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Sandia Thermal Storage Activities

Doug Brosseau, Greg Kolb – Sandia Albuquerque

Bob Bradshaw, Sandia Livermore

March 8, 2007 Trough Workshop

NREL, Golden, Colorado

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

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Sun♦Lab
Sandia National Laboratories, Albuquerque, NM
National Renewable Energy Laboratory, Golden CO

NREL

New Sandia Development of Improved Heat Transfer Fluid for Use in Solar Fields and Thermal Storage Systems

Motivation

- Reduced freeze point (compared to other salts)
- Low cost (relative to Therminol VP-1 now used)
- Thermal/chemical stability at ≥ 500ºC
- Environmentally friendly (to replace VP-1)
- Very low vapor pressure for TES
- Compatibility with materials of construction
- Excellent HTF fluid properties

HTF Developments

Current Development Status

- **Technical advance for patent has been filed**
- **Freeze point below 100°C appears achievable**
- **Durability at or above 500°C also possible**
- **Viscosities are less than 100cP near the freezing point**
- **A few candidate formulations now under test**
- **Current focus on reduced freeze point, stability testing, and limited property measurements (viscosity), blending to achieve best properties of the constituents**
- **Cost objectives obtainable, but not fully evaluated yet**

10-Tube Test for Phase Changes of Molten Salt Mixtures

Aluminum block with cavities for Pyrex tubes

Temperature stability ±0.1°C

Salt mixtures were cooled to successively lower temperatures and appearance of solid phases observed

Molten salt phase sampled by a 'cold finger'

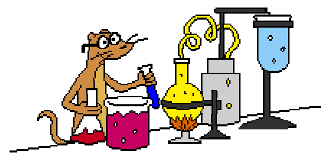
Plans for FY07

- **Phase I – Oct to Jan, $40k**
  - Screening experiments on matrix of salts
  - Freeze/melt behavior
  - Viscosity measurements
  - Stability and chemical analysis (preparations only)
- **Phase II – Jan to May, $60k**
  - Down-select to investigate most promising mixtures
  - More experiments, larger-scale, Livermore and Albuquerque (funding limited)
  - Viscosity, additives, chemical analyses
  - Investigate other key properties (if funding allows)
- **Phase III – Jun to Sep, $50k**
  - Set up longer-term experiments (materials, stability, etc.)
  - Final investigations of important chemical and physical properties
  - Documentation: extent of success will determine path for FY08

HTF Developments

Potential Larger-Scale Testing

Thermal Cycling: utilize and repair existing apparatus, and fabricate new simple apparatus, for thermal stability and possibly materials compatibility tests



Mel-Temp: apparatus for melt point determination

Phase II: apparatus being set up and refurbished at Sandia Albuquerque to support thermal stability testing, freeze/thaw, and material coupon tests.

Isothermal: freeze/thaw experiments, thermal stability, long-term materials coupons

Characteristics of Interest

- Cost
- Suppliers and availability
- Optimized formulation
- Grade and purity
- Preparation requirements
- Salt/metal interactions
- Scaling, oxide formation behavior
- Freeze point and freeze/thaw behavior
- Salt disassociation
- Thermal stability
- Viscosity vs temperature
- Thermal conductivity
- Heat capacity

Note: Not all properties will be determined in this study.

Some Economic Modeling Results for Thermal Storage Based on Molten Salt HTF in the Field

Ability to Dispatch

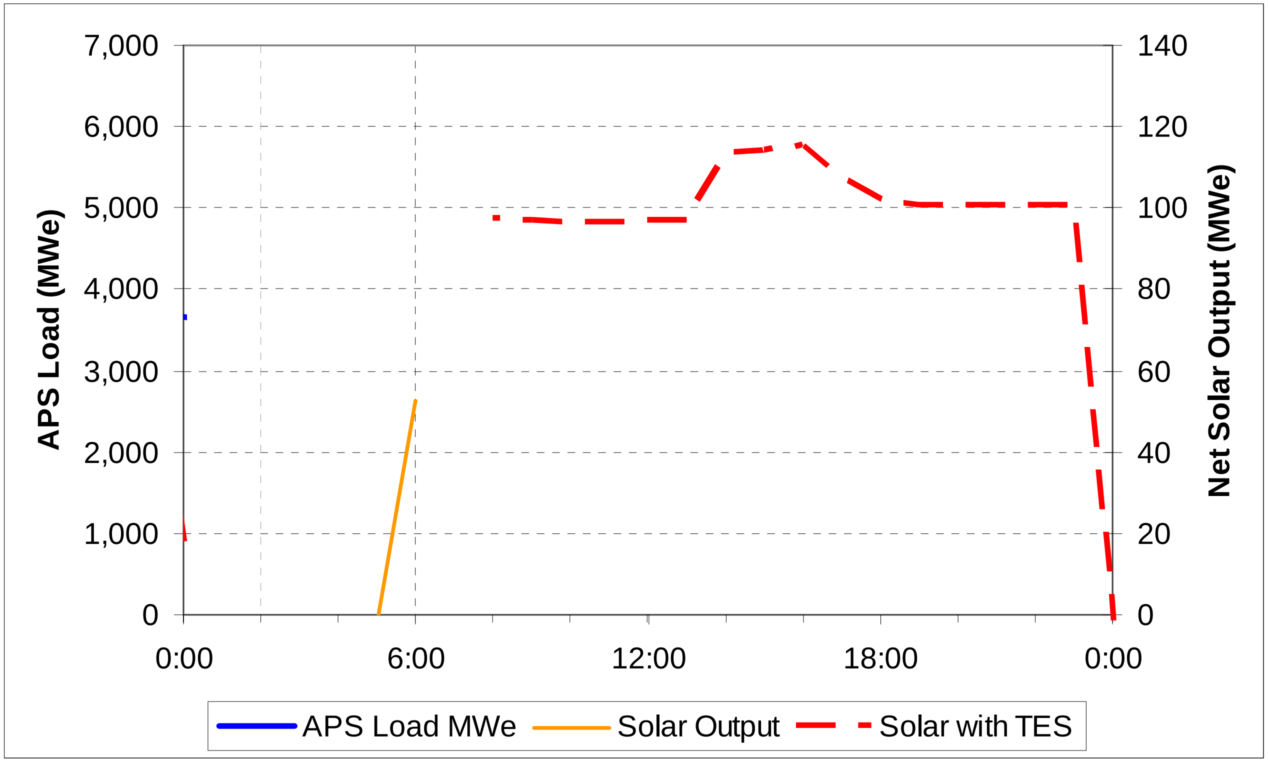


Figure 13 Parabolic Trough Plant Output Compared to the APS System Load on July 8, 2002

Is This Compelling?

Indirect Two-Tank TES at Current Oil Temps

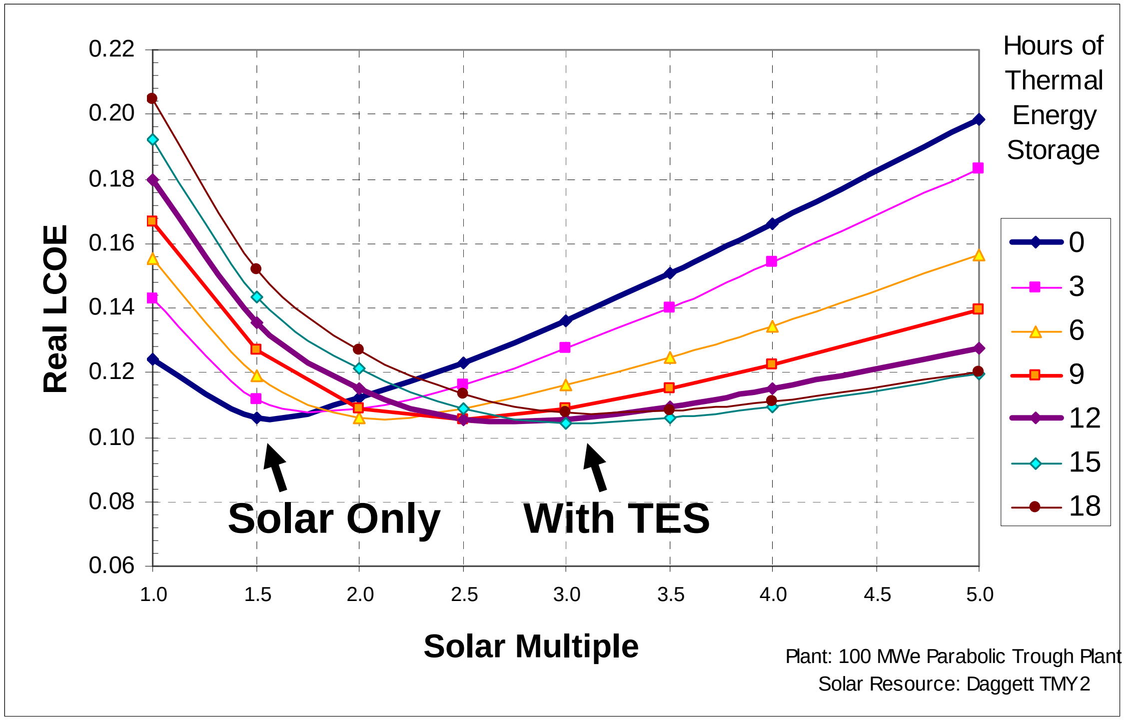


Figure 20 Levelized Cost of Power for Parabolic Trough Power Plant Using Indirect Molten-Salt 2-Tank Thermal Energy Storage Operating at 391ºC with Advanced Collector Technology

Is This Compelling?

Direct Thermocline TES at 500ºC

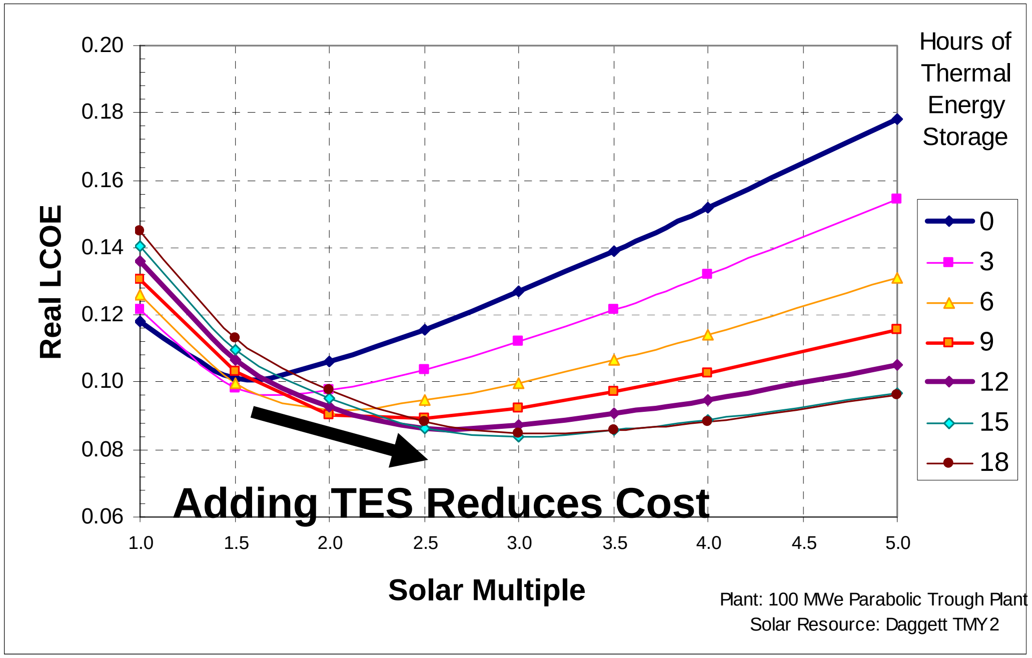
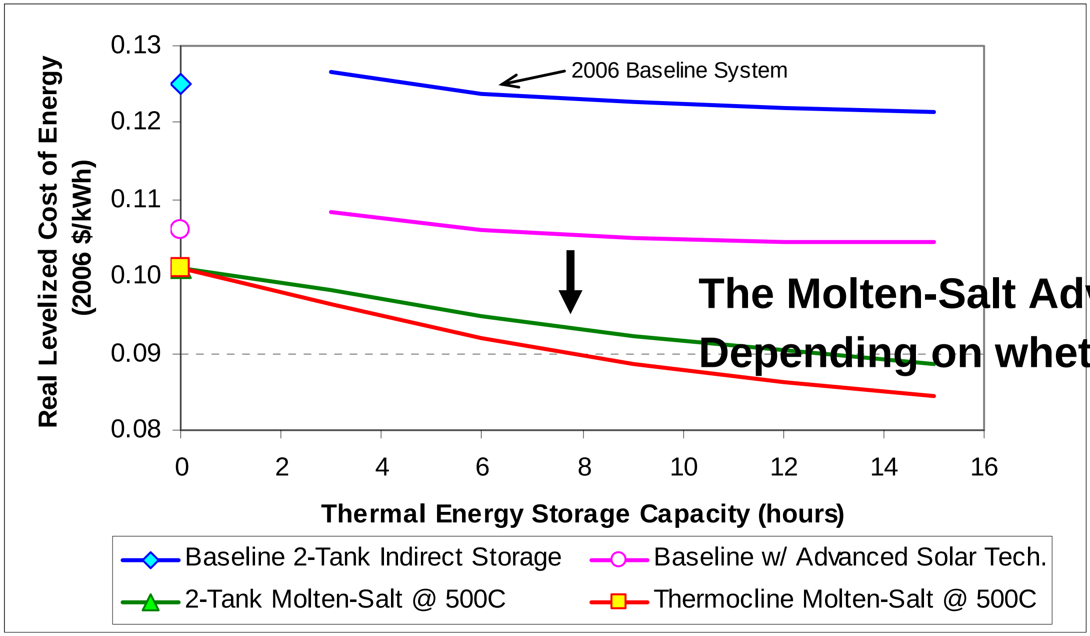


Figure 21 Levelized Cost of Power for Parabolic Trough Power Plant Using Direct Molten-Salt Thermocline Thermal Energy Storage Operating at 500ºC with Advanced Collector Technology

Yes It Is!!

LCOE by TES Type and Size



The Molten-Salt Advantage 1 – 2c/kWh Depending on whether 1 or 2 tanks

Figure 23 Real Cost of Energy as a Function of Thermal Storage Capacity and TES Technology

Ball Joint & Interconnect Development and Testing Investigations and Recommendations

(see separate ppt.)

Sandia HCE Freeze/Thaw Experimentation Using Impedance Heating

(use portions of other ppt slides)

Balljoint Evaluations at Sandia

Trough Workshop

Golden, Colorado

March 8, 2007

Doug Brosseau
Jim Moreno (retired)
Sandia National Laboratories

Topics for This Talk

- FY02 Study Objectives
- Interconnect Requirements
- Interconnect Options
- Down-Selection
- Proposed Test Plans
- Conclusions
- Status and Future Developments?

FY02 Study Objectives

- **Review interconnect options**
  - **Service requirements (temps, pressure, displacements, lifetime and cycles, insulation, materials)**

Plant Configuraton	Interconnects	$T_{loop\ out}$, C	$P_{loop\ in}$,psia,	$P_{loop\ out}$,psia
30 Mwe LS-2	Ball joints	450	185	78
		500	140	76
	Flex hoses	450	305	78
		500	212	76
80 Mwe LS-3	Ball joints	450	159	107
		500	153	123
	Flex hoses	450	188	107
		500	170	123
KJCOC specification	Flex hoses	393	600	220

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FY02 Study Objectives (cont'd)

- Review interconnect options (cont'd)
  - Balljoints, flex hoses, swivel (rotating) joints
- Evaluate design and materials solutions
  - Packing candidates
  - Balljoint alternatives (flex hoses, swivel joints, hybrids)
  - Reducing balljoint torque and leakage
- Develop test plans
  - Down-select alternatives, with viable supplier partners
  - Develop Test Plans (rough schedule and funding estimates)

Interconnect Requirements

- Hitec XL ternary molten nitrate salt formulation
- Materials compatible with Hitec XL at 500°C
- 300°C loop inlet temp, 450/500°C loop outlet temp
- Reduced pressure demands (already noted)

- 210-degree rotation daily
- ±8 inch thermal displacement of HCE along its axis
- ±2 inch thermal displacement of crossover pipe axis

- 30,000 cycle lifetime desired

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Interconnect Options

- **Balljoints**
  - **Favored at Kramer due to flex hose concerns**
  - **Lower ΔP, lower chance of fatigue failure, more reliable, cheaper**
  - **But, different seal system required for molten salt conditions**

- **Flex Hoses**
  - **Revisit given lower pressures**
  - **Salt spill consequences less severe than oil**
  - **Re-optimization of flex hose configurations…**

- **For both, freeze protection and recovery pose special challenges; topic of another talk!**

Flex Hose Configurations

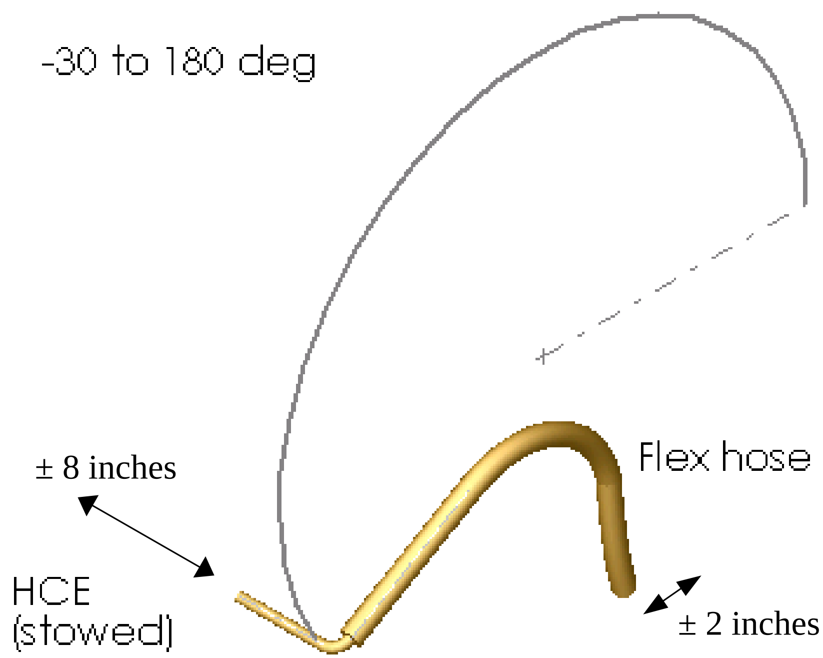

Figure 1. Interconnect geometry, showing displacements that must be accommodated (±2 inches is at loop-end crossover pipes only). The figure also illustrates the single -hose option, and the origin of its torque in the HCE's expansion.

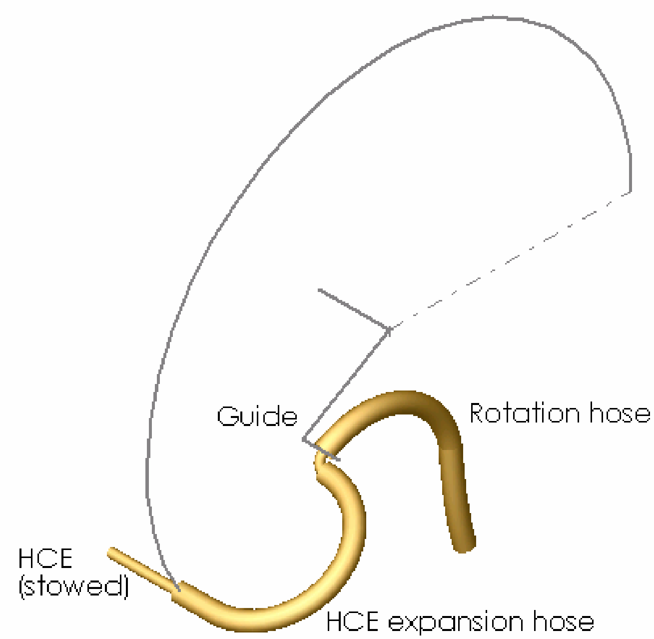

Figure 4. Two-hose reduced-torque interconnect. The guide, driven by the SCA, would include a support system (not shown) for the HCE expansion hose.

Interconnect Options

- **Swivel Joints**
  - Single axis rotary joint partially takes up cross-over displacement
  - Flex hose (short), supported by guide rail, rotates with joint, much less torque by limiting degrees of freedom

Figure 5. Rotary joint – hose interconnect. The guide, driven by the SCA, would include a support system (not shown) for the HCE expansion hose

Down Selection

- Balljoints with boron nitride-filled alumina or metallic braid, backed by boron nitride flake in the seal chamber (boron nitride not adequately tested in molten nitrate salts) – Advanced Thermal Systems partner motivated to prototype and test

- Balljoints with live-loaded pressure-assisted ceramic seals – no industry partner identified at the time

- Swivel joints with live-loaded pressure-assisted ceramic seals with lined flex hose connection to the HCE – Rotherm and American Boa very motivated to collaborate

- Optimized and lined flex hoses

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Proposed Test Plans

- Re-connect and consult with manufacturer partners on design options, materials, costs, lead times, etc.
- Contract for design and fabrication of prototypes
- Design and build test apparatus: emphasis on simplicity, yet suitable for development iterations and proof of concept
- Exercise the joints at various pressures/temperatures to characterize torque, sealing, leakage
- Modify test apparatus to mechanically and thermally cycle the joint – run 3000 cycles and identify follow-on

Conclusions

- Potential viable solutions to interconnects in molten salt service have been identified
- There are technical challenges and risks
- This is an issue needing aggressive development and resolution
- Materials issues are important to address
- Freeze protection is a related and important area to incorporate into a comprehensive test program

Salt Freeze Protection & Recovery

Trough Workshop

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Topics for This Talk

- Define the Challenge
- Past Studies and Assumptions
- Modeling Results and Issues
- Old Sandia Impedance Heating Apparatus
- Testing Approach for FY07

Are We Crazy?!

The Challenge:

Are we really serious about flowing molten salt through miles and kilometers of thin-wall steel tubes?

Are we prepared for:

- **Frequent freeze-ups?**
- **Freeze recovery?**
- **Damage on expansion?**
- **Normal startup/shutdown?**
- **Periodic HCE maintenance?**
- **Human error?**

Past Studies

Pacheco, J.E. and Kolb, W.J., "Comparison of an Impedance Heating System to Mineral Insulated Heat Trace for Power Tower Applications," 1997 ASME International Solar Energy Conference, Washington, DC, April 27-30, 1997

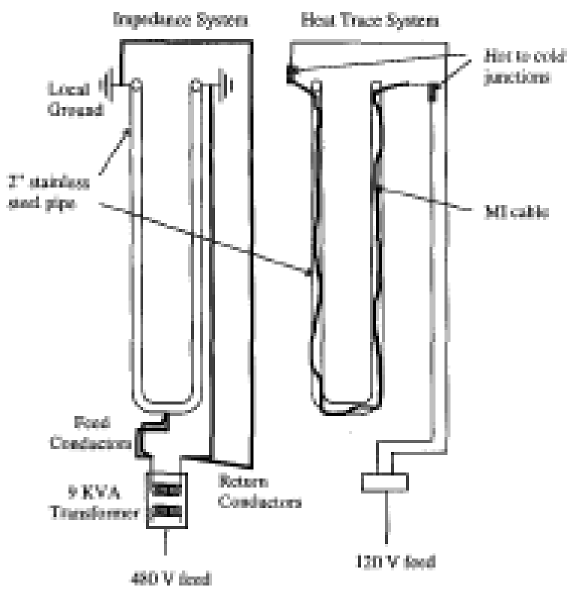
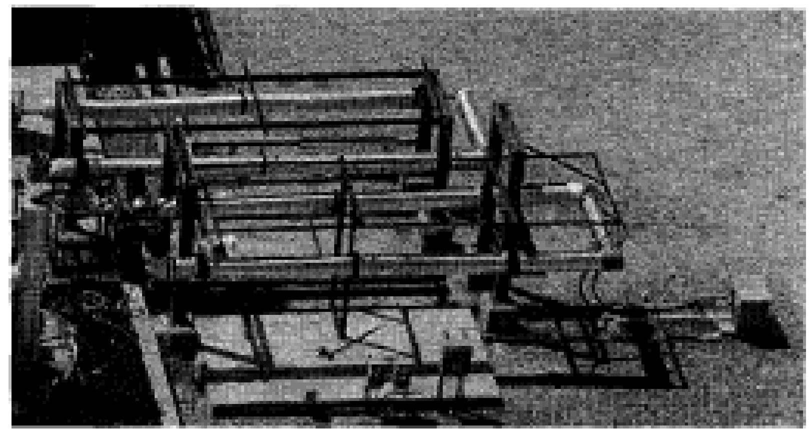


Figure 1. Schematic of impedance heating and MI heat trace system.



Limited static tests that compared and <u>demo'd the potential usefulness of impedance heating systems</u>. High steady state power required compared to heat trace; pipes only.

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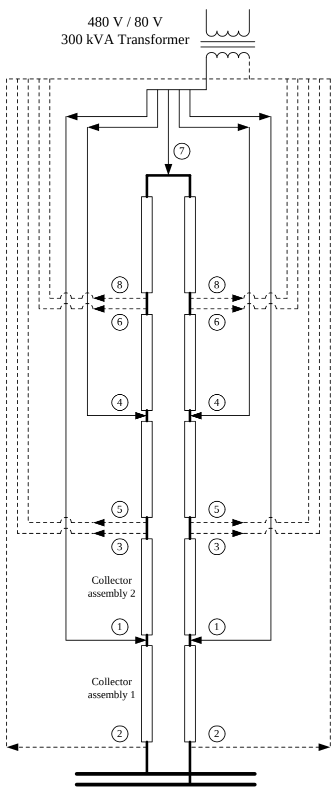
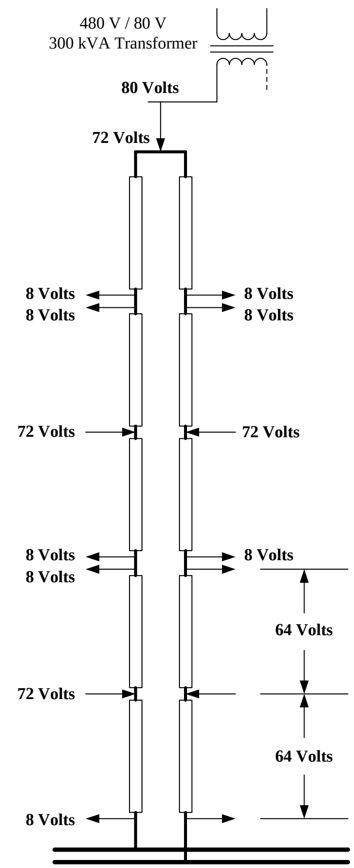
Past Studies (cont'd)

Kearney & Associates, "Engineering Evaluation of a Molten Salt HTF in a Parabolic Trough Solar Field, Task 6 Report: Final System Performance and Cost Comparisons," NREL Contract No. NAA-1-30441-04, August 20, 2001



Nexant (Bruce Kelly) impedance heating system design concepts for commercial parabolic trough plants. Each 24-HCE SCA on separate circuit. <u>Not tested, complex, careful cable sizing required, and does not take into account likely HCE condition variability in the field</u>.

Assumes 180C above ambient in 30 minutes.



Latest Concerns and Modeling

- **Kramer and Harper experience frequent freeze events with VP-1**
- **Higher salt freeze points will only worsen the situation**
- **Station blackout, loss of flow, was just one scenario…**

- **Bare tubes exist in the field and will freeze first.**
- **One frozen HCE, and the entire loop will freeze on loss of flow.**

- **Objective: we need to prove that thawing the field is possible without damaging HCE's, piping, balljoints, and other components.**

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“Typical” HCE Heat Loss Curves

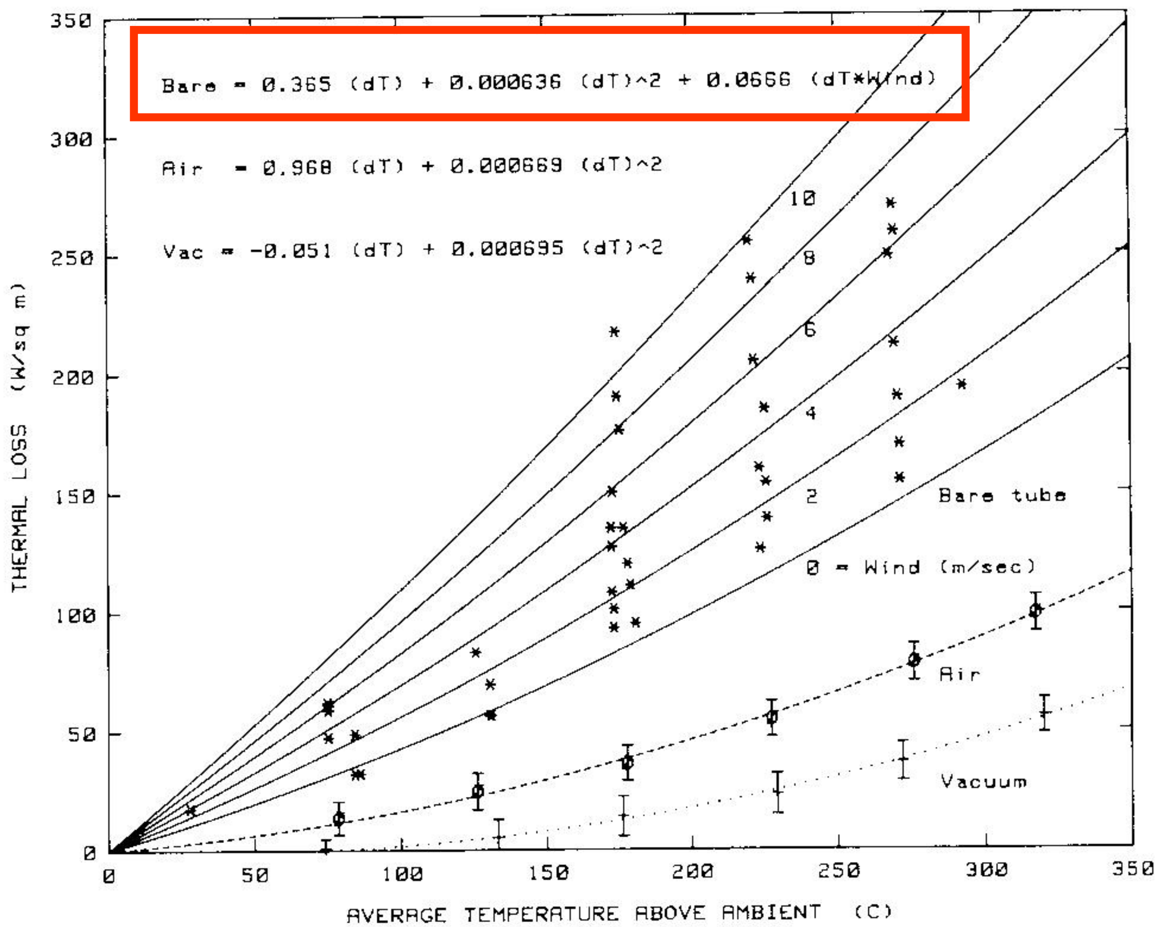

Figure D-15. SEGS LS-2 Thermal Loss vs. Temperature and Wind - Cermet Receiver.

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Pre-Heating an Empty HCE

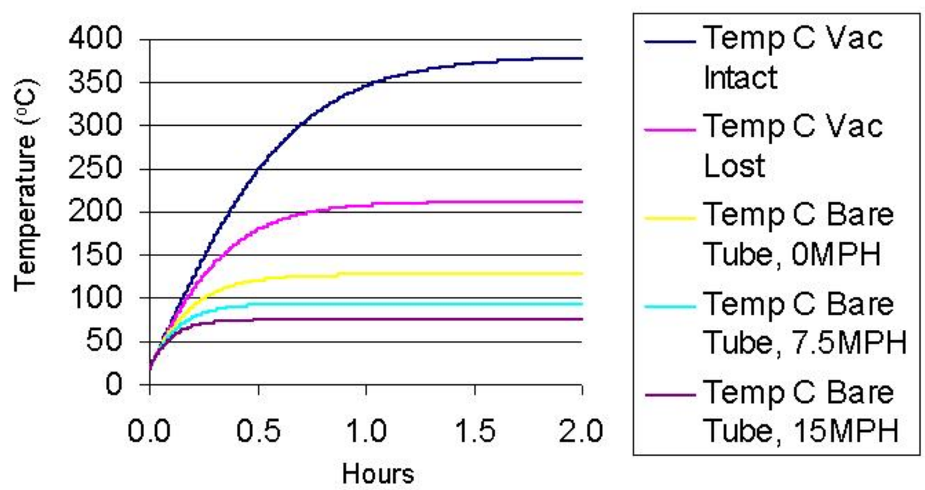

Figure 3 Heatup of empty HCE given an ambient temperature of 20C and an input power of 235 W/m.

Result: it is not possible to achieve 180°C delta with bare tubes

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Heating a Filled HCE

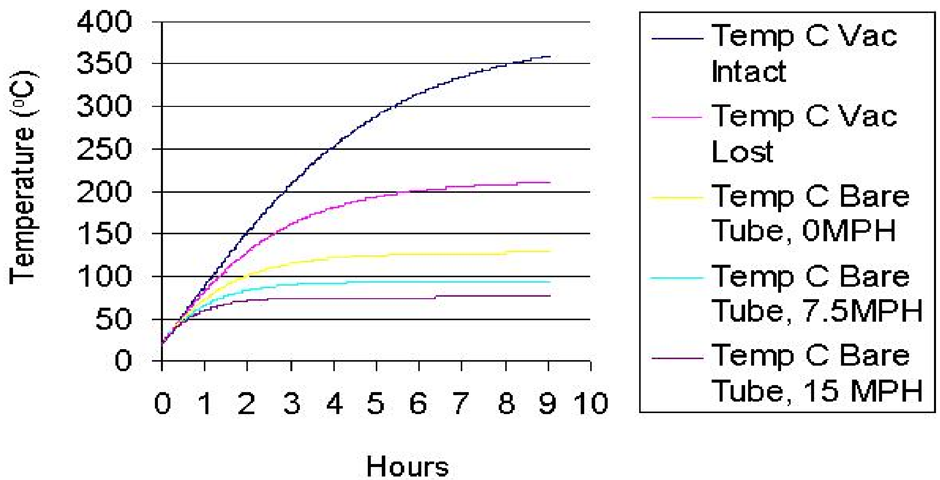

Figure 4 Heatup of a filled HCE given an ambient temperature of 20 oC and an input power of 235 W/m

Note: Model does not include isothermal thaw period. After those plateaus, temp rise continues as shown. Thawing times significantly increase compared to empty tubes.

<u>Result</u>: after a freeze-up event with salt in the HCEs, once again it is <u>not possible to achieve 180°C delta with bare tubes</u>. Variable tube conditions will cause uneven thawing, and likely HCE damage.

Available Apparatus for Testing

- INDEECO 9 KVA transformer (480 V input, multiple output terminals)
- Original control panel
- Capable of series and/or parallel on up to 9 HCE's
- HCE's in variety of conditions; access to "retired" HCE's from Kramer and/or Harper Lake
- An old salt pump (never used)
- Possible use of existing pump/valve stand (more $'s)

Testing Approach for FY07/08

Static Testing

- Study past designs, familiarize with equipment, talk to vendors
- Determine testing matrix, data needs
- Setup HCE's, test empty and full, different salt formulations, variety of HCE configurations
- Understand heat-up times, energy consumption, HCE damage rate. Validate models with vacuum intact, degraded, and bare.

NOTE: Funding has not been allocated for this testing

Pump-Loop Testing

- Likely in FY08 (setup and/or planning in FY07)
- Varying pre-heat temperatures/conditions, flow conditions
- Freezing events, freeze recovery with various HCE configurations