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

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5th Thermal-Mechanical-Chemical Energy Storage Workshop

August 2, 2023

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Project Information

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

Funding/Award#	U.S. Department of Energy Solar Energy Technologies Office / CSP Agreement # 38475
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NREL

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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.

Receiver type

Cylindrical external, cavity

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

Crescent Dunes CSP Plant in Nevada.
Photo from SolarReserve

Power cycle

Steam Rankine

Back-up fuel (when needed)

Natural gas

Cooling type

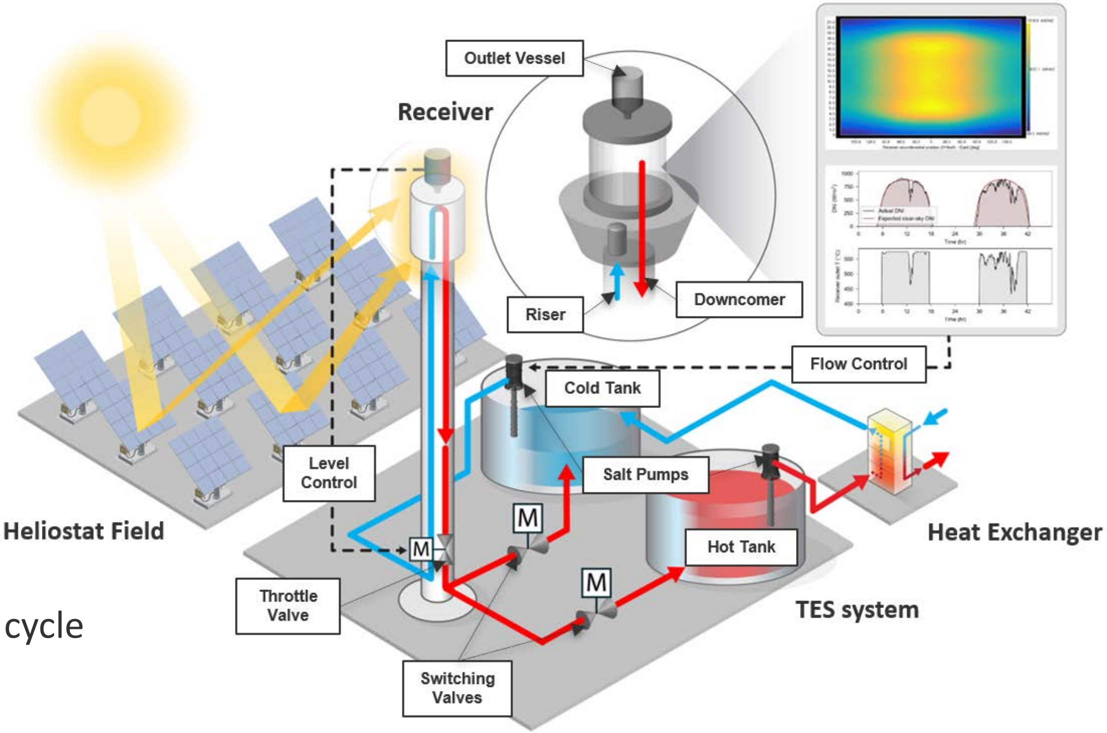
Dry (air), wet

2-Tank Molten Salt TES

Cold tank: carbon steel, 290°C.

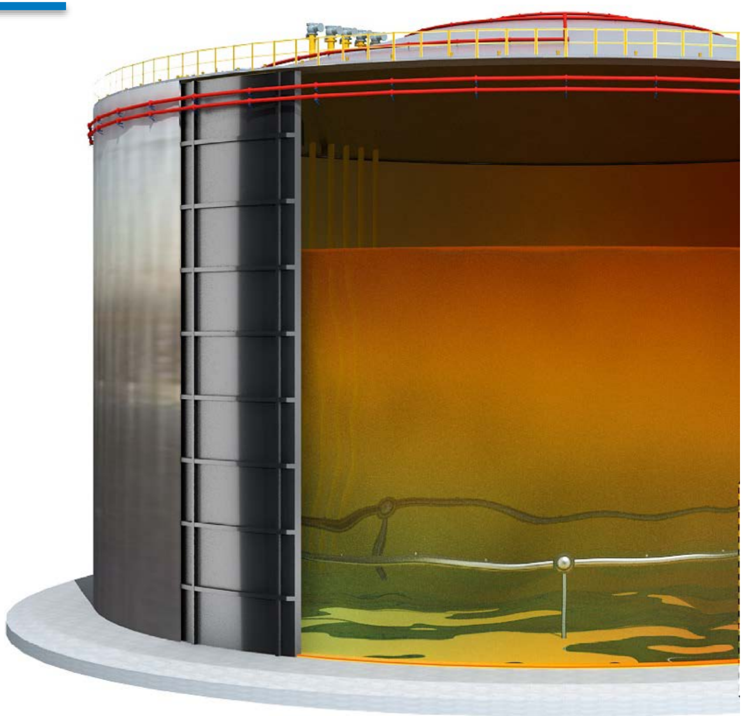
Hot tank: 347H stainless steels, 565°C.

- 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.

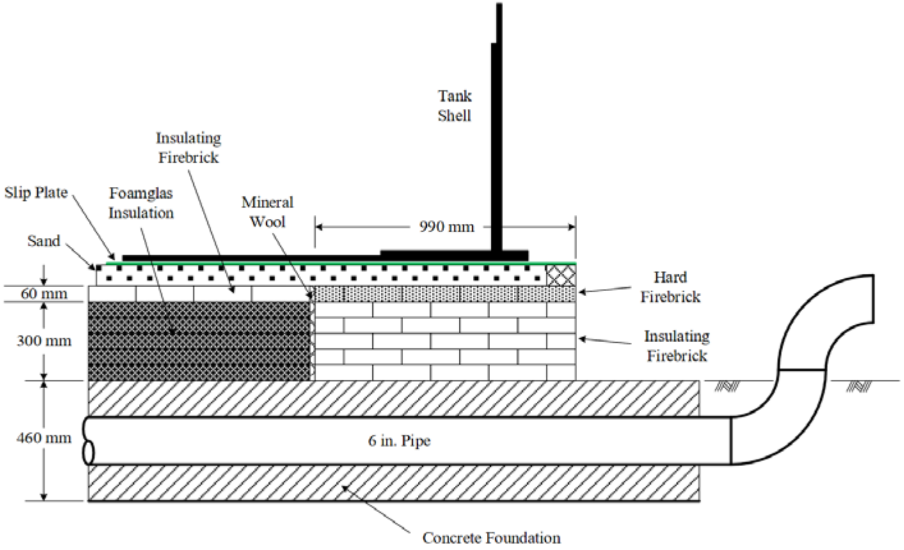


Multiple failures have been reported in molten salt tanks in CSP plants around the world.

[M. Mehos, H. Price, R. Cable, D. Kearney, B. Kelly, G. Kolb, F. Morse. 2020. Concentrating Solar Power Best Practices Study. NREL/TP-5500-75763]

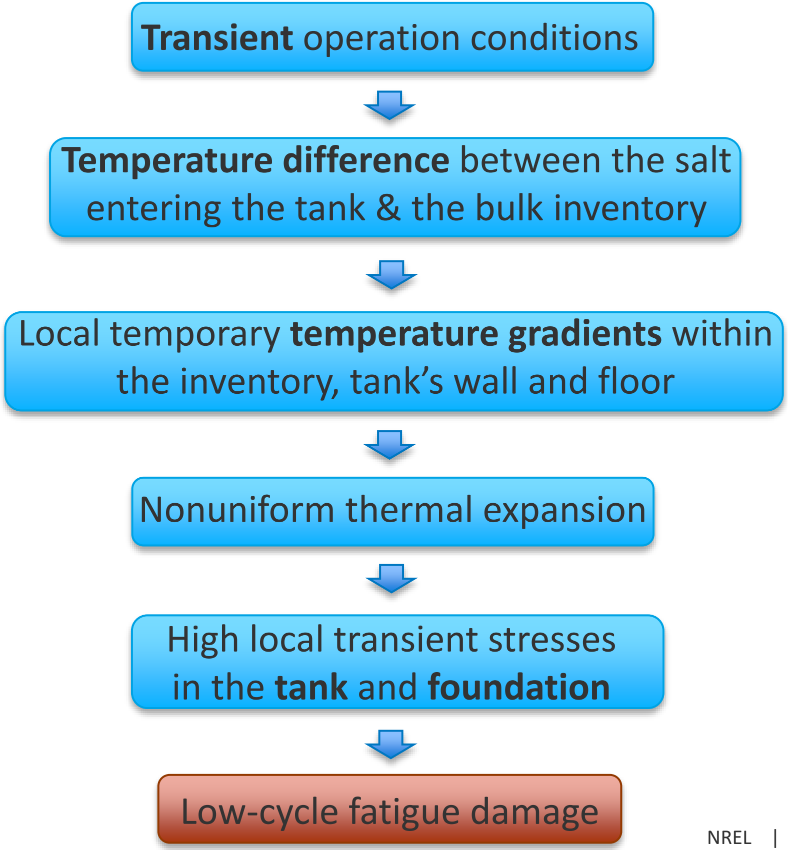
Hypothesis Failure Mechanism in Hot Tanks

Foundation - Sand, firebrick, cellular glass, and concrete



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

[M. Mehos, H. Price, R. Cable, D. Kearney, B. Kelly, G. Kolb, F. Morse. 2020. Concentrating Solar Power Best Practices Study. NREL/TP-5500-75763]



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

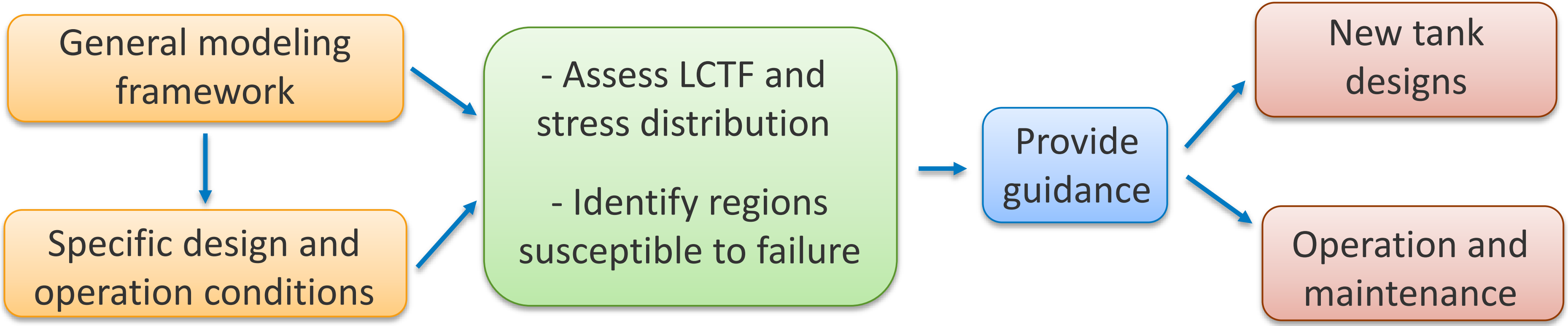
High local transient stresses in the **tank** and **foundation**

Low-cycle fatigue damage

Summary

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.



General modeling framework

Specific design and operation conditions

- Assess LCTF and stress distribution

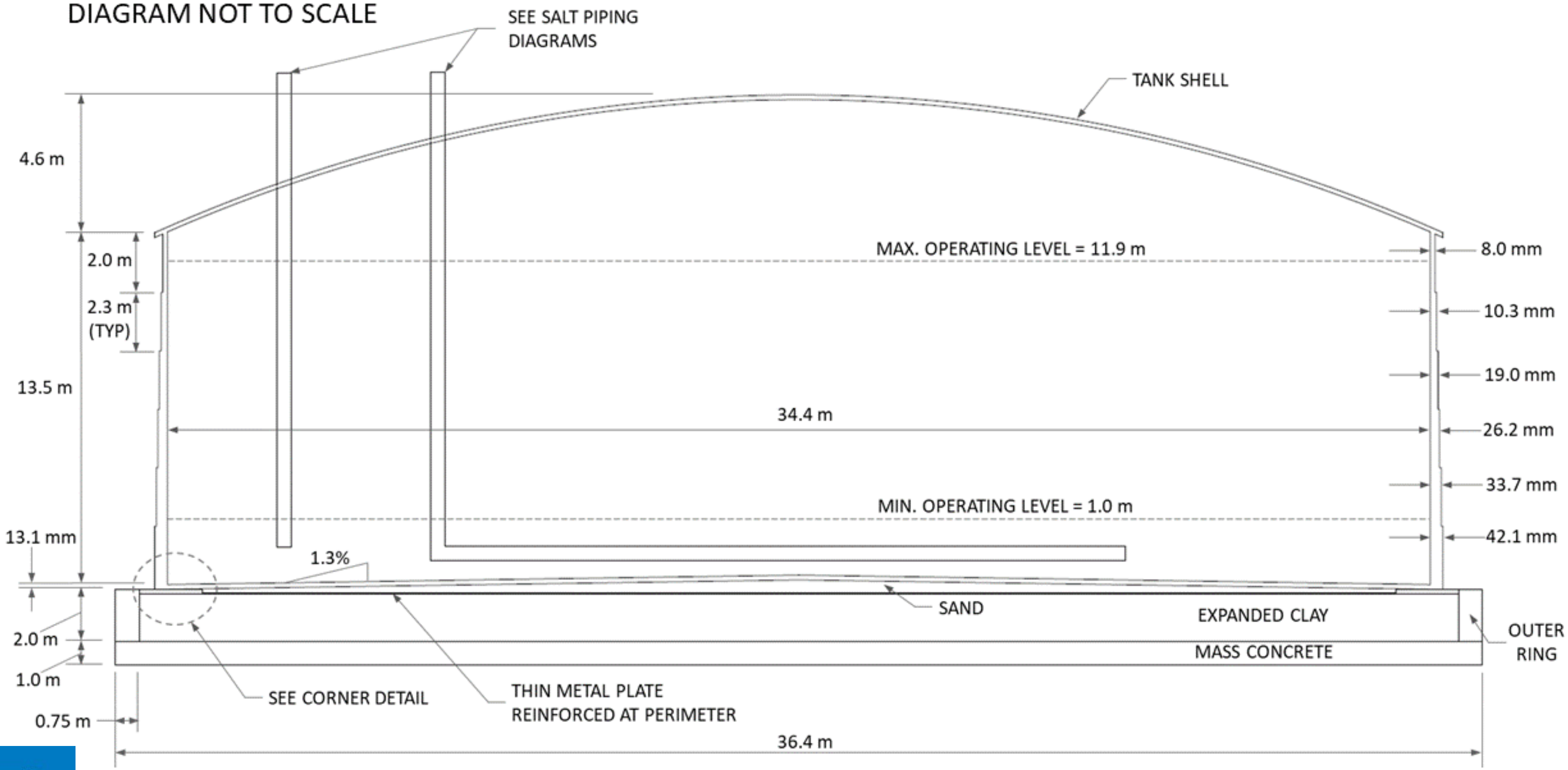
- Identify regions susceptible to failure

Provide guidance

New tank designs

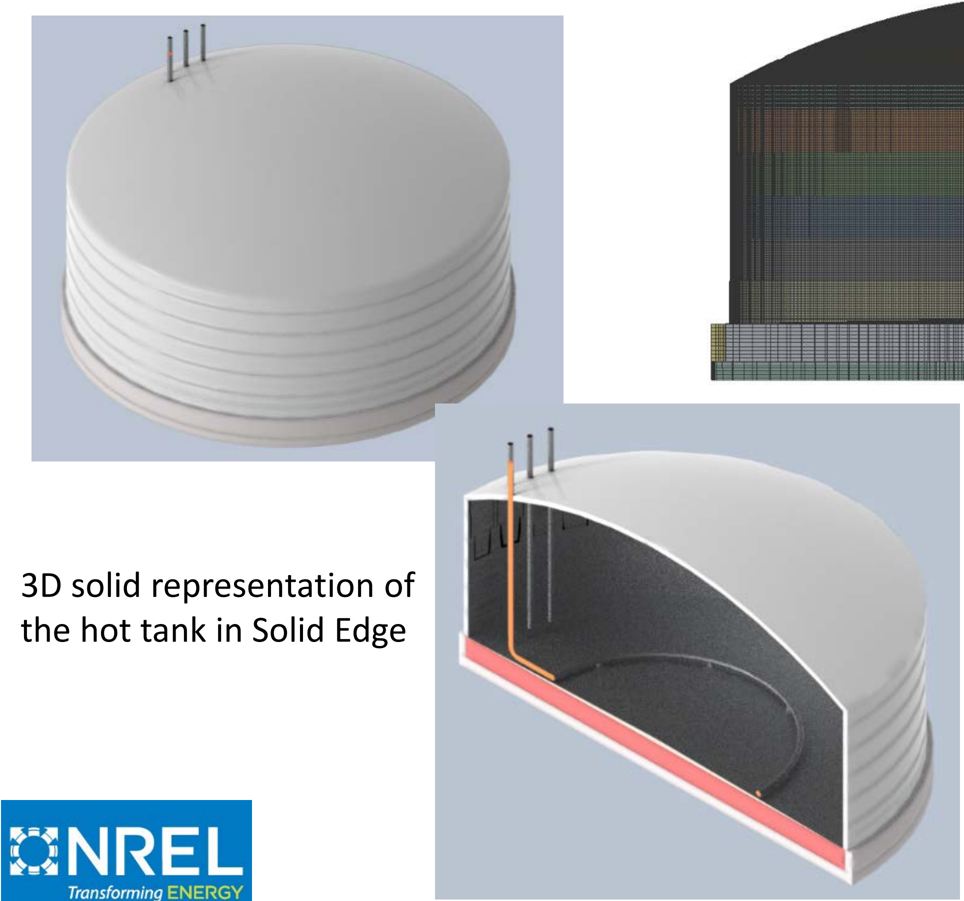
Operation and maintenance

Representative Tank Design

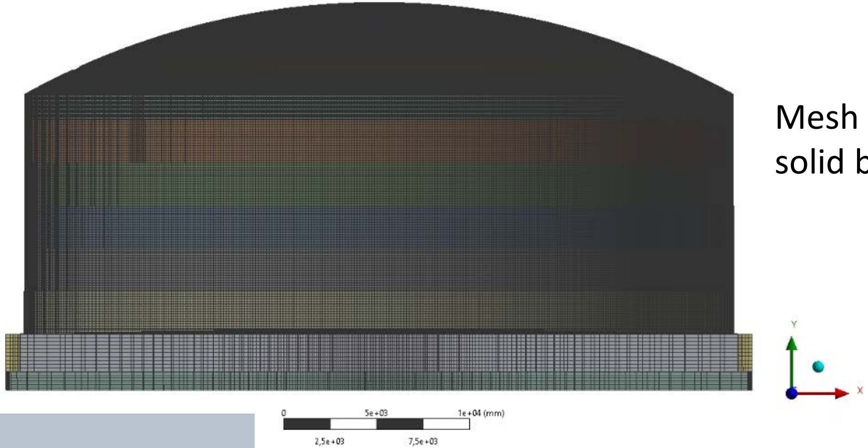


Dimensions are representative several existing hot tank designs

Representative Tank Design

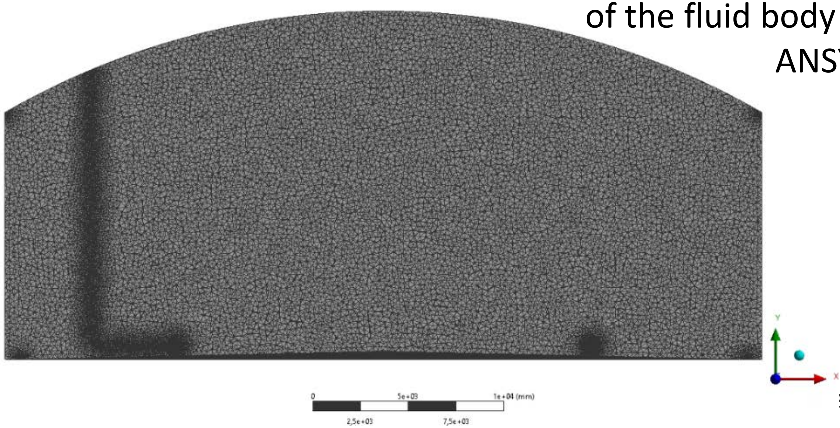


3D solid representation of the hot tank in Solid Edge

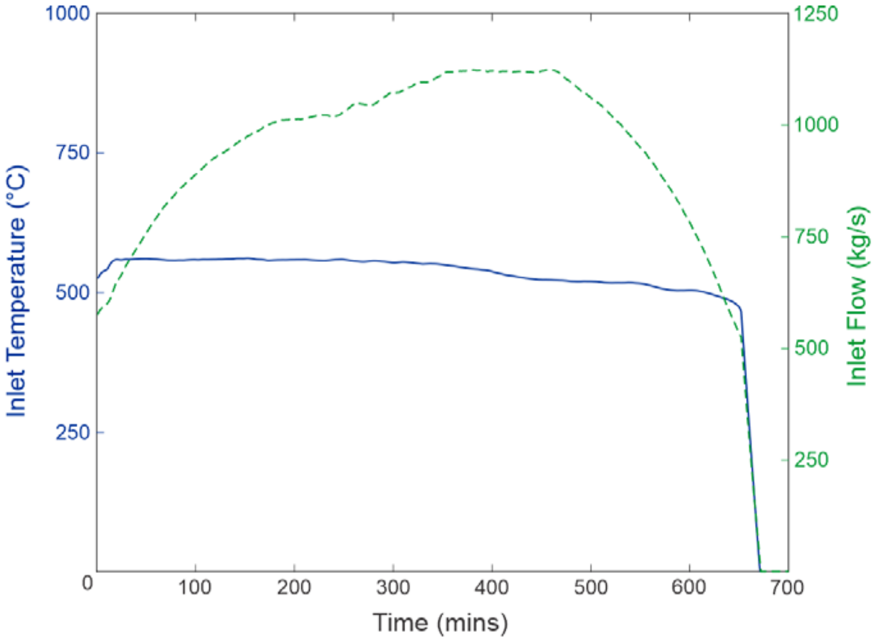


Mesh representation of solid bodies in ANSYS

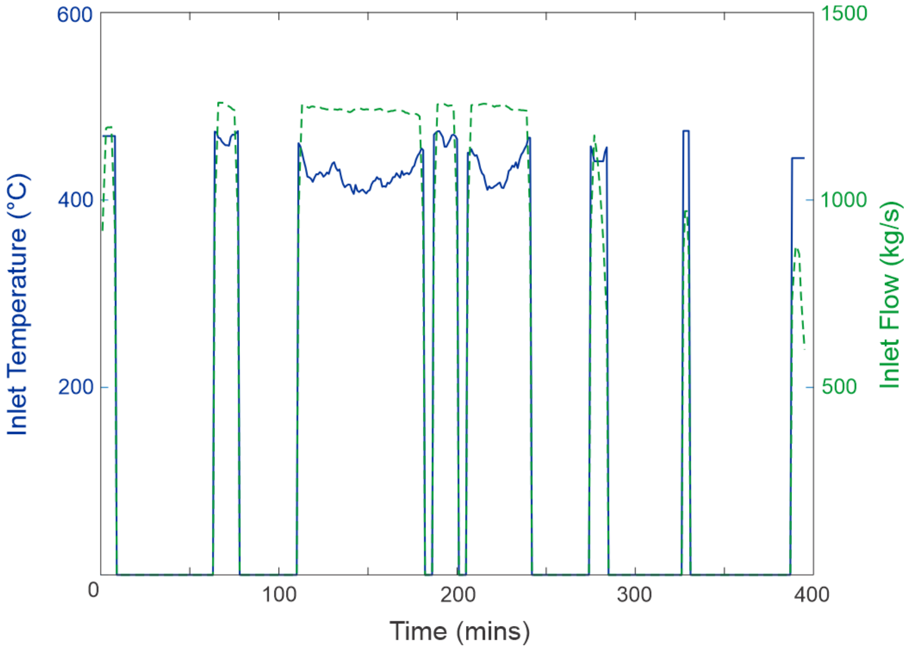
Mesh representation of the fluid body in ANSYS



Typical Plant Operation Conditions



Clear sky day



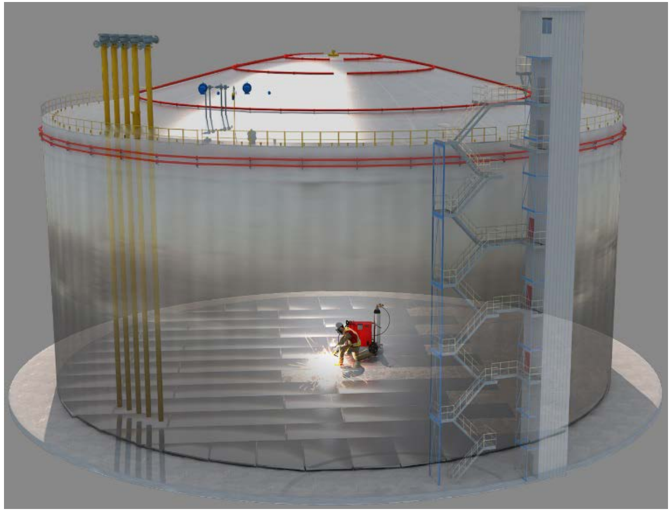
Partly-cloud sky day

The model allows the analysis of different plant operation profiles

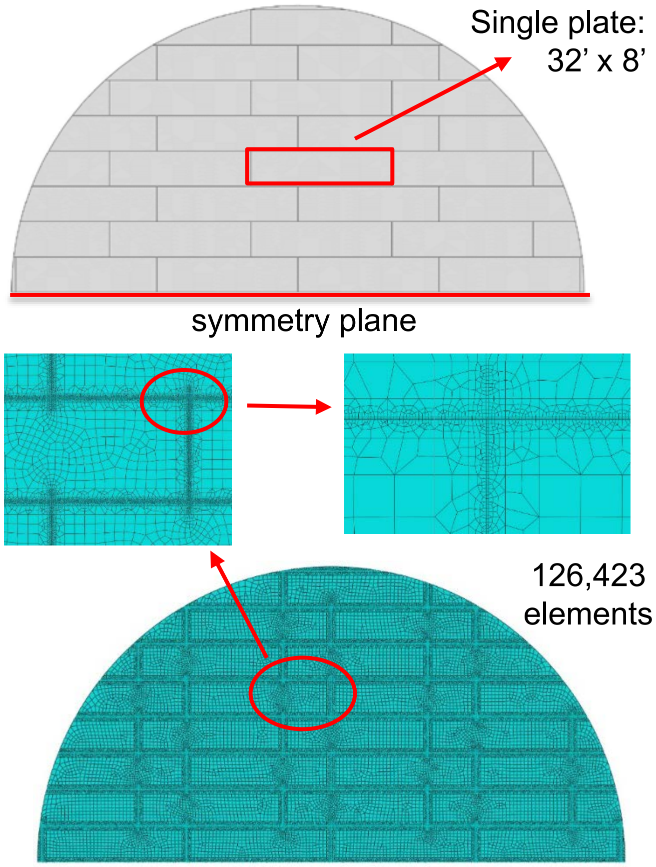
Tank Floor Fabrication Modeling

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

- ✓ 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.



Single plate: 32’ x 8’

symmetry plane

126,423 elements

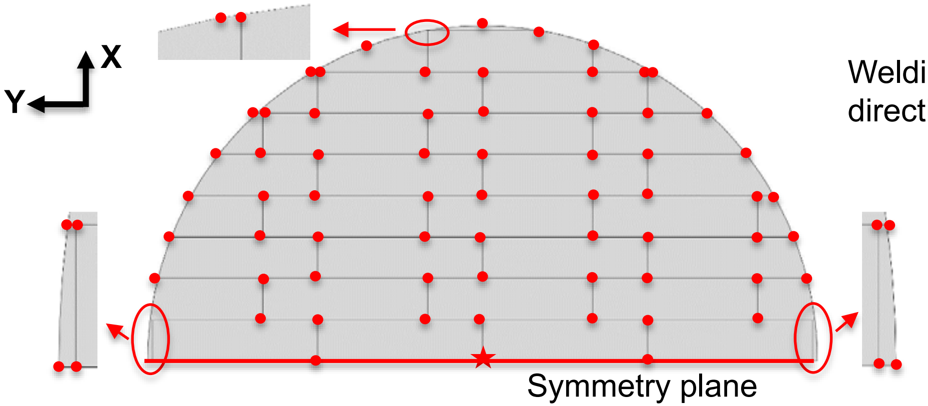
Minimum mesh size: 8 x 20 mm

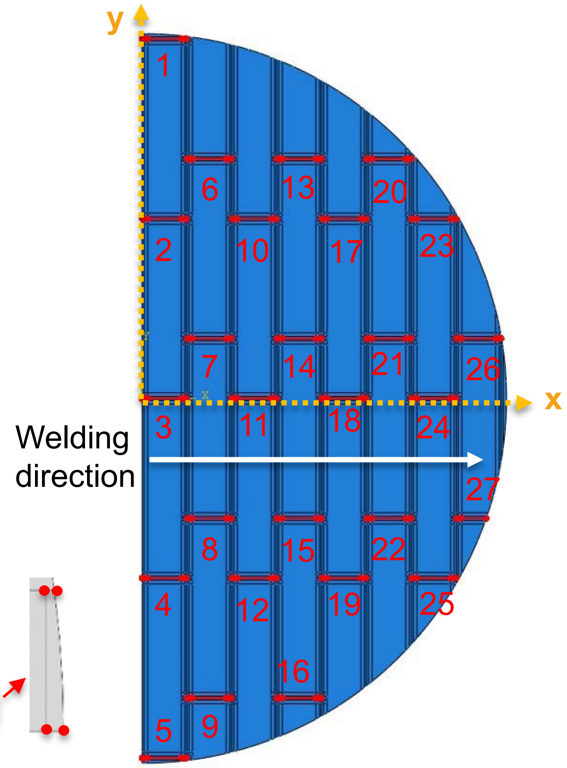
Tank Floor Fabrication Modeling

○ U1=0
U3=0
UR1=0
UR2=0

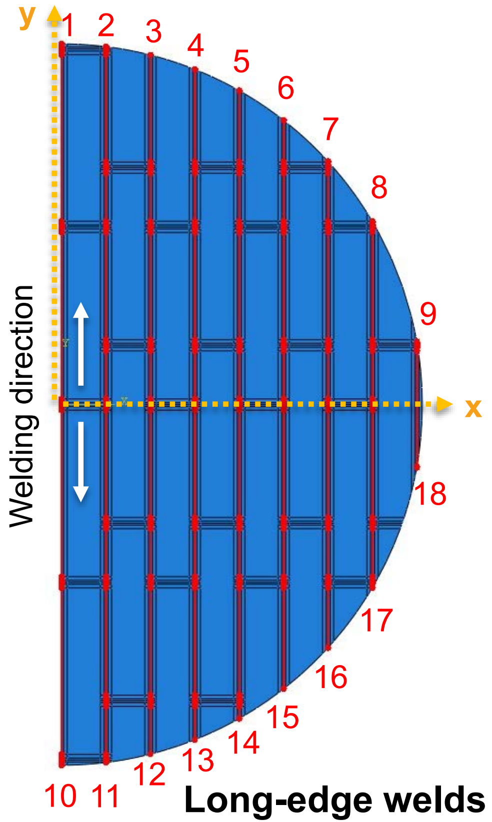
★ U1=0
U2=0
U3=0
UR1=0
UR2=0
UR3=0

● U3=0
UR1=0
UR2=0



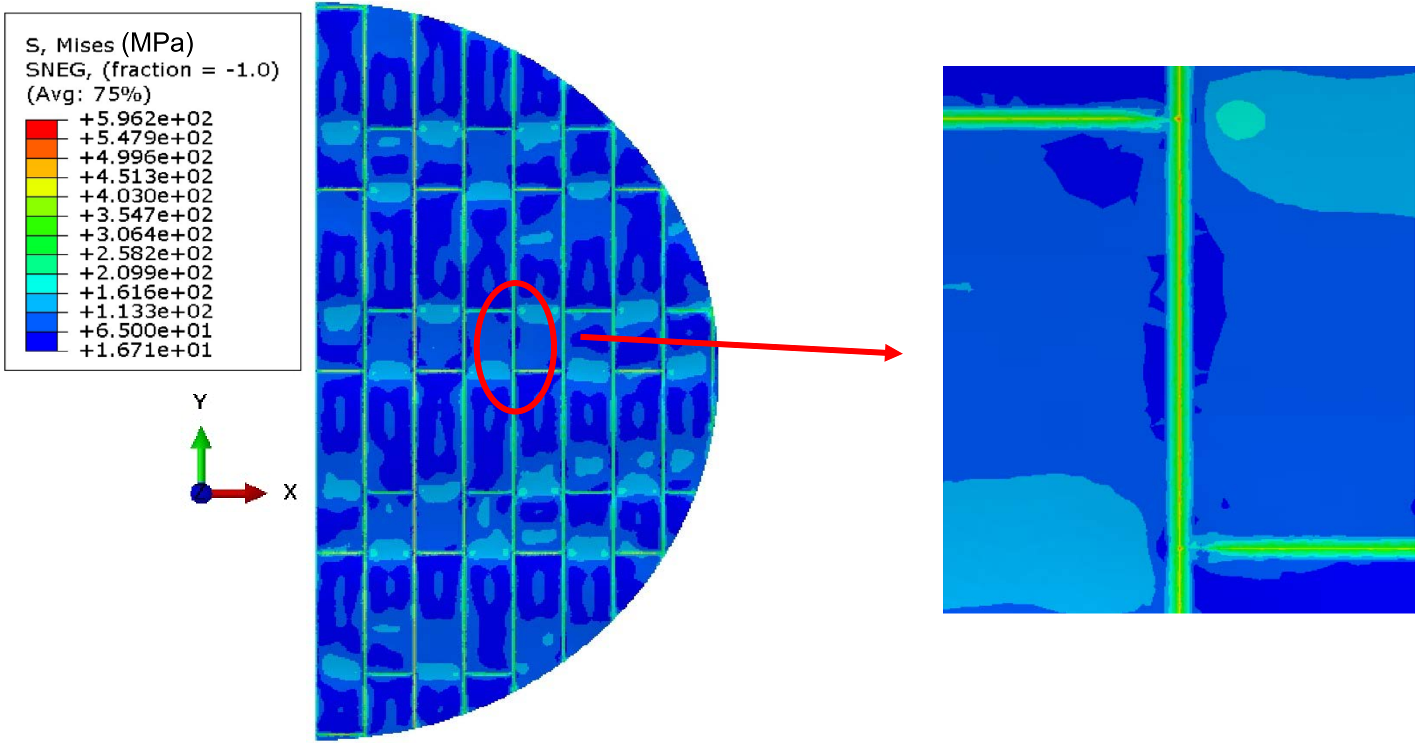


Short-edge welds



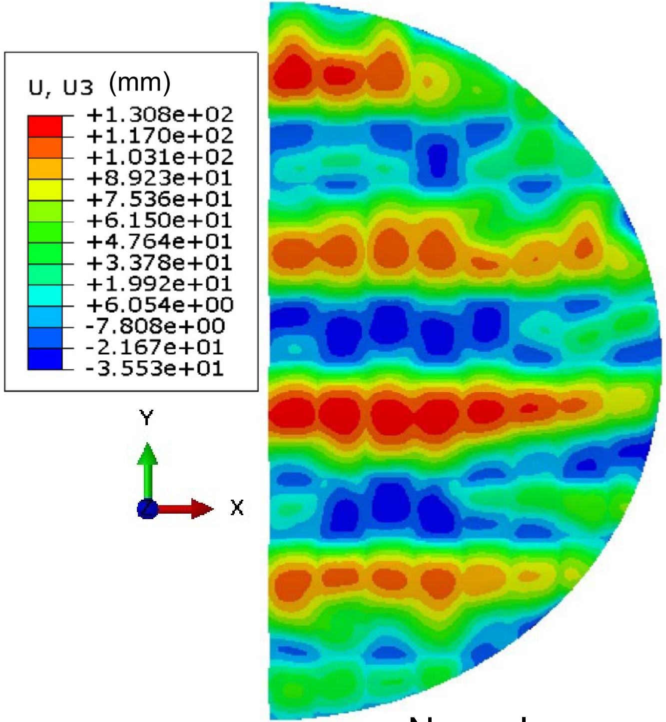
Long-edge welds

Stress Distribution in the Tank Floor

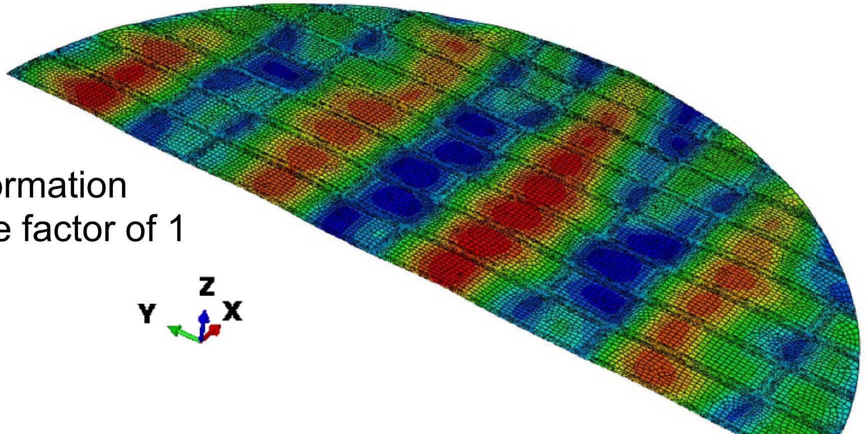


Von Mises stress contour after completion of all the welds.

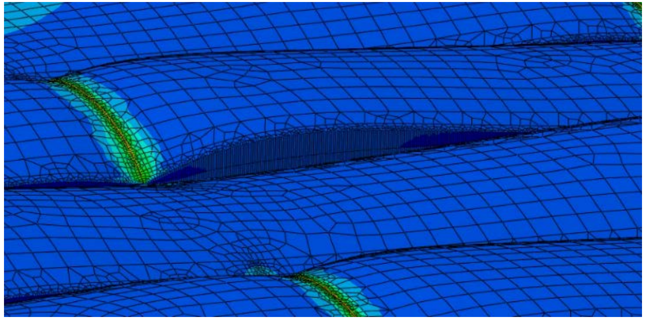
Tank Floor Deformation



Normal displacement contour



Deformation scale factor of 1

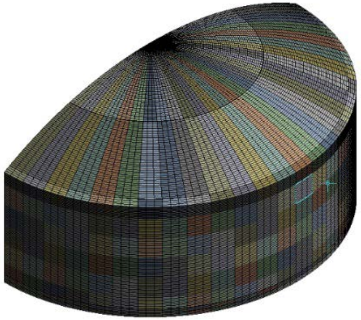


Deformation scale factor of 10

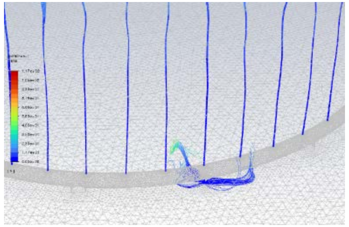
Hot Tank Model

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.

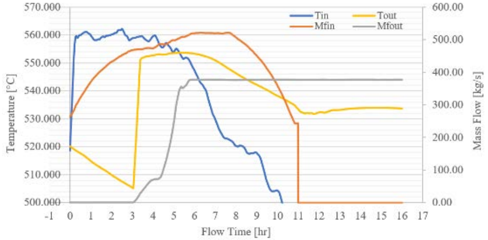
Hot Tank Model (ANSYS)



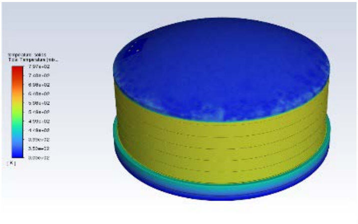
Sparger Ring CFD Model



Plant operation conditions

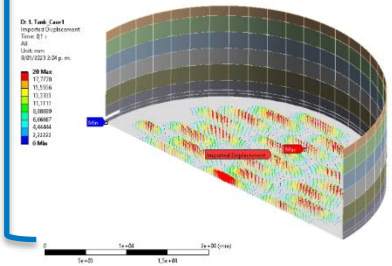


Molten Salt CFD Model

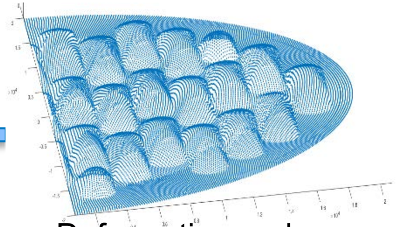


- Thermal gradients
- Stress distribution
- LCTF
- Lifetime prediction

Mechanical Model



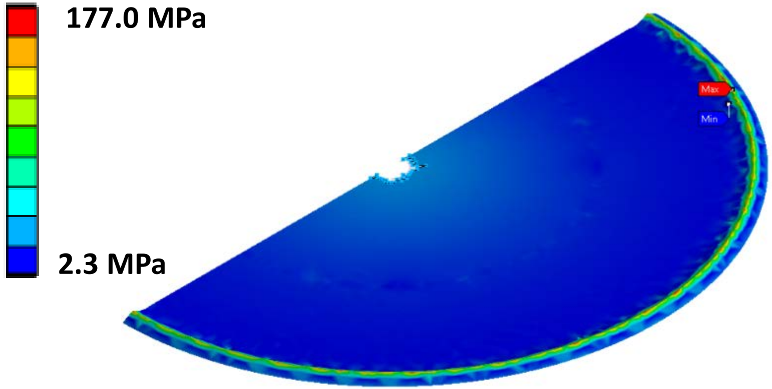
D: 1. Tank_Case1
Imported Displacement
Time: 0,1 s
All
Unit: mm
9/01/2023 2:04 p. m.



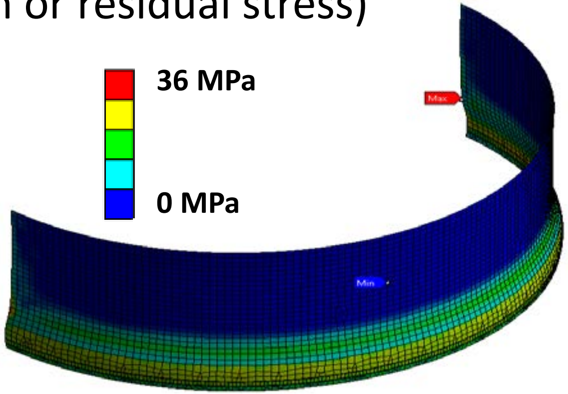
Deformation and residual stress

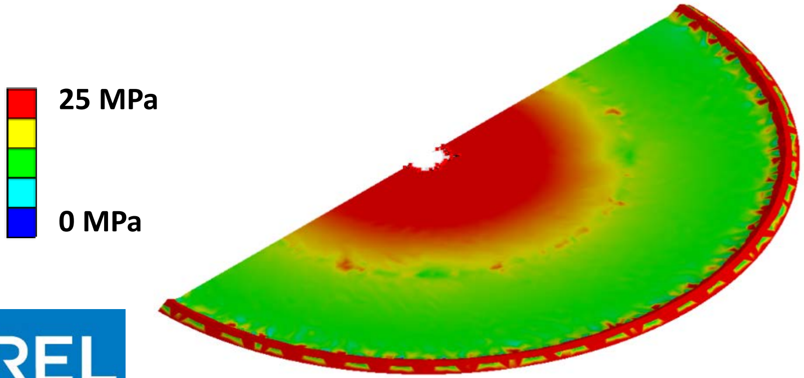
Stress Distribution in the Tank Floor and Shell

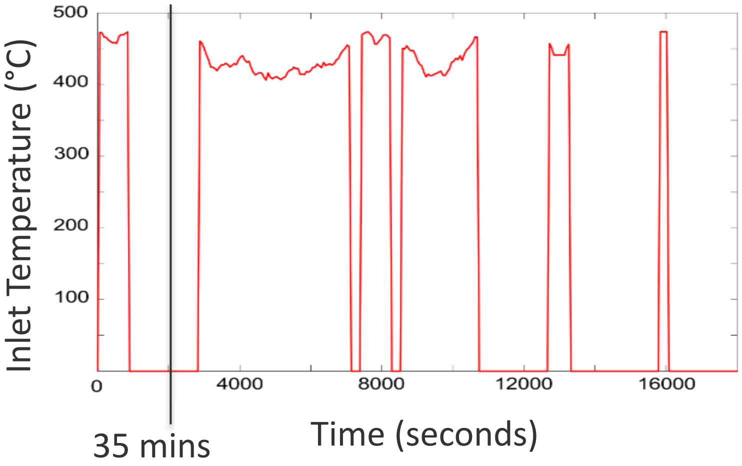
Flat floor conditions (no distortion or residual stress)



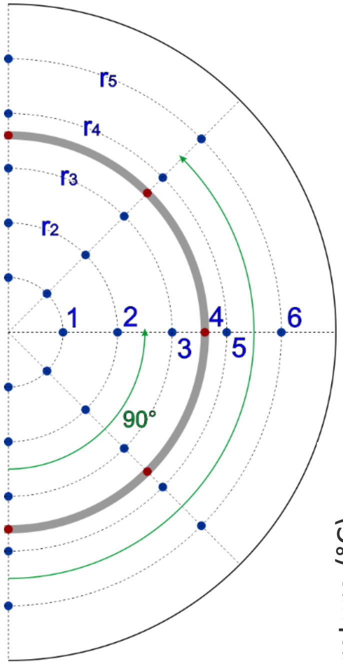
35 mins of operation







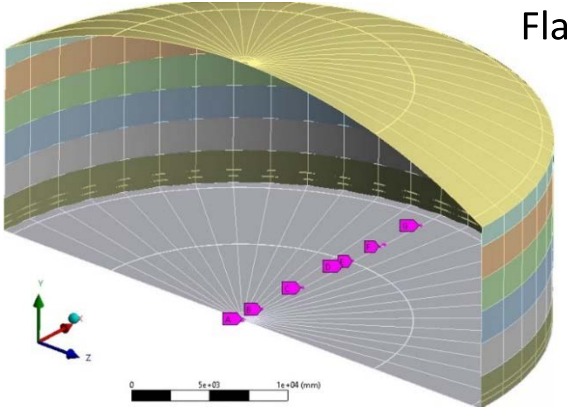
Stress Distribution in the Tank Floor and Shell



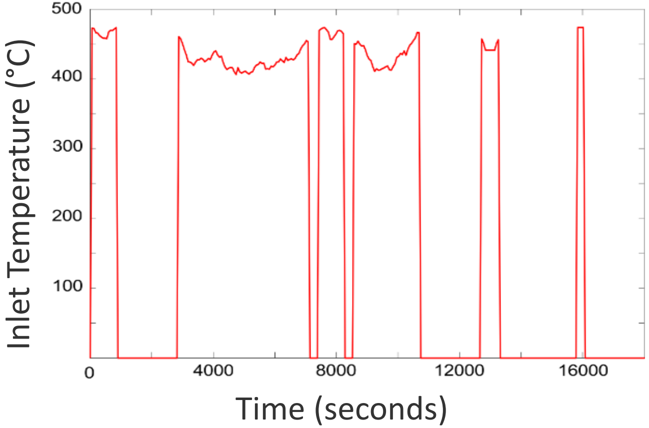
● Temperature monitor

● Temperature monitor under Sparger Ring

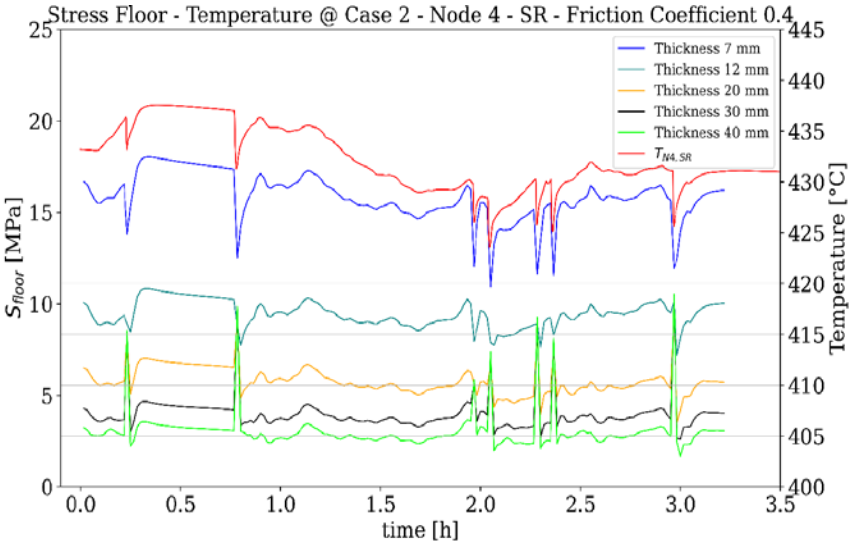
Floor monitors location



Half tank design implemented in ANSYS

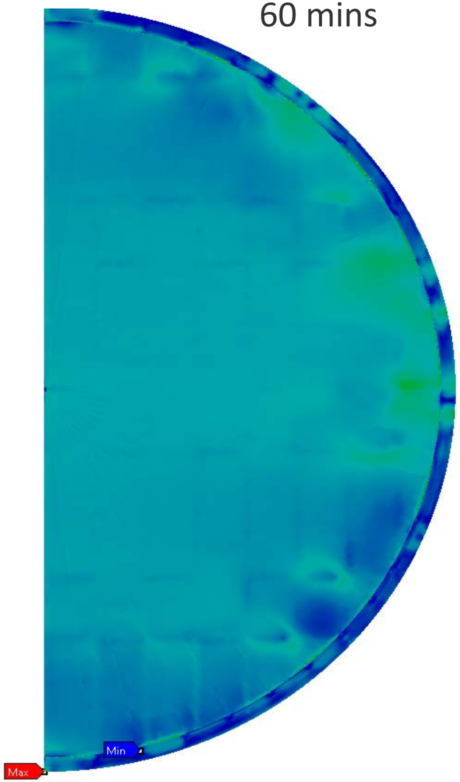


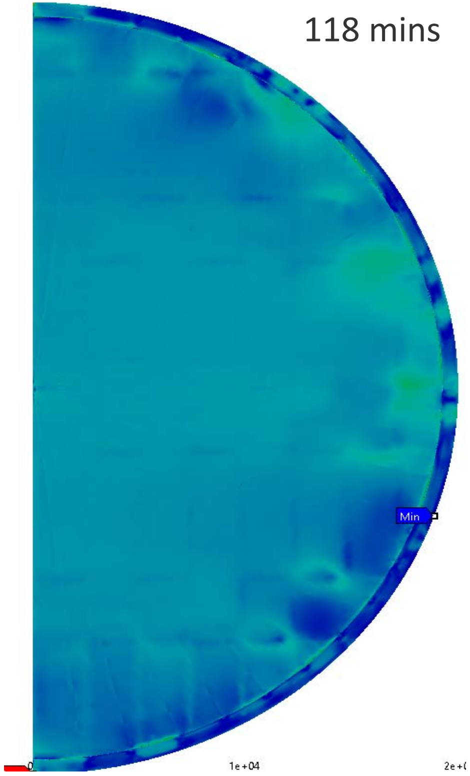
Flat floor conditions (no distortion or residual stress)

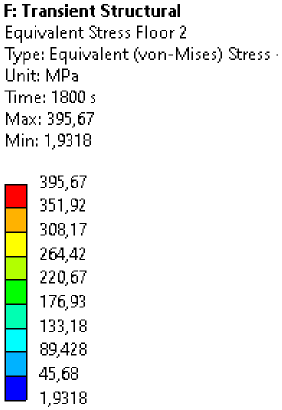


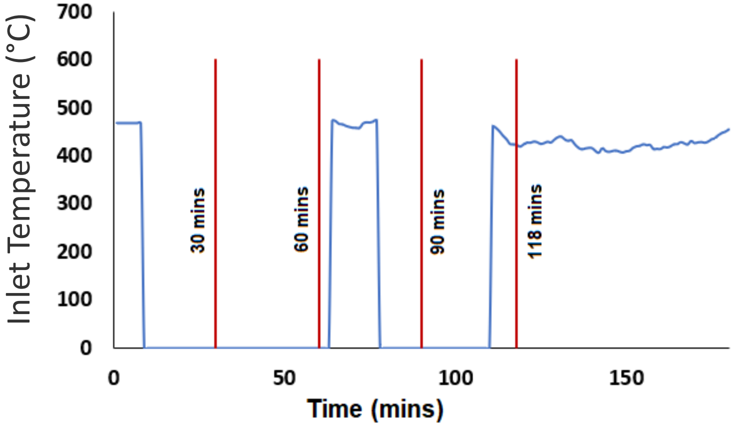
Stress evolution in the tank floor. Node 4. Friction coefficient = 0.4

Stress Distribution in the Tank Floor

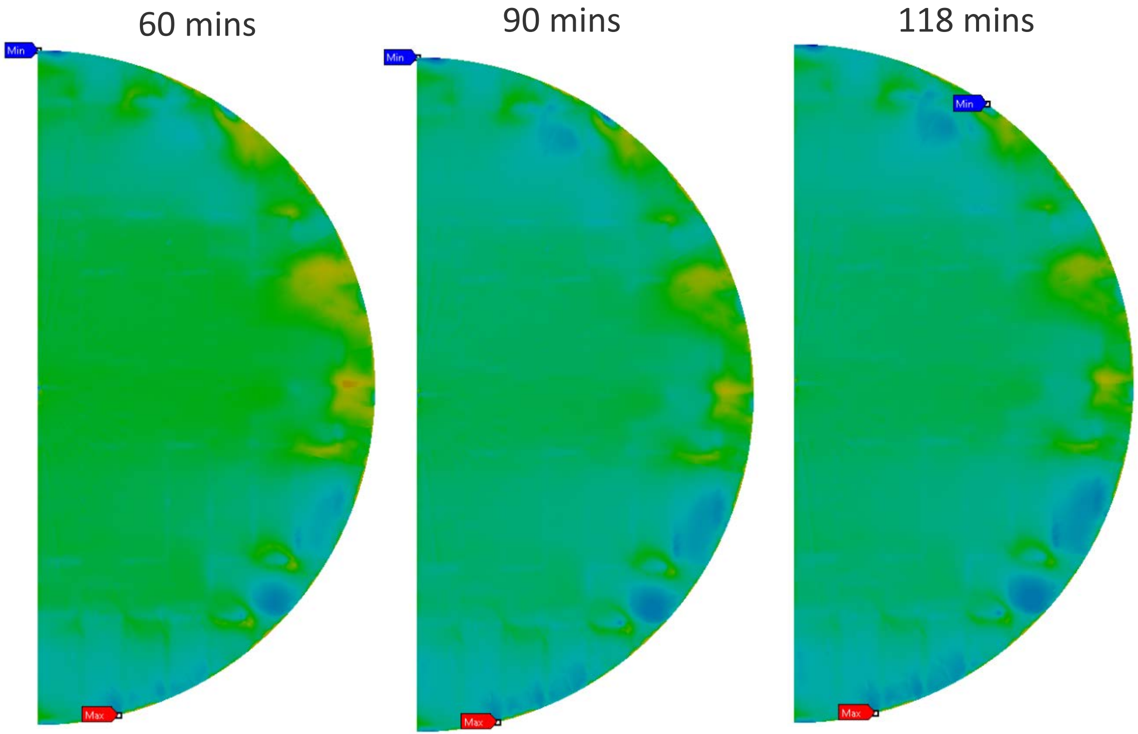

60 mins

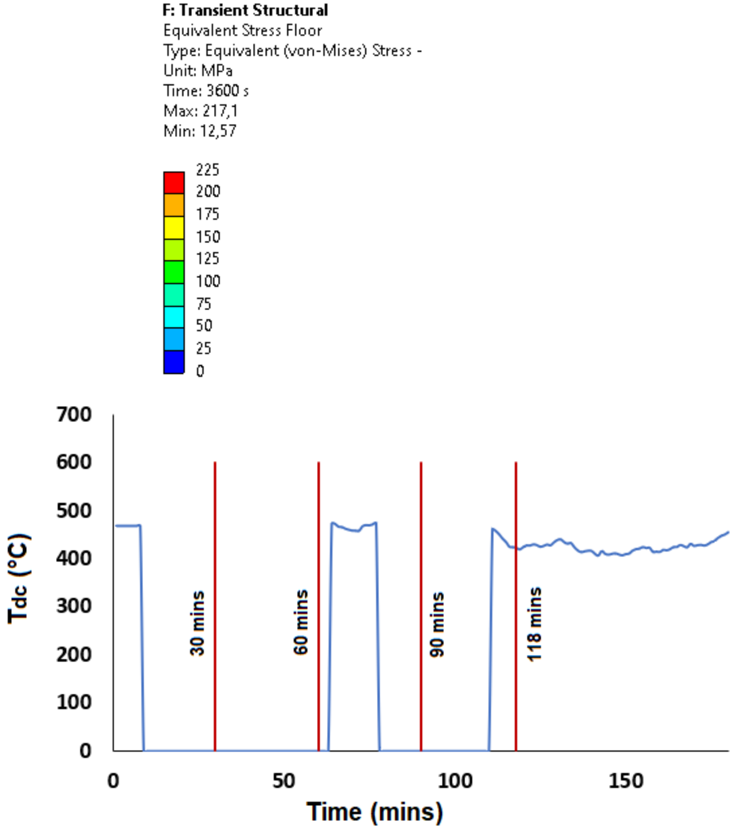

118 mins





Stress Distribution in the Tank Floor



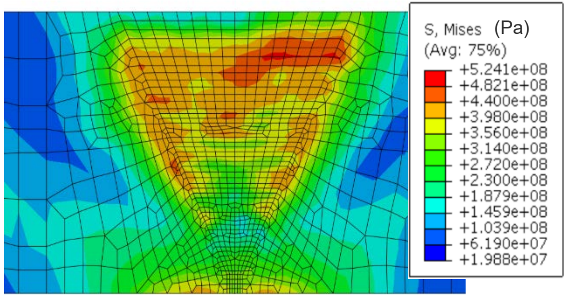

F: Transient Structural
Equivalent Stress Floor
Type: Equivalent (von-Mises) Stress -
Unit: MPa
Time: 3600 s
Max: 217,1
Min: 12,57

Stress Relaxation Cracking (SRC)

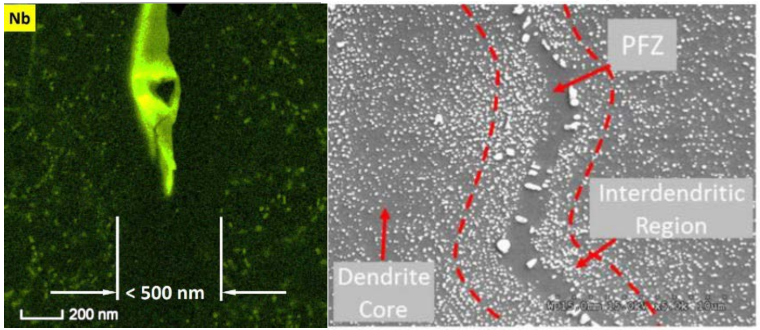
SRC is a failure mechanism associated with the relief of high residual stress during high-temp operation, leading to cracking.

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

Residual Stress/High Restraint

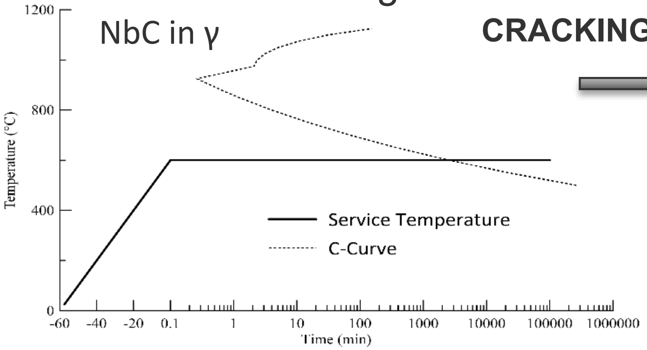


+ Susceptible Microstructures

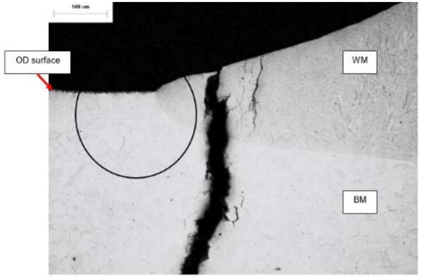


+

Reheating



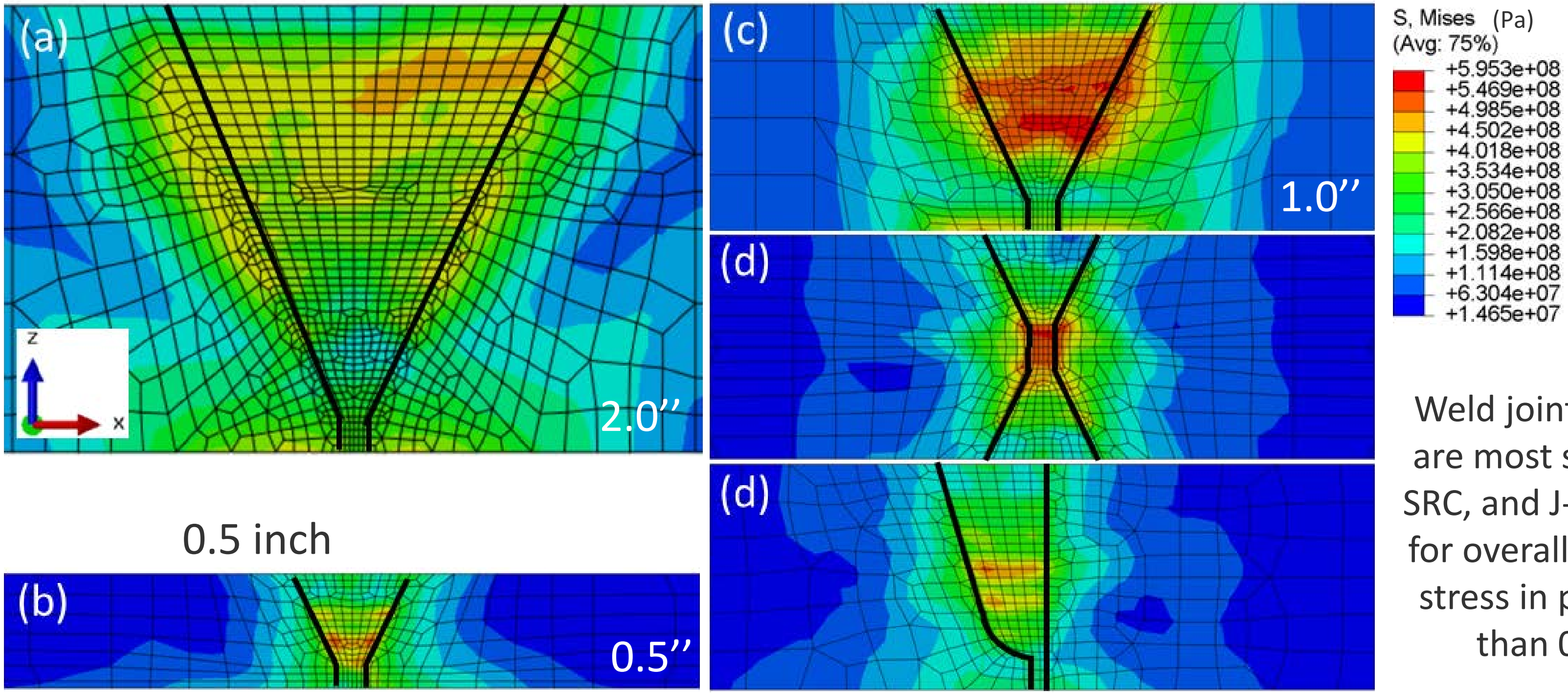
CRACKING!



[1] E. C. B. Dillingh, A; Aulbers, A.P, TNO report, 2016.
[2] J. Siefert, J. Shingledecker, and T. Lolla, *DOE Workshop:* 2021
[3] J. A. Siefert, J. P. Shingledecker, J. N. DuPont, and S. A. David. *STWJ*, vol. 21, pp. 397-428, 2016.
[4] *Xcel Energy Report*

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.

Y. Hong, T. Pickle, J. Vidal, C. Augustine, Z. Yu. “Residual stresses in 347H SS welds” Weld. J, 2023.

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

Failures in hot tanks can be attributed to multiple mechanisms, including low cycle fatigue, stress relaxation cracking, excessive deformation (buckling), and creep.

NREL Transforming ENERGY

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.

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