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Design Basis Document / Owner's Technical Specification for Nitrate Salt Systems in CSP Projects

Hypothesis of Hot Tank Failure

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Abstract. Work has begun on a Design Basis Document / Owner's Technical Specification for parabolic trough and central receiver power plants using nitrate salt as the heat transport fluid and the thermal storage medium. A principal topic of recent interest is the failures of the hot salt tanks in central receiver projects. The paper outlines a hypothesis for the source of the failures, and discusses a range of possible solutions.

Keywords: Salt Central Receiver, Hot Tank Failure Hypothesis

1. Introduction

A topic of current interest is the source of the failures seen in the hot salt tanks of commercial central receiver projects. A total of 5 failures have occurred, resulting in leakage rates of 1 to 3 m^3/hr. In other words, the failure is characteristic of a crack, rather than a rupture. Further, the failures have occurred within 1 to 2 years after the start of commercial service. The tanks are designed to accommodate the low cycle fatigue damage associated with daily cycles in pressure and temperature. However, the failures have occurred much sooner than the expected low cycle fatigue life. As such, the failures are likely due to unexpected stresses, which are much higher than originally anticipated.

2. Hot Tank Failure Hypothesis

2.1 Floor Welding

In commercial salt tanks, the floor is typically fabricated from large rectangular plates. The plates are arranged on the foundation, and then butt welded along each face. The plates have a thickness in the range of 6 to 11 mm, and the number of welding passes ranges from 2 to 4.

The welding process results in plastic deformations in the weld region, and the establishment of permanent residual stresses in each plate. The minimum elevations of the plate deformations are at the edges of the plate, and the maximum elevation is at the center of the plate. Each plate, in essence, takes on the shape of the top of a sphere with a large radius.

It can be noted that 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 commercial service.

Radial Temperature Distributions in the Floor

Commercial salt storage tanks are placed on a foundation, which typically consists of the following elements:

- A concrete base mat, through which a series of parallel cooling pipes is located. A flow of air is forced through the pipes by means of a fan.
- A primary insulating layer, beneath the majority of the floor. The insulating material can be an expanded clay, such as Utelite, or an expanded glass, such as FoamGlas.
- A ring wall, composed of a hard refractory material, at the perimeter of the tank. The refractory provides the foundation stiffness needed to support the concentrated weight of the wall and the roof.
- A solid lubricant, such as sand, on top of the primary insulating layer and the refractory ring wall.

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 resistance to conduction heat transfer in this direction is 'large'. Conversely, near the perimeter of the tank, conduction heat transfer from the floor is a combination of vertical heat transfer through the refractory material and horizontal heat transfer through the soil surrounding the refractory ring wall. The thermal conductivity of many refractories is about double the thermal conductivity of expanded clay, and the thermal conductivity of soil is a factor of 4 to 5 times the thermal conductivity of expanded clay. As such, the heat flux from the floor is greater at the tank perimeter than at the tank center.

Due to mixing within the tank inventory, 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 must also be a function of the radial position. A two-dimensional, steady-state conduction heat transfer model of the foundation was developed to explore this effect. The model is simplified by simulating the convection heat transfer from the inventory to the floor as follows:

- Case 1 - The convection heat transfer is simulated by multiplying the thermal conductivity of the salt by a factor of 100
- Case 2 - The convection heat transfer is simulated by multiplying the thermal conductivity of the salt by a factor of 10
- Case 3 - The convection heat transfer is simulated by multiplying the thermal conductivity of the salt by a factor of 1. This represents a case in which the salt is stagnant.

The calculated temperature gradients in the floor are shown in Figure 1.

For an unconstrained circular plate, subject to a radial temperature gradient, the radial stress and the tangential stress are given by the following formulas in Roark [1]:

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

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

where γ is the coefficient of thermal expansion (1/°C), E is the modulus of elasticity (kg/m-sec^2), 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). The radial and the tangential stresses are combined using the following formula:

$$\sigma_{Combined} = \sqrt{\sigma_r^2 - \sigma_r * \sigma_t + \sigma_t^2} \quad (3)$$

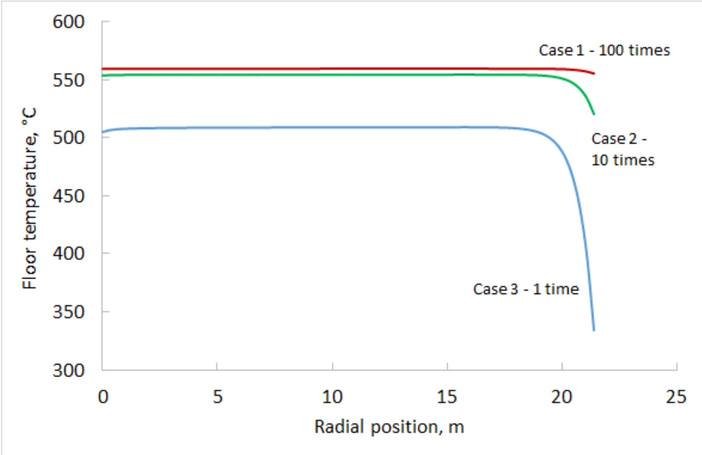

Figure 1. Radial Temperature Gradients in the Floor.

The calculated stresses for the 3 cases are shown in Figure 2. In Case 1, the peak stress in the floor occurs at the center, with a value essentially equal to the allowable stress in Section II of the ASME Code for stainless steel at 560 °C. In Case 2, the calculated stresses have exceeded the yield stress, and plastic deformations will have occurred near the center of the tank. In Case 3, this produces, at least in theory, plastic deformations from the center of the tank to about 10 percent of the radius. Of course, once the yield strength is exceeded, the model calculations are no longer applicable.

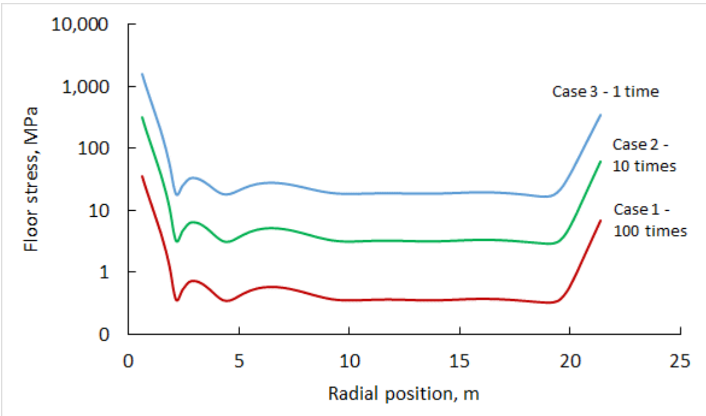

Figure 2. Calculated Stresses in the Floor.

The calculations show that any radial temperature gradient above about 35 °C is sufficient to permanently damage the floor. Further, if the inventory becomes stagnant for even a modest period of time (i.e., days), then permanent damage to the floor is essentially inevitable.

2.2 Tank Preheating

Prior to filling the tank with salt, the tank and the top of the foundation are preheated to a nominal temperature of 300 °C to prevent a thermal shock to the tank. The heating medium is combustion gas from a fossil-fired direct air heater. The gas is directed through a manway in the roof, flows down a short (2 m) temporary gas duct suspended from the roof, enters the tank with the flow directed nominally toward the center, and then exits through a second manway in the roof. The preheating period ranges from 7 to 10 days.

The preheating process is one in which damage could occur to the tank, as follows:

- Due to the relatively long preheating period, quasi steady-state temperature gradients can be established in the floor.
- The flow of preheating gas enters the tank at only one location, and the gas flow path is dictated by the location and the shape of the inlet duct. As such, the gas flow path is known on a global basis, but is largely beyond the control of the operators. Further, 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 allowable measured intra-tank temperature differentials are the same order of magnitude as the radial temperature gradient (35 °C in Case 2 above) which can damage the floor.

The floor, at the start of the preheating phase, has already buckled due to the welding processes. During preheating, a radial temperature gradient in the floor will develop, with the highest temperature near the center and the lowest temperature at the perimeter. If the gradient exceeds some threshold value, probably on the order of 35 °C, then 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 preexisting plate deformations produced during welding. As such, the floor could develop permanent buckles (ridges) even prior to the start of commercial service. As with every metal, plastic deformations have a significant detrimental effect on the low cycle fatigue life of the floor.

2.3 Initial Salt Filling

A common commercial plate dimension is 2.44 m by 9.75 m (8 ft. by 32 ft.). A representative tank diameter in a commercial project is 42 m. As such, a nominal 13 rows of plates are required to span the diameter of the tank.

As discussed above, the plates in the floor are forced into the shape of the top of a sphere with a large radius. Anecdotal evidence from the tanks in commercial projects indicate that the deformation at the center of the plate is on the order of 20 to 50 mm. If the center of the plate is raised by 50 mm, then the width of each plate is reduced by about 2 mm.

When the tank is filled, hydrostatic loads will push down on the plates, and change the shape of the plates from curved to flat. As such, the width of each plate will increase by 2 mm. Across the diameter of the tank, the total change in the width of the plates is 26 mm.

The radial stiffness of the wall is several orders of magnitude greater than the radial stiffness of the floor, particularly if the plates have already buckled due to welding. As such, the 26 mm increase in plate dimension is most likely to be converted to further buckling where the floor stresses are the highest due to existing radial temperature gradients. This location is the center of the tank. Evidence from the failures in commercial tanks show that buckling of the floor is concentrated near the center of the tank.

It can be noted that the vertical dimensions of the buckles seen in commercial tanks are larger than the calculated change in plate dimensions. However, there are a number of mechanisms, discussed below, which can produce ratcheting, the starting point of which are the buckles produced during filling.

2.4 Salt Inlet Flow Distribution

The salt flow entering the tank is typically distributed by means of a single ring header. The circumference of the header is in the range of 40 to 60 percent of the circumference of the tank. The header has a series of holes, or a group of eductors, to distribute the incoming flow with the main inventory.

The distribution arrangement is simple and offers a low cost. However, during receiver startup, or following a trip of the receiver, both the temperature and the flow rate of the salt can be well below design values. A condition can occur in which relatively cold salt leaves the distribution ring, and then sinks to the floor due to buoyancy effects. This, in turn, can lead to a non-uniform temperature distribution in the floor immediately below the distribution ring. The stresses associated with this flow condition can be estimated using the following expression from Roark [1]: A thin circular disk at a uniform temperature has the temperature changed ΔT in a small circular portion of radius a. The radial and tangential stress is given by $\sigma_r = \sigma_t = \frac{1}{2} \Delta T \gamma E$, where γ is the coefficient of thermal expansion (1/°C), and E is the modulus of elasticity (kg/m-sec^2). A local temperature depression of 54 °C results in a stress equal to the allowable stress, and a local temperature depression of 87 °C produces stresses equal to the yield stress. The local stresses can either add to, or subtract from, the stresses normally present in the floor.

It can be noted that differences between the temperature of the salt in the distribution ring and the temperature of the bulk inventory can differ, during transient conditions, by values up to at least 90 °C.

2.5 Operator Actions

During receiver startup, the temperature of the salt leaving the receiver starts at the cold salt temperature (295 °C), and then increases to the normal design temperature (565 °C). Early in the startup process, salt is directed to the cold tank to prevent a noticeable decay in the inventory temperature of the hot tank. When the salt temperature in the downcomer reaches a defined crossover temperature, the flow is directed to the hot tank. The crossover temperature is a function of the inventory temperature in the hot tank. A typical value is 20 to 50 °C below the inventory temperature in the hot tank.

The crossover temperature can be programmed in the DCS, and the control system will automatically open and close the tank diversion valves as necessary. However, as with most setpoints in the DCS, the operator is free to revise the setpoint. If the crossover setpoint is set to a low value, then additional thermal energy will be stored in the hot tank for electric energy production. During the project warranty and guarantee period, this can be an important consideration for the EPC contractor. However, the lower the setpoint, the greater the risk to the tank in terms of non-uniform temperature distributions, particularly in the floor. Experience from more than one commercial project has shown that protecting the low cycle fatigue life of the tank often takes secondary importance to meeting the contractual requirements on energy production.

2.6 Effects of Commercial Service

Once in commercial service, the tank will undergo a series of changes in level and changes in temperature. Some of these changes (i.e., an overnight decay in temperature) will place the floor into tension, and no compressive deflections will occur at the ridges. However, some number of daily changes will involve combinations of inventory level and increases in inventory temperature that place high compression loads on the floor. 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 in commercial projects. Further, electron microscope observation 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 eventually lead to a low cycle fatigue failure.

3. Solutions

The question then arises: What solutions can be effected to prevent damage to the tank? A common source of the problems seems to be compressive loads on the floor. The compressive loads can arise due to radial temperature gradients and due to friction forces.

3.1 Multiple Tanks

The peak compressive 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 damaging threshold. Further, multiple tanks would provide a degree of redundancy, and eliminate the single point of failure problem 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 to be defined and demonstrated.

3.2 Radial Gradients

A few methods for controlling the radial temperature gradient in the floor include the following:

Insulation Design The radial temperature gradients can be reduced by changing the insulation design at the perimeter of the tank. This may consist of greater insulation thicknesses on the wall at the base of the tank, and the addition of insulation on the outer edge of the refractory ring wall beneath the perimeter of the tank. Nonetheless, a radial temperature gradient will always be present, and if the inventory reaches, or approaches, a stagnation condition, then damaging stresses in the floor will result.

Perimeter Heat Addition The radial gradient can also be reduced by some form of heat addition at the tank perimeter. The heat addition might take the form of electric heaters, installed beneath the wall insulation or embedded in the refractory ring wall. The principal liability with this approach might be a slow response time due to 1) limited radiation heat fluxes from radiant heaters to the tank wall, and 2) the combination of a modest thermal conductivity and a high thermal inertia of refractory materials.

Multiple Distribution Headers An alternate approach to controlling the radial gradients is a dedicated distribution ring at the perimeter of the tank. Salt flow to the distribution ring would be supplied by recirculation from one of the hot salt pumps. The goal would be to move salt from the bulk inventory to the tank perimeter, and thereby provide forced convection heat transfer to compensate for the higher heat losses at the perimeter. The ability to move heat by forced convection is generally large relative to conduction heat transfer. As such, it should be a straightforward exercise to reduce the magnitude of the radial gradient.

Tank Scale Mixing Device Another alternate method to control the radial temperature gradient is to provide some form of a mixing device that spans the full dimensions of the tank. This might consist of a vertical shaft located at the center of the tank. Two to four vertical perforated plates would be attached to the shaft. The horizontal dimension of the plate would be somewhat less than the radius of the tank, and the height of the plate would be equal to the maximum liquid level. Rotating the shaft at a low speed, say 1 rpm, would keep the inventory mixed.

A second approach might be 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. Forcing a portion of the inventory to pass from the top of the plate to the bottom, and vice versa, would promote convection mixing at the perimeter of the tank.

3.3 Tanks Without Flat Floors

Flat bottom tanks, with self-supporting dome roofs, have been universally adopted in the solar industry due to their low cost. However, this design is not the only option for the solar industry.

3.3.1 Elevated Tanks

Elevated water storage tanks, in capacities up to 11,300 m^3 (3,000,000 gallons), are commercially available from a number of suppliers. To replicate the storage volume at Crescent Dunes (17,500 m^3), two tanks would be required.

The tanks are supported either on single column or on a series of legs, attached to the side of the tank. With this arrangement, there are no friction loads on the floor, and many of the structural problems with flat bottom tanks can be avoided.

Naturally, this type of tank has a number of characteristics which will increase the cost relative to a flat bottom tank, as follows:

- The vertical loads are taken either at a central location or by a series of columns located around the circumference of the tank. The concentrated loads, relative to a flat bottom tank, will incur a significant increase in the cost of the foundation.
- The bottom of the curved tank is exposed to hydrostatic loads which are higher than those seen in a flat bottom tank. This will lead to an increase in the thickness, and the cost, of the bottom of the tank.

Nonetheless, the cost of the hot salt tank in a solar project is on the order of 2 to 3 percent of the cost of the project. If switching from a flat bottom tank to an elevated tank doubled the cost of the tank, then the net change to the project is perhaps a 2 to 3 percent increase in the capital cost. However, if the availability of the project improves by, say, even 5 percent due to the avoidance of a tank failure, then the increase in the cost of the tank is fully justified.

3.3.2 Horizontal Tanks

The lowest risk approach is, perhaps, a field of horizontal cylindrical tanks. The tanks are supported on saddles, which avoids any problems with friction. Further, the geometry is favorable in terms of accommodating both high rates of temperature change and non-uniform temperature distributions in the inventory.

Horizontal tanks are available from a number of commercial suppliers. The maximum practical diameter and length are on the order of 3.5 m (11 ft.) and 40 m (130 ft.), respectively, based on shipping considerations. To replicate the storage volume at Crescent Dunes (17,500 m^3), some 44 tanks would be required.

The mass of steel in 44 horizontal tanks is about 2.8 times the mass of steel in a single, flat bottom tank, and a cost comparison of the two options would reflect this difference. The surface area of 44 horizontal tanks is slightly more than 6 times the surface area of a single, flat bottom tank. It would be prohibitively expensive to insulate 44 horizontal vessels, particularly if the cost of the heat loss through the insulation was considered in the analysis. However, it may be possible to locate the 44 vessels in a common enclosure, and then insulate the outside of the enclosure.

To a first order, replacing a single, flat bottom hot tank with 44 horizontal tanks is likely to triple the cost of the hot tank. However, as noted above, the cost of the hot tank is 2 to 3 percent of the cost of the project. If the cost of the tank triples, then the cost of the project increases by something approaching 6 percent. However, if the flat bottom tanks are judged to be unsuitable for service as a hot tank, then the maximum penalty incurred by switching to a low risk design is on the order of 6 percent.

Data availability statement

Some of the analyses and observations regarding tank failure modes are based on third-party information that is restricted.

Competing interests

The authors declare no competing interests.

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