CSP Gen 3 Roadmap

Technology Pathway
Molten Salt

February 01, 2017

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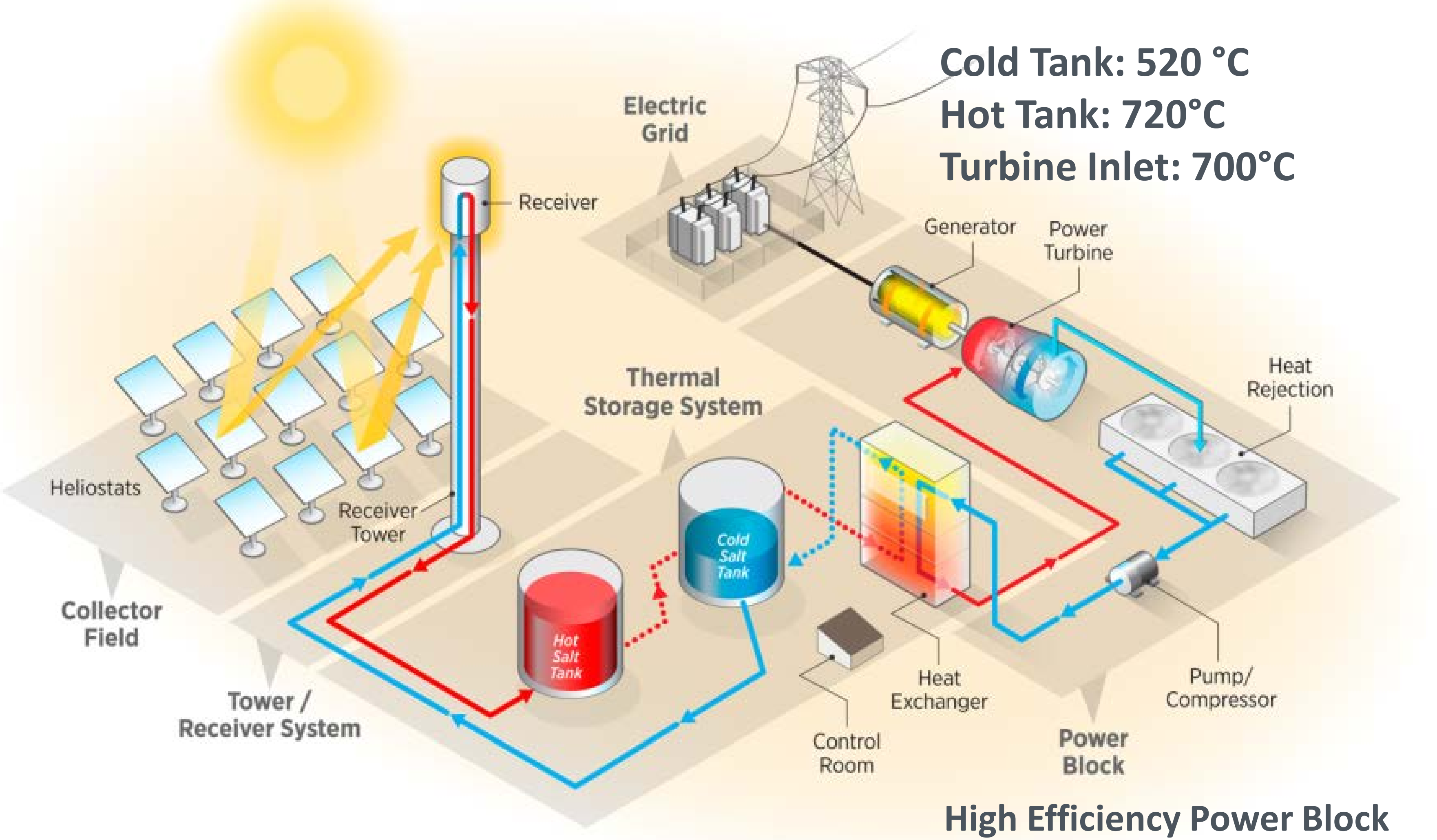
Technology Overview – Molten Salt Pathway

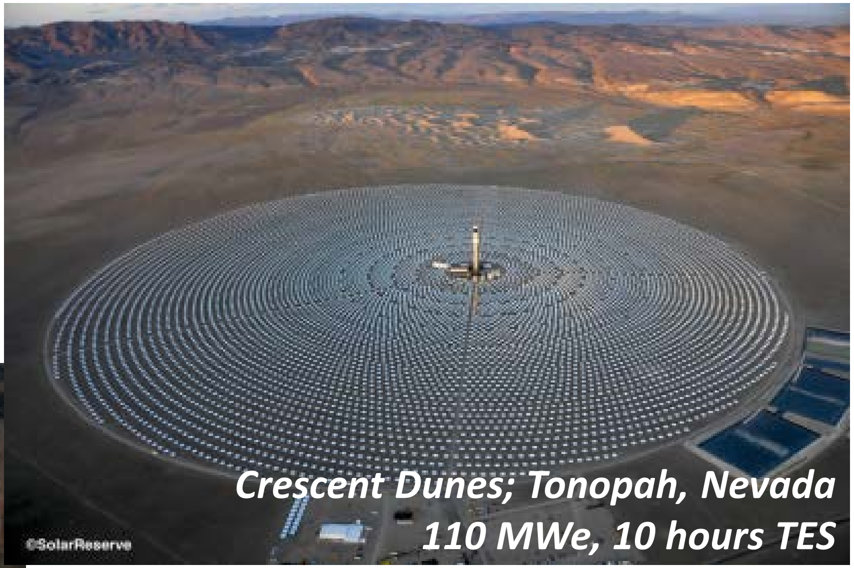


Cold Tank: 520 °C
Hot Tank: 720°C
Turbine Inlet: 700°C

High Efficiency Power Block
sCO_2 Brayton cycle

State-of-the-Art Molten Salt Technology

- Heat transfer (HTF) and thermal storage (TES) fluid = Solar Salt (Na-K/NO_3)
- Hot Tank = 585°C**;
- Cold Tank = 290°C;
- Power Block = Steam Rankine;
- Receiver = external.

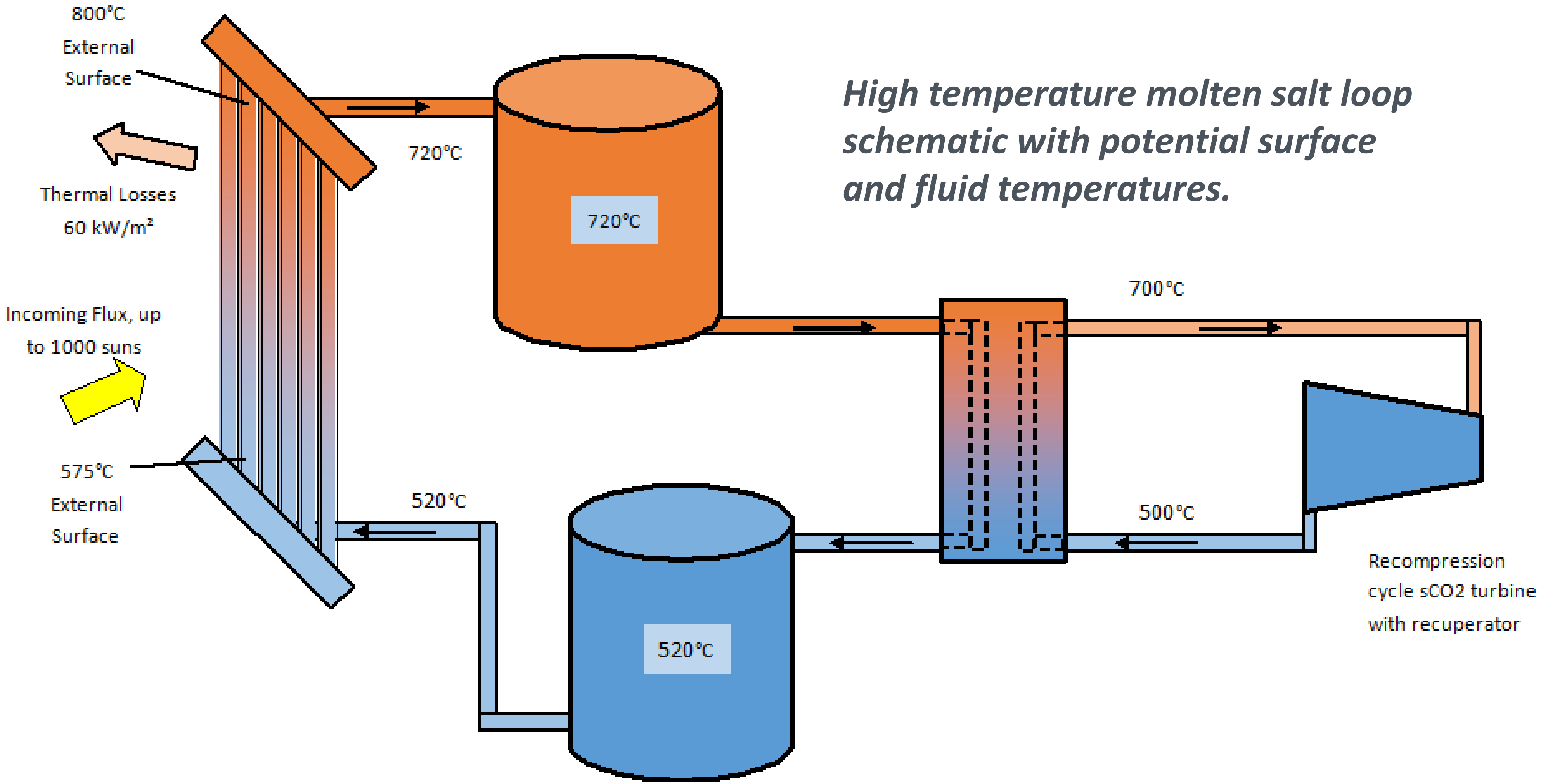


Crescent Dunes; Tonopah, Nevada
110 MWe, 10 hours TES

Gemasolar; Spain
19.9 MWe, 15 hours TES

***Possibility for higher temperatures if ullage gas chemistry is changed*

Hypothetical Advanced-Salt System



High temperature molten salt loop schematic with potential surface and fluid temperatures.

SunShot goal (integrated systems for sCO$_2$ power cycle):

- Nitrate salts decompose above ~600-620°C
- Chlorides and carbonates are good candidates

Molten Salt Technology Gaps

1. Salt Chemistry
2. Material Selection/Compatibility
3. TES Tank Design & Cost
4. Salt Receiver
5. Pumps, Valves, and Piping
6. Salt-to-sCO_2 Heat Exchanger
7. Heat Trace and Sensors

Technology Gap – Salt Chemistry

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- Stable to at least 750°C (short residence time at 800°C).
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- Corrosion performance and mitigation is needed.
- System needs to be reliable, simple to operate and inexpensive → corrosion monitoring is key and plant operators need to be able to handle any situation.

Technology Gap – Salt Chemistry

Candidate MS – HTFs (SunShot goal = $15\ \$/kWh_{th}$)

Salt Mixture	Melting Point (°C)	Heat Capacity, J/g-K	Density, kg/L	Tank Size*	Δ Volume on Melting	Notes**	Price ($\$/kWh_t$) with ΔT = 200 K
$NaNO_3$ KNO_3 (baseline)	220	1.5	1.7	1.26	+4.6%		10
$MgCl_2$ KCl	426	1.15	1.66	1.69	KCl: +22.3% $MgCl_2$: +30.5%	$BP_{(ZnCl2)}$= 732°C	5
$ZnCl_2$ NaCl KCl	204	0.81	2.4	1.66	NaCl/KCl: +14.8% NaCl: +26.1%	$BP_{(MgCl2)}$ = 1412°C	18
Na_2CO_3 K_2CO_3 Li_2CO_3	398	1.61	2.0	1	+3.6%	$EP_{(747°C)}$ = 0.014 atm $EP_{(827°C)}$ = 0.041 atm $EP_{(947°C)}$ = 0.151 atm	28

* *normalized to smallest tank for a given energy*

** *BP: boiling point temperature,*
EP: equilibrium pressure at a given temperature of CO_2

Technology Gap – Salt Chemistry
Main Attributes of the Salt Candidates

Salt	Notable Advantages
Zn-based chloride	Lowest melting point Corrosion mitigation can be achieved (exclusion of oxygen and water)
Mg-based chloride	Lowest cost per kg Corrosion mitigation can be achieved (exclusion of oxygen and water)
Ternary carbonate eutectic	High heat capacity and density leads to smallest tank volume No required purification/pre-melting. Inherently compatible with CO_2 Vast experience from molten-carbonate fuel cells operating at ~650°C.

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Main Attributes of the Salt Candidates

Salt	Notable Advantages	Notable Disadvantages
Zn-based chloride	• Lowest melting point • Corrosion mitigation can be achieved (exclusion of oxygen and water)	• Measureable vapor pressure • Very corrosive in presence of oxygen/water • Controlled purification/pre-melting required • Lowest heat capacity
Mg-based chloride	• Lowest cost per kg • Corrosion mitigation can be achieved (exclusion of oxygen and water)	• Very corrosive in presence of oxygen/water • Controlled purification/pre-melting required • Intergranular corrosion if Mg concentration too low • Highest melting point
Ternary carbonate eutectic	• High heat capacity and density leads to smallest tank volume • No required purification/pre-melting. • Inherently compatible with CO_2 • Vast experience from molten-carbonate fuel cells operating at ~650°C.	• Highest cost per kg • Lithium is a critical metal (market volatility) • High melting point

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Recommended R&D Activities

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  - Volume change to avoid deformation or rupture.

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- Total costs must include purification/pre-melting component, ullage gas, corrosion mitigation control, etc.
- Specify baseline melting/purification protocols.
- Determine compatibility with CO_2.

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- Design of components is tied to accurate and reliable salt’s thermophysical and corrosion properties.
- No pathway exists without addressing this gap.

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- Allowable impurities need to be determined.

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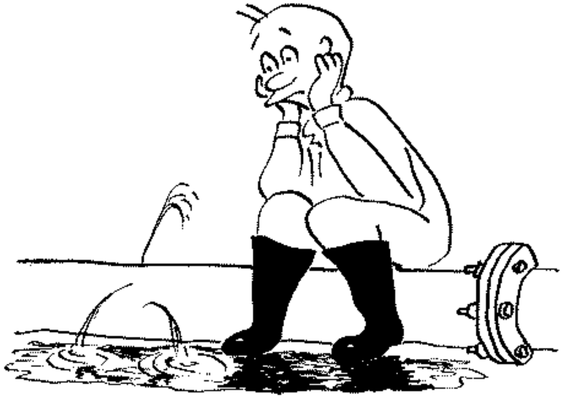
- Generate corrosion data under CSP relevant conditions.
- Characterize corrosion mitigation techniques that allow use of less-expensive materials.
- Develop rapid leak-detection and control.



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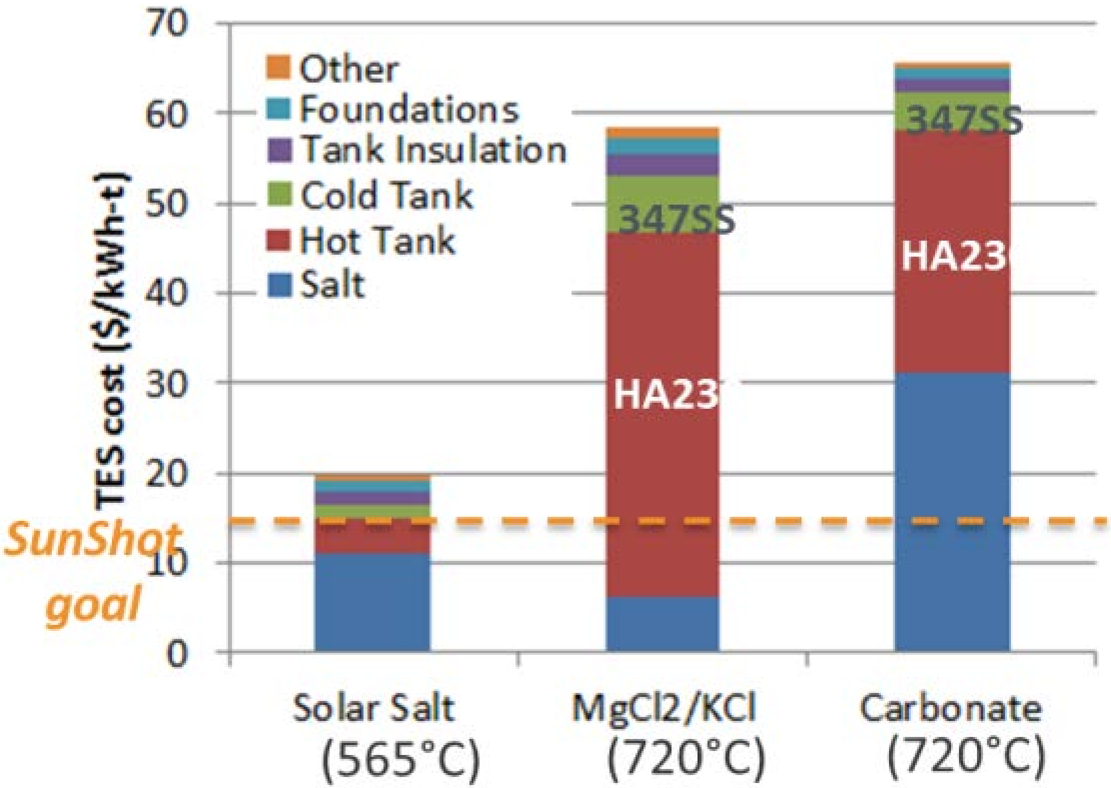
- Material compatibility will push forward the technology.

Technology Gap – Thermal Energy Storage Current Status

- Cost analysis is an extrapolation from two-tank TES,
  - Solar salt at 585°C → Mg-K/Cl and Na-K-Li/CO_3 at 720°C.



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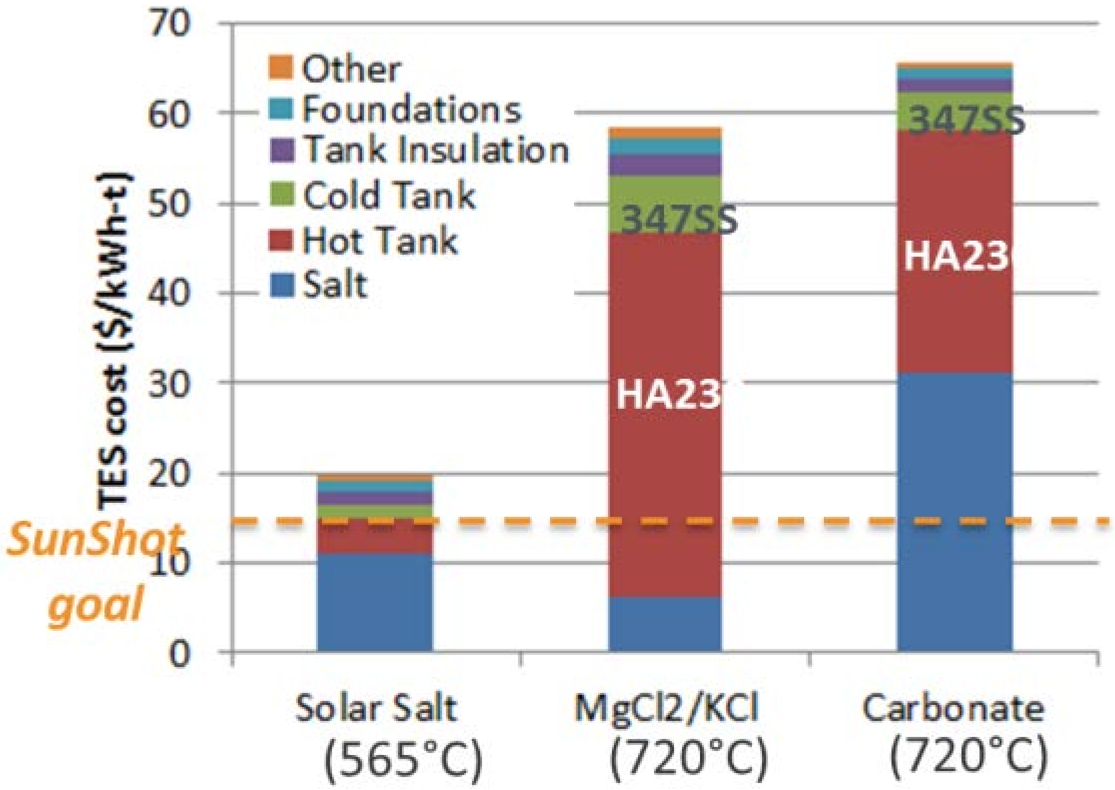

System	TES Cost ($/kWht)
SunShot goal	15
Baseline (solar salt at 565°C)	20
Mg-Cl mixture (HA230 hot tank)	58
Mg-Cl mixture (SS347 hot tank and internally insulated)	27
Ternary carbonate eutectic	66
Carbonate (SS347 hot tank and internally insulated)	46
▪ With 20% (wt) Li_2CO_3	37
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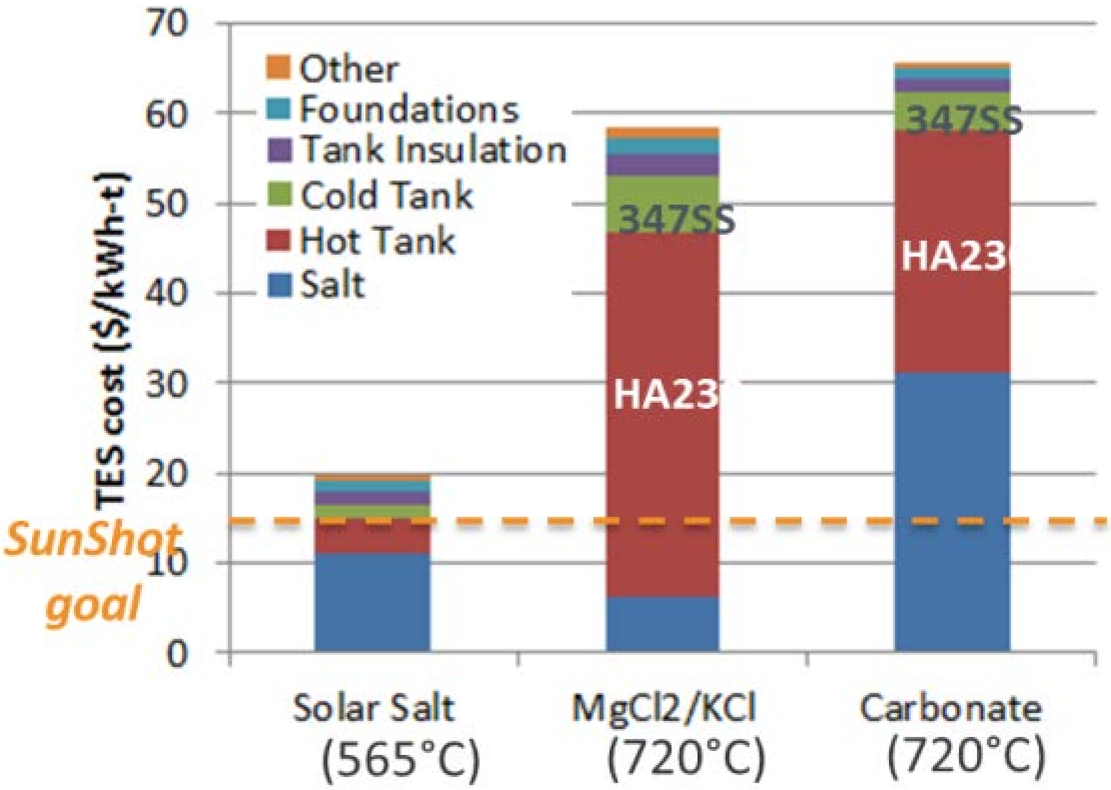

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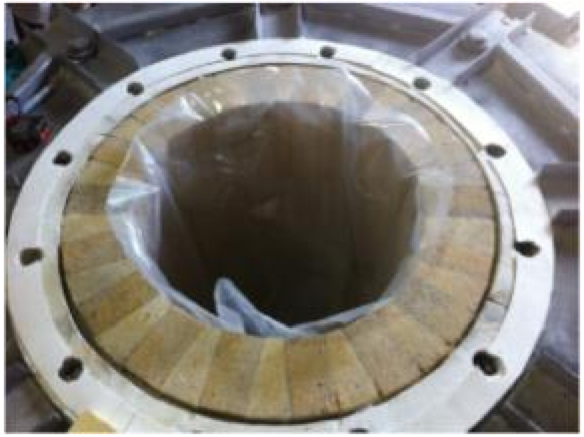
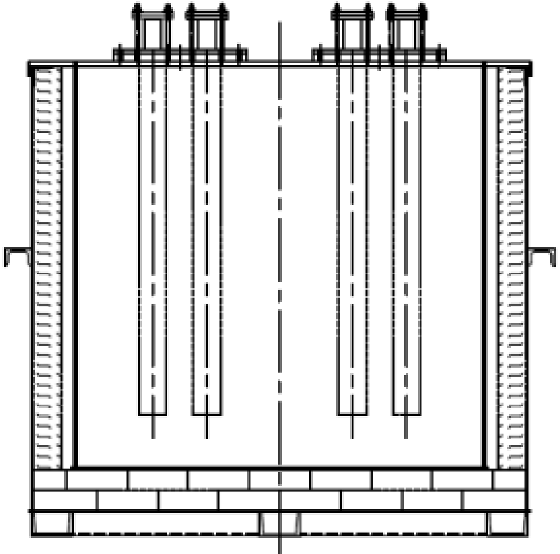
Are TES costs of $30/kWh$_t$ economically viable for MS systems?

Minimize Tank Cost through Design Changes

Externally insulated tank at Solar Two



Jonemann 2013



Upton Industries 2016 (Molten Salt Baths)

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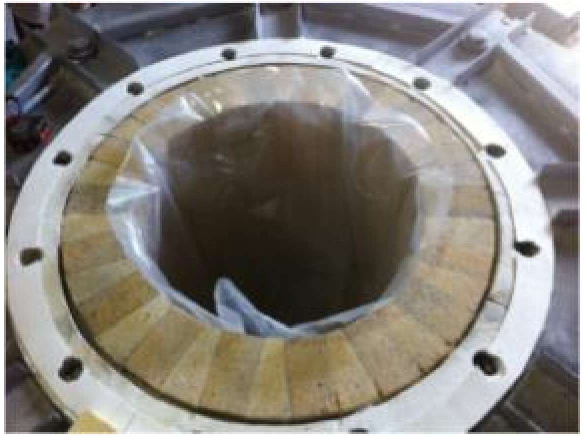

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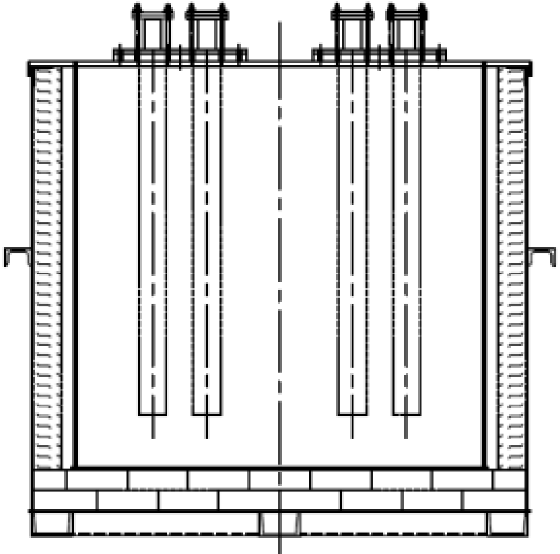

Upton Industries 2016 (Molten Salt Baths)

- Assess performance of refractory brick,
  - Chemical compatibility.
  - Heat transfer (insulation).
  - Open porosity.

Technology Gap – Thermal Energy Storage Recommended R&D Activities

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- Explore the potential of adapting designs from current industries for the salt tanks, especially the hot salt tank.

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- Develop acceptable means for cover gas implementation (dependent on salt).
- Explore the potential of adapting designs from current industries for the salt tanks, especially the hot salt tank.
- Evaluate tank foundation cooling methods for higher temperatures.

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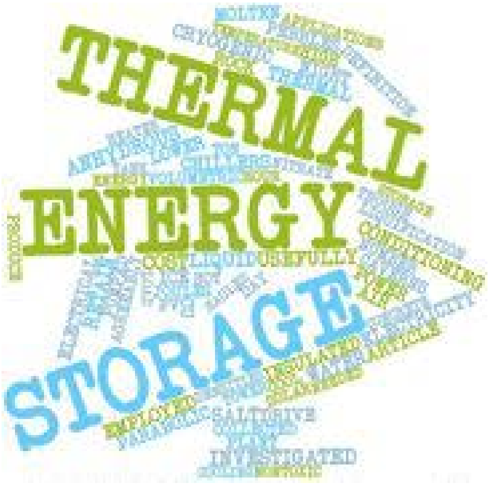
- Failure to identify design options that include low cost materials is an economic risk.



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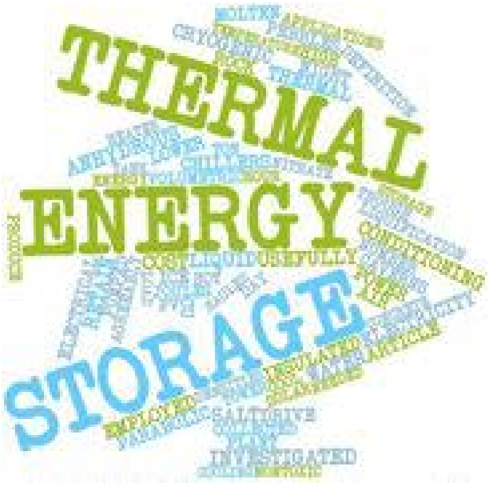
- Demonstration could be done using non-optimized designs/materials of higher cost.



Technology Gap – Salt Solar Receiver Current Status

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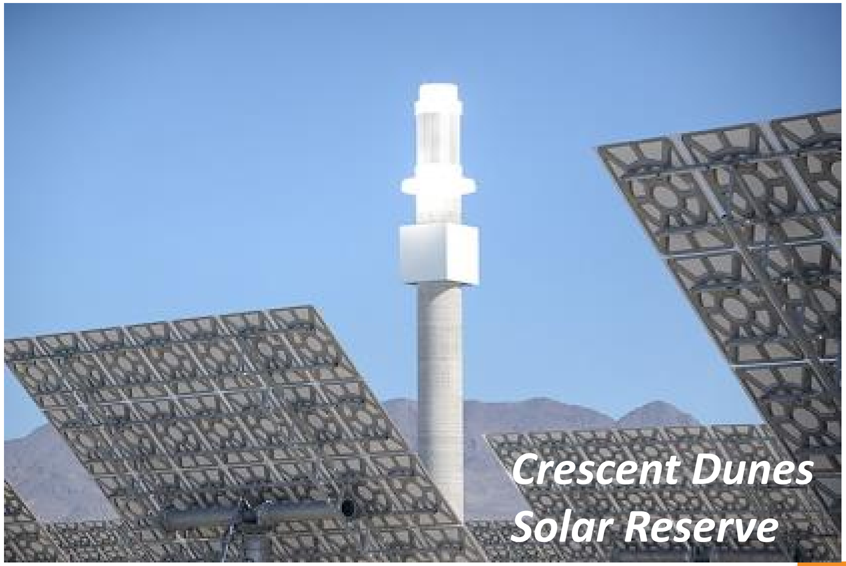

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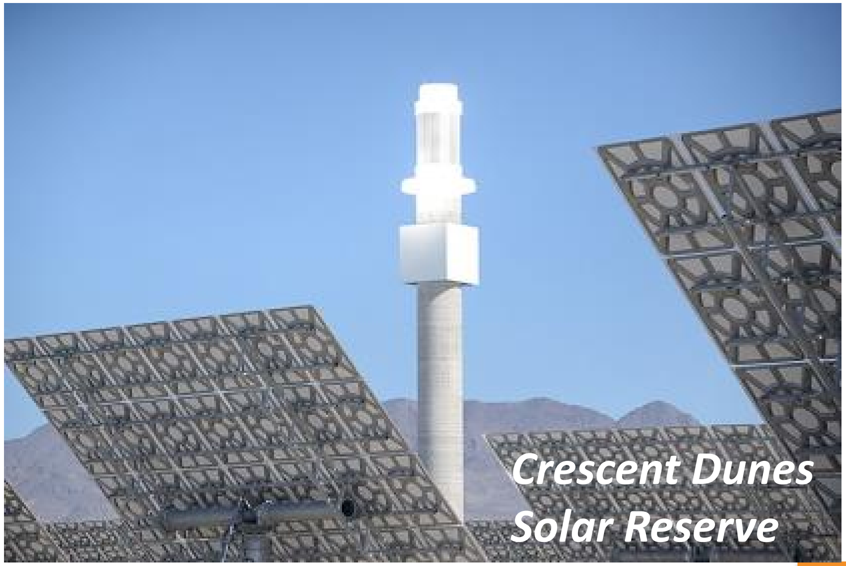

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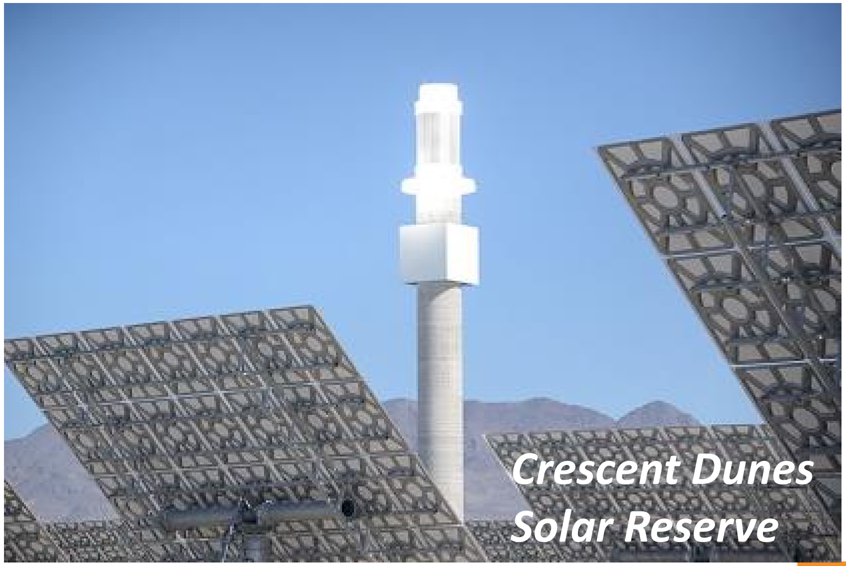

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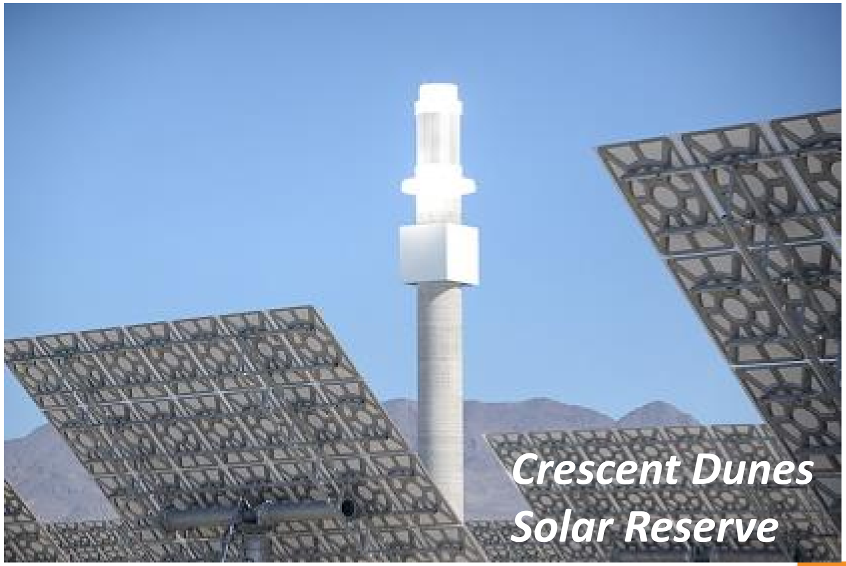
- Estimated costs for the tower and receiver combined are about $180/kW$_{th}$ (SunShot is $150/kW$_{th}$)



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Technology Gap – Salt Solar Receiver External vs. Cavity Design

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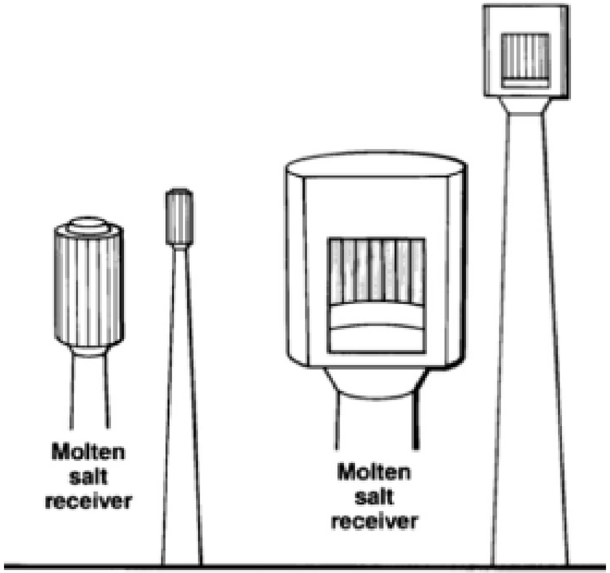

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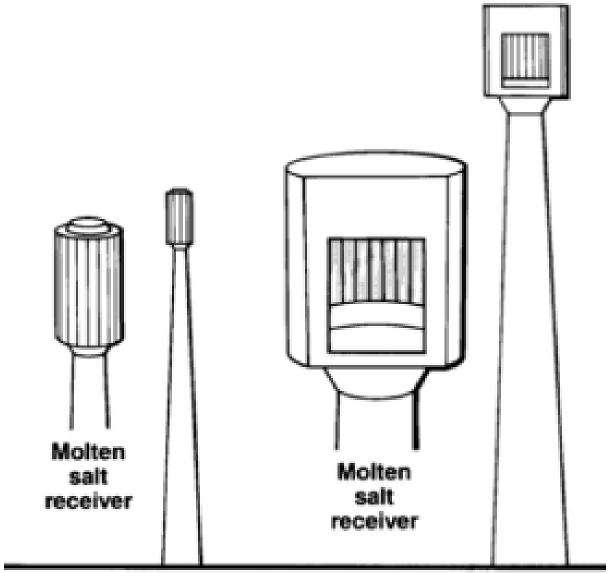
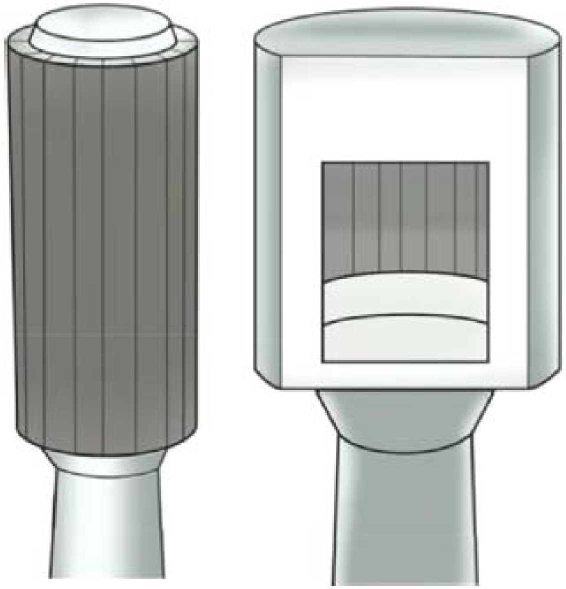
Preliminary Calculations at High Temperatures:

- North Cavity Receivers (and field) are 57% total efficiency, while External are 54%.
- Efficiency is primarily driven by optical efficiencies.





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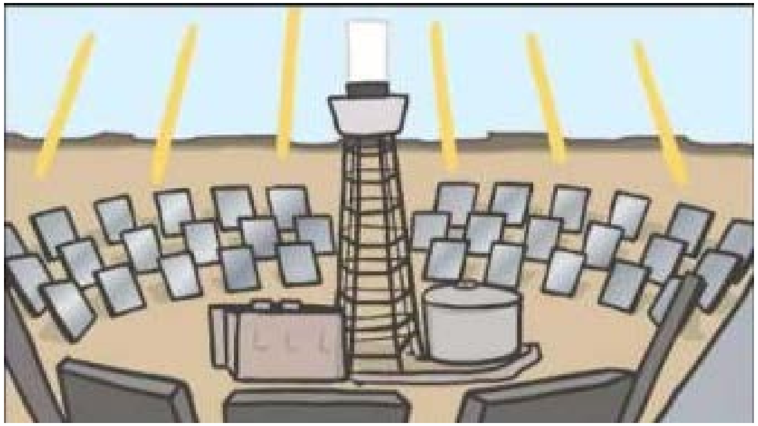

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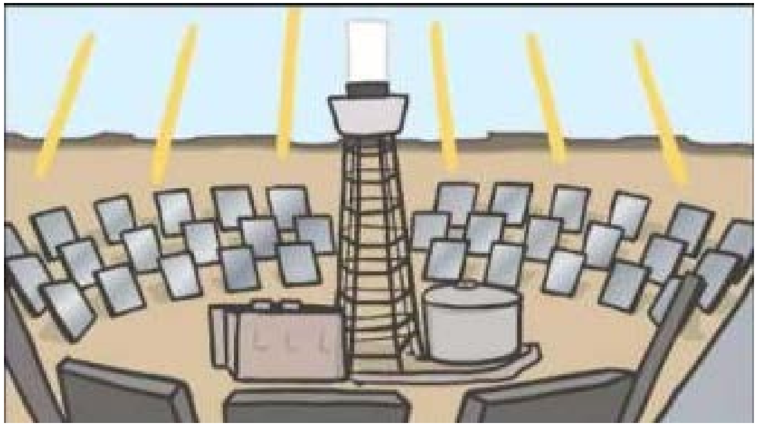

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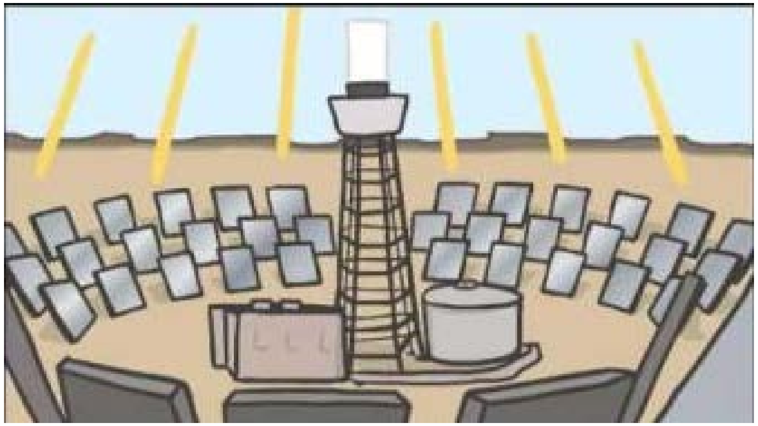

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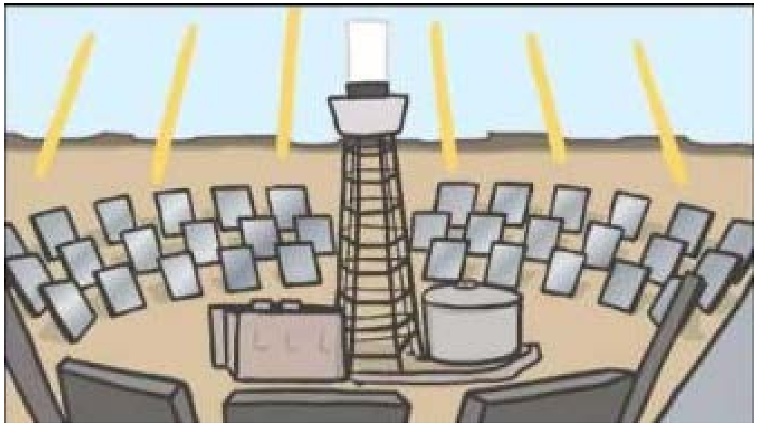

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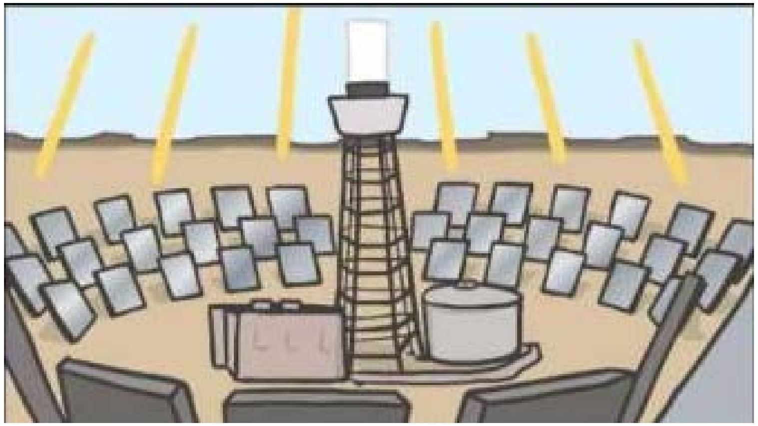

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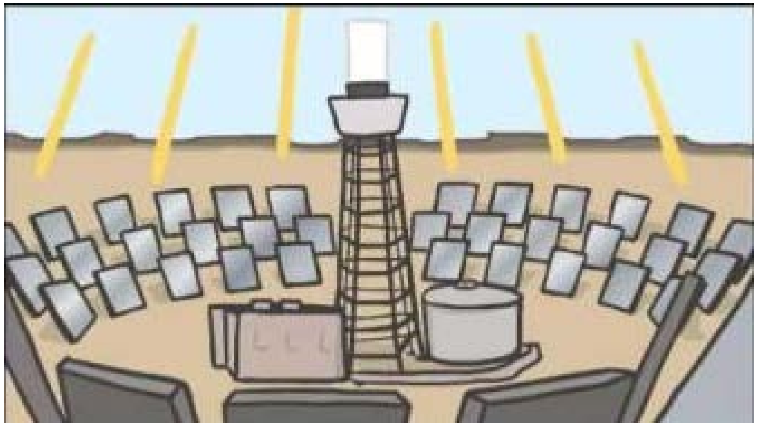
- Determine feasibility of *in-situ* heat treatment on finished components (welded) for age-strengthen alloys



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- Prove fill and drain procedure with cover gas. Develop system to maintain cover gas during drain back for off-sun idle operation.
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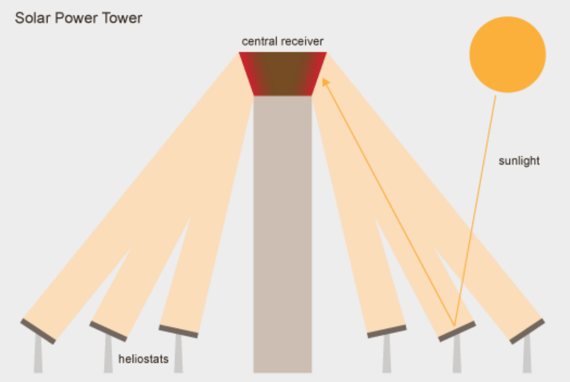
- Determine the impact on thermal performance of thicker receiver pipes, required due to reduced materials strength at the higher operating temperatures.

Technology Gap – Salt Solar Receiver Impact

- Receiver development is largely understood and is designated as an engineering effort.



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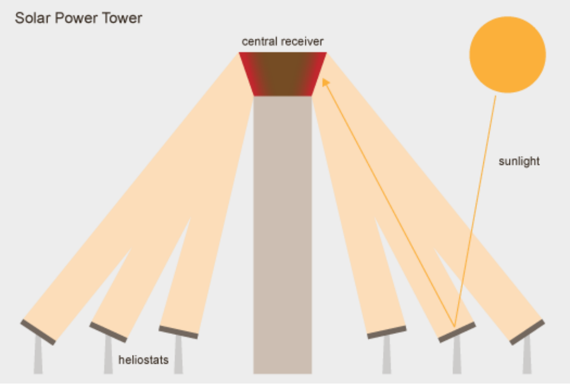

Technology Gap – Salt Solar Receiver Impact

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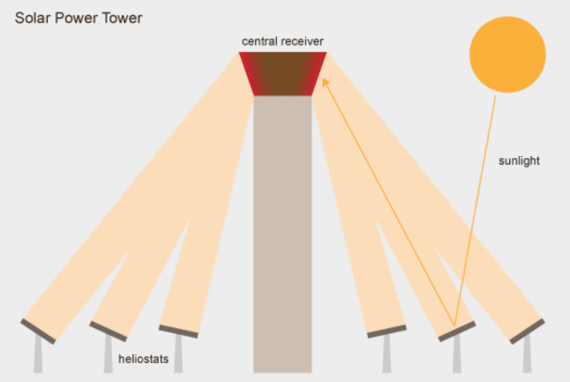
- SunShot performance goals requires substantial control of thermal losses, which will require cavities, high-temperature selective absorbers, or increased flux capabilities.



Technology Gap – Piping
Recommended R&D Activities

- Determine if mechanical properties degradation occur because of high temperatures and thermal cycling.

http://ceresist.com

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Recommended R&D Activities

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- Implement piping on larger systems to prove in technology in a plant like setting.
- Determine the feasibility of using ceramic lined pipe or *in-situ* surface treatments for internal walls.

http://ceresist.com

Technology Gap – Piping Impact

- Low-cost piping drives the economic viability of system.

Crescent Dunes Solar Reserve

Technology Gap – Piping Impact

- Low-cost piping drives the economic viability of system.
- Failure to address a cost effective solution for piping would result in MS technology not being economically feasible.

Crescent Dunes Solar Reserve

Technology Gap – Pumps
Current Status

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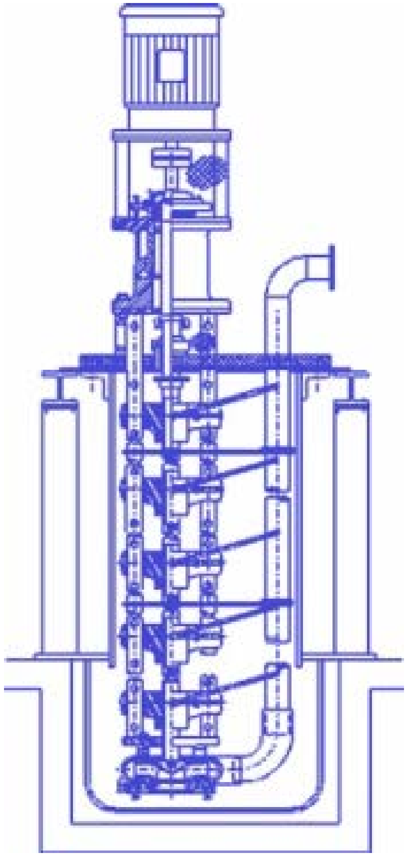
- Pumps will be a vertical single- or multi-stage sump type, mounted to the roof of the MS tanks (B&V report).
- Design and service for MS pumps above 550°C is relatively limited. At higher temperatures up to 720°C there is no available design or service experience.

Bearings

Technology Gap – Pumps



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- Lubricity of proposed salts is unclear,
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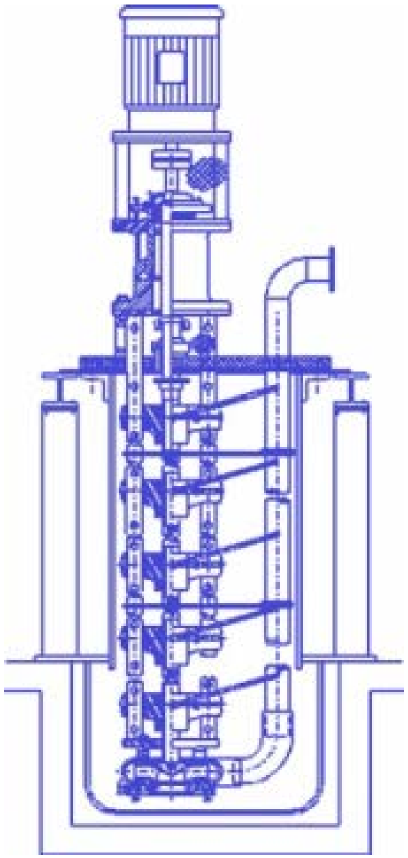

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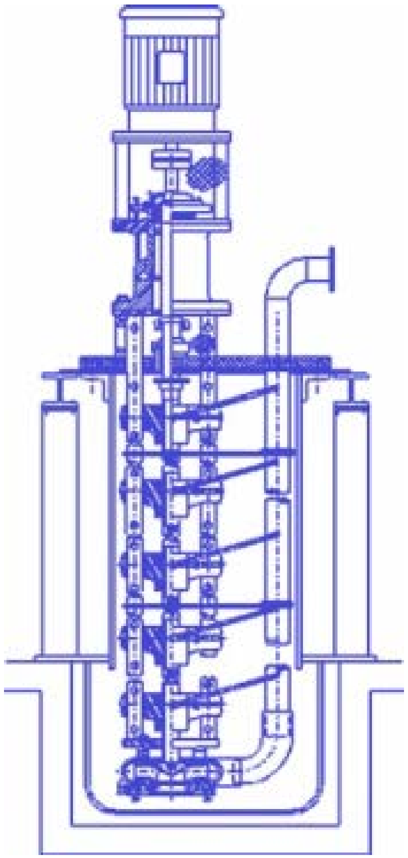

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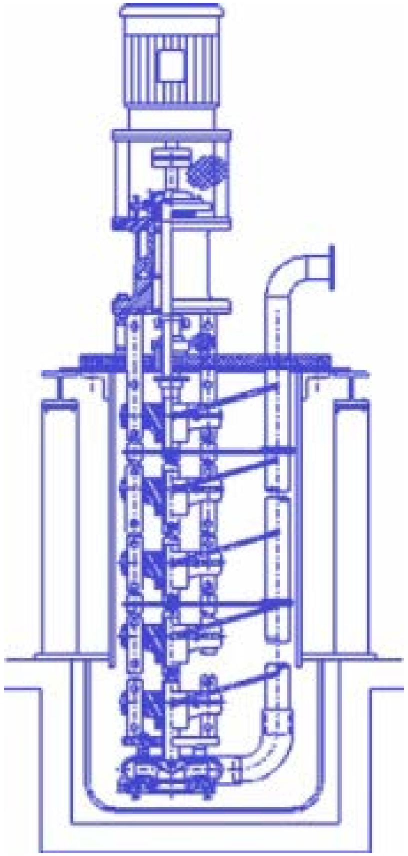

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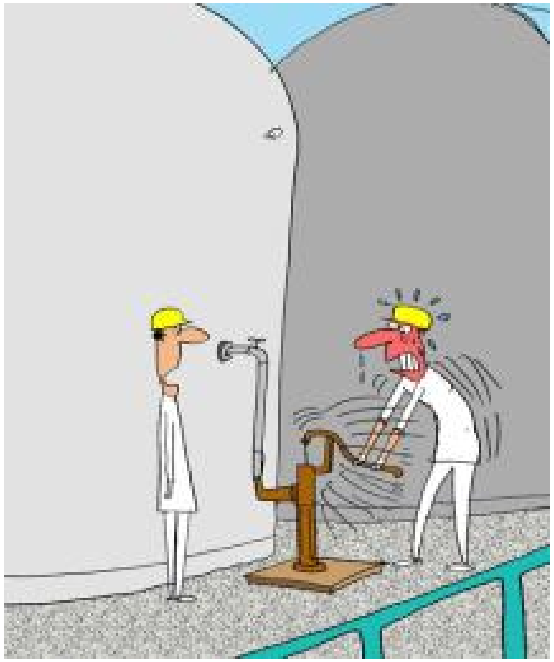
Technology Gap – Pumps
Recommended R&D Activities

- Determine pump designs for the cold/hot tanks.



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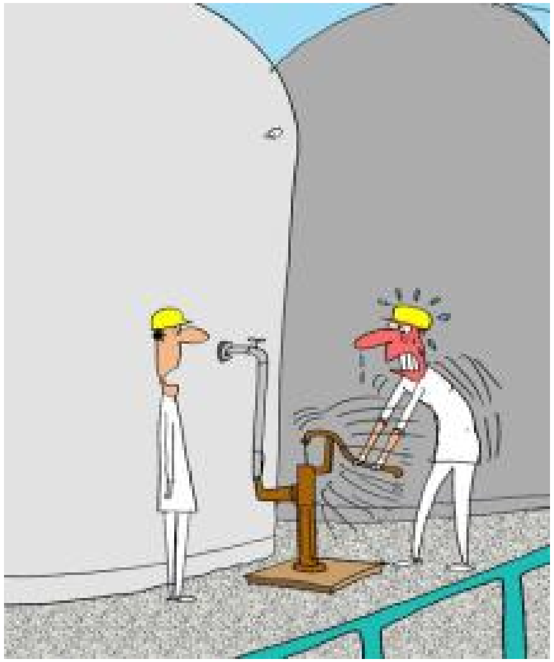

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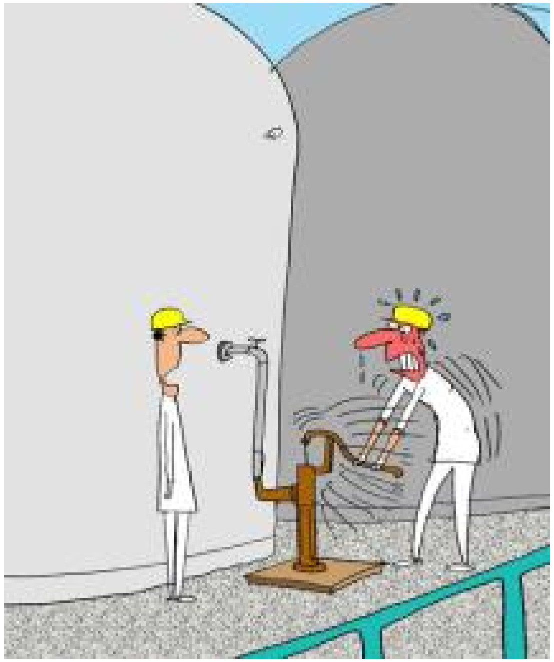

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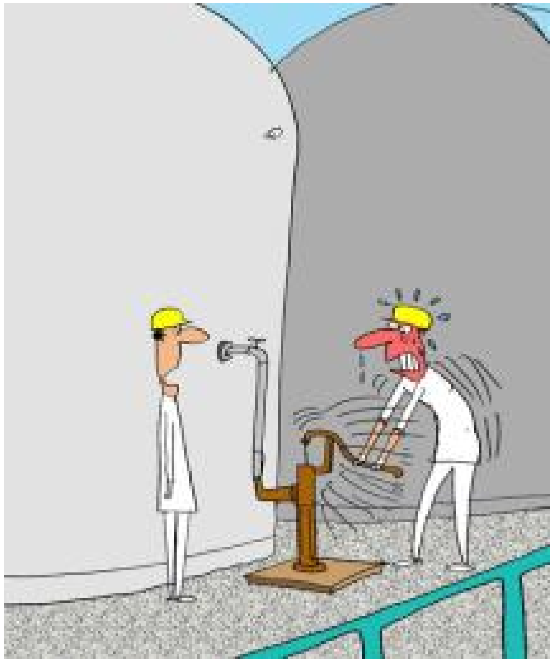

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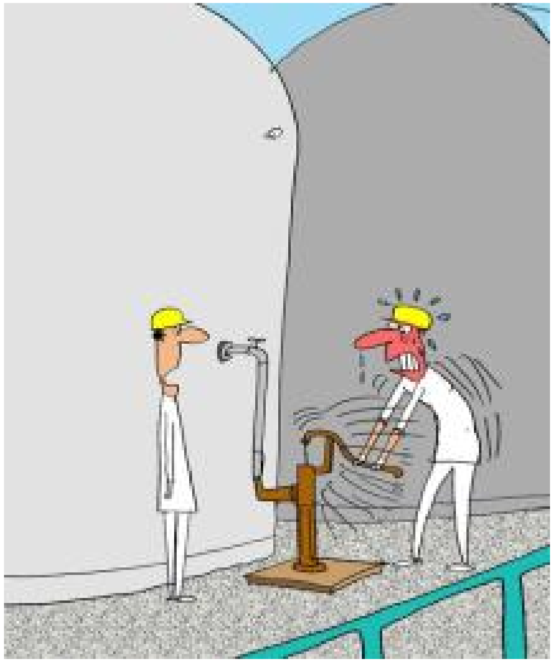

Technology Gap – Pumps Impact

- Pump designs are assumed to be able to meet requirements specified in plant designs,
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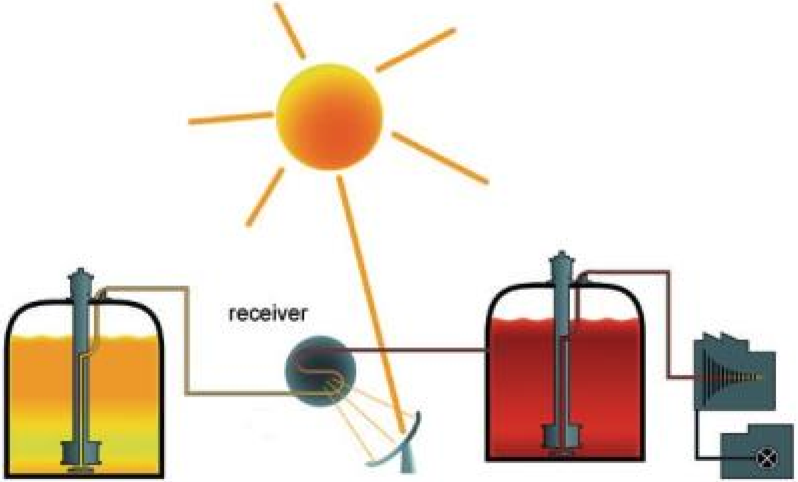

Technology Gap – Pumps
Impact

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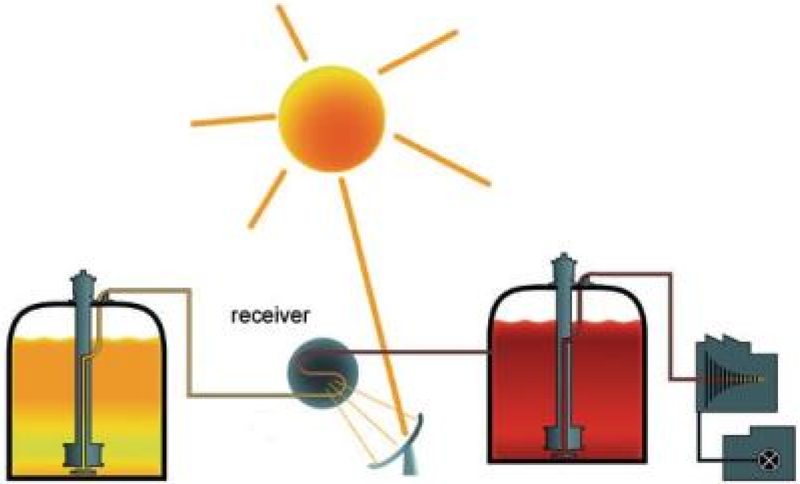
  - Pump reliability is key to the entire system

- Significant technical risks for any commercial application if short-term pump reliability in a pilot plant is not accomplished.



Technology Gap – Salt-to-sCO$_2$ Heat Exchanger

Current Status

- A salt-to-sCO$_2$ heat exchanger does not exist. Three concepts were suggested (vessel shell and tube; serpentine shell and tube; printed circuit)

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Current Status

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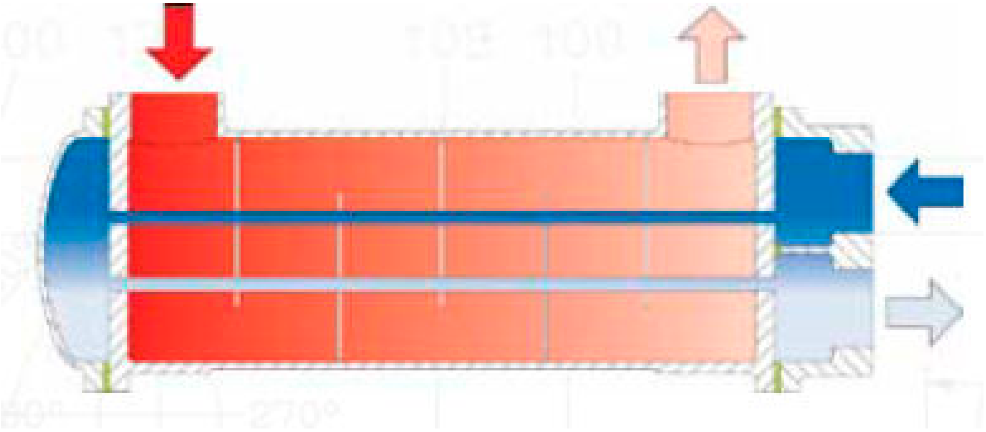
Recommended R&D Activities

- Identify promising designs.
- Develop strategies pertaining to start up/shut down.
- Assess CO_2/chloride salt compatibility.
- Demonstrate performance between sCO_2 and salt.

Technology Gap – Salt-to-sCO$_2$ Heat Exchanger
Impact

- Advanced heat-exchanger technology is important from both a performance and economic viability standpoint for the technology.



Technology Gap – Salt-to-sCO_2 Heat Exchanger Impact

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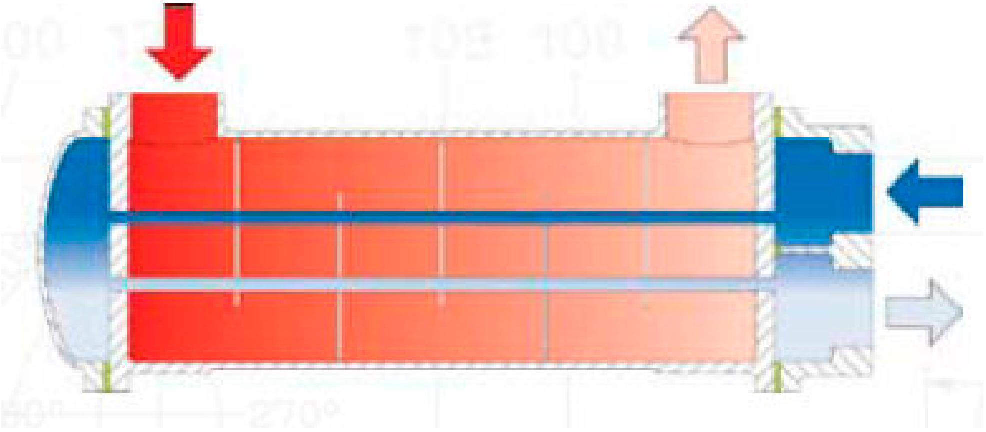
- Shell and tube is a leading technology, but advanced heat exchange concepts could be considered to improve performance and cost.



Technology Gap – Valves

Current Status

- Bellows valves were recommended to provide hermetic sealing but packed valves are preferred if a packing material is suitable:
  - Potentially less expensive and easier to maintain.
  - Rupture of bellows if actuated when salt frozen.

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Impact

- Valve designs will be an important consideration for reliability, performance, and O&M.
- If valve reliability is not accomplished it will create significant technical risks for commercial application.

Technology Gap – Valves
Recommended R&D Activities

- Determine suitable valve designs,
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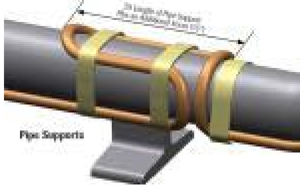
Technology Gap – Heat Trace and Insulation



Current Status

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- Detailed insulation procedures are available.*

**SAND2000-2598*

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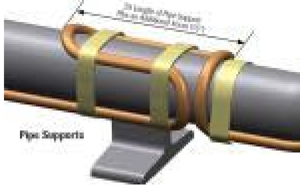

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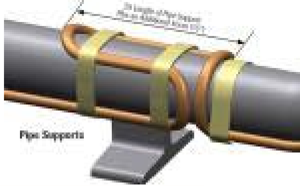
Recommended R&D Activities

- Determine best heat-trace and insulation designs.
- Radiation barriers alternating with layers of insulation might be considered.
- Test selected system with salt under test field-like conditions to determine lifetime, and maintainability.

***SAND2000-2598**

Technology Gap – Heat Trace and Insulation Impact



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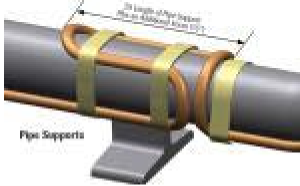

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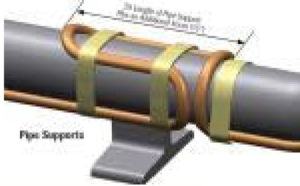

- Heat-trace and insulation solutions are assumed to exist with appropriate design and selection of materials.
- Heat trace a significant parasitic loss in current nitrate systems and must be well designed for higher temperature conditions.
- Failures in heat trace could be disastrous for demonstration purposes,
    - Could cause unplanned outages, irrecoverable component damage, and freezing problems.

Technology Gap – Sensors *(flowmeter, pressure, level , flux, and chemistry)*

Recommended R&D Activities

- Determine best designs for applications.
- Perform no-flow testing of sensor at temperature (robustness testing).
- Implement sensor on systems to prove technology.

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Impact

- Robust sensors reduce pilot plant risk with data to inform operation and control methodologies.
- Sensors for the high-temperature portions of the system do not currently exist.

Molten Salt Receiver Pathway - Summary

- MS technology represents the most familiar path toward the Gen3 goals, following requirements are key:
  - Selection of salt, and cost effective materials.
  - Corrosion understanding for component designs.
  - Design challenges are expected.
  - Redesign of hot tank to achieve TES cost metrics.

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  - Redesign of hot tank to achieve TES cost metrics.
- Critical subsystems are viewed primarily as engineering tasks.
  - Meeting acceptable cost and reliability will be the primary challenge to be overcome.

CSP Gen 3 Roadmap

Technology Pathway
Molten Salt

CSP Gen 3 Roadmap

Technology Pathway
Molten Salt