Concentrated Solar Power on Demand

CSPond: Solar Harvesting and Storage

Charles Forsberg

Department of Nuclear Science and Engineering (NSE)
Massachusetts Institute of Technology
77 Massachusetts Ave; Bld. 42-207a; Cambridge, MA 02139
Tel: (617) 324-4010; Email: cforsber@mit.edu

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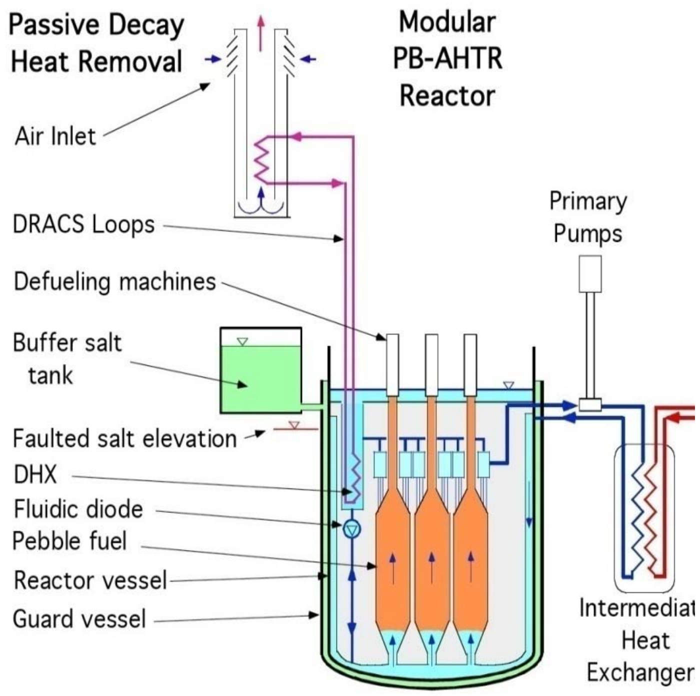
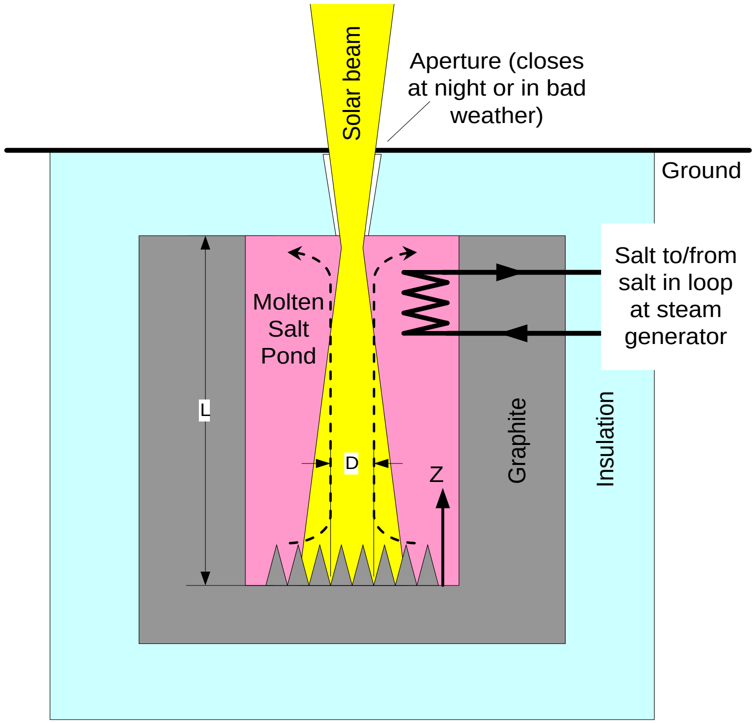
CSPond Faculty:
Alexander Slocum (ME), Jacopo Buongiorno (NSE), Charles Forsberg (NSE), Thomas McKrell (NSE), Alexander Mitsos (ME), Jean-Christophe Nave (ME)

CSPond Students:
Daniel Codd (ME), Amin Ghobeity (ME), Corey J. Noone (ME), Stefano Passerini (NSE), Jennifer Rees (ME), Folkers Rojas (ME)

Joint Mechanical and Nuclear Science and Engineering Project

Shared Liquid-Salt Technology Base





Fluoride-Salt High-Temperature Reactor (FHR)

Concentrated Solar Power on Demand (CSPonD)

Outline

- Existing solar systems
- CSPond Base Case Design
- Experimental Validation
- Alternative Design Options
- Path Forward

A. Slocum, J. Buongiorno, C. W. Forsberg, T. McKrell, A. Mitsos, J. Nave, D. Codd, A. Ghobeity, C. J. Noone, S. Passerini, F. Rojas, "Concentrated Solar Power on Demand," *J. Solar Energy*

Existing Solar Power Towers

- Mirrors reflect sunlight to boiler
- Boiler tubes on top of tall tower absorb light
- Heat water and convert to steam
- Steam turbine produces electricity
- Poor economics
  - High capital cost
  - Low thermal efficiency

PS-10, 11MWe peak, image courtesy of N. Hanumara

The Challenge is Cost

- Low efficiency system
  - In theory: high efficiency
  - In practice
    - Low steam temperatures to avoid boiler-tube thermal fatigue from variable light
      - Wind and sunlight always changing energy fluxes
    - High heat loses from exposed boiler tubes
- High costs
  - Mirrors
    - Largest cost component
    - Incentives for efficient light to electricity system
  - Tall tower

PS-10, Spain, 11MWe peak, image courtesy of N. Hanumara

CSPond
Base-Case Design

CSPond Characteristics

Combining Many Technologies in a New Way

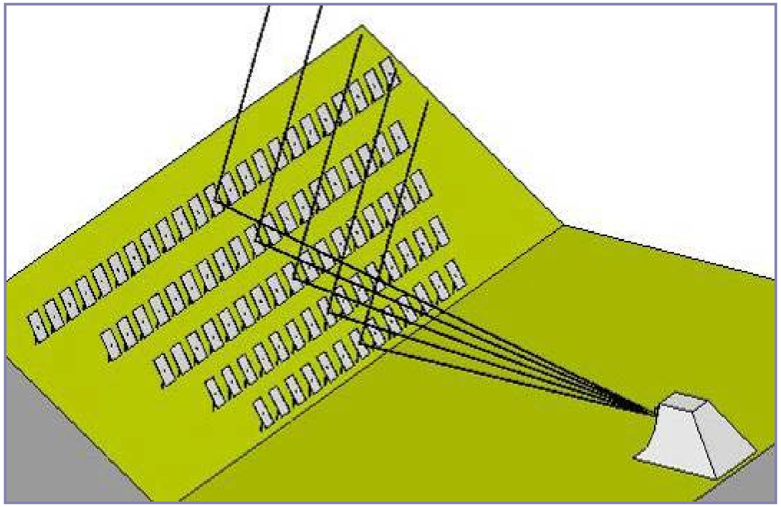
- Concentrated solar thermal power system
- Built-in thermal storage
- Heliostat field similar to solar power tower
- Radically different light receiver to:
  - Boost light-to-electricity efficiency
  - Provide thermal heat storage
- Unique features:
  - Light volumetrically absorbed in liquid salt bath
  - Salt bath could operate to 1000°C

CSPond Description

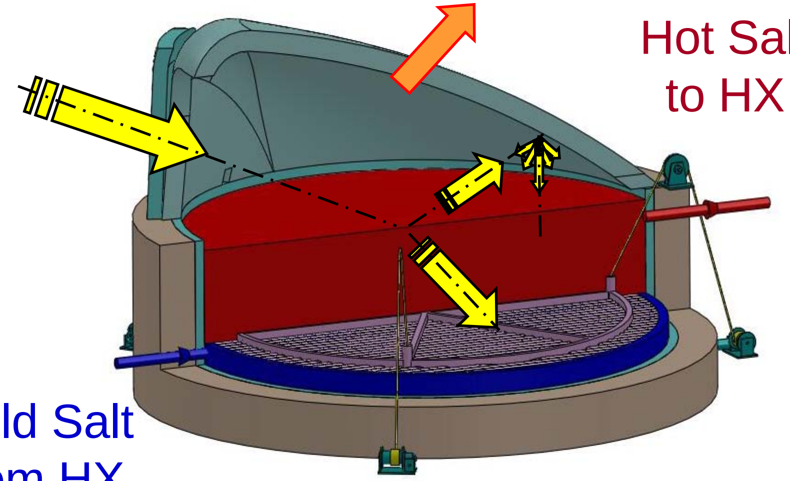
Figure Next Page

- Mirrors shine sunlight to receiver
- Receiver is a high-temperature liquid salt bath inside insulated structure with open window for focused light
    - Light volumetrically absorbed through several meters of liquid salt
    - Building minimizes heat losses by receiver
    - Enables salt temperatures to 900 C
- Small window minimizes heat losses but very high power density of sunlight through open window
    - Power density would destroy conventional boiler-tube collector
    - Light absorbed volumetrically in several meters in salt
- Requires high-temperature (semi-transparent) salt—Similar salt requirements as for FHR heat transfer loop

Two Component System



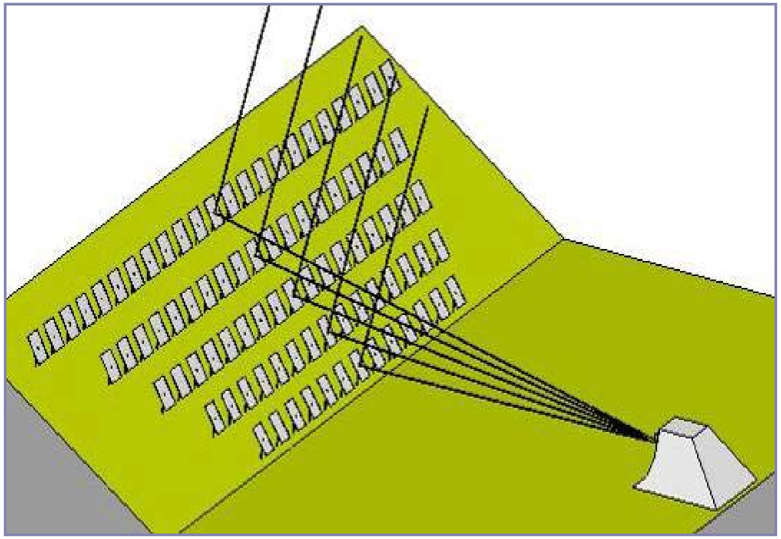
Light Reflected From Hillside Heliostat rows to CSPonD System



Light Collected Inside Insulated Building With Open Window

(Not to scale!)

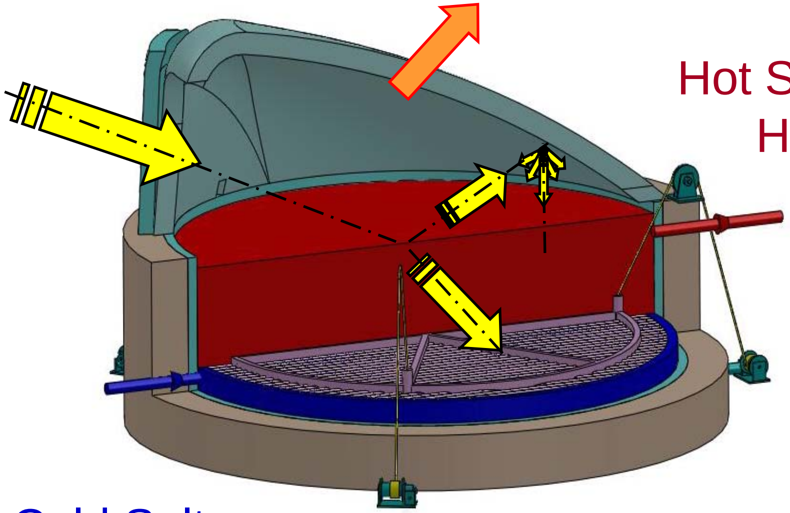
Advantages of Hillside Heliostat Field



- Eliminate tower-based receiver—heavy equipment on ground
- Avoid remote storage and high pressure pumps
- Downward focused light
- Potentially lower land costs

CSPond Light Receiver

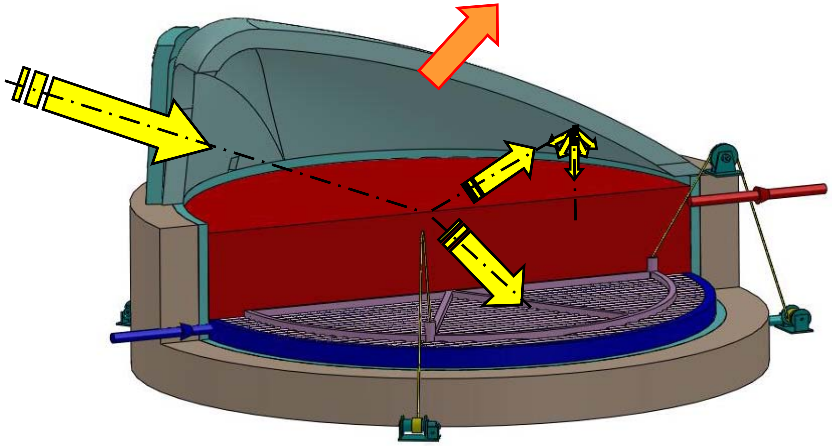
- Efficient light-to-heat collection
  - Concentrate light
  - Focus light through small open window
  - Minimize heat losses
- Challenge
  - Light energy per unit area very high
  - Will vaporize solid collectors



Light Volumetrically Absorbed in Liquid Salt Bath

Light Focused On "Transparent" Salt

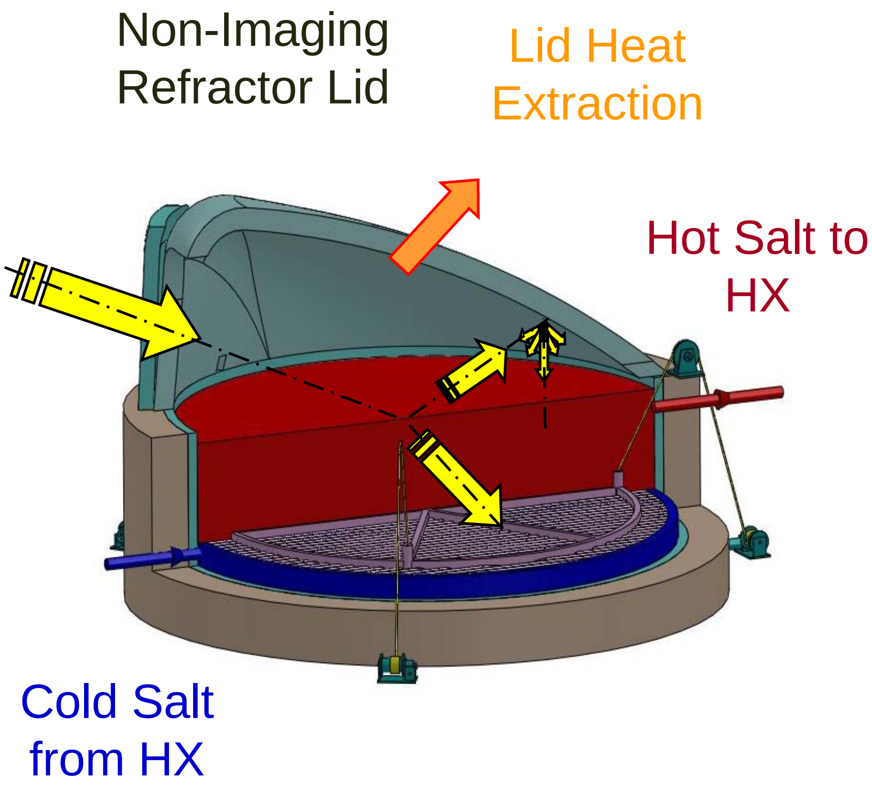
- Light volumetrically absorbed through several meters of salt
- Molten salt experience
  - Metal heat treating baths (right bottom)
  - Molten salt nuclear reactor
- Advantages
  - No light-flux limit
  - No thermal fatigue
  - Can go to extreme temperatures



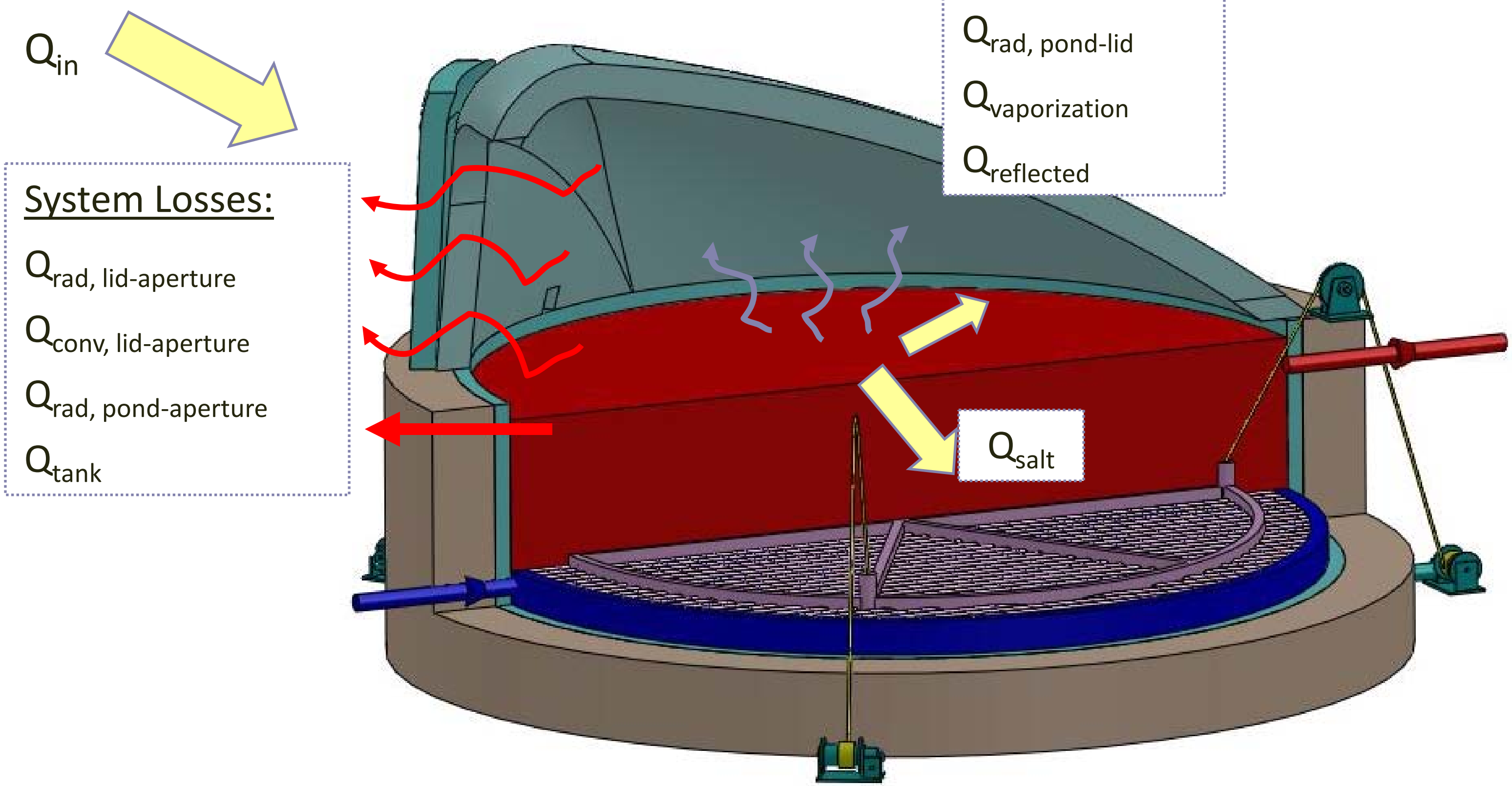
Molten Chloride Salt Bath (1100°C)

Salt Vapor Condenses On Ceiling

- Cooled ceiling: Lid Heat Extraction
- Salt buildup until "liquid" salt layer with flow back to salt bath
- Self-protecting, self-healing ceiling
- Highly reflective



Capture Efficiency: Energy Balance



$$\eta_{capture} = \frac{Q_{system}}{Q_{in}} = \frac{Q_{in} - Q_{losses}}{Q_{in}} = \frac{Q_{in} - (Q_{rad,\ l\text{-}a} + Q_{conv,\ l\text{-}a} + Q_{rad,\ p\text{-}a} + Q_{tank})}{Q_{in}}$$

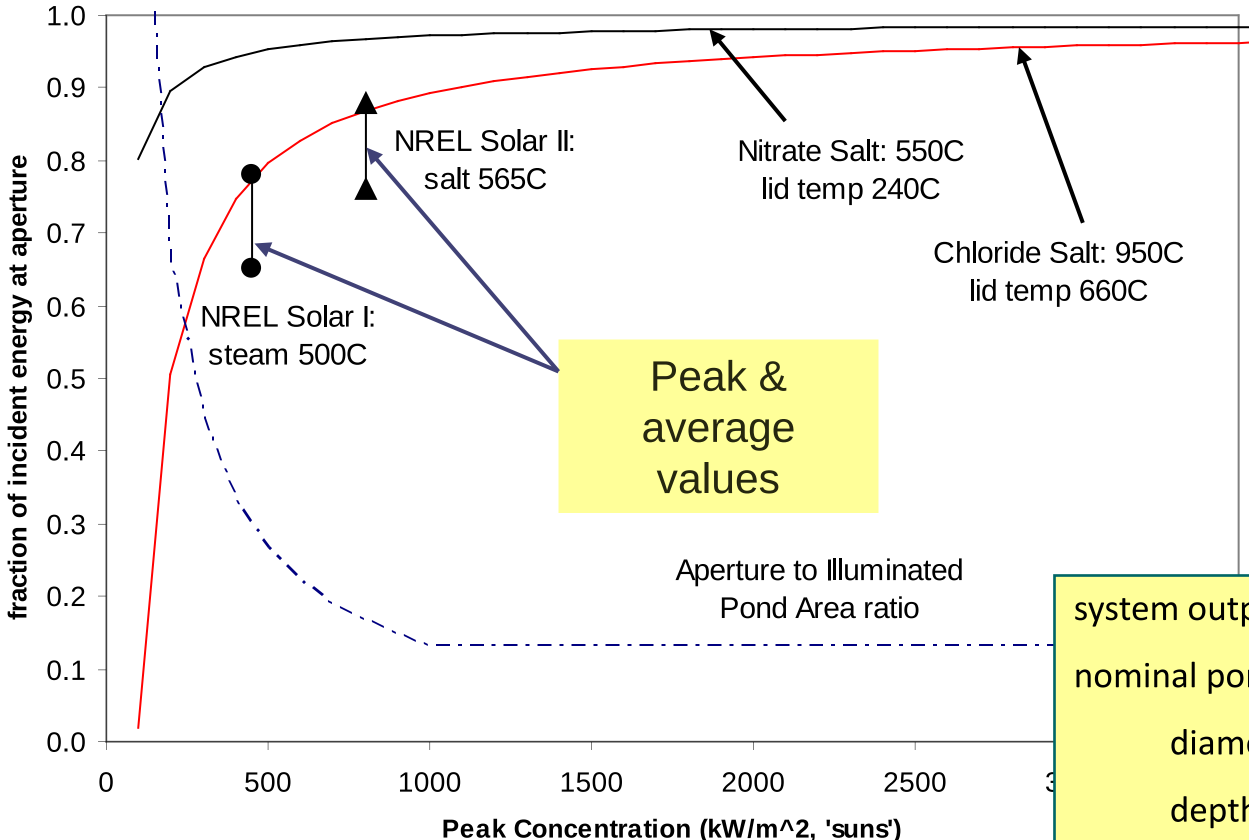
Two Classes Of Molten Salts

Appearance of molten

NaCl-KCl salt at 850°C

- Near-term: Nitrates
  - Used in some concentrated thermal energy solar systems
  - Off the shelf
  - Temperature limit of ~550°C (Degradation)
- Longer-term: Chlorides and Carbonates
  - Thermodynamically stable
  - Peak temperatures > 1000°C

System Design Enables Efficient Light Collection and High Temperatures



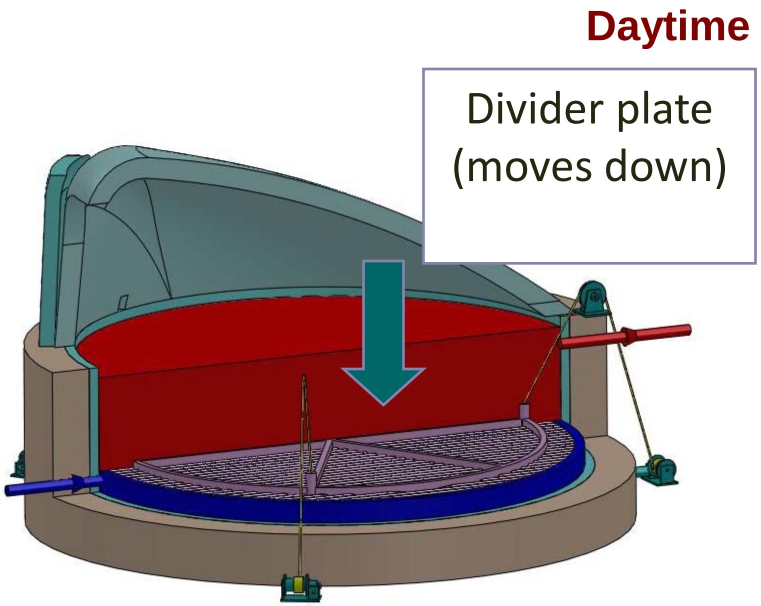
Compares favorably with measured values for CSP Power Tower Systems

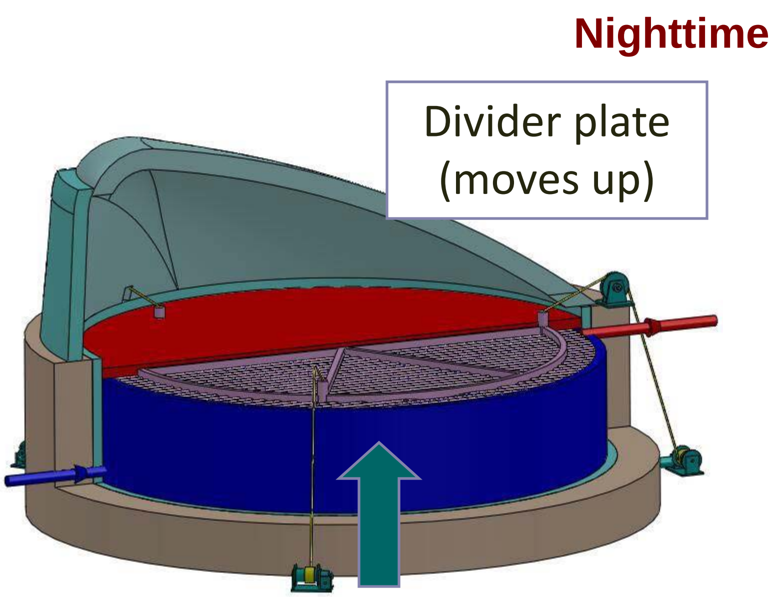
system output (MWe):	4
nominal pond size	
diameter (m):	25.0
depth (m):	5.0
avg beam down angle (deg):	21.4
Nitrate Salt, Lid peak temp (C):	550/240
Chloride Salt, Lid peak temp (C):	950/660

NREL (2003)

CSPond Integral Heat Storage

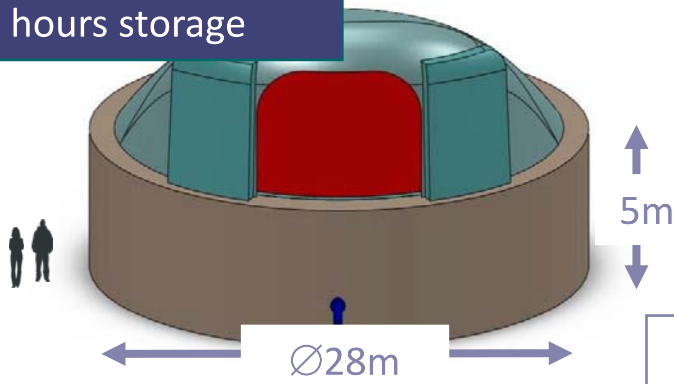
- Salt tank has insulated separator plate
- Plate functions
  - Separates hot and cold salt
  - Bottom light absorber
- Storage role
  - If excess heat input, plate sinks to provide hot salt storage volume
  - If power demand high, plate raised with cold salt storage under plate

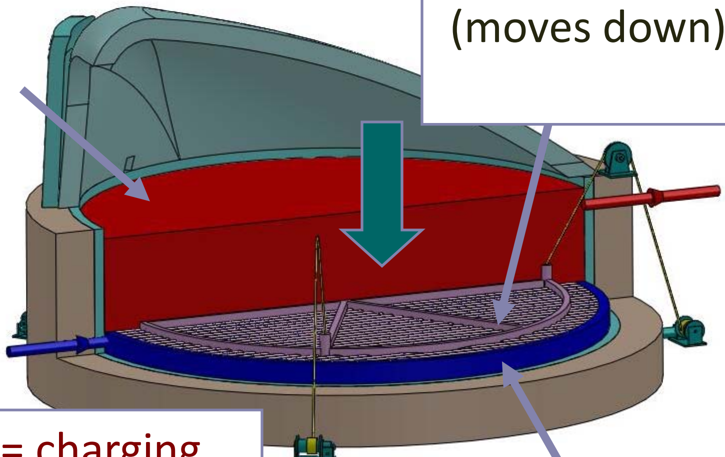




Virtual Two-Tank Concept

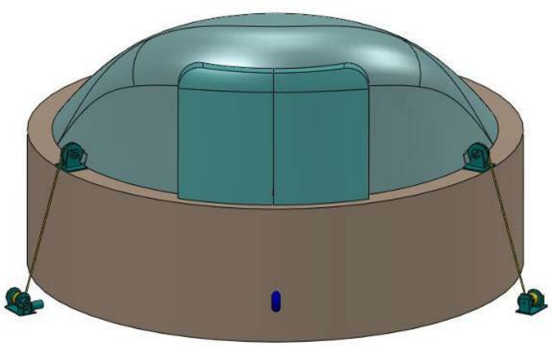
4 MW_e System Sizing:
2500 m^3 salt
40 hours storage

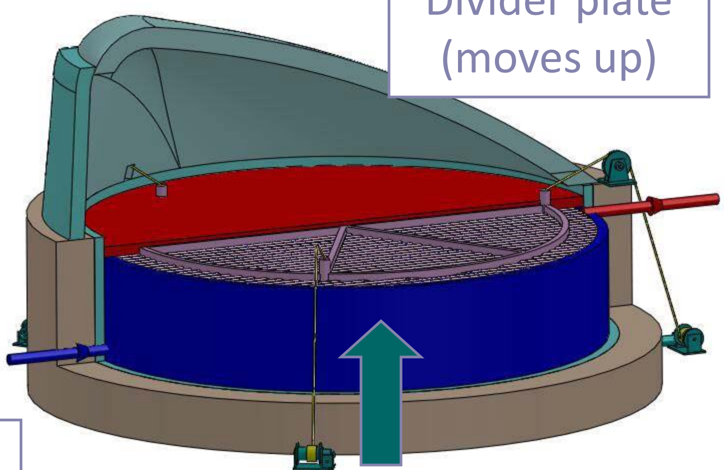




Daytime = charging

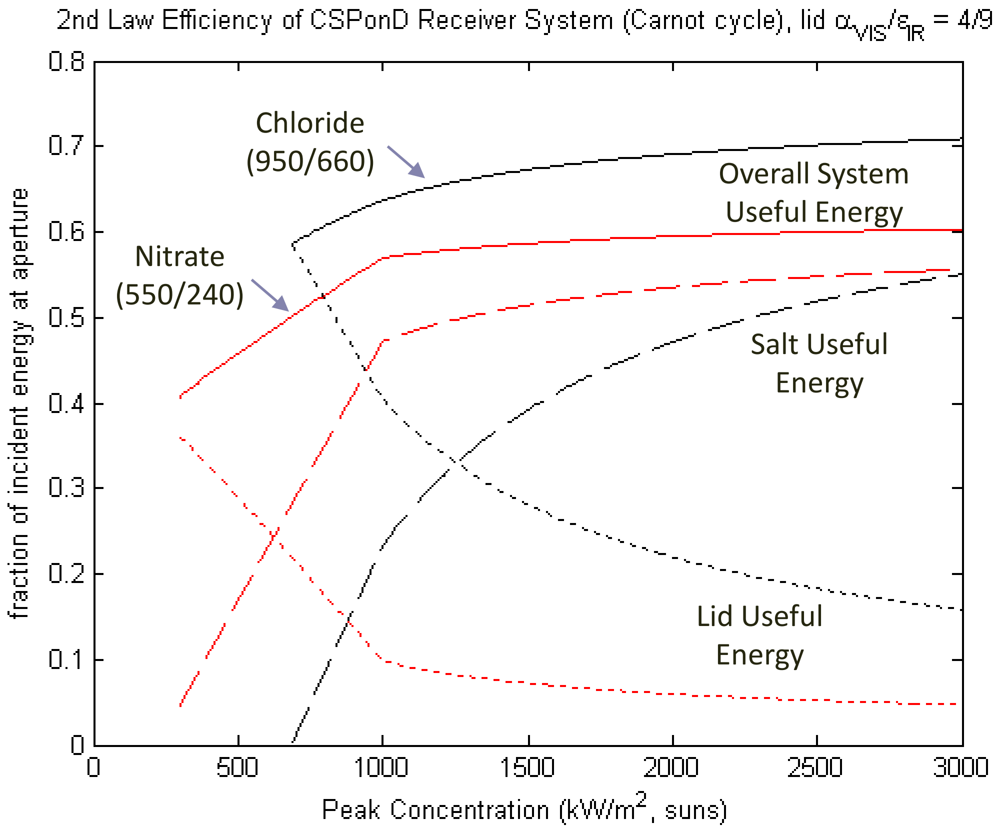
24/7 "hot salt" as the average temperature of the tank decreases when the sun is not shining





Nighttime

System Performance



Uses for lid heat:

Low temp (Nitrate)

- Power cycle pre/reheat
- RO feedwater heat
- MED feedwater heat

High temp (Chloride)

- Power cycle primary heat

system output (MWe):	4
nominal pond size	
diameter (m):	25.0
depth (m):	5.0
avg beam down angle (deg):	21.4
Nitrate Salt, Lid peak temp (C):	550/240
Chloride Salt, Lid peak temp (C):	950/660
Lid $\alpha_{vis}/\varepsilon_{ir}$	0.44
Low-temp heat rejection (C):	25

CSPond

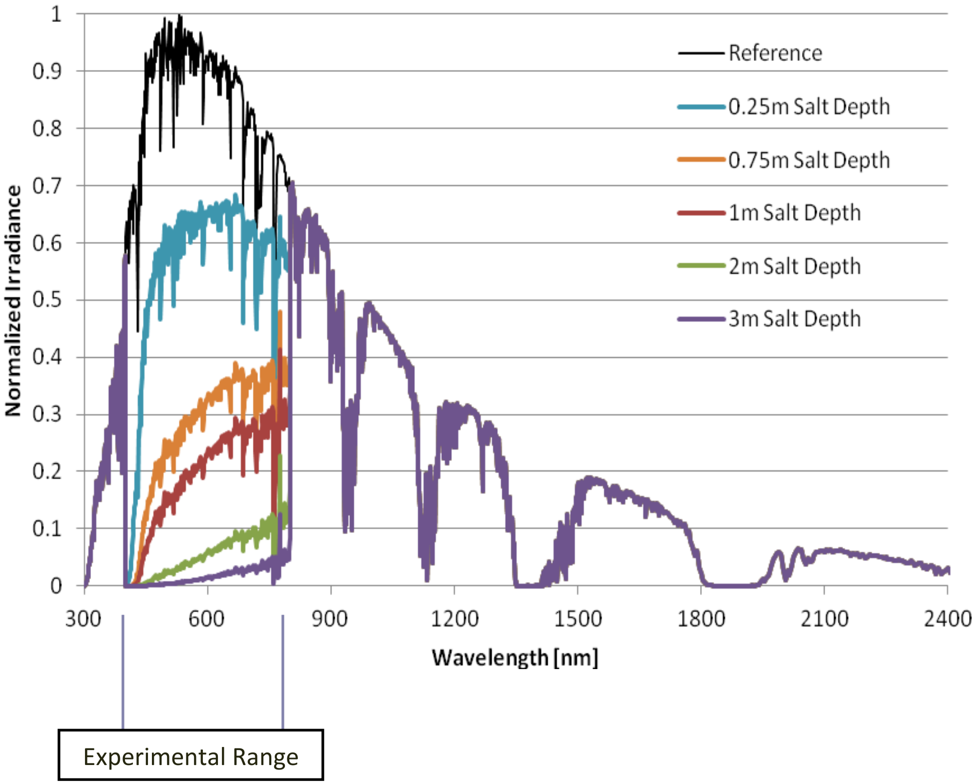
Experimental Testing and Analysis

Molten Salt Optical Characterization

(l) Variable optical path length transmission apparatus

(r) Appearance of molten NaCl-KCl salt at 850°C

Solar Irradiance Attenuation of NaCl-KCl (50-50wt%) salt at 850°C

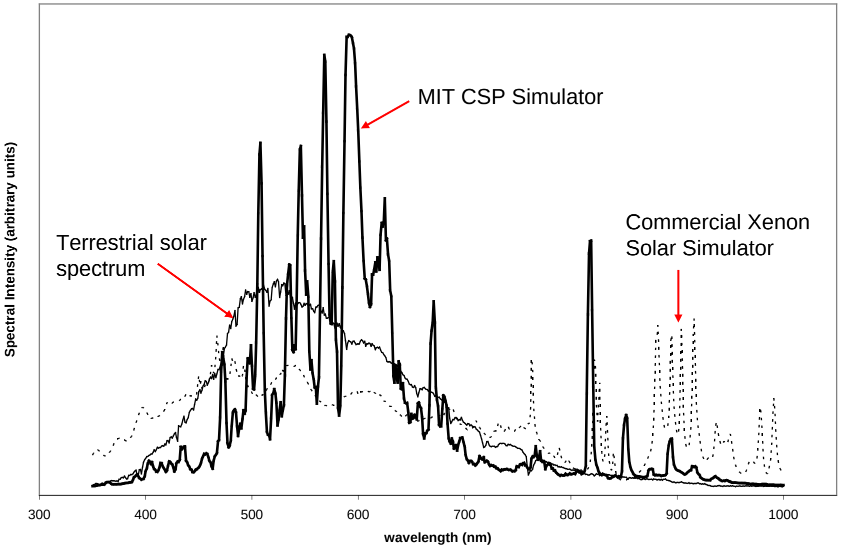


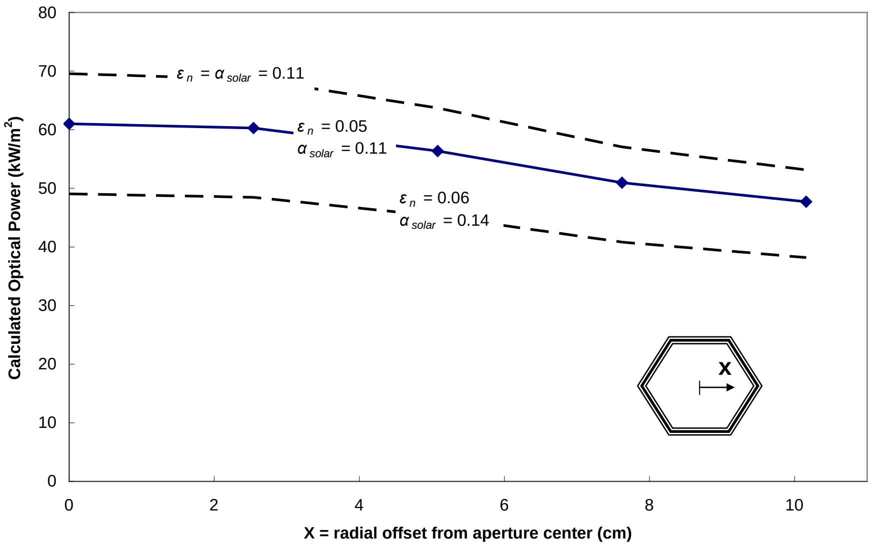
Stefano Passerini, Dr. Tom McKrell, Prof. Jacopo Buongiorno, MIT

60-Sun Solar Simulator

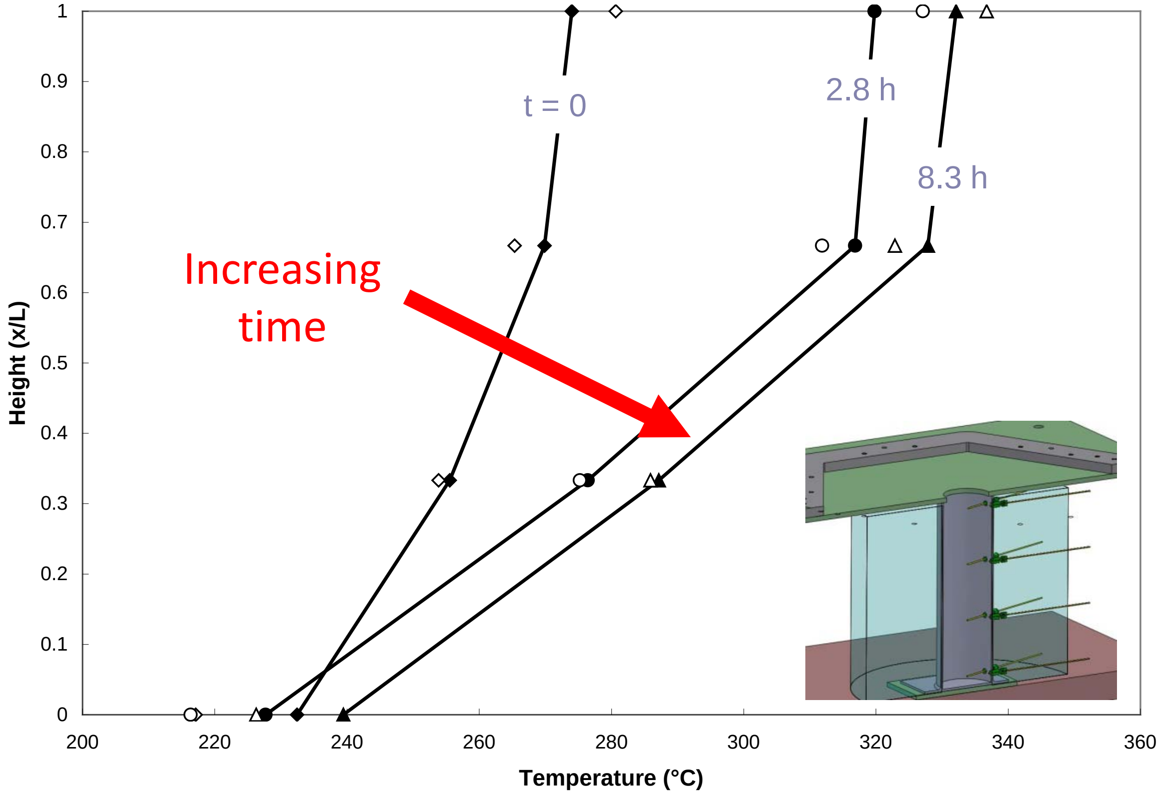
MIT CSP Solar Simulator

10.5 kW_e



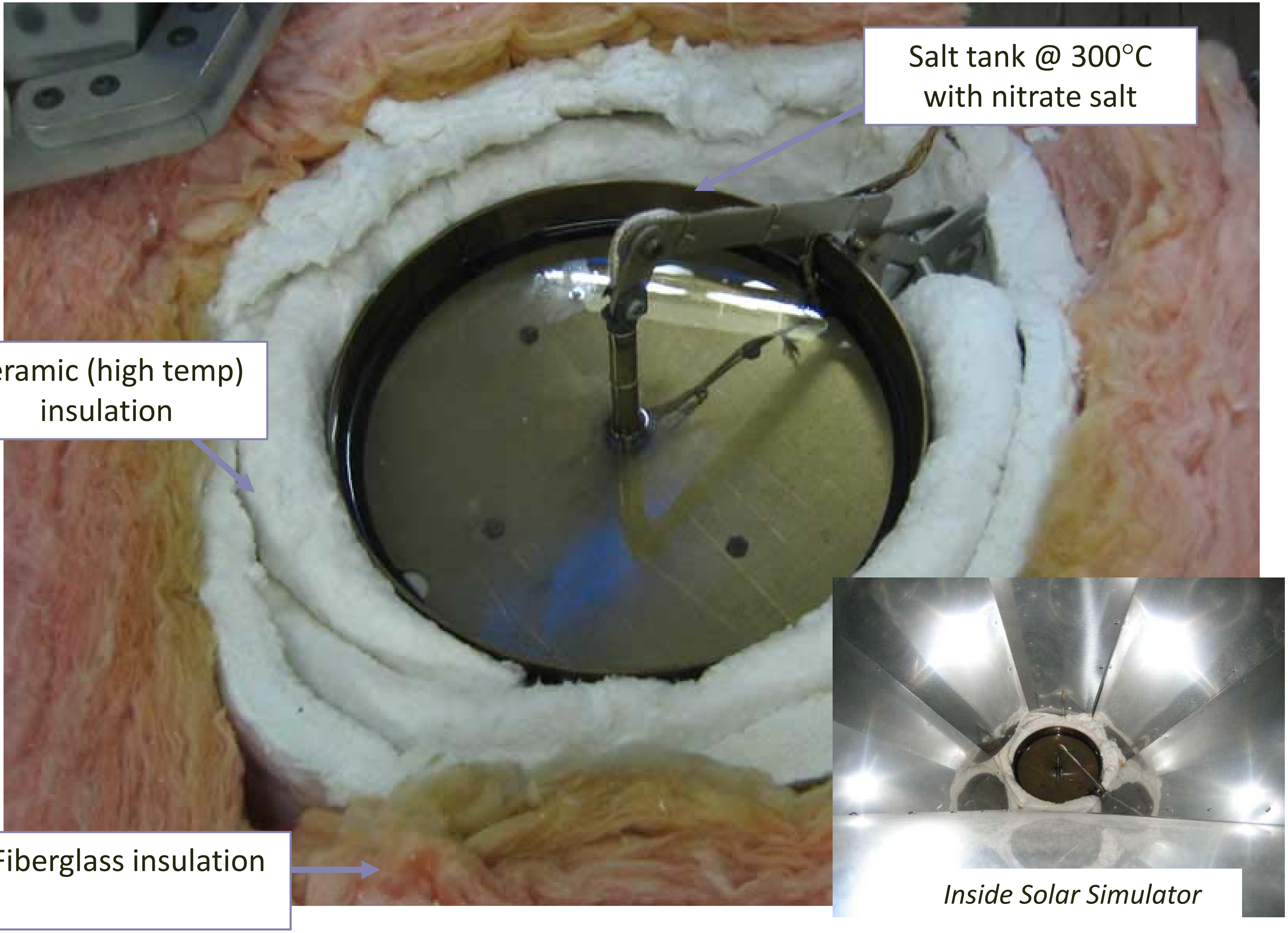


Volumetric Light Absorption



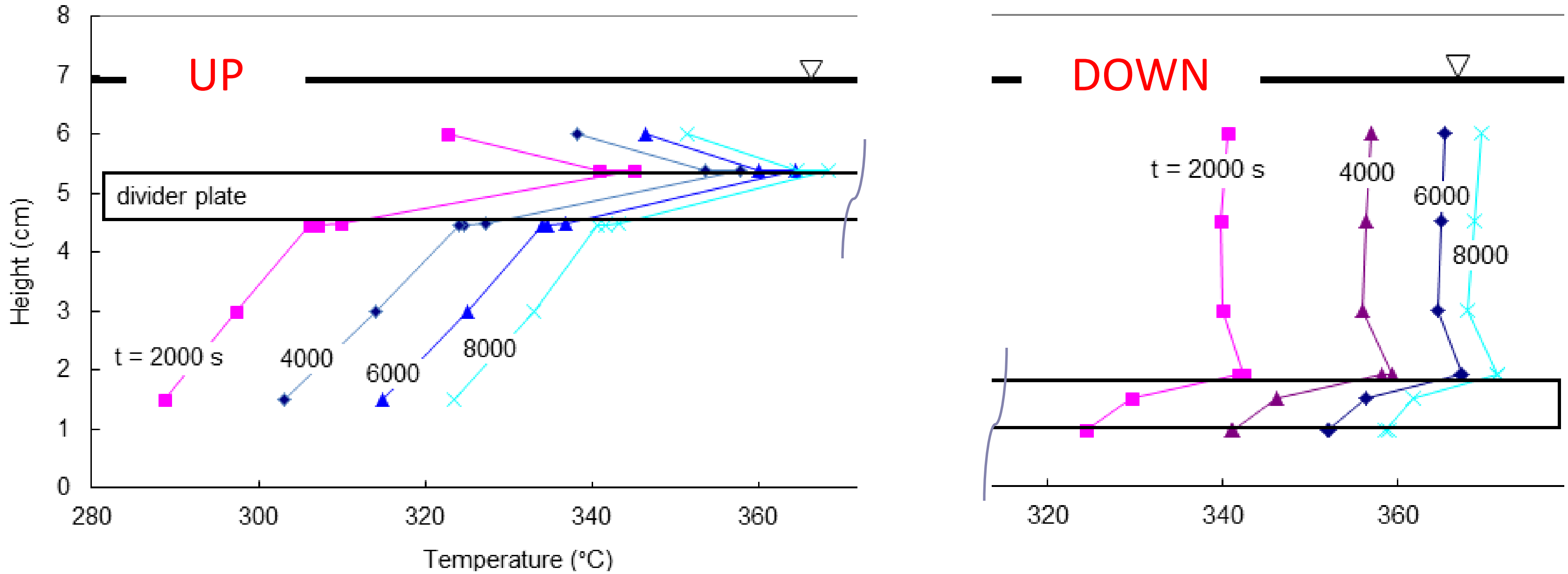
Temperature distribution of $NaNO_3$-KNO_3 (60-40wt%) heated optically

Virtual Two-Tank System Testing

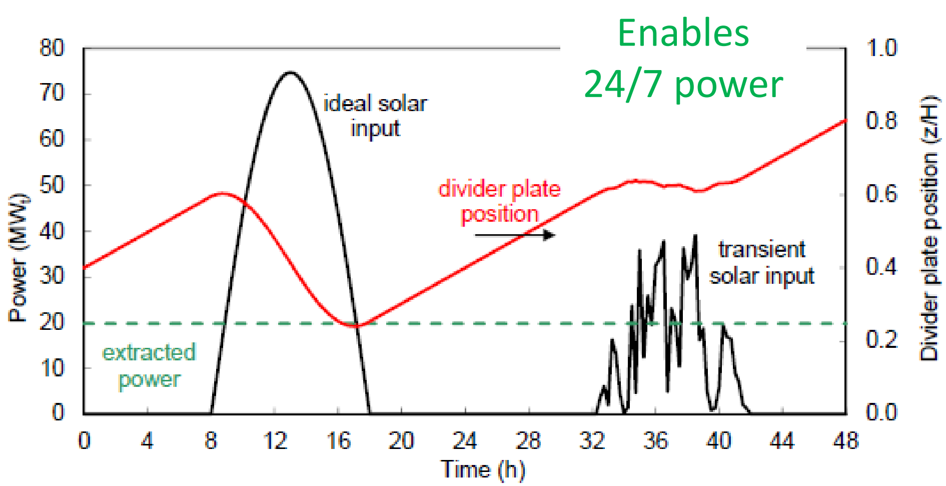


Inside Solar Simulator

Divided Thermocline Storage

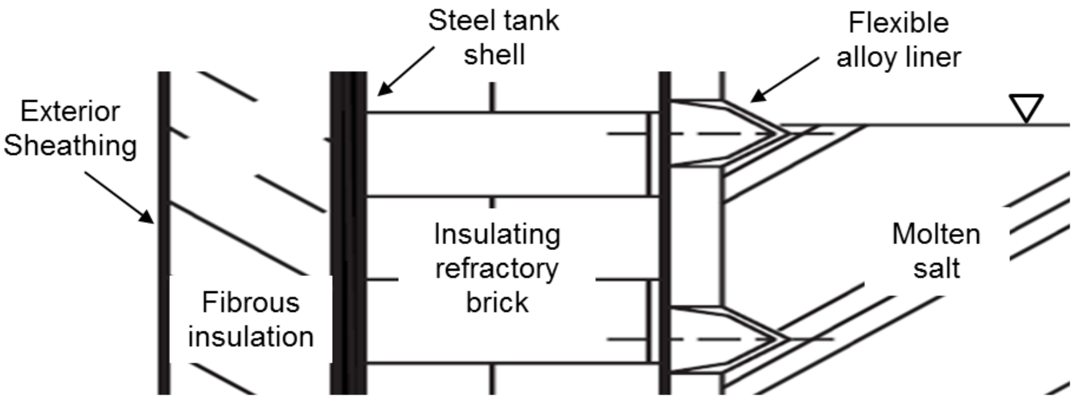


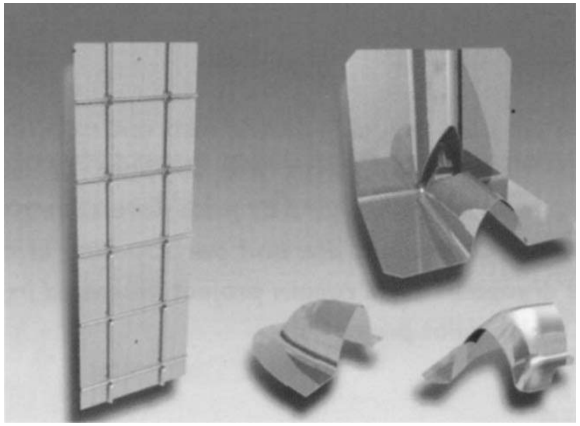
Temperature distribution of $NaNO_3$-KNO_3 (60-40wt%) heated optically



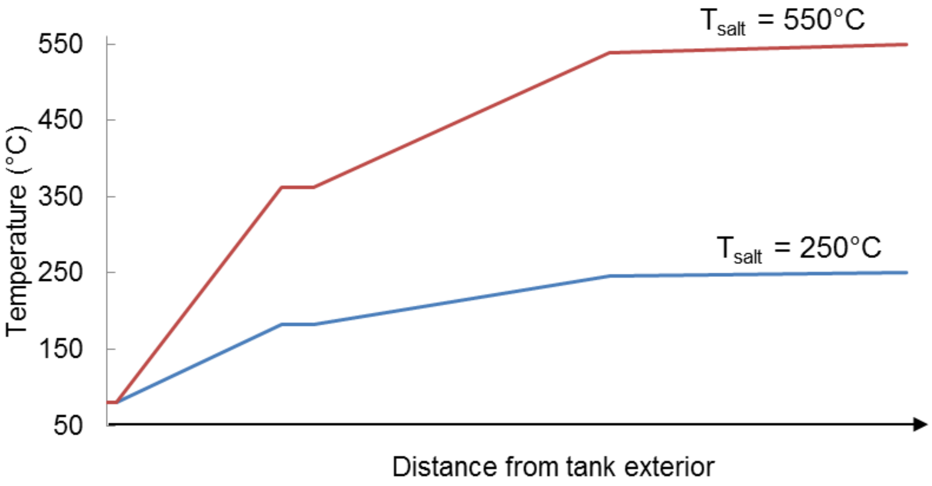
Tank Wall Design

- Flexible alloy liner
- Reduces thermal shock in refractory lining
- "Internal" firebrick insulation allows for mild steel tank shell



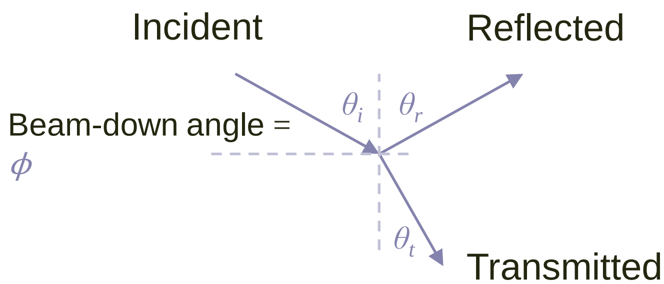


Flexible protective liner made of AISI 321H stainless steel



from Kolb (1993) and Gabbrielli (2009)

Solar Flux Distribution Modeling



$$\theta_i = 90° - \phi$$

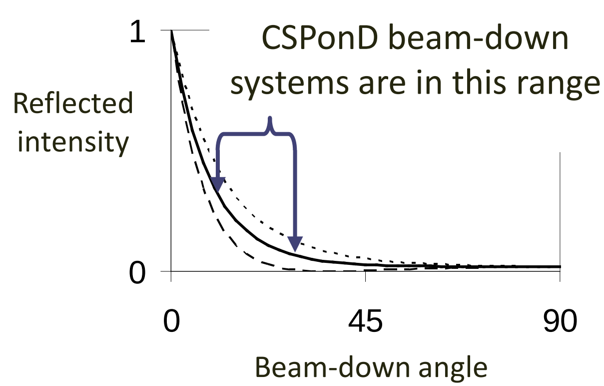
$$\theta_r = \theta_i$$

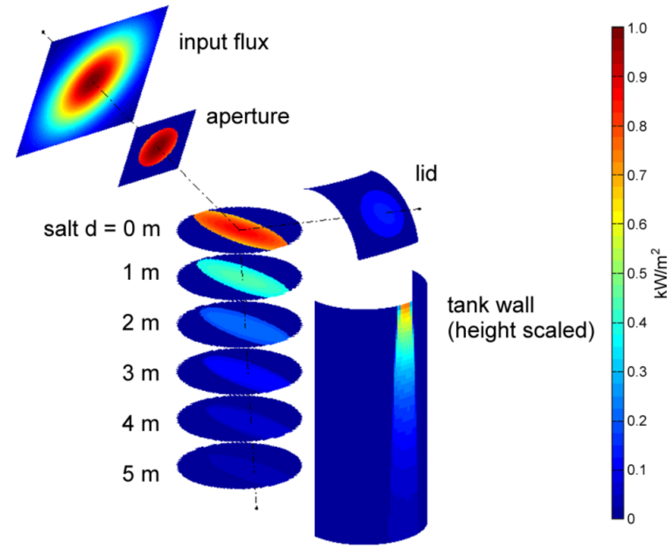
$$n_{salt} \sin\theta_t = n_{air} \sin\theta_i$$

$$R_s = \left[\frac{\sin(\theta_t - \theta_i)}{\sin(\theta_t + \theta_i)}\right]^2$$

$$R_p = \left[\frac{\tan(\theta_t - \theta_i)}{\tan(\theta_t + \theta_i)}\right]^2$$

$$R = (R_s + R_p)/2$$





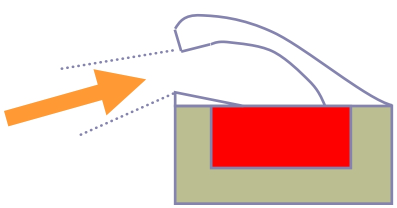
Flux distribution in receiver from a single central heliostat

CSPond

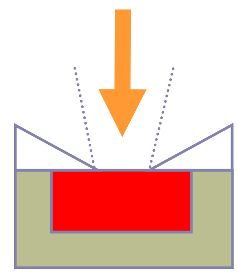
Alternative Design Options

Heliostat Field Placement Options

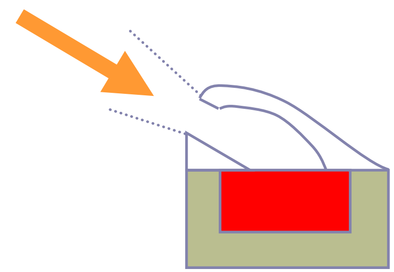
Mirrors to Hilltop Collector



Tower Reflects Light Downward



Hillside Mirrors to Collector



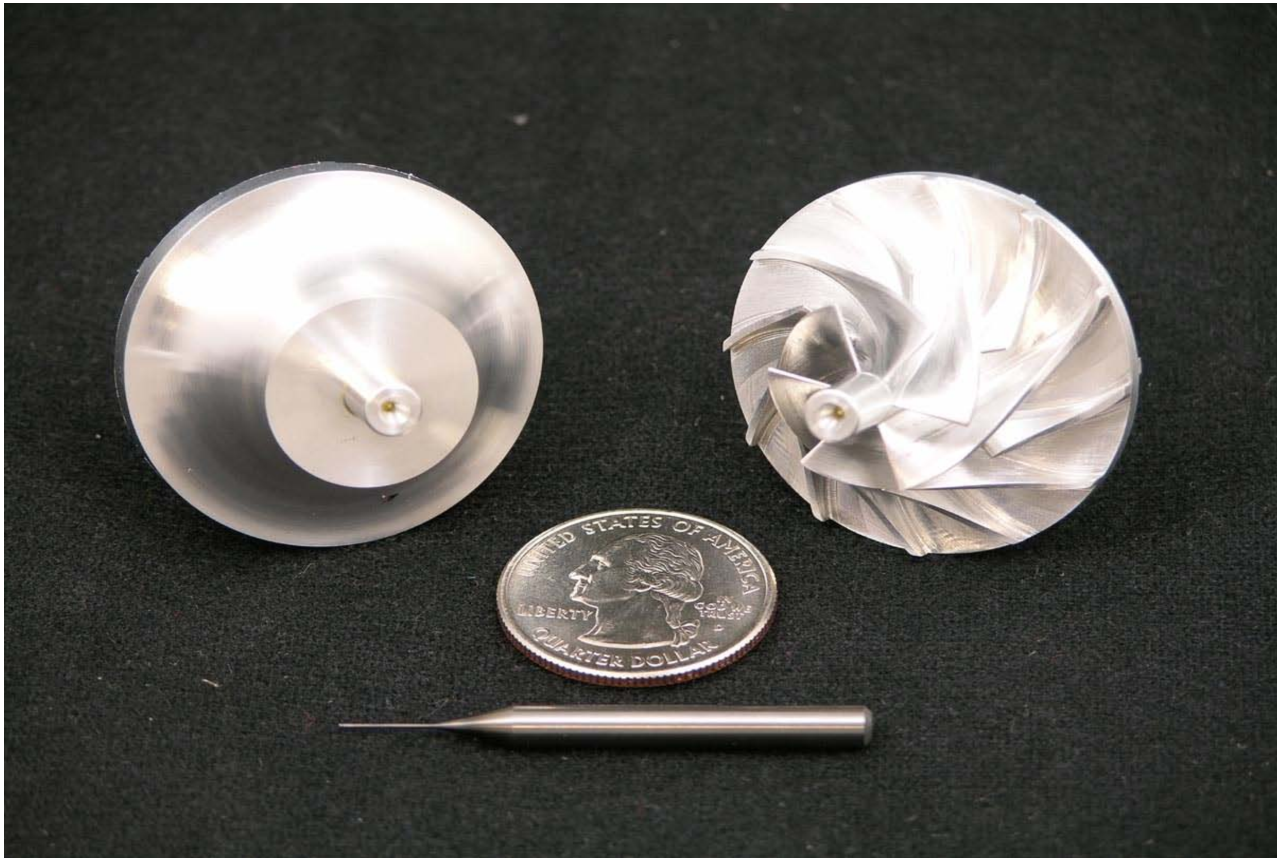
Multiple Power Cycle Options

Salt Temperature: 500°C, 700°C, and 700+°C

- Steam power cycles--Today
- Supercritical carbon dioxide power cycle
  - High efficiency
  - Very compact and potentially low cost
  - Advanced technology
- Air Brayton power cycle
  - Existing technology
  - No cooling water options
  - Requires 700 C salt temperatures

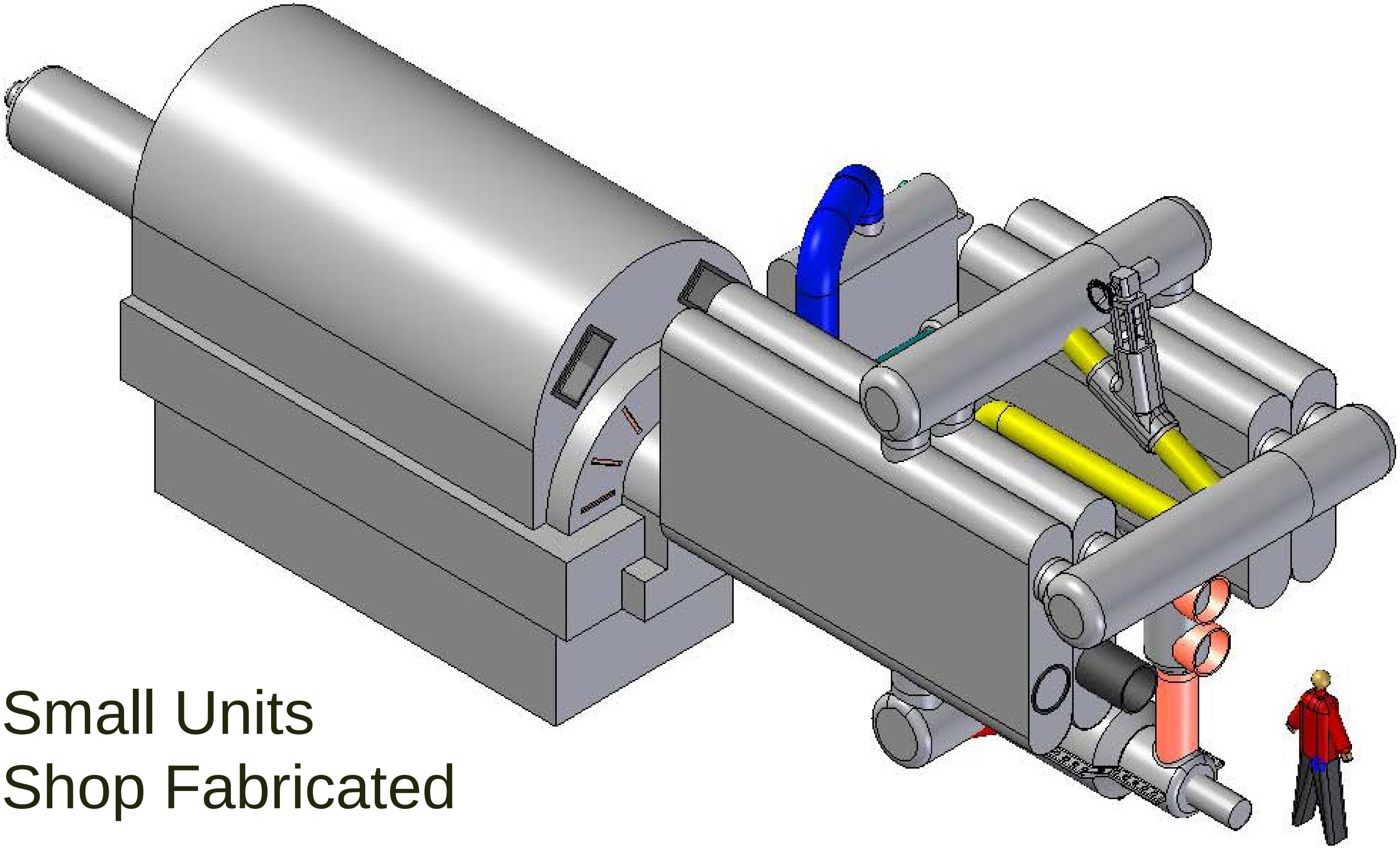
Carbon Dioxide Properties Result in Very Small Equipment

Main compressor wheel: 85kW



Manufactured by Barber & Nichols for SNL

50-MWe Power Conversion Unit

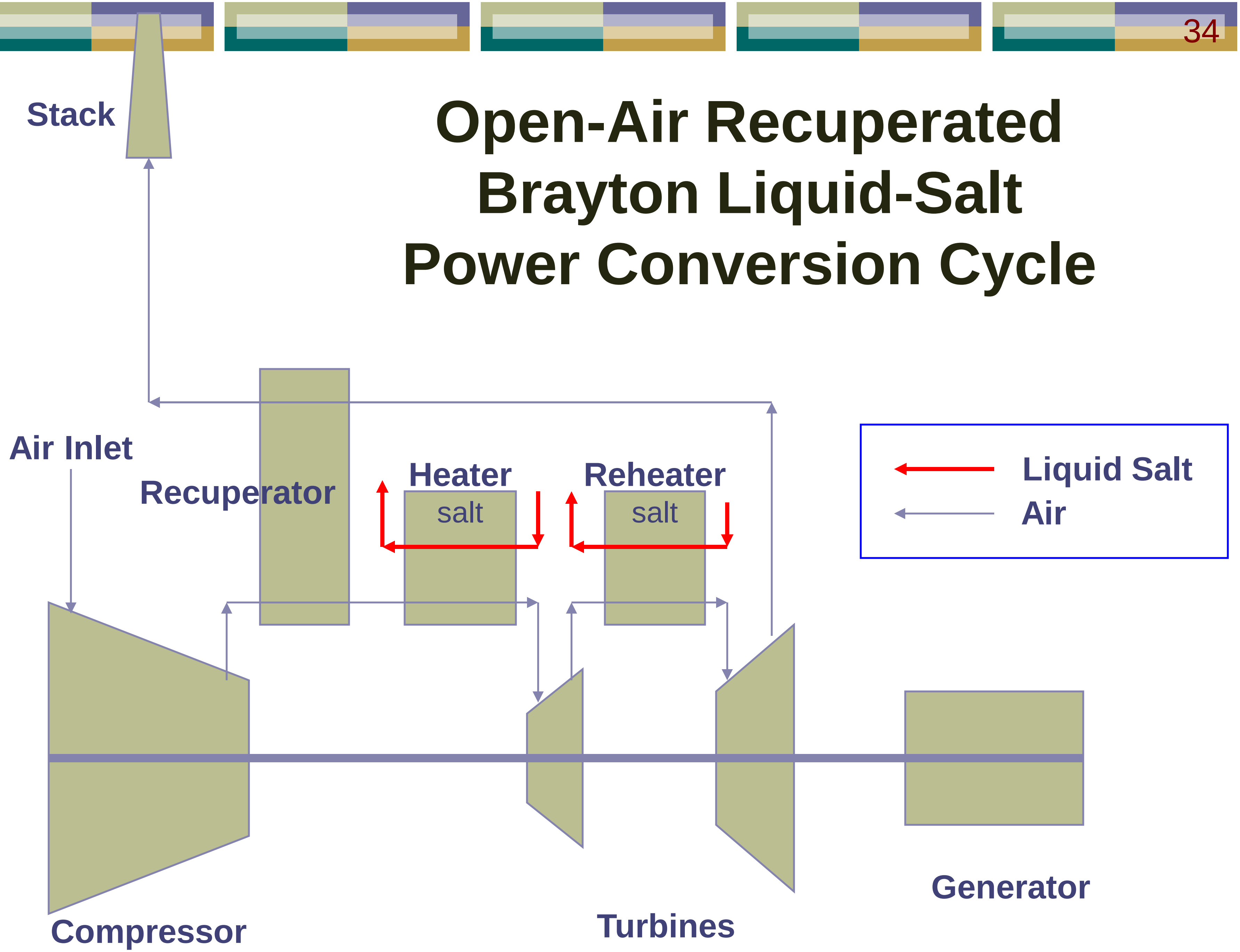


- Small Units
- Shop Fabricated

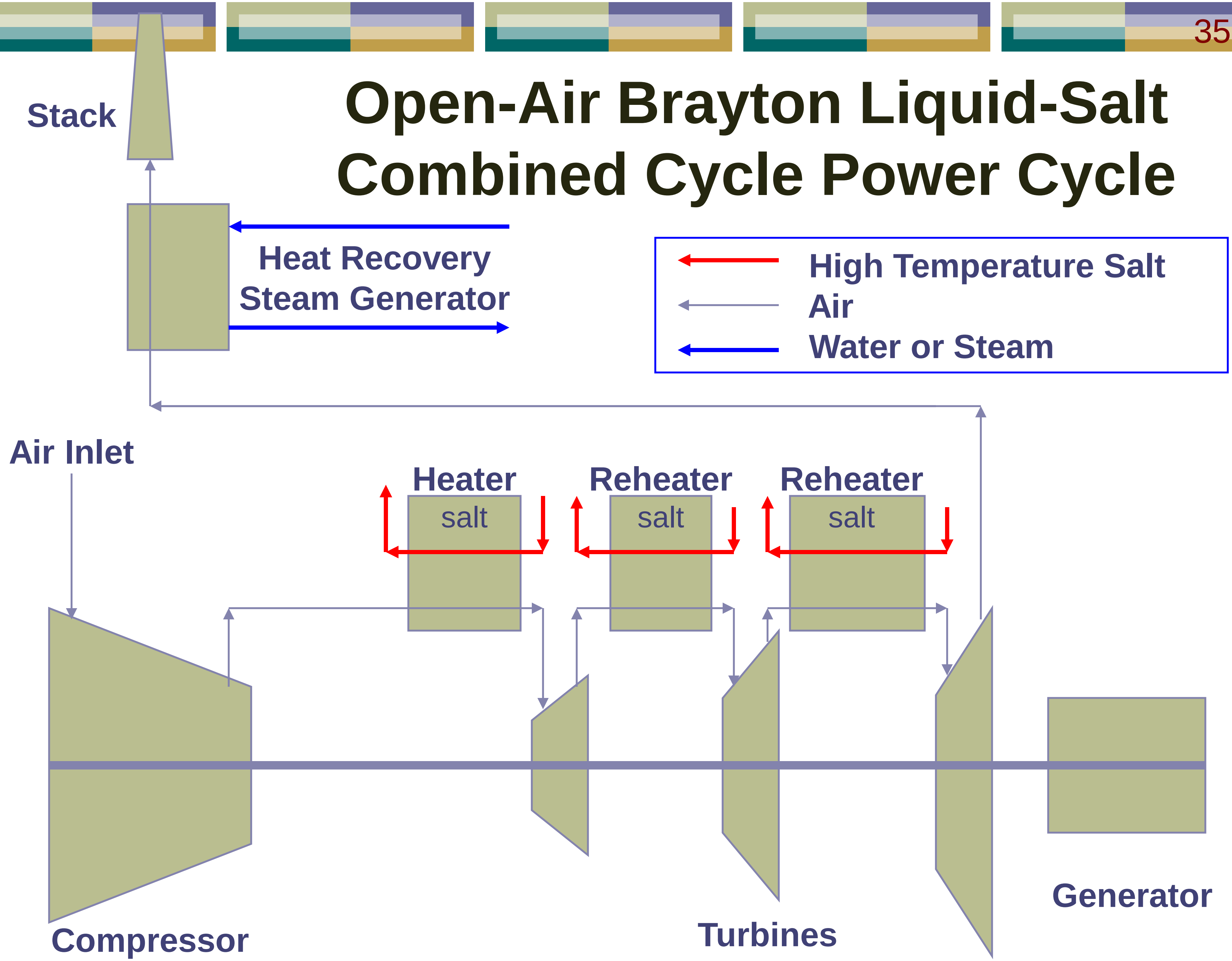
Air-Brayton Power Cycles

- Air Brayton power cycles have low cooling requirements relative to other power cycles
- Viable at salt peak temperatures of ~700 C
  - Significant efficiency penalties at lower temperatures
- Several different options

Open-Air Recuperated Brayton Liquid-Salt Power Conversion Cycle



Open-Air Brayton Liquid-Salt Combined Cycle Power Cycle



Comparison of Brayton Power Cycles

700 C[1] Salt; 100 MW(t) Plant

Cycle	Air Brayton	Combined Cycle
Efficiency	40%	44%
Condenser Heat Rejection*	None (No water requirement)	28 MW(t)

[1]Efficiency drops rapidly with peak temperature

[2]Traditional closed power cycles (Steam, Carbon Dioxide, Helium) with 50% efficiency reject 50 MW(t) to Condenser

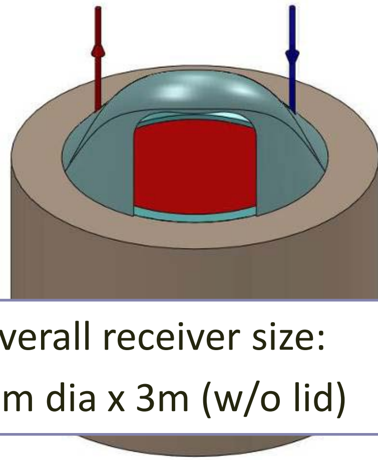
CSPond Status

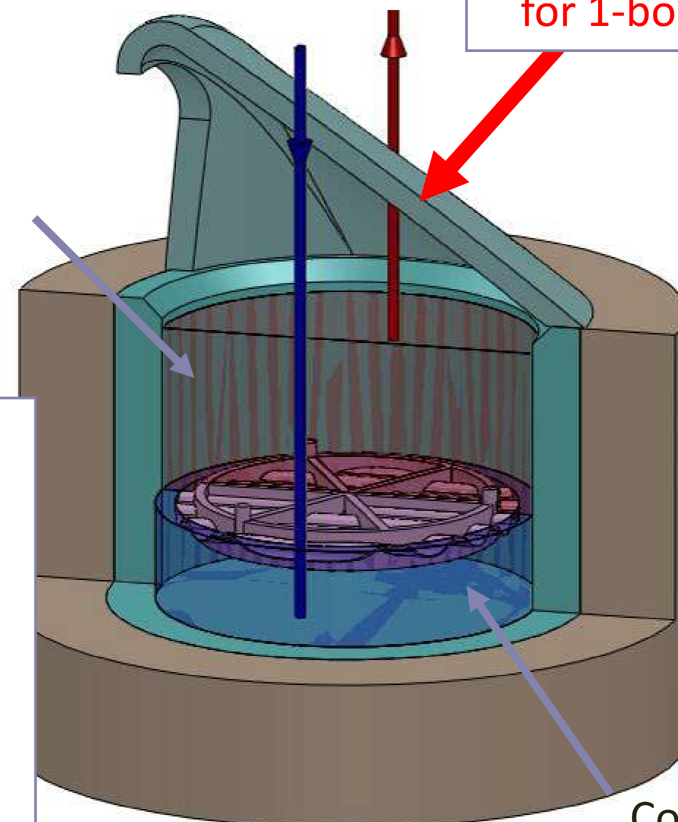
Patents Pending

Two Parallel or Sequential Paths Forward

- Small 100 kw systems integration test using nitrate salts
  - Uses proven existing solar salt
  - Rapid testing possible
- Develop higher-temperature chloride or carbonate CSPond
  - Higher efficiency with potentially lower costs
  - Robust against salt degradation
  - Follow-on integration test with different salts

Next Step: 100 kW_t Research System





<u>Salt Tank:</u>

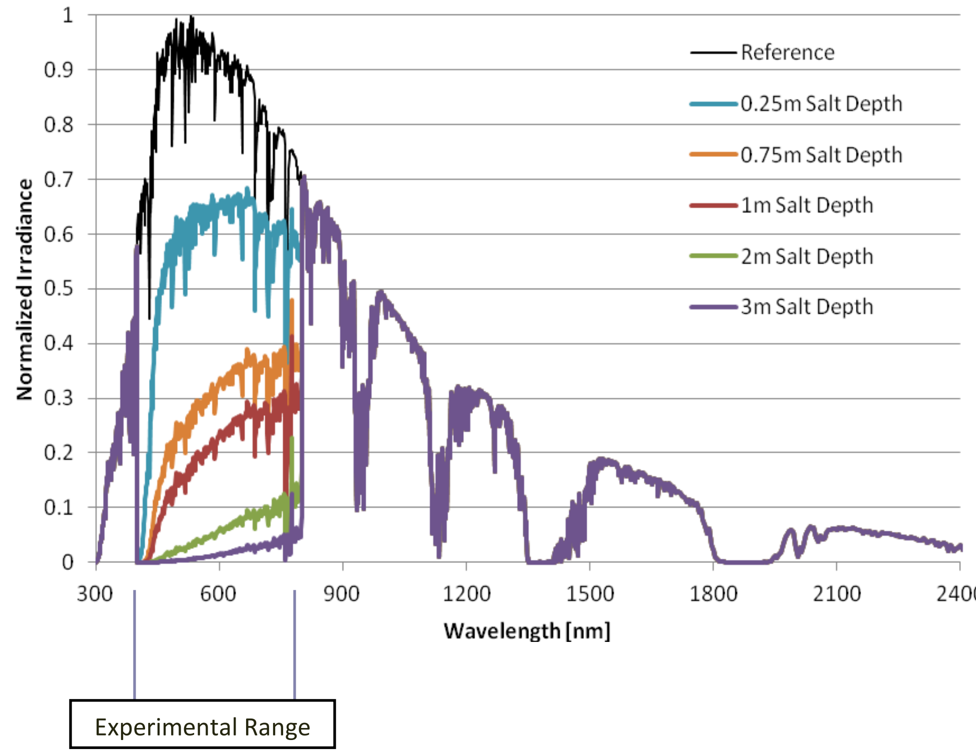
- 2m dia x 2m depth
- 6.2 m^3 salt capacity (11.2 metric tons)
- Nitrate salt (550C/275C)
- 15 h storage (1.5 MWh)
- 2.4 MWh daily solar input required for continuous operation

Not shown: aperture cover, concentration "booster", lid heat rejection system and divider plate actuator

Next Step: Alternative Salts

Insufficient Data for Non-Nitrate Systems

Solar Irradiance Attenuation of NaCl-KCl (50-50wt%) salt at 850°C



Higher temperature salts more robust (no possibility of thermal decomposition)

Higher efficiency with open air Brayton power cycles and no water requirements

Stefano Passerini, Dr. Tom McKrell, Prof. Jacopo Buongiorno, MIT

Conclusions

- Analysis and experiments indicate significantly better economics than existing concentrated solar power-tower systems (Higher efficiency)
- Significant uncertainties (Path forward)
  - No small pilot plant under realistic conditions
  - Limited review (Wider review underway now that patent filings complete)
  - Large incentives for higher-temperature salt than nitrate (more robust system and dry cooling) but limited experimental data
- Large incentives to determine commercial viability of CSPond

Questions

Biography: Charles Forsberg

Dr. Charles Forsberg is the Executive Director of the Massachusetts Institute of Technology Nuclear Fuel Cycle Study, Director and principle investigator of the High-Temperature Salt-Cooled Reactor Project, and University Lead for Idaho National Laboratory Institute for Nuclear Energy and Science (INEST) Nuclear Hybrid Energy Systems program. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. He is a Fellow of the American Nuclear Society, a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design on salt-cooled reactors. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 11 patents and has published over 200 papers.