Liquid Pathway to SunShot

1697-1544

Craig Turchi (PI)
DOE Gen3 CSP Kickoff Meeting
June 25, 2018

Crescent Dunes Solar Energy Facility, Nevada

Outline

- Project Overview
- Objectives
- Project Team
- Complementary Projects
- Schedule and Decision Points

Liquid Pathway to SunShot

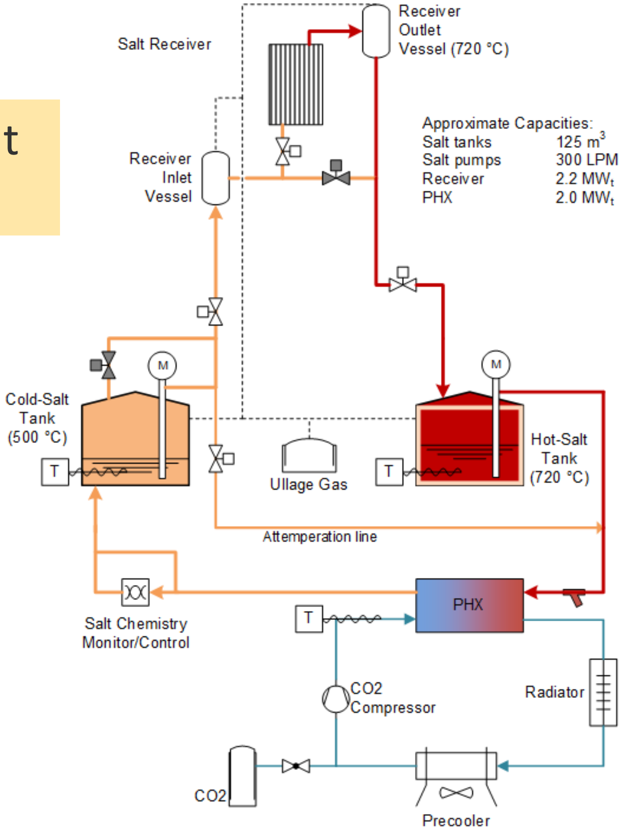
- Leverage expertise with liquid-HTF solar towers
- Use low-cost, thermally stable energy storage media
- Design for sCO_2 Brayton-cycle integration

Vast Solar's Jemalong sodium-HTF pilot facility (Australia)

SolarReserve's Crescent Dunes molten-salt HTF, Nevada, USA

Liquid-HTF Alternatives

Cl-Salt HTF



Approximate Capacities:

Salt tanks	125 m^3
Salt pumps	300 LPM
Receiver	2.2 MW_t
PHX	2.0 MW_t

Liquid-HTF Alternatives

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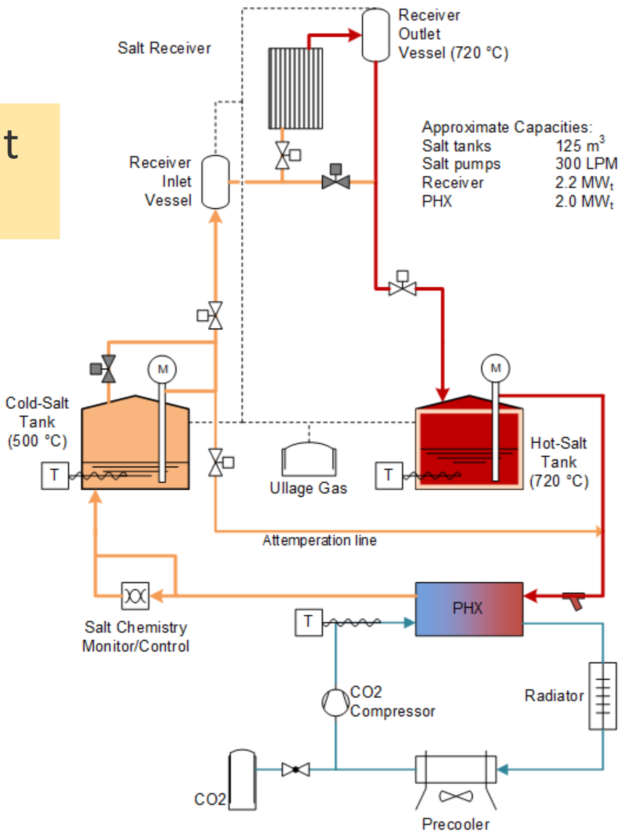

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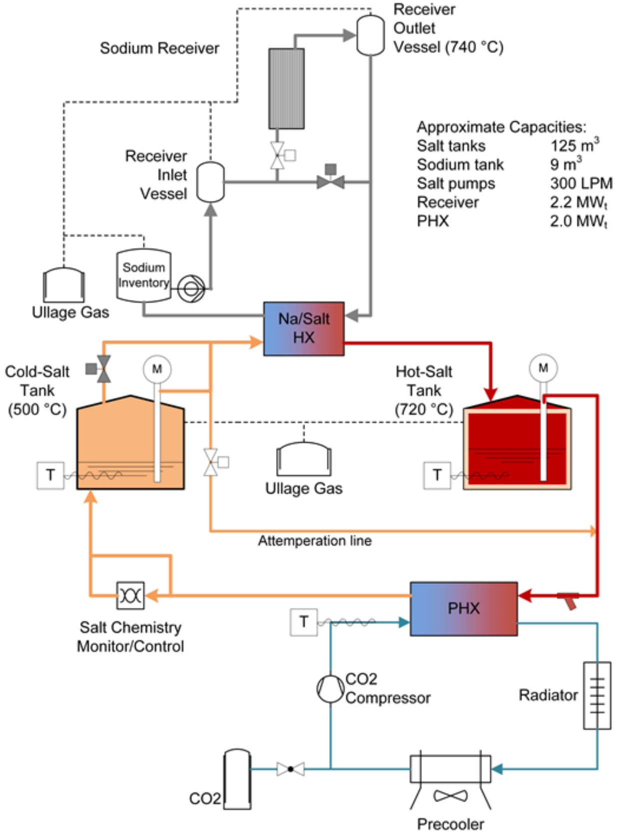


Approximate Capacities:

Salt tanks	125 m^3
Sodium tank	9 m^3
Salt pumps	300 LPM
Receiver	2.2 MW_t
PHX	2.0 MW_t

Sodium HTF

Direct-storage Na thermocline also considered

Liquid Pathway Advantages

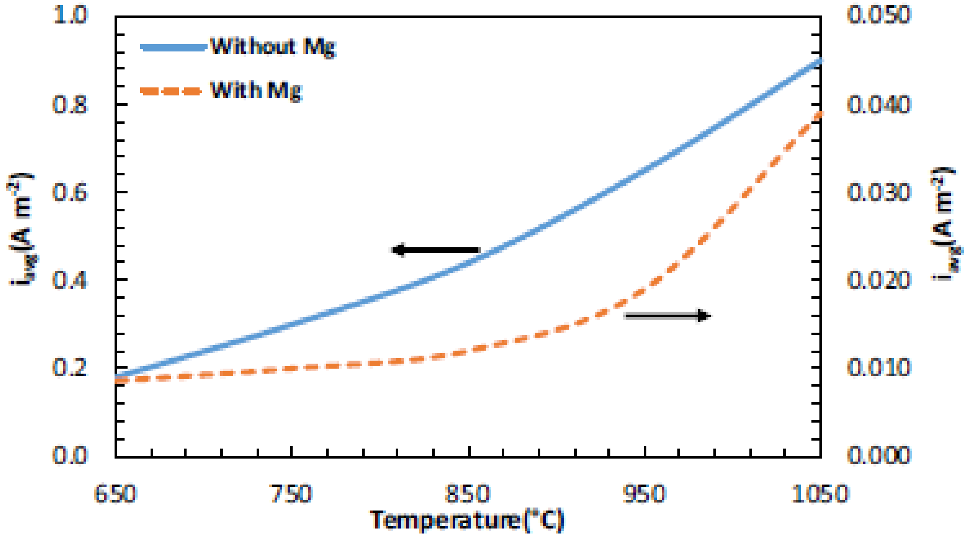
- High heat-transfer rates; low-pressure HTF
- Established approaches for piping, pump, valve, and HX design (including the receiver)
- High energy and exergy efficiency of storage (direct TES)
- Flexible dispatch–solar collection and power generation are decoupled
- Recognized and accepted by industry and financiers

Liquid Pathway Challenges

- Liquid-HTF property challenges
  - Cl salt: corrosivity & corrosion control, heat capacity, thermal conductivity, purification & melting, melting point
  - Sodium: reactivity, corrosivity & corrosion control, cost
- Containment material selection
  - Corrosion resistance, strength at temperature, durability, cost
- Receiver efficiency (90% target)
  - Flux limits, pressure drop, selective coatings, cost
- Operations
  - Startup, shutdown, power ramp rates, heat trace & freeze recovery

Technology Key: Cl-Salt Corrosion Control

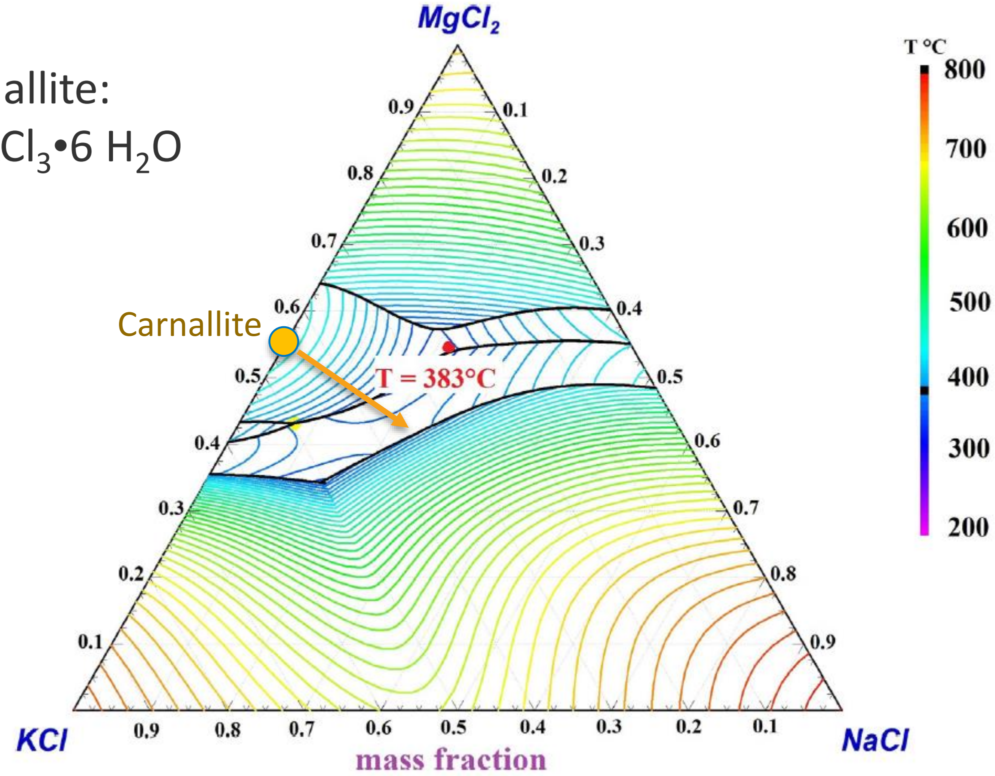
DOE-funded work has shown that control of salt chemistry dramatically reduces corrosion in Cl-salt melts



The effect of temperature on the average corrosion rate (reported via current density, note different scales) for the cases with and without cathodic protection in isothermal conditions for Haynes 230 coupons. (Mehrabadi, et al. 2017)

Cl-Salt Formulation

Carnallite:
$MgKCl_3 \cdot 6\ H_2O$



Phase diagram of Na/K/Mg–Chloride modeled with FactSage
[Mohan et al., Energy Conversion and Management 167 (2018).

Liquid Pathway

Project Overview

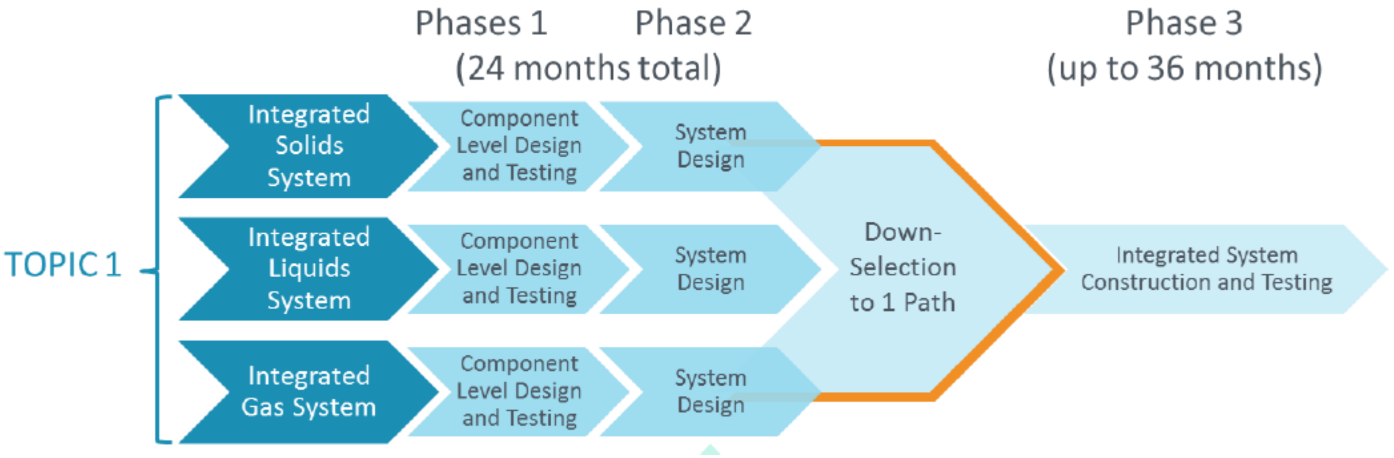
Objectives

3-Phase Project

Phase 1: Resolve critical-component issues, select materials

Phase 2: Downselect components, deliver system design & test proposal

Phase 3: Construct, test, and document system results



Phases 1-2 Objectives

1. Validate and publish the thermo-physical properties of the ternary Mg/Na/K chloride salt
2. Identify suitable insulating refractory materials for use in molten-chloride salts
3. Design and estimate the cost of an internally insulated hot-salt tank to control tank-wall temperature to less than 500°C
4. Design salt pumps, valves, and a primary HX for the 2-MW pilot facility and extrapolate design conditions to full-scale
5. Design and estimate the thermal efficiency of liquid-HTF receivers, operating at 720°C outlet HTF temperature with a target thermal efficiency approaching 90%.

➢ *Down select components and integrated-system design and submit Phase 3 proposal*

Phase 3 Objectives

(Subject to Phase 2 conclusions)

1. **Demonstrate corrosion control** in 300-series stainless steel piping (cold side) and high-Ni alloy piping (hot side) in a flowing chloride-salt loop; validate ability of chemical sensors to monitor HTF chemistry and alert operators to excursions
2. **Fabricate salt tanks** out of 300-series stainless steel with internal insulation to control tank wall temperature to less than 500°C.
3. Build and **test a liquid-HTF receiver**, operating at 720°C outlet HTF temperature with (full-scale) thermal efficiency approaching 90%.
   - Confirm heat transfer rates
   - Demonstrate operations for startup, shutdown, and power ramping
   - Evaluate and define guidelines for receiver fill and drain protocols
4. **Validate pumps**, piping, and fittings in contact with the HTF
5. **Validate primary heat exchanger performance** for heat-transfer rates and ramp rates
6. Perform component and system modeling and **simulate full-scale, SunShot-achieving performance**

End of Project Deliverables

- **Documentation package** in the form of a national laboratory report that captures component and system drawings and specifications of the 2-MW_t test system, operating protocols, and lessons learned,
- **Performance model** of annual generation of a full-scale, 100-MW_e plant based on the tested technology that illustrates the ability to achieve the SunShot goal of 6 ¢/kWh,
- **Video summary** of the project objectives, accomplishments, and impact on the future of CSP, and
- **Transition plan** on how lessons learned in the 2-MW_t test can be implemented in near-term and long-term commercial plants.

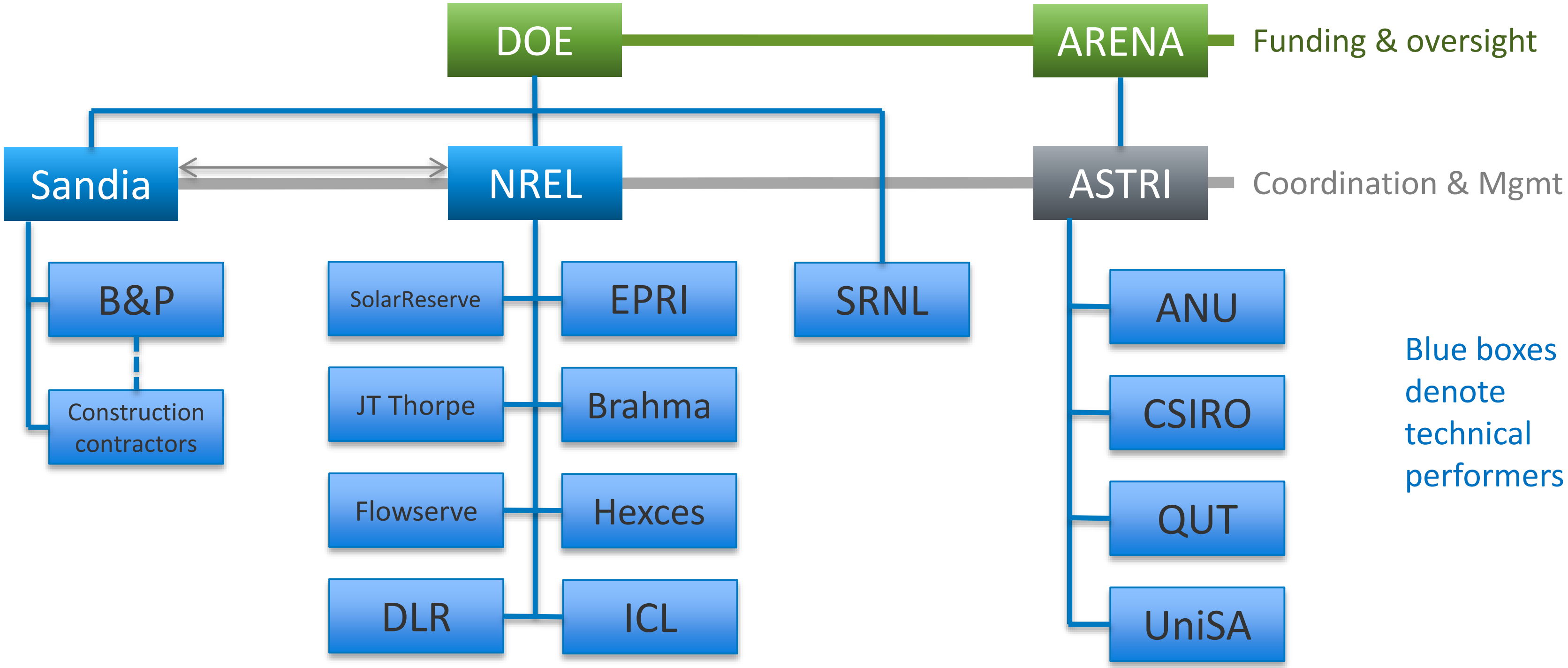
Liquid Pathway

- Project Overview
- Objectives
- **Project Team**

	Team Member	Role(s)
	NREL	Project management and reporting, Salt receiver design, TES design, corrosion & alloy selection, system analysis
	Sandia National Lab	Site Host, Planning and Operations Salt receiver design, project management and on-sun testing (Phase 3)
	Savannah River National Lab (SRNL)	Corrosion mitigation and materials selection
ASTRI Partners	Australian National University (ANU) Commonwealth Science & Industrial Research Org. (CSIRO) Queensland Technical University (QUT) University of South Australia (UniSA)	Sodium HTF and salt properties Liquid-sodium receiver, TES design, materials, salt properties, salt/sodium compatibility and heat exchange, solar field/receiver optimization
	SolarReserve	CSP Developer: CSP deployment and market analysis
	Bridgers & Paxton	Integrator: Facility design, engineering, procurement, and construction
	Brahma Group Inc.	Tanks
	JT Thorpe & Son	Refractories (tank liner)
	Flowserve	Salt pumps and valves
	Hexces	Primary heat exchanger
	ICL Innovation	Salt supply, blending and melting
	EPRI	Technical and Commercial Review panel organizer
	German Aerospace Center (DLR)	Freeze recovery protocols

Administration

Funding/Contractual connections between organizations



DOE

ARENA

Funding & oversight

Sandia

NREL

ASTRI

Coordination & Mgmt

B&P

Construction contractors

SolarReserve

EPRI

JT Thorpe

Brahma

Flowserve

Hexces

DLR

ICL

SRNL

ANU

CSIRO

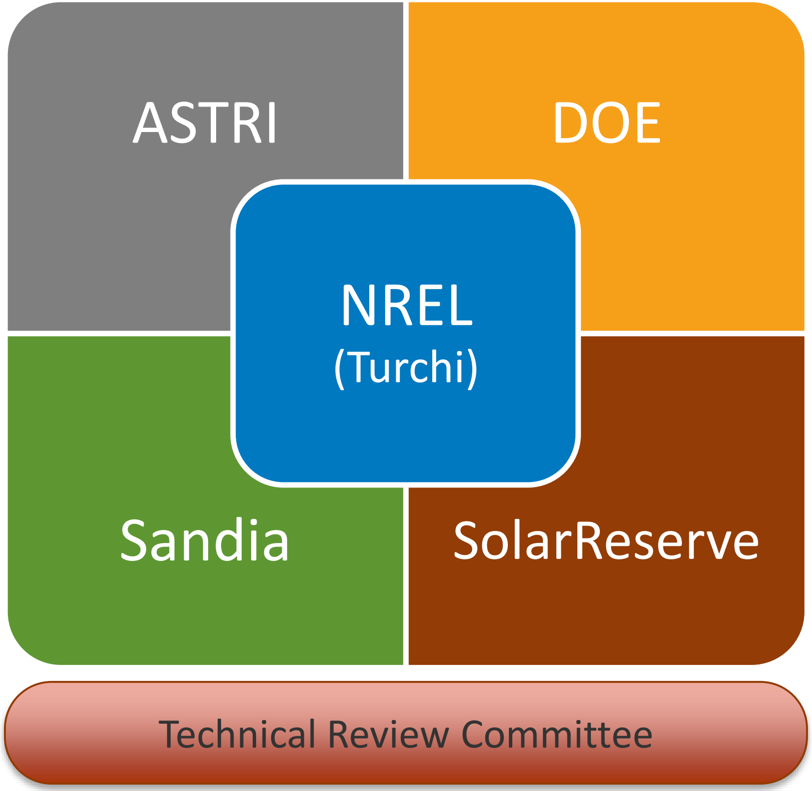
QUT

UniSA

Blue boxes denote technical performers

Leadership

- 5-member leadership team guides project and has authority over down-select decisions
- EPRI-led Technical Review Committee supports Leadership Team



ASTRI

DOE

NREL
(Turchi)

Sandia

SolarReserve

Technical Review Committee

Technology Teams

Phase 1-2

Technology teams plan and undertake tasks related to specific subsystems and components

Salt Chemistry & Sensors	Receiver: Salt	Receiver: Sodium	Salt HTF: TES Tank	Salt HTF: Pumps, Valves, Piping	Sodium HTF: Safety & TES	Primary HX	Systems Analysis
NREL	NREL	ANU	Brahma	Sandia	ANU	Hexces	NREL
SRNL	Solar Reserve	CSIRO	JT Thorpe	Flowserve	QUT		CSIRO
ICL	Sandia		NREL	B&P	UniSA		Solar Reserve
UniSA	CSIRO		UniSA		Sandia		ANU
ANU	DLR		QUT				
QUT							

Test Location

Phase 3 testing planned for Sandia’s National Solar Thermal Test Facility

Liquid Pathway

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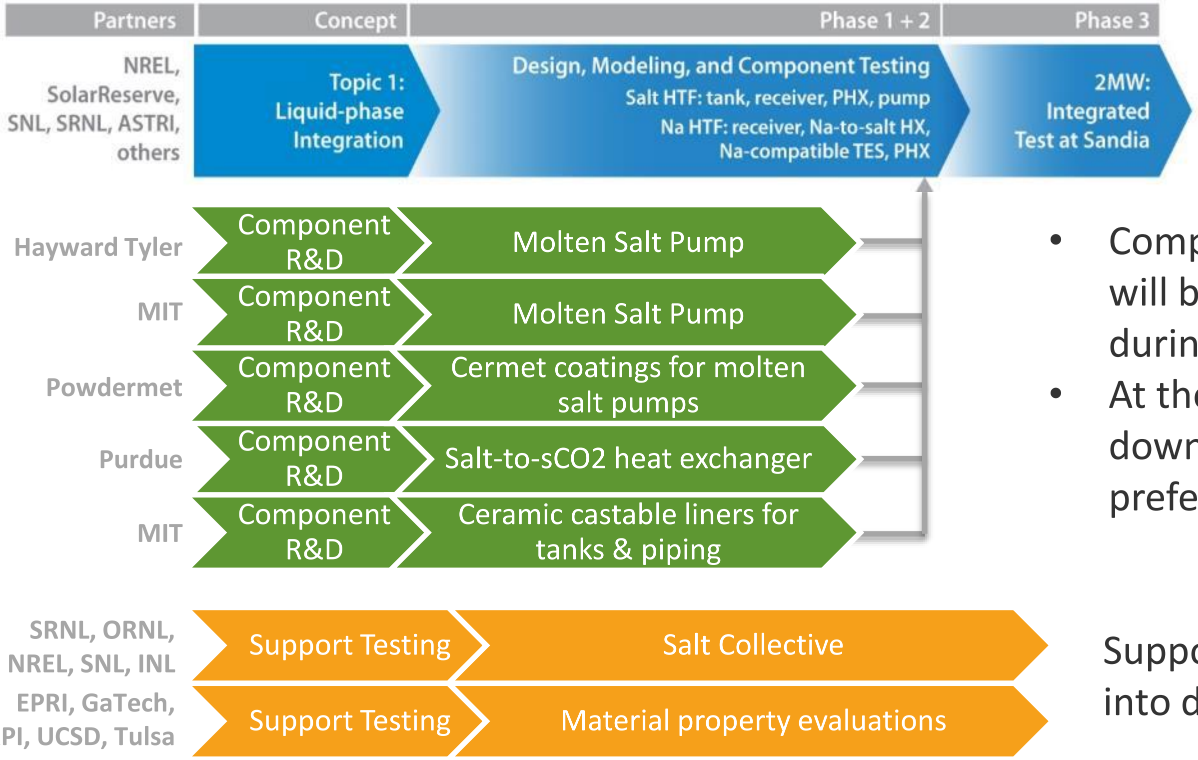
- **Complementary Projects**

Complementary Projects



Partners	Concept	Phase 1 + 2	Phase 3
NREL, SolarReserve, SNL, SRNL, ASTRI, others	Topic 1: Liquid-phase Integration	Design, Modeling, and Component Testing Salt HTF: tank, receiver, PHX, pump Na HTF: receiver, Na-to-salt HX, Na-compatible TES, PHX	2MW: Integrated Test at Sandia
Hayward Tyler	Component R&D	Molten Salt Pump	
MIT	Component R&D	Molten Salt Pump	
Powdermet	Component R&D	Cermet coatings for molten salt pumps	
Purdue	Component R&D	Salt-to-sCO2 heat exchanger	
MIT	Component R&D	Ceramic castable liners for tanks & piping	
SRNL, ORNL, NREL, SNL, INL	Support Testing	Salt Collective	
EPRI, GaTech, RPI, UCSD, Tulsa	Support Testing	Material property evaluations	

- Complementary Topic 2A work will be tracked and reviewed during Phase 1
- At the outset of Phase 2, downselections are made to the preferred system design

Support Testing feeds information into design activities

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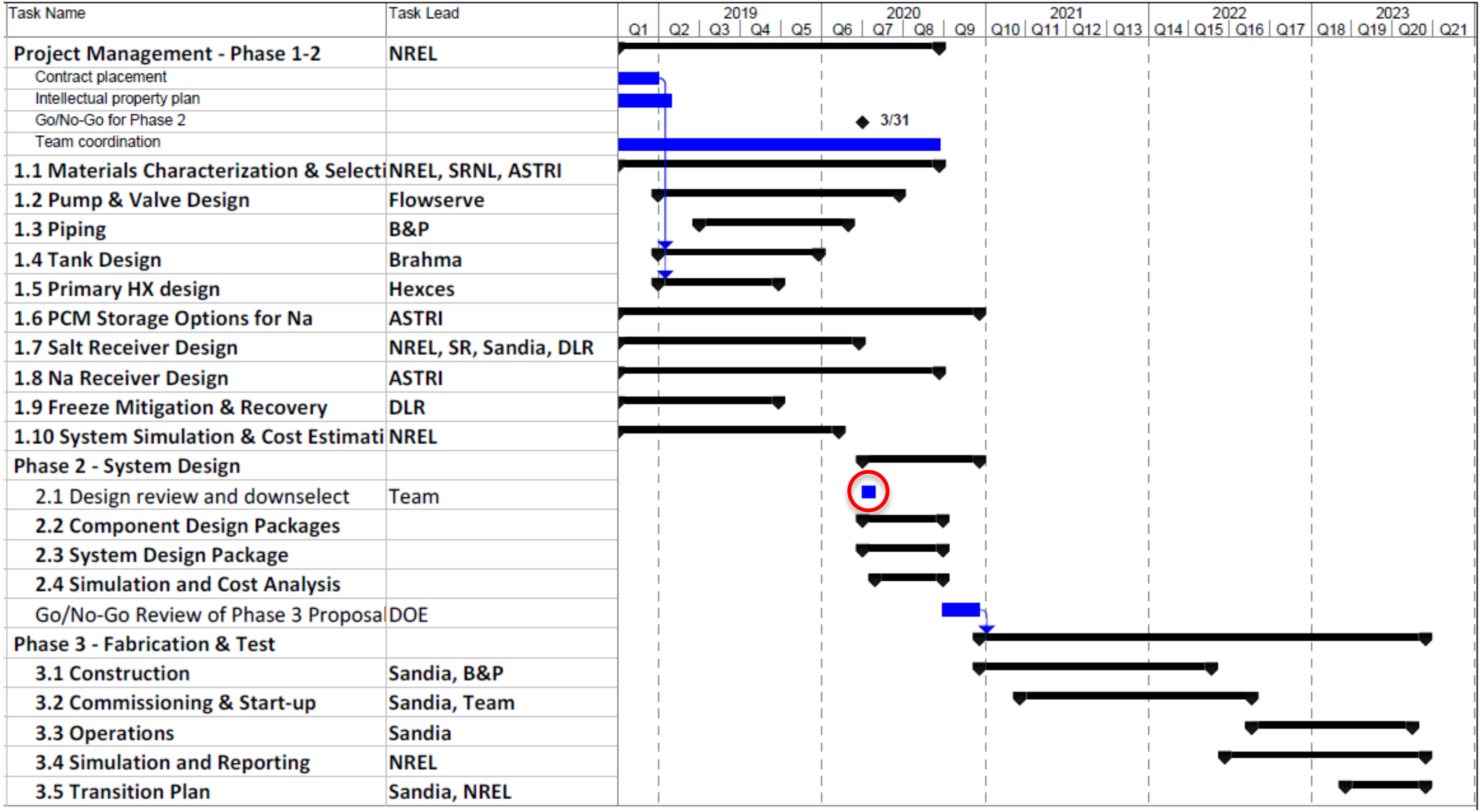
- **Schedule and Decision Points**

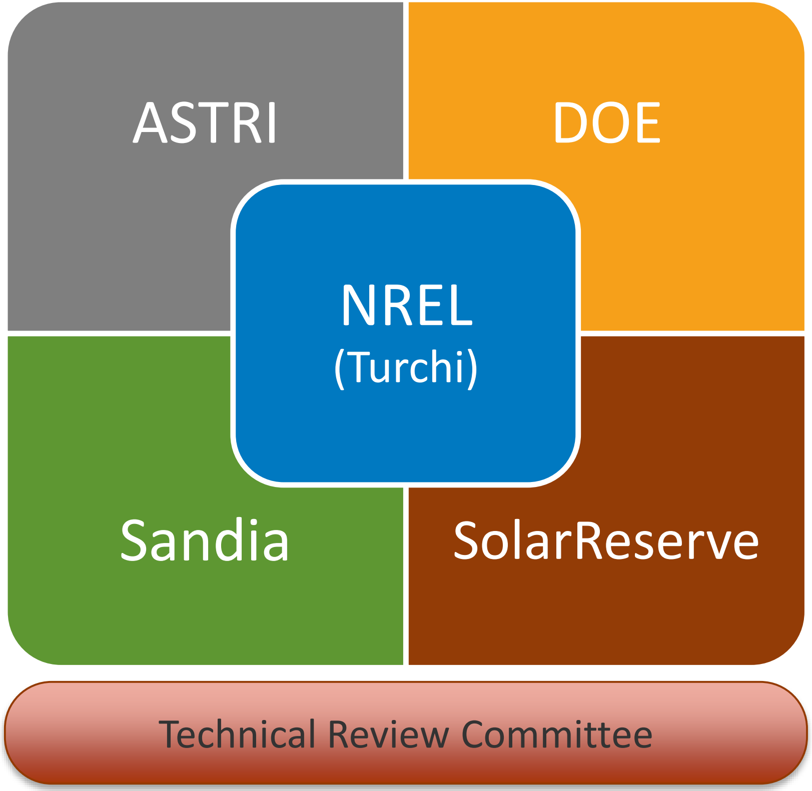
Phase Schedule



Task Name	Task Lead
Project Management - Phase 1-2	**NREL**
Contract placement	
Intellectual property plan	
Go/No-Go for Phase 2	
Team coordination	
1.1 Materials Characterization & Selecti	**NREL, SRNL, ASTRI**
1.2 Pump & Valve Design	**Flowserve**
1.3 Piping	**B&P**
1.4 Tank Design	**Brahma**
1.5 Primary HX design	**Hexces**
1.6 PCM Storage Options for Na	**ASTRI**
1.7 Salt Receiver Design	**NREL, SR, Sandia, DLR**
1.8 Na Receiver Design	**ASTRI**
1.9 Freeze Mitigation & Recovery	**DLR**
1.10 System Simulation & Cost Estimati	**NREL**
Phase 2 - System Design	
2.1 Design review and downselect	Team
2.2 Component Design Packages	
2.3 System Design Package	
2.4 Simulation and Cost Analysis	
Go/No-Go Review of Phase 3 Proposa	DOE
Phase 3 - Fabrication & Test	
3.1 Construction	**Sandia, B&P**
3.2 Commissioning & Start-up	**Sandia, Team**
3.3 Operations	**Sandia**
3.4 Simulation and Reporting	**NREL**
3.5 Transition Plan	**Sandia, NREL**

System and Component Downselection

- Leadership team has authority over downselect decisions
  - At onset of Phase 2, workshops will review options and downselect components
  - Analytic hierarchy process will be used to aid decision making
  - EPRI-led Technical Review Committee will provide guidance on market acceptance of the different system designs


ASTRI

DOE

NREL
(Turchi)

Sandia

SolarReserve

Technical Review Committee

Thank you

www.nrel.gov

Supporting Slides for Q&A Period

Go/No-Go Decision Points

Budget Period 1 Go/No-Go (Q6), Proceed with Phase 3 proposal development. NREL will present all preliminary engineering, design, cost models, sites studies, etc. to DOE and the Technical Review Committee. The component performance and cost estimates will be captured in an annual simulation model for the commercial-scale design to illustrate the path to achieving the SunShot goal of 6 ¢/kWh.

Budget Period 2 Go/No-Go (Q8). Proceed to Phase 3 procurement and construction. NREL will submit all preliminary engineering, design, cost models, sites studies, etc., embodied in the Phase 3 Submittal Package to DOE. The FOA states DOE’s intention to down-select to a single Topic Area 1 award for continuation to Phase 3 activities.

Budget Period 3 Go/No-Go (Q15). Proceed with system startup and testing. NREL will provide the Safe Operating Procedures to the Technical Review Committee and DOE's designee for verification of completion and adequacy.

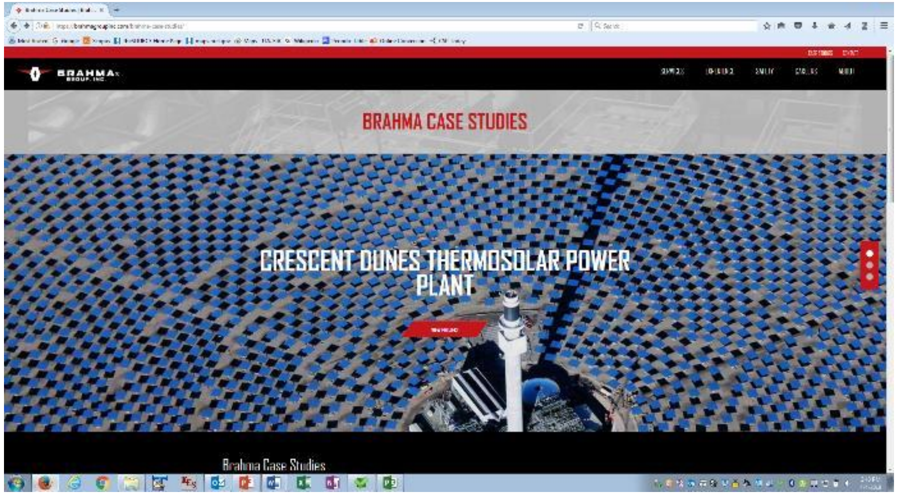
Construction Expertise

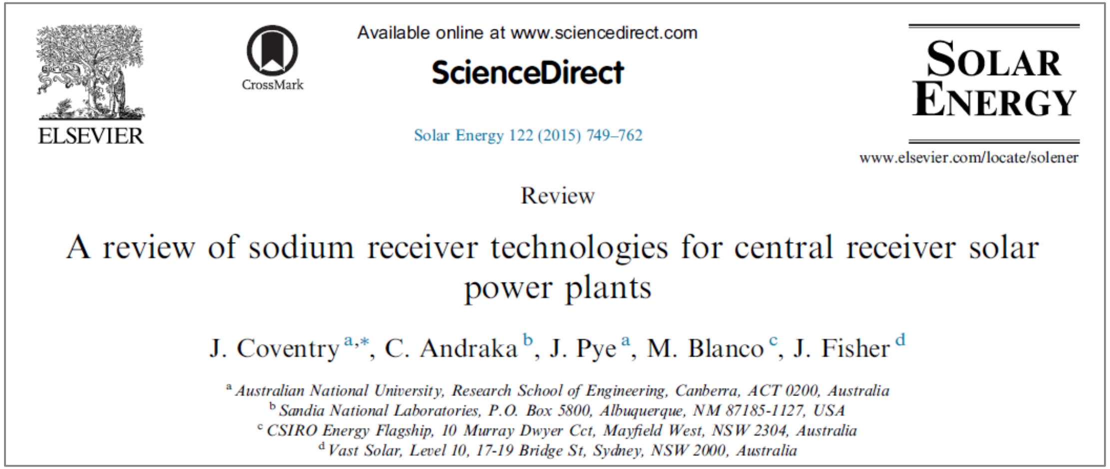

B&P was selected by Areva for their molten-salt system test at Sandia

- Bridgers & Paxton: system integrator for design and build; provide design package, system specifications, controls

- Brahma Group Inc: tank design and construction in this project, but capable EPC contractor

Brahma served as a construction contractor at Crescent Dunes





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Review

A review of sodium receiver technologies for central receiver solar power plants

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[b] *Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185-1127, USA*
[c] *CSIRO Energy Flagship, 10 Murray Dwyer Cct, Mayfield West, NSW 2304, Australia*
[d] *Vast Solar, Level 10, 17-19 Bridge St, Sydney, NSW 2000, Australia*

Fig. 5. 1.2 MW_{th} tubular sodium receiver at Vast Solar's Jemalong Solar Thermal Station.

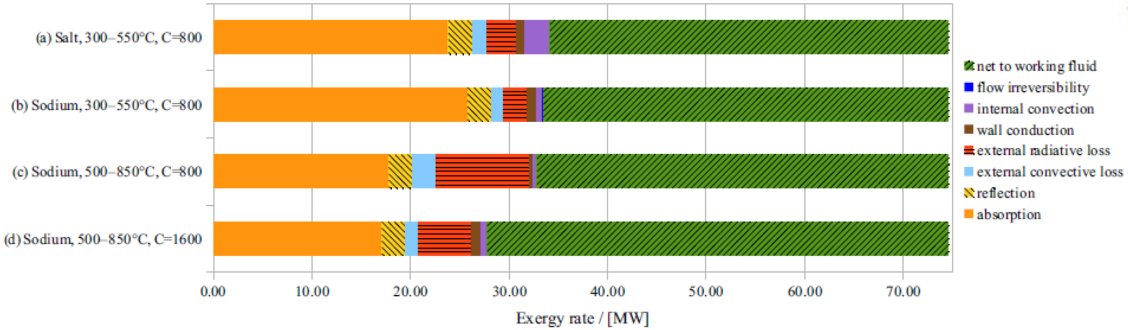
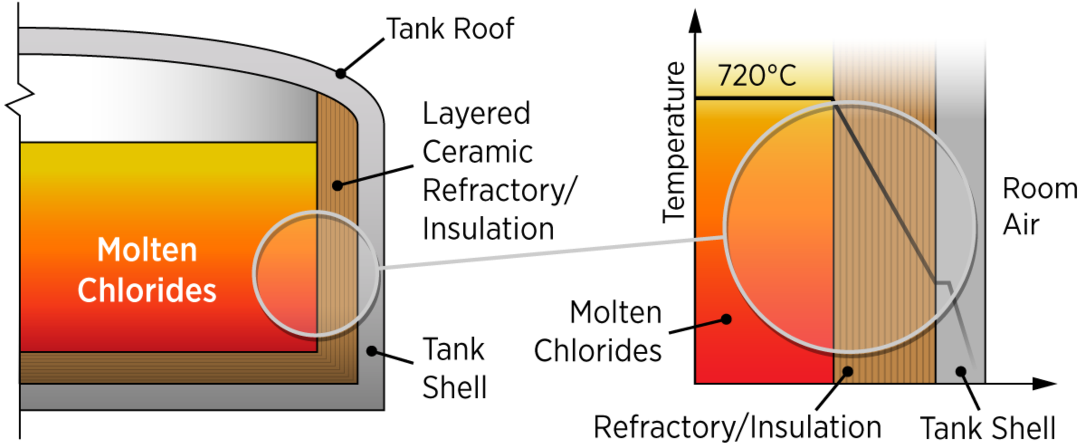


Fig. 9. Exergy balance for (a) salt and (b) sodium receivers with equal solar flux ($C = 800$) and equal 300–550 °C working fluid temperature range. Also includes (c) sodium with 500–850 °C working fluid range and (d) sodium with both 500–850 °C and $C = 1600$ (adapted from Pye et al., 2014).

Internally Insulated Tank



Tank Roof

Layered Ceramic Refractory/ Insulation

Molten Chlorides

Tank Shell

Temperature

720°C

Room Air

Molten Chlorides

Refractory/Insulation

Tank Shell