Modeling of Stress Distribution in Molten Salt Thermal Energy Storage Tanks for In-Service Central Receiver Power Plants

Julian D. Osorio
Julian.Osorio@NREL.gov

5th Thermal-Mechanical-Chemical Energy Storage Workshop

August 2, 2023
# Project Information

## Failure Analysis for Molten Salt Thermal Energy Tanks for In-Service CSP Plants

<table>
<thead>
<tr>
<th>Funding/Award#</th>
<th>U.S. Department of Energy Solar Energy Technologies Office / CSP Agreement # 38475</th>
</tr>
</thead>
</table>
| Principal Investigator | Julian D. Osorio  
Center for Energy Conversion & Storage Systems,  
National Renewable Energy Laboratory,  
15013 Denver W Pkwy, Golden, CO USA  
Email: julian.osorio@nrel.gov  
Phone: +1 303 384 6996 |

---

## Partners:

### Lead Organization
Julian D. Osorio, Mark Mehos, 
Janna Martinek, Bill Hamilton

### Solar Dynamics LLC: Luca Imponenti, Bruce Kelly, Hank Price

### Colorado School of Mines: Zhenzhen Yu, Chen Ni

### Ingeniería Térmica Ltda: Alejandro Rivera-Alvarez, Jose Torres César Nieto.
In-Service Central Receiver CSP Plants

Overview

Failure mechanisms in current concentrating solar power (CSP) hot tanks are associated with variable stress distribution and shared loads between the tank shell and the foundation during transient operation.

Operating temperatures
565°C (530°C–550°C)

Working fluid receiver/storage
Molten salt (nitrates)

Thermal energy storage
2 tanks (cold and hot)

Storage capacity with molten salts
6 to 17.5 hours

Power cycle
Steam Rankine

Back-up fuel (when needed)
Natural gas

Cooling type
Dry (air), wet

Crescent Dunes CSP Plant in Nevada. Photo from SolarReserve
2-Tank Molten Salt TES

Cold tank: carbon steel, 290°C.

Hot tank: 347H stainless steels, 565°C.

- Increase in capacity factors
- Commercial GWh energy storage at 10+ h duration
- Low capex
- Existing industry for valves and pumps
- Well-understood heat transfer properties
- Levelized cost of Electricity
- Lower intermittent operation for the power cycle
Hot TES Tank

• Salt is typically introduced into the tank by means of a circular distribution header near the bottom of the tank.

• Eductors distributed along the header are often used to promote mixing between the incoming flow and the main inventory.

• There is no design code for molten-salt tanks. *American Petroleum Institute* API 650 and ASME BPVC Section II standards are used as guidelines for tank design.

• API 650 is limited to 260°C.

Multiple failures have been reported in molten salt tanks in CSP plants around the world.

Hypothesis Failure Mechanism in Hot Tanks

Foundation - Sand, firebrick, cellular glass, and concrete

Cross-section of the hot-tank foundation at Solar Two

- Transient operation conditions
- Temperature difference between the salt entering the tank & the bulk inventory
- Local temporary temperature gradients within the inventory, tank’s wall and floor
- Nonuniform thermal expansion
- High local transient stresses in the tank and foundation
- Low-cycle fatigue damage

We are investigating a fundamental challenge facing large, 565°C molten salt TES tanks. We will develop a modeling tool to evaluate low-cycle thermal fatigue (LCTF), stress distribution, and lifetime as a function of plant operation conditions.

**Summary**

- General modeling framework
  - Assess LCTF and stress distribution
    - Identify regions susceptible to failure
- Specific design and operation conditions
- New tank designs
- Operation and maintenance

Provide guidance
Representative Tank Design

Dimensions are representative several existing hot tank designs.
Representative Tank Design

3D solid representation of the hot tank in Solid Edge

Mesh representation of solid bodies in ANSYS

Mesh representation of the fluid body in ANSYS
Typical Plant Operation Conditions

Clear sky day

Partly-cloud sky day

The model allows the analysis of different plant operation profiles
The tank floor is a critical component due to the combination of high friction loads and thermal transients.

The non-flat characteristics result in a non-uniform distribution of friction forces between floor and foundation.

The tank floor is manufactured from several thin rectangular plates that are welded together, which results in plastic deformations and residual stresses.

Single plate: 32’ x 8’

Minimum mesh size: 8 x 20 mm

126,423 elements

Symmetry plane
Tank Floor Fabrication Modeling

Symmetry plane

Welding direction

Short-edge welds

Long-edge welds

U1=0
U3=0
UR1=0
UR2=0

U1=0
U2=0
U3=0
UR1=0
UR2=0
UR3=0

X
Y

NREL
Von Mises stress contour after completion of all the welds.
Tank Floor Deformation

Normal displacement contour

Deformation scale factor of 1

Deformation scale factor of 10
The hot tank model has been validated. It incorporates computational fluid dynamics (CFD) models for the sparger ring and molten salt and a mechanical model for the tank shell and floor.
Stress Distribution in the Tank Floor and Shell

Flat floor conditions (no distortion or residual stress)

- 177.0 MPa
- 2.3 MPa
- 25 MPa
- 0 MPa

35 mins of operation

Inlet Temperature (°C)

Time (seconds)

35 mins
Stress Distribution in the Tank Floor and Shell

Half tank design implemented in ANSYS

Flat floor conditions (no distortion or residual stress)

Stress evolution in the tank floor.
Node 4. Friction coefficient = 0.4

Inlet Temperature (°C)

Time (seconds)

Stress Floor - Temperature @ Case 2 - Node 4 - SR - Friction Coefficient 0.4

Temperature (°C)

Time [h]
Stress Distribution in the Tank Floor

60 mins

90 mins

118 mins

F: Transient Structural
Equivalent Stress Floor
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 3600 s
Max: 217.1
Min: 12.5

Tdc (°C)

Time (mins)

0 100 200 300 400 500 600 700

0 50 100 150
SRC is a failure mechanism associated with the relief of high residual stress during high-temp operation, leading to cracking.

Niobium improves 347H resistance to stress corrosion cracking compared with 304H and 316H, but also increases its susceptibility to SRC.

C. Augustine, Z. Yu, T. Pickle, J. Vidal. Project agreement 33458 – “Stress relaxation cracking (SRC) of alloys at temperatures higher than 540°C.”

Stress as a Function of Thickness/Joint

Weld joints > 0.5” thick are most susceptible to SRC, and J-groove is best for overall least residual stress in plates greater than 0.5” thick.


C. Augustine, Z. Yu, T. Pickle, J. Vidal. Project agreement 33458 – “Stress relaxation cracking (SRC) of alloys at temperatures higher than 540°C.”
Conclusions

- Addressing failures in molten salt TES tanks is fundamental for the CSP industry’s survivability, but it is also important for other industrial applications using this technology (nuclear, concentrating solar thermal).

- Current failures in hot tanks are strongly influenced by their design, fabrication procedures, material characteristics, and challenging operating conditions.

- NREL will continue to explore mitigation alternatives for current tanks and conduct research to contribute to a definitive solution for new hot tanks. Some proposed efforts include:
  
  - Improving the design of current tanks.
  - Establishing safe operating conditions.
  - Developing new welding specifications for the shell and floor fabrication.
  - Evaluating the feasibility of post weld heat treatment.
  - Evaluating alternative material alternatives (base metal and welding fillers).

- NREL is willing to collaborate with industry, research centers, and academic institutions to improve reliability of molten salt thermal energy storage technology for CSP and other industrial applications.
Thank you

www.nrel.gov

NREL/PR-5700-87158

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Photo from iStock-627281636