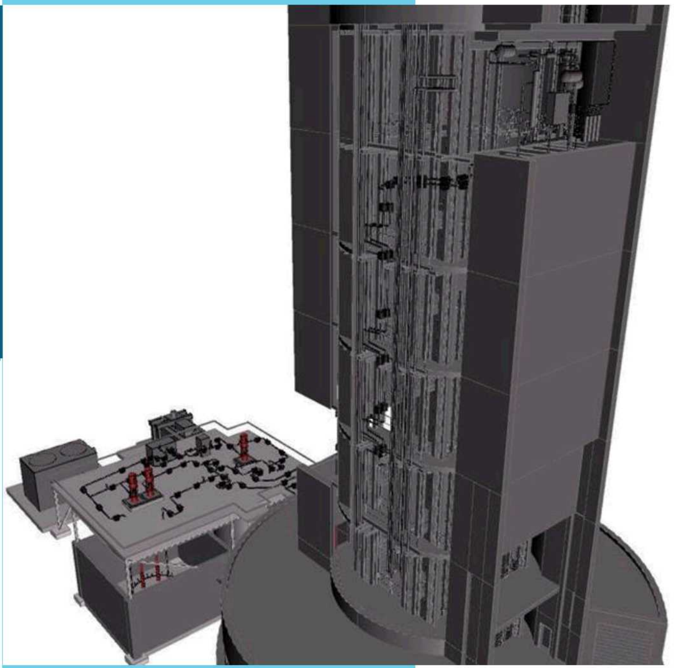
SAND2019-11665C

Operational Modes of a 2.0 MW_{th} Chloride Molten-Salt Pilot-Scale System



Kenneth M. Armijo, Matthew Carlson, Dwight Dorsey, Jesus Ortega, Dimitri Madden, Joshua Christian & Craig Turchi

Sandia National Laboratories, Albuquerque, NM

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Agenda

Objectives

- Development of a scalable 2.0MWth CSP system using a ternary chloride molten salt, with operational temperatures up to 740°C.
- Characterization of a high-temperature molten salt receiver system that can operate efficiently & reliably.

Overview

- Gen 3 Liquid-Pathway Program
- Molten Salt Technology-Approach
- System Design
- System Analysis Results

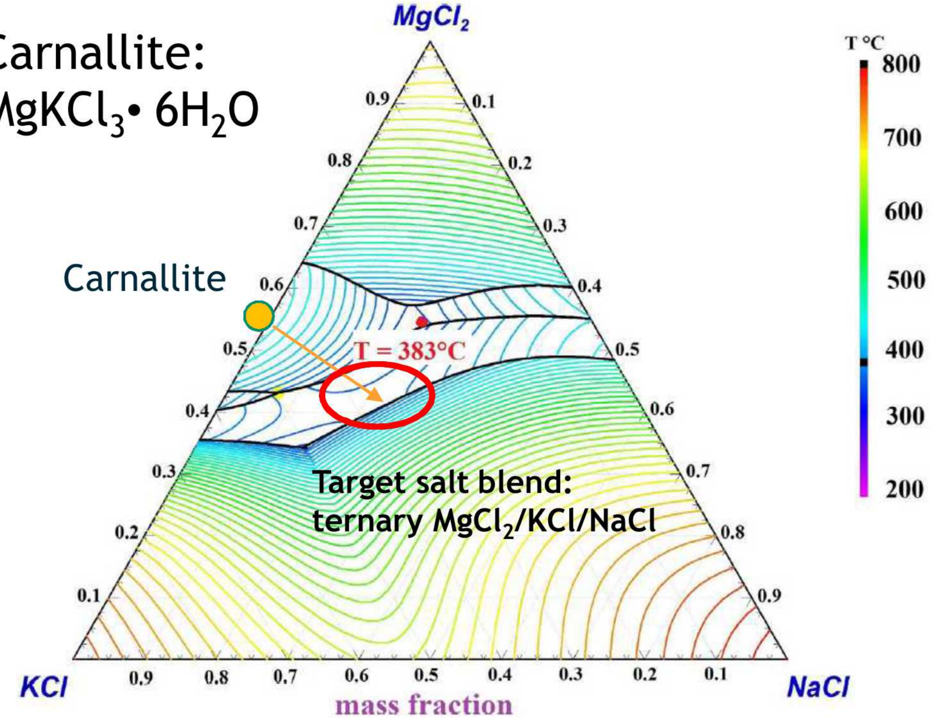
Conclusions & Future work

Transition to Gen 3 CSP Systems

- Limit of traditional solar-salt thermal stability is ~600 °C with ambient air as cover gas.
- Nitrate salt concentrating solar power (CSP) systems currently deployed are considered state-of the art heat transfer fluids (HTFs)
- To achieve $15/kWhth HTFs and LCOE of 6¢/kWh, need technologies at higher temperatures (e.g., 650 °C to 750 °C) with alternative salt chemistry composition.

Parameter	Solar Salt (Gen2)	Chloride Salt*
Mass composition	60% $NaNO_3$ 40% KNO_3	Ternary $MgCl_2$-KCl-NaCl blend
Solidification Temp (˚C)	238	426
Stability Limit (˚C)	600	>1418
Density (kg/m³)	1770 @ 500˚C	1590 @ 700˚C
Specific Heat (J/g-K)	1.53 @ 500˚C	1.1 @ 700˚C
Viscosity (cP)	1.30 @ 500˚C	1.4 @ 700˚C
Thermal Cond. (W/m-K)	0.54 @ 500˚C	0.4 @ 700˚C

Carnallite:
$MgKCl_3 \cdot 6H_2O$



Mohan et al., Energy Conversion and Management 167 (2018)

Gen 3 Liquid-Pathway System

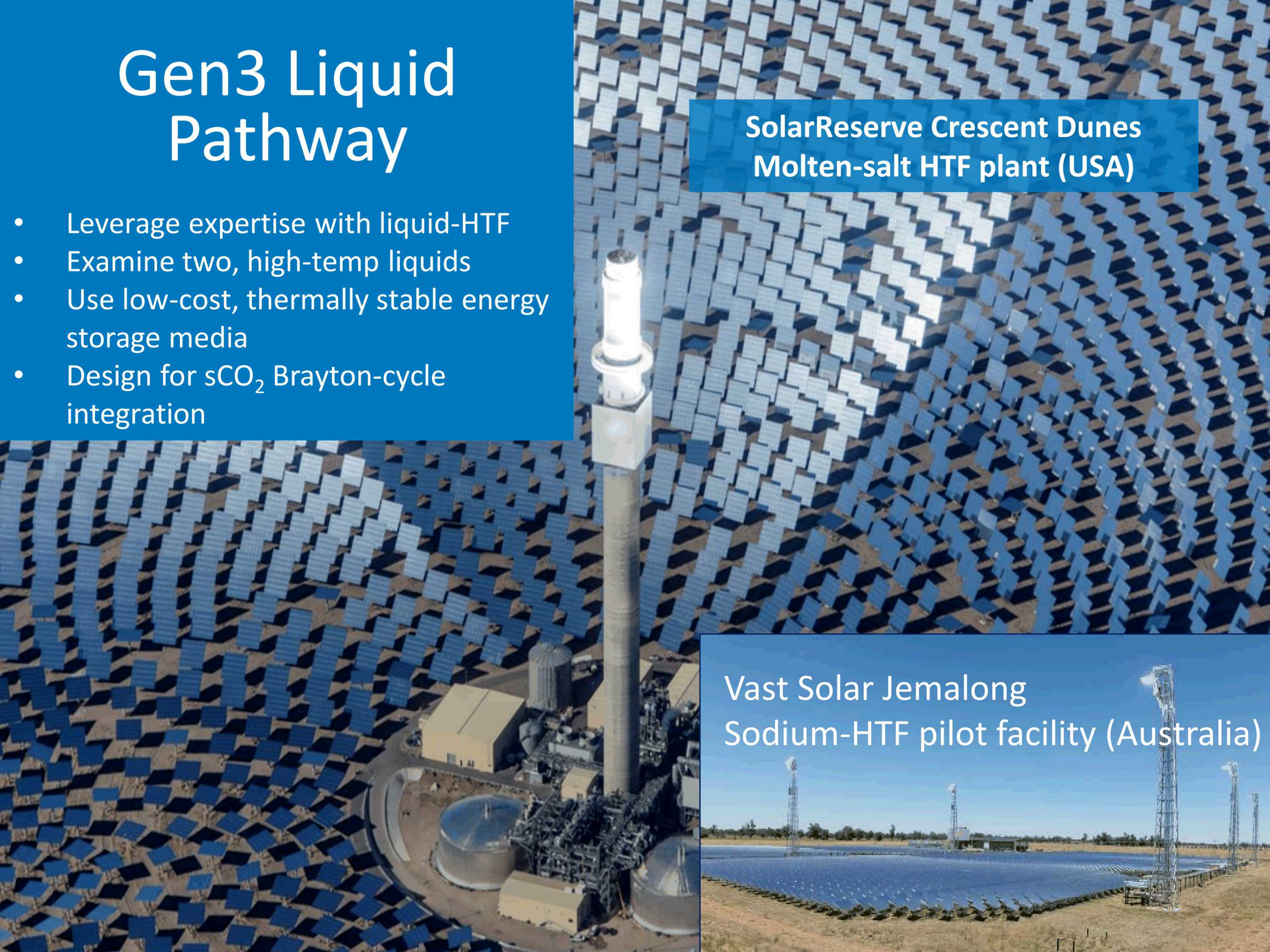
- 2.0MW_{th} Pilot-scale CSP plant developed to acheive thermodynamic performance for operation to 720 °C.
- Molten salt system HTF/TES with sCO_2 power block.
- 6 hours of TES with charging/discharging cycles.
- Established approaches for piping, pump, valve, and heat exchanger design (including the receiver).
- High energy & exergy efficiency with direct TES.
  - Flexible dispatch because solar collection and power generation are decoupled.
- Recognized and accepted by industry and financiers.

Vertical turbine salt pump. Image courtesy Flowserve.

Need molten salt system capable of temperatures above 720°C to achieve DOE 2020 SunShot Targets.

Gen3 Liquid Pathway

- Leverage expertise with liquid-HTF
- Examine two, high-temp liquids
- Use low-cost, thermally stable energy storage media
- Design for sCO_2 Brayton-cycle integration



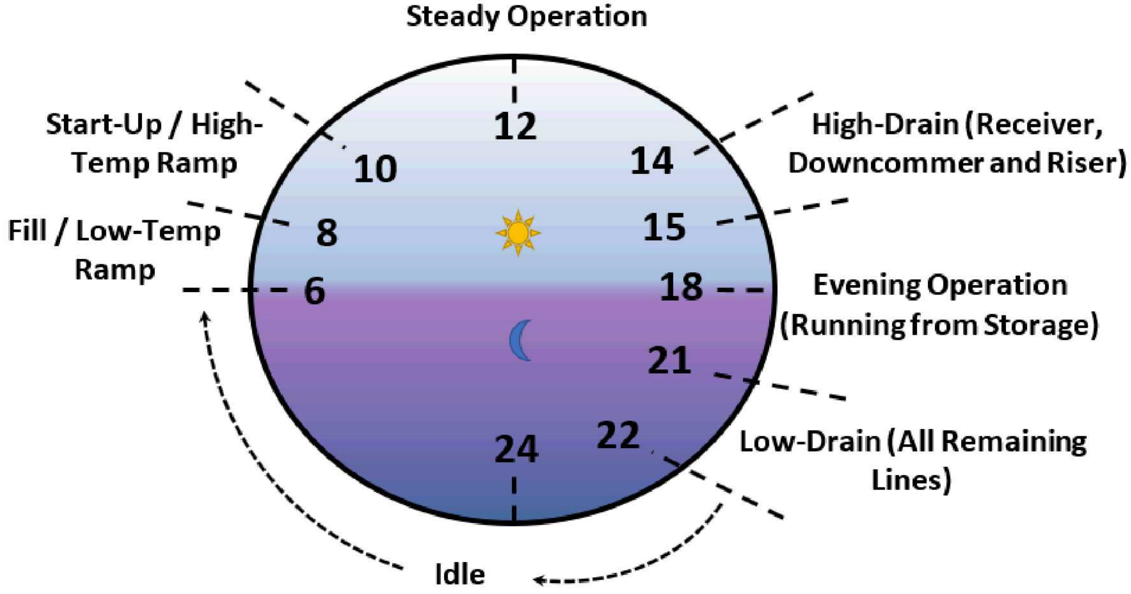
SolarReserve Crescent Dunes Molten-salt HTF plant (USA)

Vast Solar Jemalong Sodium-HTF pilot facility (Australia)

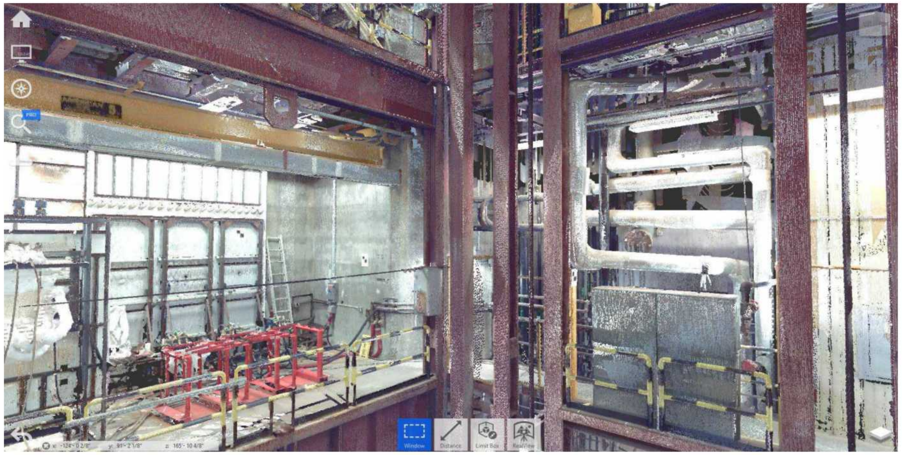
Gen 3 Liquid-Pathway Operation

Charging Operational Modes. Pilot-system operational modes consist of:

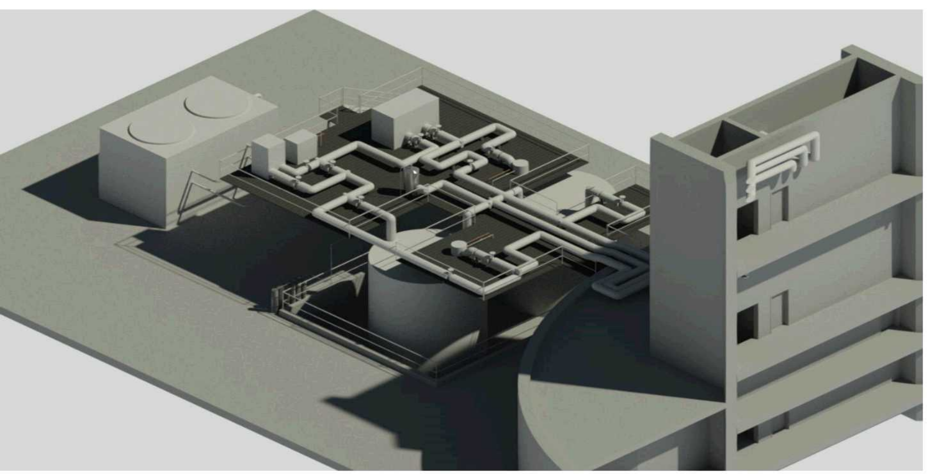
1. Fill of the riser, downcommer & receiver with low-temp. ramp-up
2. Start-up and high-temperature ramp-up of systems and components
3. Steady operation
4. Drain operation of system high-level lines and receiver
5. Drain of all lower-level system lines
6. Idle operation of cold tank and remaining wet components

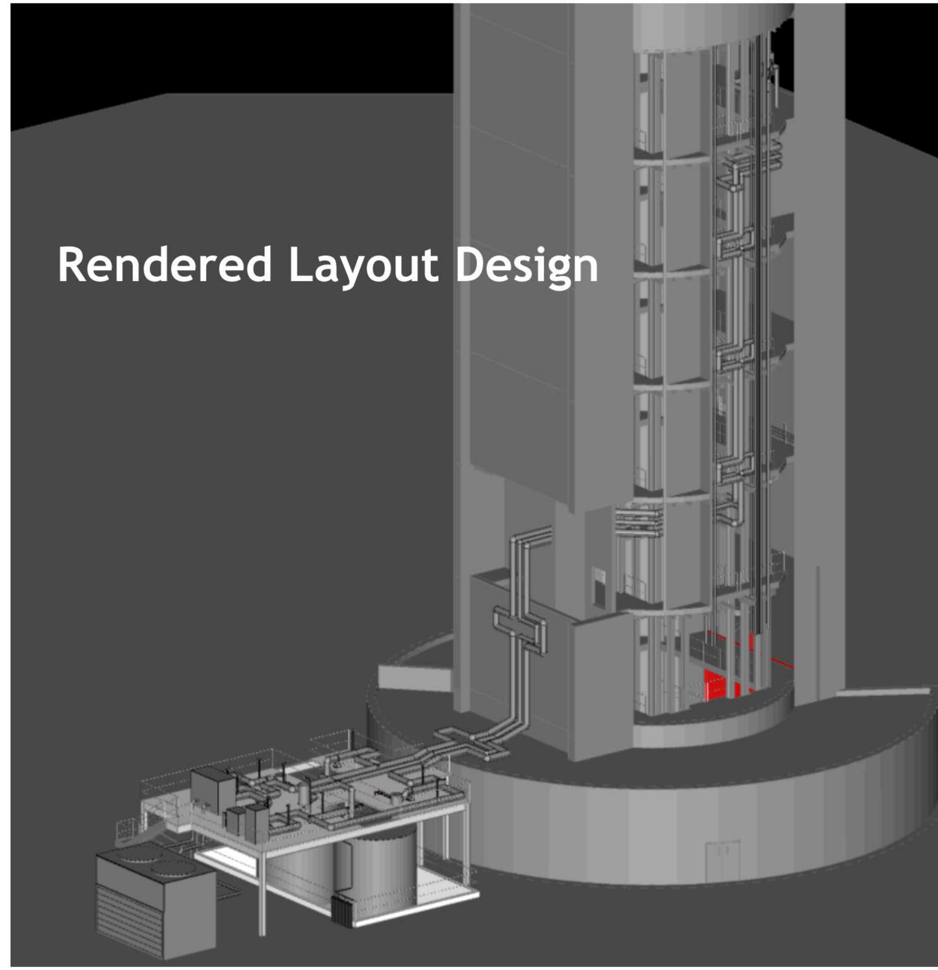


220 ft Point Cloud Tower Level

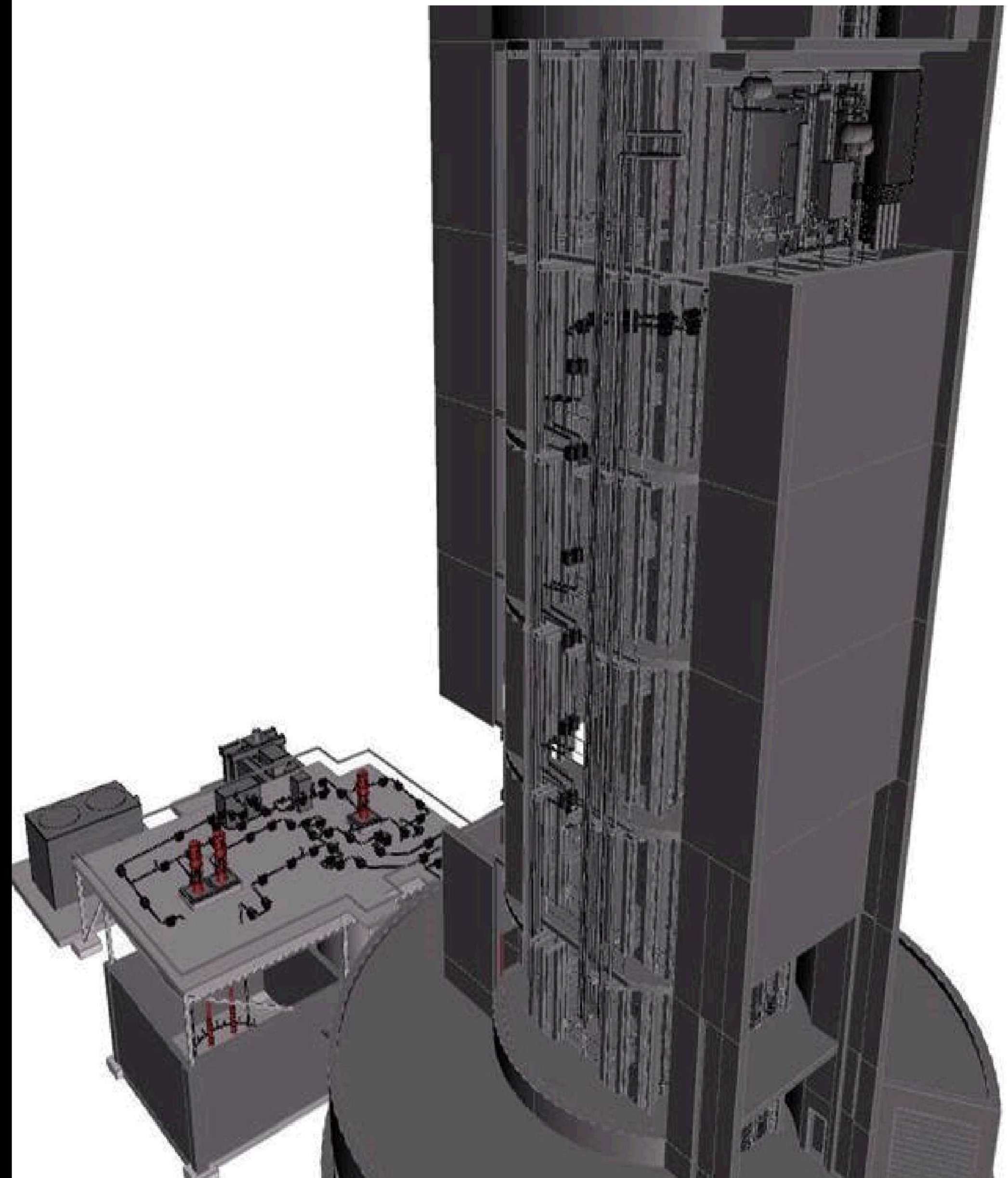


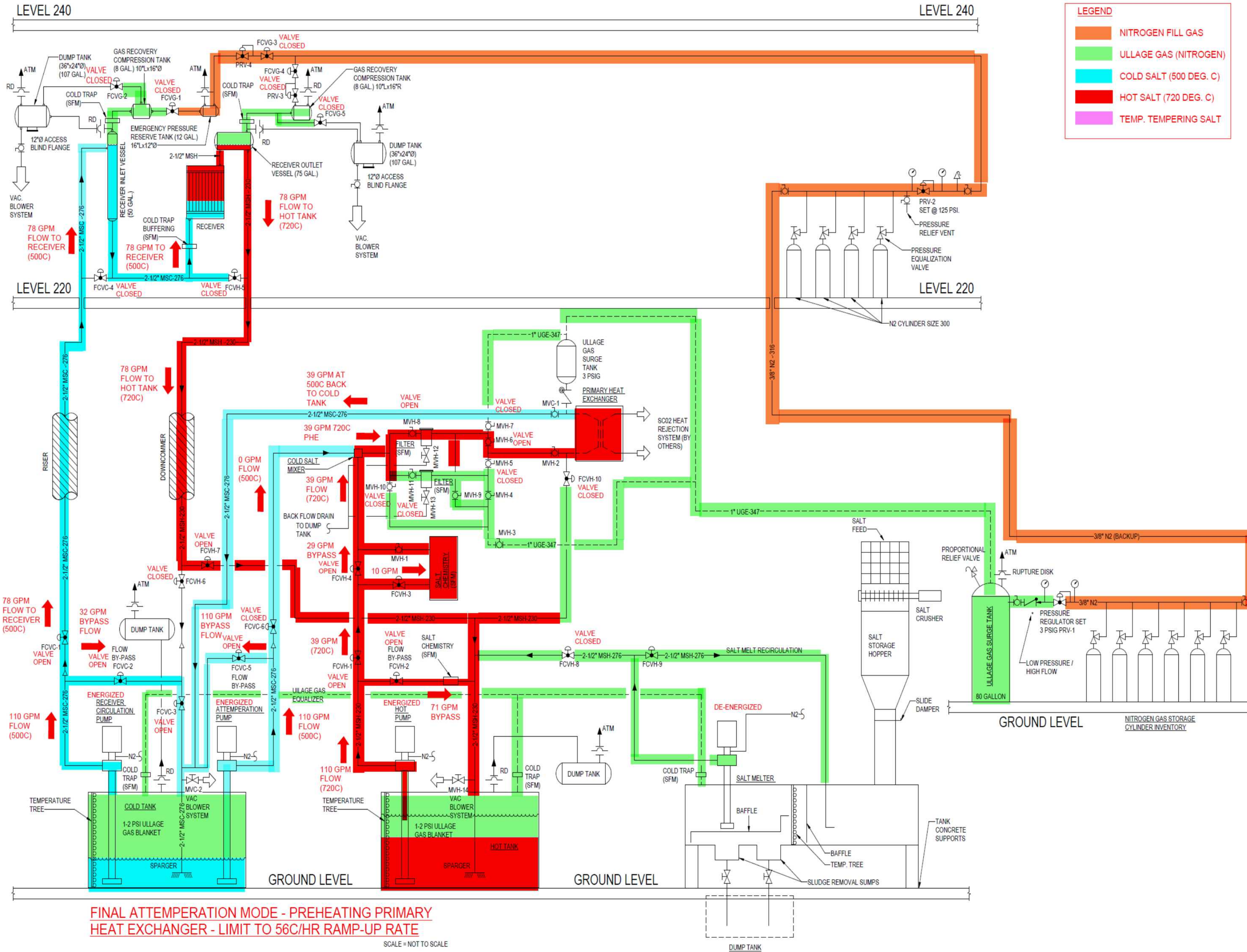
Rendered Revit 3D Model





Rendered Layout Design





FINAL ATTEMPERATION MODE - PREHEATING PRIMARY HEAT EXCHANGER - LIMIT TO 56C/HR RAMP-UP RATE

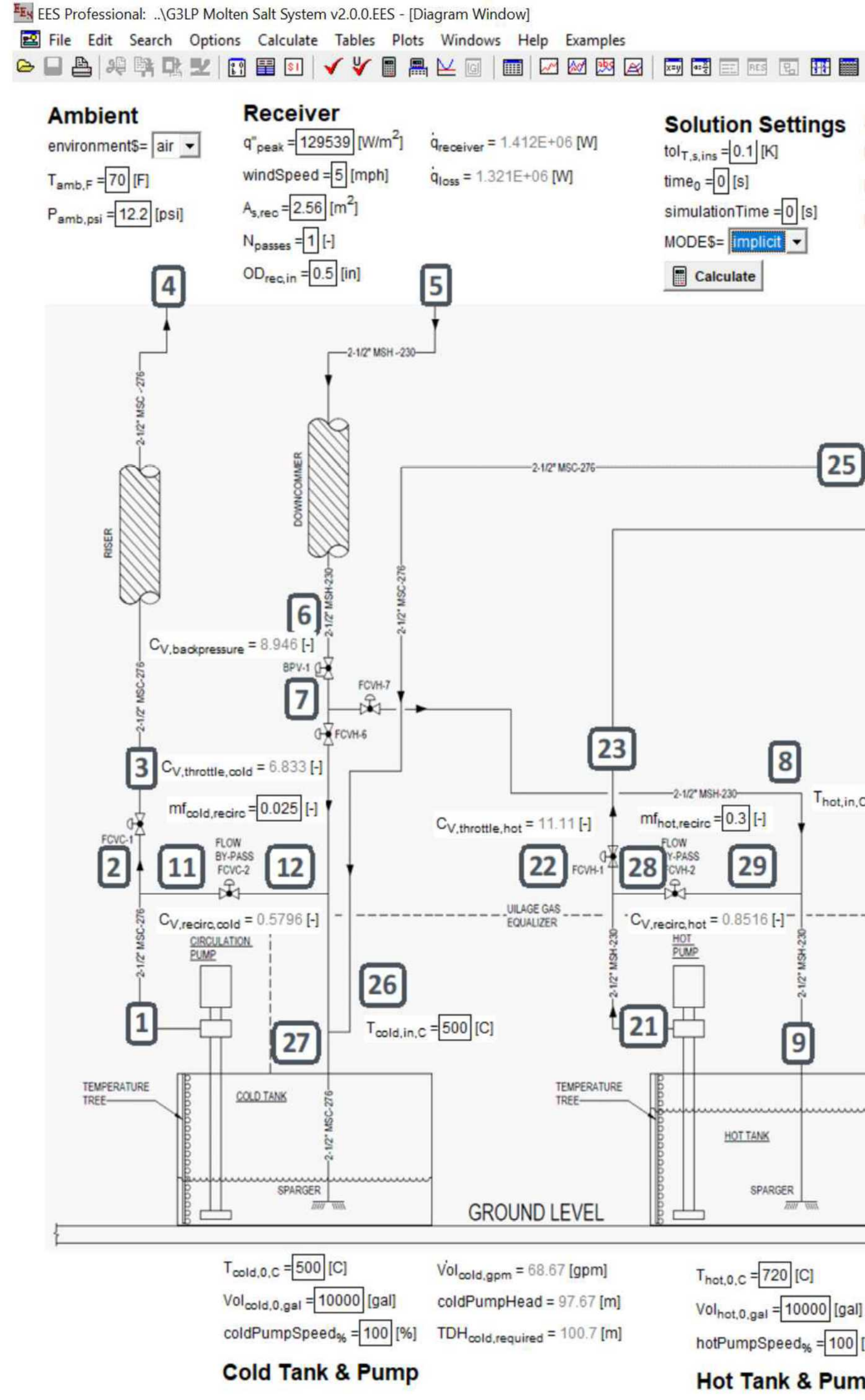
Thermodynamic System Prediction Model

EES System Model

- Model considers 3 NPS SCH80 pipe with 2 inches of insulation blanket.
- State properties calculated at inlets/outlets along both hot/cold legs of pilot-scale plant.
- User-supplied inputs & calculation settings in EES diagram window, lookup tables & parametric tables as for the solution configuration.
- Data from user input saved to and loaded from a file to simplify scenario modeling without requiring multiple copies of the EES code.
- Model developed to be configurable to facilitate parametric studies related to pump design, heat exchanger design, etc.

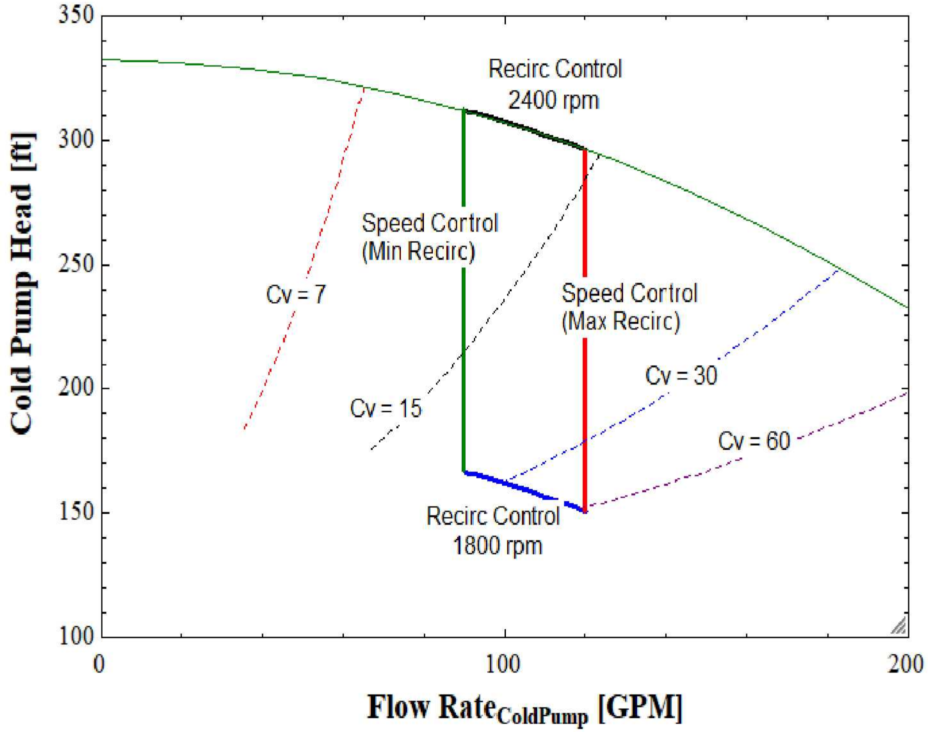
System Model

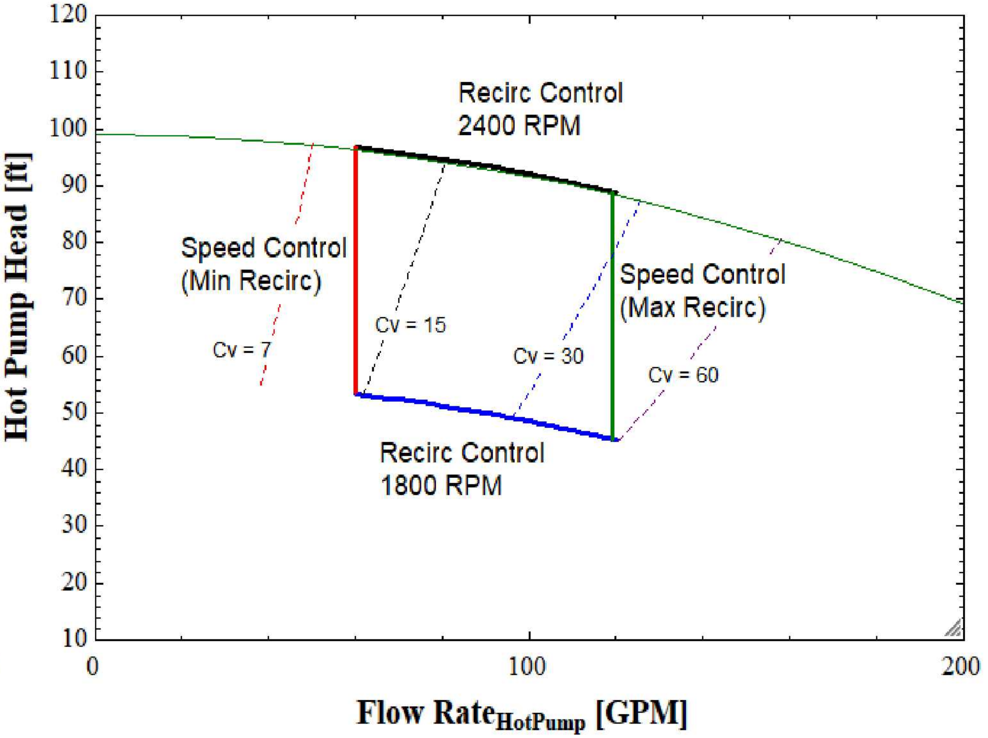
- EES System Model
  - Tank Model – Well-insulated tank with a well-mixed liquid and ullage gas systems at const. 5 psig
  - Valve/Pump Models – Steady flow calculated using the ISA S75.01 equation for sizing valves and pumps.
  - Piping Model – Implemented as standard quadratic head rise formula with fitting coefficients derived from actual head-flow curves, estimations based on design requirements for a desired head-flow curve.
- System Model Development
  - 27 state points to evaluate calculated thermodynamic temperatures, pressure and flow rates.
  - Approximations for laminar flow, and exclusion of attemporation pump, chem. control, ullage gas system and salt heat mixing tanks.
  - Salt receiver 120 ft. above lower TES and power block.



System Results

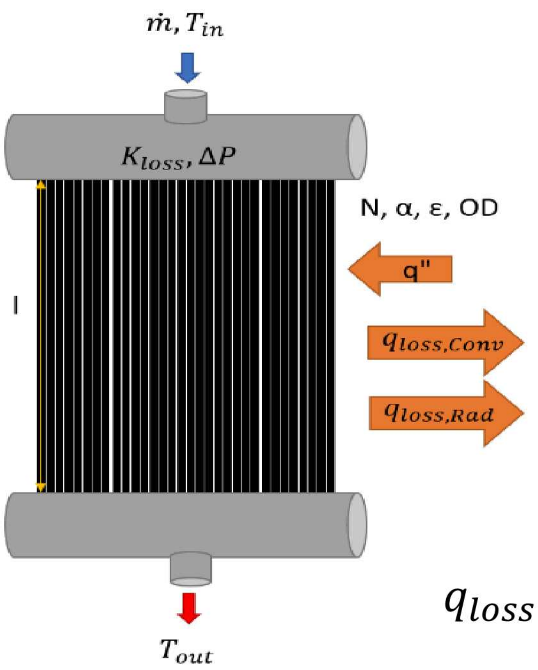
) operating envelope is bound by minimum and maximum speed control of the recirculating throttle valv
) and 2400 RPM pump operating points.
es were determined to be respectively 181.6-165.9 ft. and 311.2-327 ft. for pump flow rates of 90-120 G
) suggest a reciculating throttle valve minimum Cv of 60 required to meet the operational envelope spar
:.
gest TDH values between 49.65-57.73 ft. and 93.19-101.3 ft. for 1800 and 2400 RPM operational point
n Cv of 60 was also determined for the hot-side throttle recirculation valve for the operational envelope
hrottle recirculation valves, the results suggest relatively high Cv values requiring minimal pressure drops
ng pump operating points with minimal recirculation.





Receiver Model

- Parametric analysis was performed for a simple tubular receiver with a single-pass design.
- Receiver flux & efficiencies calculated for an estimated 2.56 m^2 aperture area based on SolTrace
  - Performed with the NSTTF heliostat field and the 120 ft. test section of the solar tower.
- Model developed w/ 40 single-pass 0.5 NPS Sch. 10 tubes constructed of an H230 material.
- Assessment performed to compare receiver performance between 2 molten salt chemistries
  - 735 ℃ operation where flux calculated with respect to tube diameter and thermal convection losses.
- Receiver sub-model to accept uniform heat flux & assess heating of vertical receiver tubes.
- Receiver model considers panel with N #tubes to allow a mass flow rate and a pressure drop.
  - Considers uniform heat flux & flow through the tubes with grey properties approximated for the tubes.



$$Q_c = \frac{2\pi L k}{\ln\left({}^{OD}/_{ID}\right)}\left(T_{s,OD} - T_{s,ID}\right)$$

$$\Delta P = \left(f\frac{L}{ID} - \sum K\right)\frac{\rho U^2}{2}$$

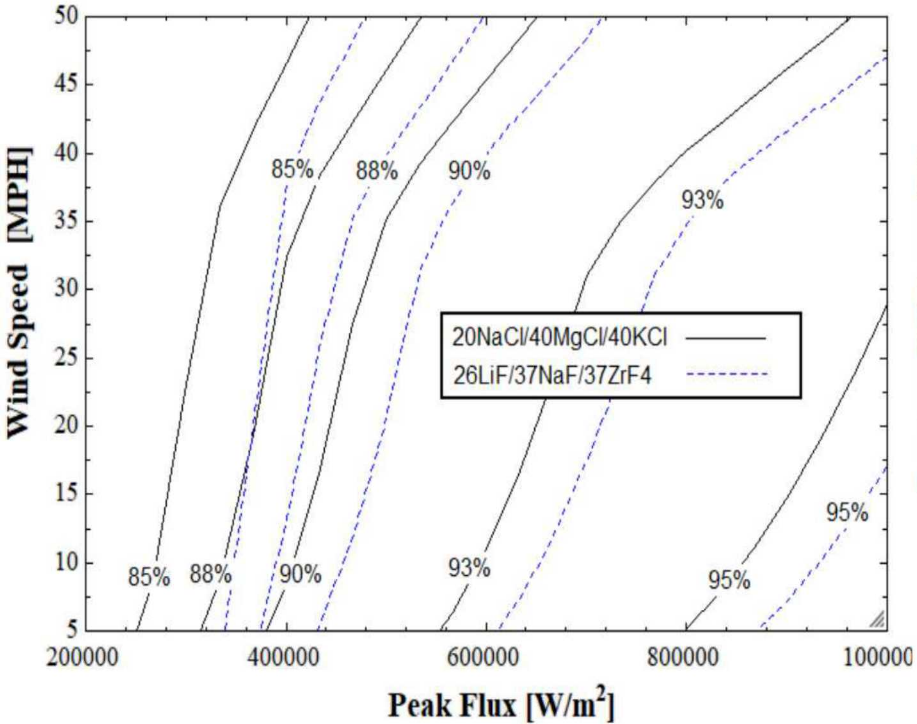
$$q_{abs,tube} = \frac{\alpha q_{in}}{N}$$

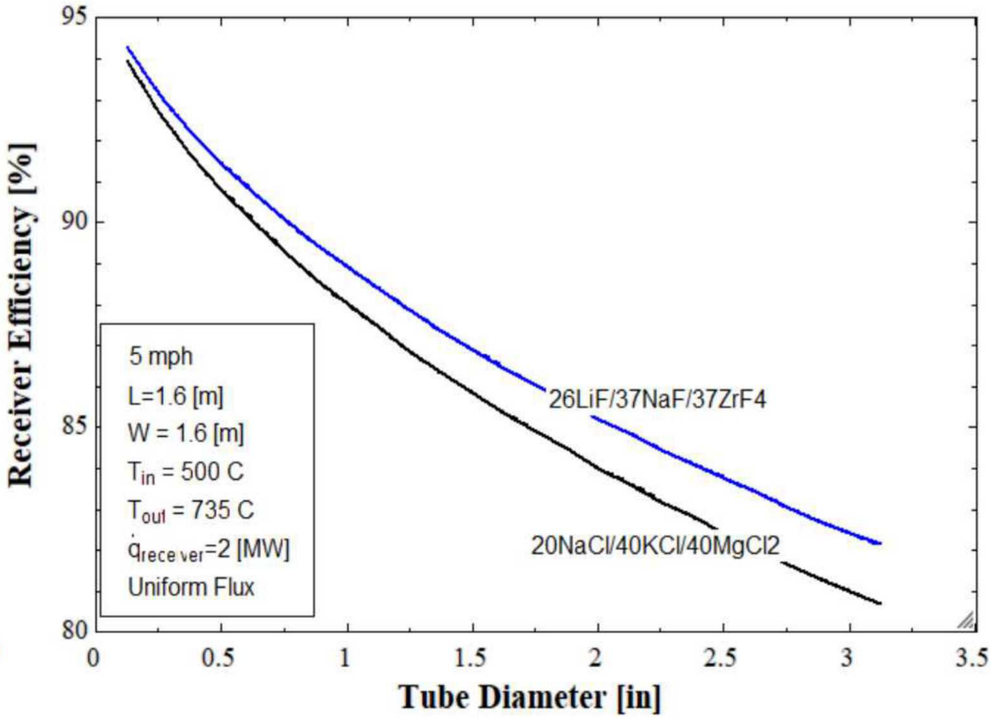
$$\frac{1}{\sqrt{f}} = -2.0\log\left(\frac{{}^{\epsilon}/_{ID}}{3.7} + \frac{2.51}{Re\sqrt{f}}\right)$$

$$q_{loss} = h_\infty\left(T_{s,OD} - T_\infty\right) + \varepsilon\sigma\left(T_{s,OD}^4 - T_\infty^4\right)$$

Receiver Results

- Results indicate receiver peak flux increases for uniform flux distribution & tube geometry.
  - Receiver efficiency sensitivity due to wind also increases.
- Required peak flux for chloride salt found to increase with wind speed by 33.3% for an 85% receiver efficiency, and 21.7% for a 95% receiver efficiency from a wind speed of 5 to 50 mph.
- Required peak flux levels found higher by avg. 11.1%, though sensitivities found to be less for efficiencies less than 90%, and greater for efficiencies greater than 93%
  - For 95% receiver efficiency, peak flux was found to increase by 13.7% for a wind speed from 5 to 17 mph.
- Receiver efficiency was found to be overall higher for the ternary flouride salt by an average of 1.2% than the ternary chloride salt, possibly due to higher k_{cond}.





Conclusions & Future Work

- System layout for 2-MWth molten-salt loop with EES thermodynamic system model operational states.

- Two molten salt chemistries compared with respect to required flux & efficiencies to achieve system design criteria including cold and hot tank temperatures of 500℃ and 720℃.

- Results suggest non-linear variation with receiver diameter
  - Ternary chloride salt required an average 11.1% lower receiver flux with lower calculated receiver efficiency compared to ternary fluoride salt.

- Sys. performance evaluated for cold/hot pumps & respective recirculation throttling valves.

- Results suggest minimum Cv of 60 for cold/hot throttle recirculation valves for operational pump speeds between 1800 and 2400 RPM.

- Future studies will include receiver flux distributions & transient operational modes.

- Future receiver model development will consider accepting SolTrace beam information from SNL NSTTF Heliostat field with transient contributions and 2D flux distributions.

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kmarmij@sandia.gov

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Thank you.