INFINIA

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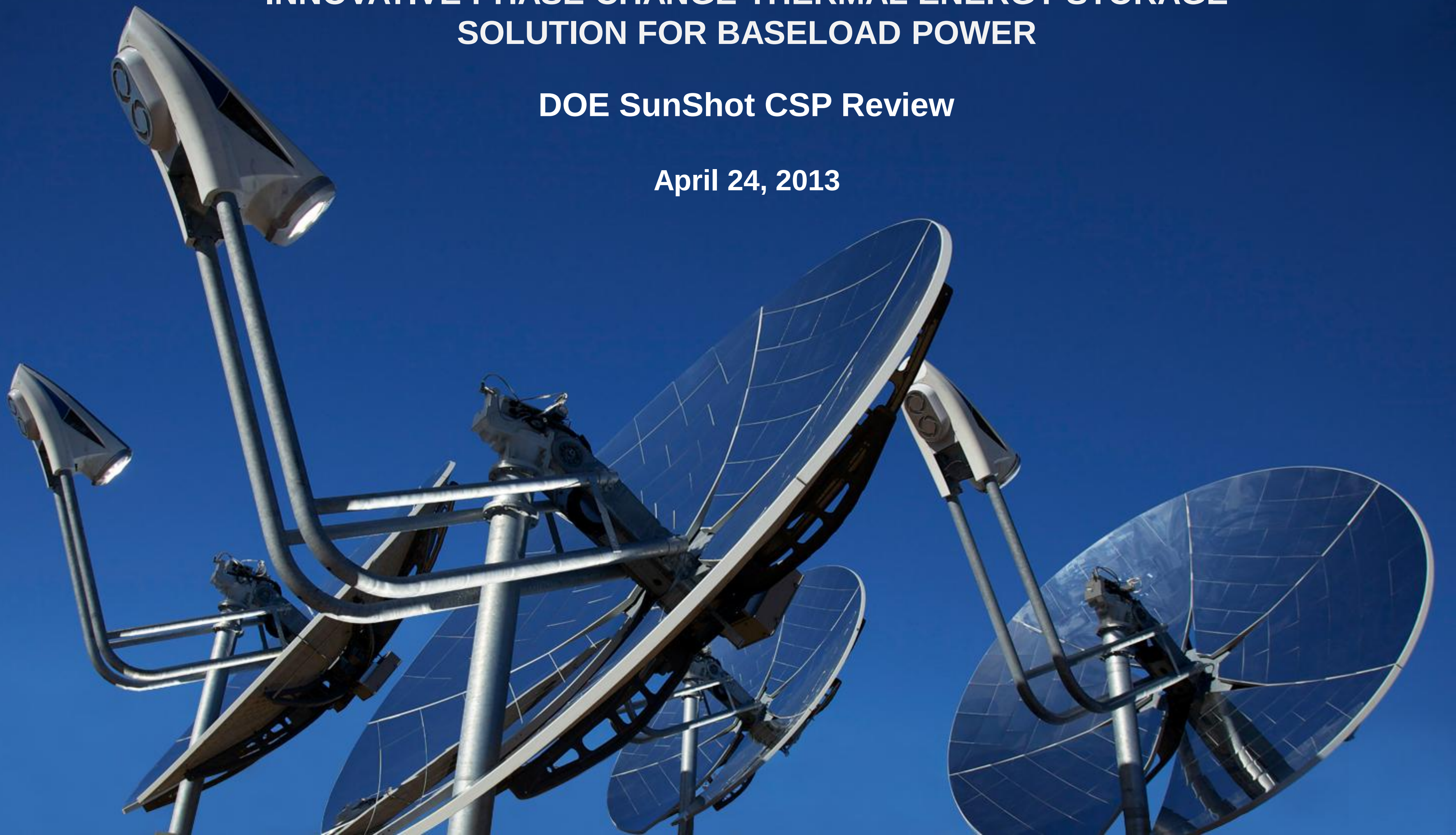
INNOVATIVE PHASE CHANGE THERMAL ENERGY STORAGE SOLUTION FOR BASELOAD POWER

DOE SunShot CSP Review

April 24, 2013



PROJECT OVERVIEW

Project Title:	Innovative Phase Change Thermal Energy Storage Solution for Baseload Power
Awardee:	Infinia Corporation
Principal Investigator:	Songgang Qiu
Presenter:	Maury White
Subcontractor:	Temple University
Project Period:	06/01/10 – 04/30/13 (Phase 1)

PRESENTATION OUTLINE

- Background & Description
- Objectives and Goals
- Infinia Baseload Technology Concept
- Advantages over Alternatives and Energy Comparison with Molten Salt TES
- Implementation Options
- Subscale Module Development and Test Results
- Lab-Scale Module Development and Test Results
- Solar Receiver to TES Heat Transport System
- System Preliminary Design
- LCOE and Capacity Factor Analysis
- Conclusions & Path Forward

BACKGROUND & DESCRIPTION

- The baseline TES approach for most Trough and Central Receiver Systems uses sensible heat capacity of molten salt
- This necessitates power converter operation over a range of temperatures which reduces integrated efficiency
- Freezing of molten salt needs to be avoided and a heat transfer fluid must be pumped throughout the system
- Phase Change Materials (PCM) provide a large increase in energy storage density by using latent heat of fusion for TES
- An Infinia heat pipe PCM TES was described earlier – this project maintains hermetic sealing but avoids heat pipes within the TES and is scalable to a high capacity

OBJECTIVES & GOALS

Overall Objective: To develop and validate an innovative, scalable phase change salt thermal energy storage (TES) system that can interface with Infinia's free-piston Stirling engines or other power converters.

Project Innovation: The phase change material latent heat energy storage offers high energy density as compared with sensible heat storage systems, while a liquid metal pool boiler heat transport system that is integral with the TES salt avoids heat pipes and costly pumping systems.

INFINIA BASELOAD TECHNOLOGY CONCEPT

- The TES salt and Na heat transport fluid are integrated into a hermetically sealed enclosure that includes the engine heater head and stratifies based on density differences

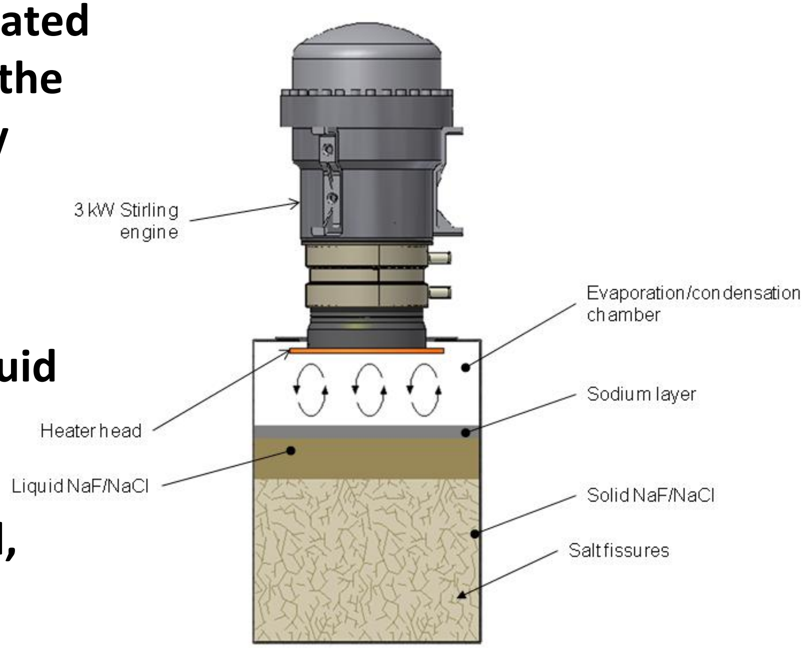
- A liquid salt layer floats on the ≈ 40% more dense solid, and a thin layer of liquid Na floats on the liquid salt.

- When heated, the salt melts and migrates upward, while the solid portions ideally settle downward.

- The liquid salt at the top transfers heat to the adjacent sodium, which causes the sodium to vaporize and the salt to solidify and drop to the bottom.

- The Na vapor will condense on the coldest surface to which it is exposed (the engine heater head).

- The Na condensate returns to the Na pool by gravity.

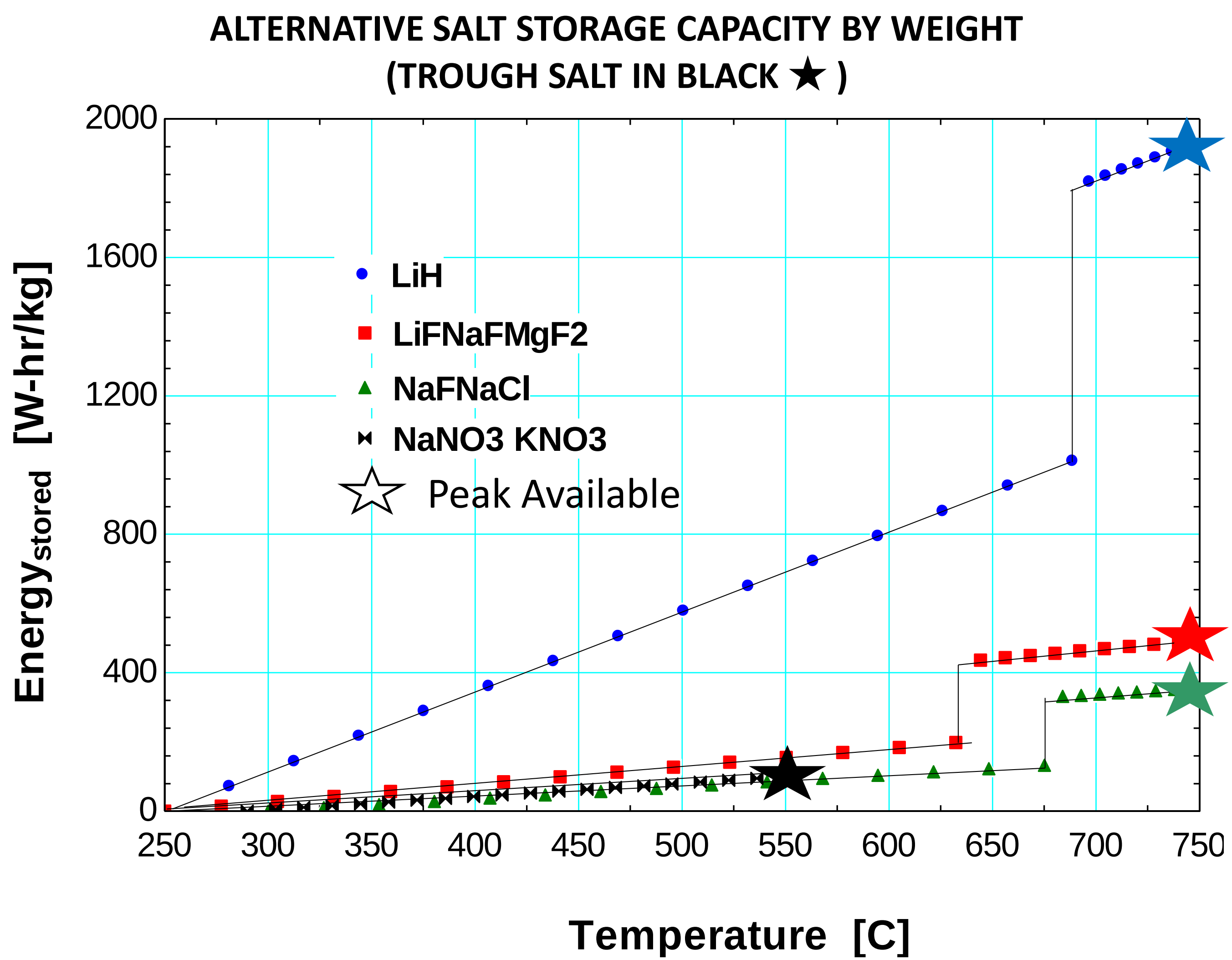


Conceptual configuration of integral salt and pool boiler TES system

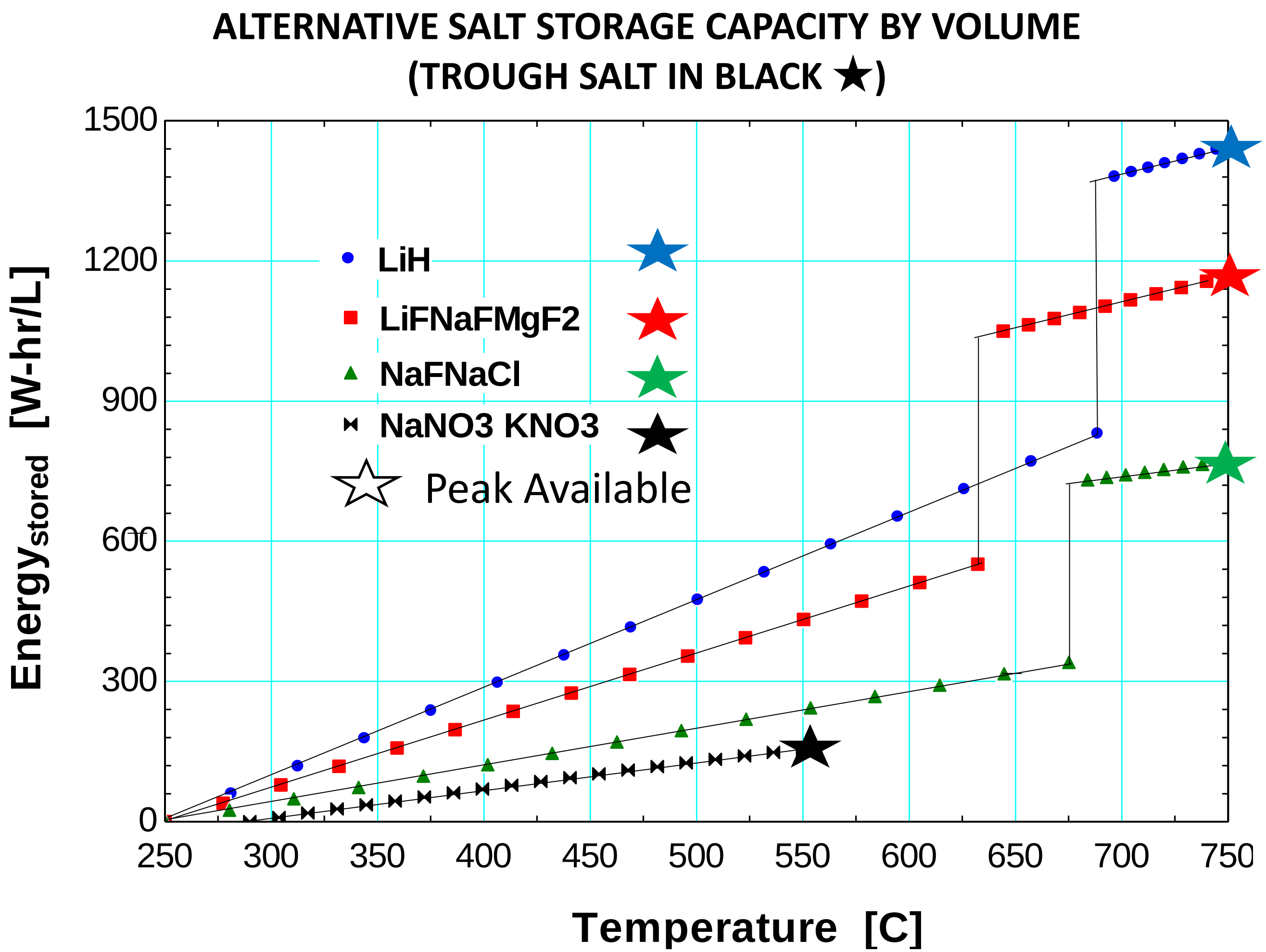
TECHNOLOGY ADVANTAGES OVER ALTERNATIVES

- Integral TES/pool boiler with latent heat storage can adapt to any type of power conversion unit from a few kW to tens or hundreds of MW
- Phase change latent heat TES has very high energy density
- Engine extracts heat near melt point to always operate at selected optimum temperature
- Eliminates the need for heat pipes to reduce cost and complexity
- Pure or eutectic salts can be selected for virtually any melt temperature from 300 C to 1300 C
- NaF/NaCl eutectic selected for very low cost with excellent 680 C melt point
- Hermetically sealed salt/liquid metal module is maintenance free
- No high temperature pumps or swivel joints needed
- Salt freezing is a non-issue that occurs during normal operation
- Earlier Infinia small LiF/NaF test module cycled through three 652°C melt/freeze cycles per day for over 4 years with negligible impact on stainless steel containment vessel

MOLTEN AND PHASE CHANGE SALT ENERGY STORAGE BY WEIGHT

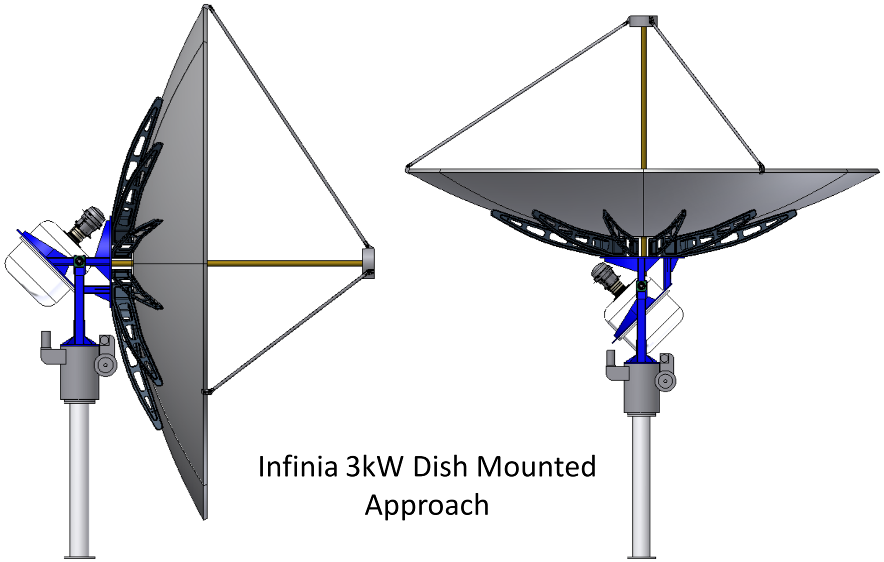


MOLTEN AND PHASE CHANGE SALT ENERGY STORAGE BY VOLUME



BASELOAD TES IMPLEMENTATION OPTIONS

- **The selected TES system design approach is to mount the module and engine behind the dish as a dish forward counterbalance**
- **A pumped loop heat pipe transports heat from the solar receiver to the TES module as with the Sandia concept**
- **The engine must be mounted above the pool boiler and avoid direct contact between salt and the heater head**
- **The TES/engine assembly must be able to rotate ±45° from vertical to cover all solar tracking positions**
- **12 hour TES is feasible for this dish configuration**
- **An alternative future potential TES configuration is to utilize a central receiver with a directly heated integral TES on a tower with various power converter options**

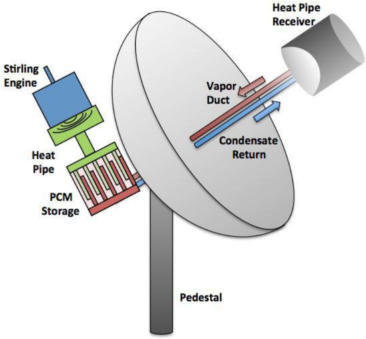


Infinia 3kW Dish Mounted Approach

Morning/Evening Position

Midday Position

30kW Tower Configuration Concept



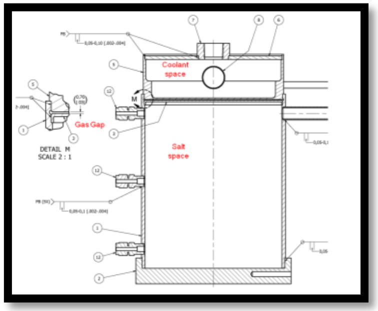
Sandia 25 kW Dish Mounted Heat Pipe TES Concept

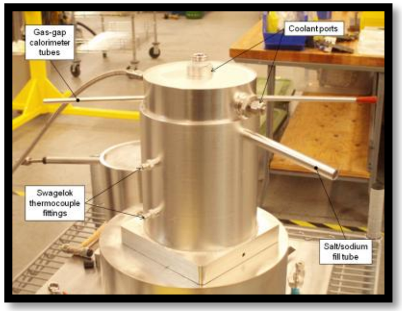
SUBSCALE TES MODULE DEVELOPMENT AND TESTING

Three generations of subscale modules were developed to:

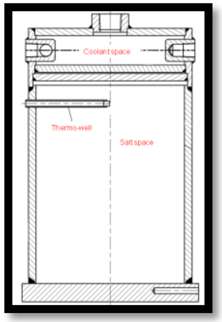
- Prove the basic physics before committing to lab-scale unit integrated with a 3 kW engine
- Gain experience processing PCM salt and sodium
- Gen 1 and Gen 2 had calorimeter, processing and instrumentation issues that limited results
- The major issue identified was the tendency of the liquid salt to form a surface crust without sinking

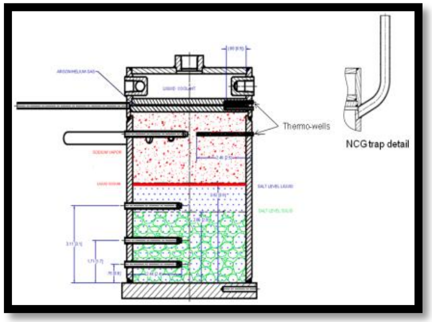
Generation1 Subscale Module



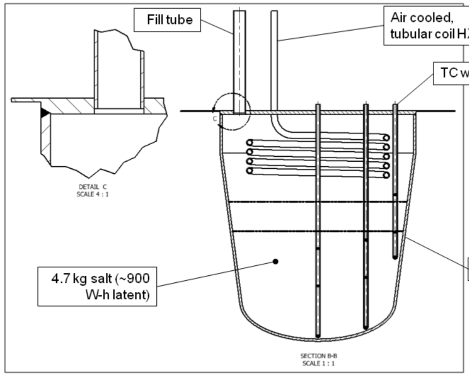


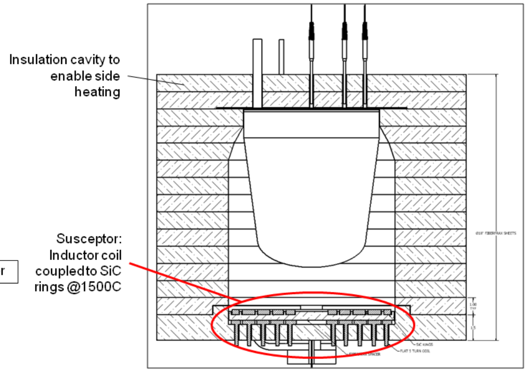
Generation 2 Subscale Module





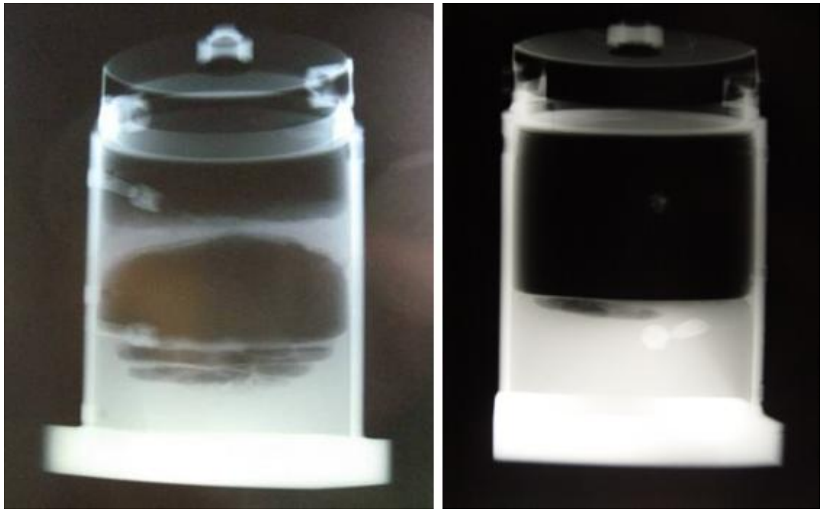
Generation 3 Subscale Module

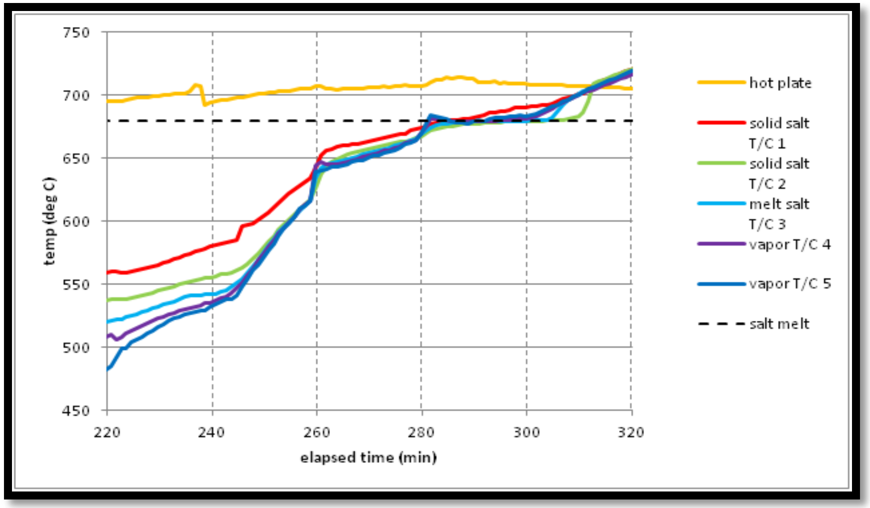




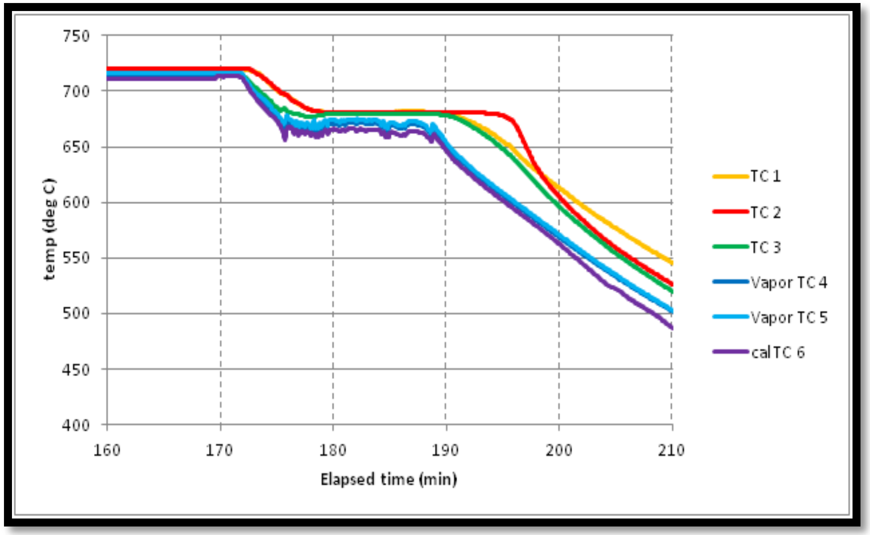
GEN 1 AND 2 SUBSCALE MODULE DESIGN AND TESTING

- Gen 1 gas gap calorimeter diaphragms damaged by Na fill subcontractor
- Temperature data during heating and cooling show phase change operation and ≈2/3 effective heat recovery
- X-Rays of Module after salt melt demonstrate salt bridge (left) and elimination of bridging by heating sides while cooling (right)





Charge Data



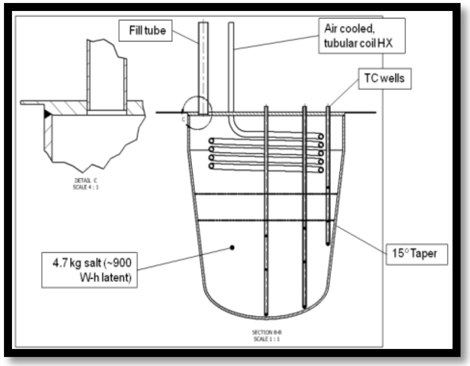
Discharge Data

GENERATION 3 TES MODULE DESIGN

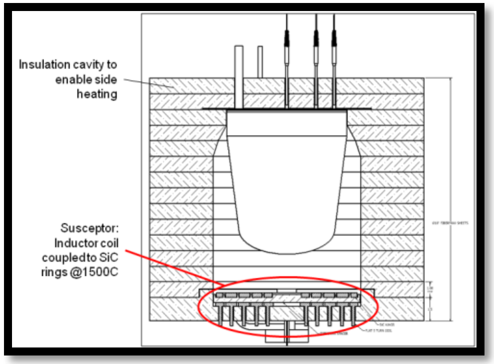
The overall objective of Gen 3 was to validate functional aspects of the Baseload concept in a scale and configuration closer to the lab-scale one-hour demonstrator.

Improvements relative to Gen 1 and Gen 2:

- ❑ Eliminated thermal short circuit around the calorimeter
- ❑ Made input heat flux more representative of actual solar conditions
- ❑ Reduced excessive insulation losses
- ❑ Introduced the effect of tapering the vessel side walls to provide easier liquid salt flow to the surface during heating



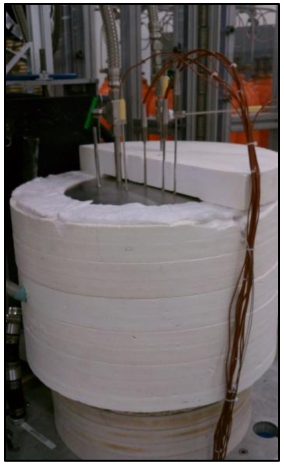
Gen 3 Subscale Module

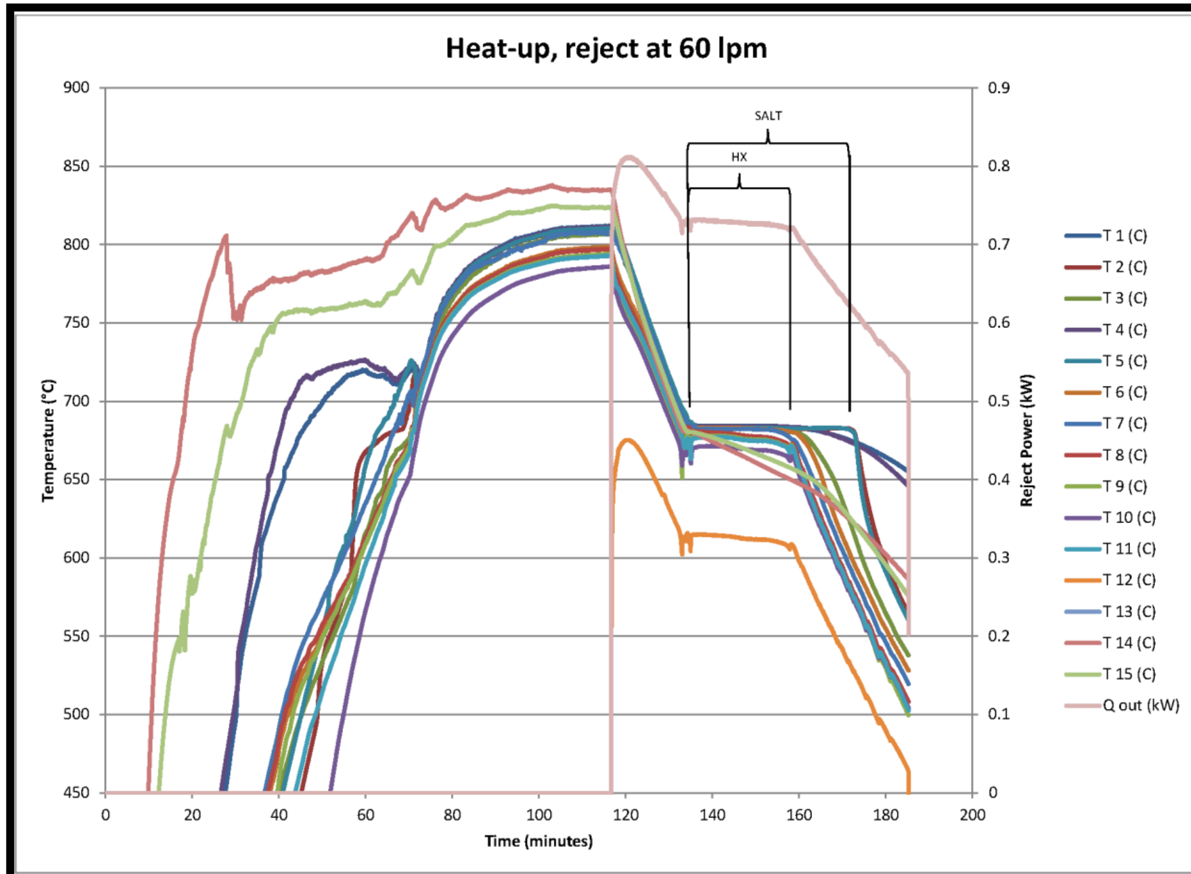


Gen 3 Module Susceptor Heating

Completed Gen 3 Modules

GENERATION 3 TEST RESULTS



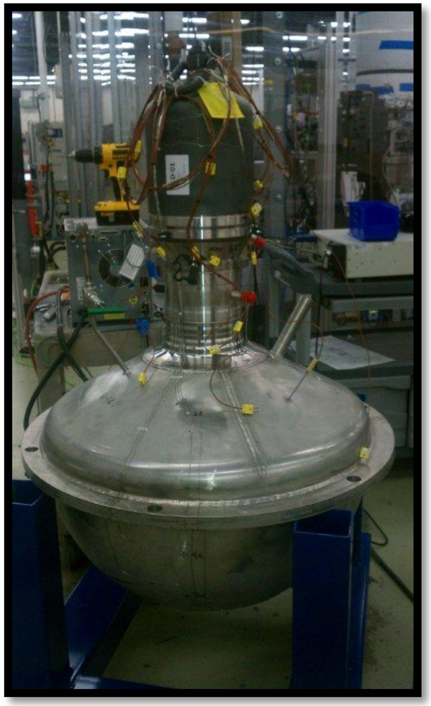


- Photo shows unit ready for testing with some insulation removed
- X-ray shows series of salt bridges formed during heat extraction
- Latent heat extraction is consistently about 2/3 that of the salt's ideal potential

TES MODULE LAB-SCALE DEMONSTRATION HARDWARE

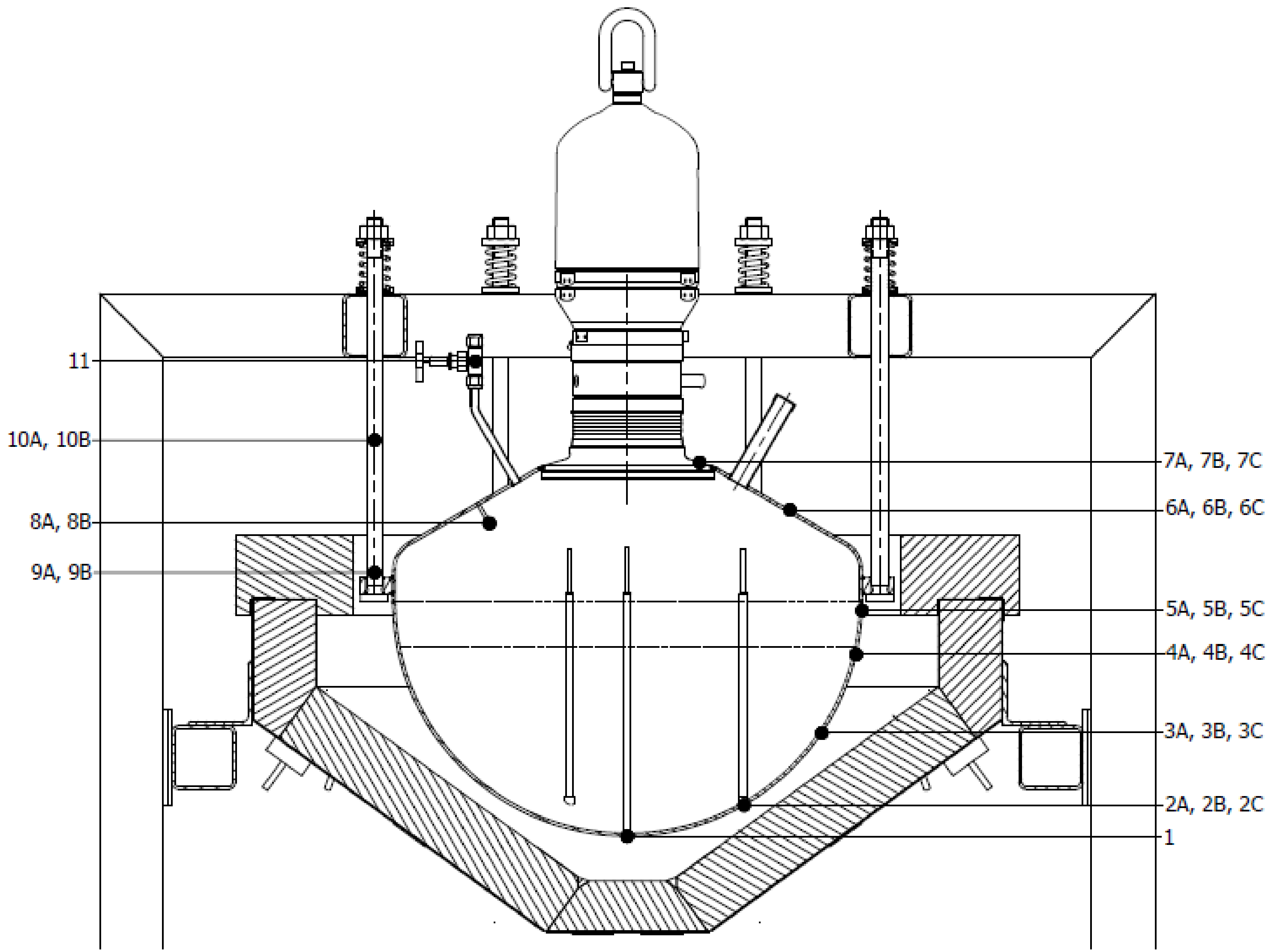
APPROACH

- Fabricated from 304 stainless steel
- Standard elliptical end cap modified for welding to heater head and standard 74 cm (29 in.) diameter hemispherical dome
- Thermosiphons incorporated internally to improve internal heat transfer function
- Charged with 170 kg NaF/NaCl eutectic salt and 6.5 kg sodium for the pool boiler
- Preliminary testing conducted December 2012



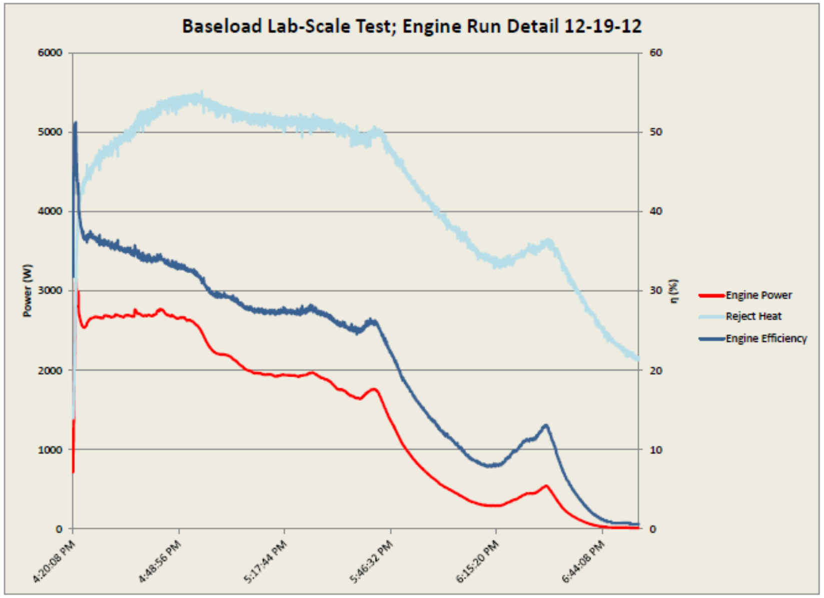
1 Hour Laboratory Module

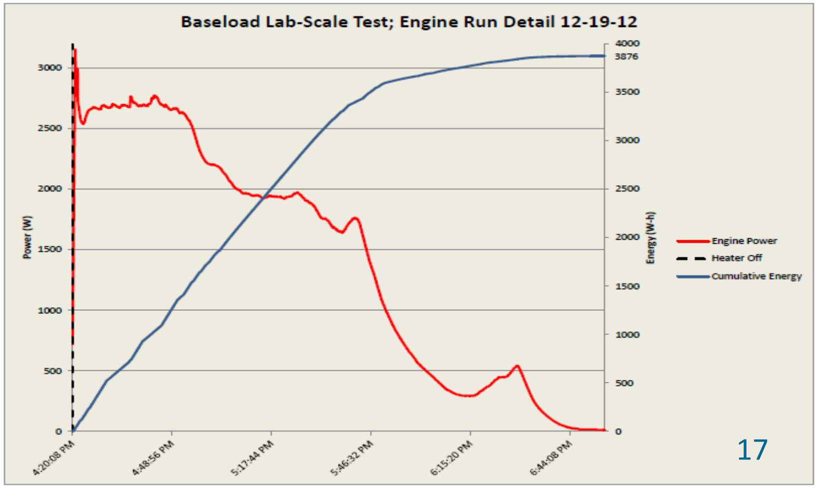
LAB-SCALE UNIT THERMOCOUPLE LOCATION IDENTIFIER



LAB SCALE TEST UNIT RESULTS AND CONCLUSIONS

- Sodium pool boiler heat transport to engine provided up to 3 kW electric output
- 3.9 kWh of engine net energy output was achieved from stored TES
- This was more than original objective but only about half the actual potential
- Salt crusting during heat extraction is the primary residual issue
- The thermosiphon designed to reduce or eliminate crusting was destroyed during fabrication so could not be evaluated





SOLAR RECEIVER/HEAT TRANSPORT SYSTEM (HTS)

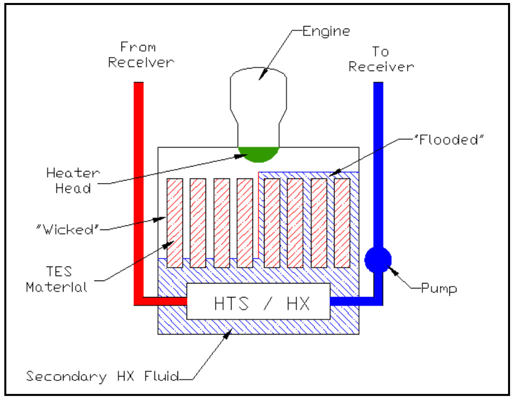
- A high-level HTS trade study was conducted
- Two basic configurations were evaluated for both dish and tower options
  - Ground-mounted engine/TES system physically de-coupled from the heat (solar) receiver
  - Engine/TES system mounted on dish or tower

- HTS using pumped loops with either molten salts or liquid metals were considered
- Stirling engines (without TES) have demonstrated improved performance when heated by liquid metal pumped loops
- A pumped loop sodium heat pipe is fundamentally different with heat transport by sodium vaporization/condensation and pumping requirements about two orders of magnitude lower

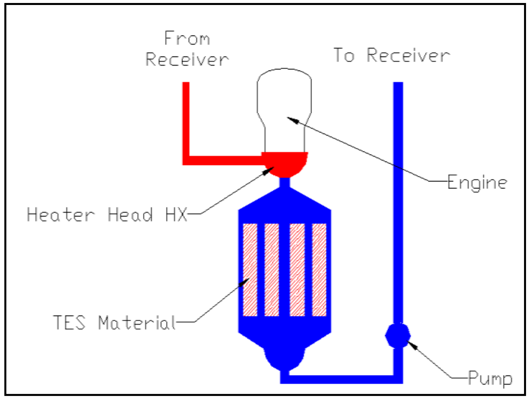
- Conclusions
  - Existing mechanical pumps for salts or liquid metal heat transport fluids are generally limited to about 500 to 550°C and require regular maintenance
  - Electromagnetic pumps can go to higher temperatures but have low efficiency
  - High costs for either system make them impractical for primary HTS pumping with systems below several tens of kW
  - A pumped loop sodium heat pipe between the solar receiver and TES/engine module behind the dish is the most practical option for a 3 kW system

HEAT TRANSPORT SYSTEM (HTS) CONCEPT EVALUATIONS

With and without intermediate HX identified

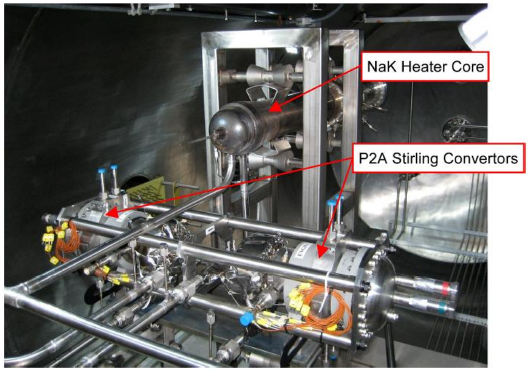


Pumped System with Intermediate HX



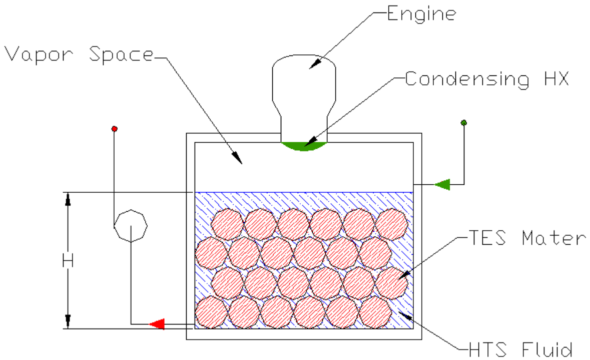
Pumped System without Intermediate HX; Closed Configuration

Similar pumped looped systems under test at NASA



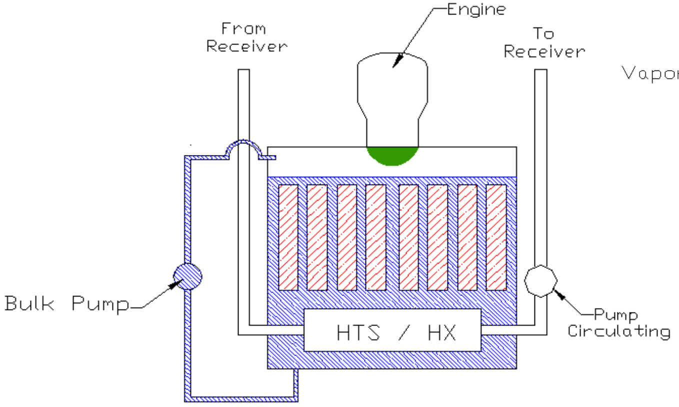
2kW Stirling Engine Test Set-Up; Liquid Metal (NaK) HTS Thermal Input

Hybrid System Employing a Single Heat Transfer Fluid Concept

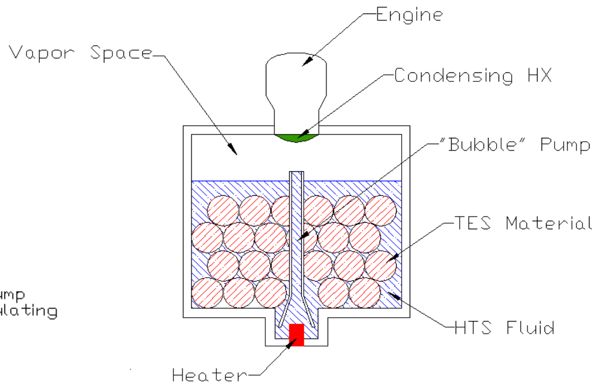


Hybrid Concept

Alternative Pump Configuration Concept Identified



Bulk Circulating Pump Configuration

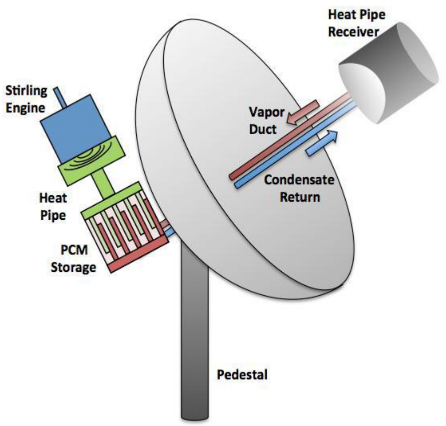


Bubble-Lift Pump

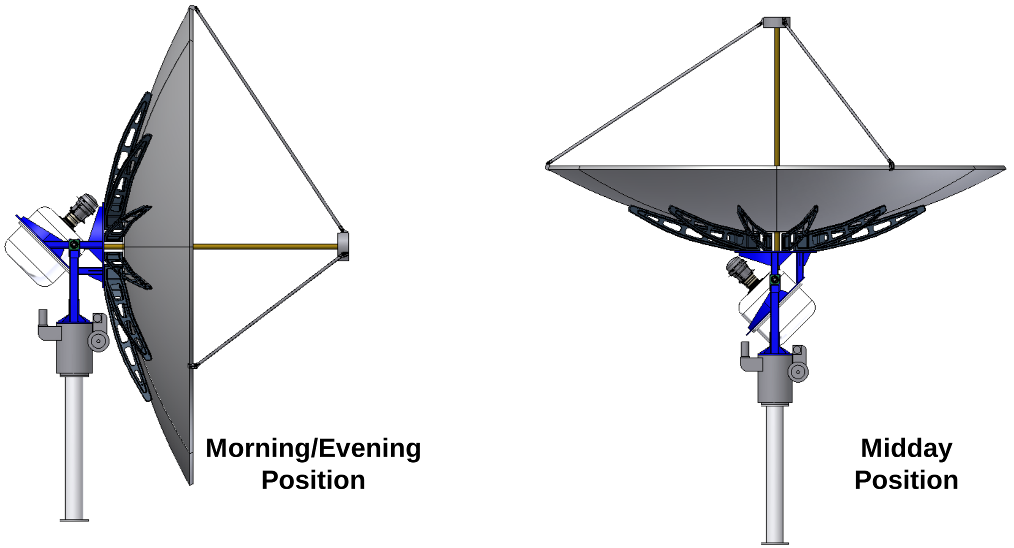
SYSTEM PRELIMINARY DESIGN RESULTS

- At this time, the larger 3 kW_e, 12-hour storage system has not been developed in detail since it is dependent on results from testing the smaller,1-hour device
- Pumped loop systems using liquid metal or salt working fluids have been deemed impractical for dish applications
  - ❑ Mechanical pumps are limited to temperatures significantly lower than can be effectively used in the current system, and even those are very expensive and sized for much larger systems
  - ❑ The only alternative to this would be to use EM pumps, which are prohibitively expensive and inefficient
- Selected approach is to utilize a pumped loop receiver-to-TES heat transport heat pipe similar to that used by a Sandia 25 kW dish engine concept that is based on an imbedded heat pipe array within the TES

SELECTED SYSTEM CONFIGURATION



Sandia 25 kW Dish Mounted Approach



Infinia 3kW Dish Mounted Approach

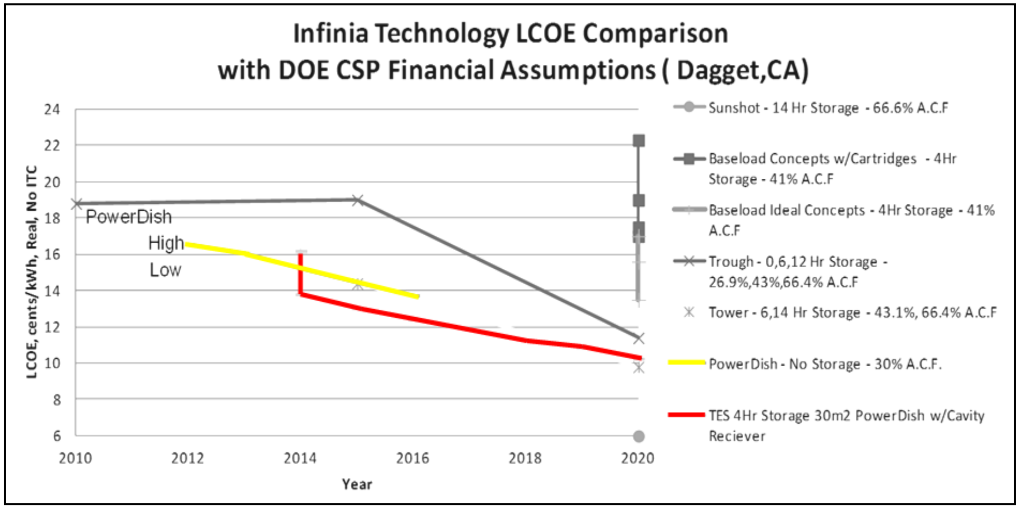
LCOE AND CAPACITY FACTOR ANALYSIS

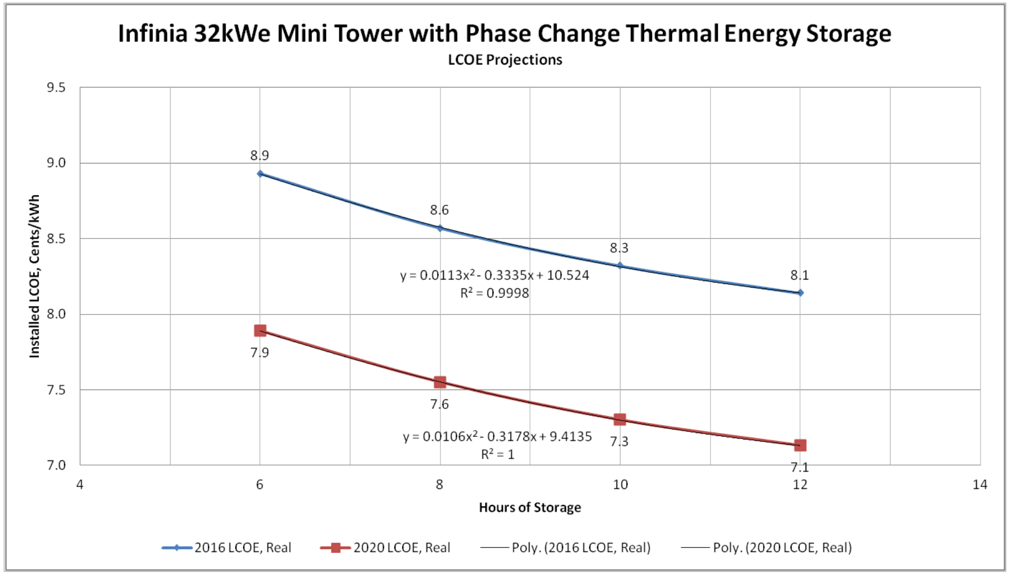
An LCOE comparison of various technologies using DOE CSP financial assumptions showed the Infinia PowerDish™ technology provides one of the lowest LCOE values.

Inclusion of TES with the PowerDish™ reduces initial costs by 20%, after which a 3% cost down with a 2% performance increase is deduced.

LCOE analysis for the PowerDish™ used 4 hours of TES.

Capacity factor analysis for a mini power tower showed a 10% LCOE reduction as capacity increased from 6 hours of TES to 12 hours.





CONCLUSIONS & PATH FORWARD

CONCLUSIONS

- Phase change salt TES offers dramatic advantages over alternative approaches
- Most elements of Infinia's simple and elegant integral TES and pool boiler concept function very well
- The salt crusting during heat extraction remains the primary unresolved issue

PATH FORWARD

- Outside funding support is needed to continue development
- More testing of existing lab-scale TES module is needed to fully characterize operation
- Further evaluation of salt physical and thermophysical processes is needed to understand and mitigate crusting problem
- Thermomechanical mitigation of crusting using thermosiphons or other means needs to be evaluated – a method for retrofitting the damaged thermosiphon has been identified and should be implemented

Thank you

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