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# FREEZE-THAW TESTS OF TROUGH RECEIVERS EMPLOYING A MOLTEN SALT WORKING FLUID

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## ABSTRACT

Several studies predict an economic benefit of using nitrate-based salts instead of the current synthetic oil within a solar parabolic trough field. However, the expected economic benefit can only be realized if the reliability and optical performance of the salt trough system is comparable to today's oil trough. Of primary concern is whether a salt-freeze accident and subsequent thaw will lead to damage of the heat collection elements (HCEs). This topic was investigated by experiments and analytical analysis. Results to date suggest that damage will not occur if the HCEs are not completely filled with salt. However, if the HCE is completely filled at the time of the freeze, the subsequent thaw can lead to plastic deformation and significant bending of the absorber tube.

## INTRODUCTION

Molten salt has been proposed in recent years as the working fluid within a parabolic trough solar field. Several studies indicate an economic benefit of using nitrate-based salts instead of the current synthetic oil [1, 2] and the Italian national lab ENEA is beginning to operate a 5 MW demonstration project in Sicily [3]. However, the expected economic benefit can only be realized if the reliability and optical performance of the salt trough system is comparable to today's oil trough. Of primary concern is the potential for a freeze accident. Since the nitrate salt has a relatively high freezing point (145 °C for HITEC salt), a station blackout or other events could lead to wide-spread freezing in the solar field within a relatively short time. When the emergency heating system is restored, the field can be thawed to restore flow within the field. The question we investigate in this paper is whether freezing and subsequent thawing of salt within the trough heat collection elements (HCEs) will lead to unacceptable damage of the tubes. For example, if salt freeze leads to permanent tube bending then trough performance would drop because the absorber tube would no longer be located in the trough focal line.

Electrical-impedance heating is a straightforward method of heating the 4 m long stainless steel tube within an HCE and is the proposed method to thaw the salt after a freeze up event. Since the electrical resistance of each tube is approximately 0.01 ohm, a voltage difference of only 3 V across the tube will deliver 900 W of heating power ($P=V^2/R$). Commercial impedance heating technology is readily available and very safe if properly installed [4]. Kelly [2] used this technology to develop a conceptual design for a proposed 55 $MW_e$ commercial-scale trough plant, as shown in Figure 1.

For this design, tubes are connected so as to achieve approximately 1 kW of impedance heating per tube; given this power only 30 minutes is required to heat an empty tube above a salt freezing point of 145 °C. Kelly designed the system to preheat the tubes before flowing salt in them; the tubes in an entire flow loop would be emptied to perform maintenance such as replacing an HCE. However, this same system could also be used to melt the salt after a freeze event. The current work investigates possible detrimental effects during freeze recovery using impedance heating and solar heating.

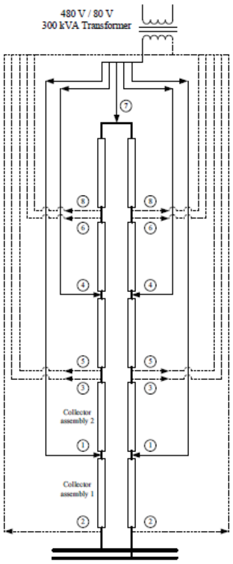

**Figure 1** Impedance heating system proposed for a commercial trough plant [2]

## TEST FACILITY DESCRIPTION

The test rig consisted of one or two HCEs and two standpipes. The HCEs we tested are used in current oil-based trough plants (4 m long, 70 mm diameter cermet-coated absorber tube with a 2 mm wall, enclosed in a vacuum maintained by a 125 mm glass envelope). The standpipes at each end were made of the same material as the absorber tube. Their function was to maintain the HCEs full of salt as the salt shrank during solidification. They also mimic the orientation of the flex hoses at the ends of the solar collector assembly when the plant is shutdown (see Figure 2).

Electrical connections were placed at the top of each standpipe. When activated, a voltage was applied across the connections (6.7 $V_{AC}$ RMS for the 2-tube configuration) to flow current through the standpipes and the HCEs and achieve the approximately 1kW of heating per tube defined by Kelly. Three thermocouples sensed salt temperature inside each 4-m HCE; one in the center, one located 15 cm inside from the left end and one located 15 cm inside from the right end, as shown in Figure 3. The inside thermocouples were not attached to the tube wall. Rather, they were loosely positioned inside the tube. Additional exterior thermocouples were spot welded to each end of the HCE (outside the glass envelope), and one of these was used to maintain a setpoint temperature using an on/off controller.[1] The bare standpipes were covered with several inches of fibrous insulation to reduce heat loss. The HCEs were supported by hanger bars, one attached at each end. When an HCE is heated from ambient to the typical trough operating temperature of 300 °C, the length of the stainless steel tube will increase approximately 1.2 cm and this growth was verified by a potentiometer device mounted coaxially at each end. The hanger system was designed to allow the tubes to freely expand. If a hanger impedes growth, the tube could bend due to restrictive clamping forces. Since we wanted to understand whether salt-freezing alone could lead to tube bending, it was imperative for the expansion system to not cause significant bending over the temperature range for the tests. Successful operation of the expansion system was verified by heating the empty tubes to nearly 300 °C with no perceptible tube deformation.

**Figure 2** HCE freeze/thaw test rig in a 2-HCE configuration (top). The impedance heater electric connection can be seen at the top of the insulated standpipe. The standpipes approximate the expected orientation of the flex hoses during shutdown of a commercial plant (bottom), the time at which a freeze event is most likely. The HCEs are usually covered to prevent heatup due to one-sun exposure prior to first use (red cover on top, white cover on bottom).

The HCEs were preheated to a temperature above the salt-freeze point and then filled with molten HITEC. Ideally the temperature of the empty tube should exactly match the temperature of the salt to avoid thermal shock upon filling. This was difficult to achieve due to variations in heat loss along the length of the rig and temperatures often varied by 50 °C or more prior to filling. After filling the HCE and standpipes with salt the temperatures throughout the rig soon equilibrated and a variation of only a few degrees was observed. During one of the fills conducted on a bright sunny day, the tube was approximately 100 °C hotter than the salt temperature. The tube bent upward toward the sun side of the

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[1] We also proposed using an infrared camera to monitor the tube surface temperature during the freeze/thaw process. However, our analysis indicated the glass envelope would filter out the infrared signal at the 145 °C freeze/thaw temperature. Thus, infrared cameras could not be used.

tube approaching the glass envelope. Upon equalization of the tube and salt temperatures, the tube returned to its original position in the center of the glass envelope. This almost-damaging event emphasizes the importance of matching tube and salt temperatures during fill since a circumferential temperature gradient can cause tube bending due to the temperature dependent coefficient of thermal expansion.

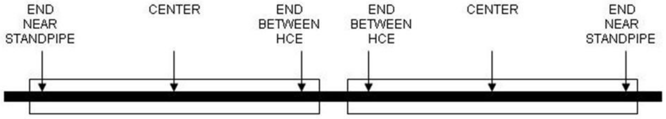


**Figure 3** Locations of thermocouples inside the 2 HCEs

## FREEZING THE HCEs

After filling the HCE and standpipes with salt, the set point on the impedance heater was increased to raise the salt temperature to nearly 300 °C. Several photographs were taken along the length of the tube to show the starting position of the "hot" absorber tube within the glass envelope. The impedance heater was then deactivated and a LabVIEW data acquisition system recorded the temperatures during the subsequent freezing event.

Typical salt cool-down data is displayed in Figure 4. It can be seen that it took about 2 hours for the salt to begin freezing given a starting temperature of approximately 175 °C. This starting temperature is relevant because in a commercial plant the salt would be circulated through the solar field during the overnight shutdown at a temperature at least 30 °C above the freezing point. The 30 °C value is a first-order guess; the optimum value would be determined by a trade study that compared thermal losses vs. freeze safety as a function of circulation temperature. The 2-hr freeze time applies to the HCEs with a good vacuum within the glass annulus. Since a commercial plant would likely have some HCEs with a lost vacuum, we constructed a mathematical model of the HCE to understand how the freeze time would shorten given a lost vacuum. A simple lumped capacitance heat transfer model was developed and solved using a forward-difference integration scheme.

$$(m_s c_{p,s} + m_{st} c_{p,st}) \frac{dT}{dt} = q_{in} - q_{out}$$

The subscript s represents the salt in the tube and st the steel tube. The heat in ($q_{in}$) can be supplied by the impedance heater or from sun heating alone. The heat loss ($q_{out}$) is a function of the status of the vacuum, tube temperature, ambient temperature, and wind speed [5, 6]. Only 1 m of the HCE was modeled and heat loss from standpipes was ignored. With $q_{in}$ set to zero, the model agreed with the test data and showed that it takes approximately 2 hrs for salt temperature to drop from 175 to 145 °C. We then modeled the heat loss assuming vacuum was lost and found it would take 40 minutes to drop the same 30 °C. Furthermore, if the glass envelope is broken and the tube is bare, the onset of freezing is predicted to occur in 10 minutes given a typical average wind speed of 5 m/s.

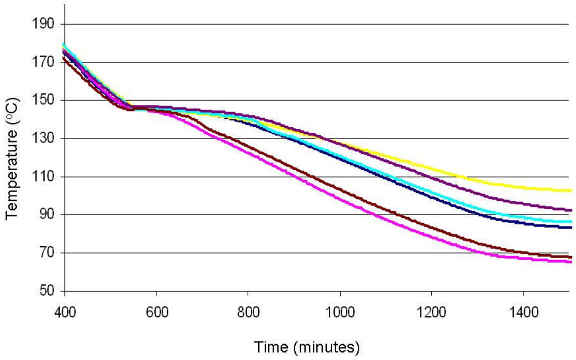


**Figure 4** Salt temperature throughout the 2 HCE rig during a freeze event. The plateau at 145 °C indicates freezing. The salt nearest each standpipe (lower 2 curves) freezes before the salt at the HCE centers (middle 2 curves) and between the HCEs (top 2 curves).

A video camera was used to monitor the center position of the tube during the freeze and a portion of the subsequent cool down towards ambient temperature. Still photos were also taken of the frozen HCE to compare with photos of the hot HCE. The absorber-tube position was observed to move by no more than a few mm. With no solar heat input, the HCEs will eventually reach ambient temperature. However, the salt is not able to reach ambient temperature during a single night. If the following day were clear, the HCE containing the frozen salt would warm up again to near the melting point. This phenomenon over many days is shown in Figure 5.

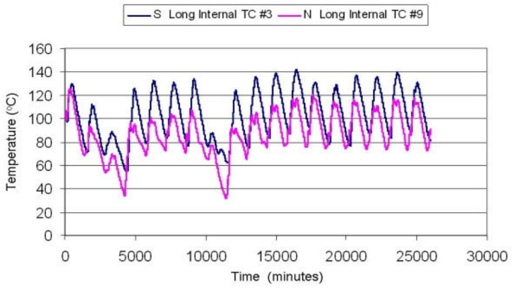


**Figure 5** Temperature of the frozen salt in the center of each tube during 19 days in April. One-sun heating of the 4-m long HCE can be as high as 280 Watts with the sun directly overhead. Nearby structures caused some tube shading. The north tube experienced more shade, thus explaining its lower temperature.

## THAWING THE HCEs

The impedance heater was activated to thaw the frozen salt within the HCEs and standpipes. The thaw was accomplished with approximately 1 kW of impedance heat per HCE and additional sun heating when present. Additional thaw tests were performed using approximately 0.3 kW of impedance heating only to mimic a controlled one-sun heat rate. A typical 1-kW thaw is shown in Figure 6.

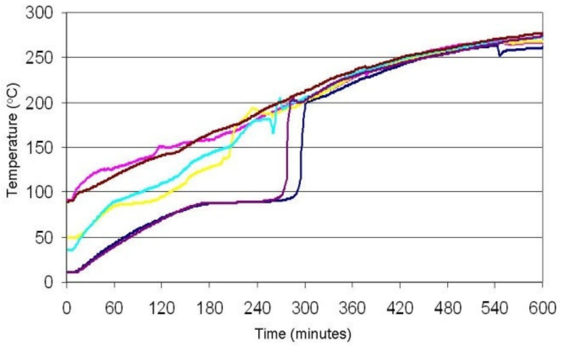


**Figure 6** Salt temperature throughout the 2-HCE rig during a ~1 kW/tube thaw. The top 2 curves are measured at the center of each HCE. The bottom 2 curves are measured at the ends of each HCE, near the standpipes. The middle 2 curves are at the center of the rig between the HCEs.

Unlike a freeze, no clear temperature plateau can be seen at the 145 °C melting temperature; the large variation in solid-salt starting temperatures and the rapid heating rate are the expected causes of this. The salt first thaws in the center of each HCE, followed by connection point between the 2 HCEs, followed by the standpipes. This sequence is logical if one considers the variations in heat loss throughout the rig. The insulating value of the vacuum is significantly higher than the fibrous insulation we used to cover the tube connections and standpipes. In addition, heat bridges exist at the HCE hanger points resulting in excessive heat loss.

## TEST RESULTS

During the first series of tests, the 2-HCE rig was subjected to 4 freeze-thaw cycles. No significant tube bending was noted, as shown in Figure 7. This was unexpected. A visual inspection revealed that when the salt was frozen, the standpipes were nearly empty of salt resulting in non-full conditions within the HCEs. A calculation revealed that the standpipes emptied because of the significant increase in salt density as it cooled from the starting temperature of 300 °C down to the 145 °C freeze point. Since the HCE tubes were not totally full during the 4 thaws, we postulate that damage was avoided because there was a free surface for the expanding salt to grow into, thus relieving stress on the pipes.

During the next series of tests the standpipes were lengthened to ensure that salt would completely fill the HCEs upon cooling and subsequent freezing. However, before we could begin this next series of tests the temperature control signal became erratic, ultimately leading to an unplanned freeze event. When we visited the test site we found the north tube badly bent downwards and the south tube bent upwards, as shown in Figure 8. The data acquisition system was not running during the event so there was no record of whether the tubes had been subjected to one or more freeze-thaw cycles. However, as described later we suspect that at least one freeze-thaw occurred before the final freeze.

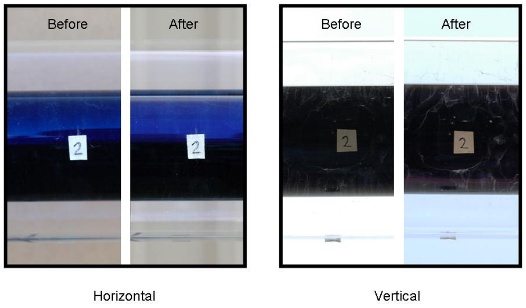
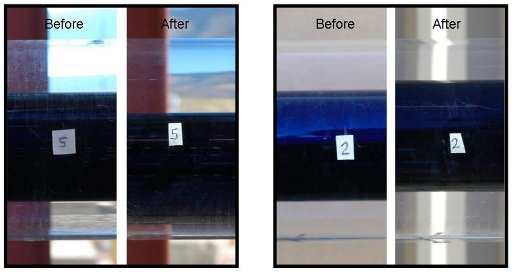


**Figure 7** Photos of the center of the south tube at a temperature of ~300 $^{o}$C before and after 4, partially filled, freeze-thaw cycles

The bent HCE was replaced and the test was performed again. This time no bending was seen after a freeze-thaw cycle with the standpipes full. Further investigation revealed there was a large air bubble in the pipes prior to the start of the test. We again postulated that damage was avoided because the bubble created a free surface for the expanding salt to grow into.



N Tube Horizontal

S Tube Horizontal

**Figure 8** Photos of tube centers after 1st bending event. North tube is bent 14 mm downward. South tube is bent 6.5 mm upward.

A final experiment was performed with a single HCE. After one freeze-thaw cycle we observed approximately 21 mm of downward bending at the center of the tube. The final state of the tube looked similar to that shown on the left side of Figure 8. A second freeze-thaw test was conducted with the same tube. Bending did not significantly increase.

## THEORETICAL ANALYSIS

Cosmos-Works models of the tests were developed to explain the experimental observations. The stainless-steel tubes are assumed to be filled with frozen HITEC-type salt. The boundary between the pipe wall and salt is modeled to be perfect with no slip due to differential shear stress between the salt and steel. Since the thermal expansion coefficient of the solid salt is 3 times higher than steel, differential forces will develop at the interface during heating and cooling events. The contraction of the solid salt, which has a thermal expansion coefficient about three times that of steel, causes the salt to be in tension (the salt is being restrained and pulled by the steel tube). The tensile stress in the salt region of the tube exceeds the tensile strength of the salt (~2 MPa) as shown in Figure 9[2]. The compressive stress in the steel tube is less than it's yield strength. Therefore, the model predicts that the salt will crack before the tube plastically deforms.

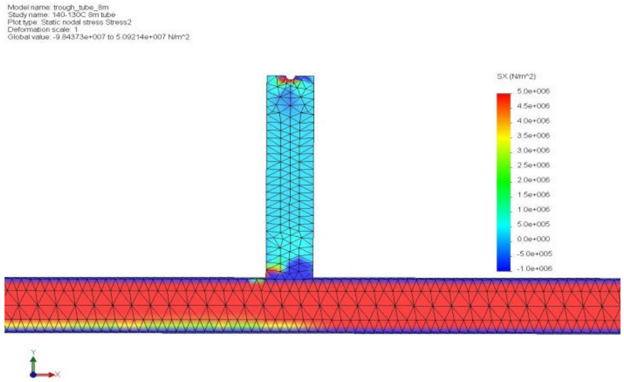


**Figure 9** Stress distribution normal to the x-direction in the pipe and salt in the vicinity of the center support after 10 °C cooling.

The exact cause of the deformation (freeze vs. thaw) is unknown, but results of the simulations indicate that the following mechanisms may have caused the bending of the tubes:

- Without impedance heating, the salt in the tube begins to freeze when the ambient temperatures dropped below 145 °C. Freezing would begin near the walls and eventually reach the center of the pipe as the latent heat of the salt is extracted.
- Within 10 °C of cooling, the tensile stress in the frozen salt would exceed its tensile strength, causing it to crack. Cracking may occur radially along the axis of the pipe, and/or it may occur axially near the walls as the frozen salt tries to pull away from the wall as it contracts.
- Molten salt within the center of the pipe will freeze last and may fill the cracks while it is still liquid. This infusion of salt could freeze along the walls at a wall temperature that is less than the freezing point of the salt. Therefore, the zero-stress temperature of the frozen salt could be less than 140 °C. Heating the frozen salt could then cause expansion over a temperature range spanning the zero-stress state and the melting point. In this study, a range of 60 °C (80 – 140 °C) was found to be sufficient to bend the tube. Tube bending is simulated in Figure 10.
- The nature of the salt freeze and its subsequent attachment to the tube wall can lead to bending. For example, when the salt freezes it undergoes a 5% volume reduction relative to its liquid state. This phenomena would likely cause voids along the top side of the tube wall (due to gravity). Since the frozen salt has better contact with the bottom side of the tube, the tube bottom would experience higher tensile forces than the top upon reheat of the frozen salt. The mismatch in forces would cause the tube to bend downward, as observed for the single HCE test case.

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[2] We assume the tensile strength of HITEC salt should be similar to published literature on other salts. We will measure the actual tensile strength of HITEC in the future.

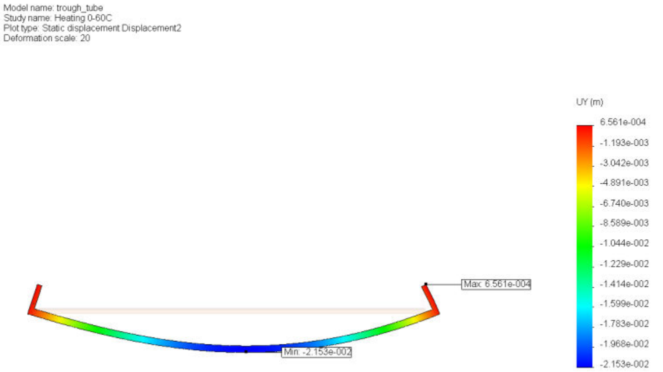

**Figure 10** Cosmos-Works model of tube bending

## CONCLUSIONS

The main conclusions of the testing and analysis completed thus far are the following:

1. Impedance heating is a straight-forward method of preheating HCEs prior to filling with salt and can also be used to thaw frozen salt.

2. It is very important to match salt and tube temperatures prior to filling with salt. Carelessness could result in rapid tube bending and permanent damage to the HCE.

3. If an HCE is not completely filled with frozen salt, permanent tube bending is unlikely during the thaw.

4. When salt cools down from a high-temperature molten state and then freezes, there is significant volumetric shrinkage. Thus, because of the long length of the SCA in a commercial field (typically 150 m long), the flex hoses would likely be empty after SCA freezeup and the HCEs in the SCA could be expected to be partially full. Thawing HCEs that are partially full are not expected to lead to tube damage based on our test results.

5. Cosmos-Works analysis suggests that plastic strain of tube metal could occur during thaw, but not during the freeze. During cool down following the freeze, stress will be relieved because salt will crack due to tensile failure. During heat up prior to thaw, salt will be in compression and will not fail. This leads to very high stresses within tube.

6. After the tube plastically deforms the first time, additional significant deformation do not appear to occur after additional freeze/thaws. We believe this is due to work-hardening of the steel during the plastic deformation.

## FUTURE WORK

A new series of tests will be performed. The test rig will be improved to more closely mimic the dimensions of the HCE supports used in commercial trough plants. Special HCEs with removable glass envelopes and a vacuum-pump system will be used. This will allow the installation of strain gauges, thermocouples, and other instruments on the surface of the tubes inside the evacuated annulus. These special HCEs will be provided to Sandia by a commercial HCE supplier and we will work with the supplier to define future tests.

We will continue to improve our Cosmos-Works models to gain a better understanding of the conditions that lead to tube bending. The analysis requires salt-parameter data that are currently unknown, e.g., solid-salt tensile strength and wall-adhesion strength. We will perform lab tests to measure these properties; this should greatly improve our models.

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