Heat Transfer and Latent Heat Storage in Inorganic Molten Salts for Concentrating Solar Power Plants

Project Review Slides

May 18, 2011

Department Of Energy
Research and Development
Concept and Component Feasibility Studies
Project Number DE-FG36-08GO18148

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DOE Project Summary

Heat Transfer and Latent Heat Storage in Inorganic Molten Salts for Concentrating Solar Power Plants

Partners

- **Project lead:** Terrafore, inc
- **Team Members**:
  University of California, Riverside (UCR),
  Pratt Whitney Rocketdyne (PWR),
  Jet Propulsion Labs (JPL)
  Consultant: Dr. H. Venkatsetty

Status/ Timeline

Phase 1 Kick-off date: March 2009

Phase 1 Complete: January 2010

Phase 2 Kick-off date: April 2010

Phase 2 Expect to complete: Aug 2011

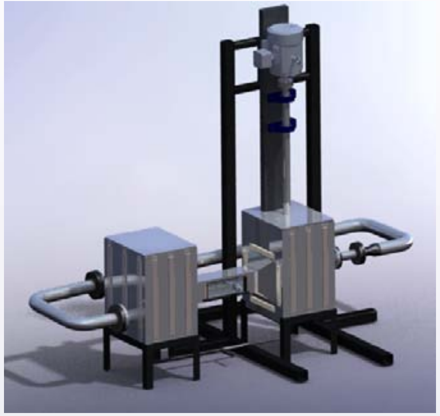
Objective / Barriers Addressed

- Select an economical and efficient media for various CSP systems (salt melting temperatures 275C to 375C and operating temperatures to 550 C)
- Design an efficient and economical heat exchanger to extract heat when storage media solidifies.
  - Identify additives and coatings to improve efficiency of heat exchange
  - Conduct tests with a laboratory scale system
- Develop analytical model for tank and heat exchanger

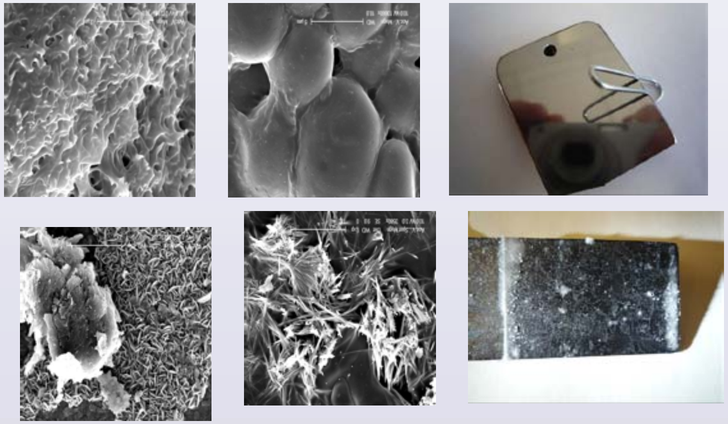
Phase 1 Summary

Phase 1 Accomplishments

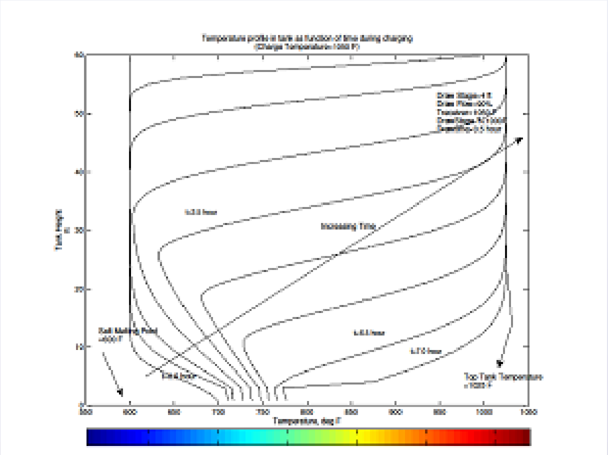
- *Selected four salt mixtures for CSP systems*
- *Identified thirteen different coatings and selected two coatings for heat exchanger tubes*
- *Integrated TES model with power tower simulation*
- *Tested coatings in a benchtop system*



Single tube bench top test rig



Qualitative dip tests with coatings



Charge & controller model for PCM tank

Summary Phase 2 Program Plan

Phase 2 Tasks

Task 2.1. Provide Detailed Design of a Laboratory Prototype (100%)

Task 2.2. Procure Materials and Setup Experiments (100%)

Task 2.3. Develop Heat Exchanger Models & Conduct Simulations (90%)

Task 2.4. Conduct Tests on Lab Prototype (75%)

Task 2.5. Evaluate Test Data and Modify Prototype

Task 2.6. Conduct System Simulation (75%)

Milestones

Complete lab prototype

Demonstrate heat transfer coefficient >500 W/m2-K

Demonstrate pumpability of solid salt slurry

Go/ No-Go Criteria

Salt slurry must be pumpable and heat transfer coefficient must exceed 150 W/m2-K

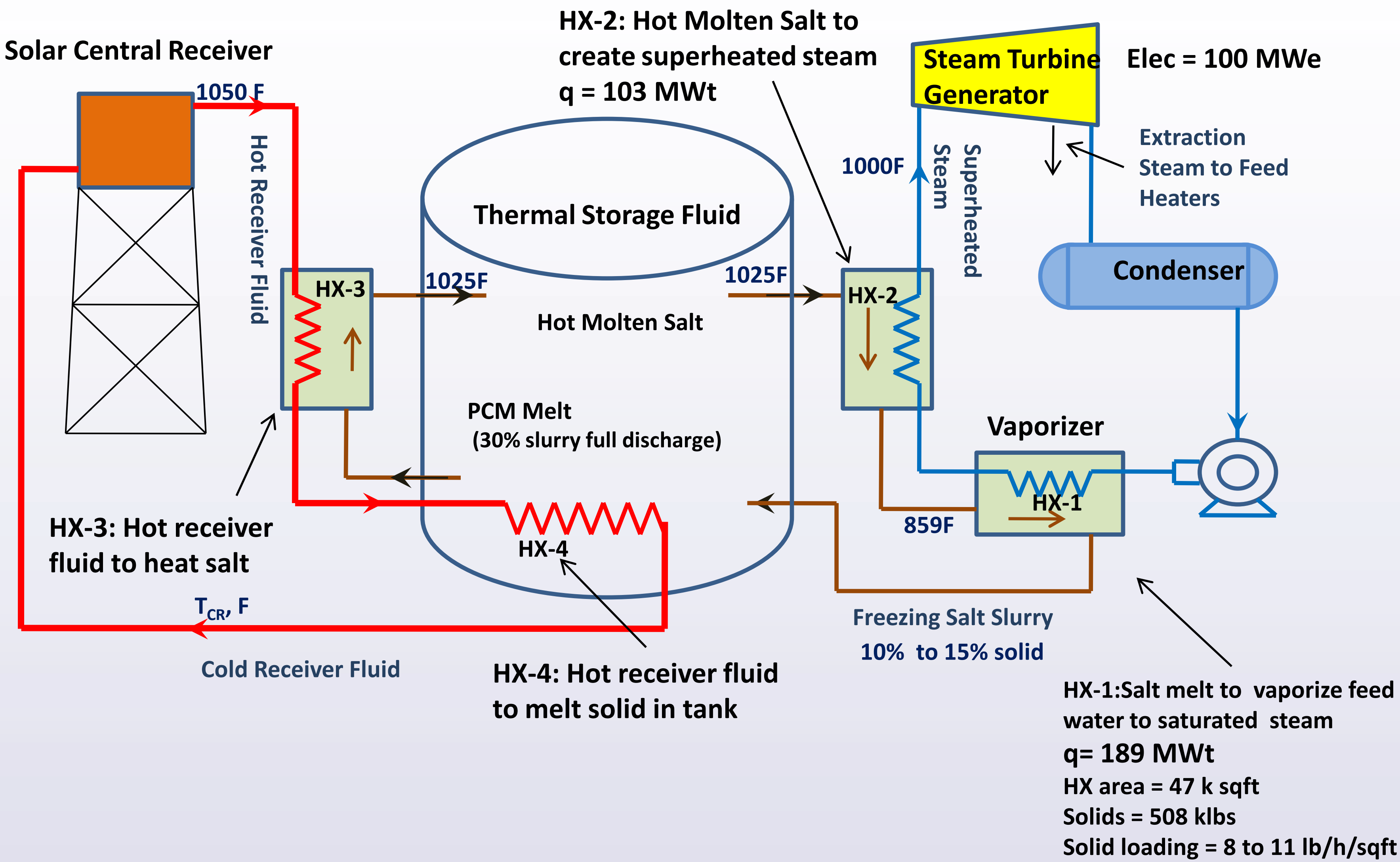
Phase 2 Objective

Design an efficient and economical heat exchanger to extract heat when storage media solidifies

1. Conduct scientific studies to select the best 'anti-stick' (salt-phobic' coating for heat exchanger tubes
   a. Experiment with different coatings
   b. Study the solidification morphology of *dilute eutectic* salt
2. Construct a laboratory 'flow-loop' setup to test the Terrafore concept with dilute eutectic NaNO3-NaOH and coated shell and tube heat exchanger
3. Conduct experiments with the coated tube heat exchanger and develop heat transfer correlations
4. Integrate the TES model into the larger Solar Tower simulation model for optimization and simulation studies in Phase 3

   Develop a model for PCM stratification, charging/ discharging

Improve Coefficient of Heat Transfer in HX-1 during Discharge of PCM – TES



A Power Tower – TES System Configuration

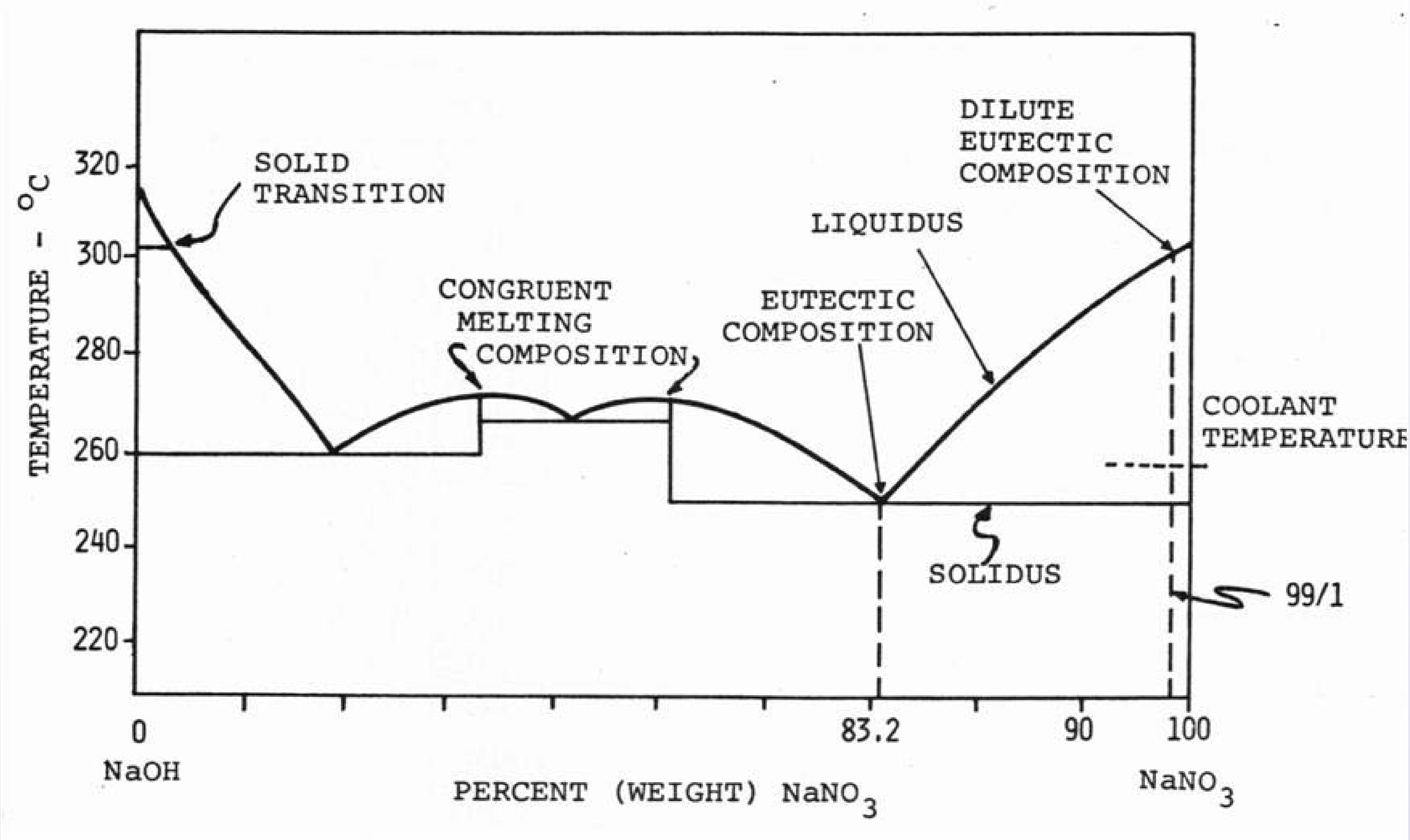
A Solution for PCM Heat Transfer

Terrafore's innovative approach to heat transfer has three elements:

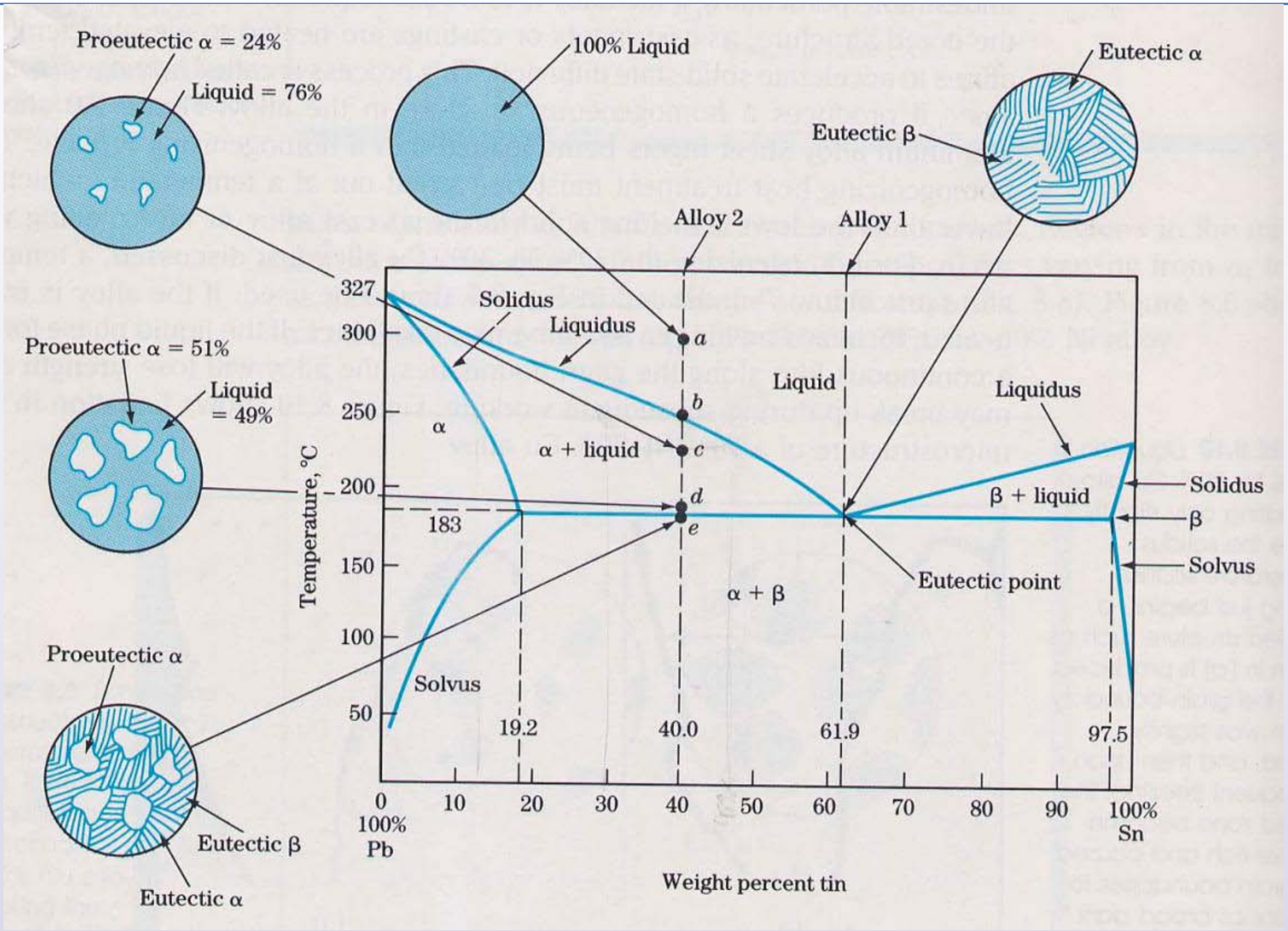
- A *dilute eutectic* composition of salt mixtures that form a eutectic with a specific phase diagram called *simple* phase diagram
- An additive(s) that will cause the salt to solidify as a slush which can be easily washed off the heat transfer surface;
- A coating on the heat exchanger tubes that discourages strong adhesion of freezing salt*;*

Pump the salt through an external heat exchanger
Use a shell and coated tube heat exchangers

Phase Diagram of NaNO3-NaOH

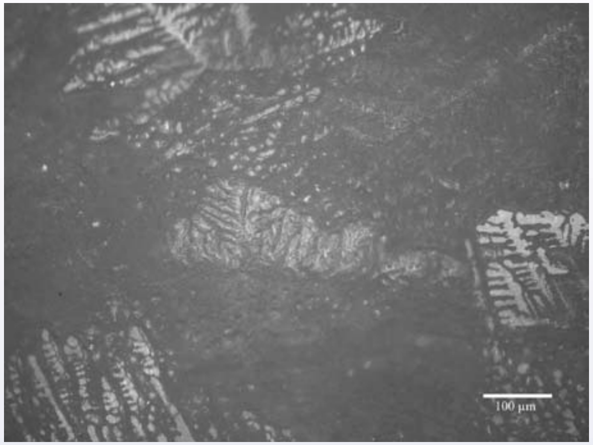


Development of S-L Mixture

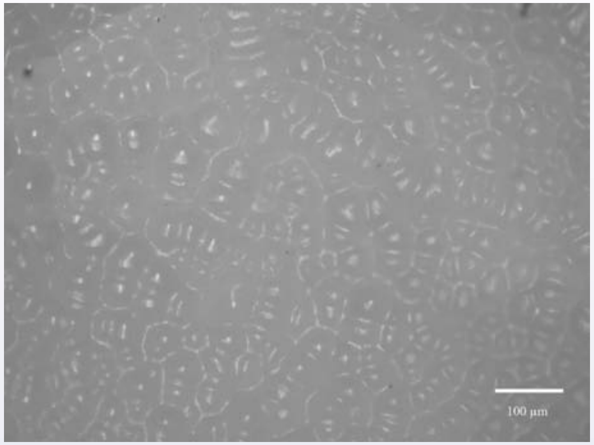


Solidification Morphology

90%KNO3-10%KOH
Air cooled



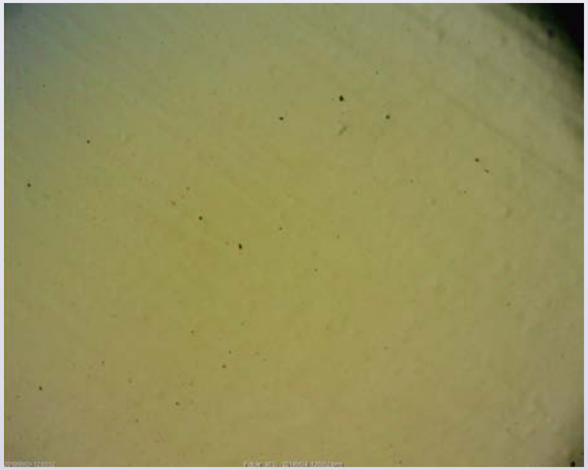
90%NaNO3-10%KNO3
Furnace cooled



Electro-polish surface prior to coating

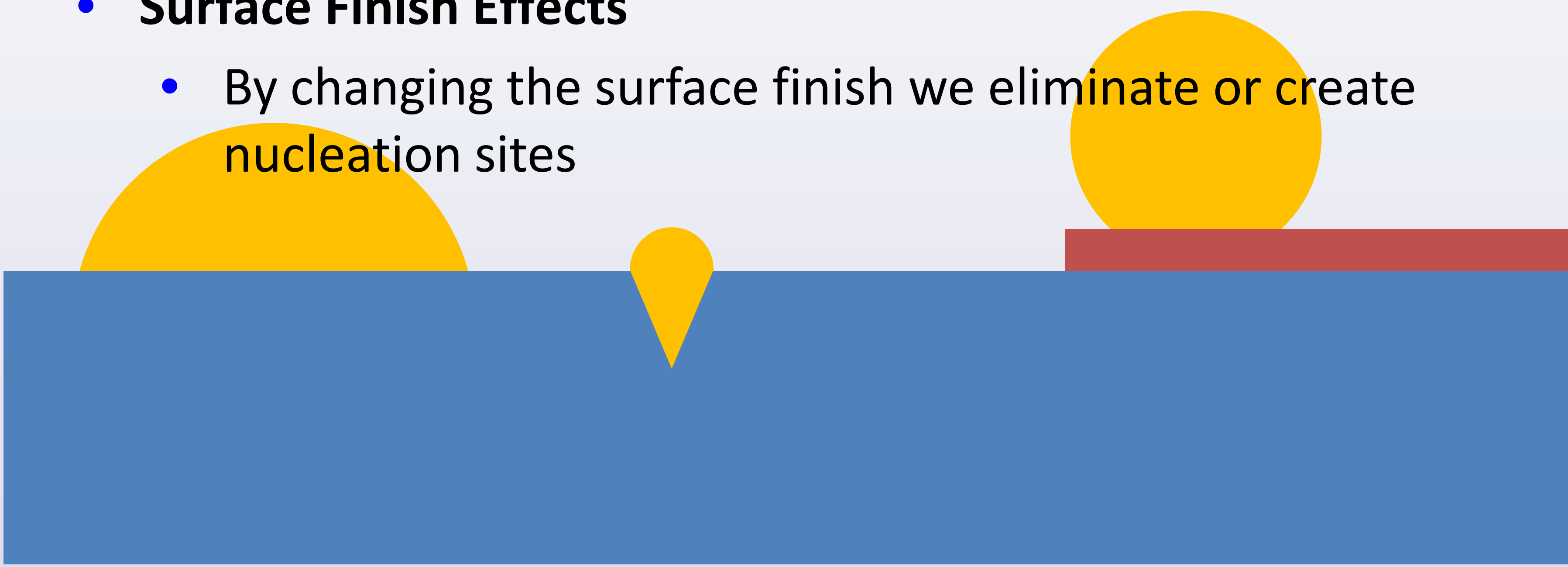
Pre-Polish

Post-Polish

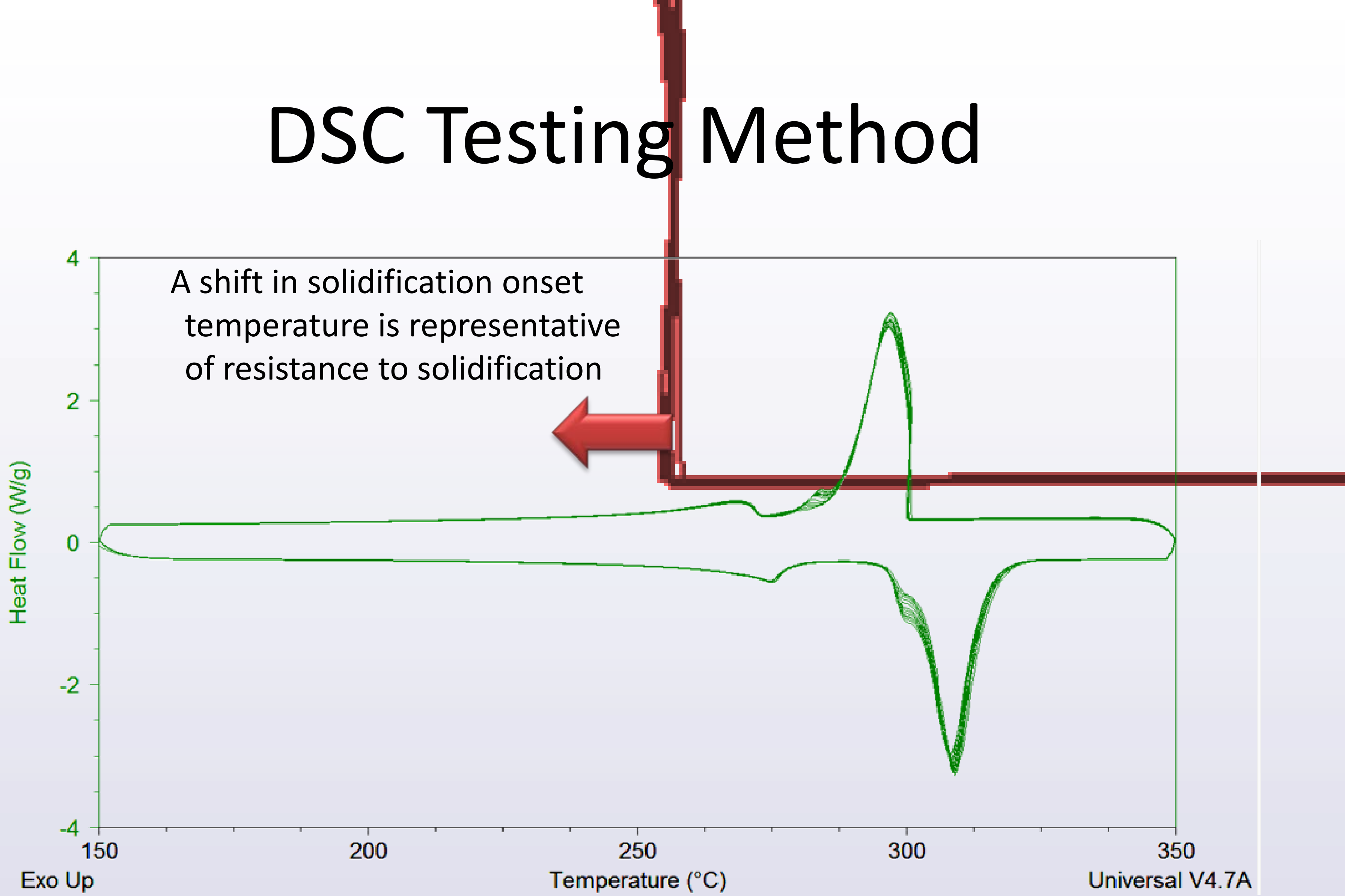


Assessing Solidification on Heat Exchanger

- **Heat Exchanger Material Effects**
  - By changing surface material we change the surface energies between phases, thereby changing the free energy change for solidification
- **Surface Finish Effects**
  - By changing the surface finish we eliminate or create nucleation sites



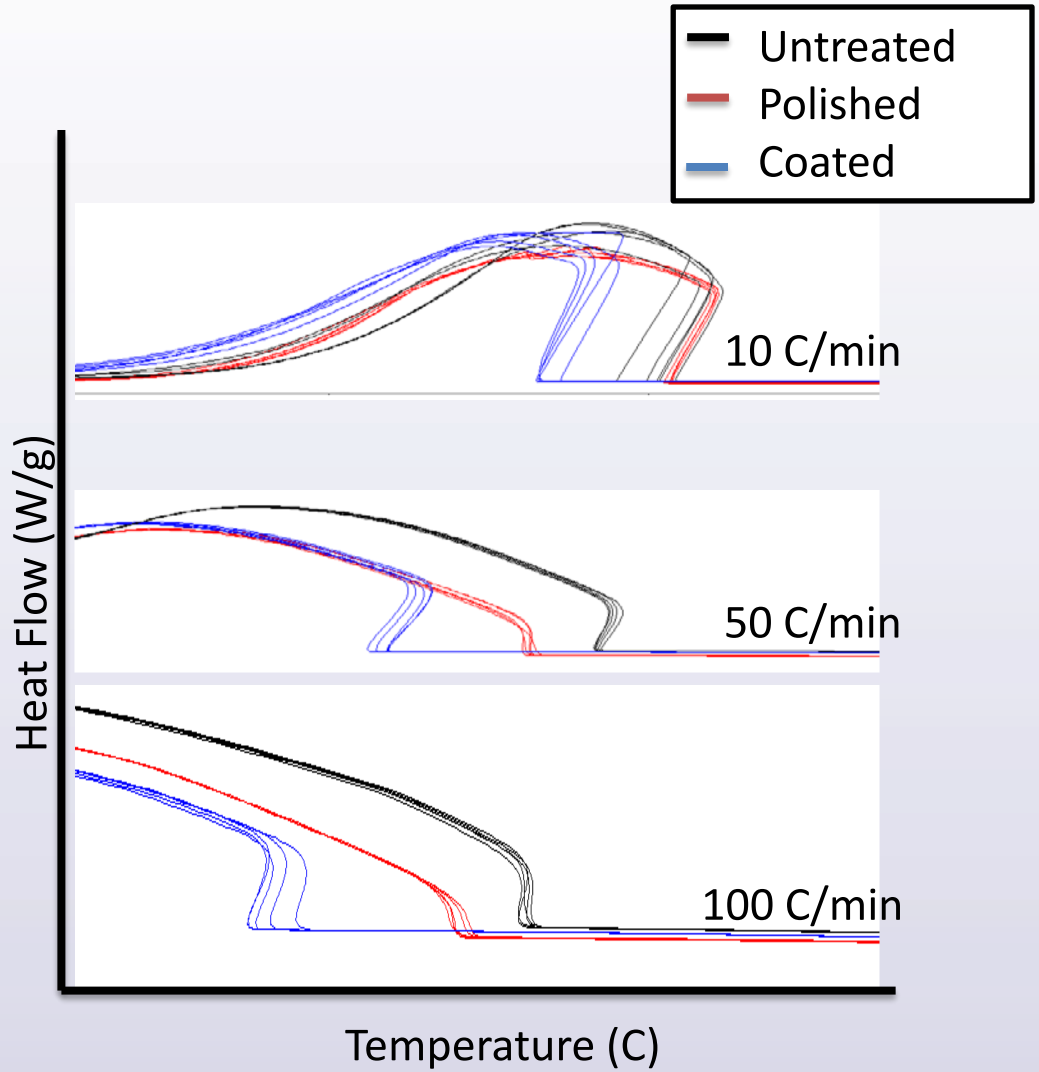
DSC Testing Method



Our hypothesis: Coatings that cause a larger shift in solidification temperature will have better 'anti-stickability' of salt to coated surface

Evidence of Solidification Shift

- Coatings can cause a significant shift in solidification!
- Surface Finish can also cause a shift in solidification.
- The effect is amplified with increasing cooling rate



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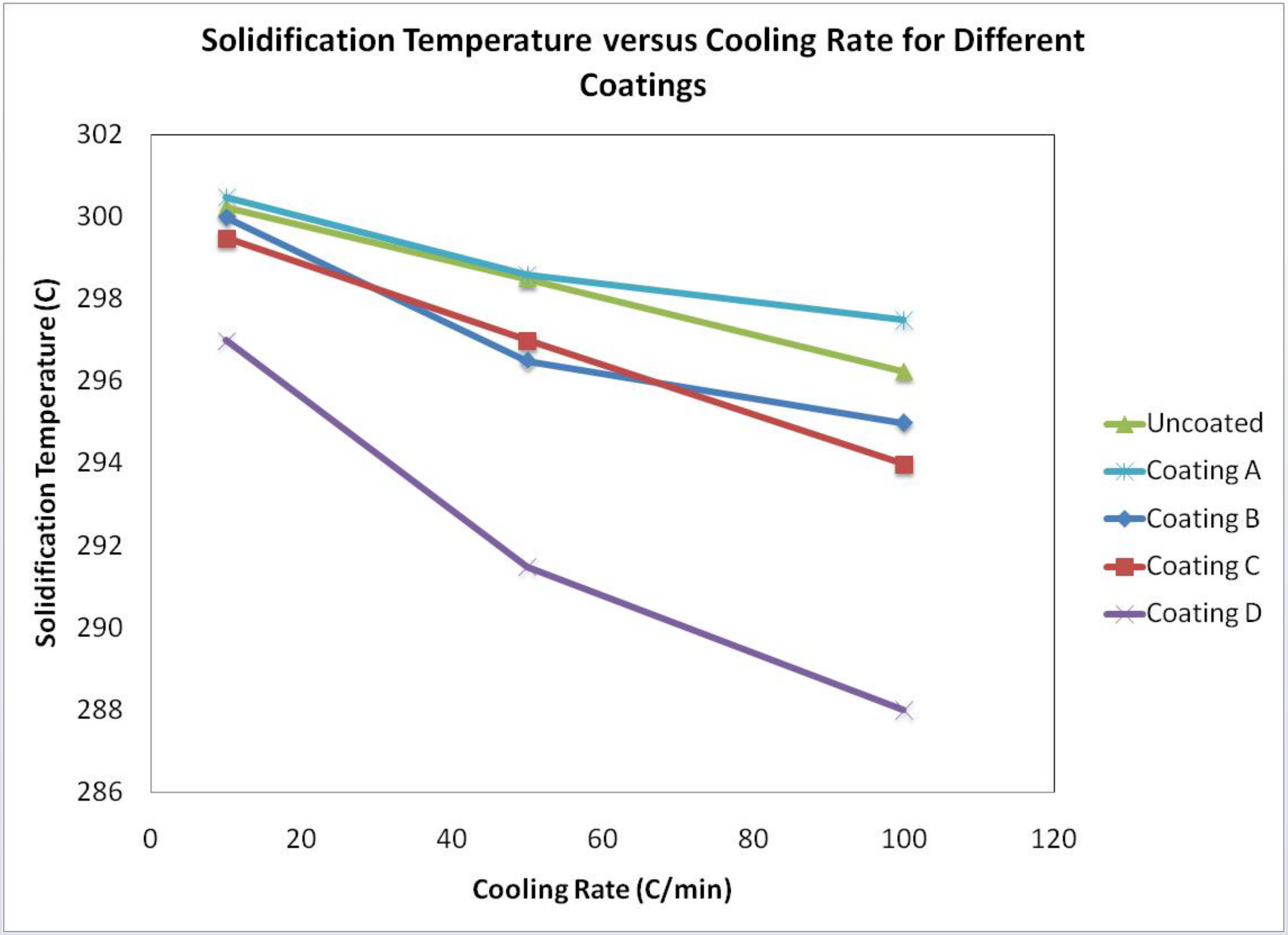
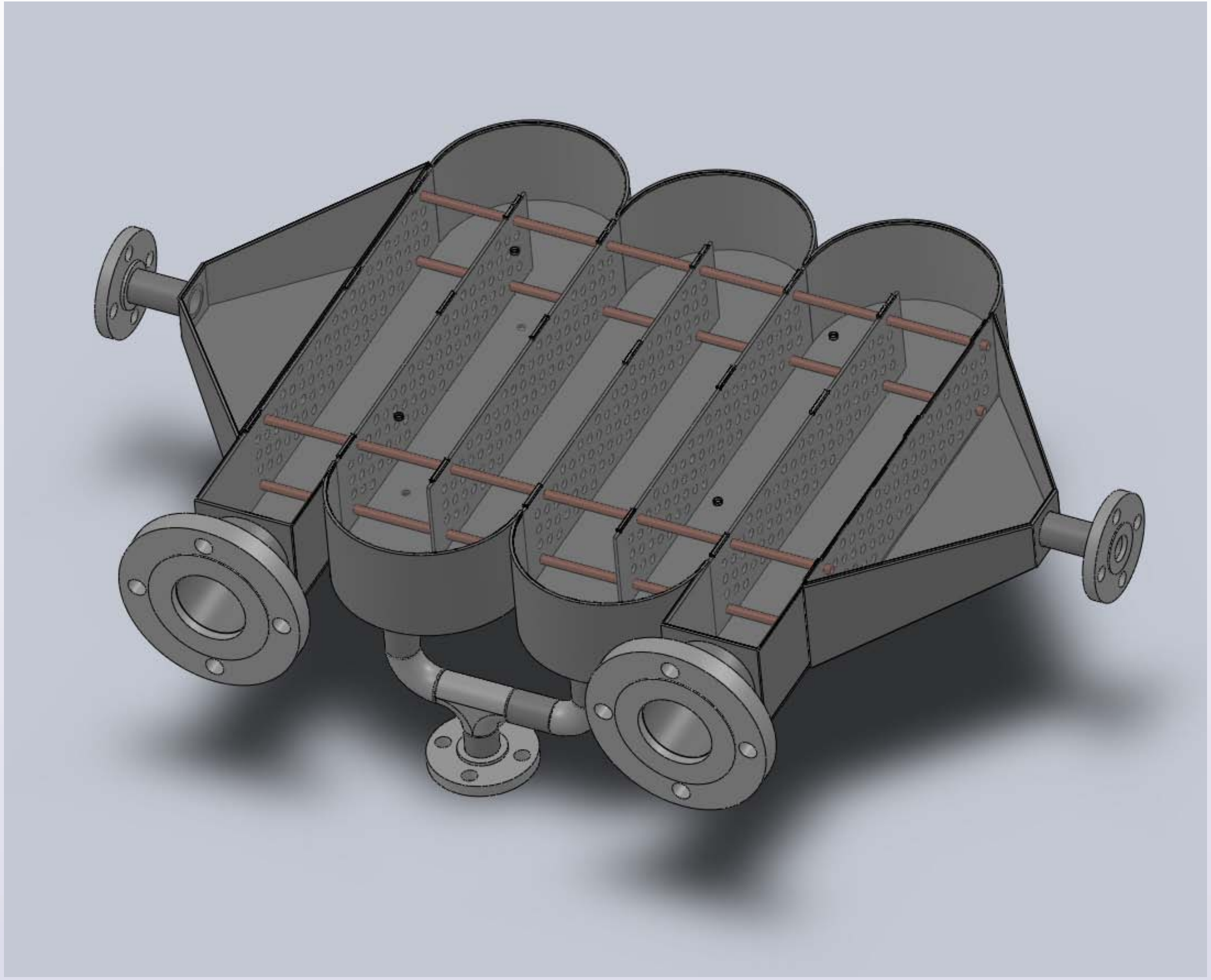
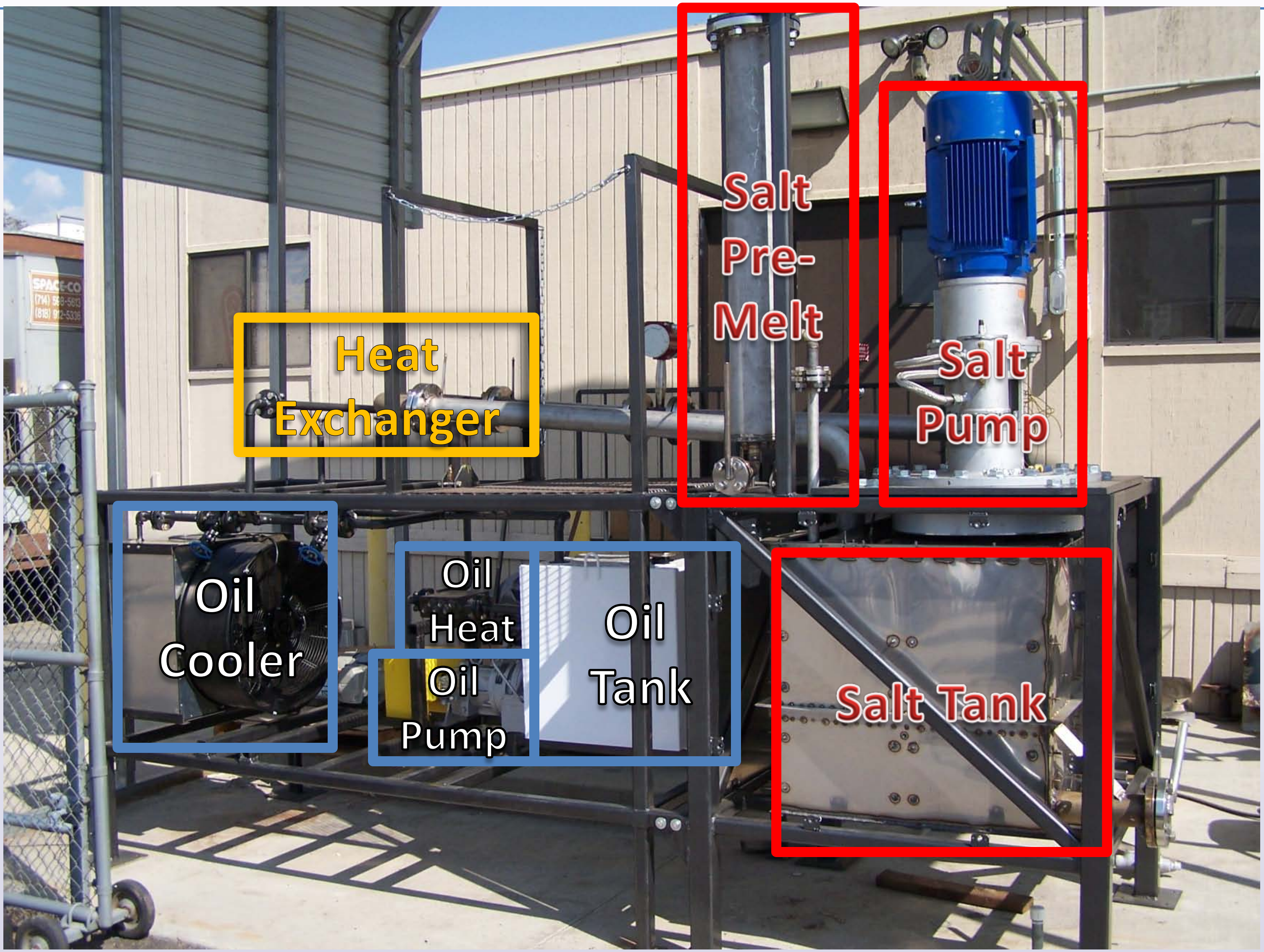
Effects of Coatings on Solidification



Final Heat Exchanger Design



PCM-TES Experiment Test Setup



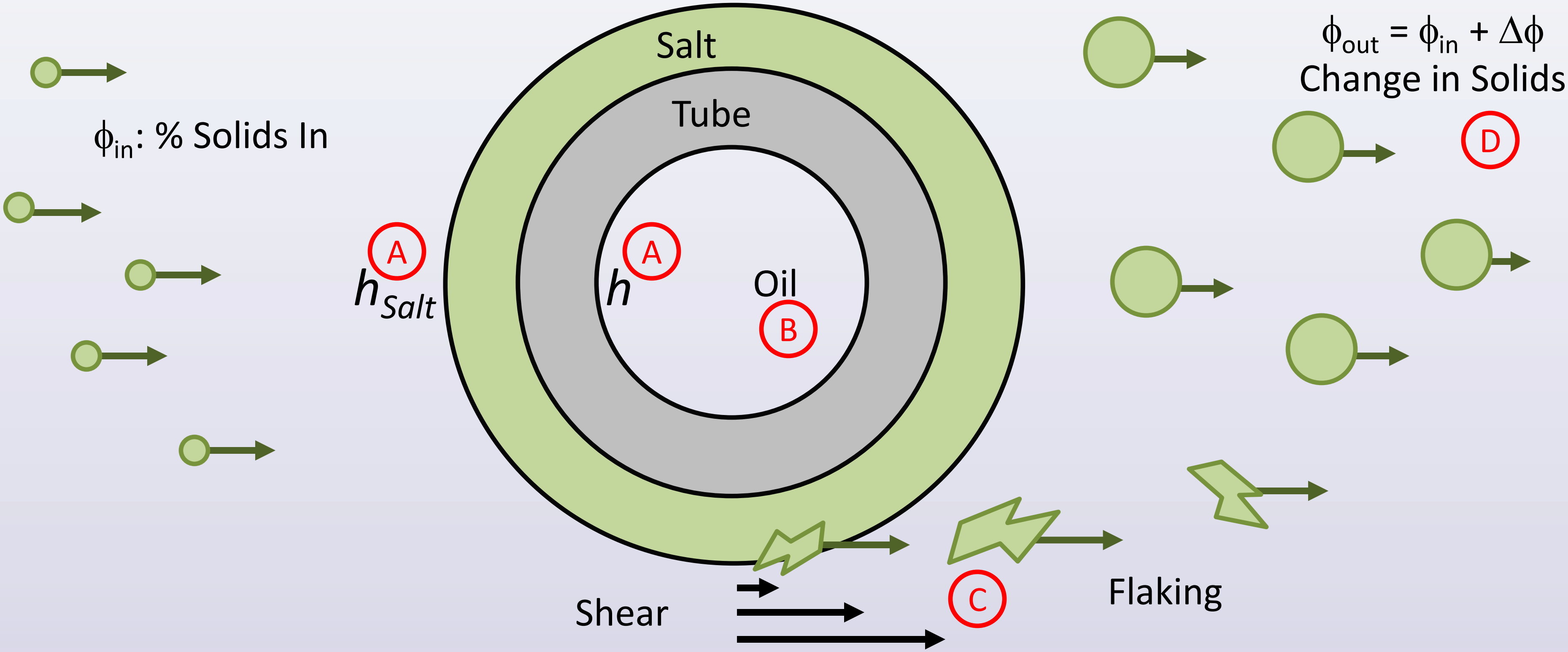
Thermal Design Objectives

(A) High oil heat transfer $\rightarrow$ better isolate the heat transfer of salt side.

(B) Low pressure drop $\rightarrow$ smaller pumps.

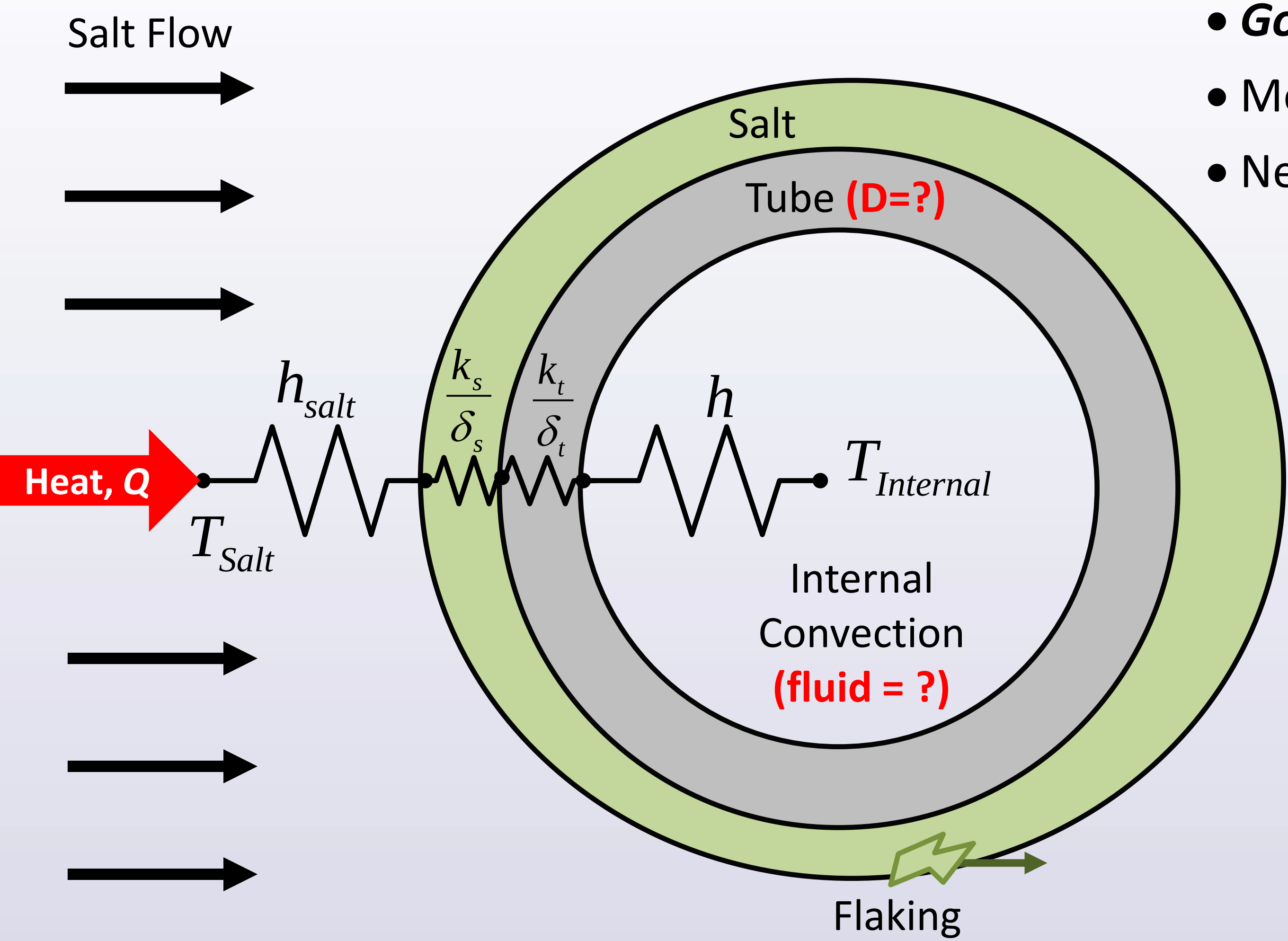
(C) High Reynolds number $\rightarrow$ large shear forces to flake off salt.

(D) Large change in solid fraction per pass.



Goal of Thermal Experiments: **Determine h_{Salt}**

- ***Goal: Determine h_{Salt}.***
- Measure: T_{Salt}, $T_{Internal}$, & Q.
- Need: h_{Salt} as dominant R.



$$\frac{1}{U} = \frac{1}{h_{Salt}} + \frac{\delta_S}{k_S} + \frac{\delta_t}{k_t} + \frac{1}{h}$$

Best Case, $\delta_S \rightarrow 0$

Thin SS Tube

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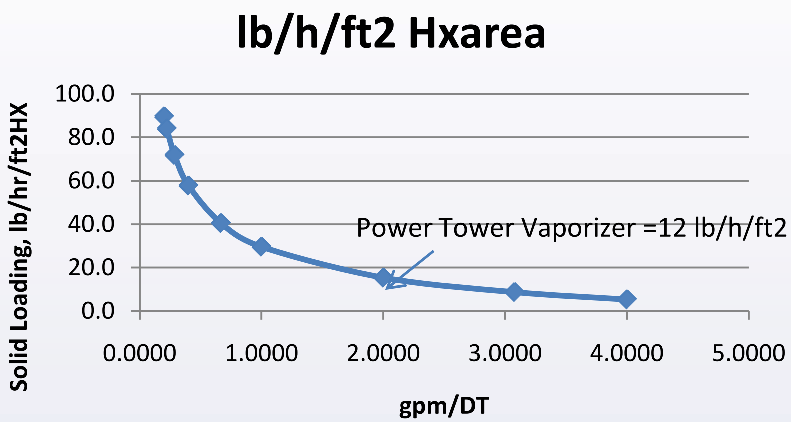
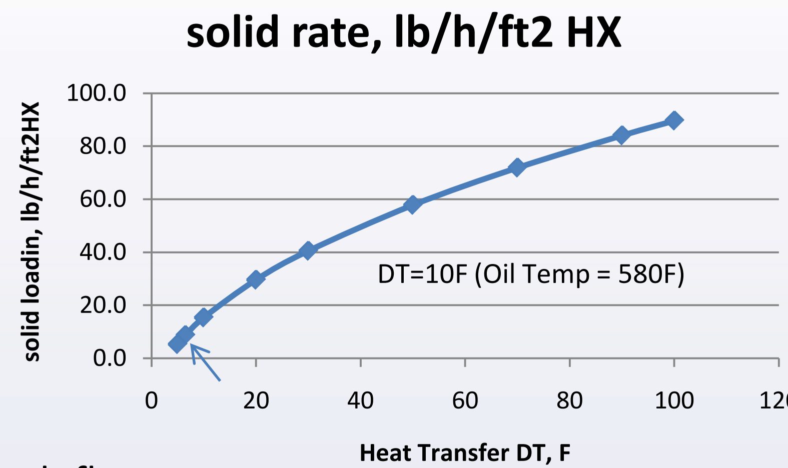
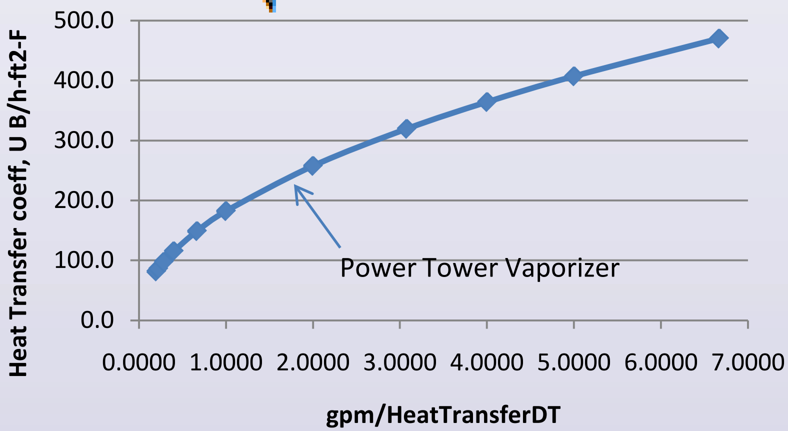
Solid Loading in Heat Exchanger





$$h = \sqrt{\frac{k * Hf * m}{Vhx * \Delta T}}$$

gpm/DT = salt flow rate to heat transfer delta T



- Power Tower solid loading of 8 to 16 lb/h/ft2HX corresponds to 10% to 20% solid slurry
- Experiment solid loading of 12 lb/h/ft2 HX corresponds to 1% solid slurry

PCM Latent Heat TES experiment
Design of Experiment

Study Parameters

Temperature of oil	various
Temperature of salt	high, medium, low
Flow rate of salt	high, low
Flow Rate of Oil	high, medium, low

Expected Outputs

Heat transfer coefficient (h-salt) as a function of solidification at near solidification temperature

Heat transfer coefficient (h-salt) as a function of salt flow and heat transfer temperature difference

Heat transfer coefficient correlation from liquid molten salt

Pumpability of freezing mixture

Experience with handling high temperature molten salts near freezing point

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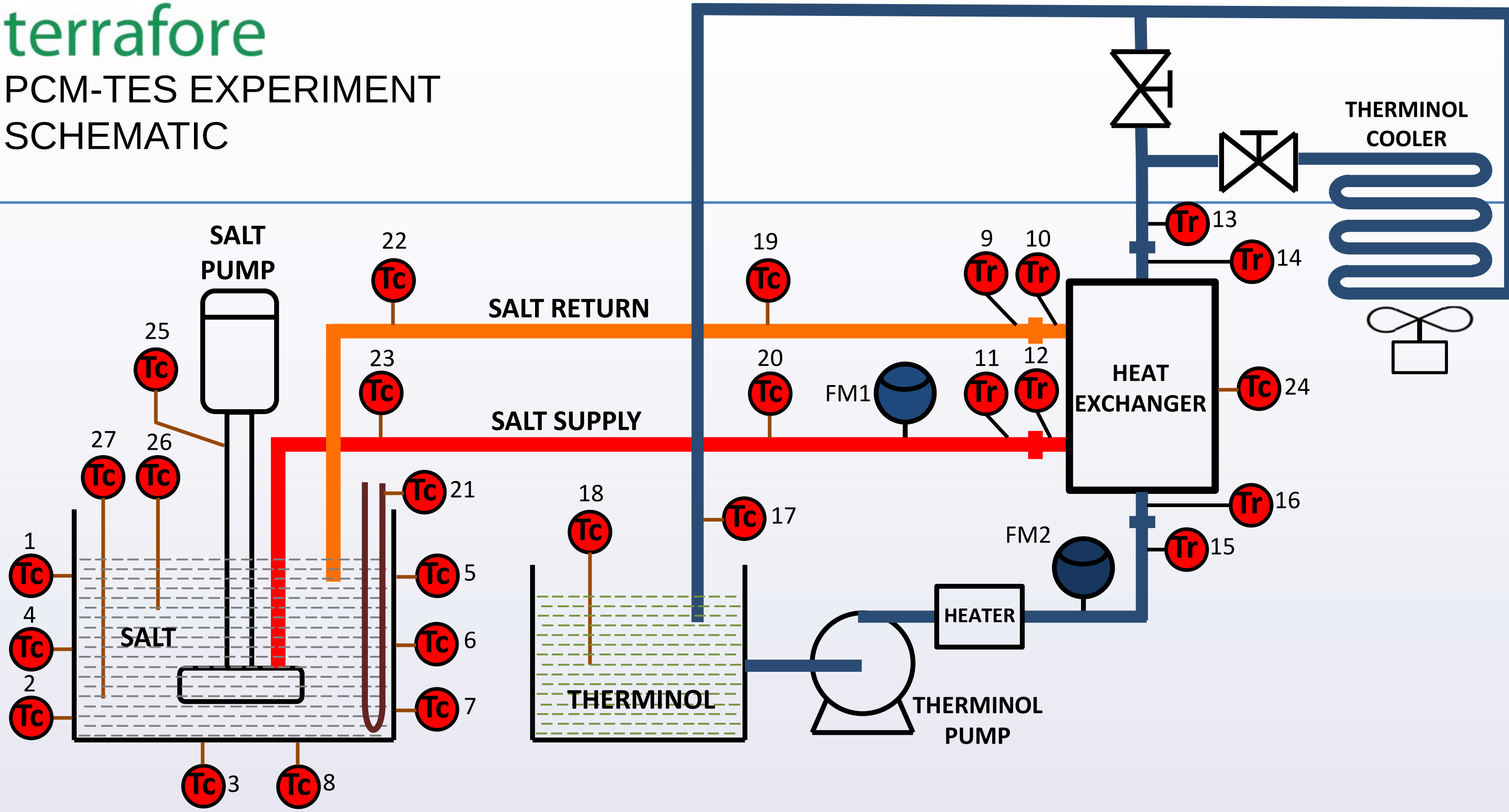
PCM-TES EXPERIMENT SCHEMATIC



1	Upper Strip Heater TC	11	HX salt Return Far Side RTD	21	Salt Heater TC
2	Lower Strip Heater TC	12	HX Salt Return Near Side RTD	22	Salt Return Pipe Wall TC
3	Bottom Strip Heater TC	13	HX Therminol Supply Far Side RTD	23	Salt Supply Pipe Wall TC
4	Salt Tank Wall TC	14	HX Therminol Supply Near Side RTD	24	HX Wall TC
5	Salt Tank Wall TC	15	HX Therminol Return Far Side RTD	25	Salt Pump Housing TC
6	Salt Tank Wall TC	16	HX Therminol Return Near Side RTD	26	Salt Tank Shallow TC
7	Salt Tank Wall TC	17	Therminol Return TC	27	Salt Tank Deep TC
8	Salt Tank Bottom TC	18	Therminol Tank TC	FM1	Salt Flow Meter
9	HX Salt Supply Far Side RTD	19	Salt Return Pipe Heater TC	FM2	Therminol Flow Meter
10	HX Salt Supply Near Side RTD	20	Salt Supply Pipe Heater TC		

Summary Status

- Designed and completed setting up the experiment with
  - Fabricated heat exchanger with tubes electropolished and then coated with smooth chrome coating
  - Assembled flow loop with customized salt and therminol pumps
  - Completed extensive setup and pre-operative processes in preparation for performance testing
  - Established successful salt and therminol circulation systems
- Failure of weld in the heat exchanger during testing
  - Repairing heat exchanger and modifying flow loop
  - Schedule to conduct experiment mid-July 2011
- Preparing a comprehensive Lessons Learned document