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Abengoa Solar Sunshot Conference Project Review

Development of Molten-Salt Heat Transfer Fluid Technology for Parabolic Trough Solar Power Plants

Contract #: DE-FC36-08GO18038

Presenter/PI: Dylan Grogan, PE

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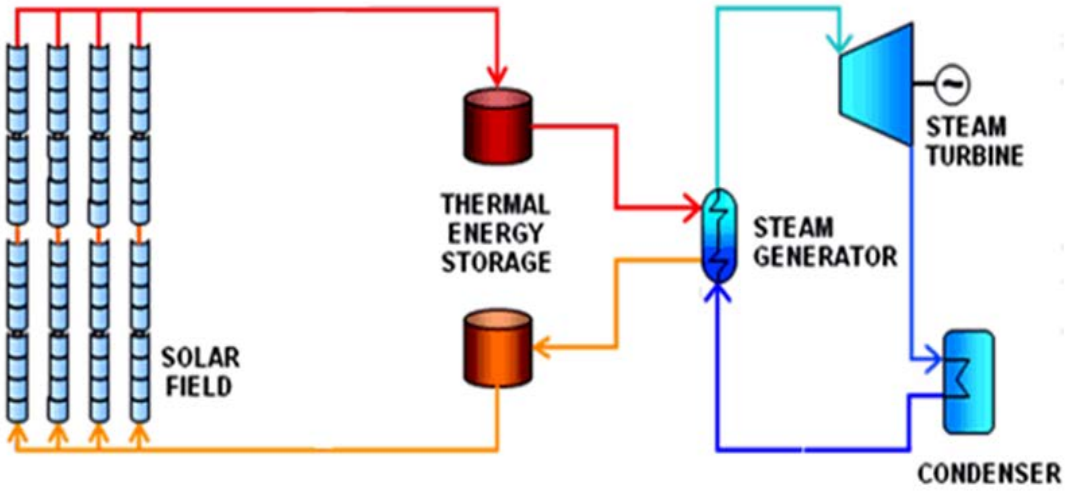
Presentation Outline

- Project Objectives
- Significant Results and Conclusions
  - Phase 1 – (April 2008 – July 2010)
  - Phase 2 – (March 2011 – December 2012)
- Summary of Technical Challenges and Achievements



MS Trough Project Objectives

- Determine whether the inorganic fluids [molten salts] offer a sufficient reduction in levelized energy costs to pursue further development, and to develop the components required for their use.
  - Determine the concept feasibility and economic potential for replacement of the current generation of organic heat transport fluids with low freeze point molten salts.
  - Develop the technologies required for the use of molten salts
  - Conduct the field tests necessary for the introduction of molten salts in a commercial project
- Go/No-go Criteria (Phase 2 to 3)
  - Demonstrate that all key risk areas are being addressed
  - The detailed economic and performance projections for a molten-salt HTF CSP plant show an LCOE of below $0.12/kWhe (real 2009 $), with a 10% ITC

Phase 1 Conclusions and Results

- Molten salt HTF enables use of a direct thermal storage system
  - Which reduces TES cost and improves TES performance
- Direct Thermocline TES not competitive with Direct 2-Tank TES
- Turbine efficiency increases due to increased steam temperature and pressure enabled by molten salt
- Freeze protection and recovery system a significant cost for a molten salt plant, thus needs optimizing
- Due to the higher operating temperature, a molten salt plant with 6 hrs and 2-Tank TES, requires ~50% of the salt needed for an equivalently sized oil plant with 6 hrs of storage capacity
  - Therefore, a molten salt plant becomes more economically attractive relative to an oil plant as salt prices increase

Review of Phase 2 Activities

- Process Development
  - Molten salt characterization studies
- Molten Salt Collector Design
  - Designed necessary improvements to deploy molten salt HTF in Abengoa's latest large aperture collector design
- Molten Salt Component Testing
  - Tested valves, joints, pressure transducers in a lab environment
  - Corrosion study of receiver tube coupons
  - Detailed design of the freeze protection and recovery system for a commercial plant
- Plant Performance and Economic Analysis
  - Developed an advanced performance and cost model of a140 MW commercial molten salt plant
  - Engineering, procurement, and construction (EPC) quote for a 140 MW plant

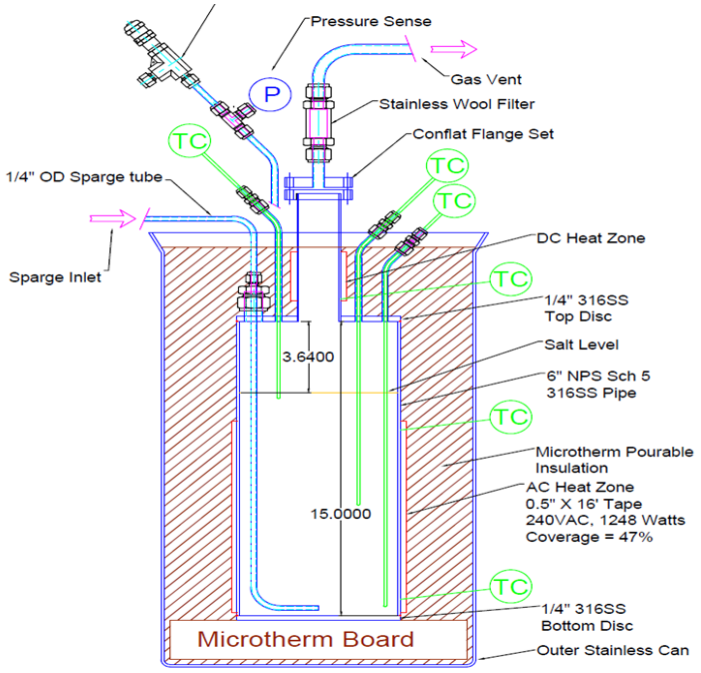
Salt Characterization

- Thermal Physical Properties of Molten Salts
  - Eutectic composition
  - Specific heat
  - Density
  - Viscosity
- Salt is difficult to work with, which expectedly makes it difficult to obtain reliable data from labs
- We have learned to oversee lab testing in person to improve results

Salt Thermal/Electrochemical Stability

- Long term (4,000 hr) thermal/electro-chemical stability test
- Four test pots with 10 kg of salt per pot
- 5 temperature steps (800 hr ea) - ranged from 450°C to 585°C
- Measurement frequency:
  - salt chemistry – 200 hours
  - off-gas composition – 12 hours

Salt Thermal/Electrochemical Stability

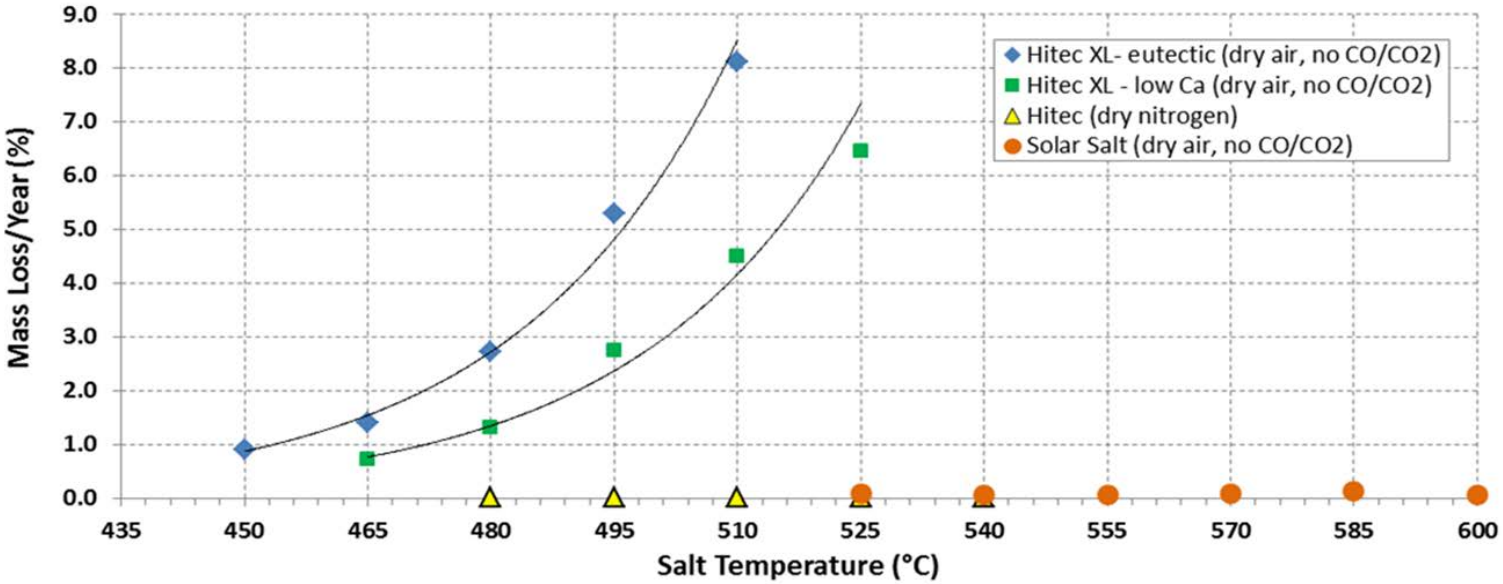


	Salt Constituent Weight Percent				
Salt Name	$NaNO_3$	KNO_3	$Ca(NO_3)_2$	$NaNO_2$	Cover Gas
Hitec XL (eutectic)	12	46	42	-	Air (dry, no CO/CO_2)
Hitec XL (low calcium)	30	50	20	-	Air (dry, no CO/CO_2)
Hitec	7	53	-	40	Nitrogen (dry)
Solar Salt	60	40	-	-	Air (dry, no CO/CO2)

Salt Thermal/Electrochemical Stability

- Conclusions:
  - Hitec XL (eutectic and low calcium): Confirmed decomposition at temperatures in the range of 450-465˚C due to NO_X off-gassing – **Calcium Nitrate officially discarded as a candidate for commercial use**
  - Thermal/electrochemical stability is a likely a function of numerous independent variables
    - Temperature
    - Nitrate/Nitrite percentages
    - Partial pressure and cover gas composition
    - Water vapor concentration in cover gas
    - Oxide ion concentration

Average mass loss rate of salt vs. temperature (based only on NO/NO_2 off-gassing)



Molten Salt Large Aperture Collector Design

- Improved design of receiver tube support arm due to:
  - electrical isolation for impedance heating
  - additional weight from high salt density and larger receiver tubes
- Design changes improved performance of Abengoa's large aperture collector for all other HTF's
- Integration of freeze protection and recovery system into the design of the collector

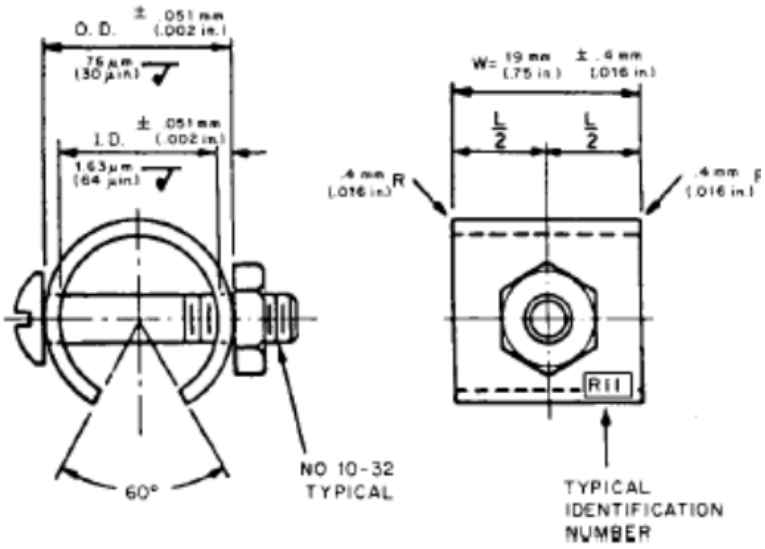
Corrosion Testing

- Stabilized stainless steels tested

Tube Type	%C	%Mn	%P	%S	%Si	%Cr	%Ni	%Mo	%N	%Ti
316Ti SS – vendor A	0.032	0.82	0.029	0.001	0.47	16.56	10.53	2.02	N/A	0.35
321 SS – Vendor B	0.02*	1.79	0.026	1E-04	0.53	17.20	9.00	N/A	0.01	0.170
316Ti SS – Vendor B	No information available									

* Results in L-grade classification and limitations on use

- Coupons
  - Unstressed
  - Stressed-compression (C-ring)
  - Stressed-tension (C-ring)
  - Welded
  - Sanded sections on each coupon
- Concerns
  - Pitting
  - Intergranular stress corrosion cracking (IGSSC)
  - Knife line attack



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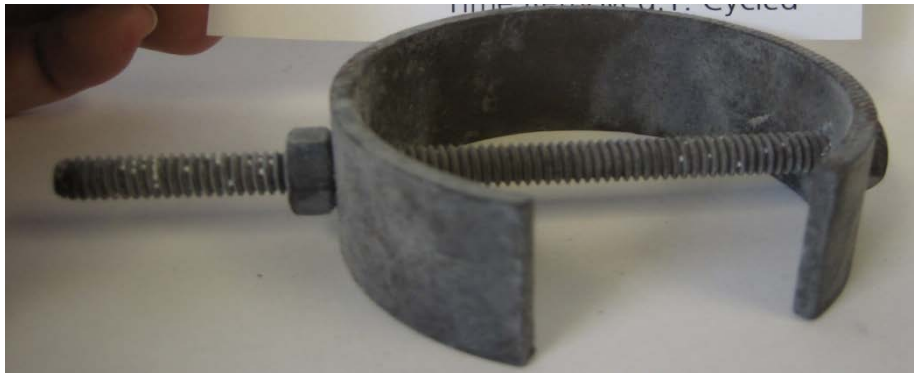
Corrosion Testing

- Salt Bath (@Sandia)
  - Salt Pots
  - Hitec XL
  - 0.55-0.56% chloride
  - 500°C
  - Sparged with air
  - Thermal cycled coupons included
  - 3000 hours

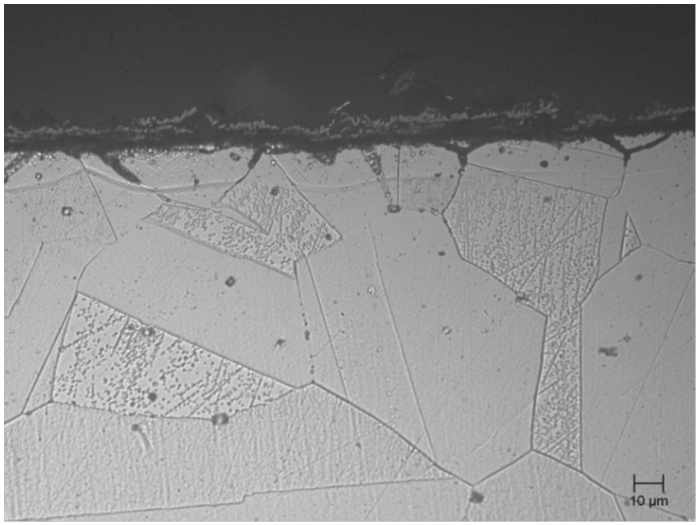
Coupon Type	Heat Treatment
Unstressed	N/A
Stressed	Stress-relief @1100ºC
Welded	Post-weld heat treatment @700ºC

Corrosion Testing

- Results
  - Analysis indicates acceptable corrosion of 316Ti and 321 with 500°C Hitec XL and 0.55wt% chloride
  - No pitting, IGSSC, knife line attack
  - Spalling seen on all coupons (mostly calcium oxide)
  - Calcium carbonate also detected on coupon surfaces
  - Grain boundary oxidation
    - stabilized at ~10-15 µm deep by 1000 hrs
  - Decomposition of Hitec XL confirmed
    - 44% $Ca(NO_3)_2$ reduced to ~33% by weight



SS 316Ti after 3000 hrs

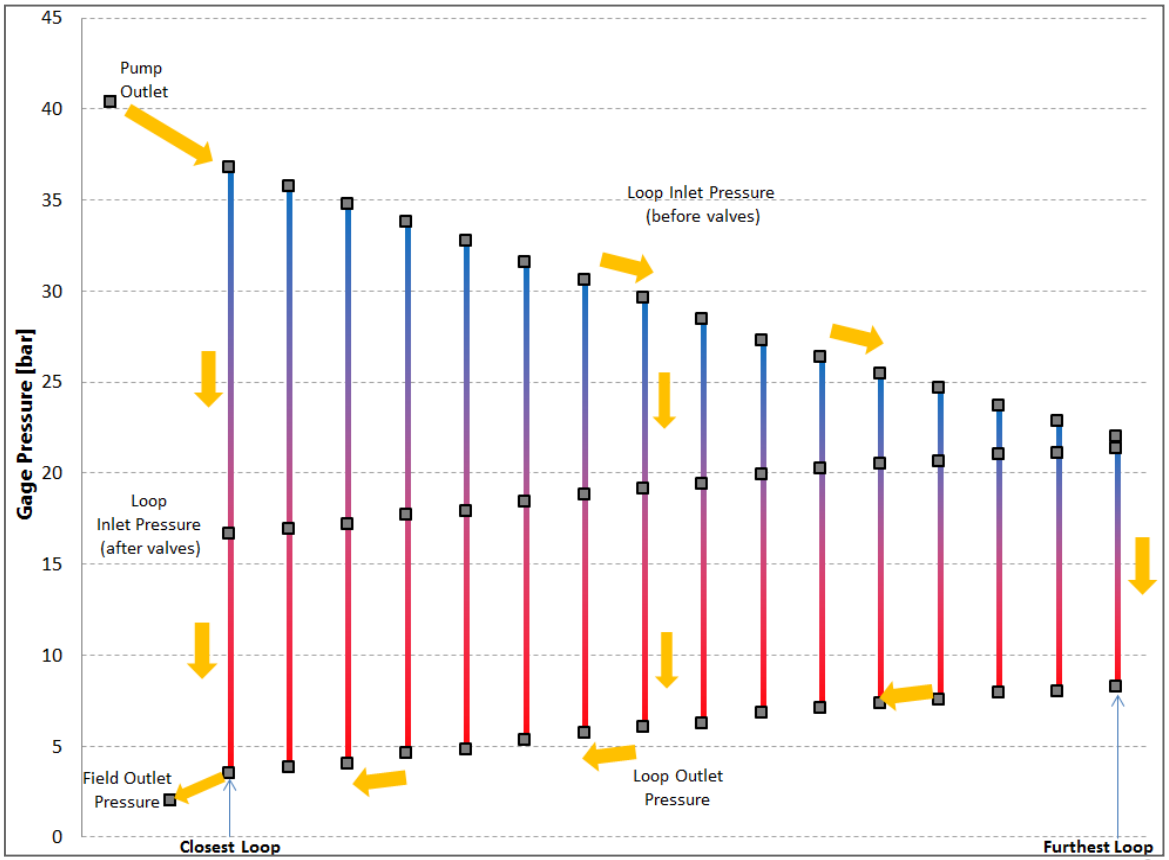


SEM image: SS 321 after 3000 hrs

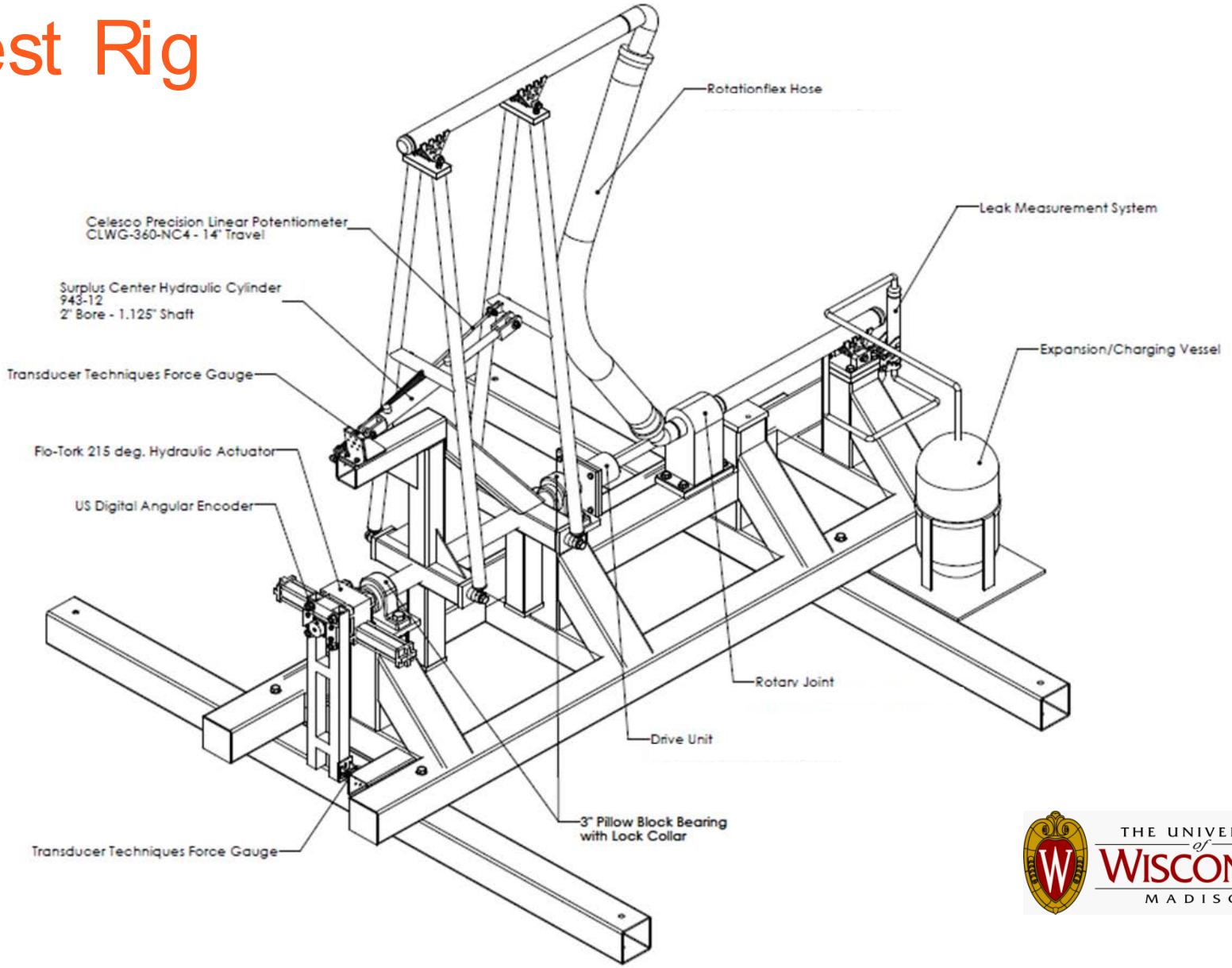
Collector Interconnection Testing

- Testing Goal: mimic Collector motion and Commercial plant conditions
- Emphasis on instrumentation and data acquisition

- Collector Joint Acceptance Criteria
  - Operate up to 500°C to 550°C
  - Pressure: 25 bar
  - Cycle life ≥11,000 (30 years)
  - Torque ≤ 750 N-m
  - Must survive multiple freeze and thaw cycles



Test Rig



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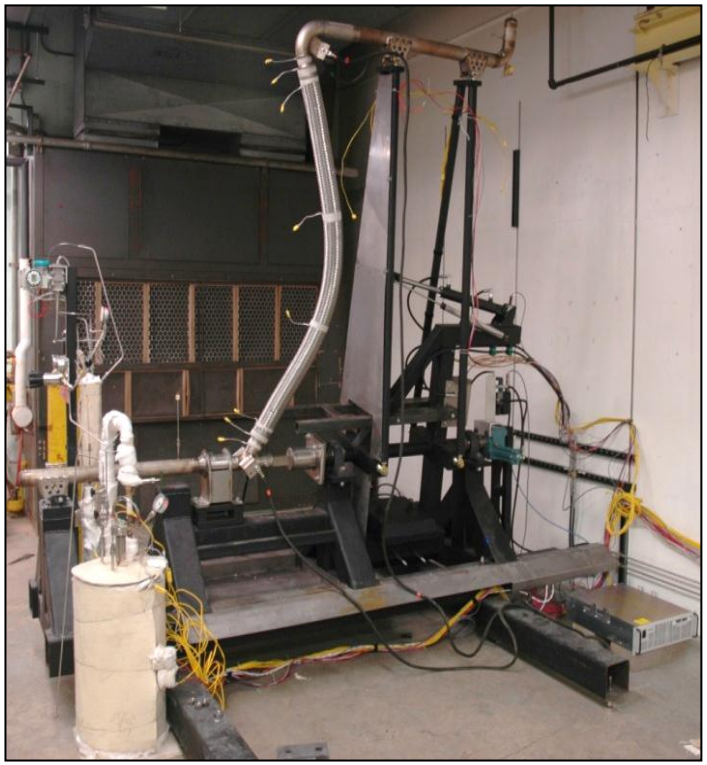
Collector Interconnection Testing

- Tested more than 13 different variations of ball joint and rotary joint designs with very limited success
  - Cannot find a pliable seal material that is compatible with 500°C molten salt
  - Limited success with hard materials used in face seal designs

Ball Joint Assembly



Rotary Joint & Flexhose Assembly

Molten Salt Valve Testing

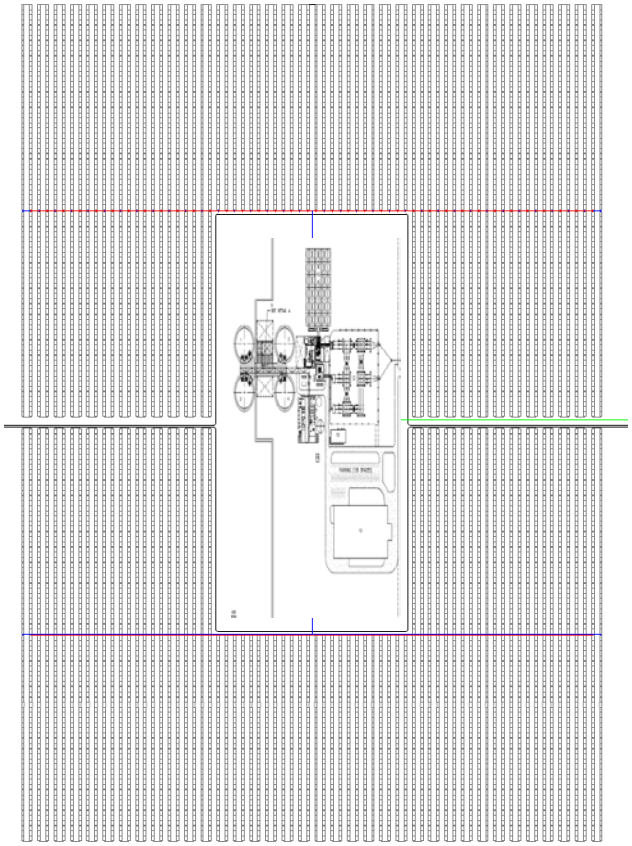
- Test conditions
  - Fluid – Solar Salt
  - Pressure – up to 40 bar
  - Temperature – up to 500°C
  - Chlorides ≤0.5% (by weight)
  - Capable of surviving freeze/thaw

- Successfully tested multiple valve designs
  - Shut-off valves
    - Triple offset valves
    - Gate valves
  - Flow control valves
    - Globe valves

Valve Test Rig

Commercial Molten Salt Plant

- Commercial MS Plant Specifications – Phase 2
  - 140 MWe_{gross}
  - 6 hours thermal energy storage (TES)
  - Dry Cooling
  - Land area = 1.4 mi^2
  - Location – Gila Bend, AZ
- Obtained EPC quote for commercial molten salt plant
- Analyzed optimum operating temperature, plant layout, TES dispatch strategy, etc.



Freeze Protection and Recovery

- Lessons Learned
  - Salt freeze point has an unexpectedly low impact on installed cost of the freeze protection system
  - Focus on reduction of heating zones and transformers to reduce cost
  - Freezing Feeder/Header pipes must be avoided

- Future Plans
  - Collector row and interconnection design changes to reduce heating zones and transformers
  - Test the commercial design and installation in a Pilot Plant

Plant Performance & Economic Analysis

- Model developments and analysis projects completed:
  - Developed more refined Power Block model
  - Analysis of collector size, spacing, receiver tube size, etc.
  - Model sensitivity to salt properties
  - Alternative plant designs
  - Optimization of solar multiple & TES size for 140MW plant
  - Impact of TES dispatch strategy on bulk salt temperatures and freeze risk

- End Result: Achieved LCOE's < 12 ¢/kWhe
  - Therefore passed Phase 2 Go/No Go Criteria

Review of Technical Challenges & Achievements

- ☑ Validate leak-free valve designs for commercial plant operation
- ☑ Design and test molten salt freeze protection and recovery system
- ☑ Test long term corrosion of economically viable materials for piping, tanks, and components
- ☑ Characterization of salt chemistry, behavior, and thermophysical properties over an extended time period
- ☑ Confirm the economic and performance potential of a commercial molten salt plant
  - ➢ Results show there is a potential for up to 30% reduction in Capital Cost/Annual Plant Performance
- ☐ Develop a robust and reliable rotating collector interconnection for commercial plant operation
  - ➢ Consequentially DOE's support of Phase 3 was not approved and the project will continue with internal funds

Thank You