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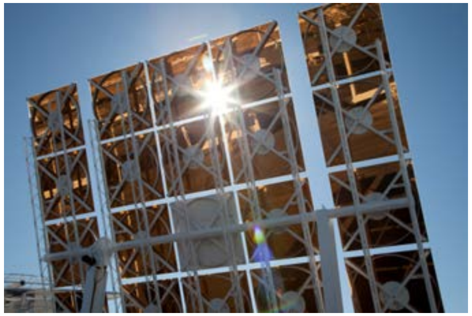

Dish Stirling High Performance Thermal Storage

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SunShot U.S. Department of Energy

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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National Solar Thermal Test Facility:
World Class Capabilities at Your Service

- Testing
  - 5MW$_t$ Central Receiver
  - 80kW dish test beds
  - Molten Salt Test Loop
  - Optical metrology
- Development and analysis
  - Optical models
  - Thermal models
  - System models
  - On-site machine shop and fabrication
- Key software tools
  - Available for licensing
  - Optical metrology for development and production
  - Glint and glare
  - Design tools

National Solar Thermal Test Facility:
Rich Dish Stirling Tradition

- Involvement with most Dish Stirling developments since the 1980’s
- Key expertise:
  - Systems level design and development
  - Controls and tracking algorithms
  - Dish optical design and analysis
  - Optical metrology
  - Optical alignment
  - Reliability analysis and improvement
  - Receiver design, materials, analysis, and testing
  - Heat pipe receivers
  - Mirror fabrication
  - Assembly
  - Testing
  - Performance validation
- Key partnerships:
  - DOE
  - McDonnell Douglas
  - SAIC
  - LaJet/Sunpower
  - Cummins Power Generation
  - Infinia/STC
  - Boeing
  - Stirling Energy systems

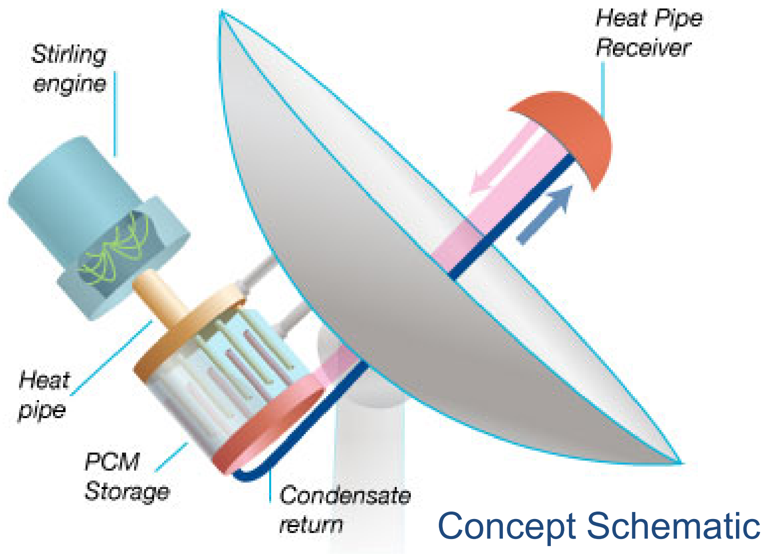
Dish Storage Project Objectives

- Goal:
  - Provide a feasible technical solution for 6 hours of storage on large (25kWe) dish Stirling systems
  - Enable high performance dish Stirling systems to increase capacity into evening hours

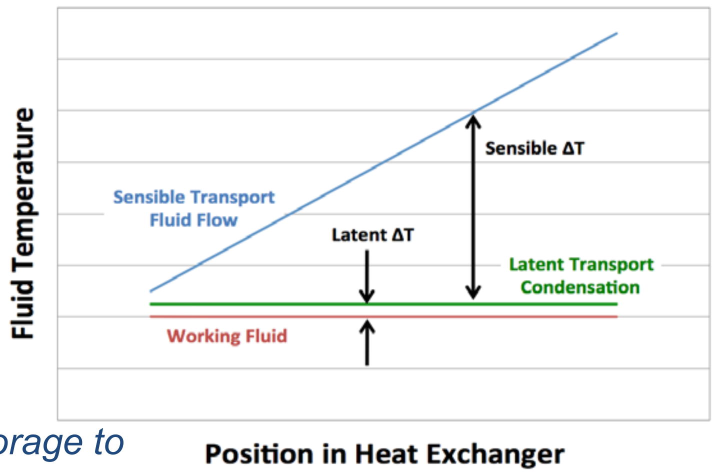
- Innovation:
  - Dish Stirling systems have demonstrated path to SunShot Cost Goals of 6-8 ¢/kWh, and is further enhanced by storage
  - Concepts for dish storage currently pursued are limited to small dish systems with limited time of storage due to weight at focus
  - Proposed solution improves system performance, lowers LCOE, and reduces system cost through more efficient structural design

Technical Approach Overview

- Latent transport and storage system matches Stirling isothermal input
  - High performance latent storage
  - Heat pipe input and output
- Rear-mounted storage and engine
  - Balanced dish
  - Closes pedestal gap allowing efficient structure
- Pumped return negates elevation change issues



Concept Schematic

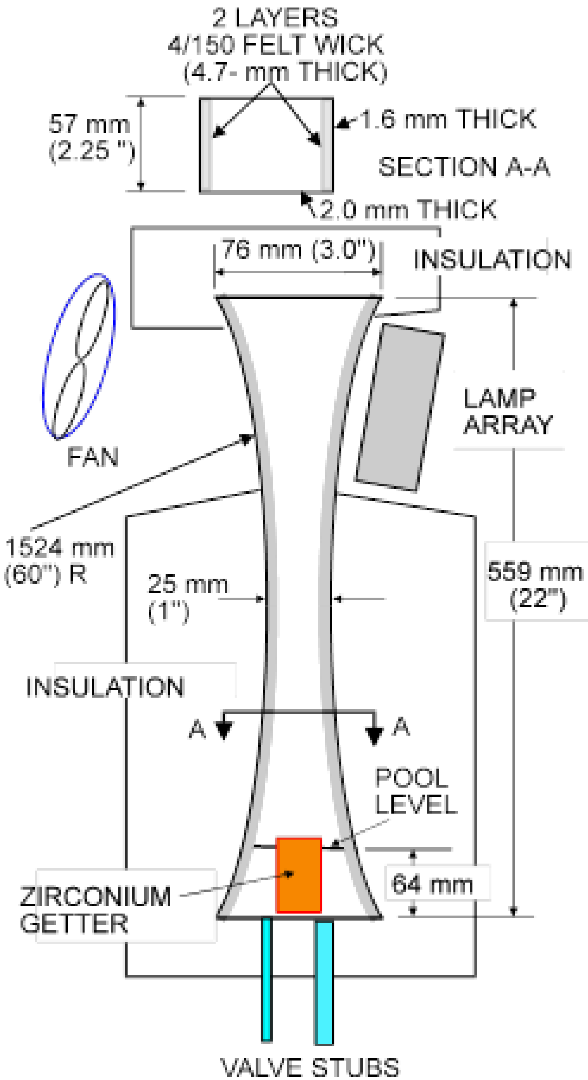


Isothermal input requires latent transport and storage to avoid high exergy losses

Technical Approach: Key Development Areas

Heat Pipe Wick Performance

- Durable wick structure design
- High performance
  - 100W/cm²
  - 100kW throughput
- Bench-scale testing
  - 24/7 unattended test
  - Demonstrated to duplicate on-sun conditions
  - 20,000 hour goal
  - Funded with FY12 AOP funds
  - Ongoing testing to be funded by project
- Leverage NSTTF "High Consequence Test Cells" facility



Heat Pipe Durability Test Schematic

Technical Approach: Key Development Areas

PCM Characterization and Selection

- Identify PCM candidates that meet criterion
  - Known properties
  - FactSage software
- Fabricate and test physical and thermal properties of candidates
  - Melting point, heat capacities, conductivity, basic compatibility
- Downselect leading candidates based on criterion

Criterion	Implications
Melting Point	Needs to match Stirling cycle. Ideally between 750 °C and 800 °C.
Heat of Fusion	Equal to the gravimetric density, determines the mass of the storage media needed to meet the storage requirements. Implications of system support structure and system balance.
Volumetric Storage Density	Gravimetric storage density times the mass density of the material. This impacts the size of the storage media, and therefore the quantity of containment material as well as the thermal losses by conduction.
Thermal Conductivity	Low conductivity leads to higher temperature drops on charge and discharge, impacting exergetic efficiency. Can be mitigated with a higher density of heat pipe condensers and evaporators, but at a system monetary cost.
Material Compatibility	The PCM must have compatibility at temperature with reasonable containment materials over long periods.
Stability	The PCM must not break down over time at temperature. This includes major changes such as separation of components and changes in composition, as well as minor issues such as outgassing and changes in melting point.
Coefficient of Thermal Expansion	This can impact the design of the containment and may require volumetric accommodation of size changes with temperature.
Phase Change Volumetric Expansion	This can lead to voids, increasing thermal resistance through the solid phase, and can potentially cause damage to the heat pipe tubes.
Vapor pressure	Related to stability, a high vapor pressure can lead to containment issues and/or higher cost for containment.
Cost	The cost of the PCM directly impacts the LCOE of the system.

Technical Approach: Key Development Areas

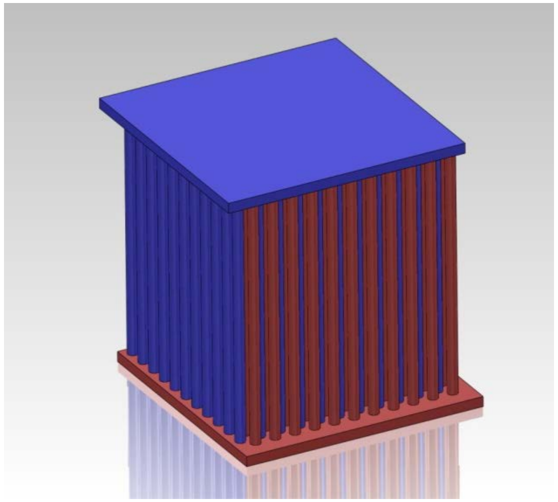
PCM Compatibility With Shell Materials

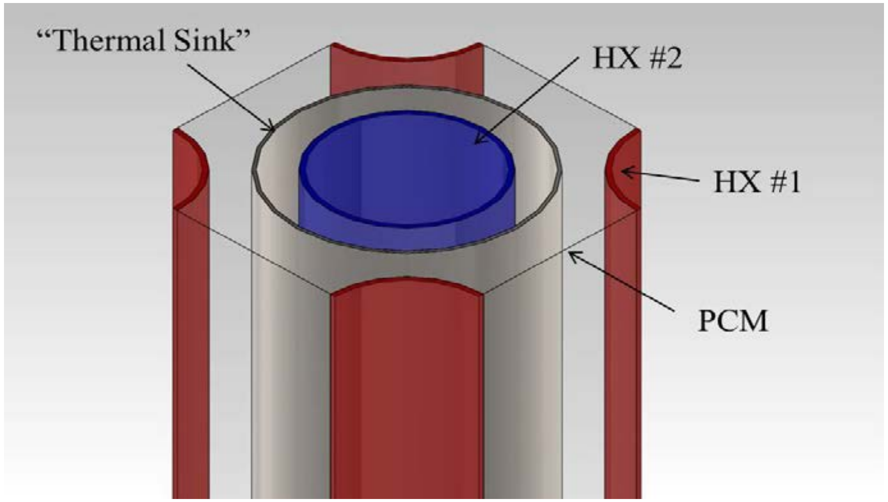
- Multiple capsule exposure tests at temperature
- Destructive metallurgical evaluation
- Short-term (500-hour) results apply to test rig
- Long-term (20,000-hour) apply to commercial embodiment

Technical Approach: Key Development Areas

PCM system thermal & mechanical modeling

- Detailed solid, liquid, and mushy zone modeling
- State-of-the-art phase change model
- Free convection in partially-melted state
- Extension to 3-D to include gravity angle changes
- FEA coupling to evaluate freeze-thaw volume changes
- Completed model to aid in system optimization and design process





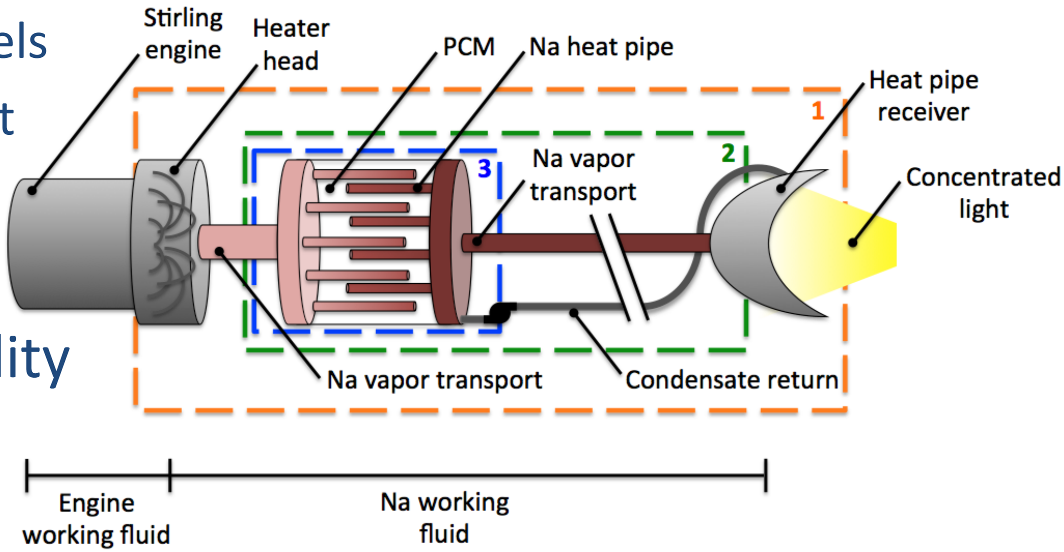
Full and Subscale model examples

Technical Approach: Key Development Areas

System Level Design and Testing

- System design and optimization
  - Apply model to optimize PCM/heat pipe interfaces
  - Conceptual systems design
- PCM Module integrated test
  - Hardware validation module
  - Validate PCM section models
  - Heat-pipe input and output
  - Electrically heated
- Test in NSTTF Engine/Receiver Test Facility

PCM module schematic. Integrated module test would consider Control Volume 3



Technical Approach: Scope Limitations

Important considerations not being addressed in this project:

- **Engine/Heat Pipe Interface**: This is engine specific. However, it represents a potentially tough issue in managing differential thermal expansion and condensate management.
- **Liquid Metal Pump**: Commercial Electro-magnetic pumps are available, but may need custom design for the pressure and flow rates anticipated.
- **Thermal expansion issues**: the piping and hardware cover a large linear extent, and thermal expansion issues must be addressed in the system design.
- **Freezing and startup**: Sodium inventory in the pair of heat pipe systems must be managed through freezing and startup in various orientations
- **Ratcheting (thermo-mechanical):** Multi-cycle ratcheting effects will be considered in the proposed work, but may be embodiment-specific
- **Management of full storage (shedding):** Excess energy collected may be shed through cycling the system on-and-off sun, but less stressful alternatives may be considered, such as active cooling
- **Safety:** While minimal unconstrained sodium inventory is expected, the introduction of sodium and other hot metallics may increase site safety concerns.
- **Dish redesign**: A dish redesign to take advantage of the rebalance will be necessary, and should be tackled by the dish system IP owner.
- **Deployment issues**: The heat pipe storage system is a large hermetically sealed system. Logistics must be considered in the design, fabrication, filling, and processing of the large heat pipes.
- **Low cost containment**: The efforts in this program ultimately demonstrate technical feasibility. However, with appropriate compatibility testing and engineering, lower cost containment materials, including insulation, may be identified.

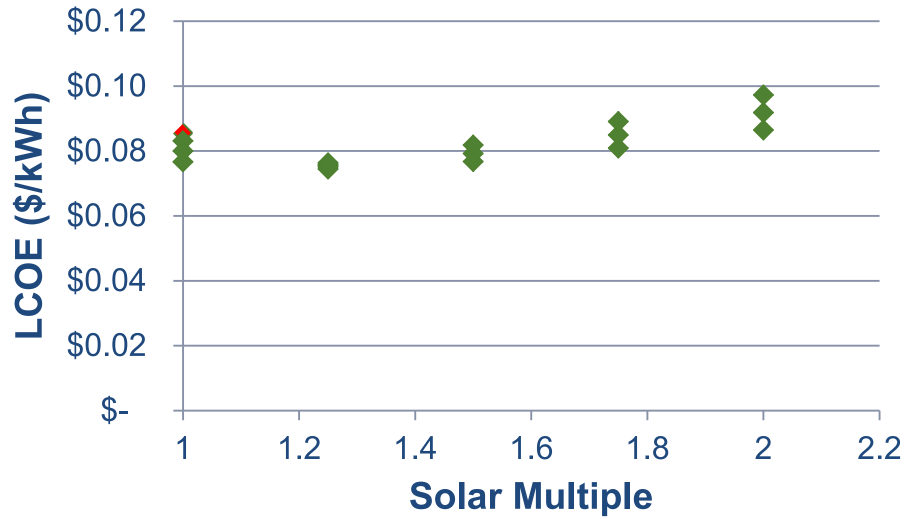
Intellectual Merit and Impact

- Innovations
  - High capacity (6-hour) storage for dish Stirling systems
    - Eliminate flexures and rotating joints needed for ground mount
    - Eliminate high cantilever mass
  - Leads to balanced dish system without slot, lowering cost
  - 3-D PCM modeling with variable gravity vector, metallic PCM, and heat pipe interface

- Impact
  - Extend applicability of dish Stirling to high capacity systems
  - Reduce LCOE of dish Stirling systems
  - Enable high performance, low LCOE dish Stirling systems to compete with CSP *and* PV SunShot goals
  - Differentiation from PV solar-only aspects

Results: System Study

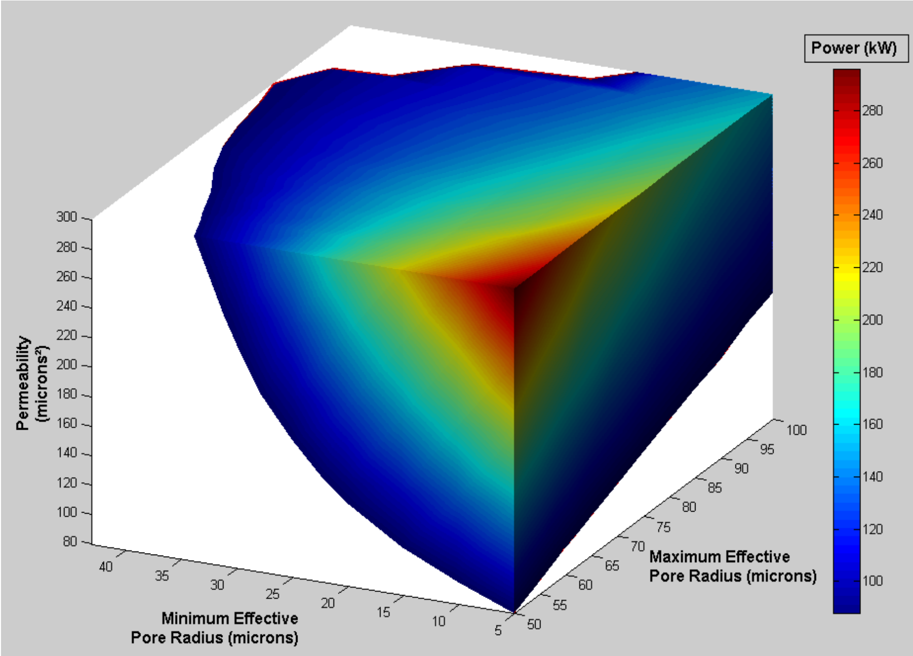
- Simple performance and economic study
  - Engine performance based on measured results
  - Vary solar multiple, storage quantity
- Storage improves LCOE *and* profit
- Allowable cost much higher than SunShot goals
- Solar multiple 1.25 optimal for 6 hours
- Very fast response time advantageous



Case	LCOE ($/kWh)	Profit ($/kWh)	Cost ($k/dish)	Cost ($/kWh$_{th}$)
No Storage	0.086	0.056	0	0
Base	0.076	0.072	21	52
Level LCOE	0.086	0.062	33	82
Level Profit	0.092	0.056	40	99
SunShot	0.06	--	6.5	16

Results: Heat Pipe Wick

- Survey of past work and available felt metals
  - Smaller fibers improve performance
  - Larger fibers improve robustness
  - Combined fibers must be considered
- Wick layup path forward identified
  - Intermediate fiber sizes
  - Alternate fiber materials identified to improve strength
  - Blended layup possible
- Modeling by wick developer critical to meet criterion
- Receiver wick requirements are stringent
- Service vendors identified



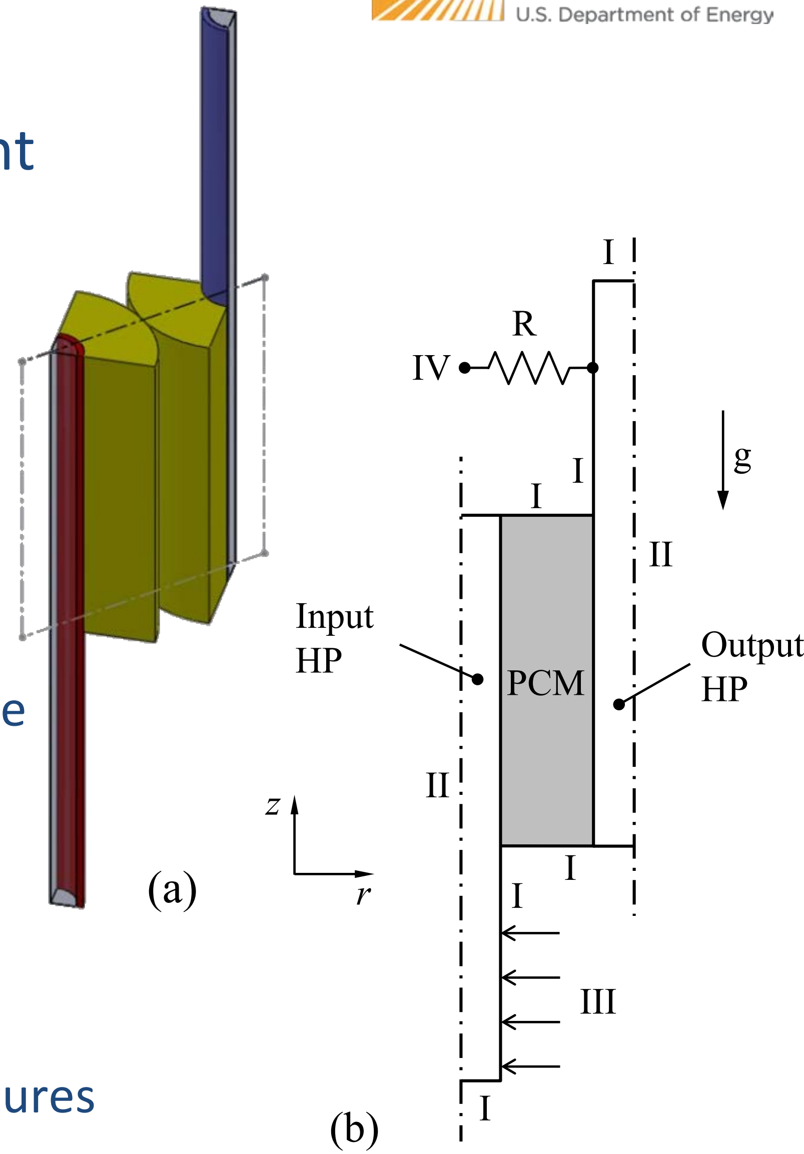
Wick Allowable Design Space

Results: PCM Selection

- PCM materials downselected for further study
  - 2 salts, 2 metallic PCM's
  - Proprietary selections
- Primary considerations for Selection
  - FactSage analysis for Eutectic melting point
  - Mass and volume for 6 hour storage
  - Rough order cost based on raw materials
- Two PCM's fabricated for physical measurements
  - Reasonable match to FactSage
- Potential for shell metal interactions identified in HSC modeling

Results: Storage Model

- 2-D PCM system model development
  - Separate heat pipe input and output
  - Realistic operational sequences
  - 2-d for fast operation
- Based on past UCONN models
  - Free convection in PCM
  - Heat pipe interfaces
  - Adaptive timestep to accurately capture melt zone
- Outputs
  - Time-based melt zones
  - Exergy analysis
  - Net system performance and temperatures



Summary

- A path to 6-hour dish storage has been identified
  - Performance improvements possible
  - Better match to utility value
- Latent transport and storage
  - Key to match dish Stirling isothermal input
- Wick options in development
- Potential PCM’s identified
  - Metallic PCM’s minimize conductivity issues
  - Materials compatibility must be demonstrated
- PCM model progressing
  - Key to system optimization and design