Temperature-Staged Thermal Energy Storage Enabling Low Thermal Exergy Loss Reflux Boiling in Full Spectrum Solar Systems

IMECE2016-67013

2016 ASME International Mechanical Engineering Congress & Exposition
Phoenix, AZ

Terry J. Hendricks, Bill J. Nesmith, Jonathan Grandidier

Jet Propulsion Laboratory/California Institute of Technology, Pasadena, CA

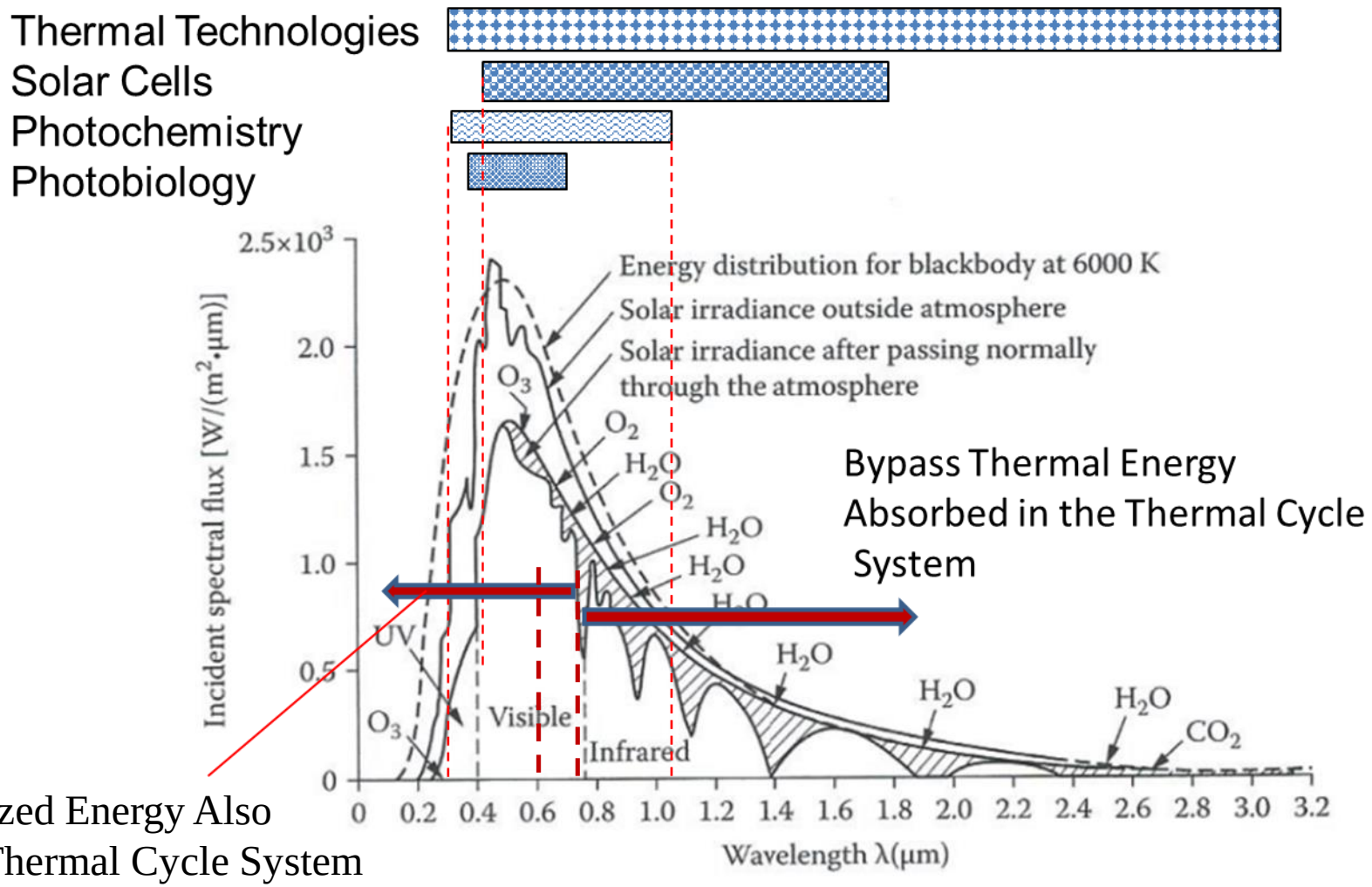
15 November 2016

Copyright 2016 California Institute of Technology. U.S. Government sponsorship acknowledged.

Full-Spectrum Solar / Thermal Cycle Power Systems

- Hybrid Concentrated Solar PV/Thermodynamic Cycle Power Systems to Achieve High Exergy Efficiency
  - Some System Concepts Implement Wave-Splitting Design Approaches
- Optimum λ-split @ ~1.7 eV – 1.11 eV (0.73 μm -1.12 μm)

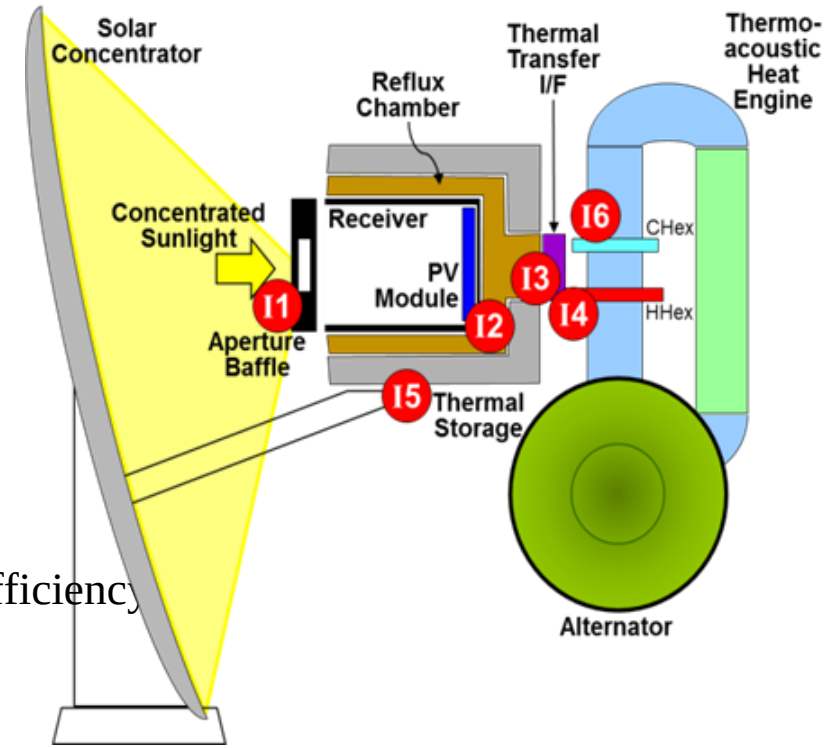
- **Technical Challenges**
  - High Temperature PV cells
  - Compact Stirling cycles, Brayton cycles, Organic Rankine cycles
  - Wavelength splitting (efficiency)
  - Thermal interfaces
  - High-Temperature thermal energy storage (<$15/kW$_{th}$)
  - Cost
    - LCOE ~ $0.06/kWhr is high bar



Cell Thermalized Energy Also Absorbed in Thermal Cycle System

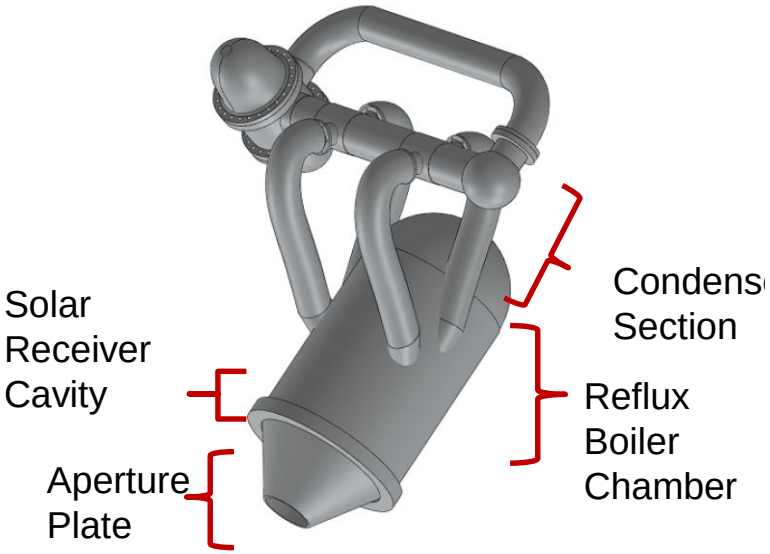
FSPOT-X System Description & Function

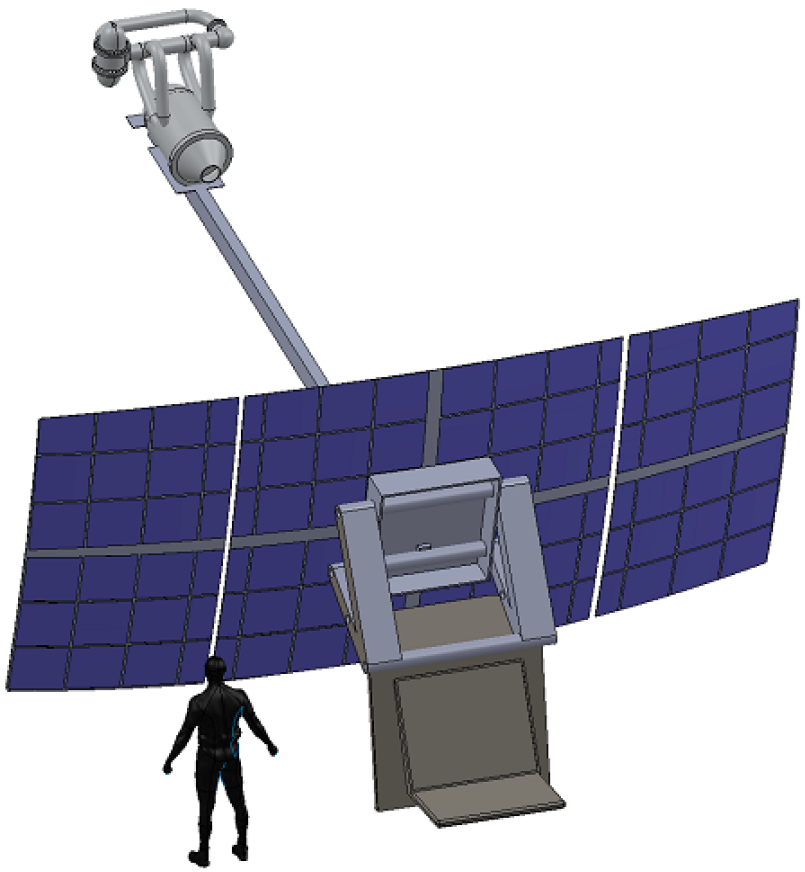
- Hybrid Photovoltaic (PV) / Thermoacoustic Power Conversion (TAPC) System Incorporating Thermal Energy Storage (TES)
  - Photovoltaics Captures & Converts Energy @ Low Wavelengths
  - Reflux Boiling System for Efficient, Low Exergy Heat Transfer
  - TAPC Captures & Converts Thermal Energy @ Longer Wavelengths
  - TES Integrated into Reflux Boiling System To Store Thermal Energy
- Benefits
  - Increased System-Level Performance (Power & Efficiency)
  - Increased System Dispatchability – Longer Off-Sun Operation
  - Leads to Lower LCOE Costs
- Goals
  - > 10 kWe TA engine at 300-350 C and 37 C reject temperature at > 25% TAPC efficiency
  - High-temperature PV efficiency >20% (@ 350°C)
  - Overall system efficiency ~44%
- Reflux Boiler / TES is Critical to System Operation
  - Low Exergy Thermal Transport into TAPC
  - Low Exergy Thermal Transport Into/Out of TES



Reflux Boiler Design

Receiver Cavity/Thermal Energy Storage/TAPC Thermal Interface is critical to system success

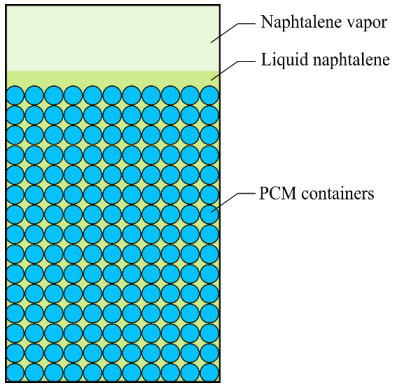


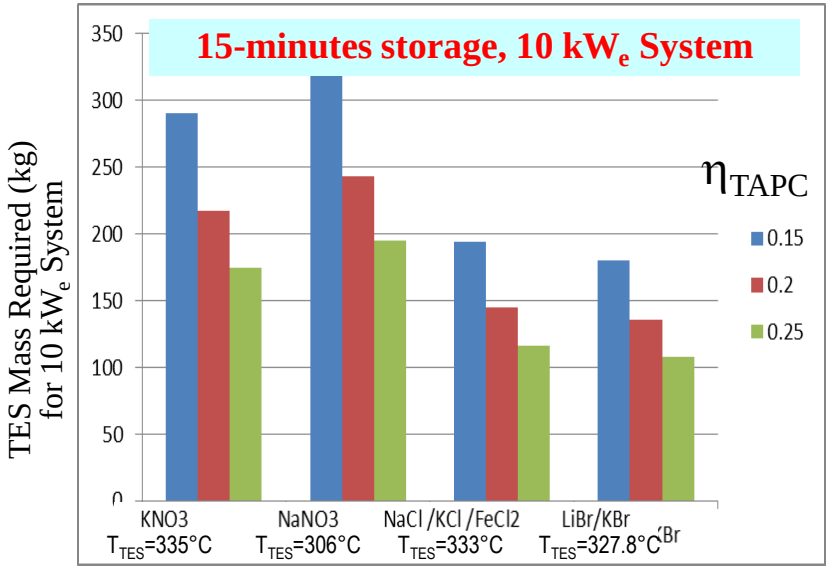


Initial TES Design Challenges & Material Options – 10 kW_e System

Design Challenge	Impact	Design Approaches
Low Internal Thermal Conductance	Controls Thermal Transport to TAPC and Thermal Energy Storage Rates	• Microchannel Designs • Micro-encapsulation • Heat pipe enhancement • Internal design optimization • Internal Testing to Validate Performance
Temperature Matching with PV/TAPC Requirements	Operating Temperature Controls PV/TAPC Performance, Selected Temperature Determined by Overall System Performance Optimization	• Several TES materials across wide temperature range • Cascaded or staged design • $NaCl–KCl–MgCl_2$ -- ~390°C
TES Containment Integration & Thermal Interfaces & Isothermal Design	Reduced Thermal Transport to TAPC and Thermal Energy Storage Rates, Eliminate Corrosion-Induced Failures	• Heat pipe enhanced • Naphthalene or Dowtherm A Working Fluids

- State-of-the-art TES Materials (right and following next chart)
- Innovative TES Spheres in "Pebble Bed" Configuration

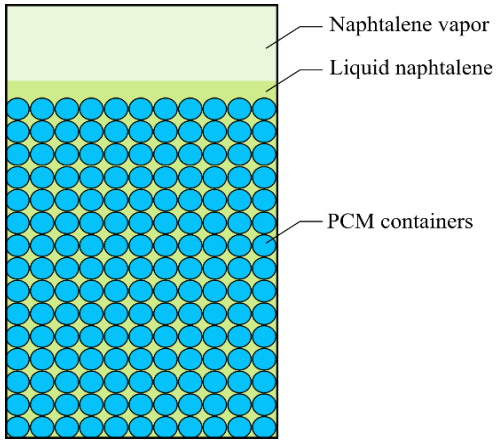




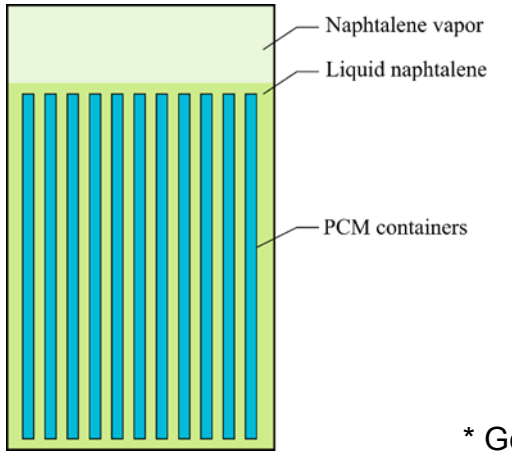
Thermal Energy Storage

- $FeCl_2$-NaCl-KCl - The most appropriate cost effective PCM that melts around 335°C and operates with a high cyclic efficiency in the temperature range of 300-350°C.
- Other PCMs* considered are shown below – Could use these in certain TES configurations

Eutectic	Melting Point, °C	Composition mol%	Theoretical Latent heat (J/g)
$FeCl_2$-NaCl-KCl	333	33.5-33.5-33.0	309
$FeCl_2$-NaCl-KCl	310	44.5-29.2-26.3	187
$FeCl_2$-NaCl-KCl	319	37.1-11.8-51.1	142
MgCl2-KCl-NaCl	331	34.4-65.7-25.1	198
Zn- Mg	340	52-48 wt%	180
CuCl- NaCl	314	73 - 27	-
CuCl- KCl	325	30 - 70	-
LiBr/KBr	328		333

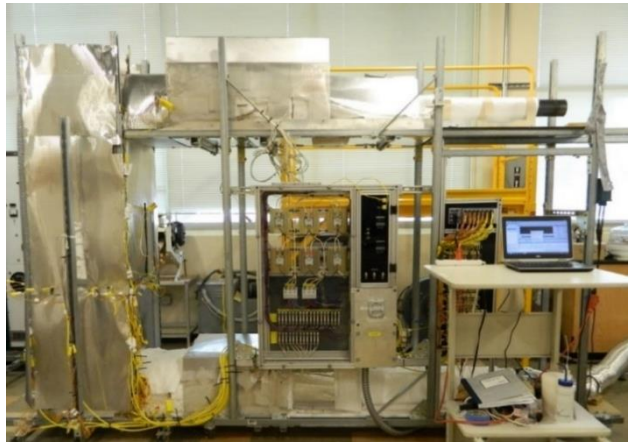


Spherical TES Design



Cylindrical TES Design

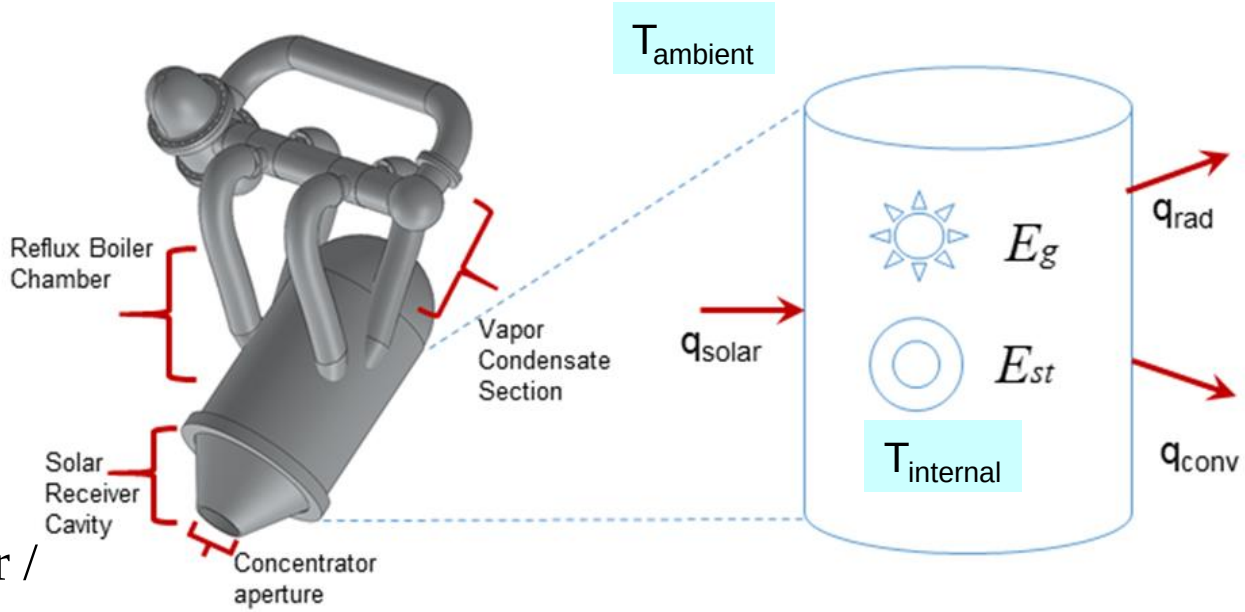
Thermal Energy Storage Test Setup at University of South Florida (USF)



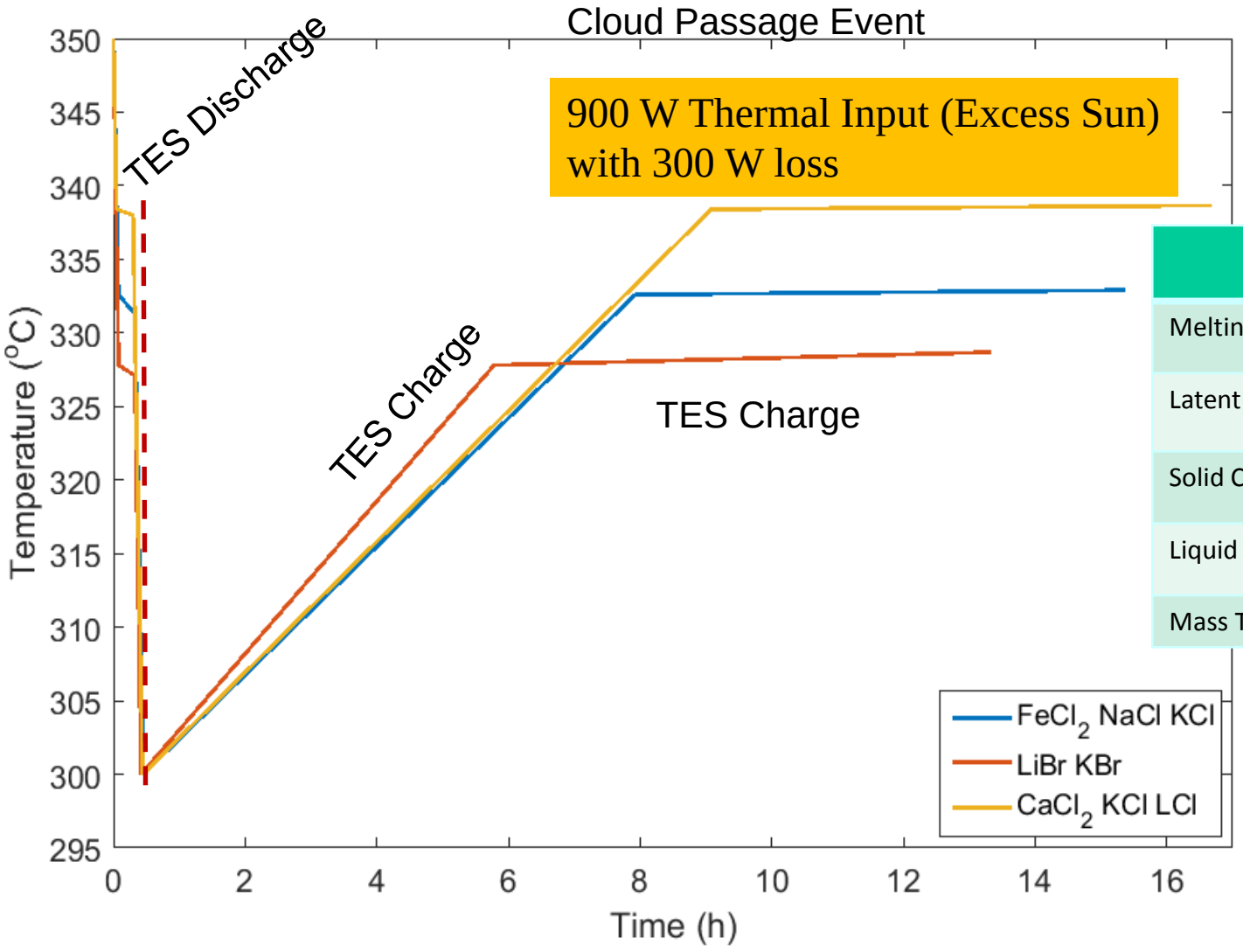
* Gomez, J., "High-Temperature Phase Change Materials (PCM) Candidates for Thermal Energy Storage (TES) Applications", U.S. DOE-NREL Milestone Report, NREL/TP-5500-51446, Contract No. DE-AC36-08GO28308, September 2011

Lumped Capacitance Thermal Analysis

- JPL/Northrup Grumman Reflux Boiler / TES Design Configuration
- TES Thermal Sources & Thermal Sinks Included
- Working Fluid & Chamber Structure Included
- Solar Sources Included
- TAPC Thermal Sink Included
- Differentiates Discharge & Charge Rates for Different TES Materials
- Identifies Solar Input Thresholds – Therefore Reflector / Dish Requirements
- Helps Distinguish & Quantify Cost/Performance Tradeoffs



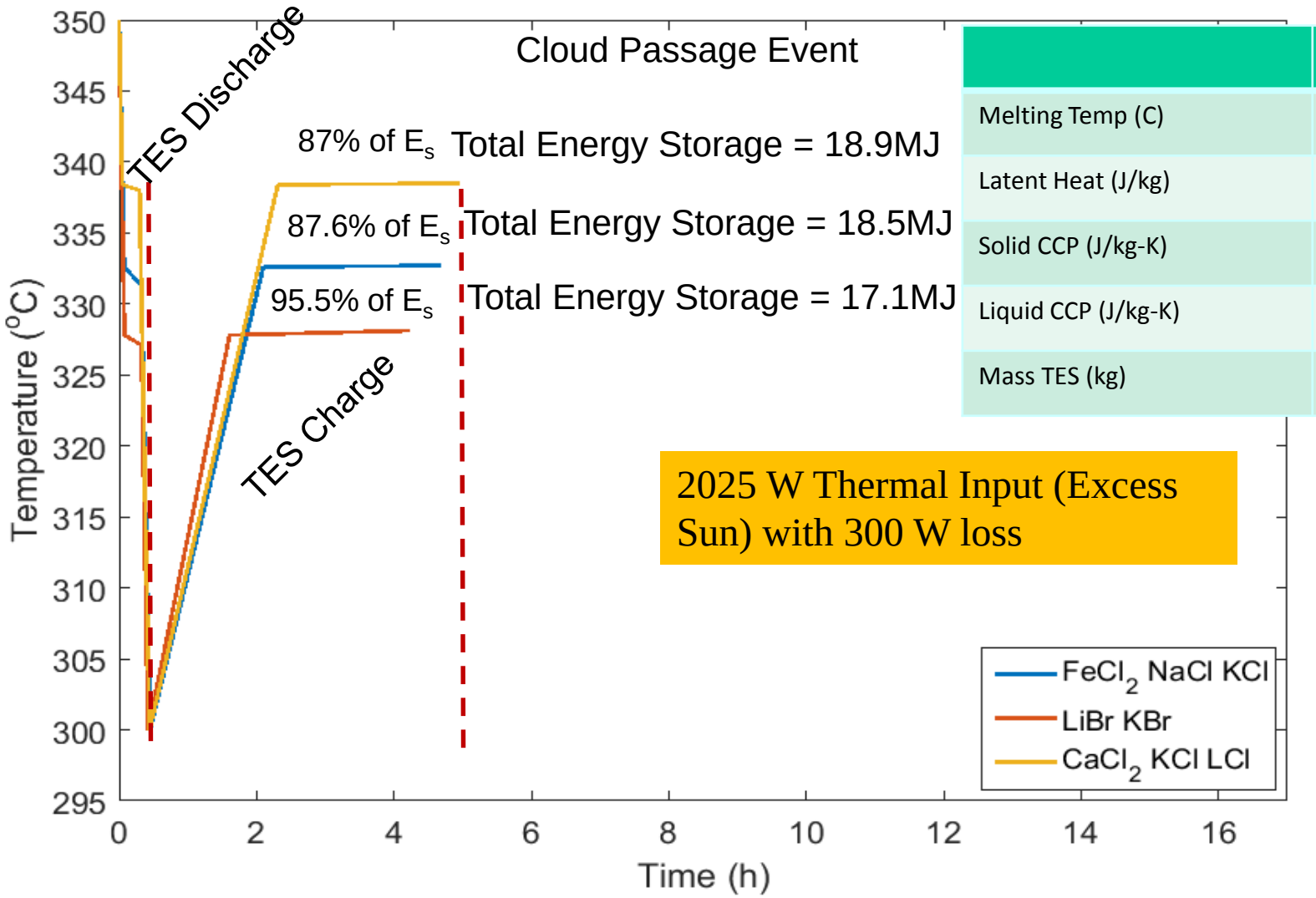
TES Thermal Analysis – Low Excess Sun (Solar Dish Too Small)



	$FeCl_2$ NaCl KCl	LiBr KBr	$CaCl_2$ KCl LiCl
Melting Temp (C)	332.6	327.8	338.4
Latent Heat (J/kg)	308880	333000	241200
Solid CCP (J/kg-K)	1326	562	950
Liquid CCP (J/kg-K)	1695	672	1200
Mass TES (kg)	52.5	49.0	68.0

- Long Charge Times - Untenable
- Sensible Charge Time Comparable to Latent Charge
- Need Threshold Solar Level

TES Thermal Analysis – Reasonable Excess Sun (1/2 Solar Dish Available)

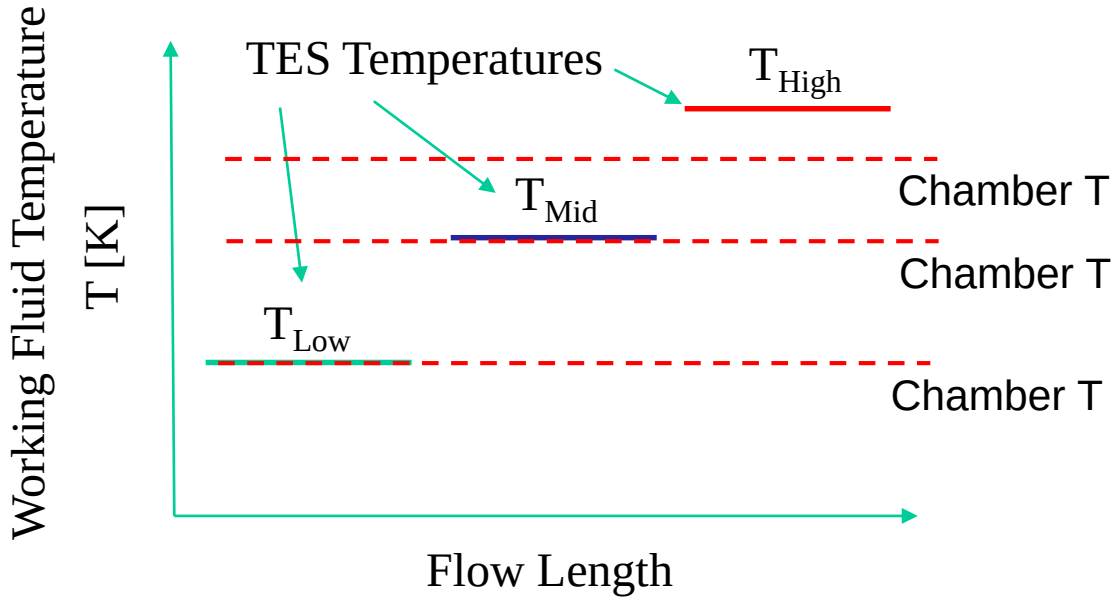


	$FeCl_2$ NaCl KCl	LiBr KBr	$CaCl_2$ KCl LiCl
Melting Temp (C)	332.6	327.8	338.4
Latent Heat (J/kg)	308880	333000	241200
Solid CCP (J/kg-K)	1326	562	950
Liquid CCP (J/kg-K)	1695	672	1200
Mass TES (kg)	52.5	49.0	68.0

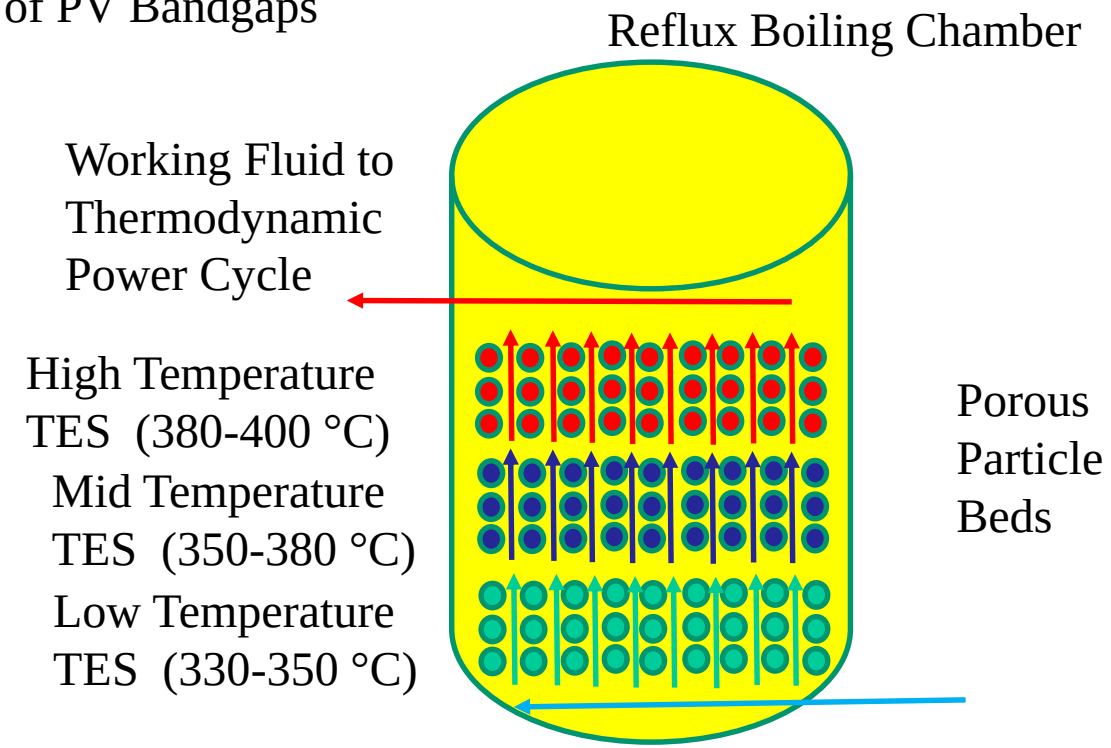
- Much Shorter Charge Times
- Sensible Charge Times Shorter than Latent Charge
- LiBr/KBr Shortest – But Most Expensive
- $FeCl_2$/NaCl/KCl Least Expensive

Multiple TES Materials

- $S_{Gen} \sim (Q/T)$ is Lower in This Scheme
- Highest Temperature TES Gives Thermal "Switch" Capability
- 3 TES Layer Analogous to 3 PV Bandgaps (Thermal Phonons vs. Near-IR/Visible Photons)
- Extending: Infinite TES Layer Analogous with Infinite Number of PV Bandgaps

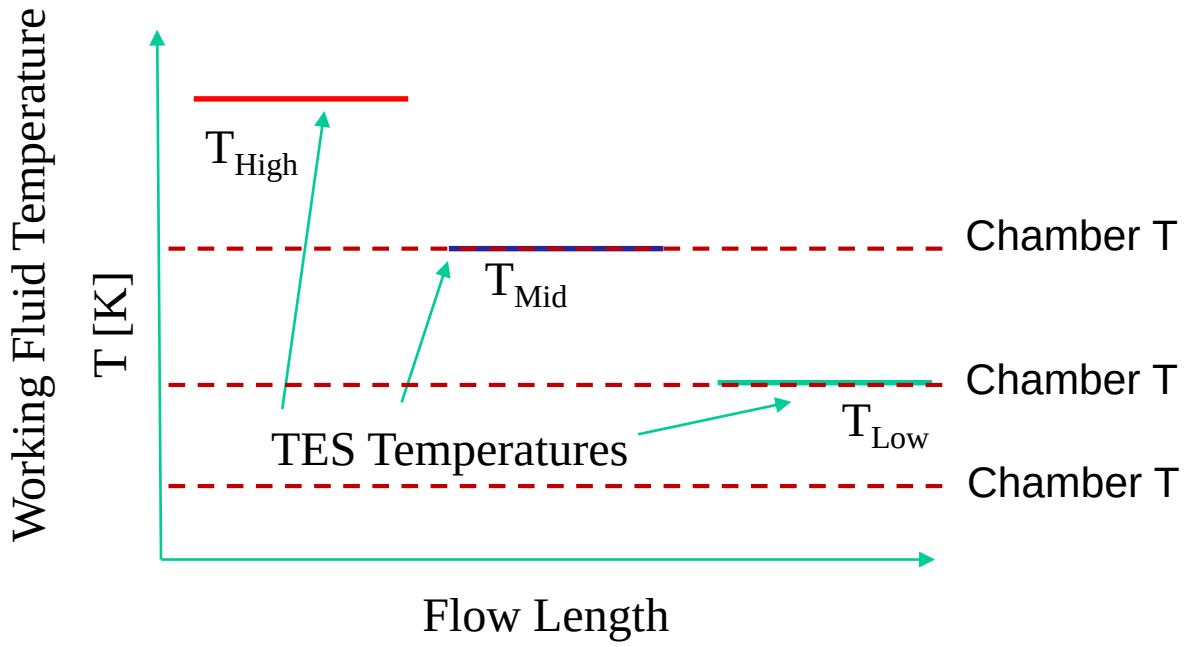


TES Discharge Process

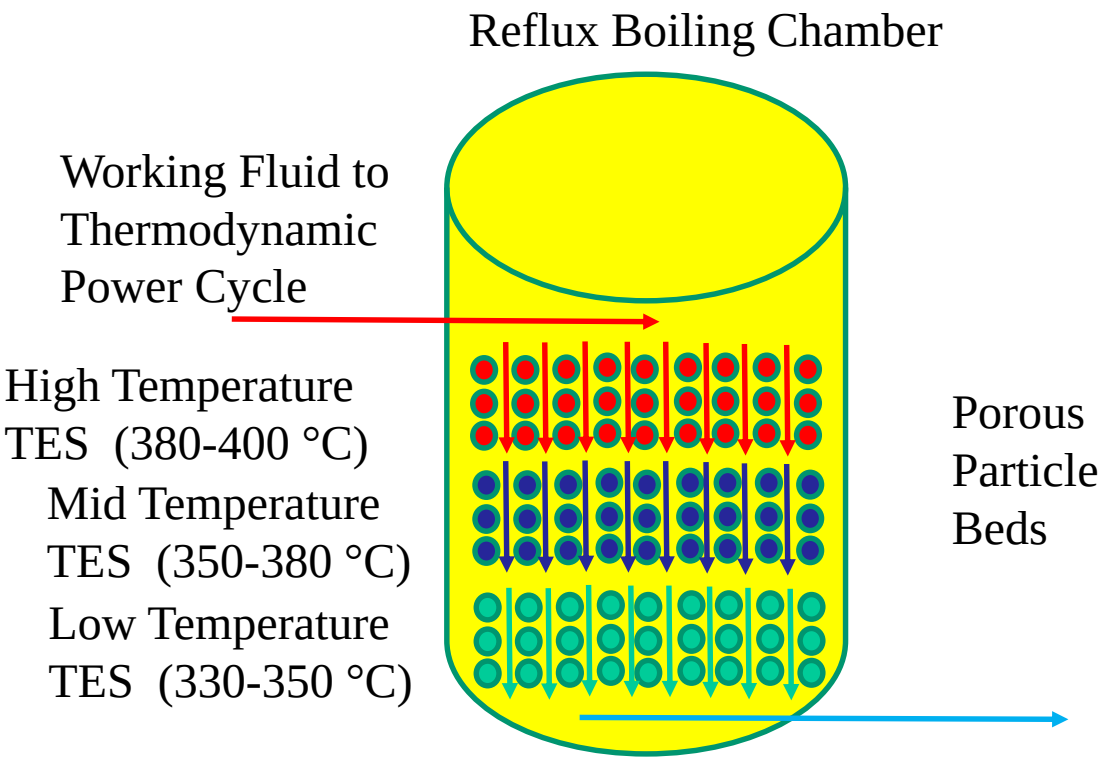


Multiple TES Materials

- S_{Gen} ~ (Q/T) is Lower in This Scheme
- Highest Temperature TES Gives Thermal "Switch" Capability



TES Charge Process



Multiple Temperature-Staged Analysis

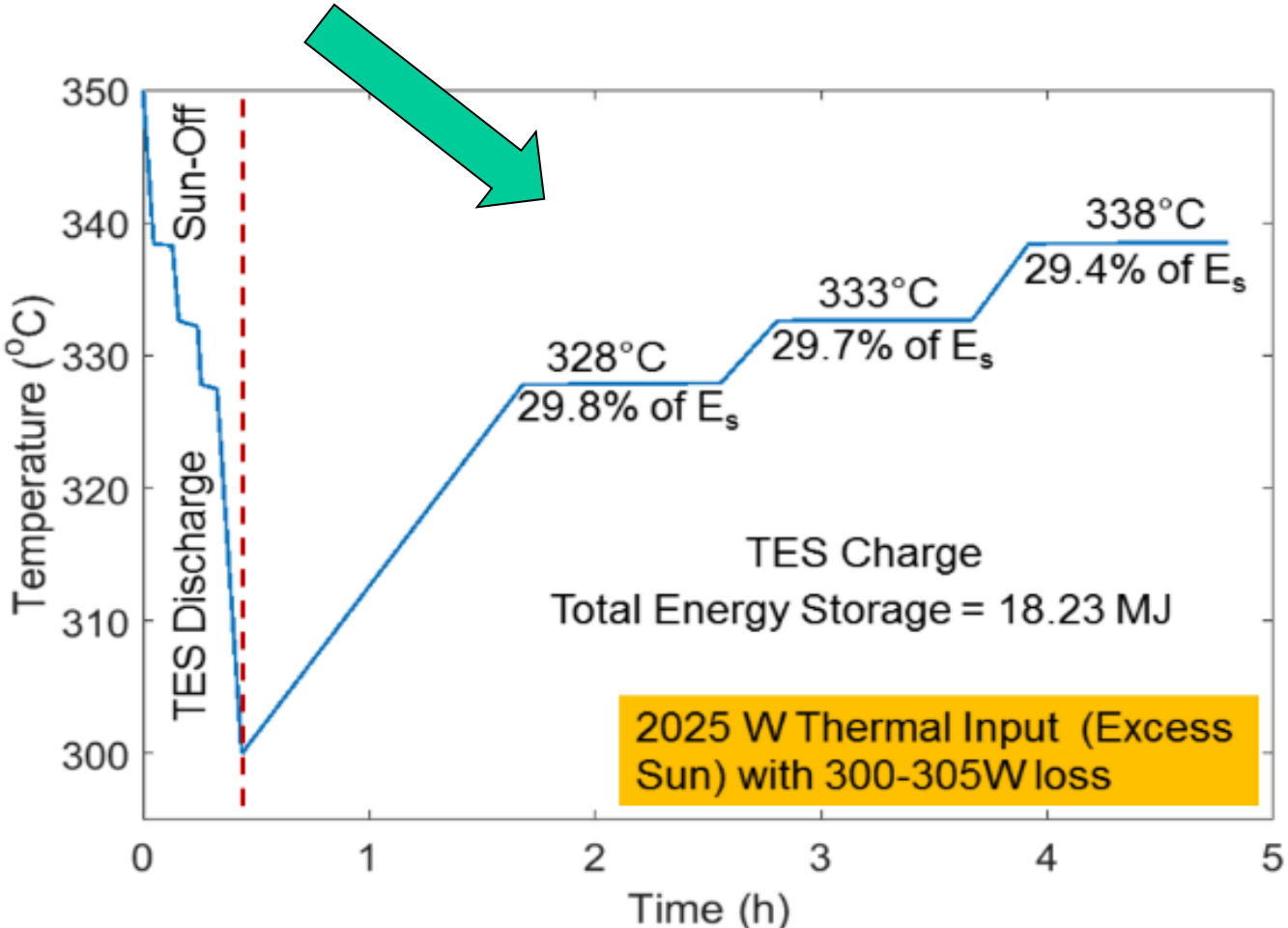
- Different Charge / Discharge Scenarios Considered
  - Fast Charge Scenario during initial charge-up in morning using full thermal input capability will create charge up time same as discharge time (~15 minutes)
  - Typical Mid-Day Re-Charge after short Sun-Off period (~15 minutes)

❖ Allows One to Charge / Discharge in Incremental Steps

❖ This Lowers the Total Thermal Exergy Loss in the Round-Trip Process

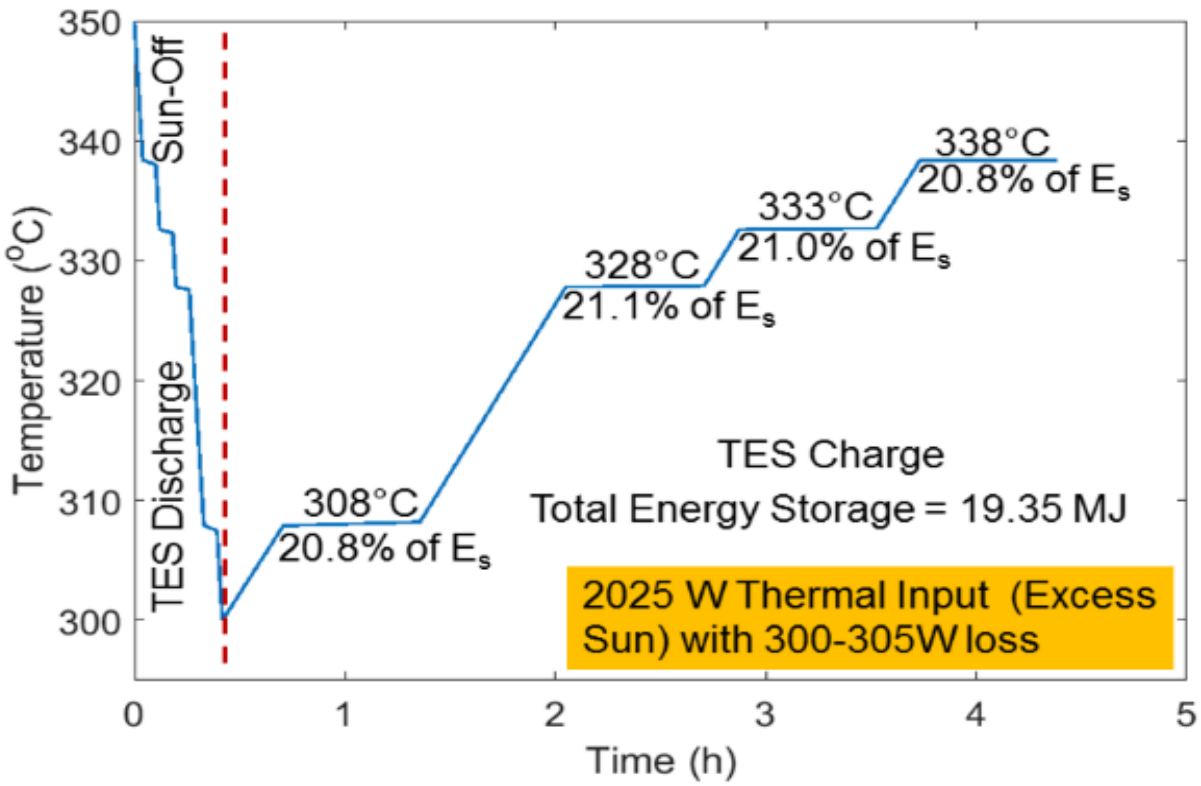
❖ Back to 90% Energy Storage in PCM with Higher Ultimate Storage Temperature

❖ Can Be Extended to More Stages, but Benefits Depend on Specific Designs, Thermophysical Properties, & Cost



Multiple Temperature-Staged Analysis

- Temperature staging of multiple TES materials does offer design and performance benefits as demonstrated in these analyses and results,
- It does require judicious selection of the TES materials with close consideration and matching of their thermophysical properties and phase change temperatures.
- Thermal storage performance with multiple TES materials can store thermal energy at multiple temperature levels
  - Providing thermal exergy benefits
  - Storing more thermal energy between set thermal limits
  - Providing higher ultimate storage temperatures
  - Providing a "thermal switch" capability to accommodate any runaway thermal excursions or extreme transients in Hybrid Solar Photovoltaic / Thermoacoustic Power Converter system.



Multiple Temperature-Staged Analysis

- Four TES configurations were considered using 4 TES materials to establish temperature stages
- Latent and Sensible Heat entropy was evaluated using entropy equations shown in the paper
- Minimizing entropy depends strongly on material selections and their particular phase change temperatures
- Low Entropy Cases Also Have Highest Latent Heat Storage Fractions

	KNO3/KCl TES1	LiBr KBr TES2	FeCl2 NaCl KCl TES3	CaCl2 KCl LiCl TES4
Melting Temp (C)	307.8	327.8	332.6	338.4
Latent Heat (J/kg)	105630	333000	308880	241200
Solid CCP (J/kg-K)	1156	562	1326	950
Liquid CCP (J/kg-K)	1177	672	1695	1200
Mass TES (kg)	152.6	49	52.5	68

TES 23 & TES 234 Configurations Clearly Low Entropy Cases

	Total Energy Stored (MJ)	Latent Heat Storage Fraction (%)	Highest Latent Storage Temperature Obtained	Latent Heat Entropy-Eq.7 (J/K)	Sensible Heat Entropy-Eq.6 (J/K)
TES 23	17.86	0.9107	332.6°C	0.083	6482
TES 34	18.83	0.8584	338.4°C	~0.1	7916
TES 234	18.23	0.8897	338.4°C	0.174	6716
TES 1234	19.35	0.8369	338.4°C	0.315	8164

Key Exergy Optimization Design Parameters

- The TES optimization process is completely controlled by:
  - $(C_{p,TES}/h_{lat,TES})$
  - $(C_{p,Naph}/h_{lat,TES})$ ratios
  - (m_{Naph}/m_{TES}) ratio
  - TES operating temperature of interest
  - Cost and safety of these different TES materials
- Lower $(C_{p,TES}/h_{lat,TES})$ and $(C_{p,Naph}/h_{lat,TES})$ ratios leading to lower entropy generation (lower exergy) designs.
- This TES optimization process is then tempered by the critically important cost and safety considerations of the various TES options.
- Initial system-level models and analyses have provided critical design sizing information and demonstrated key thermal performance sensitivities associated with the current hybrid power system.

Fraction of Carnot Efficiency

$$\eta_{frac-Carnot} = 1 - \left[\frac{C_{p,TES}}{h_{lat,TES}} + \left(\frac{m_{Naph}}{m_{TES}} \right) \cdot \left(\frac{C_{p,Naph}}{h_{lat,TES}} \right) \right] \cdot \left(T_f - T_i \right)$$

Summary

- Reflux Boiler / TES is Critical to System Operation
  - Low exergy thermal transport into TAPC
  - Low exergy yhermal transport Into/Out of TES
  - TES designed directly into reflux boiler system
- Several TES Materials Investigated – Work in Progress
  - Various chemistries
  - Various phase-change temperatures
  - Various energy storage densities
- Temperature Staging of TES Can Lower Thermal Exergy as System Charges/Discharges
  - More heat transfer occurs at lower temperature differentials at each stage
  - Large fraction of thermal energy stored at appropriate phase change temperatures
  - Optimization depends strongly on TES materials selected, their phase change temperature, & key design parameters mentioned on previous slide
  - Provides for higher ultimate storage temperature – Important for TAPC integration
  - Design pathway could yield lower cost system depending on TES materials choices – Still evaluating Details
- Future Work Will Incorporate & Optimize This Approach into System-Level Designs & Configurations

Acknowledgements

Authors would like to acknowledge support from David E. Lee, Program Manager, Northrop Grumman Aerospace Systems, Redondo Beach, CA in this work.

The authors also gratefully thank the U.S. Department of Energy, ARPA-E for their support of this work through Award #DE-AR0000466.

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract to the National Aeronautics and Space Administration.

BACKUP

New TES Encapsulation Technology

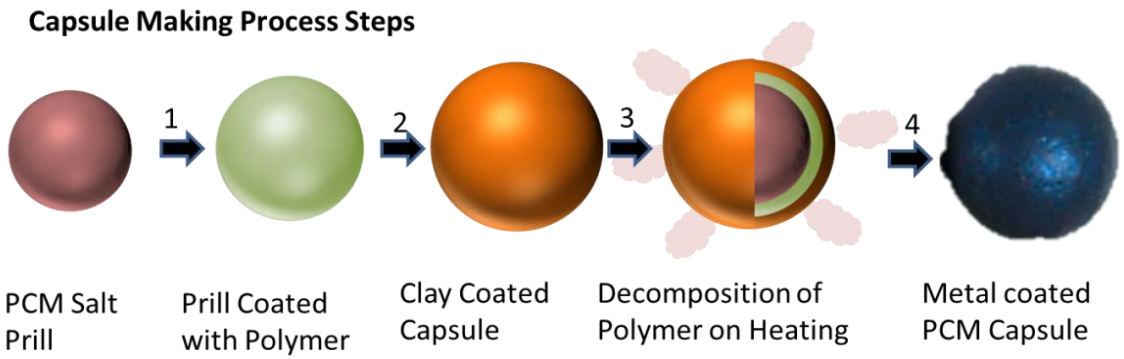


Figure 3: *TerraCaps:* Nickel-Coated Final Product

- A major technology breakthrough enables
  - Small Capsules have large heat transfer area
  - Creates the required void inside capsules for salt to expand on heating using a common encapsulation method
- Technology proven in the laboratory in gm qty
  - Used readily available KNO3 prills…
- JPL Obtaining Small Quantities to Embark on N-Compatibility Verification