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

## 2016 MRS Spring Meeting
## Phoenix, AZ

Terry J. Hendricks, Bill J. Nesmith, Juan Cepeda-Rizo, Jonathan Grandidier
Jet Propulsion Laboratory/California Institute of Technology, Pasadena, CA

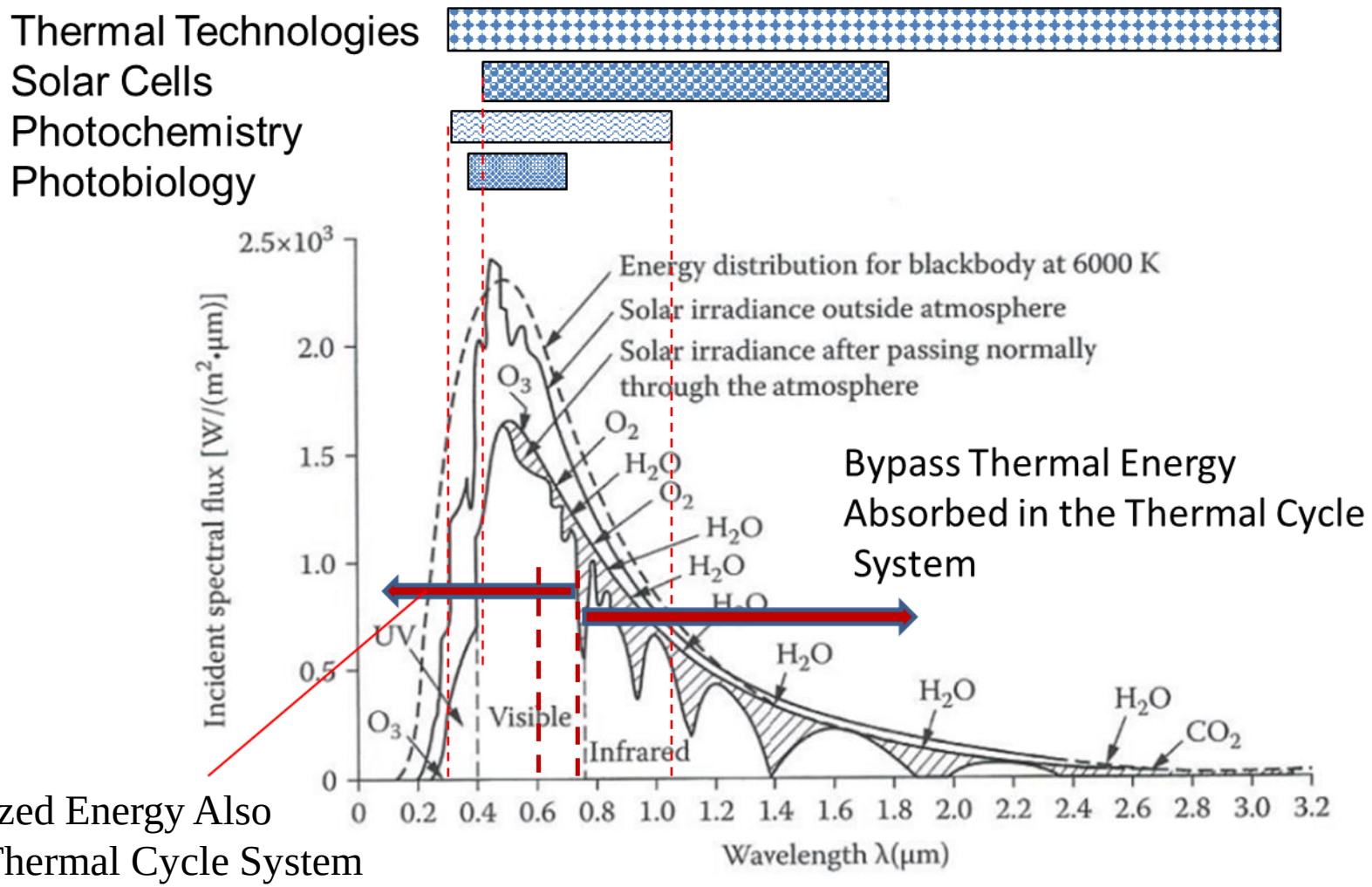
**29 March 2016**

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

# Full-Spectrum Solar / Thermal Cycle Power Systems

- Hybrid Concentrated Solar PV/Thermodynamic Cycle Wavelength-Splitting Systems to Achieve High Exergy Efficiency
- 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

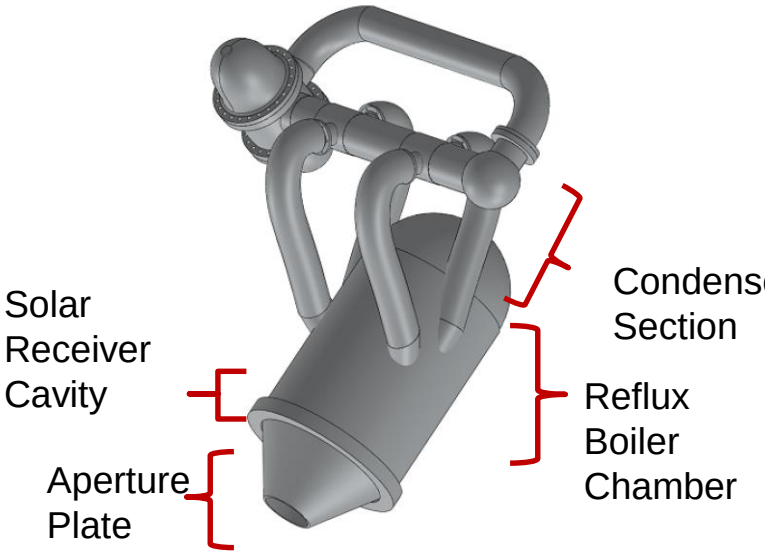
# FSPOT-X System Description & Function

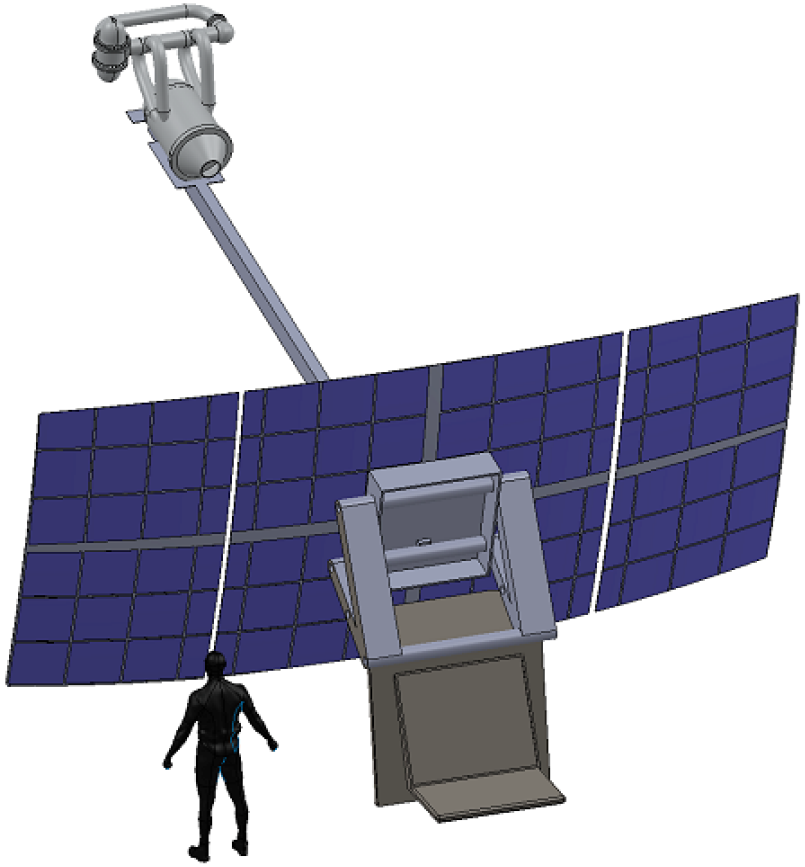
- Hybrid Photovoltaic (PV) / Thermoacoustic Power Conversion (TAPC) System Incorporating Thermal Energy Storage (TES)
  - Photovoltaics Captures & Converts Energy @ Low Wavelengths
  - Reflux Boiling System for Efficient, Low Exergy Heat Transfer
  - TAPC Captures & Converts Thermal Energy @ Longer Wavelengths
  - 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$^{o}$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


Use or disclosure of data contained on this page is subject to the restriction(s) on the title page of this document

# Reflux Boiler Design

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



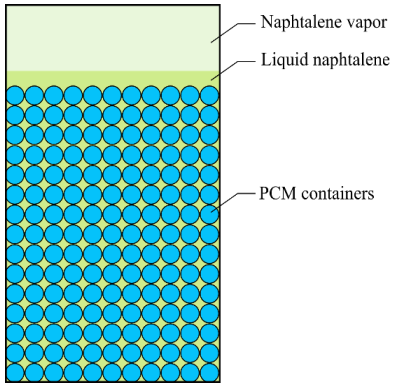



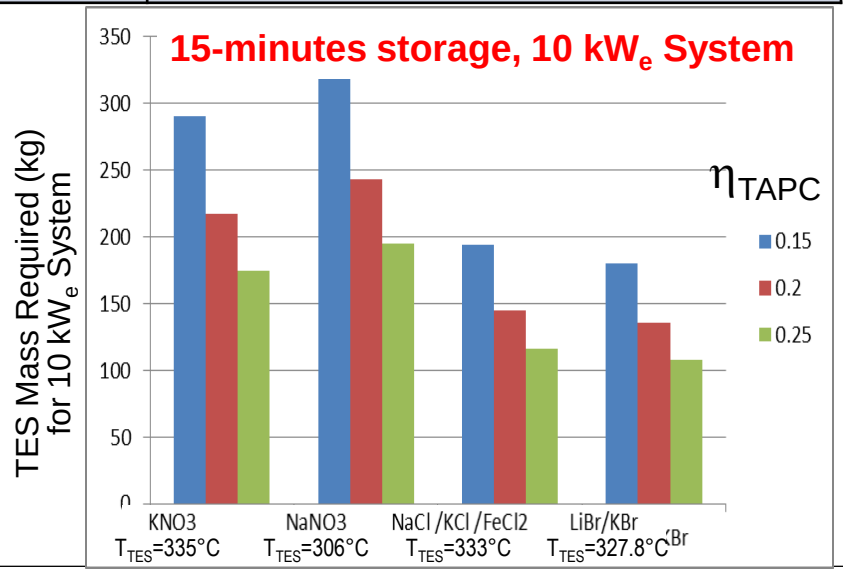

Use or disclosure of data contained on this page is subject to the restriction(s) on the title page of this document

# 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<br>• Micro-encapsulation<br>• Heat pipe enhancement<br>• Internal design optimization<br>• 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<br>• Cascaded or staged design<br>• $NaCl–KCl–MgCl_2$ -- ~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<br>• Antimony Bromide or Dowtherm A Working Fluids |

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



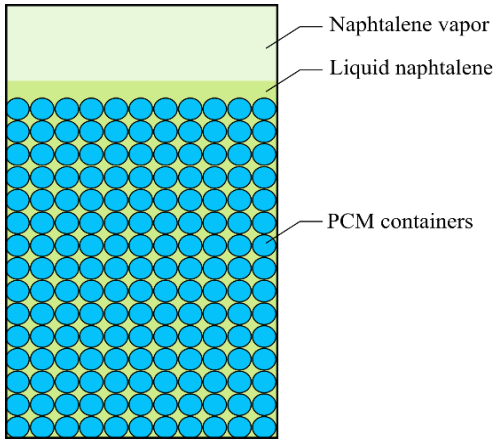



Use or disclosure of data contained on this page is subject to the restriction(s) on the title page of this document

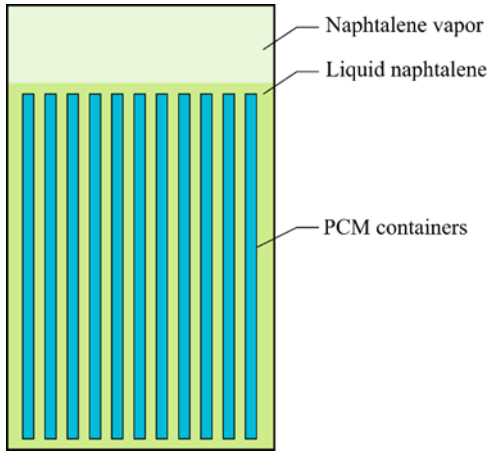
# Thermal Energy Storage

- $FeCl_2$-NaCl-KCl - The most appropriate cost effective PCM that melts around 335C 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 |

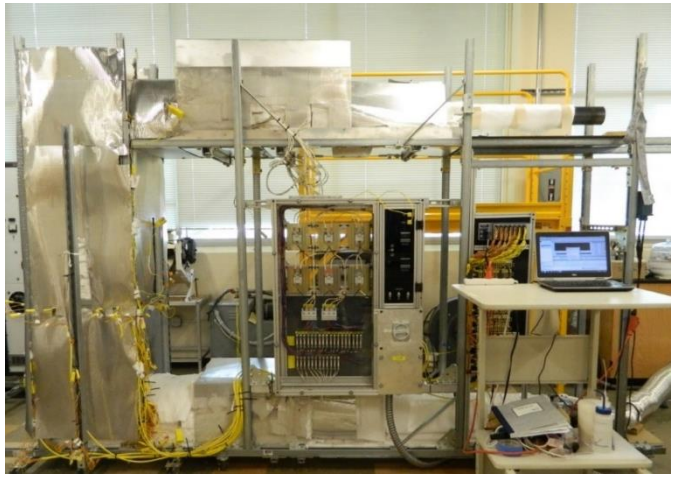



Spherical TES Design




Cylindrical TES Design

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

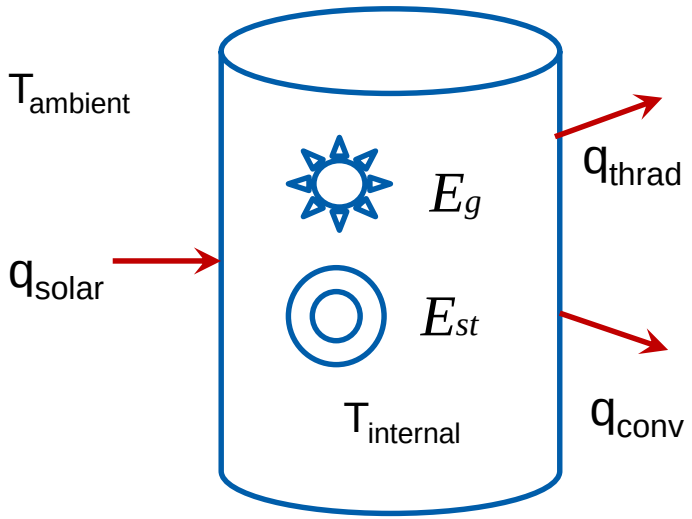




Use or disclosure of data contained on this page is subject to the restriction(s) on the title page of this document

# Lumped Capacitance Thermal Analysis

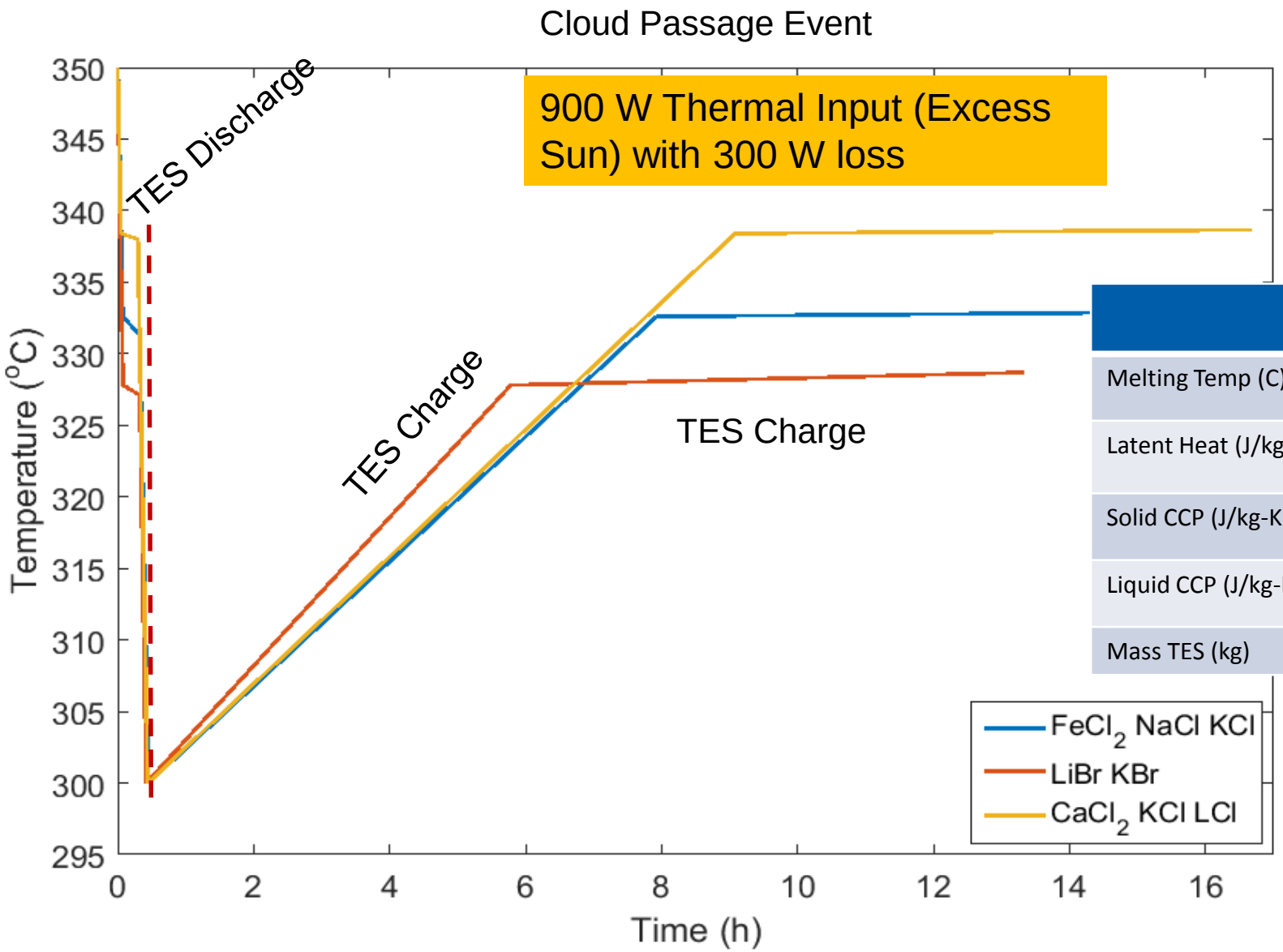
- JPL/Northrup Grumman Reflux Boiler / TES Design Configuration
- TES Thermal Sources & Thermal Sinks Included
- Working Fluid & Chamber Structure Included
- Solar Sources Included
- TAPC Thermal Sink Included




- Differentiates Discharge & Charge Rates for Different TES Materials
- Identifies Solar Input Thresholds – Therefore Reflector / Dish Requirements
- Helps Distinguish & Quantify Cost/Performance Tradeoffs


Use or disclosure of data contained on this page is subject to the restriction(s) on the title page of this document

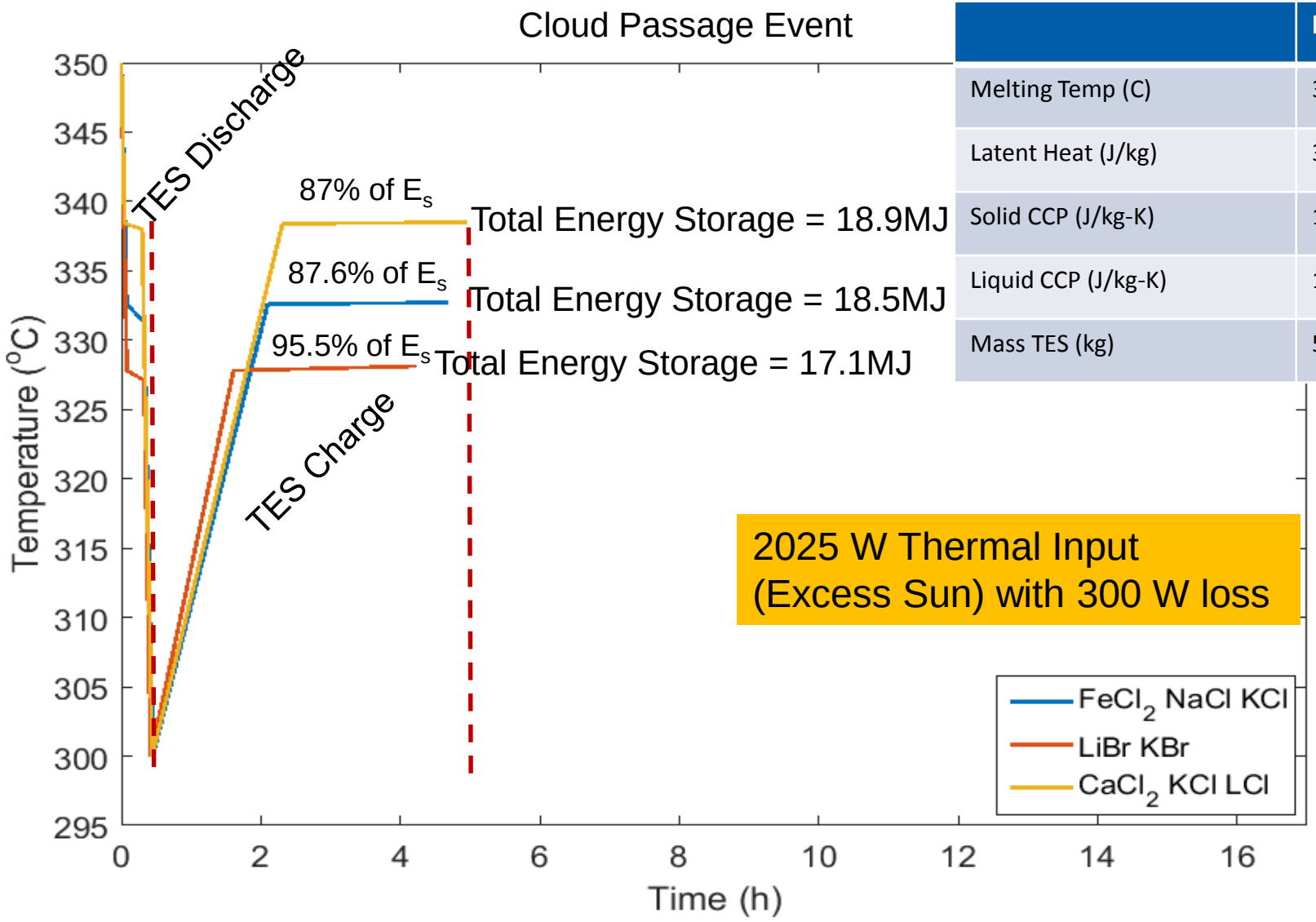
# TES Thermal Analysis – Low Excess Sun (Solar Dish Too Small)




| | $FeCl_2$ NaCl KCl | LBr KBr | $CaCl_2$ KCl LCl |
|---|---|---|---|
| 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 | LBr KBr | $CaCl_2$ KCl LCl |
|---|---|---|---|
| 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 |

2025 W Thermal Input (Excess Sun) with 300 W loss

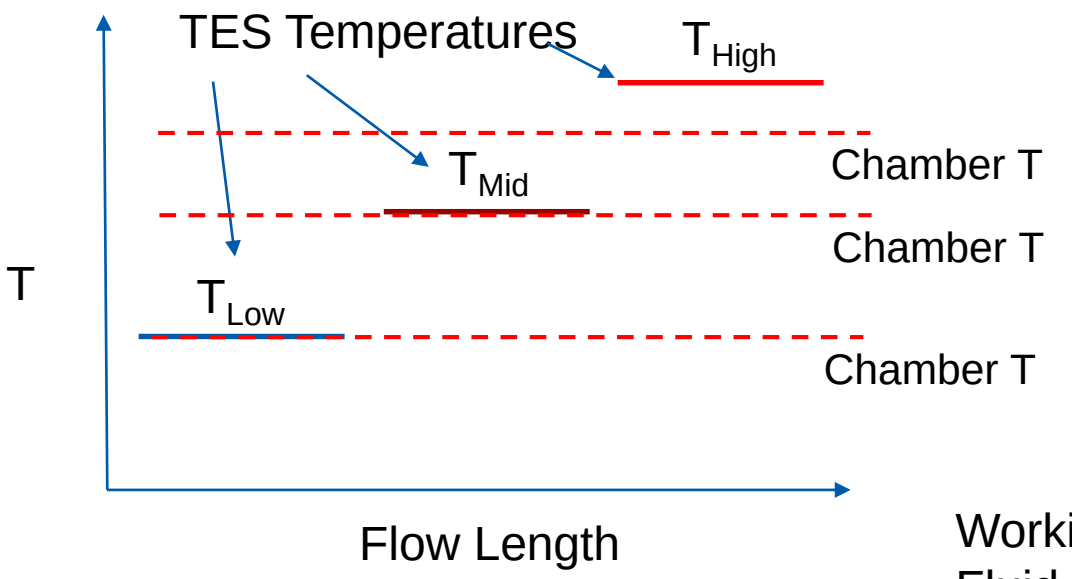
- Much Shorter Charge Times
- Sensible Charge Times Shorter than Latent Charge
- LiBr/KBr Shortest – But Most Expensive
- $FeCl_2$/NaCl/KCl Least Expensive

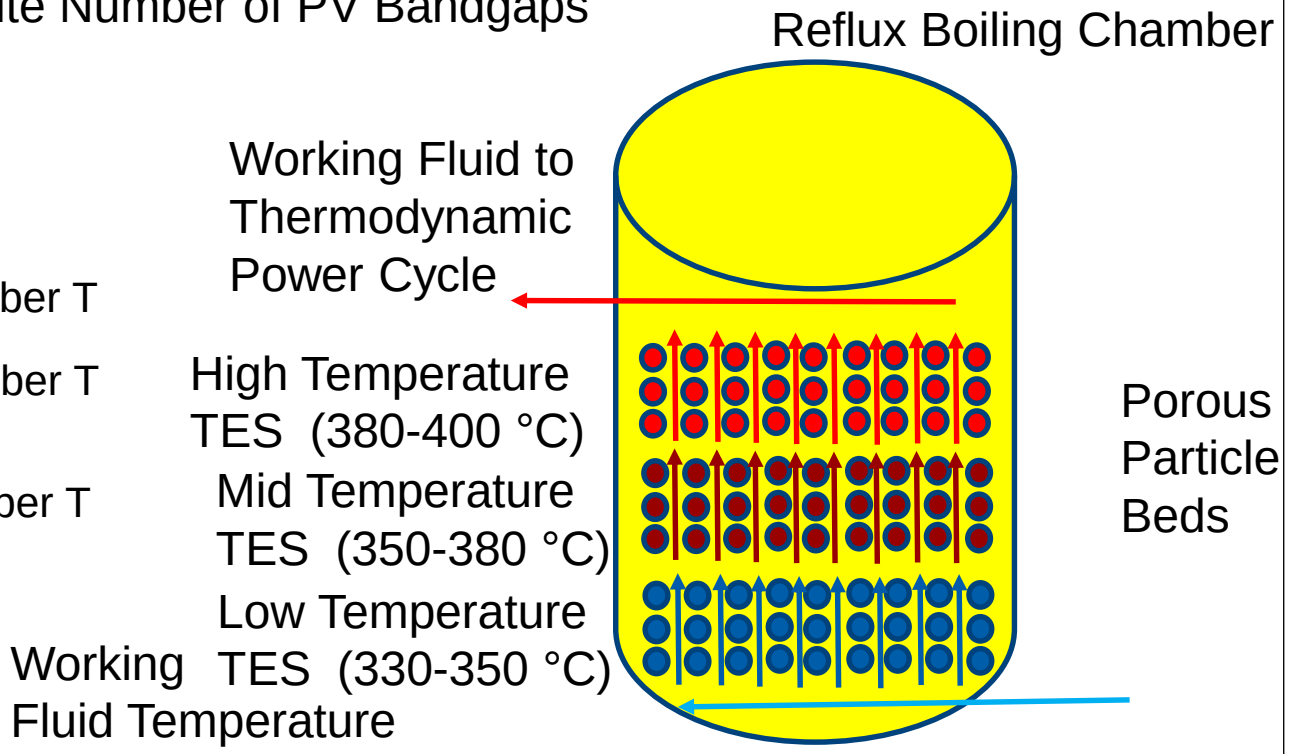
Use or disclosure of data contained on this page is subject to the restriction(s) on the title page of this document

# Multiple TES Materials

- $S_{Gen}$ ~ (Q/T) is Lower in This Scheme
- 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



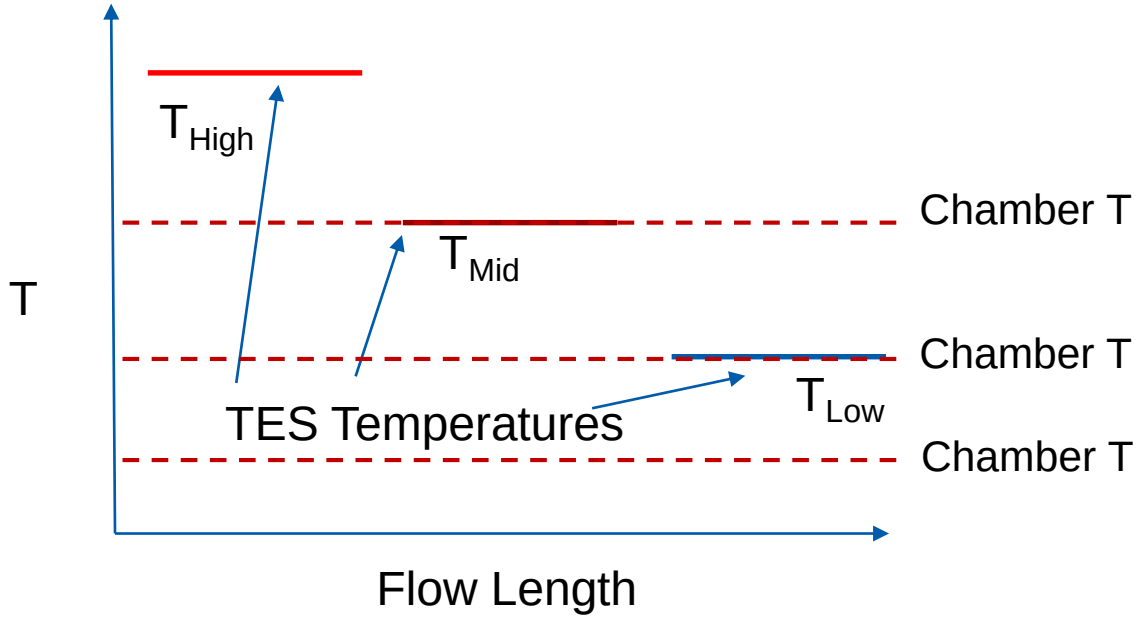



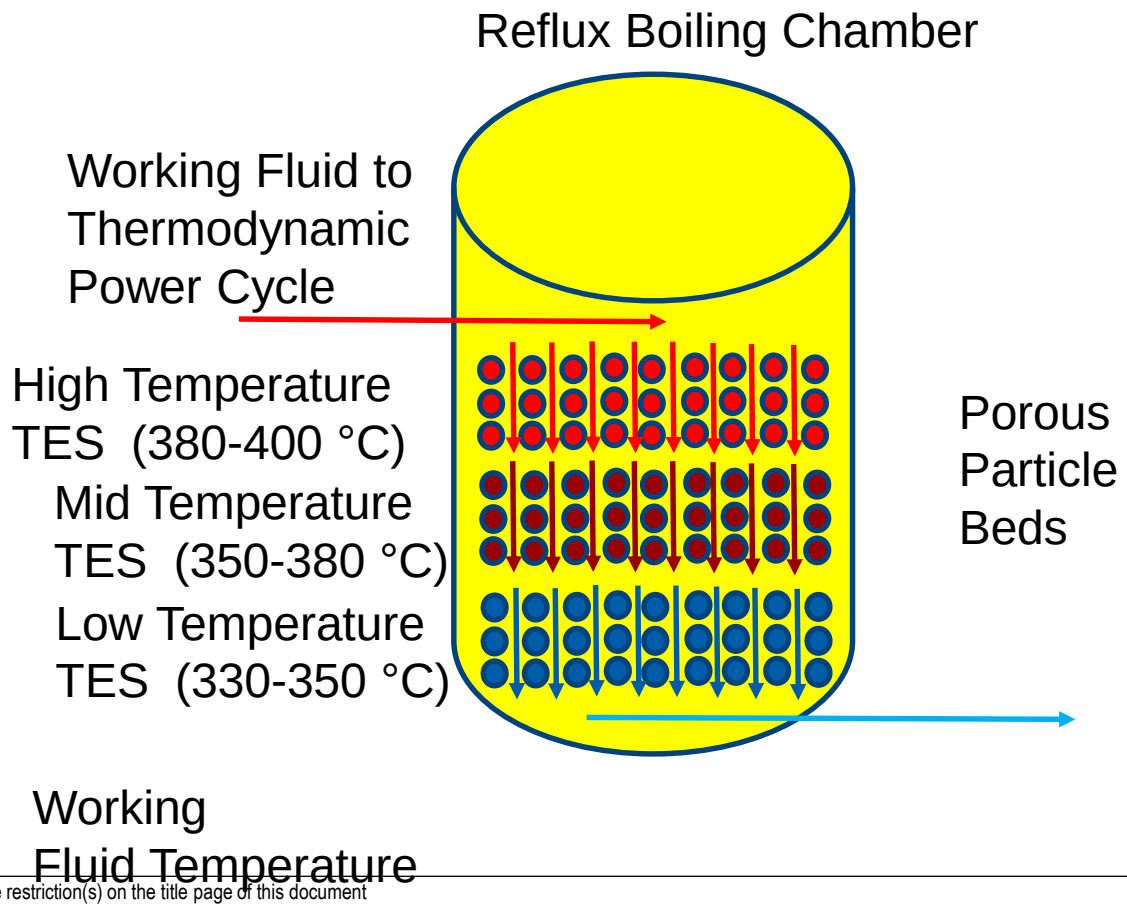

Use or disclosure of data contained on this page is subject to the restriction(s) on the title page of this document

# Multiple TES Materials

## TES Charge Process

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




Use or disclosure of data contained on this page is subject to the restriction(s) on the title page of this document

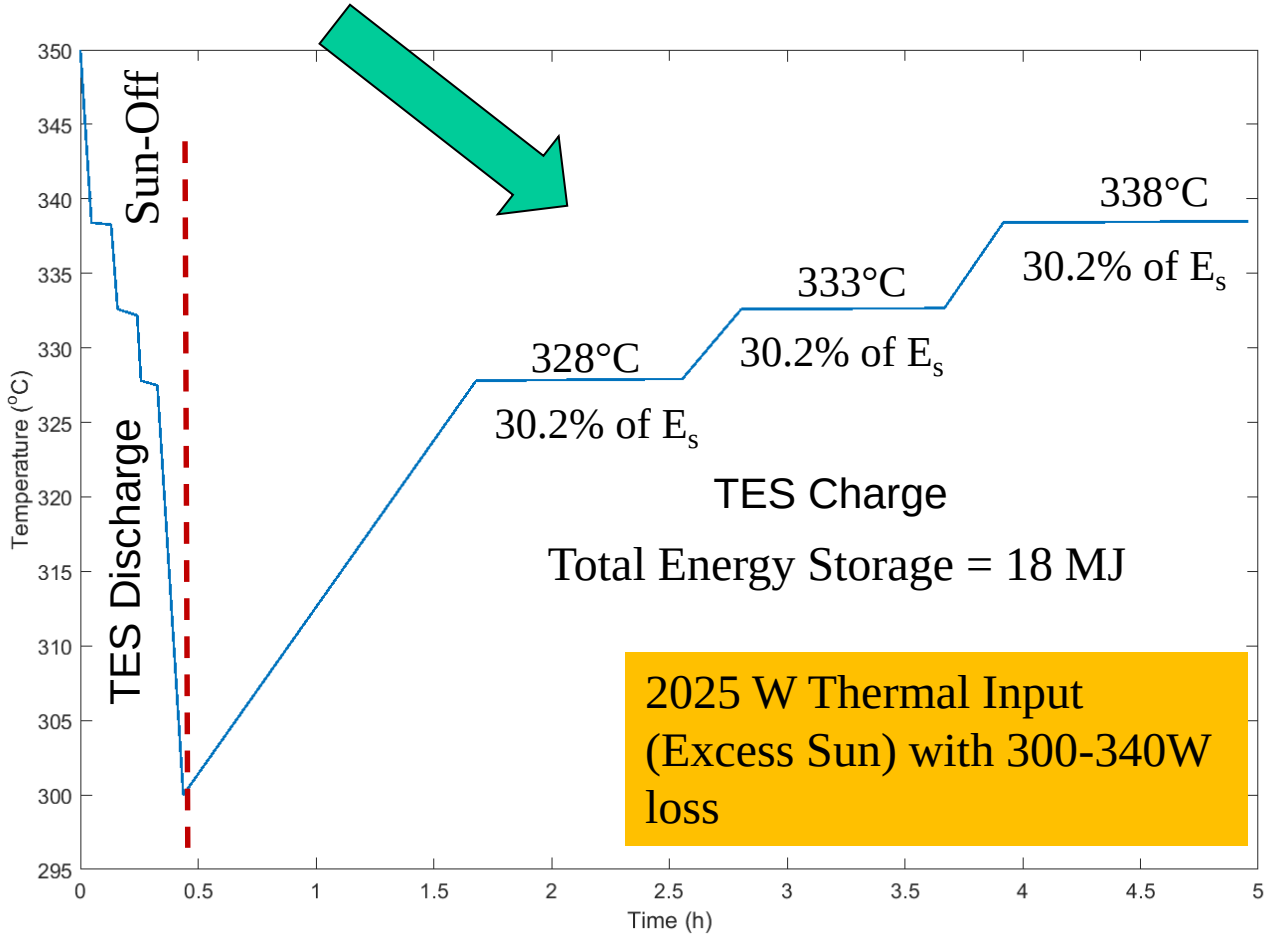
# Multiple Temperature-Staged Analysis

- 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



# TES Design Tradeoffs

- Requirements: 15 minutes at ~4.5 kW Power

| 4.5kWh thermal (in Spherical capsules) | LH =200kJ/kg | LH =309kJ/kg |
|---|---|---|
| PCM weight | 57 kg | 40.8 kg |
| Number of 1in spherical capsule | 3310 | 2380 |
| Weight of polymer coating | 6 kg | 4.36kg |
| | | |

| 4.5kWh thermal In steel tubes | LH =200kJ/kg | LH =309kJ/kg |
|---|---|---|
| PCM weight | 46 kg | 35kg |
| Number of 1in Steel tubes, 0.45m ht. | 131 | 101 |
| Weight of steel tubes | 53 kg | 40.8kg |
| | | |


Use or disclosure of data contained on this page is subject to the restriction(s) on the title page of this document

# TES Design Tradeoffs

- Requirements: 15 minutes at ~10 kW Power

| 10kWh thermal (in Spherical capsules) | 200 kJ/kg | 309 kJ/kg |
|---|---|---|
| PCM weight | 126 kg | 81.6 kg |
| Number of 1in spherical capsule | 7400 | 4790 |
| Weight of polymer coating | 14 kg | 9.0 kg |
| Size of tank | 0.45m dia.<br>0.57m ht. | 0.45m dia.<br>0.44m ht. |

| 10kWh thermal In steel tubes | LH =200kJ/kg | LH =309kJ/kg |
|---|---|---|
| PCM weight | 102 kg | 77.7kg |
| Number of 1in Diameter Steel tubes, 0.45m ht. | 291 | 219 |
| Weight of steel tubes | 118 kg | 89.3kg |
| Size of tank | 0.45m dia.<br>0.53m ht. | 0.45m dia<br>0.41m ht. |


Use or disclosure of data contained on this page is subject to the restriction(s) on the title page of this document

# Summary

- Reflux Boiler / TES is Critical to System Operation
  - Low Exergy Thermal Transport into TAPC
  - Low Exergy Thermal Transport Into/Out of TES
  - TES Designed Directly into Reflux Boiler System
- Several TES Materials Investigated
  - 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
  - Larger Fraction of Thermal Energy Stored at Appropriate Phase Change Temperatures
  - 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 This Approach into System-Level Designs & Configurations


Use or disclosure of data contained on this page is subject to the restriction(s) on the title page of this document

# Acknowledgements

Authors would like to acknowledge support from David E. Lee, Program Manager, Northrup 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.