in the weld region
  - Plate thicknesses range from 6 - 11 mm, number of welding passes ranges from 2 – 4.
  - The welding process results in plastic deformations in the weld region, and the establishment of permanent residual stresses in each plate.
    - The minimum deformations are at the edges of the plate, and the maximum elevation of the deformation is at the center of the plate.
    - Each plate takes on the shape of the top of a sphere with a large radius
  - The floor, after welding, is no longer flat; i.e., the floor has, in effect, buckled at each of the plate seams. This has important implications for the stability of the floor once the tank has been commissioned and is placed into service.

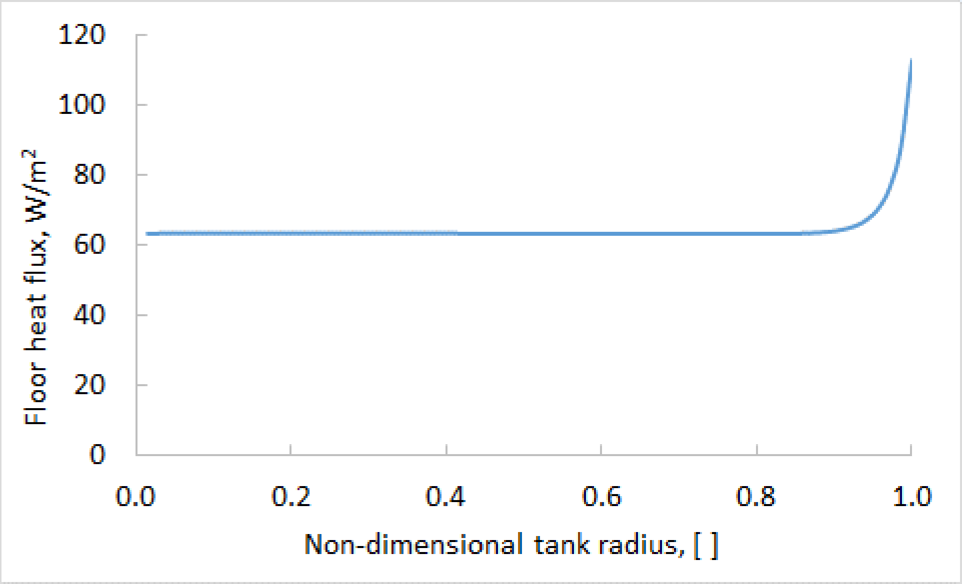
Hot Tank Failure Hypothesis - Continued

- Radial Temperature Distributions in the Floor
  - Near the center of the tank, conduction heat transfer from the floor into the foundation is primarily one-dimensional; i.e., straight down. The thermal conductivity of expanded clay is low, and the overall thermal resistance in this direction is 'large'.
  - Near the perimeter, conduction heat transfer is a combination of vertical heat transfer through the refractory ring wall and horizontal heat transfer through the soil surrounding the refractory ring wall.
    - The thermal conductivity of many refractories is double that of expanded clay.
    - The thermal conductivity of soil is 4 to 5 times the conductivity of expanded clay.
    - Conduction heat transfer at the perimeter of the floor is approximately double the conduction heat transfer at the center of the floor.
  - Due to mixing, the temperature of the inventory is largely isotropic. As such, if the heat flux from the floor to the foundation is a function of the radial position, then the temperature of the floor is also a function of the radial position.

Hot Tank Failure Hypothesis - Continued

- Radial Temperature Distributions in the Floor - Continued

Heat flux through the floor is a function of the radial position



- Floor temperatures calculated from a two-dimensional, steady-state conduction model of the foundation.
- Convection heat transfer from the bulk inventory to the floor modeled as 100, 10, and 1 times the thermal conductivity of the salt.

Hot Tank Failure Hypothesis - Continued

- Radial Temperature Distributions in the Floor – Continued
  - Unconstrained circular plate subject to a radial temperature gradient, the radial stress and the tangential stress are given by Roark:

$$\sigma_r = \gamma E \left(\frac{1}{R^2} \int_0^R Tr\, dr - \frac{1}{r^2} \int_0^r Tr\, dr \right)$$

$$\sigma_t = \gamma E \left(-T + \frac{1}{R^2} \int_0^R Tr\, dr - \frac{1}{r^2} \int_0^r Tr\, dr \right)$$

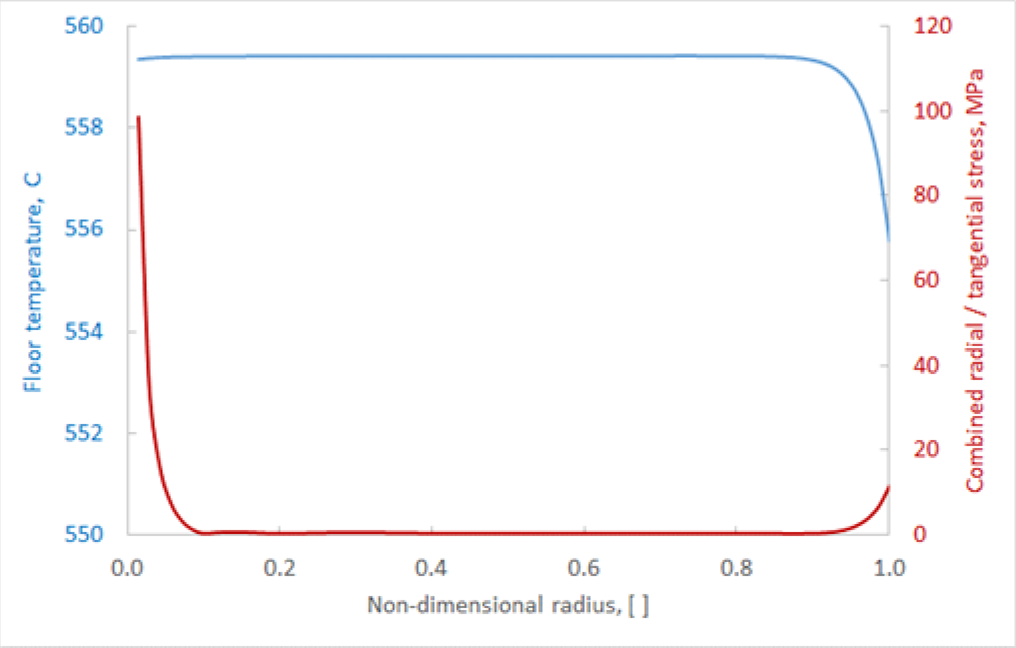
where γ is the coefficient of thermal expansion (1/°C), E is the modulus of elasticity (kg/m-sec2), R is the radius of the disc (m), and T is the temperature at any point a distance r from the center minus the temperature of the coldest part of the disc (°C)

  - Radial and tangential stresses combine as:

$$\sigma_{Combined} = \sqrt{\sigma_{Radial}^2 - \sigma_{Radial} * \sigma_{Tangential} + \sigma_{Tangential}^2}$$

Hot Tank Failure Hypothesis - Continued

- Radial Temperature Distributions in the Floor – Continued
  - Case 1: 100 times the thermal conductivity of the salt



  - 4 °C radial temperature gradient establishes stresses equal to ASME Section II allowable stress values

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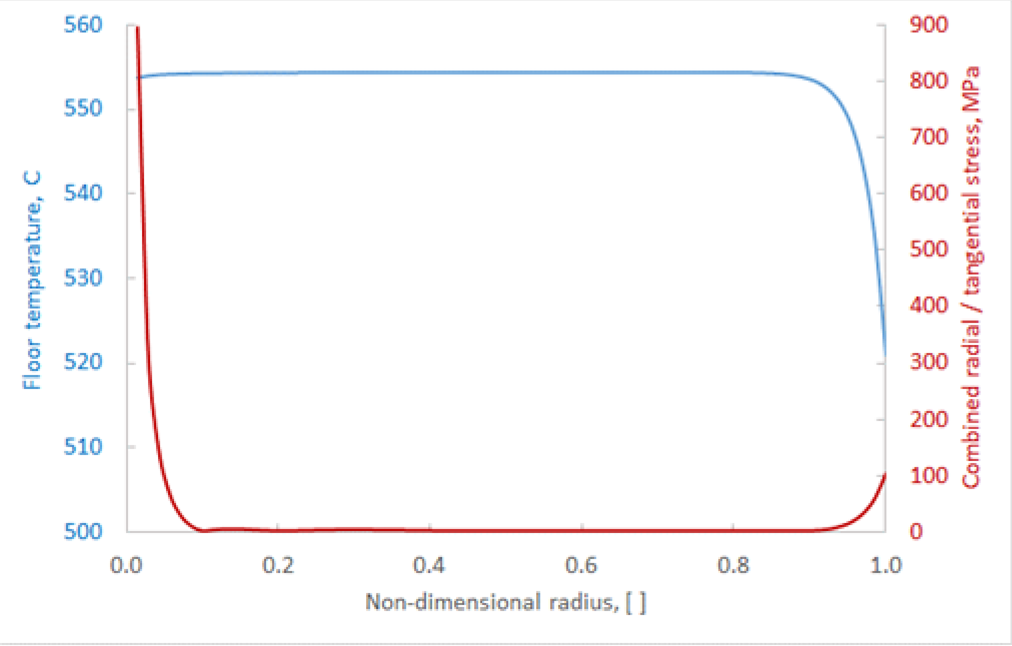
Hot Tank Failure Hypothesis - Continued

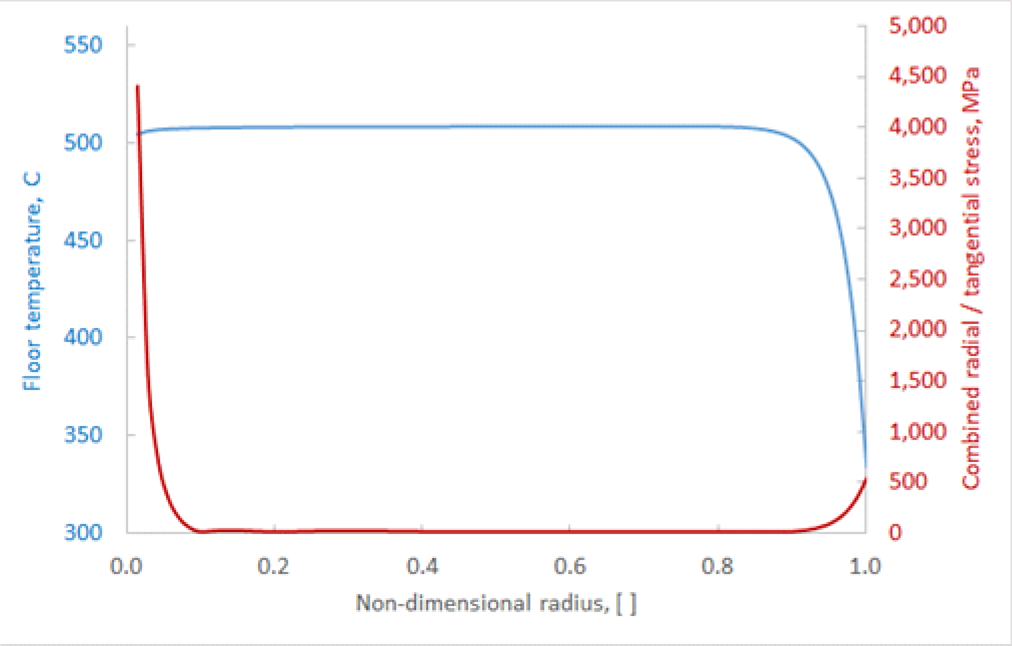
- Radial Temperature Distributions in the Floor – Continued
  - Case 2: 10 times the thermal conductivity of the salt



  - 35 °C radial temperature gradient establishes stresses above the yield stress at the center of the tank

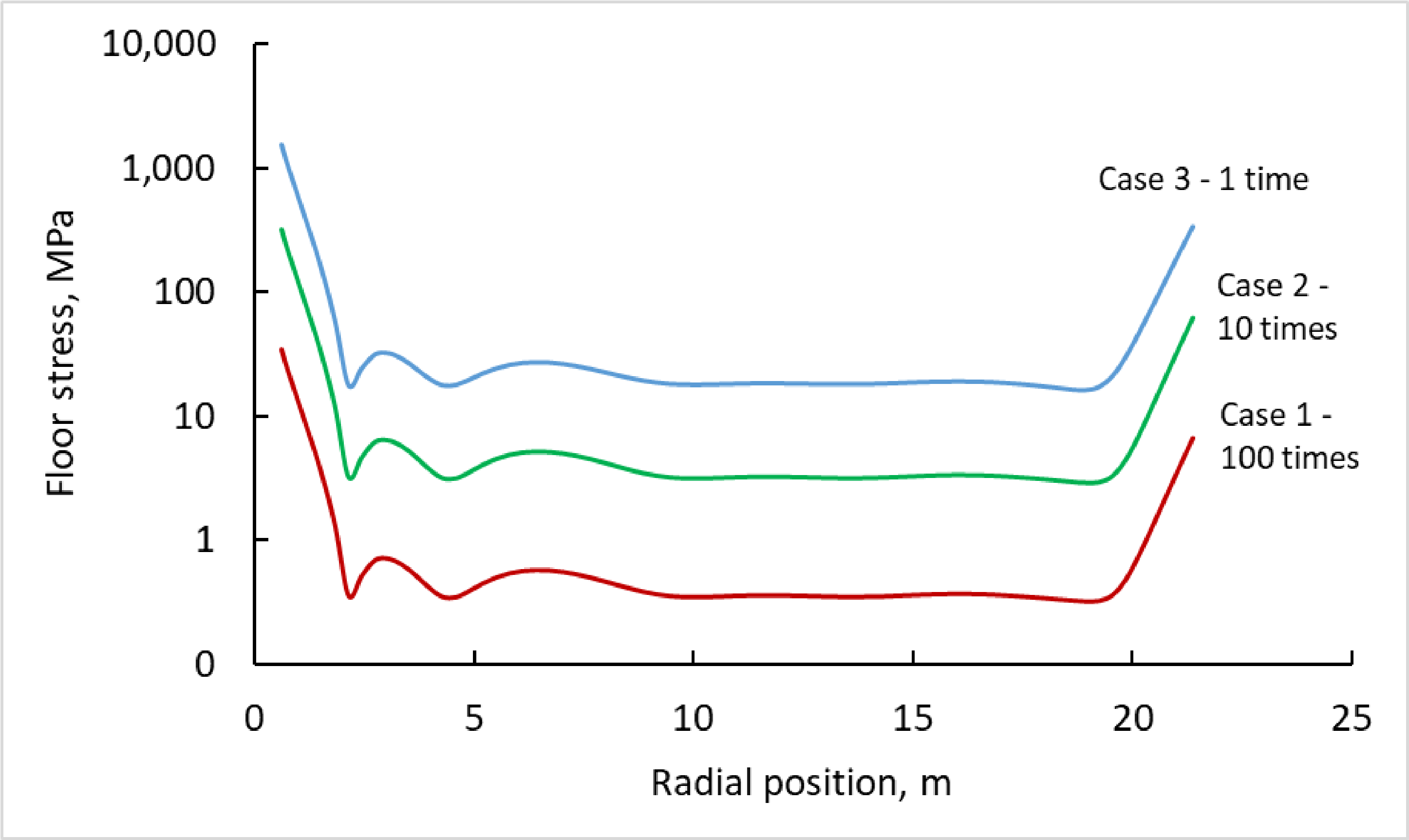
Hot Tank Failure Hypothesis - Continued

- Radial Temperature Distributions in the Floor – Continued
  - Case 3: 1 times the thermal conductivity of the salt



  - 200 °C radial temperature gradient plastically deforms the center of the floor
  - If the inventory become stagnant, permanent damage to the floor occurs

Hot Tank Failure Hypothesis - Continued



Hot Tank Failure Hypothesis - Continued

- Tank Preheating
  - The tank and the top of the foundation are preheated to a temperature of at least 280°C to prevent a thermal shock to the tank.
    - The heating medium is combustion gas from a propane- or a natural gas-fired air heater.
  - The preheating process can damage the tank, as follows:
    - The long preheating time can establish quasi steady-state temperature gradients.
    - The flow of preheating gas enters the tank at only one location. Gas at high temperatures has a low density and is generally a poor mechanism for heat transfer. The combination of inexact control over the gas flow and the low heat transfer coefficients can result in unavoidable non-uniform temperature distributions in the tank.
    - The floor, at the start of the preheating phase, has already buckled due to the welding processes. If the radial gradient established during preheating exceeds some threshold value (perhaps 35 °C from Case 2), the compression stresses near the center of the tank will exceed the yield value.
    - The buckling resistance of the floor will be very low due to the pre-existing plate deformations produced during welding and the absence of hydrostatic loads from the salt inventory to stabilize the floor. As such, the floor could develop permanent buckles even prior to the start of commercial service.

Hot Tank Failure Hypothesis - Continued

- Cumulative Effects
  - Plastic deformations in the floor can result from welding the floor plates, preheating the tank, and filling the tank with salt. The deformations may well take the form of buckles, or ridges, near the center of the tank where the stresses are the highest.
  - Once in commercial service, the tank will undergo changes in level and temperature, some of which will place the floor into compression. If some of these loads cause the floor to yield, then the displacements are likely to appear as increases in the height of the ridges.
  - At some point, the height of the ridges reaches a value which produces a crack at the top of the ridge, and the floor starts to leak. This failure geometry has been observed, to the author's knowledge, in two commercial projects.
  - Electron microscope examinations of the cracks show evidence of low cycle fatigue. One theory as to the source of the leaks is an initial plastic deformation of the floor, followed by additional plastic deformations in commercial service, which lead to a low cycle fatigue failure.

Potential Solutions

- A common source of problems seems to be compressive loads on the floor.
- Multiple tanks
  - The peak loads in the floor are, to some degree, a function of the tank diameter.
  - Substituting two 50-percent capacity tanks, or three 33-percent capacity tanks, for one 100-percent capacity tank could reduce the loads in the floor to values below a yet-to-be-defined damage threshold.
  - Multiple tanks would provide a degree of redundancy and eliminate the single point of failure with one 100-percent capacity tank.
  - Nonetheless, the failure mechanisms in commercial tanks are not yet fully understood. Adopting smaller tanks may be a step toward a reliable design approach, but the maximum allowable tank dimensions have yet to be defined and demonstrated.

Potential Solutions - Continued

- Controlling the Radial Temperature Gradients
  - Multiple distribution headers: A dedicated distribution header would be located at the perimeter of the tank. Salt could be supplied by recirculation from one of the hot salt pumps. Moving salt from the bulk inventory to the perimeter provides forced convection heat transfer to compensate for higher losses at the perimeter.
  - Tank scale mixing device: Provide a mixing device that spans the full dimensions of the tank.
    - A vertical shaft located at the center of the tank, with two to four vertical perforated plates attached to the shaft. Rotating the shaft at a low speed, say 1 rpm, would keep the inventory mixed.
    - A perforated plate, with a diameter slightly less than the diameter of the tank. The plate would vertically traverse the depth of the inventory once every few minutes.
    - The principal liability is a backup power source for the above with an availability of 100 percent. Should the inventory become stagnant, permanent damage to the floor will occur.

Potential Solutions - Continued

- Tanks Without Flat Floors
  - Elevated tanks:
    - Similar to water storage tanks in small towns
    - No friction forces on the floor
    - Only tensile stresses on the wall and the floor
    - Two of the tanks pictured replicate Crescent Dunes
    - Concentrated loads on the foundation will markedly increase the cost of the foundation
    - If the cost of an elevated hot tank + foundation is twice as expensive as the cost of a current design + foundation, this increases the capital cost of the plant by about 3 percent
    - Justified by the improvement in plant availability

Potential Solutions - Continued

- Tanks Without Flat Floors - Continued
  - Horizontal tanks:
    - Commercially available
      - 3.5 m diameter and 40 m long from the propane and the liquified natural gas industries
      - 44 tanks would replicate Crescent Dunes
    - Perhaps the lowest risk approach
      - Tanks supported on saddles avoid problems with friction
      - Favorable geometry for tolerating high rates of temperature change and non-uniform temperature distributions
    - Mass of steel in 44 horizontal tanks
      - 2.8 times the mass of steel in the hot tank at Crescent Dunes
      - Translates directly to an increase in cost relative to Crescent Dunes

Potential Solutions - Continued

- Tanks Without Flat Floors - Continued
  - Horizontal tanks - Continued
    - External surface area in 44 horizontal tanks
      - 6 times the surface area of the hot tank at Crescent Dunes
      - Prohibitively expensive to insulate, both in terms of capital cost and heat loss
      - May be possible to locate 44 vessels in a common enclosure, then insulate the enclosure
    - Whatever the approach, the cost is likely to be triple that of Crescent Dunes
    - Results in an increase in the plant capital cost of 6 percent
  - Switching to either an elevated tank or to horizontal tanks will increase the capital cost by 3 to 6 percent, but this may be a necessary step to project financing.