SunShot
U.S. Department of Energy

CSP Program Summit 2016

BraytonEnergy

HIGH-EFFICIENCY LOW-COST SOLAR RECEIVER FOR USE IN A SUPERCRITICAL CO_2 RECOMPRESSION CYCLE

SRNL

LOW-COST METAL HYDRIDE THERMAL ENERGY STORAGE SYSTEM FOR CSP SYSTEMS

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SOLAR RECEIVER WITH INTEGRATED THERMAL STORAGE FOR A SUPERCRITICAL CO_2 POWER CYCLE

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Shaun Sullivan
Brayton Energy

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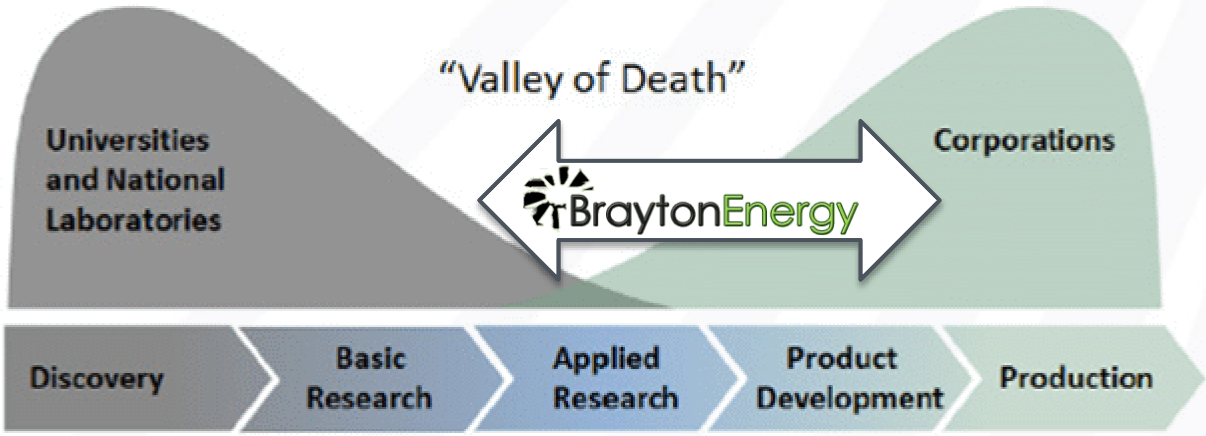
Savannah River National Lab.

HIGH-EFFICIENCY LOW-COST SOLAR RECEIVER FOR USE IN A SUPERCRITICAL CO_2 RECOMPRESSION CYCLE

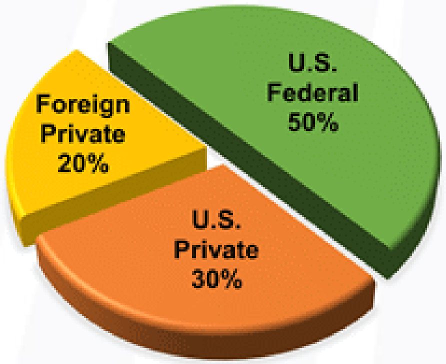
PROJECT NAME	High-Efficiency Low-Cost Solar Receiver for use in a Supercritical CO_2 (sCO_2) Recompression Cycle
FUNDING OPPORTUNITY	DE-FOA-0000595 SunShot Concentrating Solar Power (CSP) R&D
PRINCIPAL INVESTIGATOR	Shaun Sullivan
LEAD ORGANIZATION	Brayton Energy, LLC
PROJECT DURATION	36 months
PROJECT BUDGET	$ 3,150,316

"… to design and build hardware solutions for sustainable, efficient energy systems through applied research, revolutionary innovation, sound engineering, and dedicated partnerships with our clients."

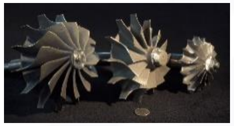
- A private Advanced Energy R&D firm
- Located in Hampton, NH
  - About 50 miles north of Boston



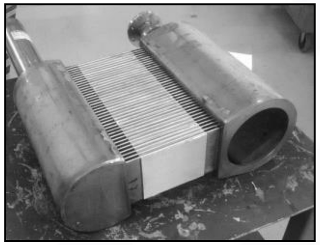
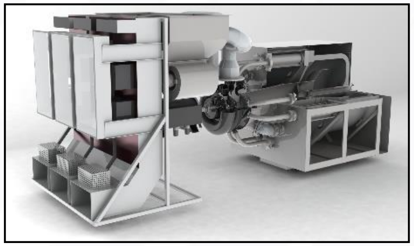
SRI International

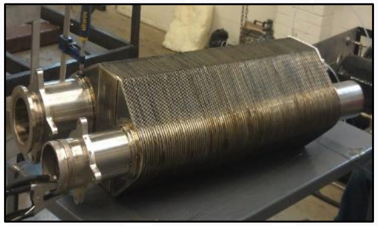


- Turbomachinery solutions
  - Power systems
  - Biomass
  - UAVs
  - Transportation
- CSP components
- High-temperature compact heat exchangers
- Advanced system modeling and analysis
- Energy storage solutions (thermal, CAES)





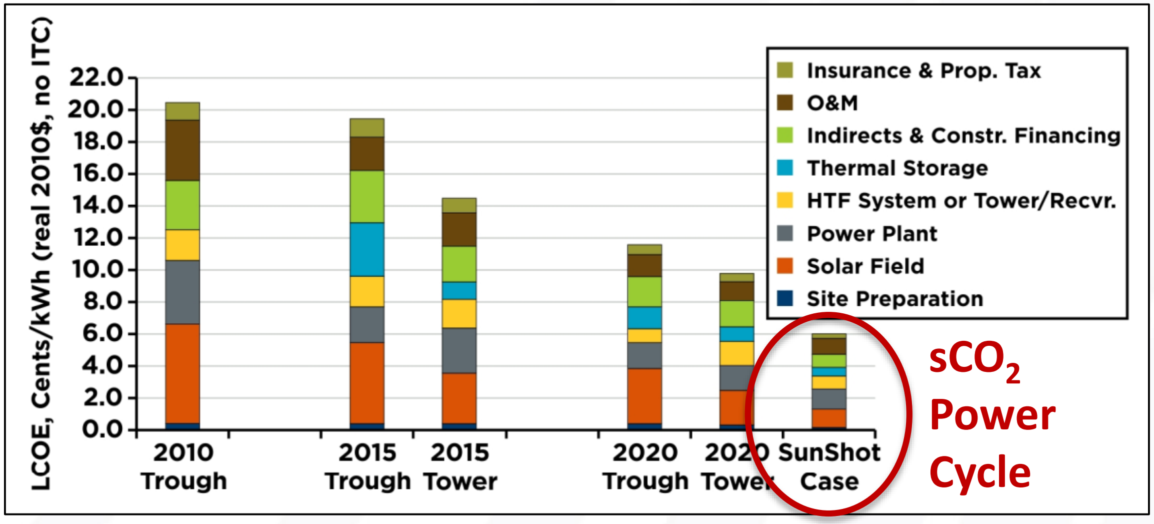







Overview

- In its 2012 SunShot Vision Study, the DoE identified high-efficiency sCO_2 power cycles as an enabling technology critical to achieving the 6¢/kWh LCOE goal



- At that time, there was no existing receiver technology for transferring absorbed solar energy directly into sCO_2
  - Challenging operating conditions (>700 C, 25 MPa)

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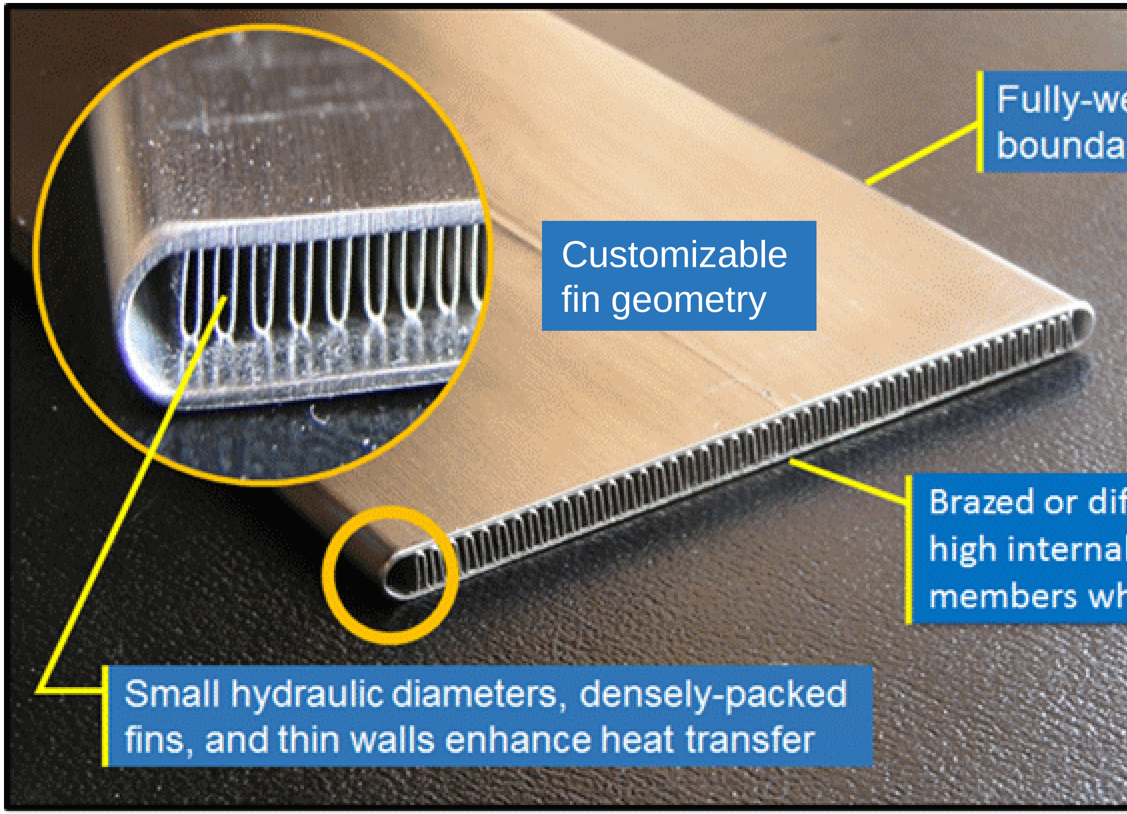
sCO_2 Receiver Technology



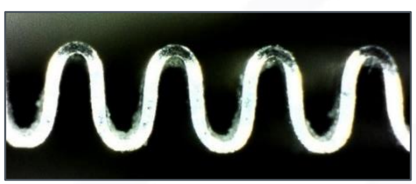
Fully-welded pressure boundary ensures sealing

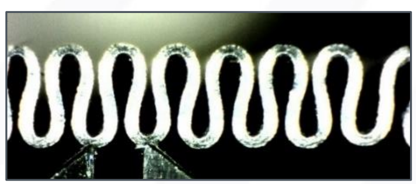
Individually tested for quality control

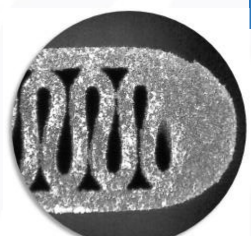
Brazed or diffusion (TLP*) bonded fins react high internal pressure, acting as tension support members while enhancing heat transfer.

* *Transient liquid phase (TLP)*

Thin structures reduce thermal stresses, enabling long fatigue lives







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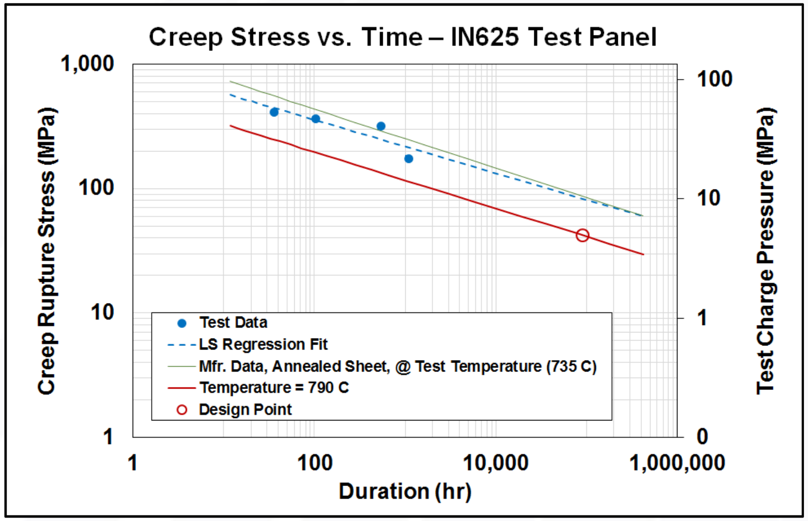
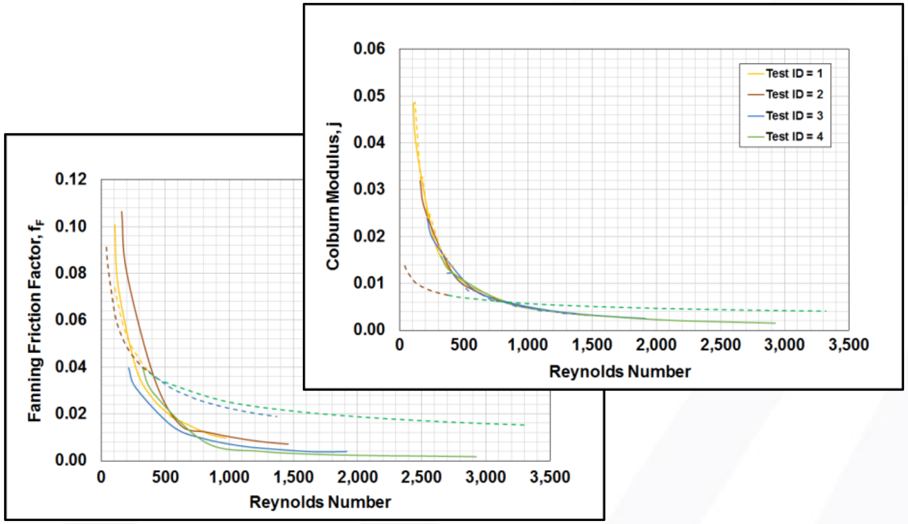
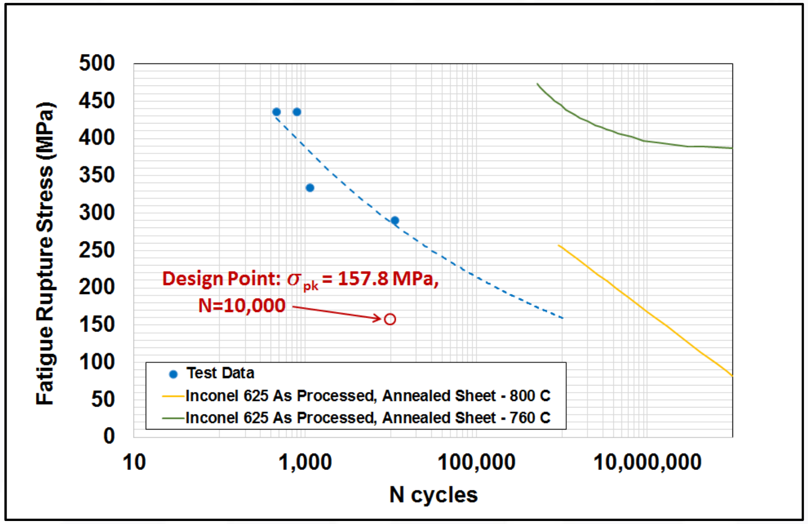
Mechanical Design, Performance, & Validation Testing

- Cold Burst Tests: > 100 MPa
- Creep and Fatigue Testing
  - 800 C, 140 MPa max.
- Colburn Modulus j
- Friction Factor







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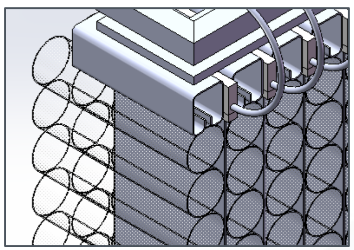
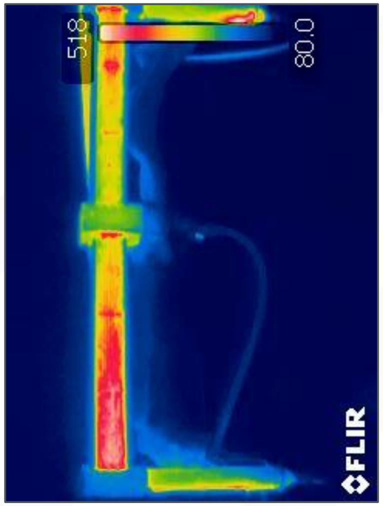
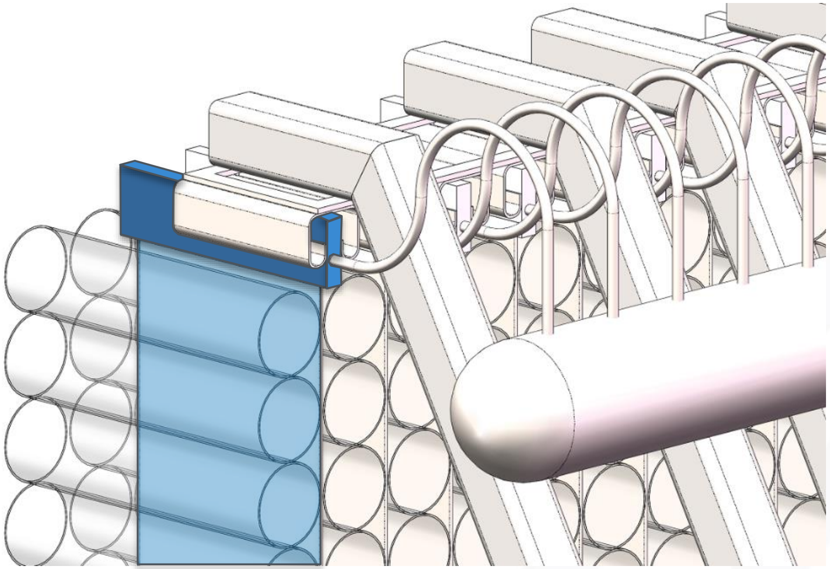
Low-Cost Quartz Tube Window

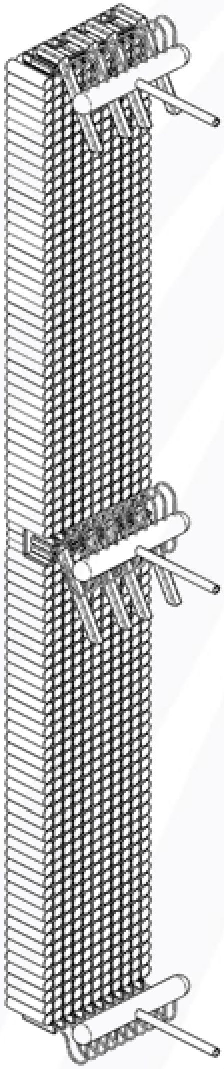
- Low-Cost Commodity Tubes
- Reduces Radiation Losses
  - Transparent to visible light
  - Opaque to infrared radiation
- Impedes Convection Losses
- **5% (6 pt.) performance benefit**

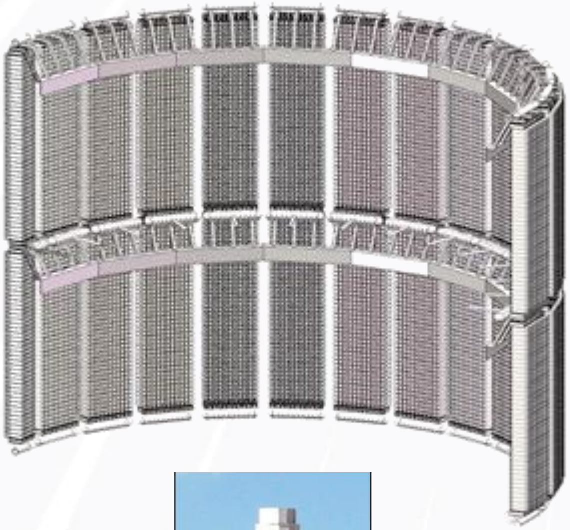




Solar Receiver







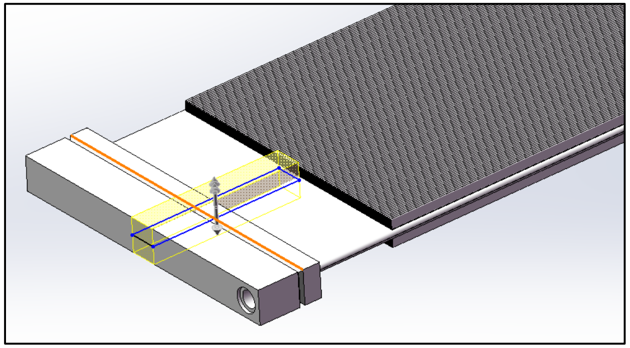
- Cylindrical
  - 4 m Diameter
  - 4 m Height
- 20 MW_{th} Design Heat Rate
  - Designed for sCO_2 Engines currently under development

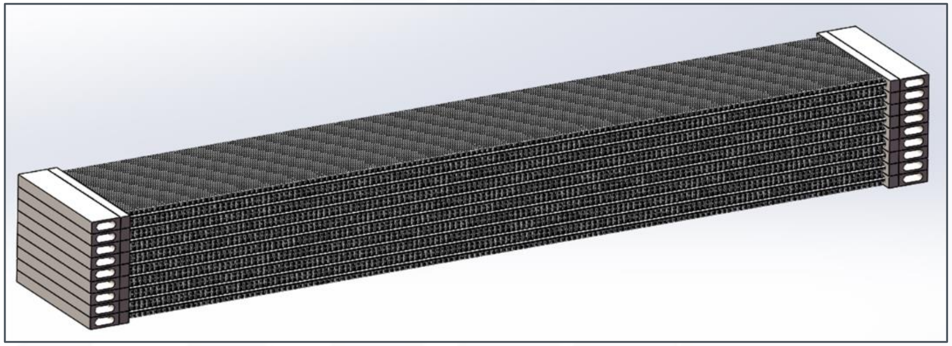
Program Results

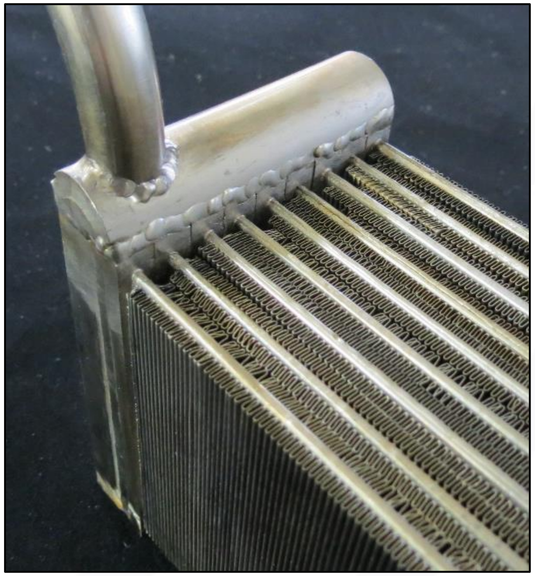
PERFORMANCE METRIC	SUNSHOT TARGET	CAVITY RECEIVER BRAYTON TARGET	CAVITY RECEIVER BRAYTON RESULTS[1]	EXTERNAL RECEIVER BRAYTON TARGET	EXTERNAL RECEIVER BRAYTON RESULTS
Receiver Creep Life	n/a	≥ 90,000 hours	60,000 hours	≥ 90,000 hours	90,000 hours
Receiver Fatigue Life	≥ 10,000 cycles	≥ 10,000 cycles	≥ 100,000 cycles	≥ 10,000 cycles	≥ 100,000 cycles
Receiver Cost	≤ $150/kW$_{th}$	≤ $120/kW$_{th}$	$98/kW$_{th}$	≤ $150/kW$_{th}$	$124/kW$_{th}$
HTF Exit Temeprature	≥ 650 ºC	≥ 750 ºC	750 ºC	715 ºC	715 ºC
Receiver Efficiency $\eta_{thermal}$	n/a	≥ 95%	94.9%	*(partner defined)*	90.62%
Receiver Efficiency $\eta_{annualized}$	≥ 90%	≥ 92%	93.1%	*(partner defined)*	88.36%
System Efficiency Gain	-	-	-	≥ 15.00%	30.30% (10.27 pts.)
Quartz Window Benefit	-	-	-	≥ 2.00%	5.50% (6.10 pts.)

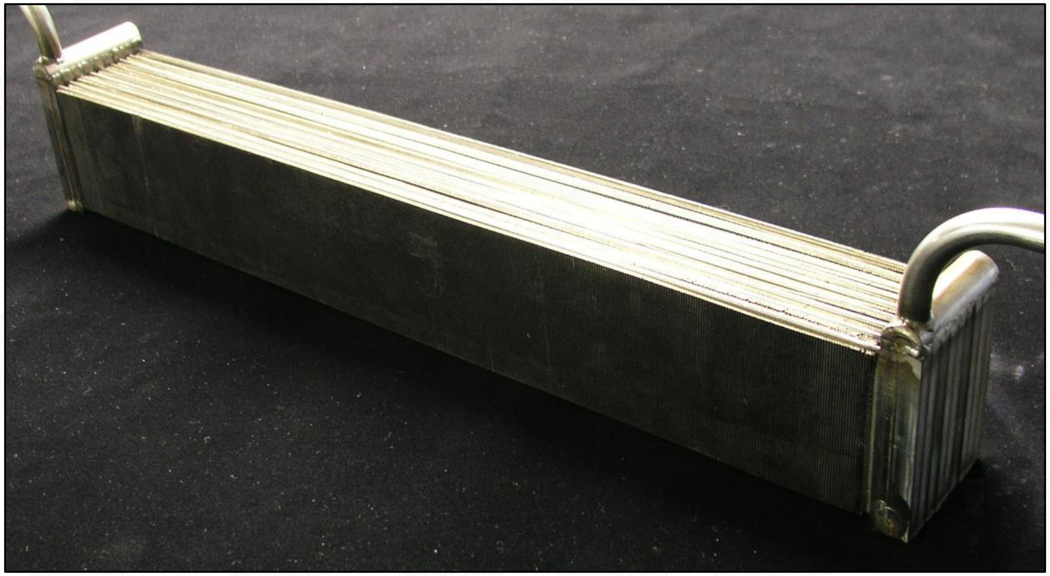
- Meets or exceeds all technical and cost goals of program
  - High Performance, Long Life (creep + fatigue), Low Cost
- 30% (10+ pts.) System Efficiency (receiver + cycle) gain as compared to state-of-the-art CSP Steam Cycle
- Tailored to be compatible with the sCO_2 engine cycles currently under development through the SunShot program

sCO2 Heat Exchangers

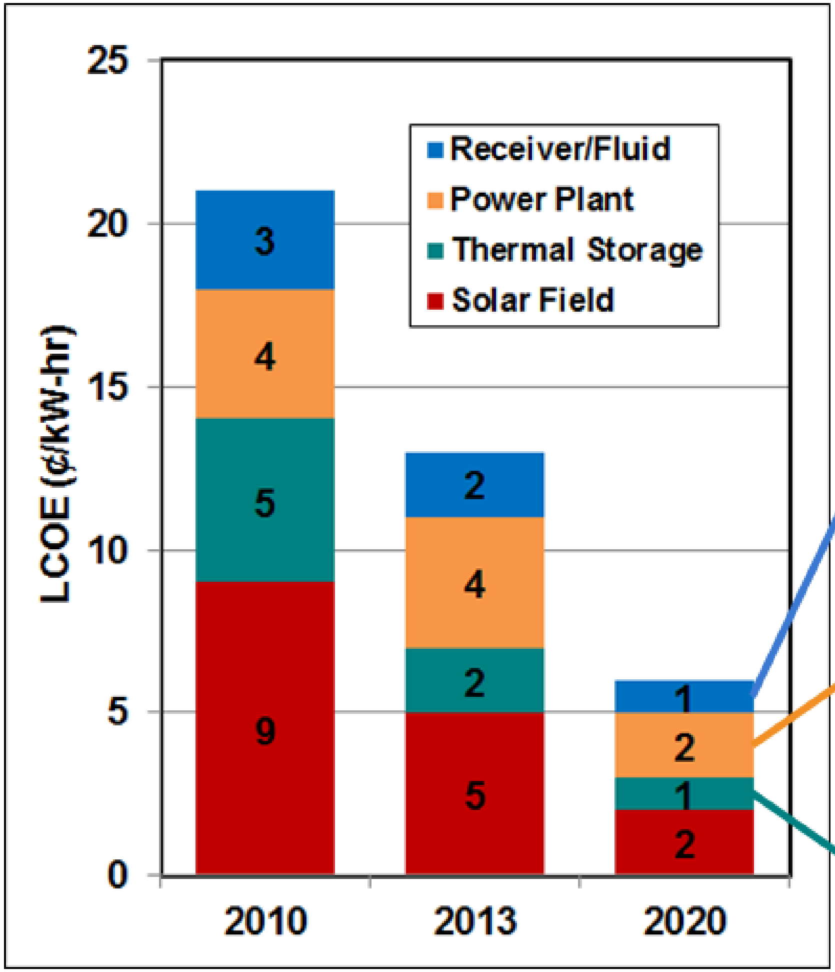








sCO_2 Heat Exchangers



- Industry-leading design:
  - High Effectiveness
  - Compact, less weight
  - Lower-cost

Low-cost modular panel solar receivers for high-efficiency engine configurations

Low-cost compact high-temperature heat exchangers and recuperators for high-efficiency power cycles

Low-cost compact high-temperature working fluid (sCO_2) to molten salt heat exchangers

LOW-COST METAL HYDRIDE THERMAL ENERGY STORAGE SYSTEM FOR CSP SYSTEMS

PROJECT NAME	Low-Cost Metal Hydride Thermal Energy Storage System for CSP Systems
FUNDING OPPORTUNITY	SunShot Lab Proposal Development Process (LPDP), Concentrating Solar Power (CSP) Subprogram
PRINCIPAL INVESTIGATOR	Ragaiy Zidan, Ted Motyka
LEAD ORGANIZATION	Savannah River National Laboratory
PROJECT PARTNERS	Curtin University
PROJECT DURATION	36 months
PROJECT BUDGET	$ 1,873,333

SRNL

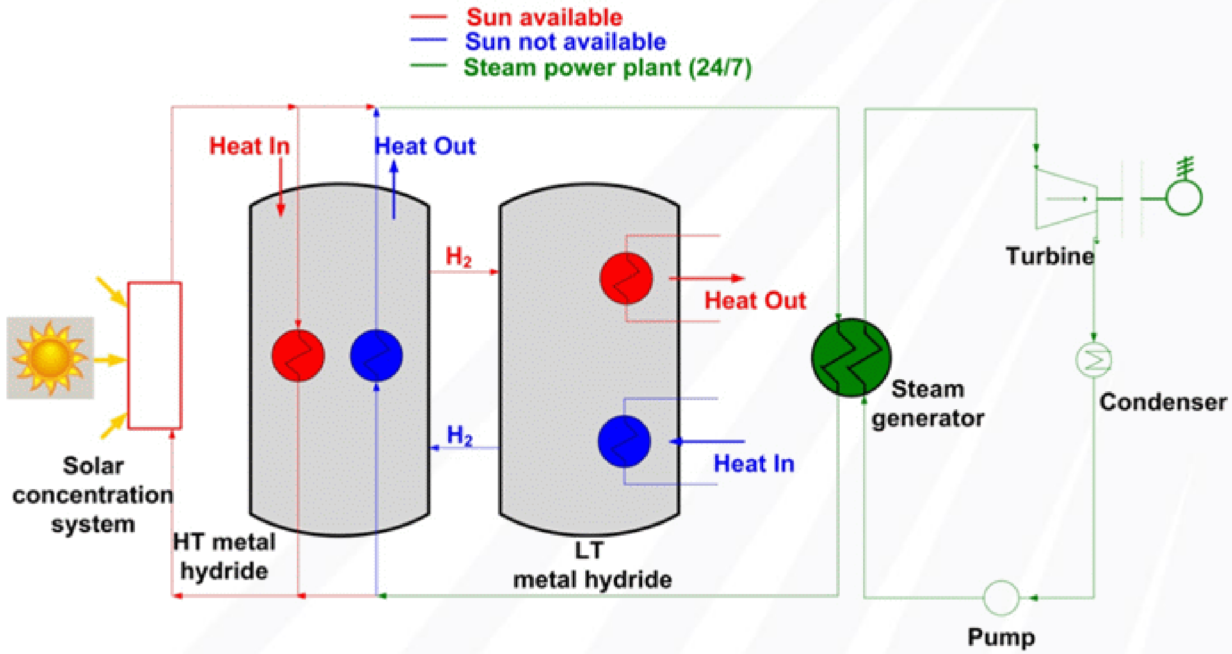
- Located at the Savannah River Site (SRS), Aiken SC
- Newest National Laboratory (11yrs) but with > 60 years of R&D as a Federal Lab
  - ~ 900 Staff
- Multi-Program Laboratory
  - >60% of funding from non-SRS customers
- Core Capabilities
  - Chemical Processing/Separation
  - Materials Science
  - Hydrogen/Tritium
  - Environmental Science

Hydrogen Storage Engineering
CENTER OF EXCELLENCE

Metal Hydride Based Thermal Energy Storage for Concentrating Solar Power Plants

- Objective:
  - Evaluate and demonstrate a metal hydride-based Thermal Energy Storage (TES) system for use with a Concentrating Solar Power (CSP) system.
- Why metal hydrides:
  - Metal hydrides (MH) have a unique ability to deliver low-cost, high capacity and energy efficient TES systems for CSP applications.
  - New higher capacity and lower cost metal hydride materials have recently become available.
  - SRNL's unique approach, based on integration of modeling and hydride material development, has been applied to help solve this challenge.

Metal Hydride CSP Schematic



Energy Storage Density for Several Metal Hydride Materials.

Material	Energy Storage Density
Molten salt	153
Phase change mat'l ($NaNO_3$)	282
CaH_2	4934 kJ/kg
LiH	8397 kJ/kg
TiH_2	1900 – 2842 kJ/kg
$NaMgH_3$	1721 – 2881 kJ/kg
Mg_2FeH_6	2090 kJ/kg
MgH_2	2814 kJ/kg

Metal Hydrides (CaH₂ through MgH₂)

Thermal Energy Storage is based on Reversible Chemical Reactions

SRNL

SunShot CSP TES Targets

- TES system techno-economic targets:
  - charging time of less than 6h,
  - volumetric energy density ≥ $25 kWh_{th}/m^3$,
  - cycle life demonstrates ≤5% degradation in thermal capacity over 1000 exercises with a plausible and valid pathway to less than 1% degradation
  - operating temperature ≥ 650 ºC
  - exergetic efficiency ≥ 95%.
  - cost estimation must demonstrate a viable path to TES cost of $\$15/kWh_{th}$

Metal Hydride TES Project Period 1

- SRNL and partner Curtin University collected and evaluated material property data for over 20 MH candidates.
- Three potential pairs of materials were selected as the most promising materials capable of meeting many of the DOE SunShot targets. These material pairs included:
  - 1) Mg_2FeH_6/$NaMgH_3$- $NaAlH_4$ (SAH),
  - 2) $TiH_{1.72}$ – TiXY and
  - 3) CaH_2 – TiXY(where X & Y are typically Fe, Mn).
- None of the existing pairs of materials could meet all of the DOE targets.

The challenge therefore for Periods 2 and 3 were to either modify or develop a new lower cost, higher temperature materials and systems that could meet or exceed the DOE Targets

C. Corgnale, B. Hardy, T. Motyka, R.Zidan, J. Teprovich, B. Peters "Screening Analysis of Metal Hydride Based Thermal Energy Storage Systems for Concentrating Solar Power Plants," Ren*ewable and Sustainable Energy Reviews,38*,2014,821-833.

D.Sheppard, C.Corgnale, B.Hardy, T.Motyka, R.Zidan, M.Paskevicious, C. Buckley "Hydriding characteristics of NaMgH2F with preliminary technical and cost evaluation of magnesium-based metal hydride materials for concentrating solar power thermal storage" *RSC Advances,*51(4),2014,26552-62

Period 2/3 Material Development, Characterization and Performance Accomplishments

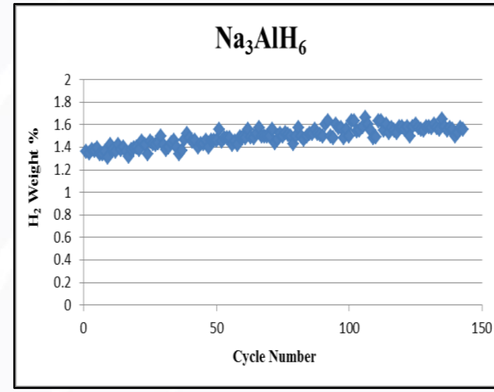
- Na_3AlH_6 with additives was identified as leading low-cost LTMH pairing material over $NaAlH_4$
- A variety of HTMHs were investigated for TES applications. These include MgH_2, Mg_2FeH_6, $NaMgH_3$, TiAl, $NaMgH_2F$.
- Thermal and kinetic properties of the above materials were measured including enthalpy, entropy, bulk density, hydrogen capacity, activation energy, thermal conductivity, etc.

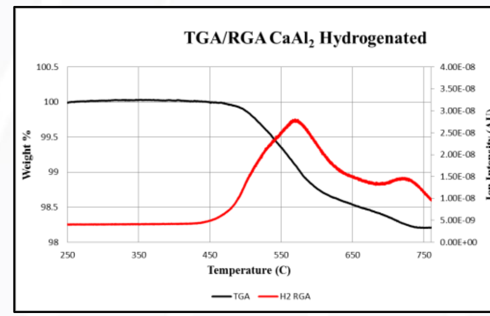
New approach : $MH_x/A_y \rightleftarrows M_xA_y + x/2H_2 \uparrow\downarrow$

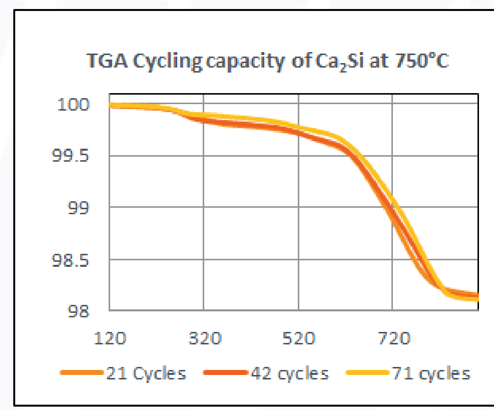
Example $CaH_2/Si \rightleftarrows Ca_2Si + H_2 \uparrow\downarrow$

- A low cost metal hydride capable of reversibly storing ~ 2 wt. % hydrogen at 750 °C was demonstrated for the first time. *This material is currently the most promising high temperature metal hydride material discovered for TES applications at high temperatures (> 650 °C) which is capable of meeting DOE cost targets.*

R. Zidan "Storing High Exergetic Thermal Energy Based on Reversible Alloying and High Enthalpy Hydrides", **Patent Application No. 62/087,939**

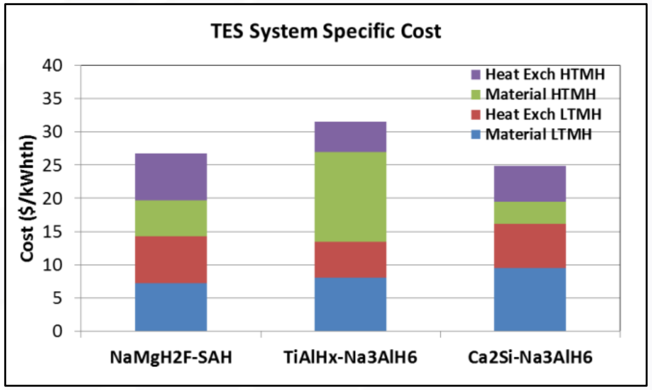


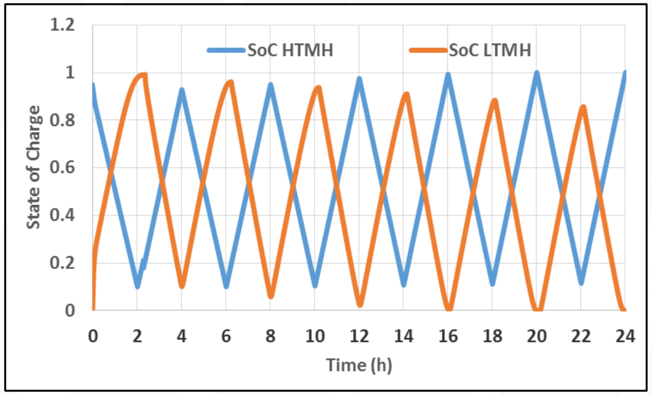


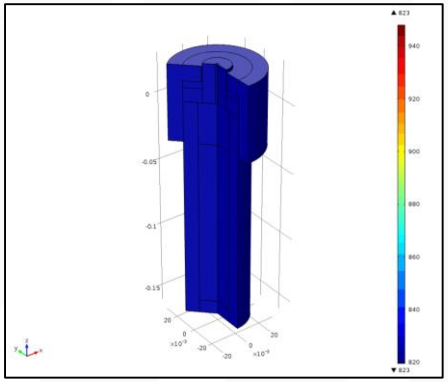


Period 2/3 System Modeling & Techno-Economic Analysis Accomplishments

- A screening analysis tool was developed to evaluate the performance of the MH based TES system against targets. The screening criteria included: system cost, system exergetic efficiency, volumetric efficiency, operating temperature.
- A TES system model was developed to model the coupled MH pairs. The model is a lumped parameters transient model that incorporates mass and energy balance equations along with the kinetics of the two materials.
- A detailed Finite-Element based model was developed to evaluate the detailed behavior of the MH system, highlighting the gradients inside the reactor. The model includes mass, energy and momentum balance as well as the kinetics of the MH materials.



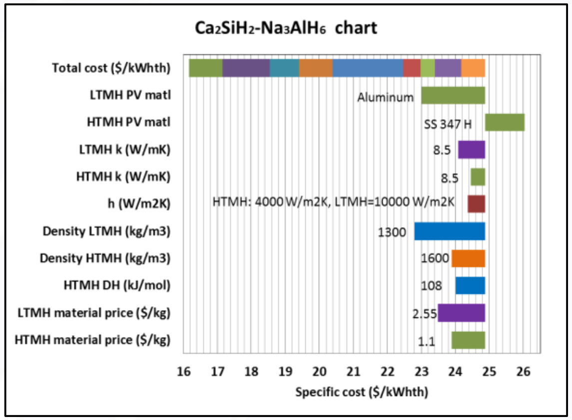


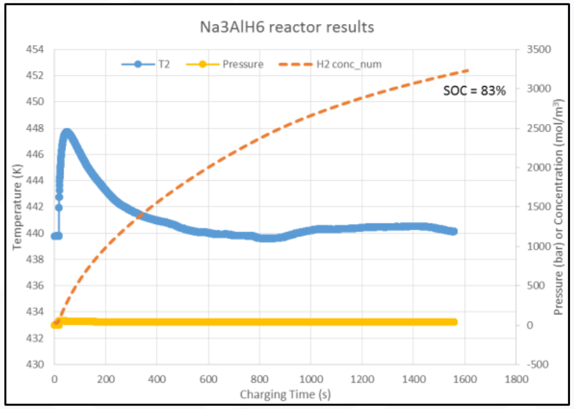


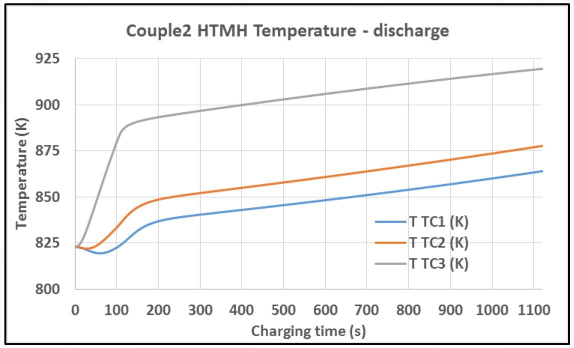
P.Ward, C.Corgnale, J.Teprovich, B.Hardy, T.Motyka, B.Peters, R.Zidan "High performance metal hydride for TES " Journal of *Alloys and Compounds, 645(1)*,2015,S374-S378

Period 2/3 System Modeling & Techno-Economic Analysis Accomplishments cont.

- A statistical cost methodology was developed and applied showing that the newly developed composite CaH_2/Si based material can achieve a cost of ~16 $/kWhth under selected conditions.
- An integrated TES system model was developed in MatLab® and was integrated into a Trnsys® program, to simulate an overall solar plant.
- The detailed MH model was used to simulate the behavior of modified LTMH material (Na_3AlH_6) and to compare the obtained results with experimental data.
- MH pairing was examined and modeled using the previously developed system model both as separate MHs and as paired materials.







Metal Hydride TES Project Overall Accomplishments

	State of the art before SunShot project:	*End of SunShot project:*	*SunShot targets*
TES system (High T matl – Low T matl)	MgH_2-$MmNi_5$	Ca_2Si-Na_3AlH_6	
Cost ($\$/kWh_{th}$)	200	24.9, down to 16.1 based on statistical evaluations as per SunShot	15
Exergetic efficiency (%)	72	93	95
Operating temperature (°C)	Lower than 500	650-750	650
Volumetric density (kWh/m^3)	270	193	25

Components and material were considered, approaching DOE targets

P.Ward, et al "Technical challenges and future direction for high efficiency metal hydride thermal energy storage systems" Applied Physics *A,122:462,2016*

Metal Hydride TES Project Summary

- With DOE support during this project, SRNL has quickly become a world leader in this technology.
- SRNL has applied for a potentially transformational patent and had 6 peer-reviewed papers published in this area.
- With its partner CU, SRNL initiated an International Energy Agency (IEA) working group for MH TES technology and has helped create significant international research interest and excitement in this area.
- SRNL has also received considerable interest from several solar system design and installation firms, including United Sun Systems and Brayton Energy.
- SRNL has received additional funding to continue its MH TES development from Brayton Energy as well as through a special Laboratory Directed Research and Development Initiative.

SOLAR RECEIVER WITH INTEGRATED THERMAL STORAGE FOR A SUPERCRITICAL CO_2 POWER CYCLE

PROJECT NAME	Solar Receiver with Integrated Thermal Storage for a Supercritical Carbon Dioxide Power Cycle
FUNDING OPPORTUNITY	DE-FOA-0001186 CSP: **A**dvanced **P**rojects **O**ffering **L**ow **L**COE **O**pportunities (APOLLO)
PRINCIPAL INVESTIGATOR	Shaun Sullivan
LEAD ORGANIZATION	Brayton Energy, LLC
PROJECT PARTNERS	Savannah River National Laboratory Greenway Energy, Inc.
PROJECT DURATION	39 months
PROJECT BUDGET	$ 3,295,953

GreenWayEnergy®
POWERFUL EXPERTS

- Founded in 2006
- Clean Energy & Energy Storage
  - Fuel Cell System Development & Deployment
  - H_2 Storage Material Electrochemical Scale-up
  - Fuel Reforming and Purification
  - Battery Research
  - Betavoltaics & Tritium Research
  - Bioelectrochemical Sensors
- Electrochemical Engineering Research Focus

Roadmap to Low-Cost CSP

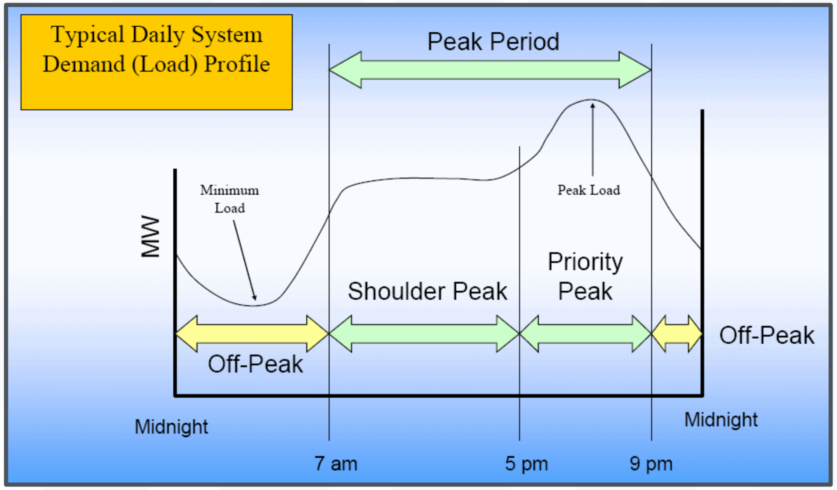
- Couple the design of critical technologies:

Low-Cost High-Efficiency Solar Receiver	⟷	High-Temperature Energy-Dense TES	⟷	High-Efficiency Recompression sCO_2-Brayton Cycle Engine

- Adopt demonstrated enabling technologies:

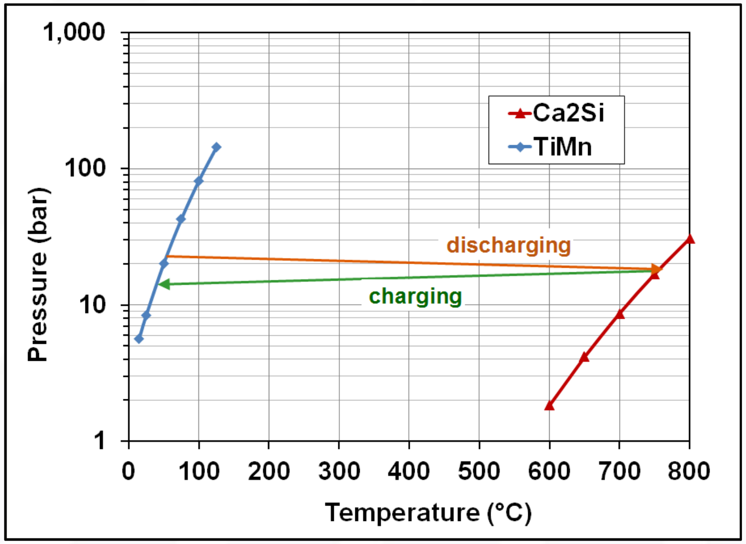
Commercial Wind Turbine Tower Technology	Low-Cost High-Performance sCO_2 Heat Exchangers	Economic Modular Heliostat Designs

- Employ a High-Impact Nominal Operating Profile
  - 10 MW_e for 8 hrs. during day
  - 10 MW_e for 4 hrs. at night



Metal Hydride

- Characteristics for this Application:
  - Approximately isothermal (HTMH: 715 to 745 C) operation
  - Moderately High Pressure (1.5-3.0 MPa)
- HTMH Volume:
  - Interacts directly with receiver and engine cycle
  - Approx. 160 m^3 of material
    - A cylinder with Diameter = 5.8 m, Height = 5.8 m
  - **UP-TOWER MOUNTING OF TES SYSTEM POSSIBLE**



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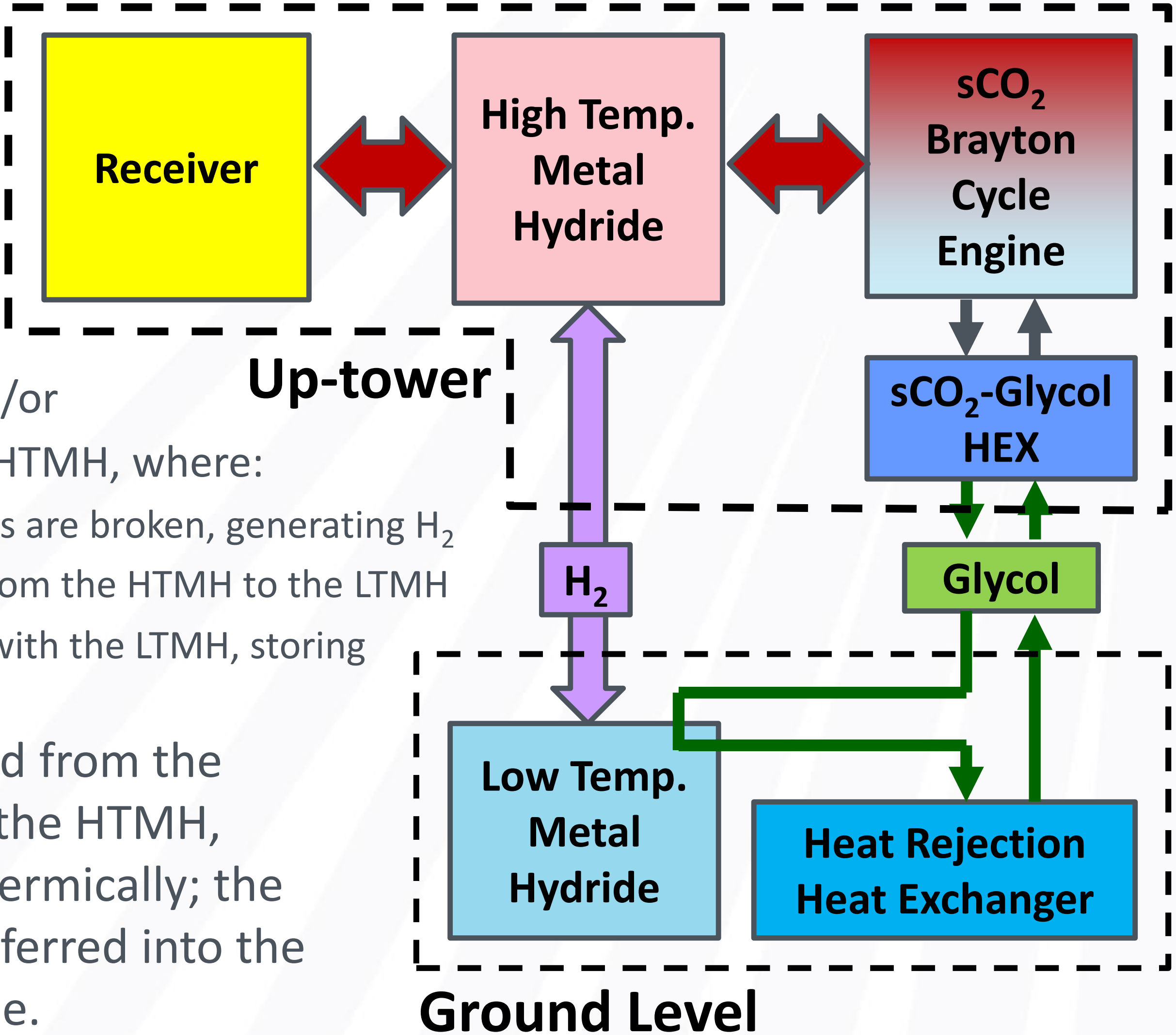
Operational Overview

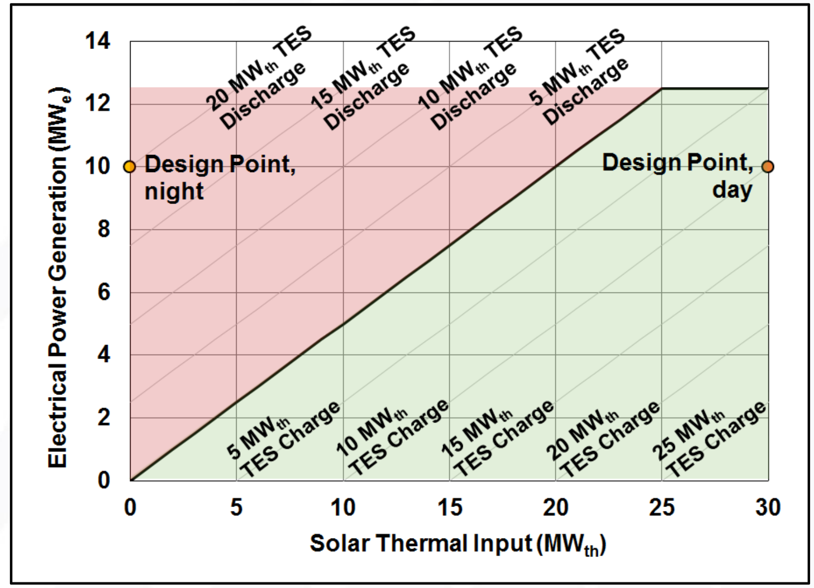
- During the day, concentrated solar energy is absorbed by receiver and is:
  - Transferred to the sCO_2 to run the engine directly, and/or
  - Conveyed into the HTMH, where:
    1. Chemical bonds are broken, generating H_2
    2. The H_2 flows from the HTMH to the LTMH
    3. The H_2 bonds with the LTMH, storing the energy
- At night, H_2 is released from the LTMH and flows into the HTMH, where it bonds exothermically; the released heat is transferred into the sCO_2 to run the engine.



Program Summary

BraytonEnergy

- Solar Receiver
- Thermal Transport
- sCO_2-to-Glycol Heat Exchanger
- Hydrogen Transport
- High-Temperature Recuperator
- Low-Temperature Recuperator



SRNL

GreenWayEnergy POWERFUL EXPERTS

- High Temperature Metal Hydride
- Low Temperature Metal Hydride

sCO_2 Turbine Inlet Temp.	715 C
sCO_2 Cycle Rated Power	10 MW_e
TES Energetic Efficency	99%
TES Exergetic Efficency	95%
TES Storage Capacity	80 MWh_{th}
TES Discharge Duration	4 hours
Operating Life	90,000 hrs
Cycle Life	10k cycles
LCOE	\$0.06/kW_{th}

Thank You!

Integrated Modular CSP Incorporating Up-Tower Receiver, Engine, and Thermal Energy Storage