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HEAT TRANSFER ENHANCEMENT STRATEGIES FOR ADVANCED THERMAL STORAGE SYSTEMS

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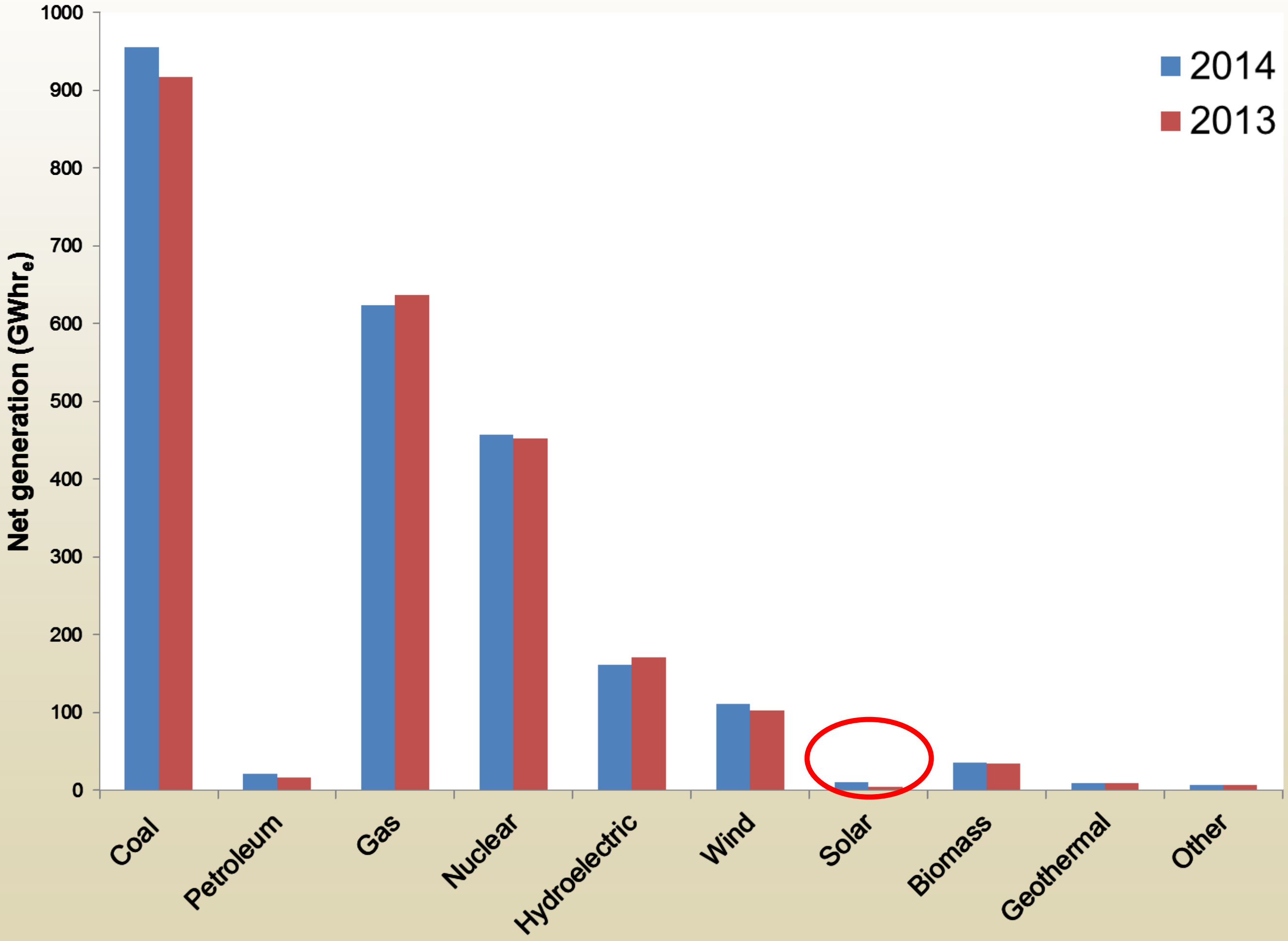
Outline

- Thermal energy storage
- Phase change materials for TES
- Inorganic salts as storage media
- Conductivity enhancement
- Radiative heat transfer enhancement
- Conclusions / future work

Thermal Energy Storage (TES)

- TES should play an important role in the energy portfolio of the near future, improving overall energy usage efficiency by
  - Capturing process / waste heat
  - Regulating the temperature of sensitive electronics
  - Building heating / cooling
  - Increasing capacity for power generation

Total yearly electricity generation, U.S.[1]



[1] U.S. Energy Information Administration (EIA), *Electric Power Monthly with Data for July 2014*, Sep 2014.

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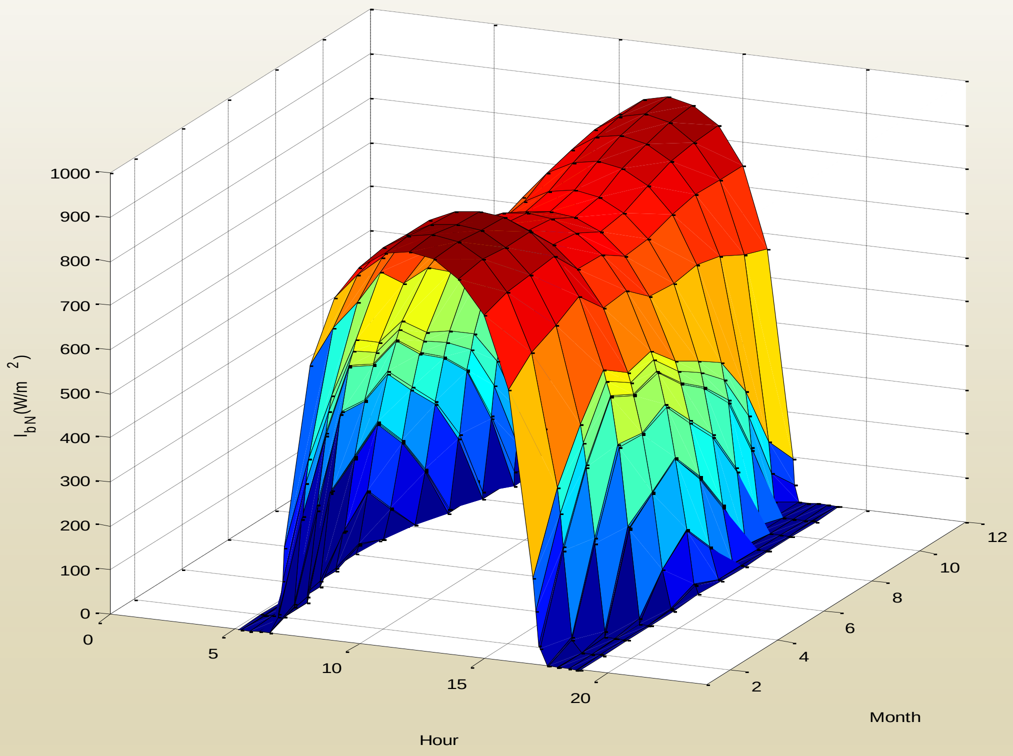
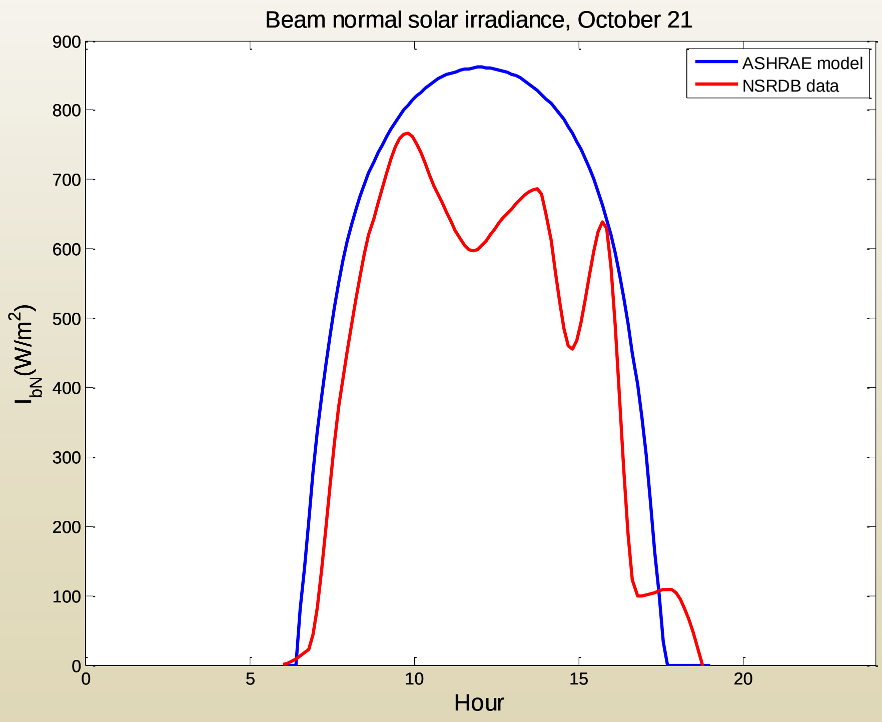
Need for energy storage: Solar irradiance (Tampa, Florida)





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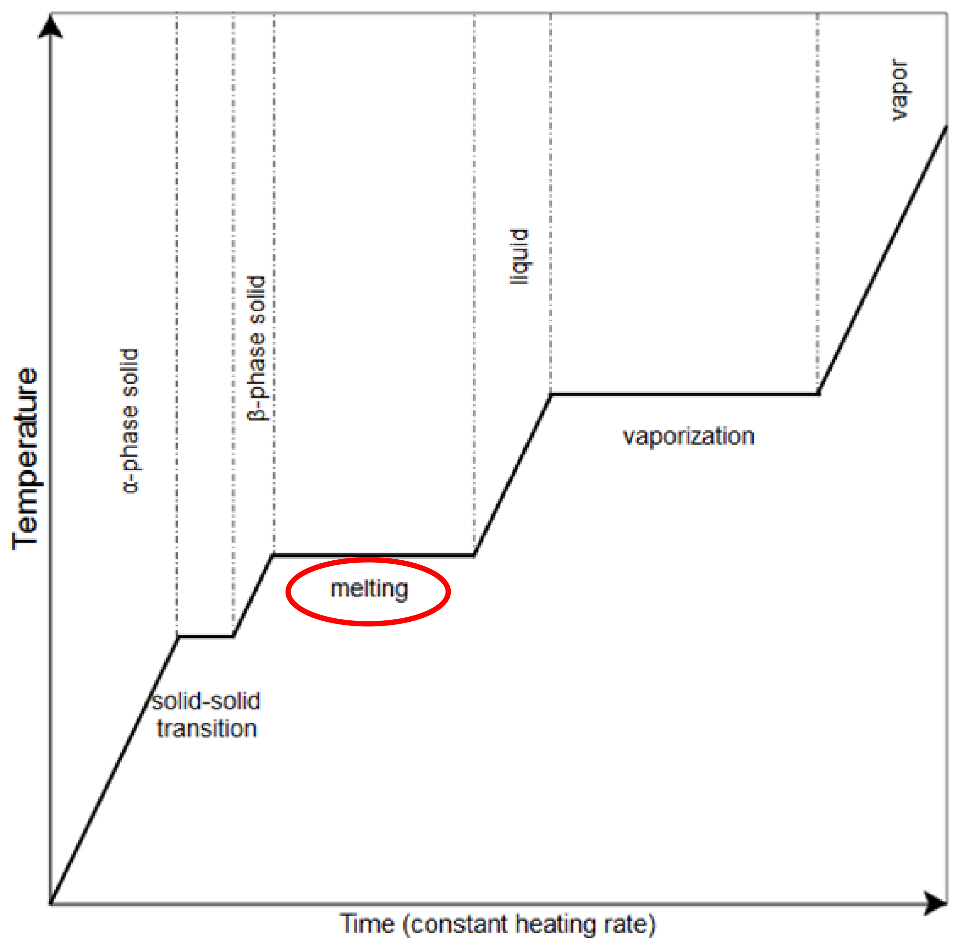
The need for energy storage

- Renewable energy technologies, including solar thermal power, suffer from intermittency:
  - Insolation limited to daylight hours
  - Cloud cover / other atmospheric variability
- **Thermal energy storage (TES)** strategies are needed to account for this intermittency
- Typical storage strategy involves harnessing peak energy output for use during lag periods.

Types of TES

- Sensible heat
  - Stored by heating a certain mass of material of constant phase (i.e., does not melt)
  - Depends on the specific heat capacity of the material
- Latent heat
  - Stored by heating a mass of material through a phase transition (solid-solid, solid-liquid, solid-gas, liquid-gas)—**phase change materials (PCMs)**
- Thermochemical reaction
  - Stored by heating a compound / compounds until it (reversibly) undergoes an endothermic chemical reaction

Generalized phase change process



Latent heat storage: Higher storage density

$$Q = \int_{T_1}^{T_m} mc_{p,s}dT + m\lambda + \int_{T_m}^{T_2} mc_{p,l}dT$$

- For operating range of 260 to 560°C
  - KNO_3-$NaNO_3$ (sensible only) → 212 kWh/m^3
  - $NaNO_3$ (sensible and latent) → 347 kWh/m^3

- For operating range of 260 to 360°C
  - KNO_3-$NaNO_3$ (sensible only) → 77.1 kWh/m^3
  - $NaNO_3$ (sensible and latent) → 186 kWh/m^3

- 60% and 140% increase in storage density, respectively

Anhydrous salt PCMs

- Inexpensive
- Resistant to oxidative degradation
- Relatively easy to handle in the molten state
- High latent heats of fusion
- *Major drawback*—low thermal conductivity
  - NaCl: 0.8 W/m-K [1]
  - $NaNO_3$: 0.6 W/m-K [2]
  - Compare to metal oxides (10-100 W/m-K) or metals (>100 W/m-K)

[2] M. V. Smirnov, V. A. Khokhlov, and E. S. Filatov, "Thermal-Conductivity of Molten Alkali-Halides and Their Mixtures," *Electrochimica Acta,* vol. 32, pp. 1019-1026, Jul 1987.
[3] G. J. Janz, *Molten salts handbook*. New York,: Academic Press, 1967.

Heat transfer enhancement

- Variety of methods have been explored to enhance heat transfer in PCMs
  - Extended surfaces
  - Encapsulation
  - Additives / matrices for heat transfer enhancement

High conductivity additives / matrices

- Limited work has been done with metal matrices impregnated with salt PCMs, but these have been shown to corrode under oxidation by nitrate salts (as has graphite in some cases)
- Main issues:
  - Material compatibility
  - Maintenance of additive dispersion

Other modes of heat transfer?

- Convective heat transfer can dominate the melting process, so much of the design of PCM containment or extended surfaces has attempted to enhance convective transfer
- Radiative transfer?
  - Prior work (e.g., Drotning [4]) has focused on use of additives to increase *solar availability*—that is, radiative transfer in the UV-visible-NIR
  - The potential of thermal (infrared) radiative transfer remains largely unexplored for PCMs

[4]W. D. Drotning, "Optical-Properties of Solar-Absorbing Oxide Particles Suspended in a Molten-Salt Heat-Transfer Fluid," *Solar Energy,* vol. 20, pp. 313-319, 1978.

Research strategy

Improve charging / discharging times for heat storage units by using novel enhanced inorganic salt thermal storage media by

- Inclusion of higher conductivity nanoparticles to increase thermal conductivity
- Inclusion of nanoparticles (very low concentration) to increase absorption coefficient of relatively transparent salts (e.g. chlorides)
- Inclusion of soluble materials to increase absorption coefficient (e.g., CuCl in NaCl)

Increasing *radiative* transfer

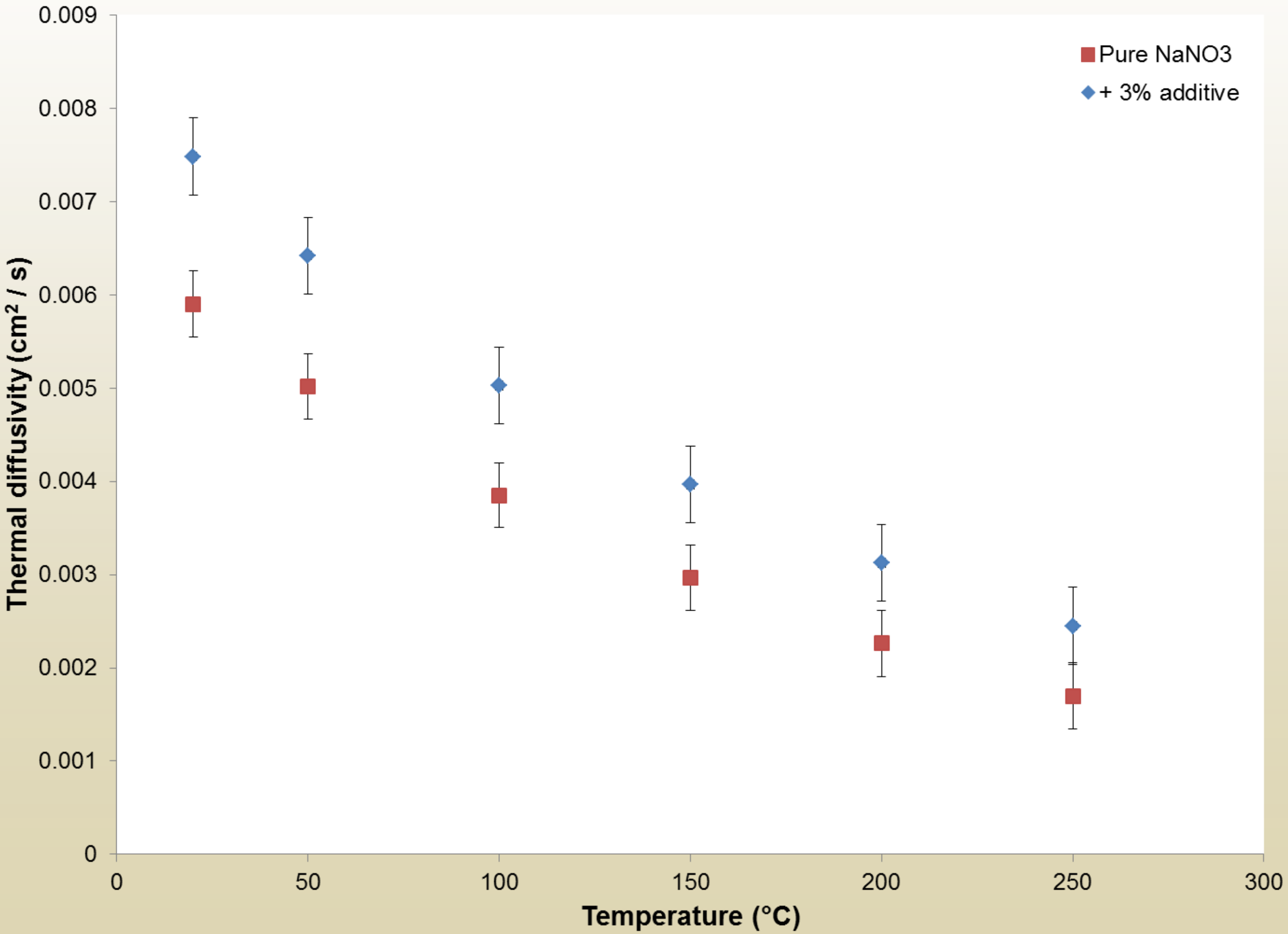
Experimental methods

- Thermal conductivity
  - Diffusivity via laser flash method (Linseis XFA-500)

$$\alpha = \frac{k}{\rho c_p}$$

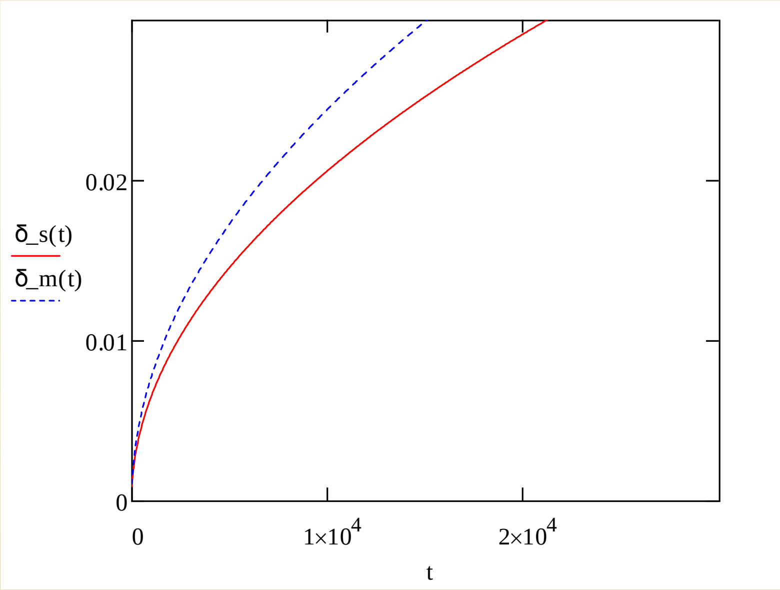
  - Density / specific heat from literature, or measured independently
    - Hot plate / bubble method
    - Differential scanning calorimetry (DSC)
- Thermophysical properties (T_m, ΔH_{fus}, c_p)
  - DSC (TA SDT-Q600)
- Radiative absorption
  - FTIR spectroscopy (Jasco 6300)—transmission, reflection, emission

Diffusivity / conductivity enhancement



Potential for conductivity enhancement

- For additive-$NaNO_3$ composites, conductivity enhancement of ~40% near melting point
- Consider slab solidification, high conductivity wall, high convective transfer w/ HTF[6]
- $\lambda\rho(1-\phi)\frac{d\delta}{dt} = \frac{T_s - T_c}{\frac{1}{h_c}+\frac{w}{k_w}+\frac{\delta}{k}}$
- $\delta = \left\{\frac{2k'}{1-\phi}\left[\frac{(T_s-T_c)}{\lambda\rho}t\right]\right\}^{1/2}$
- Approximately **30%** reduction in discharge time



[6]R. Siegel, "Solidification of Low Conductivity Material Containing Dispersed High Conductivity Particles," *International Journal of Heat and Mass Transfer,* vol. 20, pp. 1087-1089, 1977.

Novel concept: Additives to enhance thermal radiative heat transfer

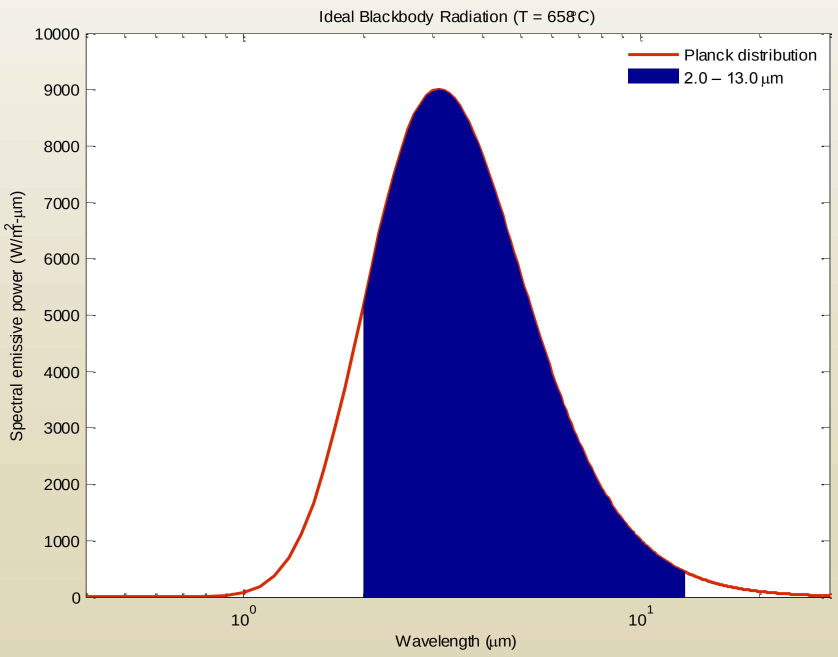
- As solar thermal plants (power tower) reach higher temperatures / efficiencies, higher melting salts will be needed
- (K-Na)Cl eutectic is ideal candidate
  - $T_m = 658°\text{C} \quad \Delta H_{fus} = 278 \text{ J/g}$
- Also, pure NaCl
  - $T_m = 800.7°\text{C} \quad \Delta H_{fus} = 484 \text{ J/g}$
- NOTE: transparent to infrared (thermal) radiation in region of 0.5 to 20.0 μm
- We add IR active compounds to absorb thermal radiation, improve overall heat transfer rates

Ivanpah SEGS[7]

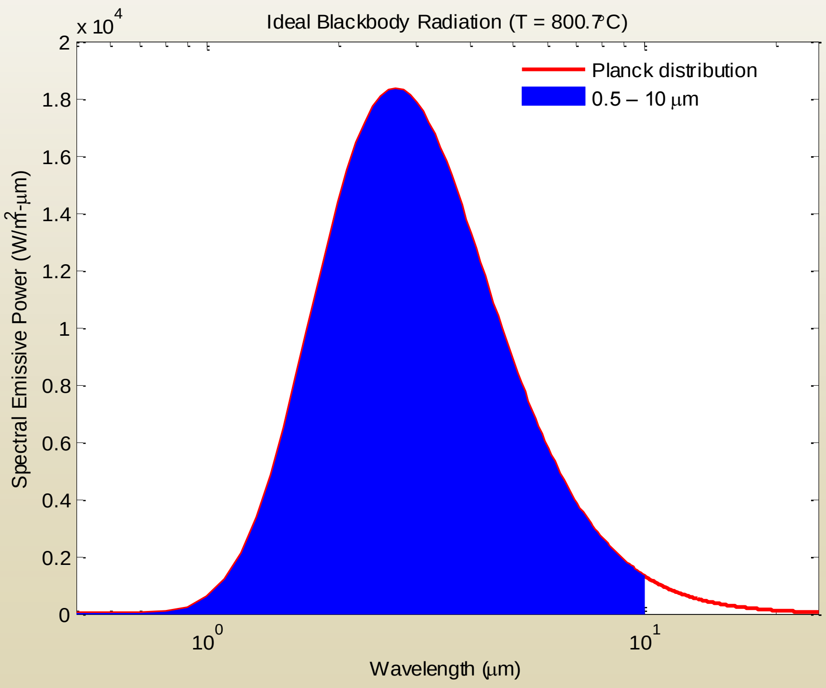
[7] M. Strauss, "Take a Look at the World's Largest Solar Thermal Farm," *Smithsonian Magazine*, Nov 2012 (http://www.smithsonianmag.com/science-nature/take-a-look-at-the-worlds-largest-solar-thermal-farm-91577483/).

Planck distribution

90%



93%



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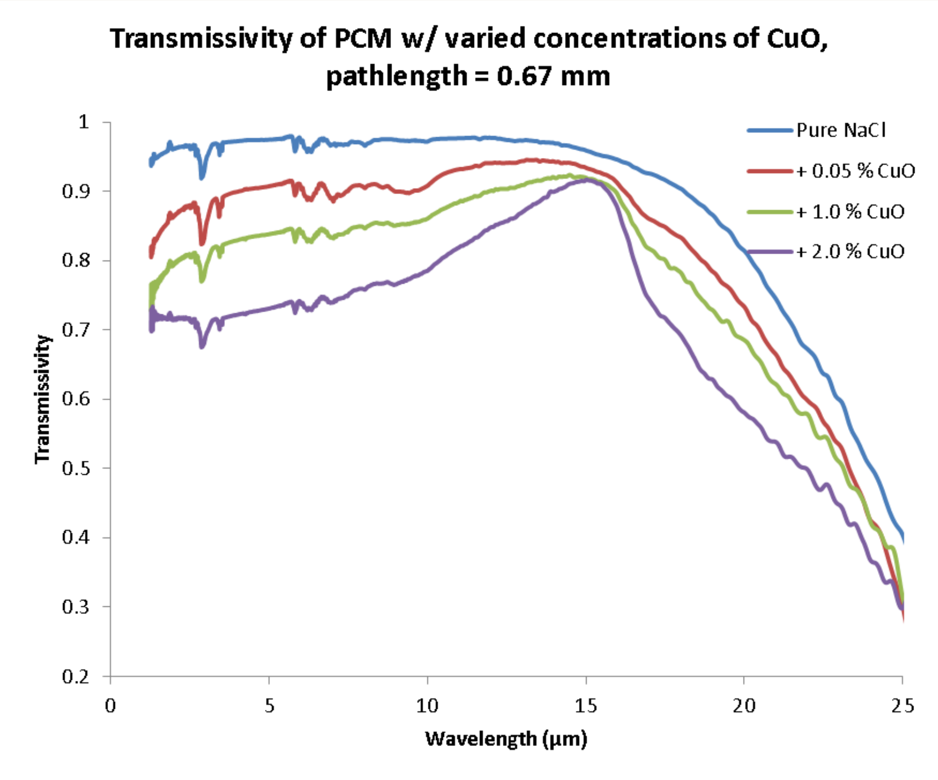
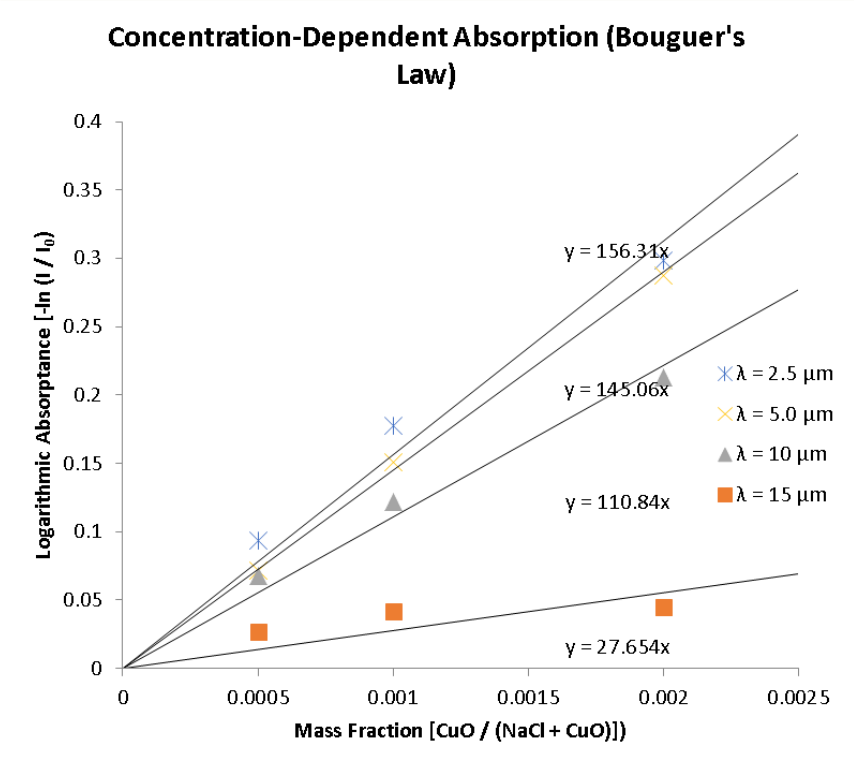
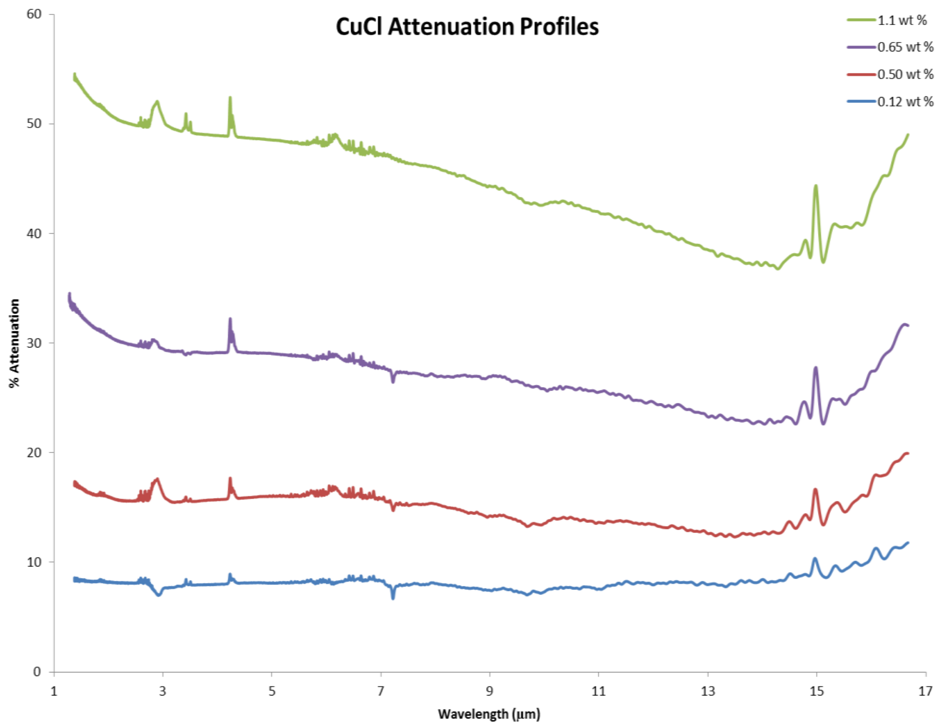
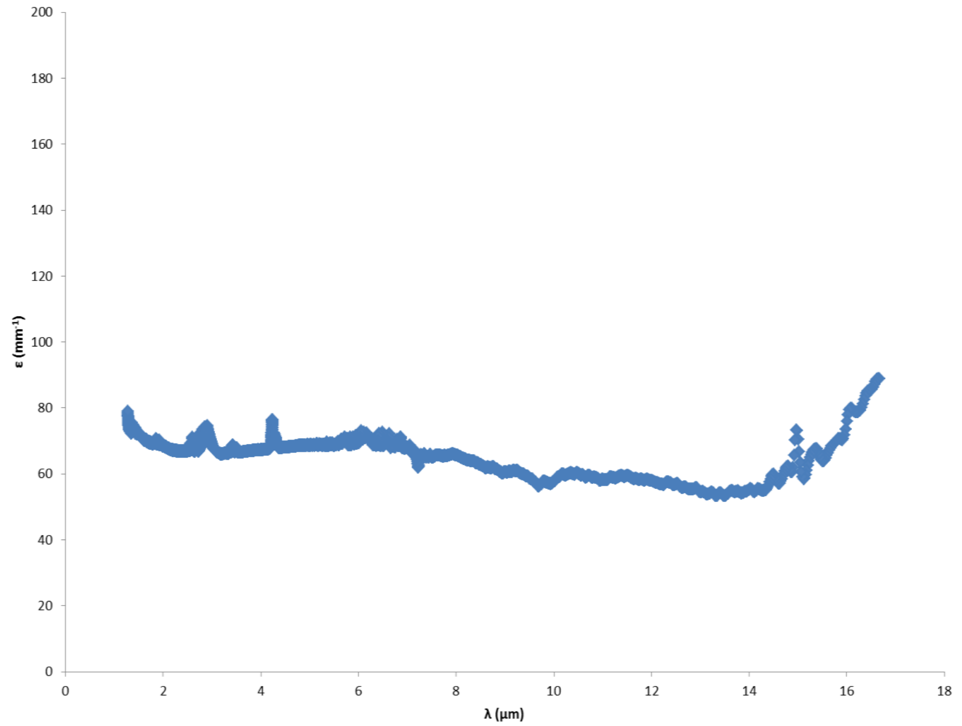
Absorptivity enhancement, CuO





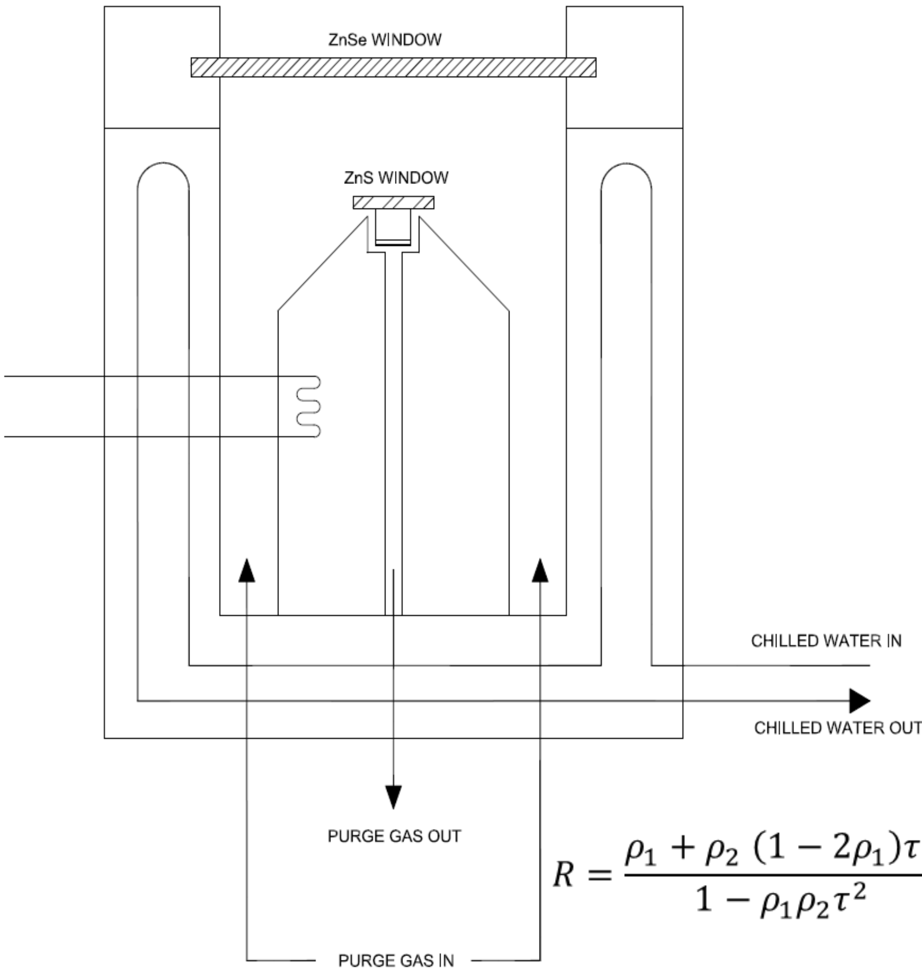
Absorptivity enhancement, CuCl



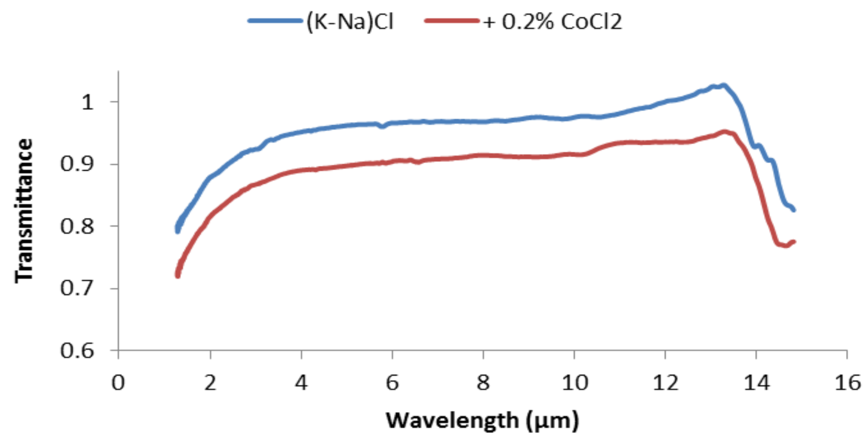


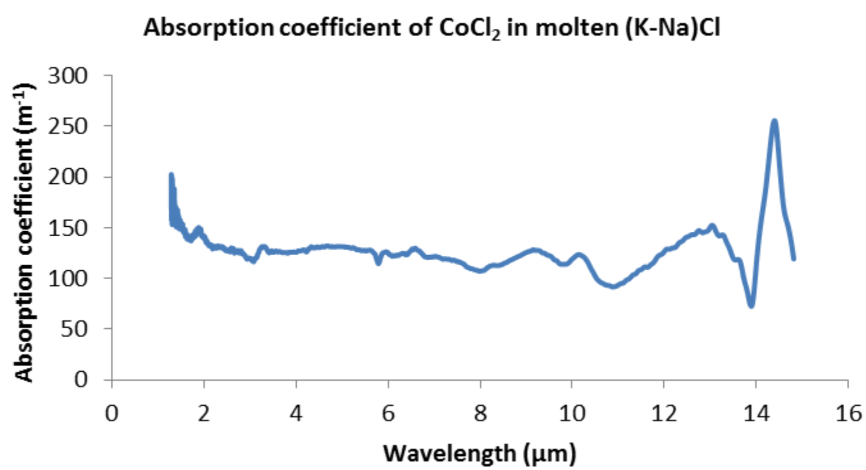
High temperature IR reflectance apparatus

- Test of efficacy of IR absorption in molten salt: $CoCl_2$ absorption coefficient



$$R = \frac{\rho_1 + \rho_2\,(1 - 2\rho_1)\tau^2}{1 - \rho_1\rho_2\tau^2}$$





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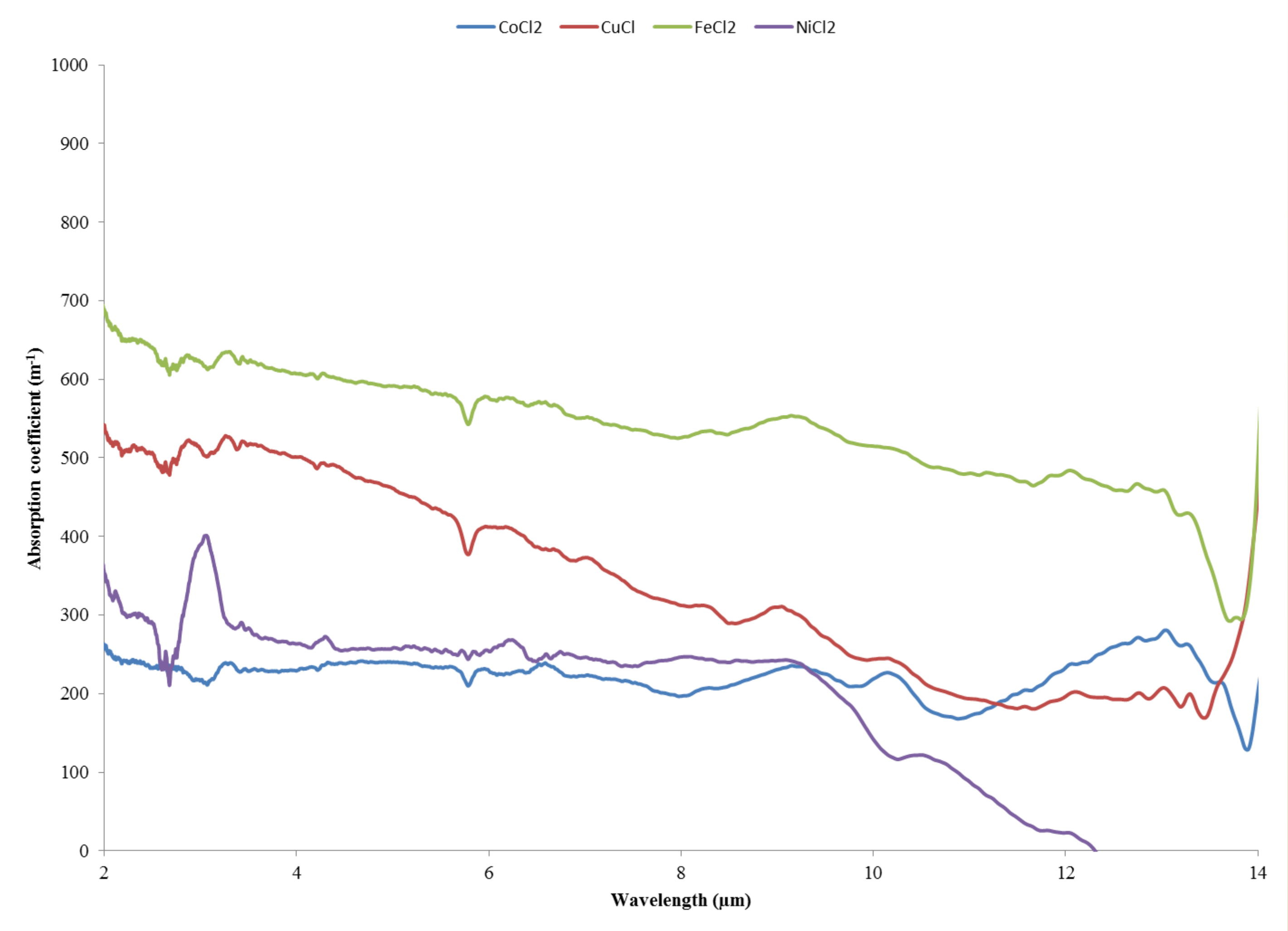
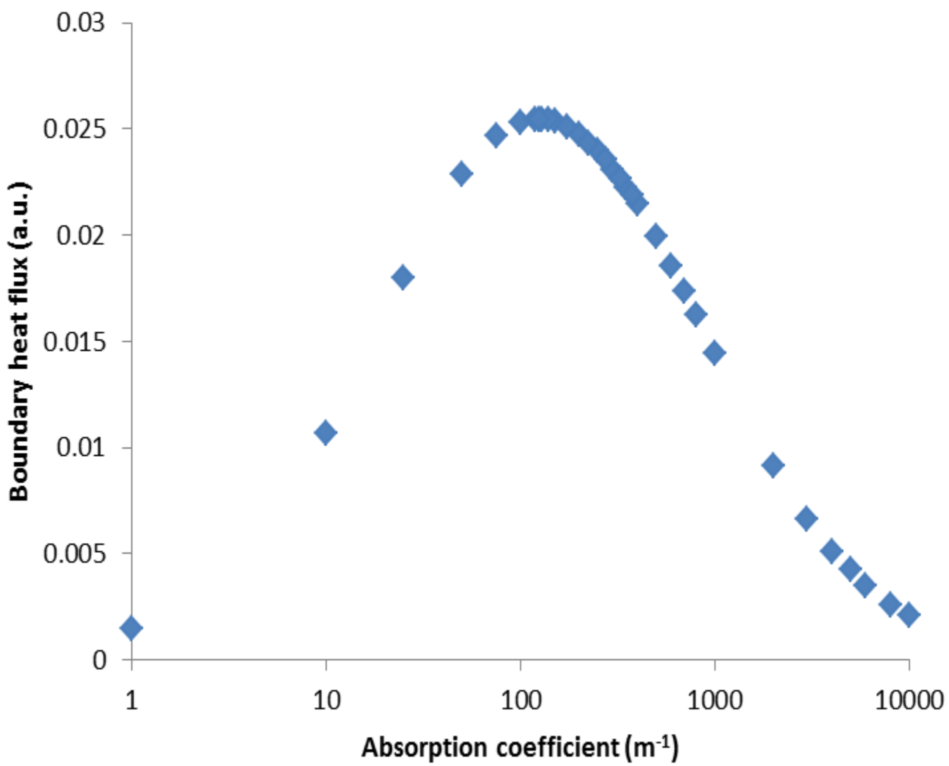
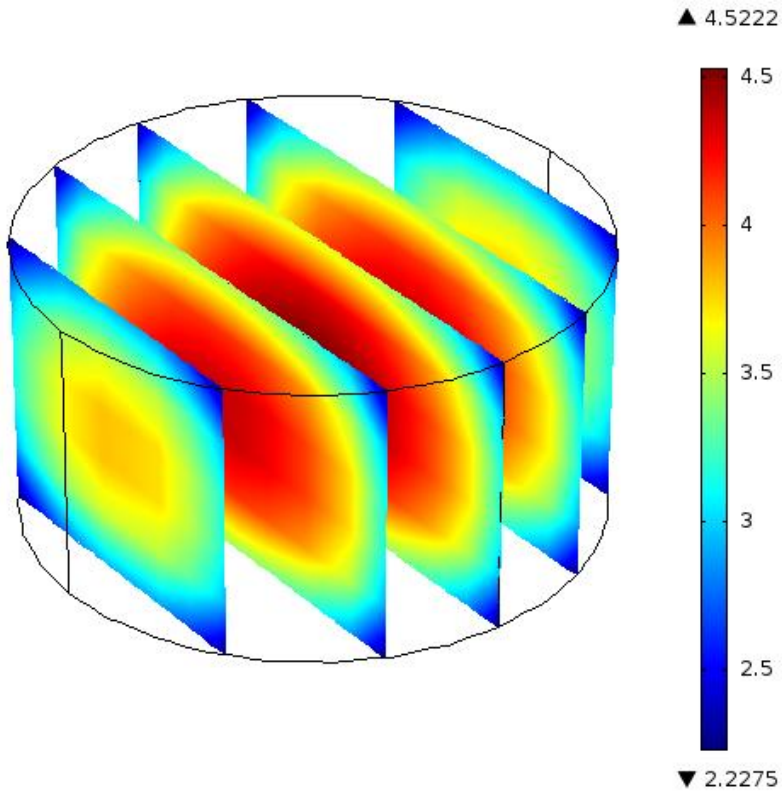
Absorption coefficient, molten salt



Simulation: Optimum absorption coefficient





Conclusions / future work

- Demonstrated conductivity enhancement for nitrate salt-based TES systems currently in use in solar thermal applications
- Quantified infrared absorption enhancement in higher temperature chloride salts
- Next steps:
  - Modeling of transient heat transfer process
  - Determination of optimum additive / PCM composition for scale-up

THANK YOU