



Sandia
National
Laboratories

SAND2019-14225C

U.S. DOE Gen3 and SunShot 2030 Concentrating Solar Power R&D: *In search of \$0.05/kWh, autonomy and seasonal storage*



SASEC2019

6TH SOUTH AFRICAN SOLAR ENERGY CONFERENCE

25 – 27 November | East London, South Africa

Paul Gauche, Manager CSP Program & NSTTF,
Sandia National Laboratories



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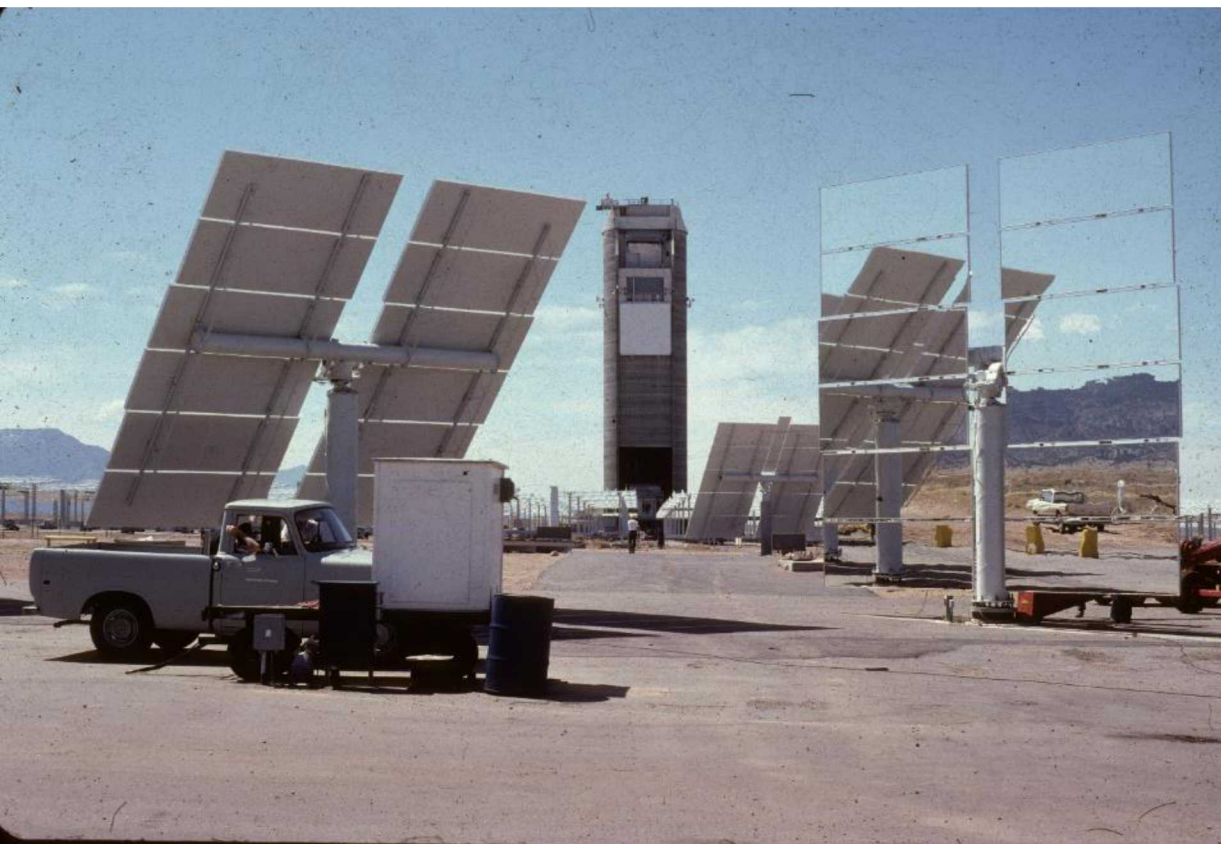
SAND2019-XXX

- **About CSP at Sandia National Laboratories**
- **Current and anticipated DOE R&D**
 - Overview by the U.S. Department of Energy
- **Development of sCO₂ power cycles**
 - Commercially-relevant sCO₂ pilot systems
 - Ongoing sCO₂ research and future plans
- **Gen3 projects – The Big 3**
- **Optics and autonomy**
- **Fuels and long duration storage**



About CSP at Sandia Labs

Progress Toward Commercial Deployment of sCO₂ Brayton Power Cycles



Brief History of CSP (Sandia View)



Solar One and
Solar Two
10 MW_e
Daggett, CA
1980's - 1990's



Stirling Energy Systems
1.5 MW_e, AZ, 2010



Ivanpah, steam, 377
MW_e, CA,
2014



1970's

1980's -
1990's

2000's

SunShot &
Gen3
2011 -



National Solar Thermal Test Facility
6 MW_t, Albuquerque, NM, Open 1978



SEGS, 1980's
9 trough plants
354 MW_e, CA



Gemasolar, molten salt, 19
MW_e, Spain, 2011



Crescent Dunes, molten salt,
110 MW_e, NV, 2015

Glint/Glare, Thermal Emissions, Avian Hazards



Glint and glare may cause unwanted visual impacts

- Pilots, air-traffic controllers, motorists
- Retinal burn, temporary after-image, veiling, distraction



Glare from Ivanpah CSP Plant

Infrared emissions

- Heated objects can emit infrared radiation that may interfere with infrared sensors

Avian Flux Hazards

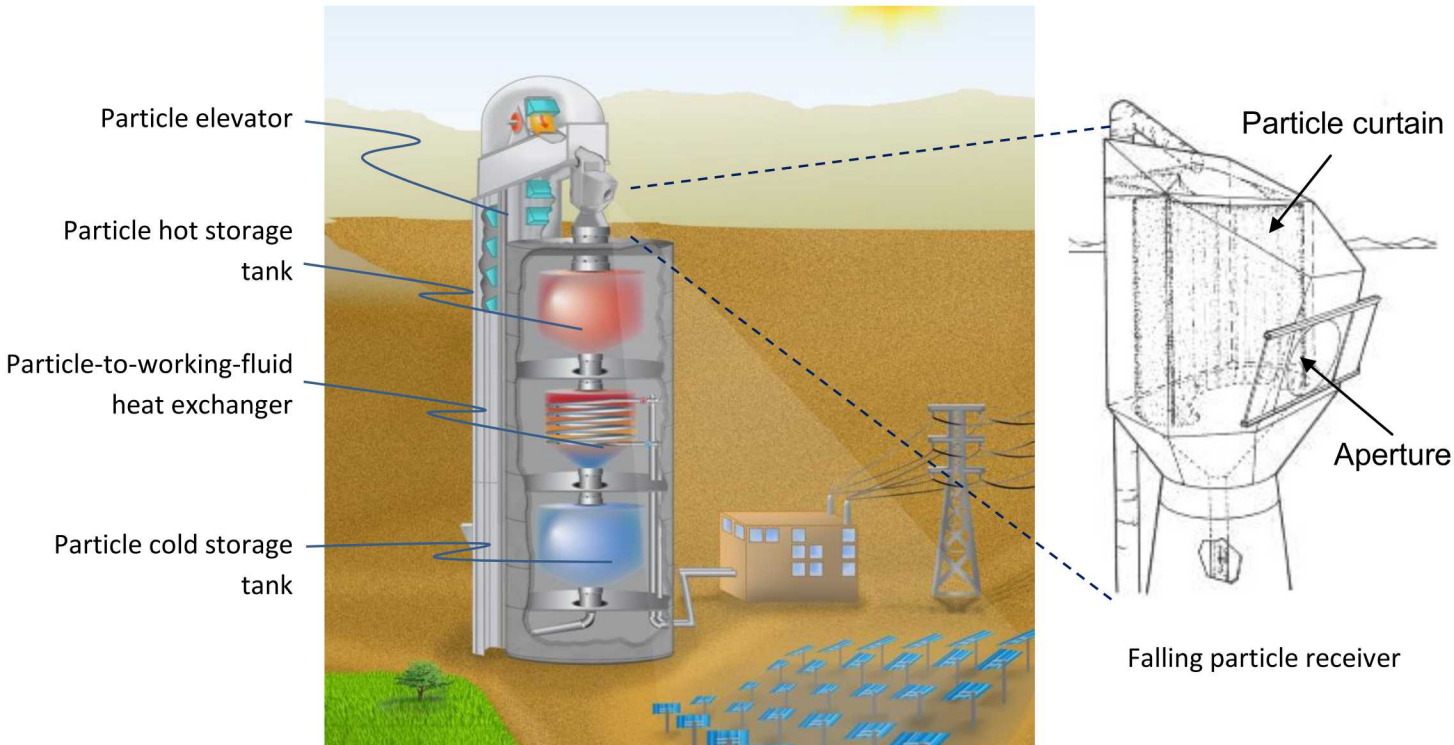
- Concentrated sunlight can singe birds



Thermal emission from receiver at ~600 C

MacGillivray Warbler with “Grade 3” solar flux injury found at Ivanpah CSP Plant (Kagan et al., 2014);

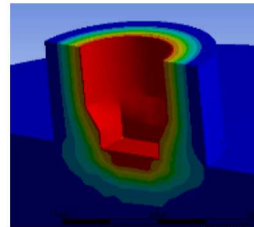
High Temperature Falling Particle Receiver (DOE SunShot Award FY13 – FY16)



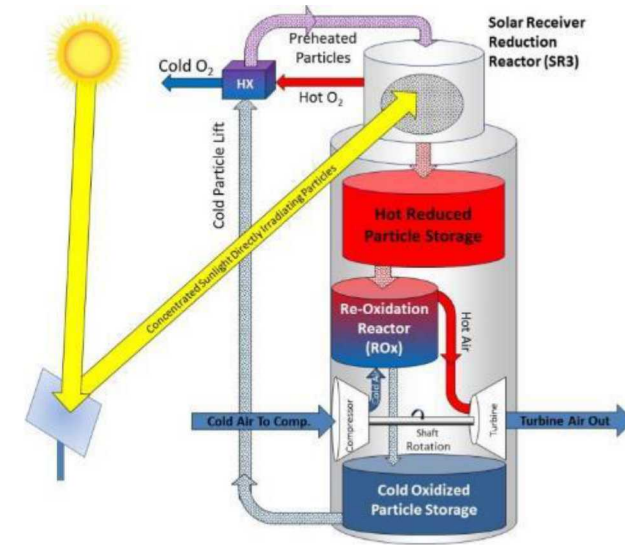
Sandia Research in Thermal Energy Storage



Corrosion studies in molten salt up to 700 C in "salt pots"



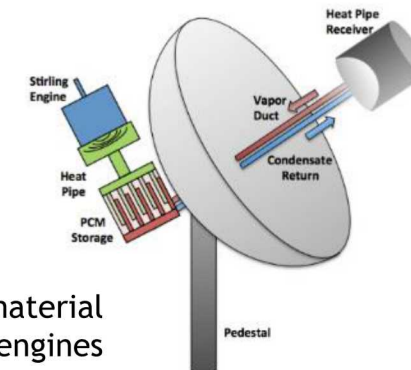
Ceramic particle storage and heating with falling particle receiver



Thermochemical particle storage with reduction/oxidation of perovskites



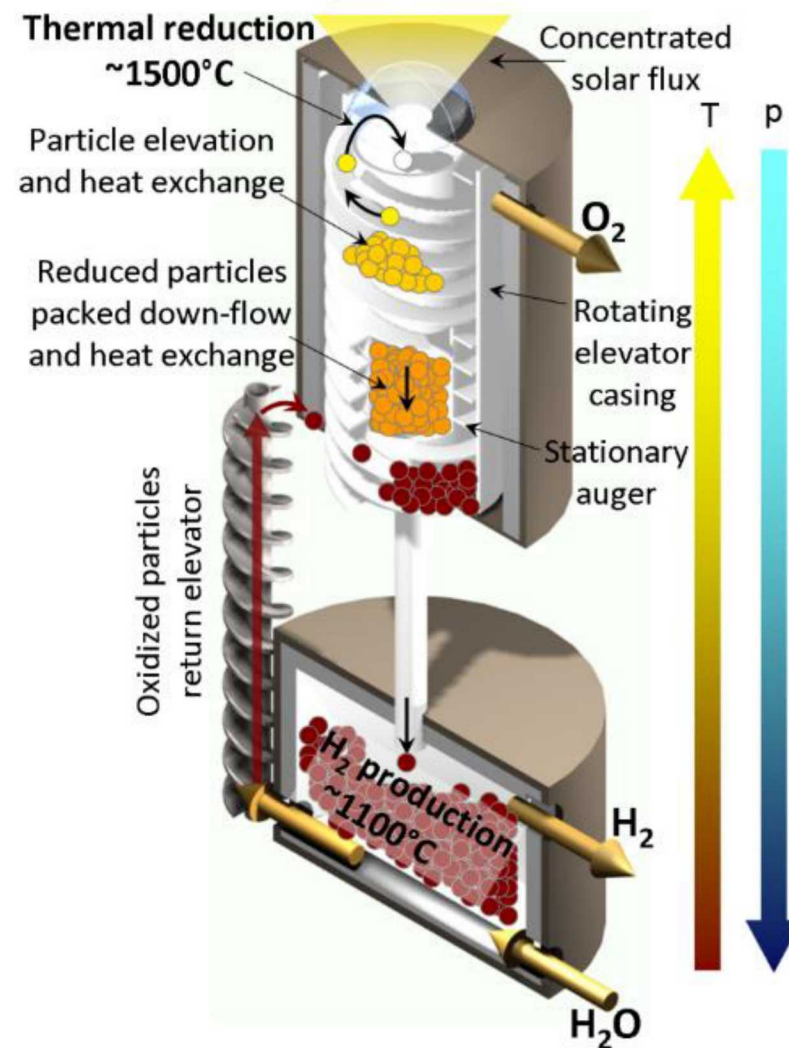
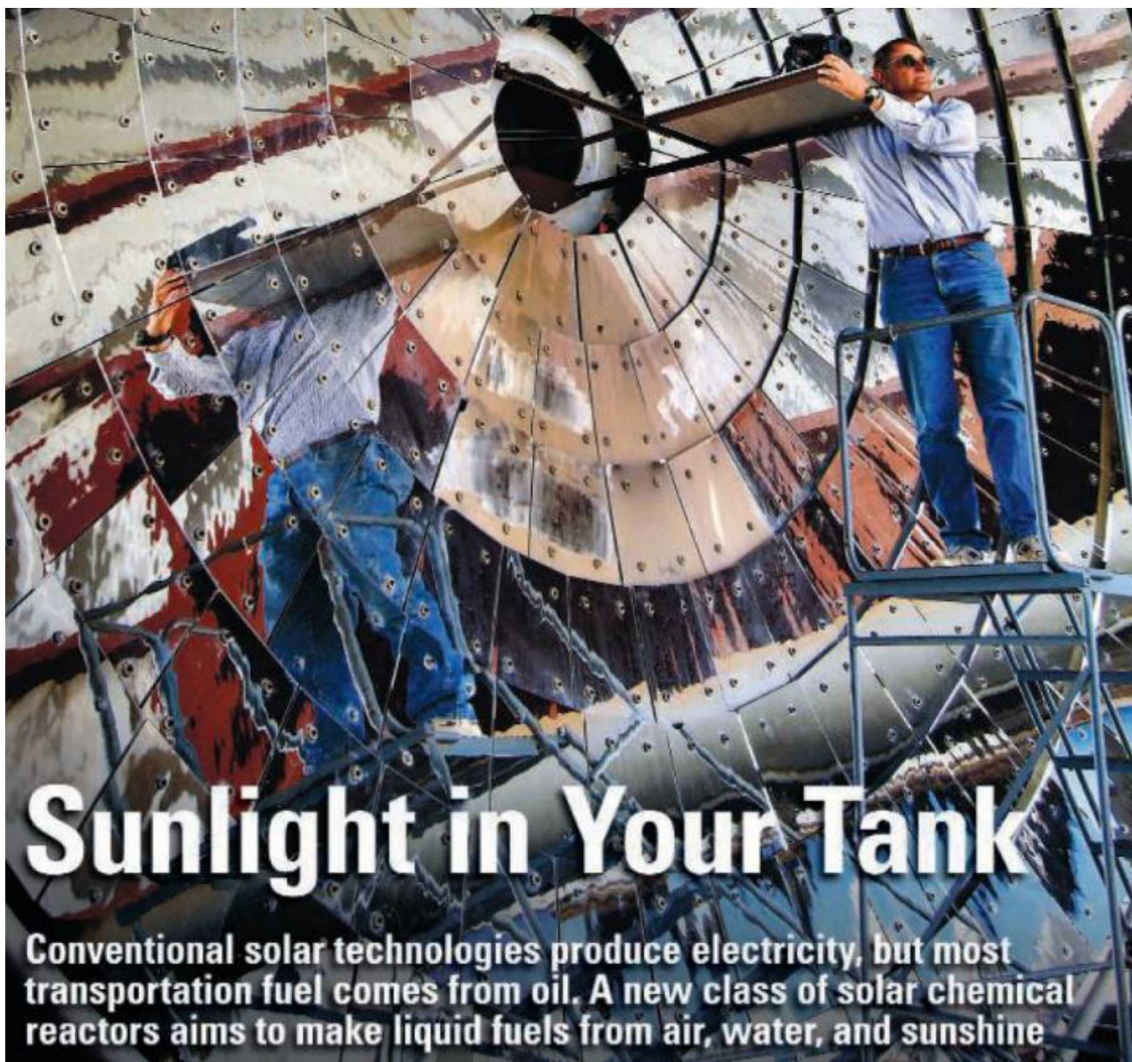
Component testing with molten-salt test loop



Latent phase-change material storage in dish engines

Solar Fuels

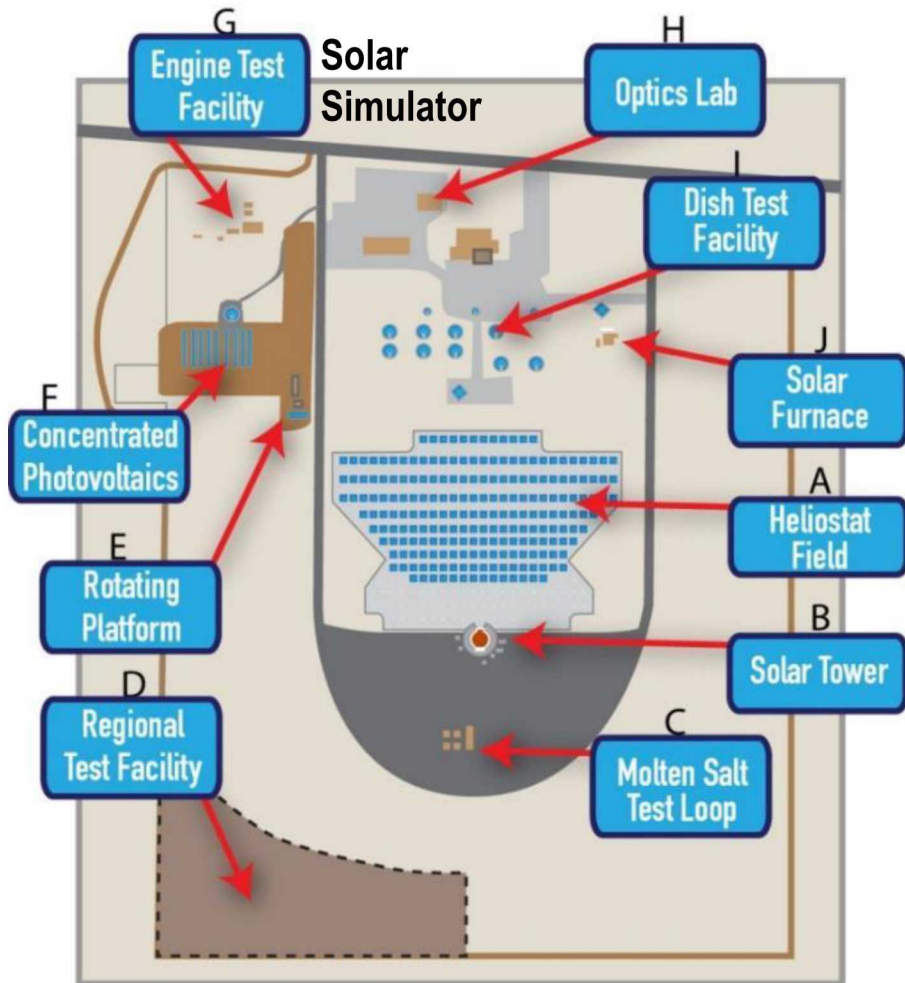
Creating hydrogen and liquid fuels with concentrated sunlight



Science (2009)

Ermanoski et al.

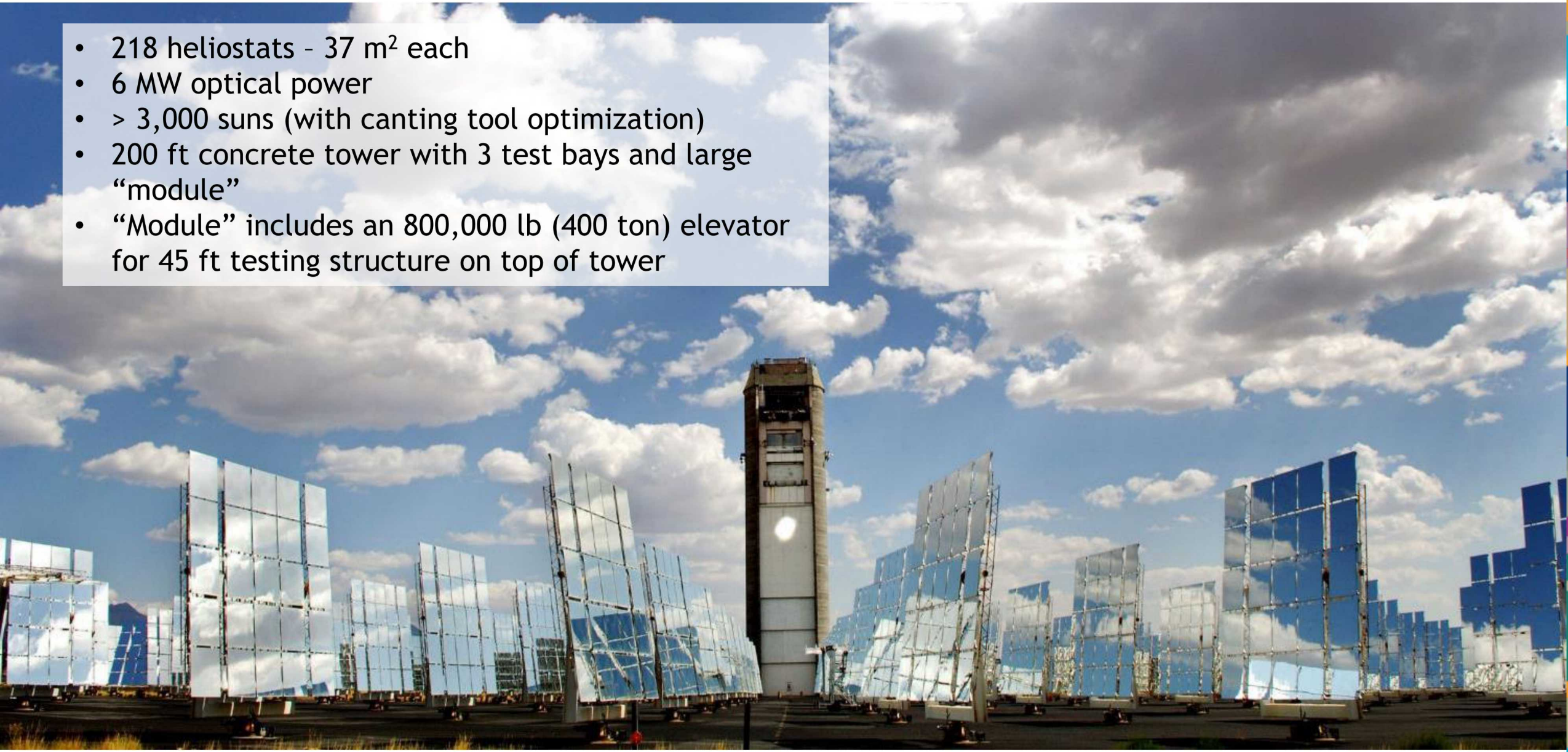
The National Solar Thermal Test Facility



NSTTF is a DOE Designated User Facility

- Strategic Partnerships Projects (SPP)
- Cooperative Research And Development Agreement (CRADA)

- 218 heliostats - 37 m² each
- 6 MW optical power
- > 3,000 suns (with canting tool optimization)
- 200 ft concrete tower with 3 test bays and large “module”
- “Module” includes an 800,000 lb (400 ton) elevator for 45 ft testing structure on top of tower

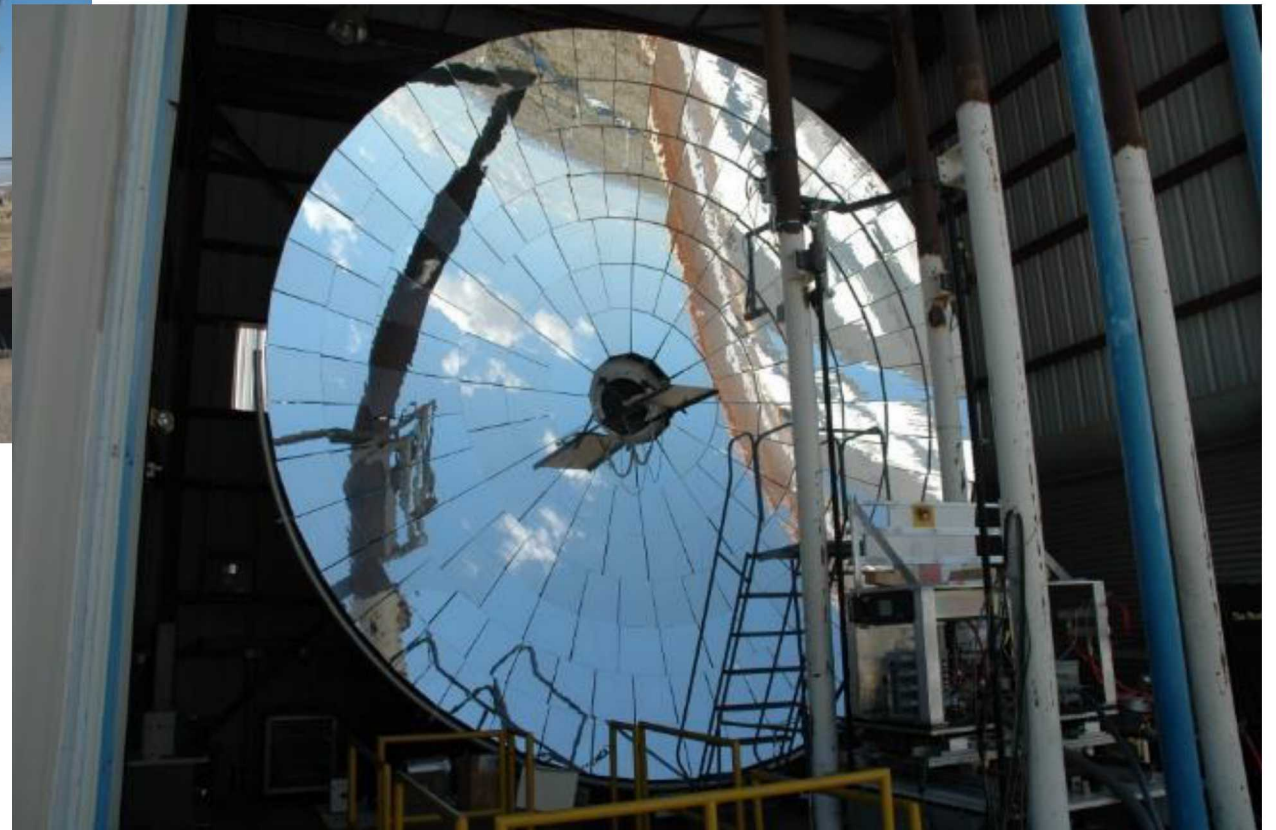




16 kW Solar Furnace

Peak flux $\sim 600 \text{ W/cm}^2$ (6000
suns)

5 cm spot size



Molten-Salt Test Loop

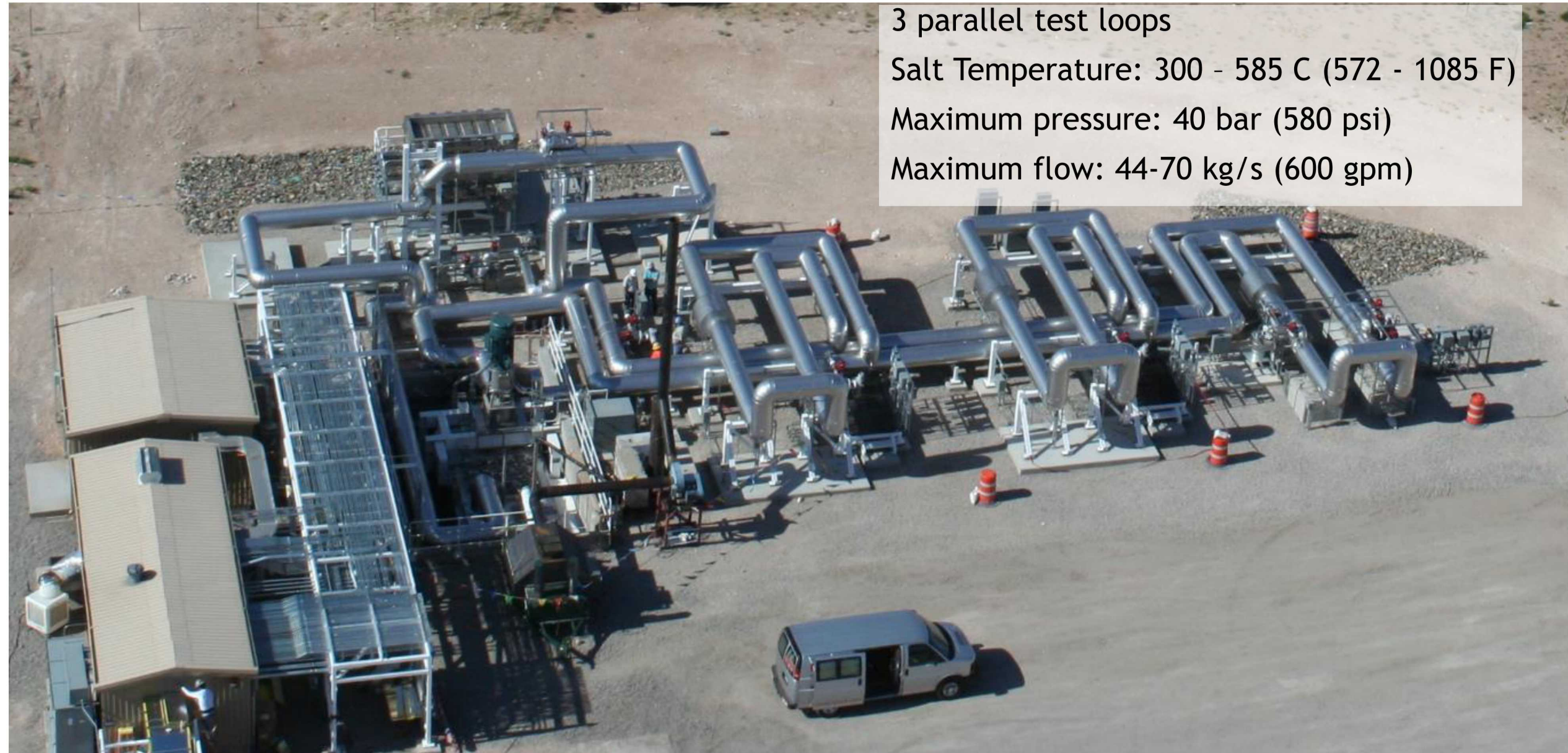


3 parallel test loops

Salt Temperature: 300 - 585 C (572 - 1085 F)

Maximum pressure: 40 bar (580 psi)

Maximum flow: 44-70 kg/s (600 gpm)





Current and anticipated DOE R&D

Progress Toward Commercial Deployment of sCO₂ Brayton Power Cycles

2018 – 2020 DOE Research Themes



- **2018: Gen3 CSP:** The final program for SunShot2020
 - Large funded projects culminating in a new high temperature + sCO₂ pilot (2019 – 2023)

- **2019: Beyond Gen3:** Towards SunShot 2030 (\$0.05/kWh for baseload or \$0.10/kWh peaking)
 - **Firm Thermal Energy Storage**
 - Long-term TES: Systems storing energy for weekly or seasonal dispatch
 - Pumped heat electricity storage for CSP: Concepts to enable charging of TES via off-peak grid electricity
 - Commercializing TES: Projects pursuing near-term market adoption
 - **Materials & Manufacturing**
 - **Autonomous CSP Collector Field**

- **2020: RFI: Supercritical Carbon Dioxide Power Cycles Integrated with Thermal Energy Storage**
 - “...feedback on technologies to integrate and demonstrate advanced supercritical carbon dioxide (sCO₂) Brayton power cycles that are indirectly heated via thermal energy storage at a turbine inlet temperature (TIT) range between 550 and 630°C...”

DOE Research and Development on sCO₂ Power Cycles

Dr. Avi Shultz

Program Manager

Solar Energy Technologies Office

DOE sCO₂ Workshop

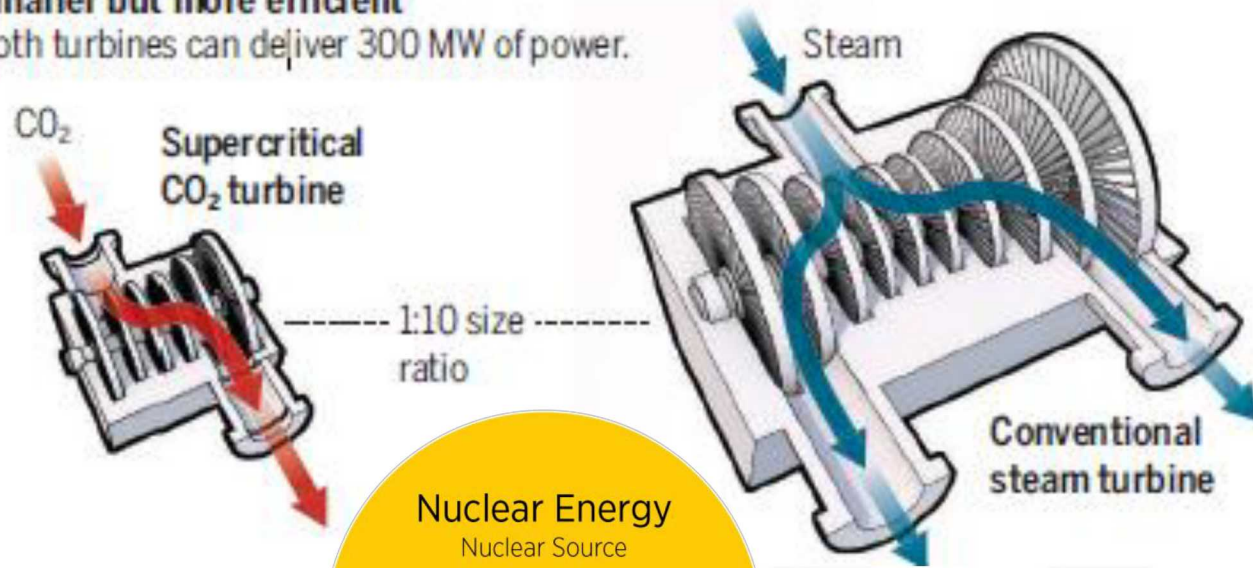
October 31-November 1, 2019

National Renewable Energy Laboratory, Golden, Colorado

Next Generation CSP will Leverage Next Generation Power Cycles

Smaller but more efficient

Both turbines can deliver 300 MW of power.



Nuclear Energy
Nuclear Source

sCO₂

Team Challenges

- » Turbomachinery
- » Advanced Recuperators
- » Materials Development
- » Sensors & Controls
- » Systems Integration and Modeling

Fossil Energy
Direct-fire

Renewable Power
Concentrating Solar

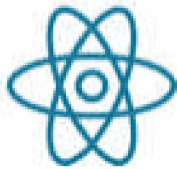
Advantages of the sCO₂ Brayton Cycle:

- Higher Efficiency (50% at TIT of 720 °C)
- Compact Components
- Smaller Turbine Footprint (by a factor > 10)
- Reduced Power Block Costs
- Amenable to Dry Cooling
- Scalability (Sub 100 MW)
- Operational Simplicity (No Phase Change)

Thermal Energy Storage + sCO₂ Power Cycles



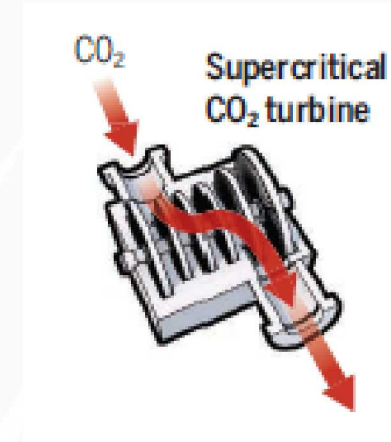
COAL



NUCLEAR



SOLAR
THERMAL
(CSP)



Thermal Resource Limitations:

- **Difficult to modulate** heat generation from nuclear fission
- Ramping coal boilers significantly **reduces lifetime**
- Solar thermal is a **variable energy resource**

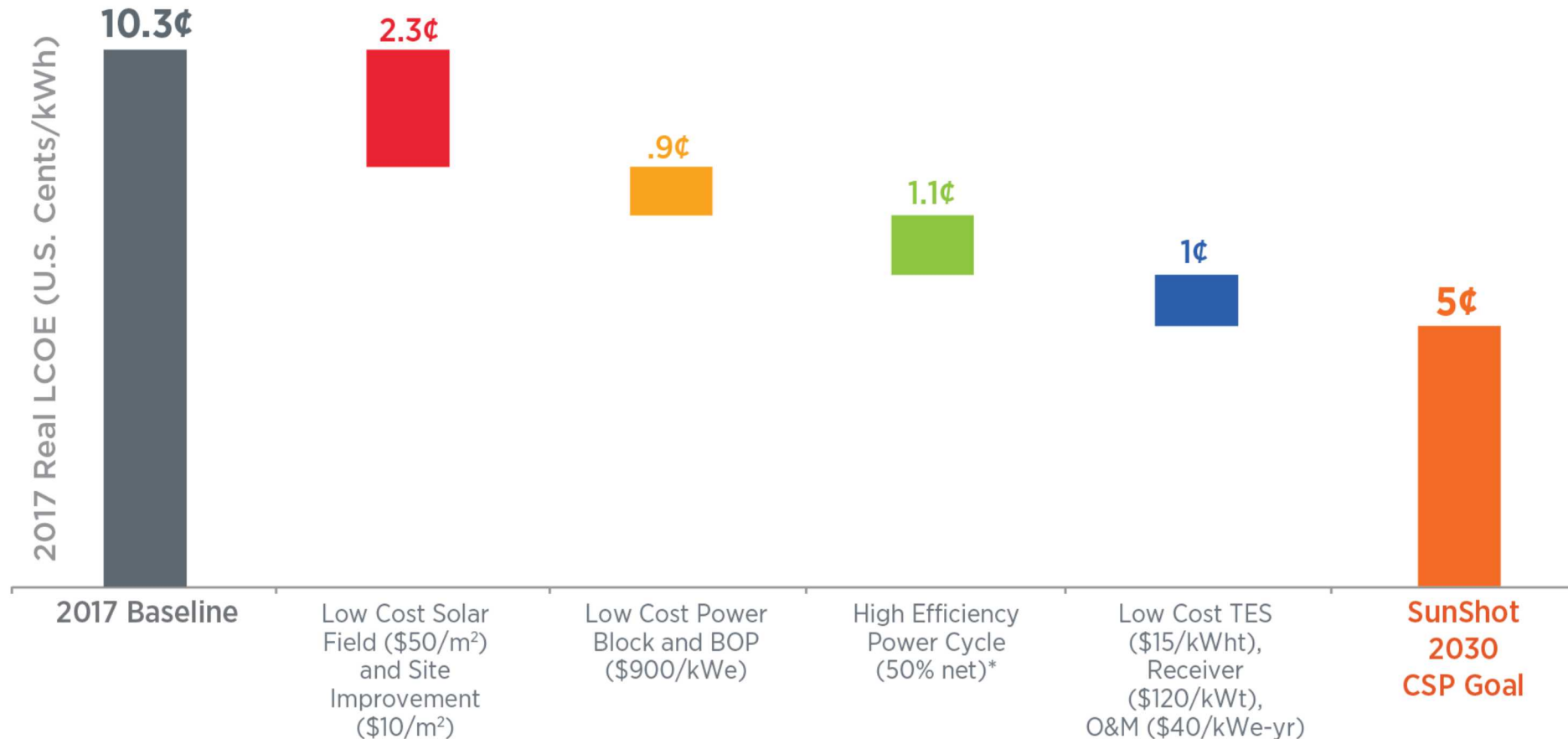
Thermal Energy Storage:

- **On-demand**, dispatchable energy generation
- **Increased reliability** due to buffering of variations in primary energy resource
- Technology readily scales to **long duration** (≥ 10 hours)

sCO₂ Power Cycles:

- Readily scalable to **< 100 MW** without significant loss in efficiency for **improved flexibility and siting**
- **Similar or higher efficiency** than steam cycles
- **Compact components** and **lower capital cost** for the same power output
- Much more amenable to **dry cooling** than conventional power cycles

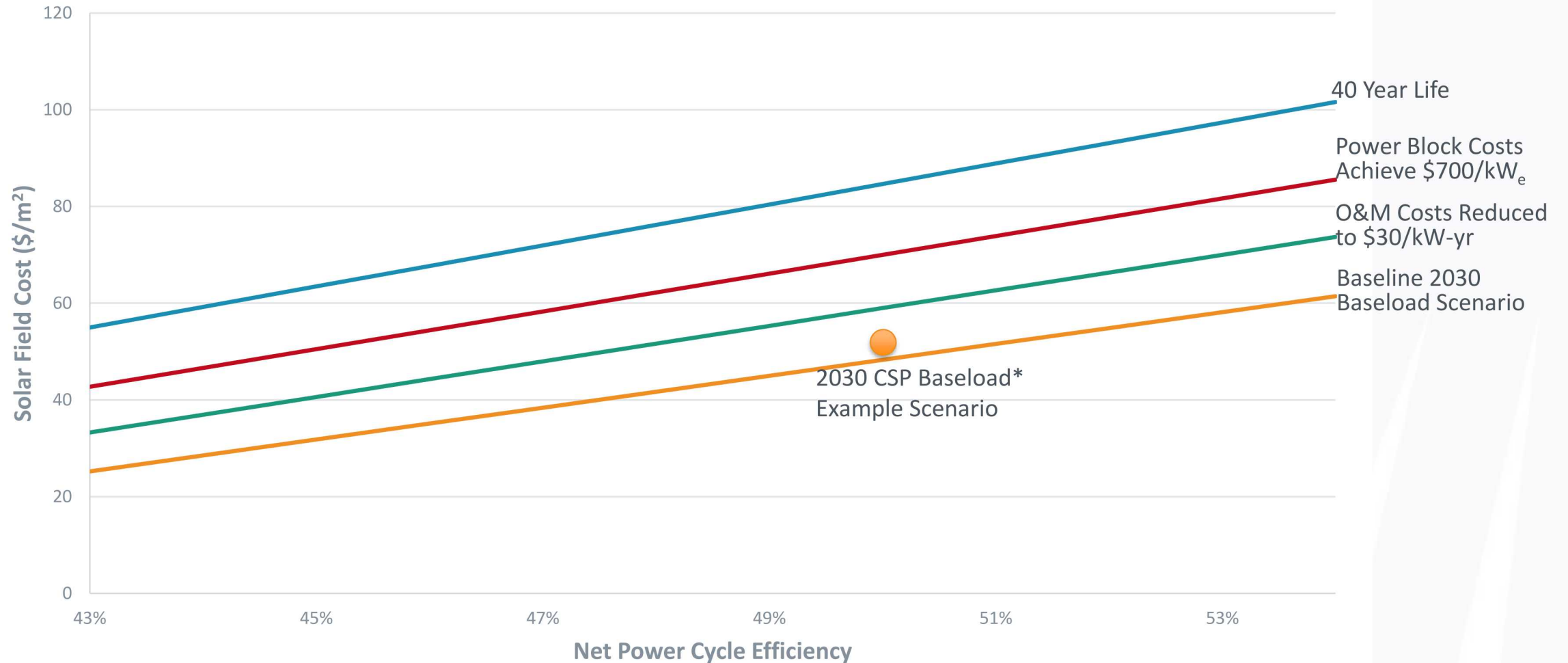
A Pathway to 5 Cents per KWh for Baseload CSP



*Assumes a gross to net conversion factor of 0.9

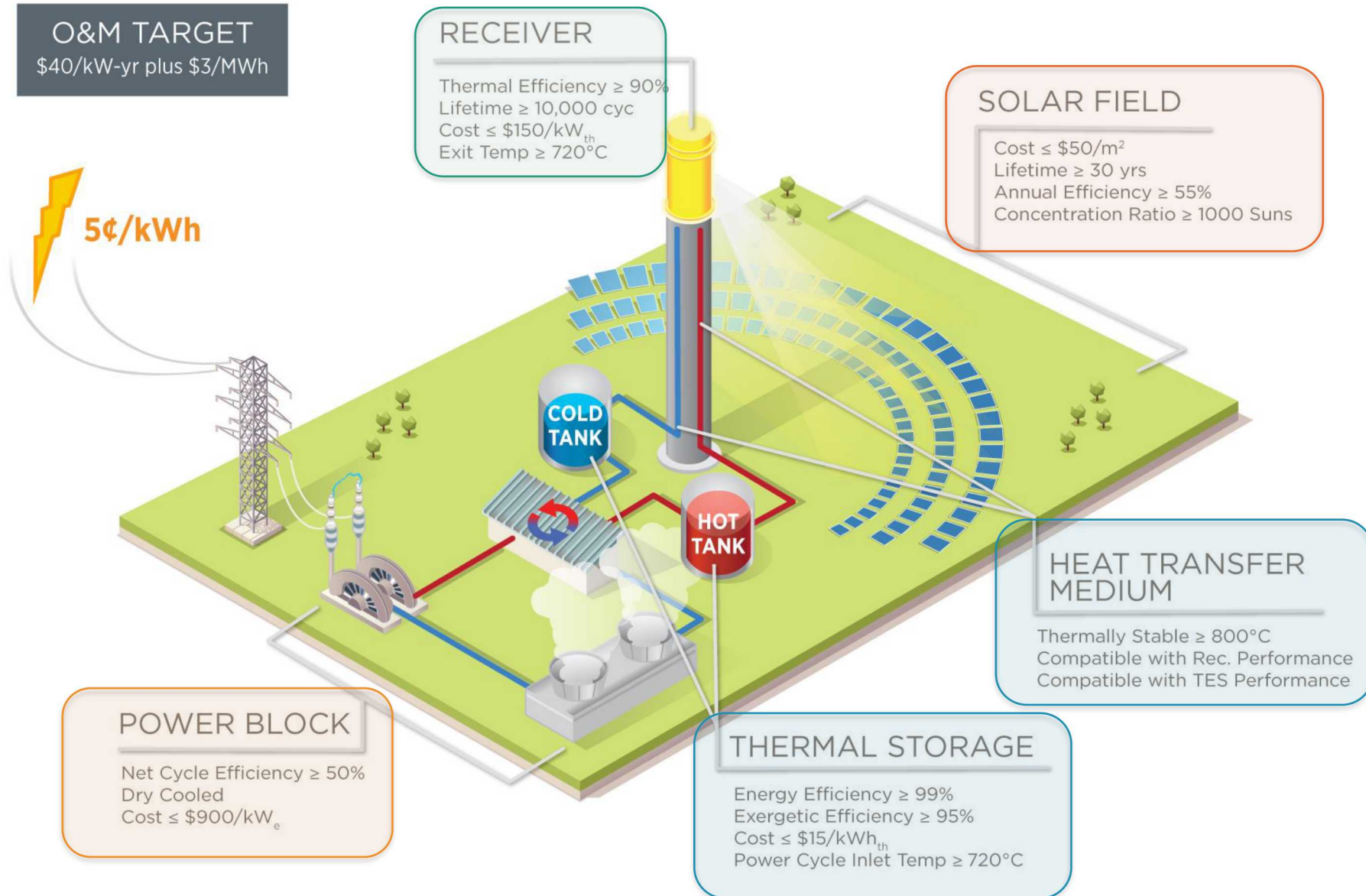
Pathways to Achieving SunShot 2030 Goals

All lines represent 5¢/kWh LCOE in a typical Southwestern U.S. climate



*Baseload power plant is defined as a CSP plant with greater than or equal to 12 hours of storage

CSP Program Technical Targets



Competitive Programs

\$33M	FY19 SETO FOA (2019)
\$22M	FY18 SETO FOA (2019)
\$21M	Solar Desalination (2018)
\$22M	FY19-21 National Lab Call (2018)
\$70M	Gen3 CSP Systems (2018)
\$15M	Gen3 CSP Lab Support (2018)
\$9M	COLLECTS (2016)
\$32M	CSP: APOLLO (2015)
\$29M	CSP SuNLaMP (2015)
\$1.4M	SolarMat II (2014)
\$10M	CSP: ELEMENTS (2014)
\$1.1M	SunShot Incubator (Recurring)
\$4M	PREDICTS (2013)
\$2M	SolarMat (2013)
\$10M	CSP-HIBRED (2013)
\$27M	National Lab R&D (2012)
\$10M	SunShot MURI (2012)
\$56M	CSP SunShot R&D (2012)
\$0.5M	BRIDGE (2012)
\$62M	CSP Baseload (2010)

SETO sCO₂ Power Cycle Portfolio by Category

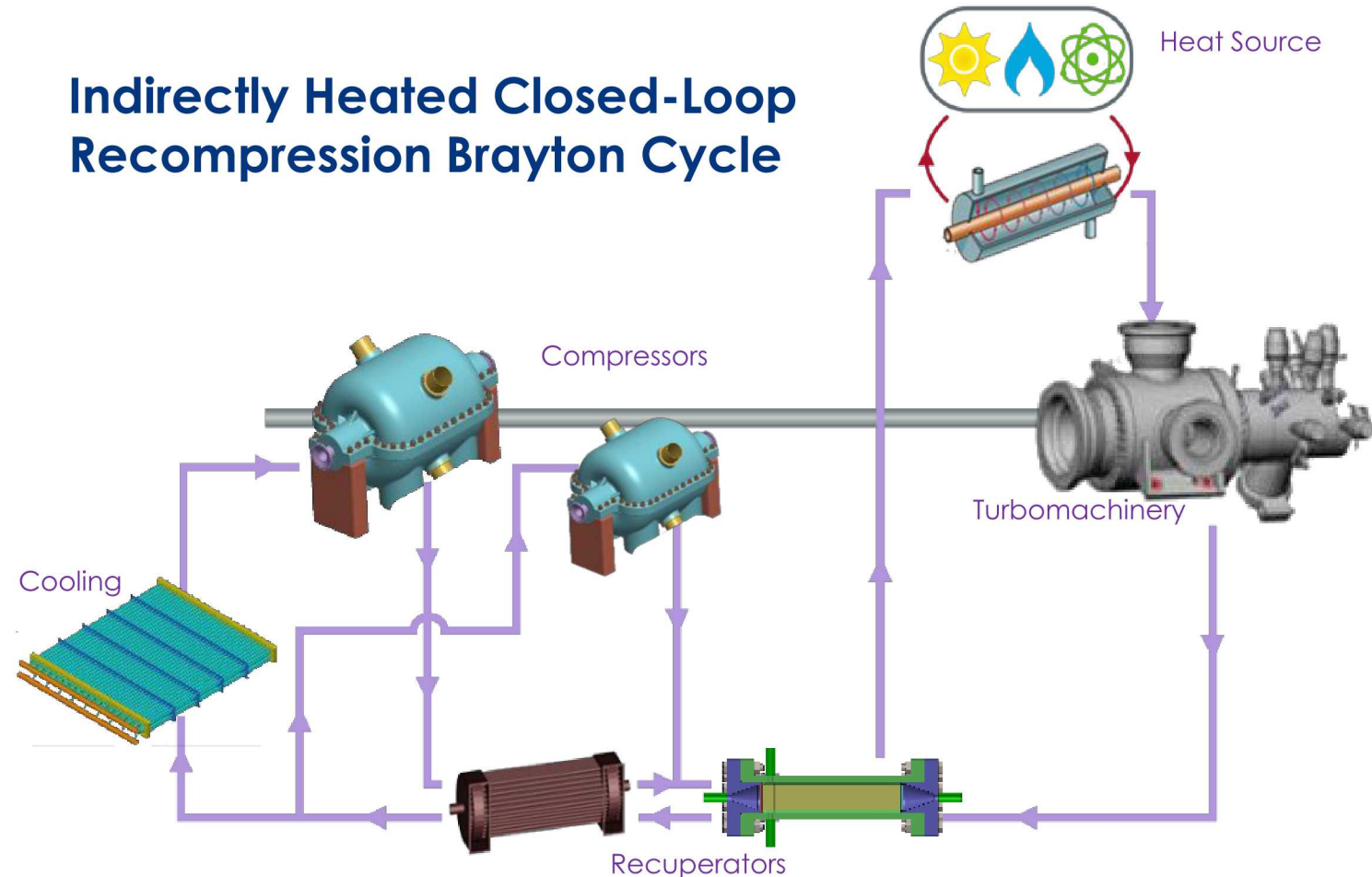
CATEGORY	PROJECT TITLE	PRIME
Turbomachinery	Compression System Design and Testing for sCO ₂ CSP Operation	GE
	Development of an Integrally-Geared sCO ₂ Compressor	SwRI
	High-Temperature Dry-Gas Seal Development and Testing	SwRI
	Gas Lubricated Bearings for Drivetrain in sCO ₂ Cycle	GE
Materials	Fabrication and Application of High Temperature Ni-Based Alloys	EPRI
Other Components	Development and Testing of a Switched-Bed Regenerator	UW-Madison
	sCO ₂ Power Cycle with Integrated Thermochemical Energy Storage	Echogen Power Systems
	Additively Manufacturing Recuperators via DMLM and Binder Jet Technology	GE
	Development of a High-Efficiency Hybrid Dry Cooler System	SwRI
Technoeconomics	Cycle Modeling, Integration with CSP, and Technoeconomics	NREL

DOE sCO₂ Crosscut Initiative: STEP Facility

10 MW_e STEP Pilot Facility

- Demonstrate models, controls, instrumentation, etc.
- Resolve issues common to multiple potential heat sources
- Facility Capabilities
 - Reconfigurable
 - 700°C operation
 - 300 bar
- Explore:
 - Operability
 - Cycle configuration
 - Component performance

Indirectly Heated Closed-Loop Recompression Brayton Cycle

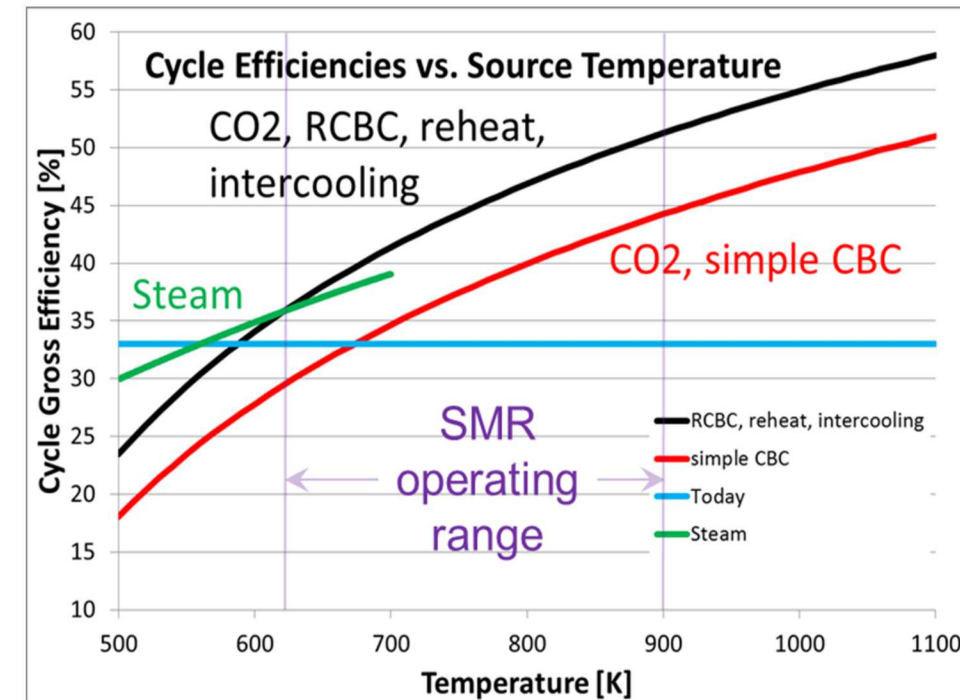


Project status: Major equipment on order; power cycle building under construction. Testing planned for 2021.



Office of Nuclear Energy - STEP R&D & Energy Conversion

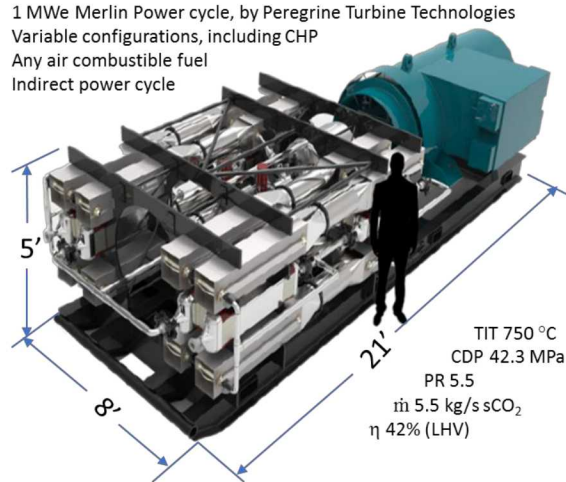
- **STEP R&D Program**
 - Activities focused on reducing technology risk, and component development
 - Established 8 test configurations (Development Platforms):
 - 1 MWe Test Article, Heat Exchanger (SEARCH), Particle Imaging Velocimetry (PIV), Seals, Bearings, Turbocompressor (Core), Dry Heat Rejection (Tall Loop), Parallel Compression
- **ART Energy Conversion Team focuses on Sodium Fast Reactor Application**
 - Technology Roadmap/Project Management Plan/System Engineering Model completed
 - Commercialization of the sCO₂ system by 2030
 - Operating Recompression Closed Brayton Cycle (RCBC) at a turbine inlet of 550C (→ 700+C)
 - Development of Intermediate Sodium to CO₂ Heat Exchanger (Primary Heat Exchanger)
 - Sodium Drain, Fill, Plug in PCHE and Sodium/CO₂ interactions
- **ART Engages Industry to Advance TRL of Components HTGR and MSR (550C & 750C)**
 - Federal Biz Ops (FBO) announcement to establish CRADA Lab & Industry collaborations



Technical Accomplishments

Turbomachinery

- 1 MWe Test article redesigned and initial testing completed
- Model and validation of turbo-machinery dry gas seals and hybrid gas bearings completed

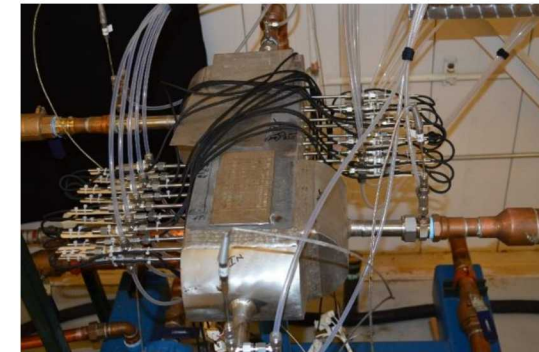


Systems Analysis & Integration

- Plant Dynamics Code (PDC) for sCO₂ developed; validation ongoing
- Testing and data from RCBC sCO₂ integrated recompression loop

Heat Exchangers

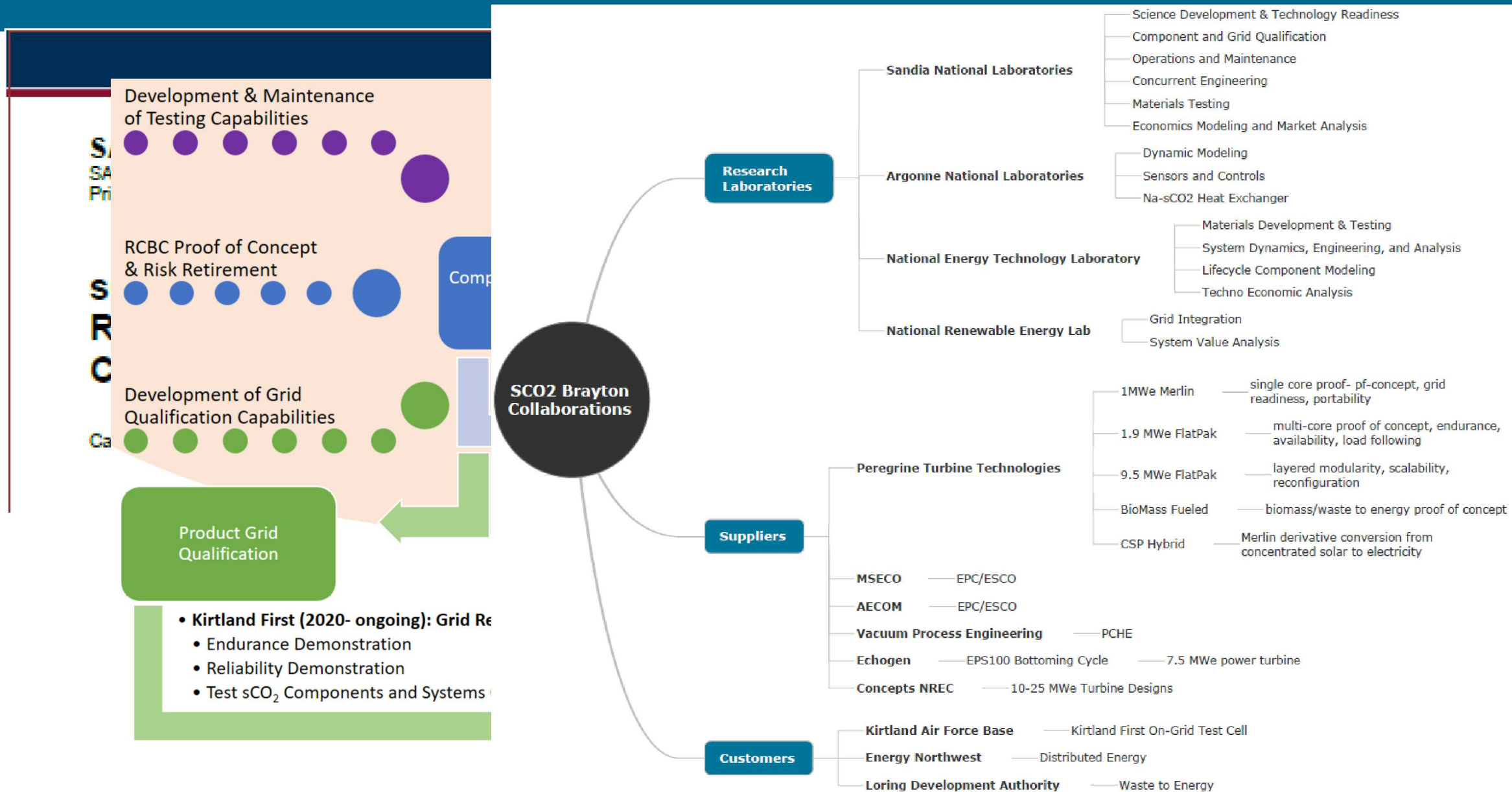
- ASME-qualified manufacture of diffusion-bonded, printed circuit heat exchangers



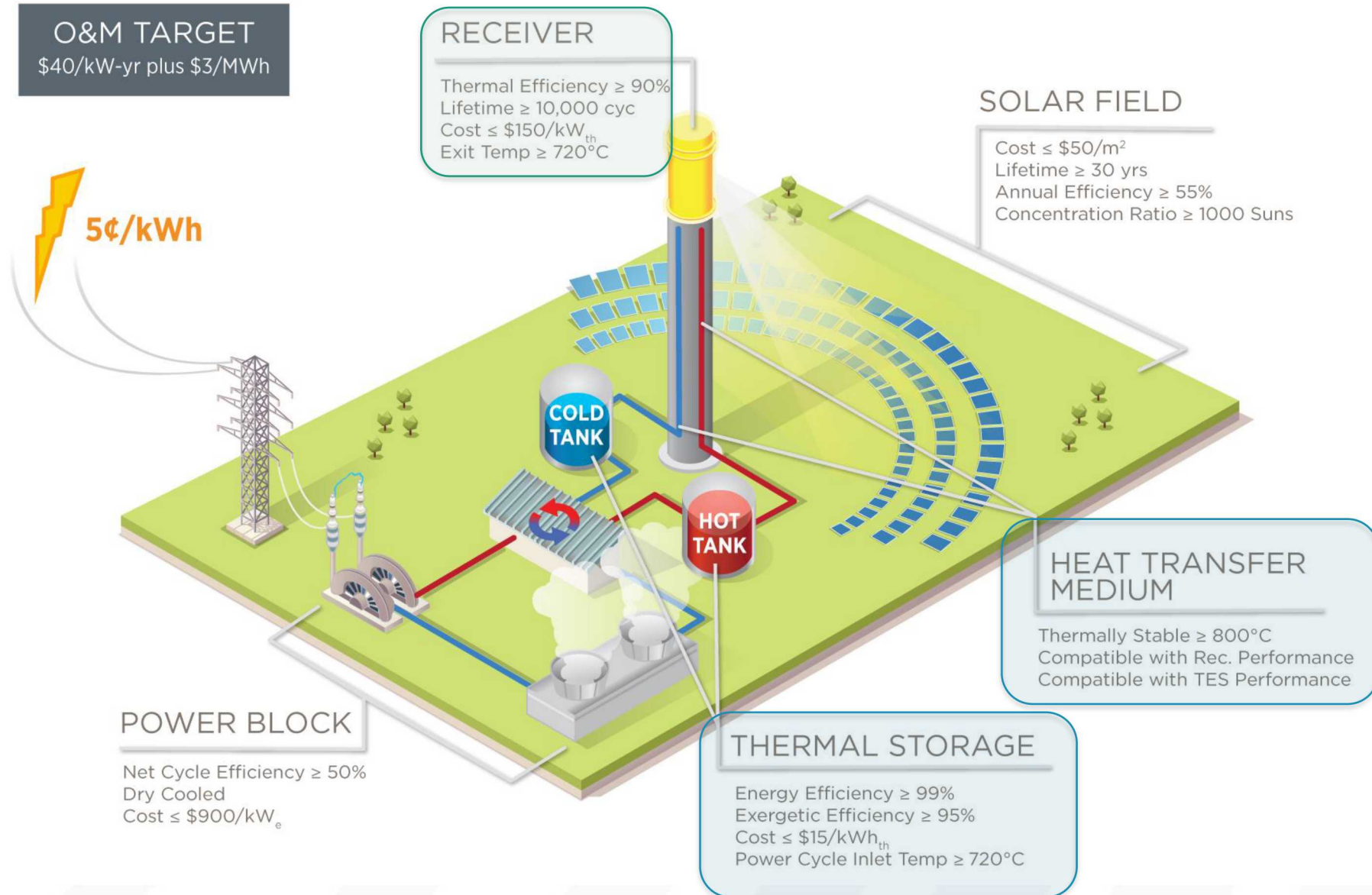
Materials

- Built high-temperature/pressure sCO₂ autoclaves at the SNL Materials Test Facility
- ASME Inconel 740 Code certification at 800 C for non-nuclear application
- Completed sCO₂ oxidation and corrosion tests for validation models
- Completed successful model for predictive impacts on corrosion, creep, and alloy fatigue life

Sandia – sCO₂ Roadmap for NE Applications



CSP Program Technical Targets



Gen3 CSP: Raising the Temperature of Solar Thermal Systems



Total federal funds awarded in 2018:

\$85,000,000 over 25 projects in 3 Topics:

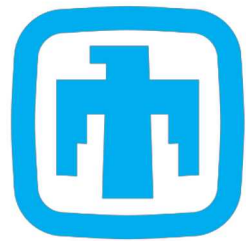
Topic 1: Integrated, multi-MW test facility
Mark Mehos, Craig Turchi, Judith Vidal, Michael Wagner, and Zhiwen Ma
National Renewable Energy Laboratory
Golden, Colorado

Topic 2A: Individual Component Development
Clifford Ho, William Kolb, and Charles Andrake
Sandia National Laboratories
Livermore, California

Topic 2B and National Lab Support: Assessing Gen3 Research and Analysis
Alan Kruizenga
Sandia National Laboratories
Livermore, California

<http://www.nrel.gov/docs/ty17osti/67464.pdf>

Gen3 CSP Topic 1 Awardees



**Sandia
National
Laboratories**

DOE Award (P1-2): \$9,464,755



NATIONAL RENEWABLE ENERGY LABORATORY

DOE Award (P1-2): \$8,067,661



DOE Award (P1-2): \$7,570,647

COLLECTOR FIELD	RECEIVER	THERMAL TRANSPORT	THERMAL STORAGE	HEAT TRANSFER MEDIA	HEAT EXCHANGE	POWER CYCLE
SOLID MEDIA	<ul style="list-style-type: none"> • Thermal Efficiency: • Particle Loss • Flow Velocity Control and Monitoring 	<ul style="list-style-type: none"> • Reliability • Mechanical and Thermal Efficiency • Scalability • Insulation 	<ul style="list-style-type: none"> • Charging and Discharging • Particle loss, Efficiency, Scalability 	<ul style="list-style-type: none"> • Particle Attrition • Optimized Performance Character 	<ul style="list-style-type: none"> • Low Cycle Fatigue • Particle Mass Flow Control • Ramp Rates & Transients 	
MOLTEN SALT	<ul style="list-style-type: none"> • Thermal Conductivity • Thermal Stability • Tube Strength and Durability 	<ul style="list-style-type: none"> • Pipe Material Compatibility • Freeze Recovery • Pumps Valves Seals • Leak Detect 	<ul style="list-style-type: none"> • Corrosion Behavior • Chemistry Monitoring and control • Tank Cost 	<ul style="list-style-type: none"> • Characterize Material Properties • Cost / Supply Chain 	<ul style="list-style-type: none"> • Material Compatibility w/ salt & CO₂ • Freeze Protection • Thermal Ramp Rates 	
GAS	<ul style="list-style-type: none"> • High Pressure Fatigue • Absorptivity Control and Thermal Loss Management 	<ul style="list-style-type: none"> • Recirculator Cost & Operating Power • Large Pipes High Cost 	<ul style="list-style-type: none"> • Storage Concept not Determined 	<ul style="list-style-type: none"> • Low Thermal Conductivity • Low Heat Capacity 	<ul style="list-style-type: none"> • Requires High Area • Multiple Heat Exchangers • Cascading Temperature 	

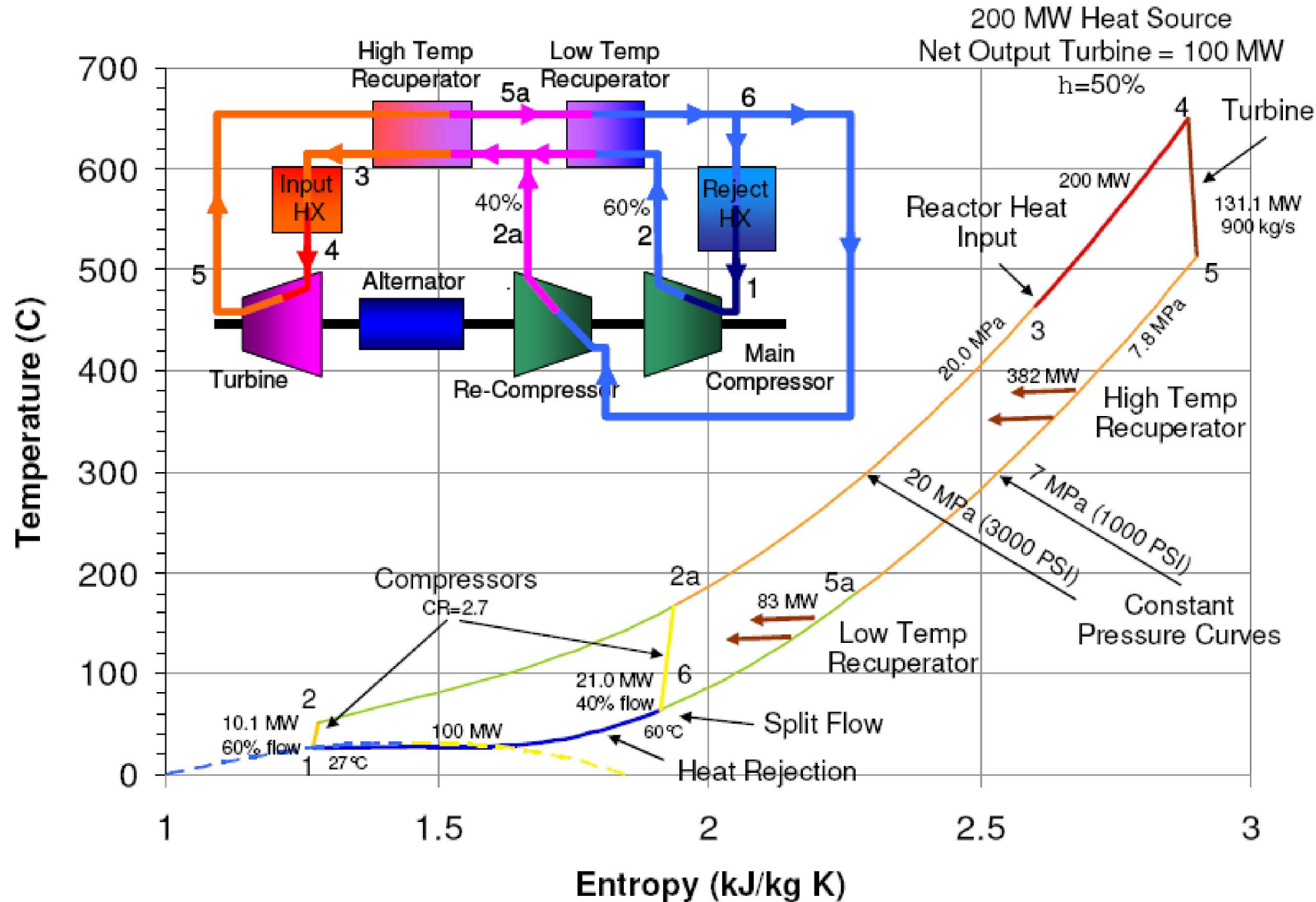


Development of sCO₂ power cycles

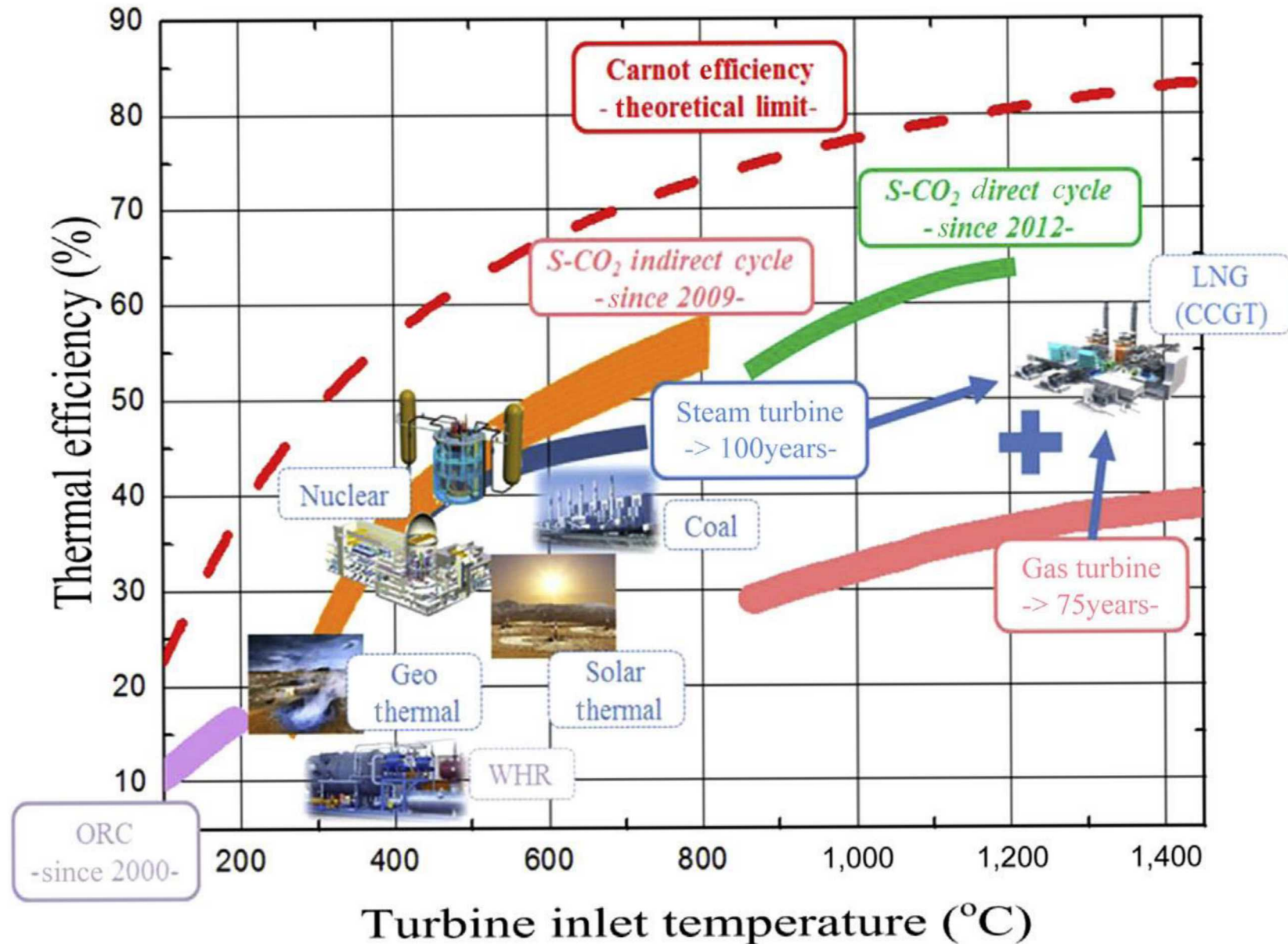
Progress Toward Commercial Deployment of sCO₂ Brayton Power Cycles

Matthew D. Carlson, Sandia National Laboratories

The sCO₂ Brayton Cycle [1]



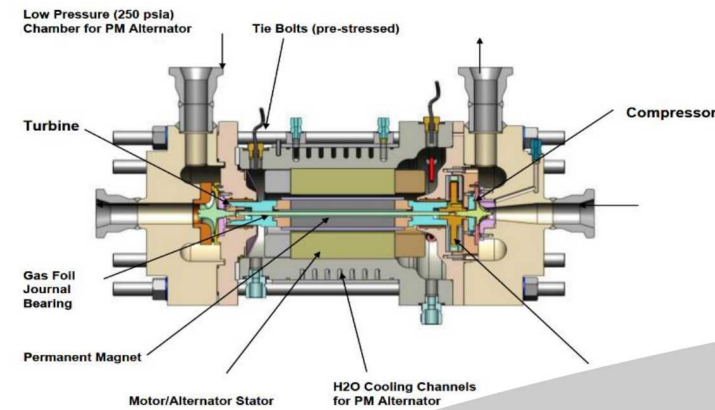
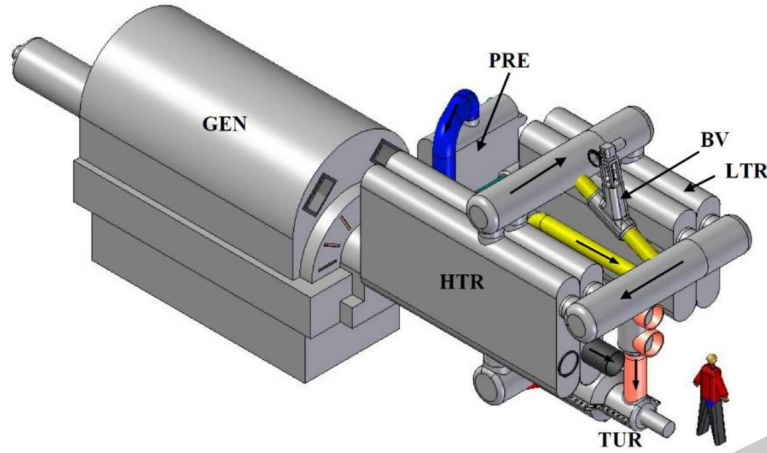
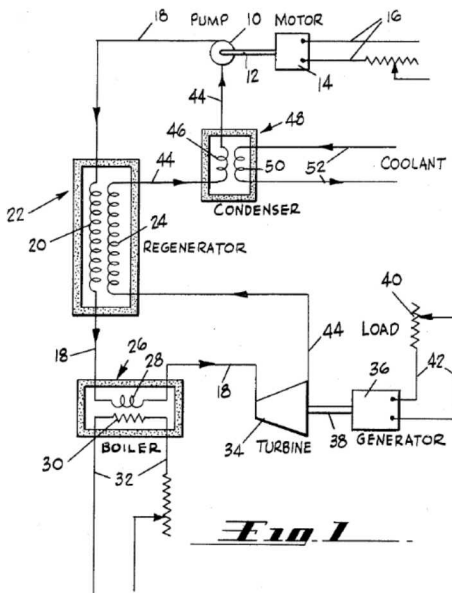
Comparison to Other Power Cycles [2]



Critical Milestones in sCO₂ R&D



1985
Heatric



○ **1997**
Research
Revival

○ **1963**
Cycle
Concept

○ **2007**
Prototypes
First sCO₂
Symposium

○ **2013**
Widespread
Interest
ASME Turbo
Expo Track

[3-6]



Commercially-relevant sCO₂ pilot systems

Progress Toward Commercial Deployment of sCO₂ Brayton Power Cycles

Matthew D. Carlson, Sandia National Laboratories

Echogen Power Systems – Akron, Ohio, USA [7,8]



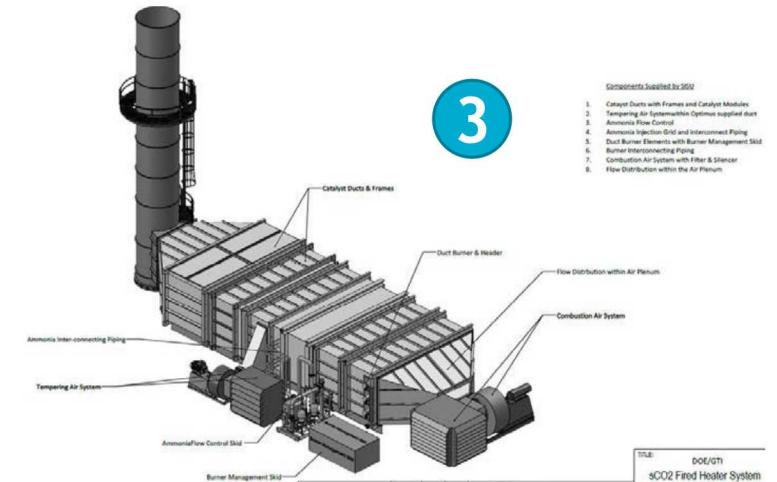
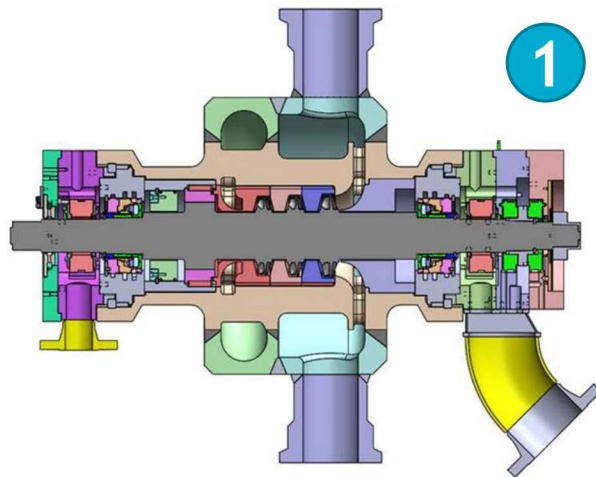
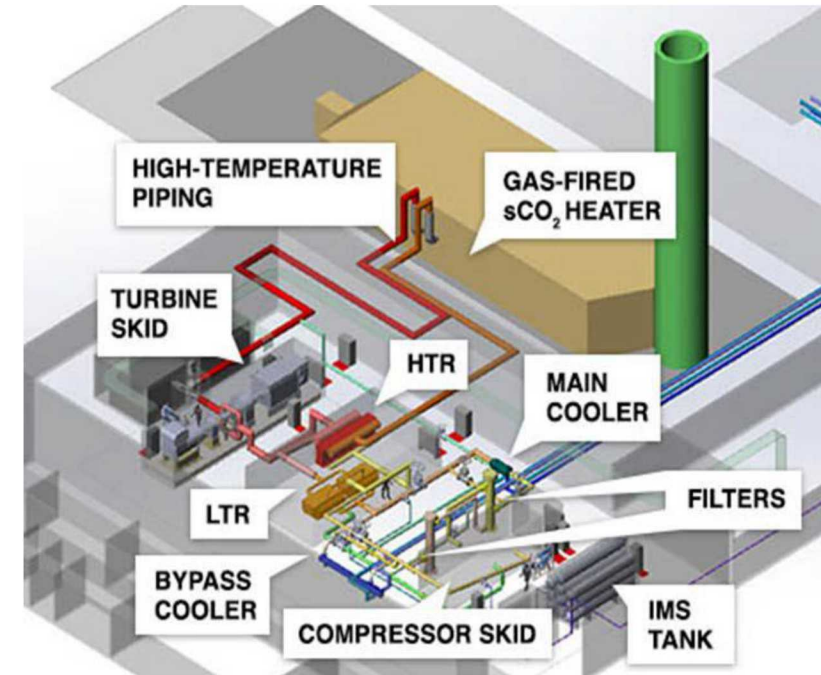
- First commercial sCO₂ Brayton power system
- Significant technical milestones including:
 1. Transportable skid-mounted system
 2. 7.3 MW_e design, 3.1 MW_e demonstrated
 3. 16 MW_{th} sCO₂ recuperator (200 kW/K)
 4. Validation of design and transient models



STEP 10 MW_{th} Demonstration – San Antonio, Texas, USA [9]



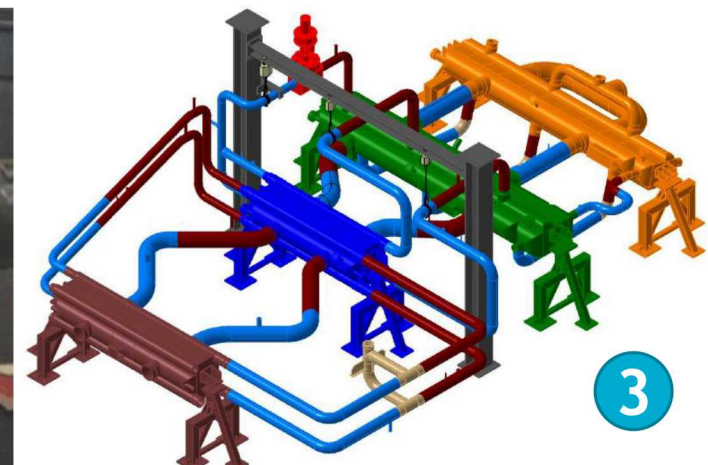
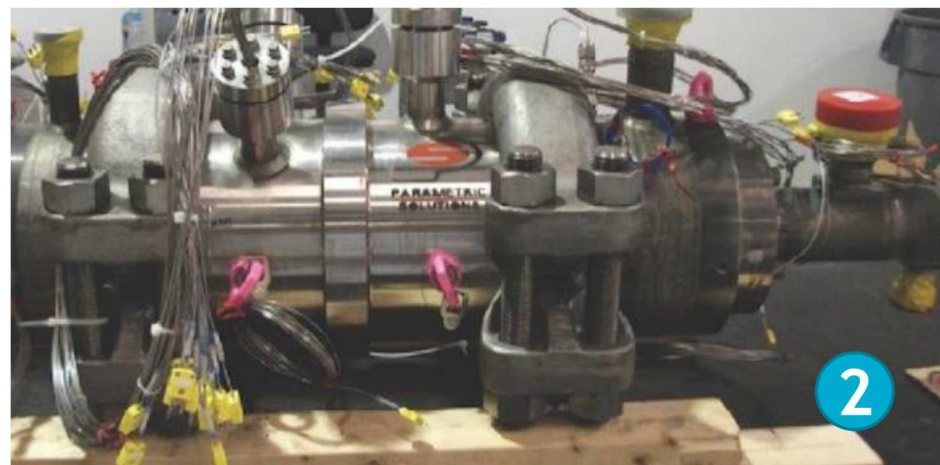
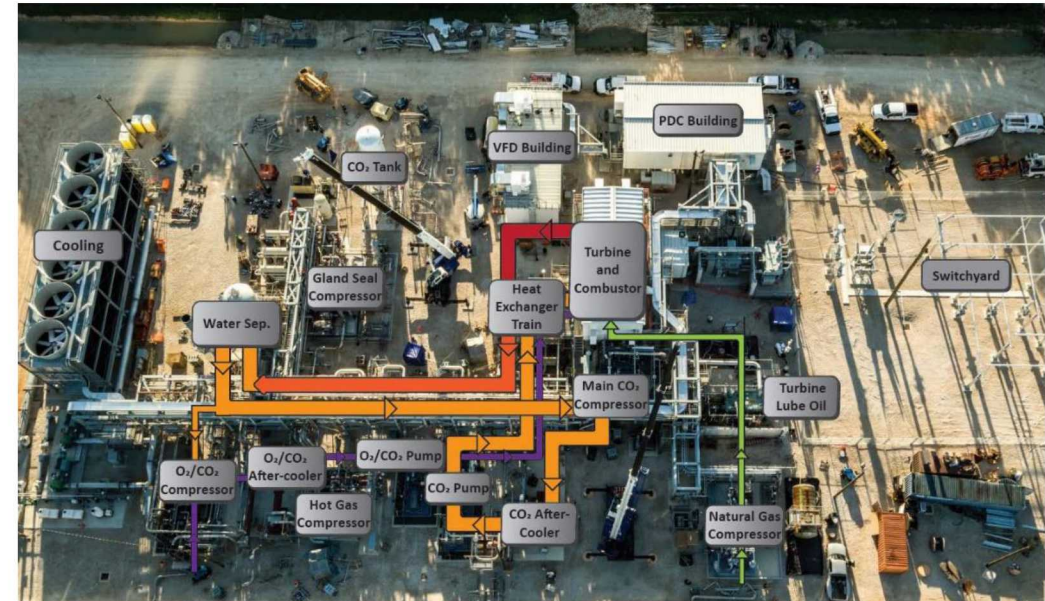
- Largest indirect-fired sCO₂ Brayton cycle
- Significant technical milestones including:
 1. 16 MW_{th} SwRI/GE turbine design
 2. 700 °C 740H turbine stop/control valve
 3. 715 °C 740H gas-fired heater
 4. Scheduled for operation in 2021



NET Power 50 MW_{th} Demonstration – La Porte, Texas, USA [10-13]



- Largest sCO₂ Brayton power system
- Significant technical milestones including:
 1. 50 MW_{th} Toshiba turbine
 2. High pressure oxyfuel combustor
 3. Alloy 617 diffusion bonded heat exchanger
 4. First fire on 2018-05-30





Ongoing sCO₂ research and future plans

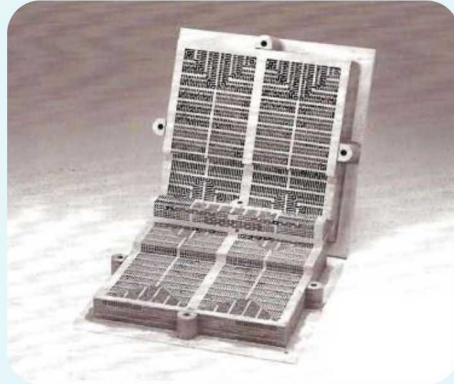
Progress Toward Commercial Deployment of sCO₂ Brayton Power Cycles

Matthew D. Carlson, Sandia National Laboratories

Design [14,15]



Chemically Milled
Diffusion Bonded



Chemically Blanked
Diffusion Bonded



Micro-Tube and Shell

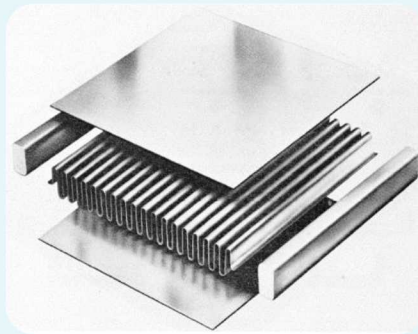
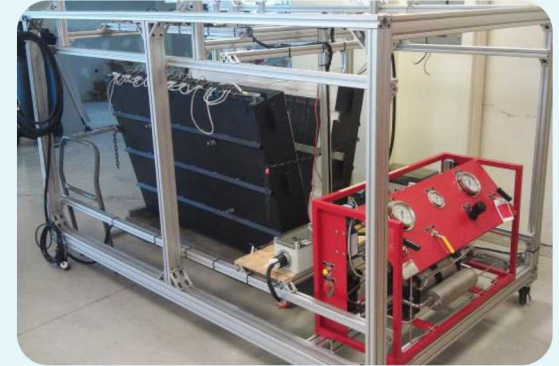


Plate-Fin

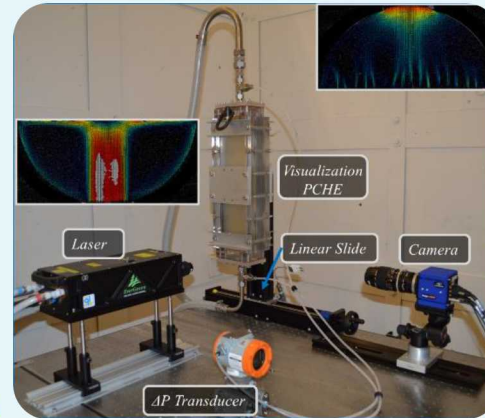
Testing [16]



Pressure Fatigue



Thermal Fatigue & Creep

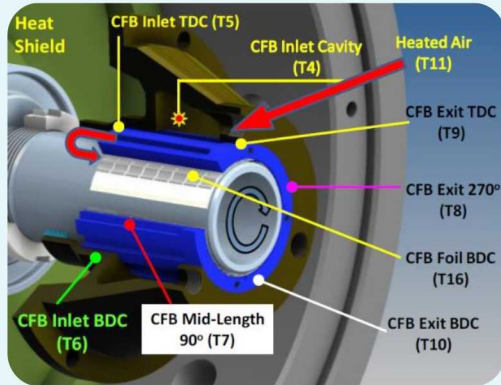


Flow Distribution

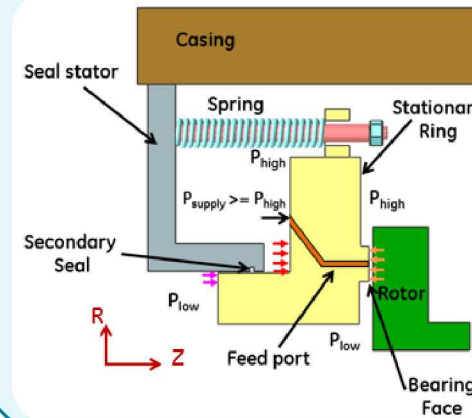


Performance

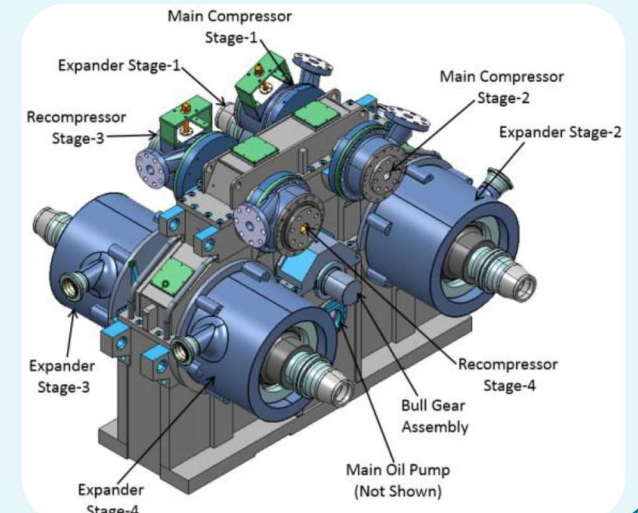
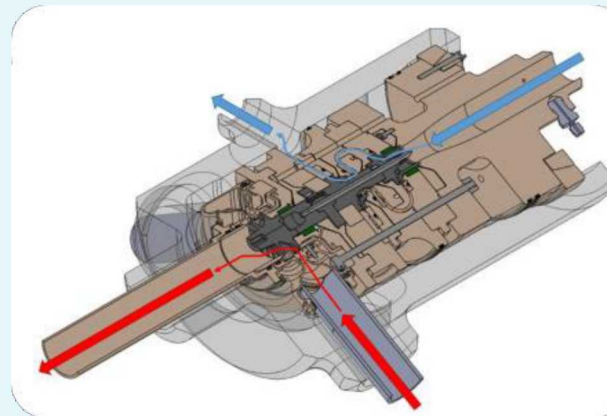
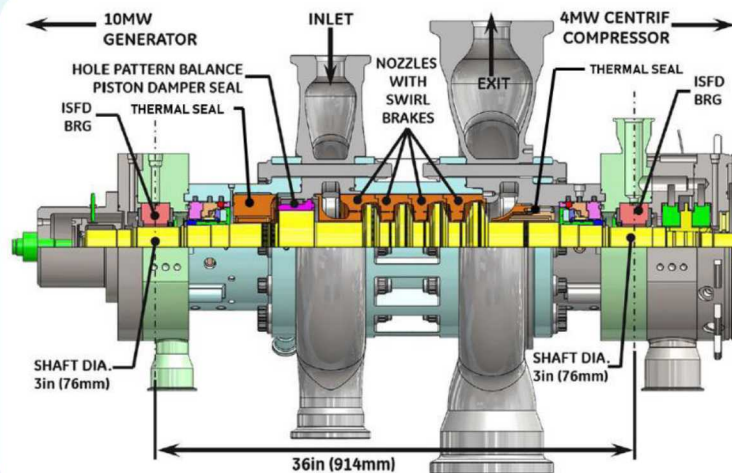
Bearings [17]



Seals [18]



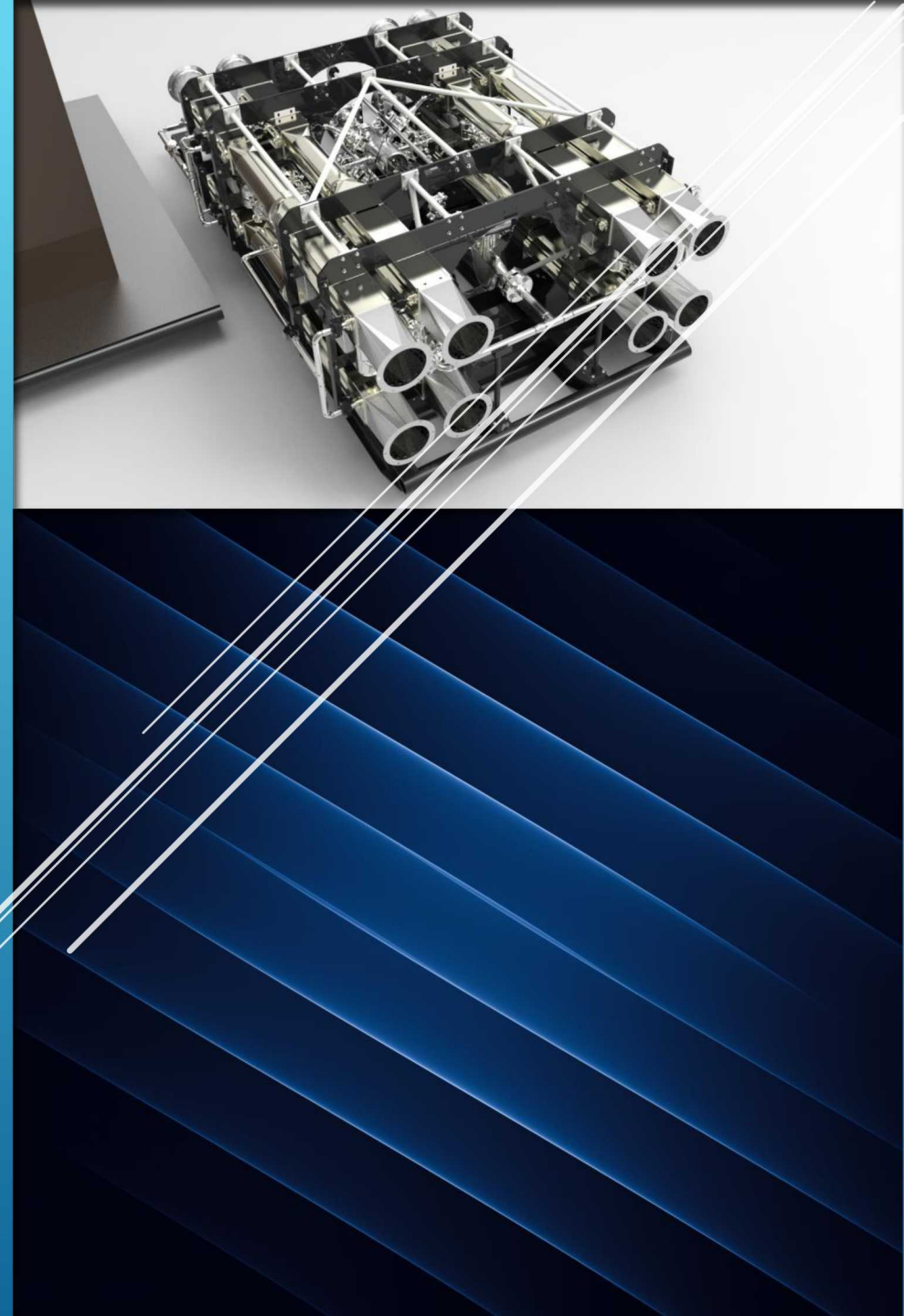
Integration [19-21]



NREL SCO2 POWER CYCLE WORKSHOP 2019

David Stapp
CEO/CTO
Peregrine Turbine Technologies, LLC

October 31, 2019

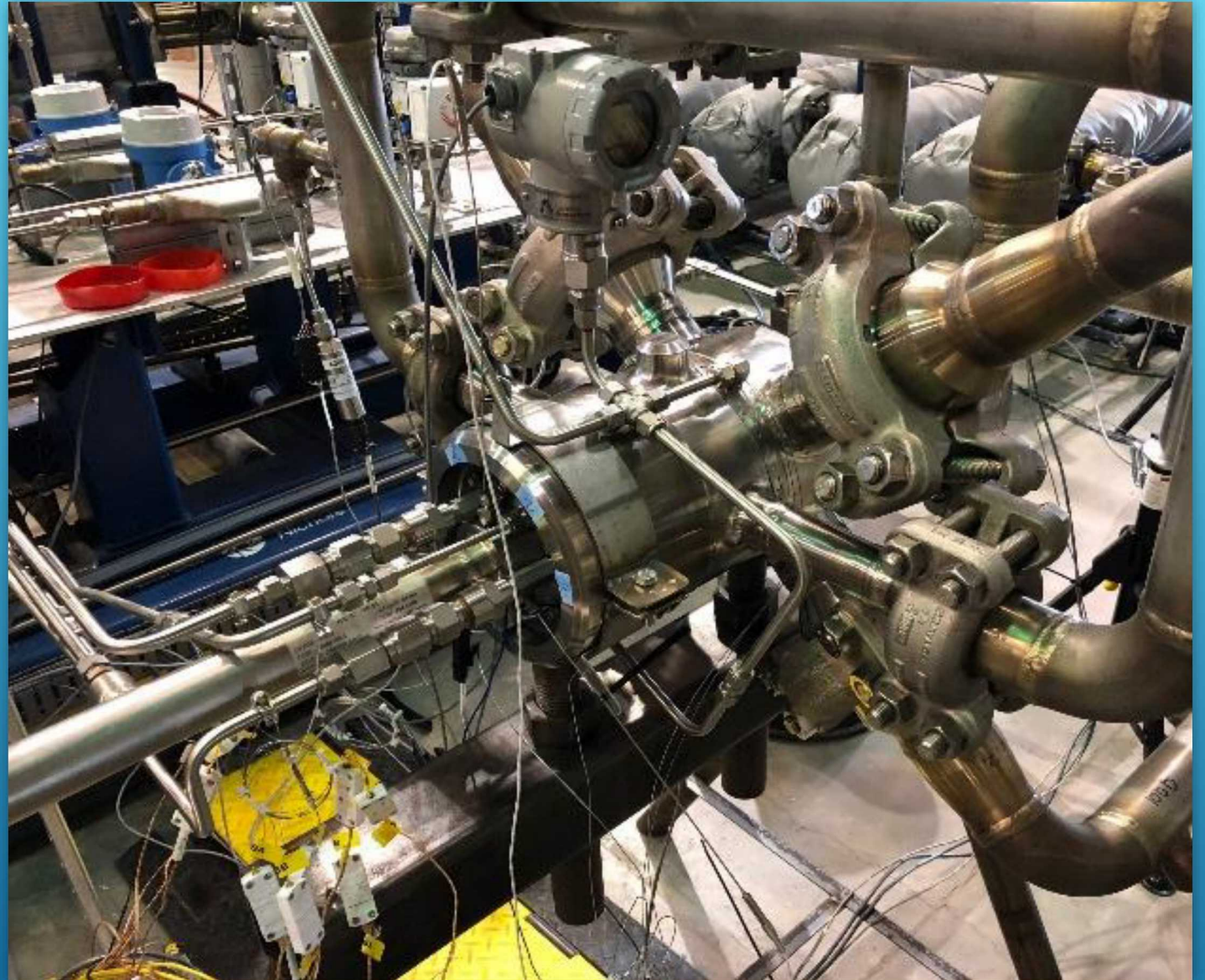


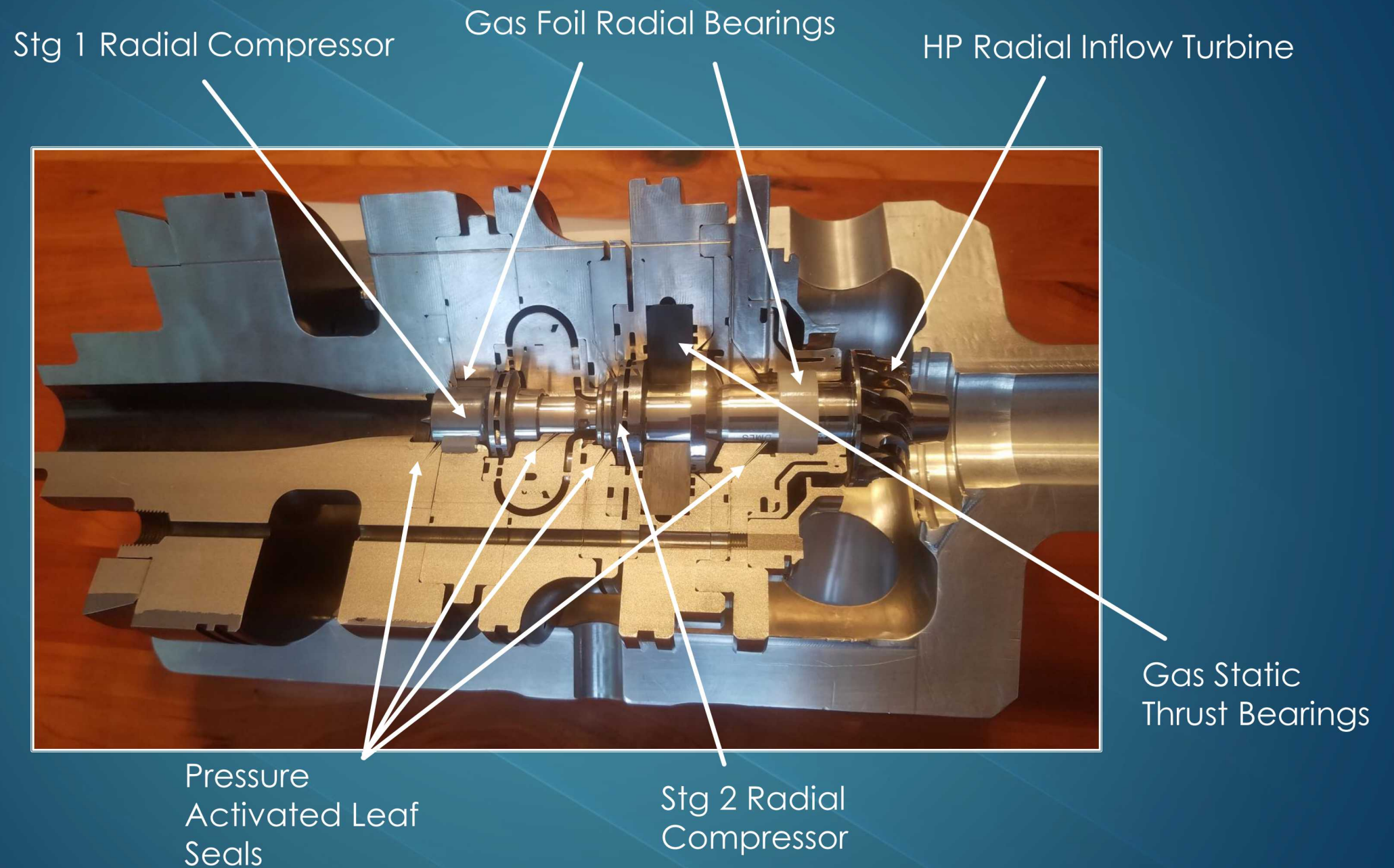
Peregrine Turbopump:

Designed under an AFRL SBIR Phase III with private match. Part of a two-spool 1MW asynchronous electric power generator.

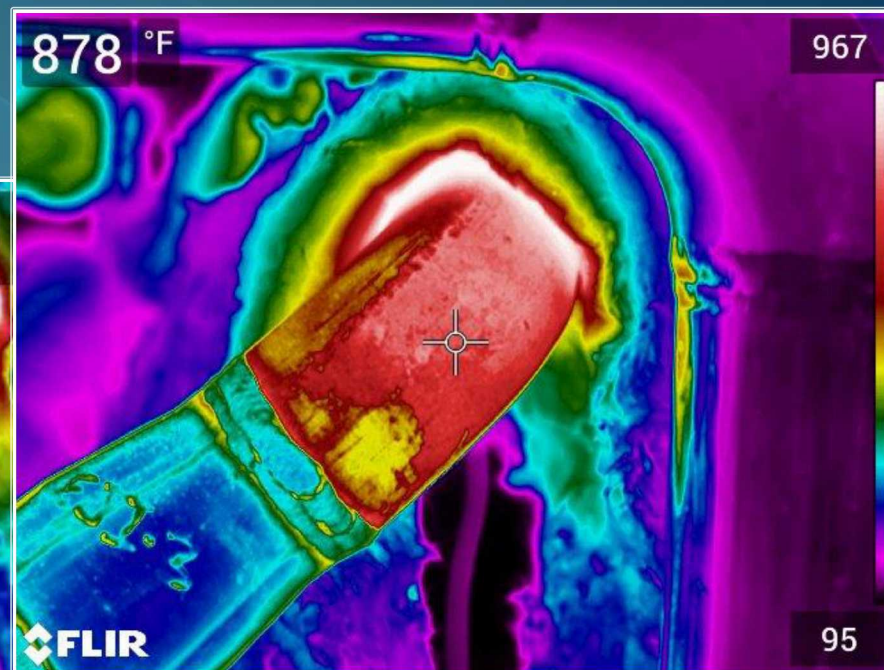
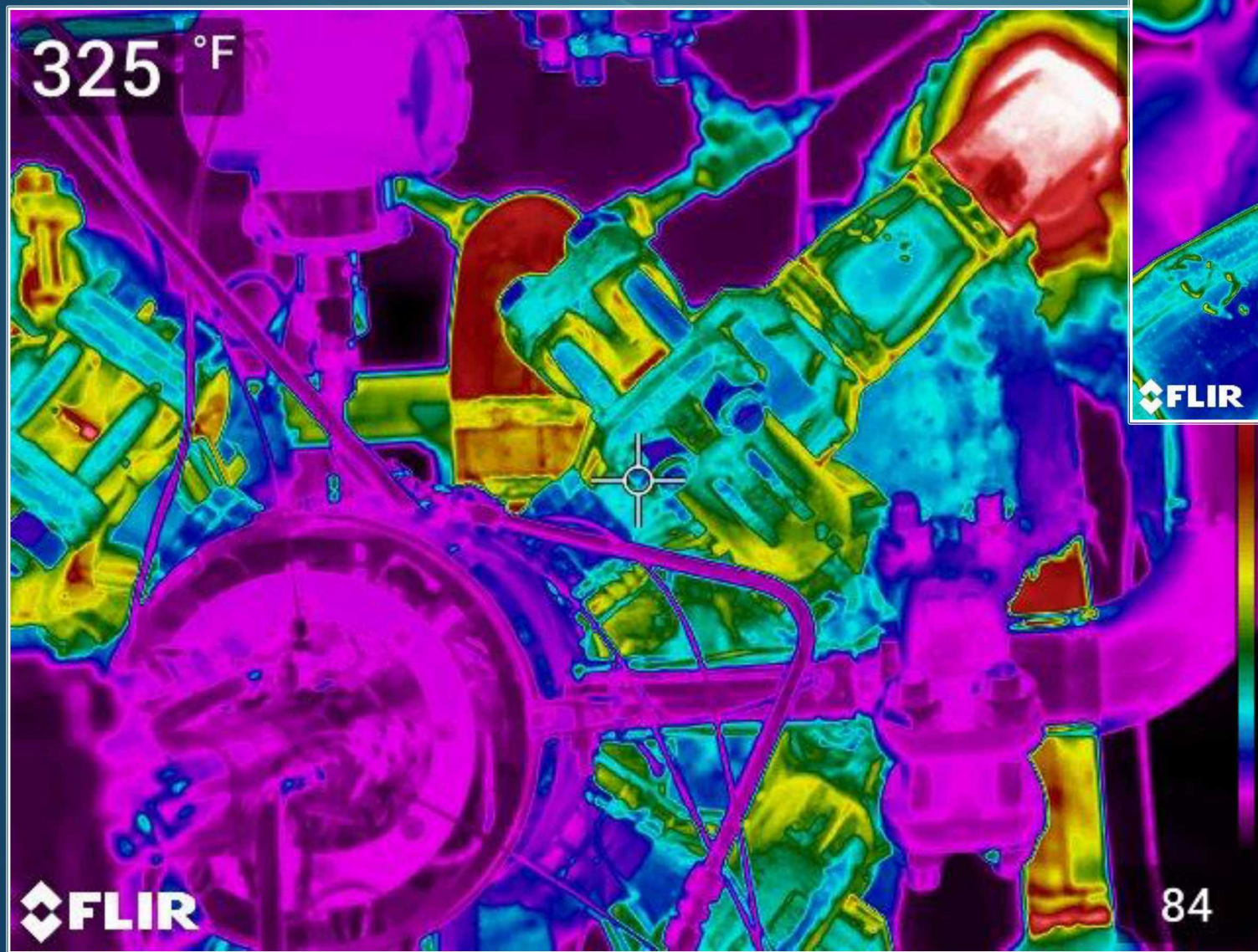
- Motorless Operation, blowdown start
- CDP – 6220 psi (42.9 MPa)
- Mass Flow Rate – 12.13 lbm/s
- Pressure Ratio – 5.5
- Turbine Inlet Temp - 1382°F (750°C)
- Design Speed – 118,350 rpm

Approximately 40 hrs of testing completed at Sandia to date with speeds up to 91krpm and turbine inlet temps of 1000°F. Expect to surpass 200 hrs by year end.

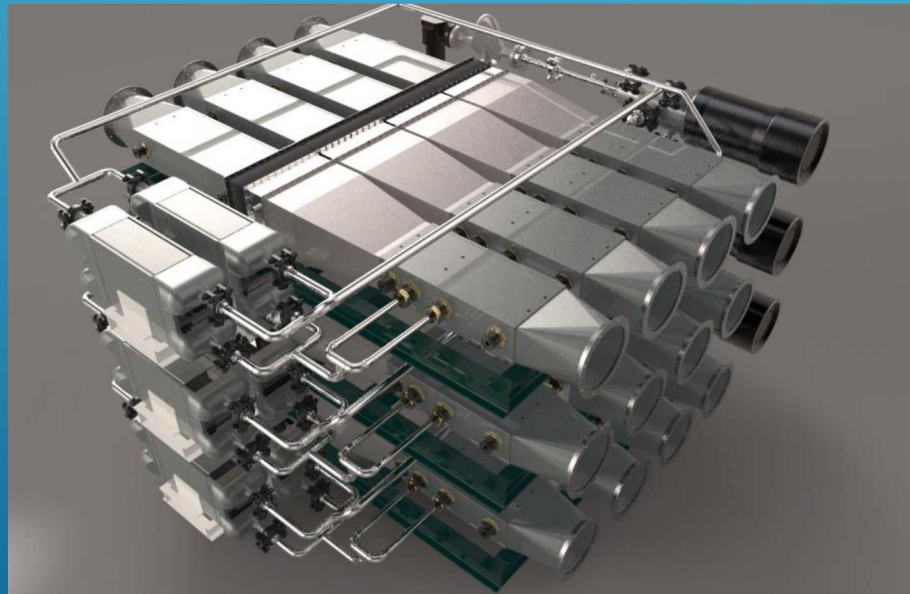
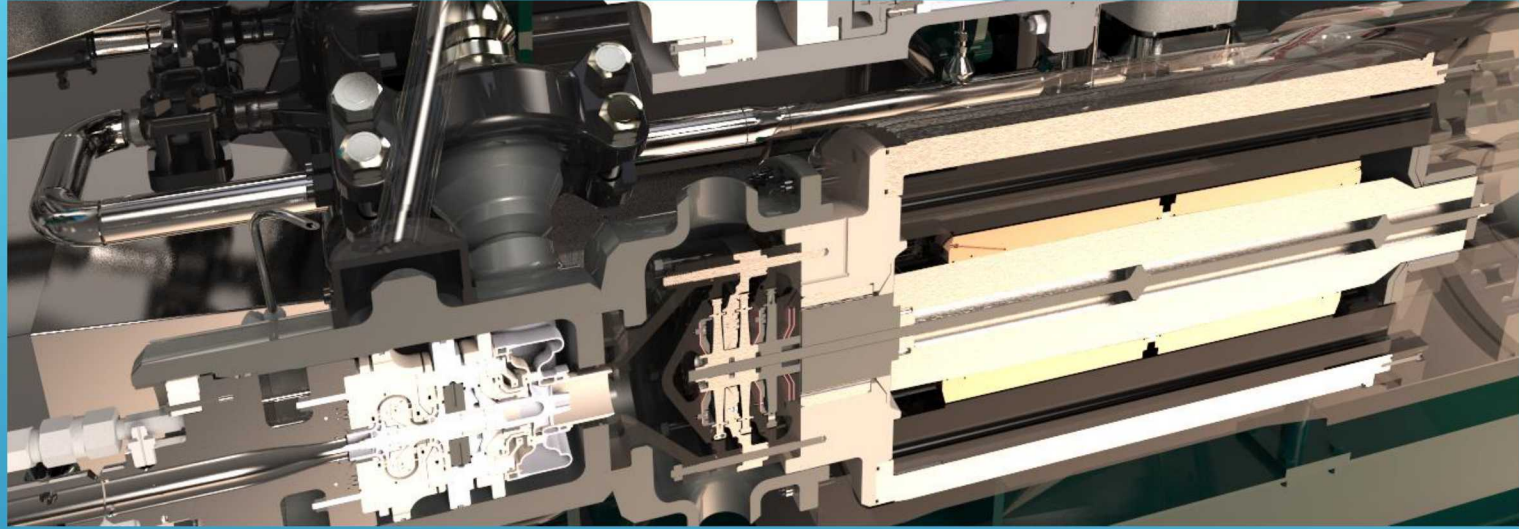








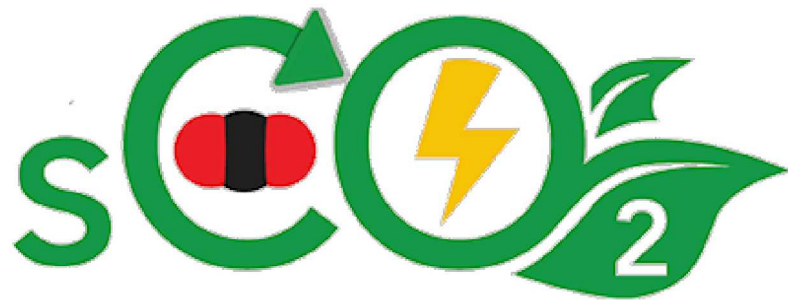
- Application of Modular Design Solutions



Future Conferences with an sCO₂ R&D Focus



7th International sCO₂ Power Cycles Symposium – 2020



Tutorial Sessions: March 30, 2020

Conference: March 31-April 2, 2020



**Turbo Expo
Turbomachinery Technical Conference
& Exposition**

Presented by the ASME International Gas Turbine Institute

ExCeL London Convention Center, London, England

Conference: June 22 – 26, 2020
Exhibition: June 23 – 25, 2020

[Submit Abstract](#)



Gen3 projects – The Big 3

Progress Toward Commercial Deployment of sCO₂ Brayton Power Cycles

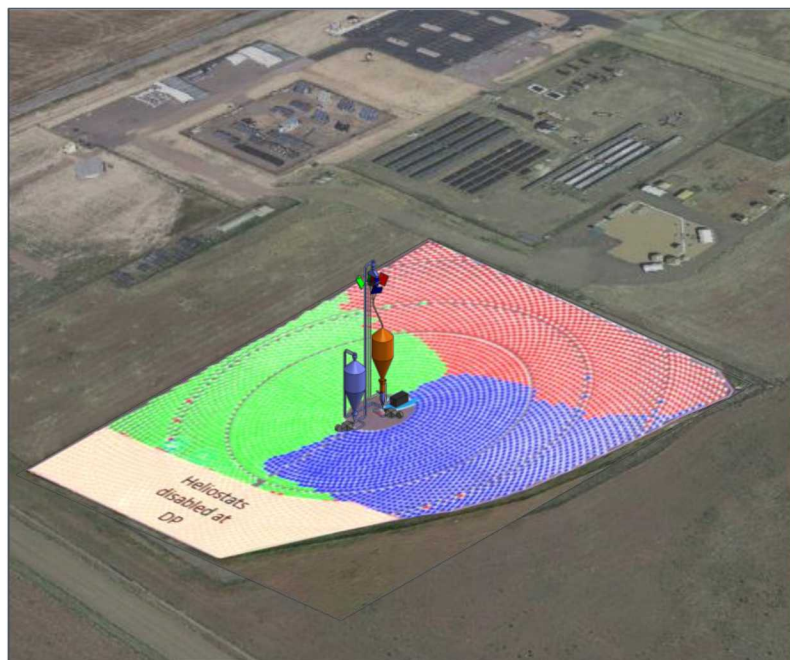


**SOLAR ENERGY
TECHNOLOGIES OFFICE**
U.S. Department Of Energy



Quarterly Report

Gen3 Gas Phase System Development & Demonstration



Principal Investigator: Shaun Sullivan

Other Contributors:    



 **ECHOGEN**
power systems

 **Heliogen**

 **EPRI**

Greg Mehos, Ph.D., P.E.

 **SolarDynamics**

energy.gov/solar-office



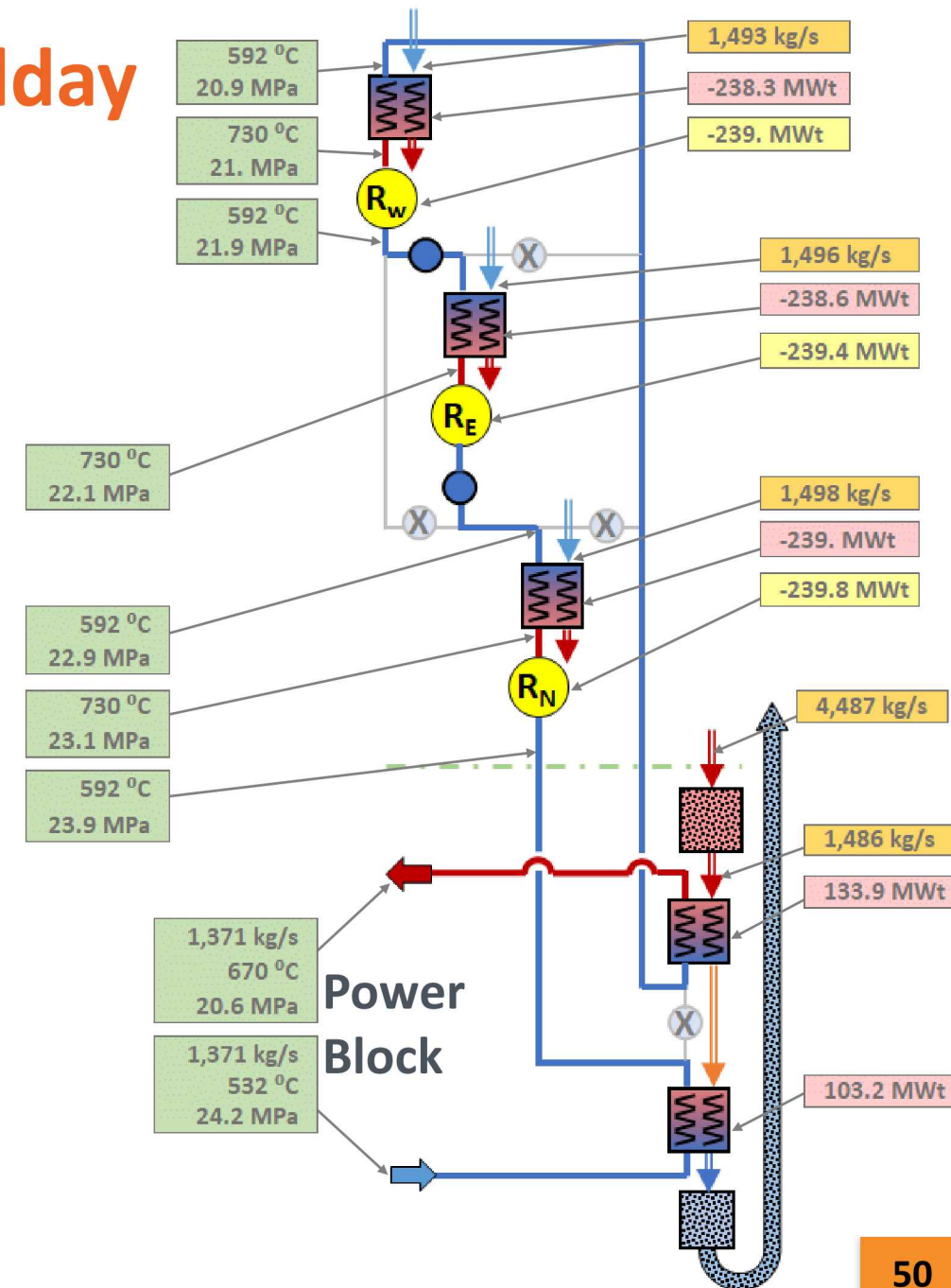
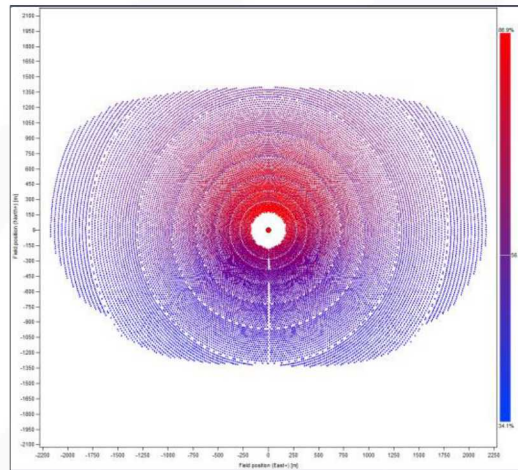
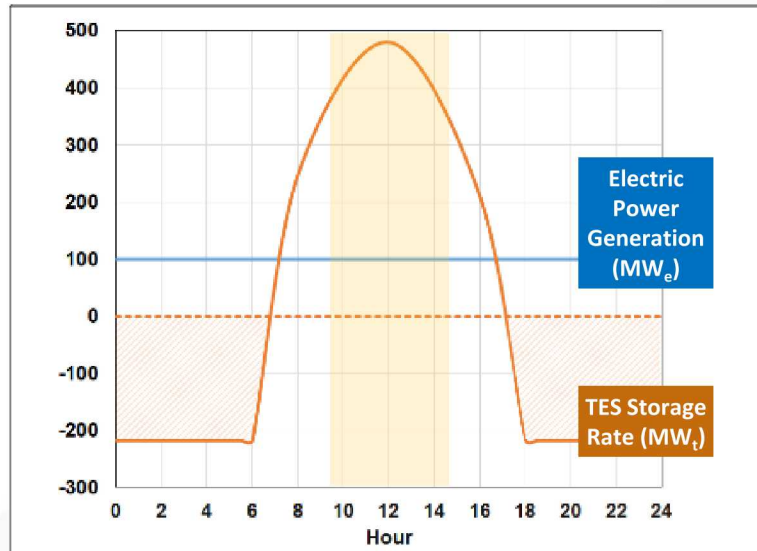
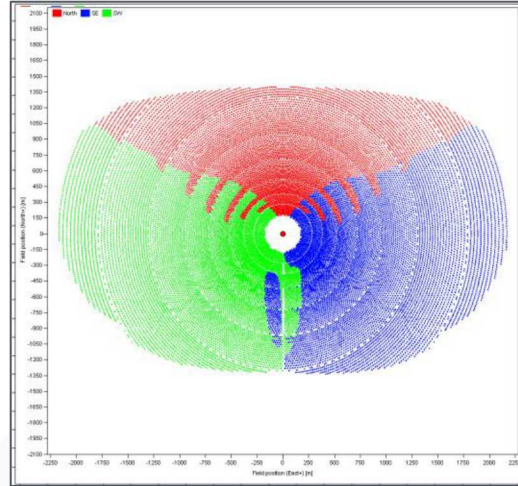
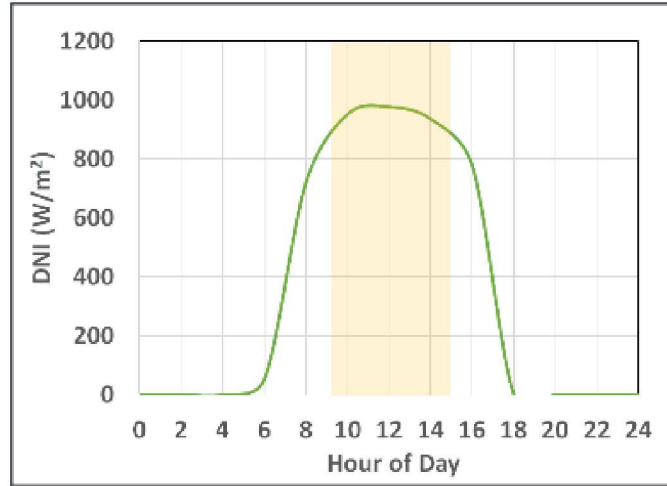
Award # DE-EE0008368

 **SolarTAC**
Technology Acceleration Center

 **SOLEX**
THERMAL SCIENCE

 **WISCONSIN**
UNIVERSITY OF WISCONSIN-MADISON

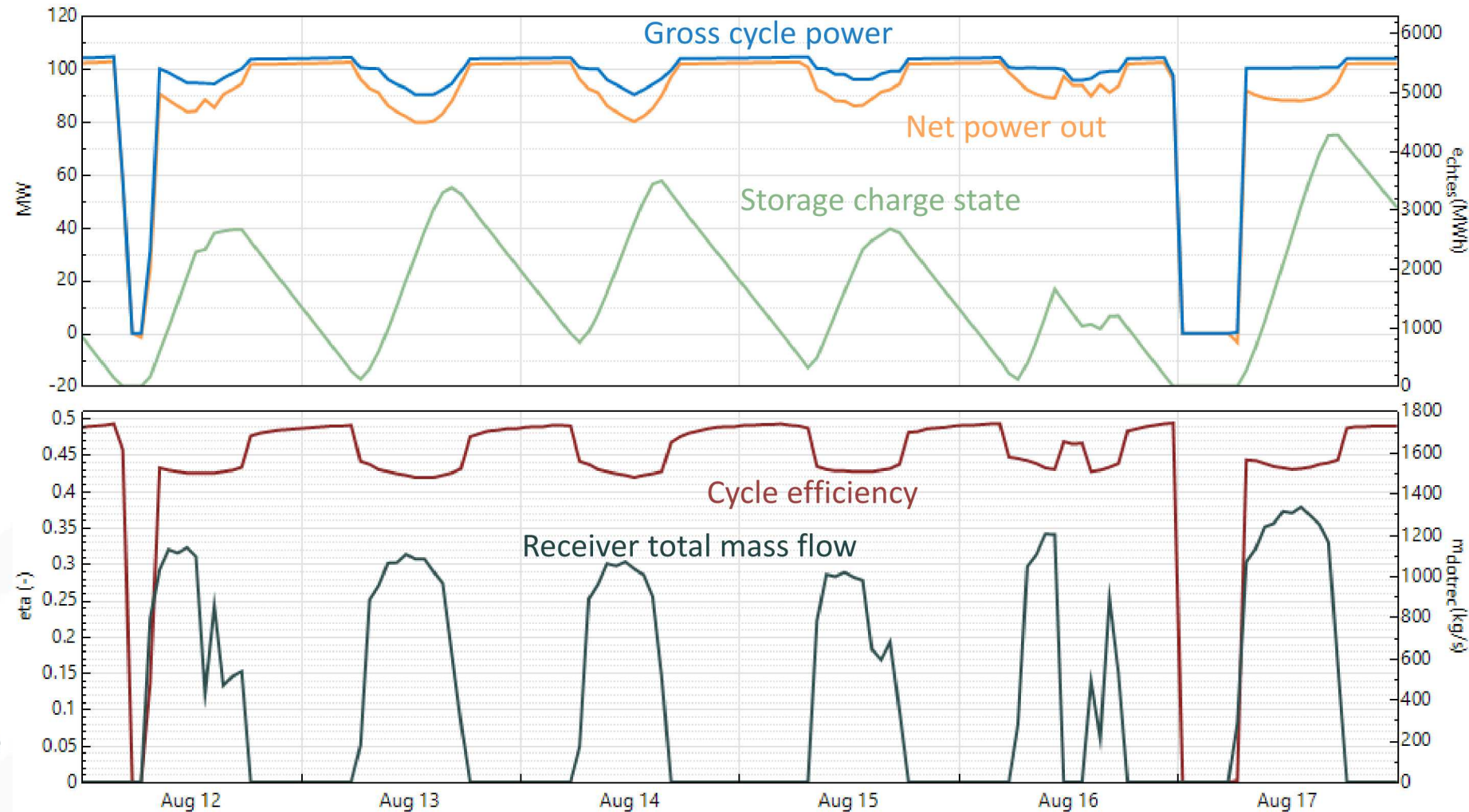
Commercial Baseload Operation: Midday



Integrated Performance and LCOE Modeling

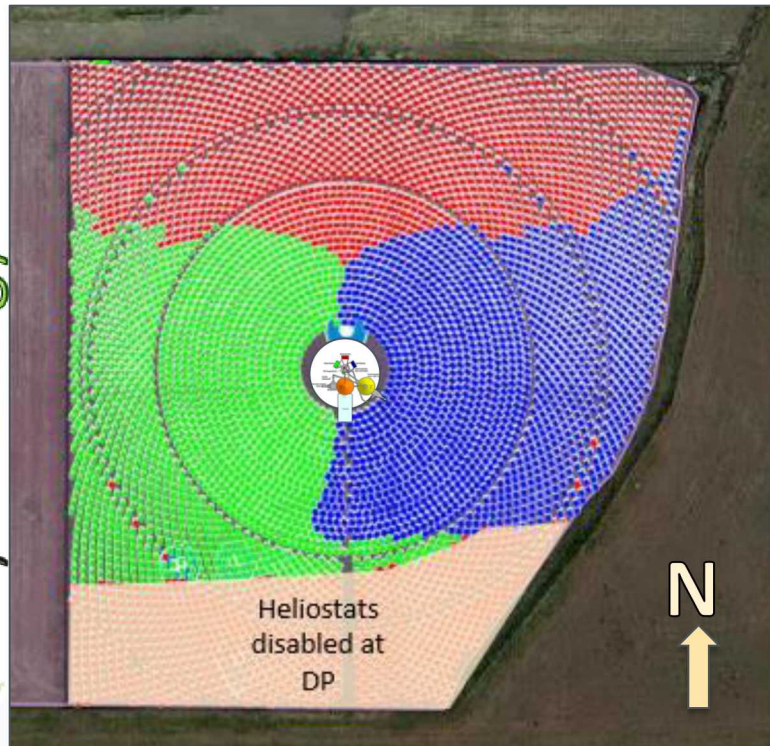
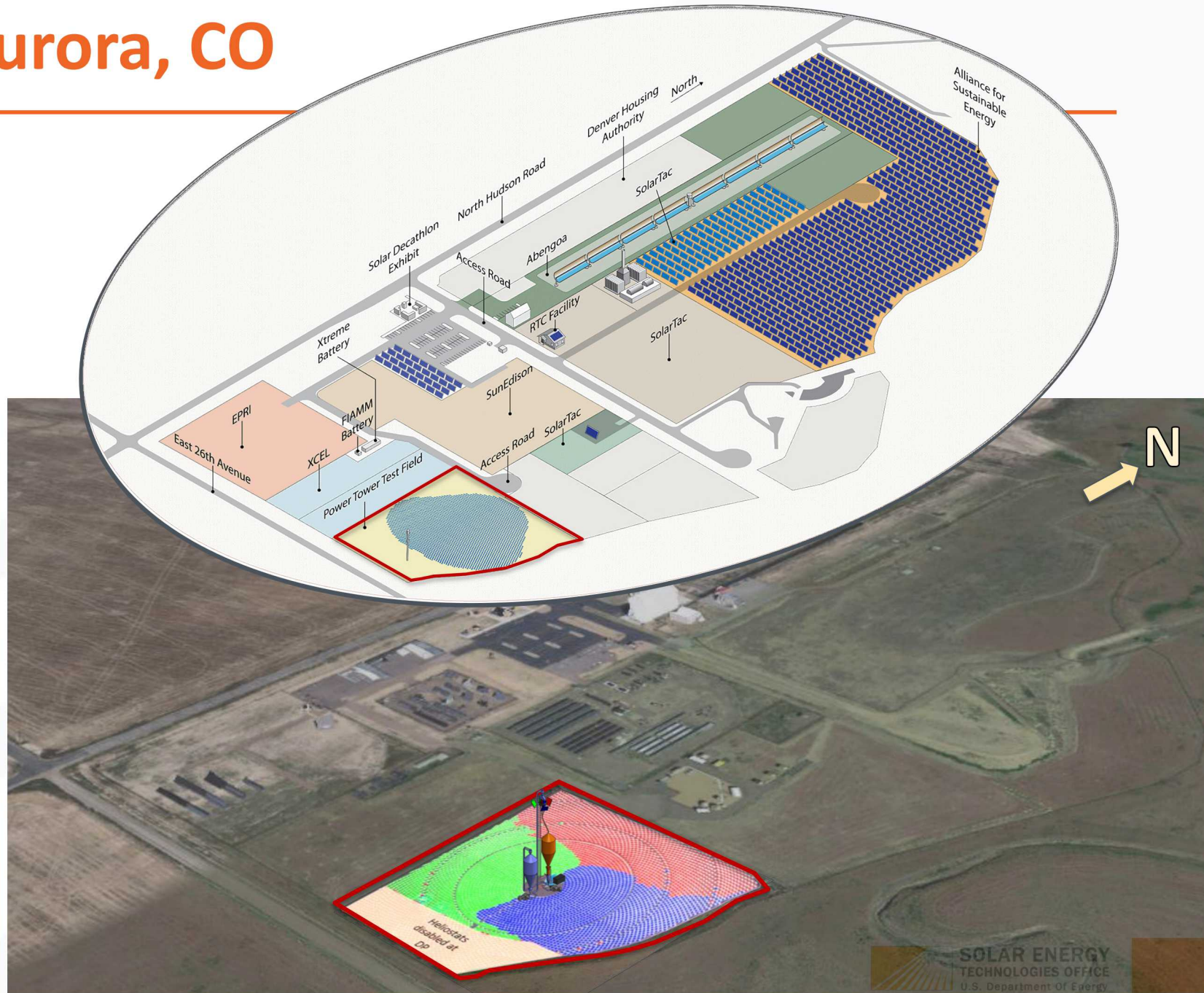
- Initial studies assume baseload configuration
 - Peaker configuration achieved with sCO₂ circulator and independent HTF loop
- Difference between gross and net power due to parasitics (including particle lift)

LCOE < \$0.06/kWh_e

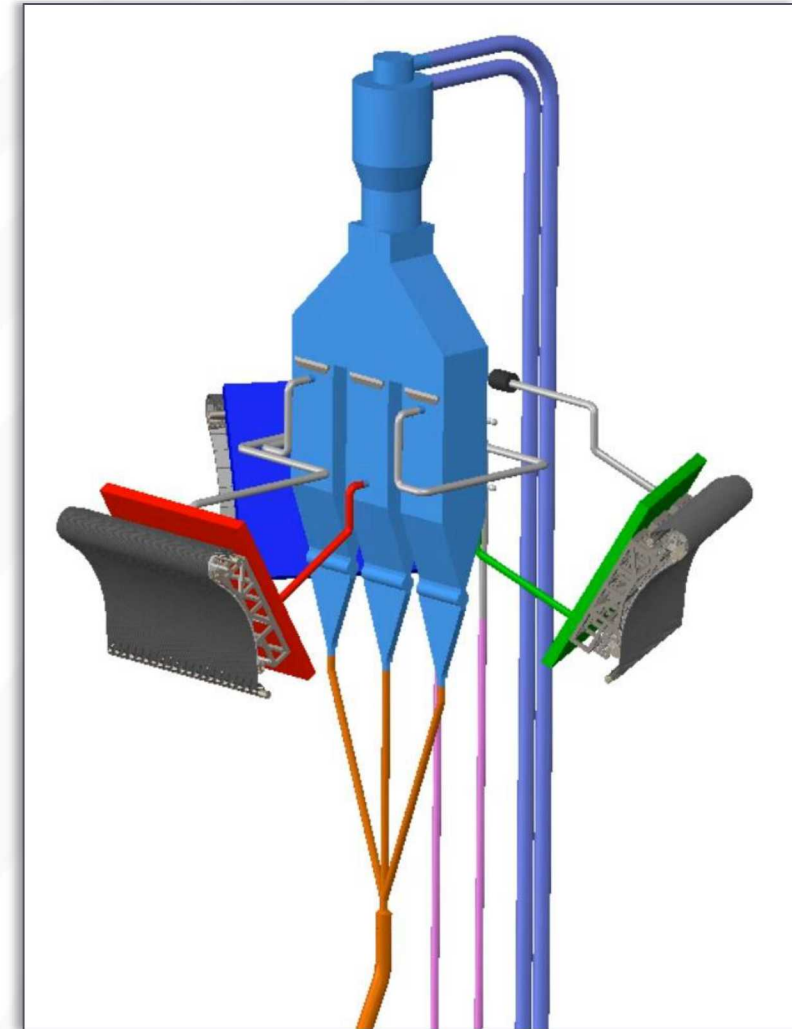
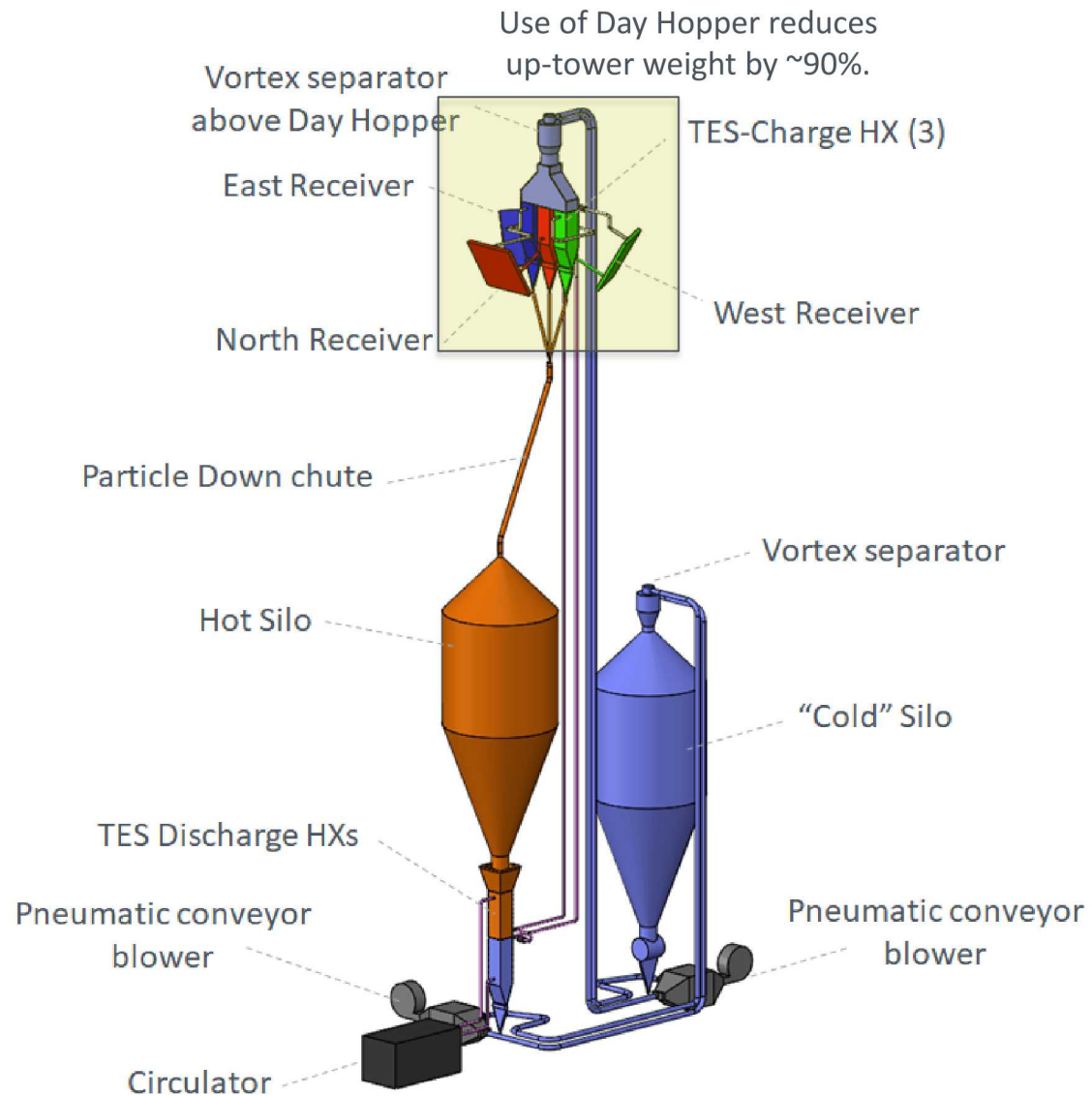


Phase 3 Testing: Aurora, CO

- 3 MW_t System
- 1 MW_t “Power Block”
- Fully representative operation



Phase 3 Layout



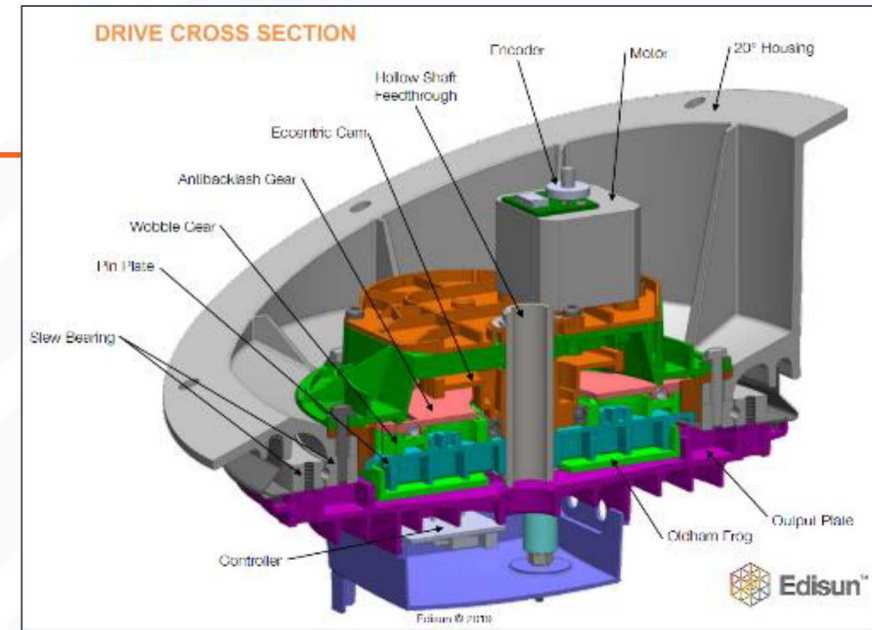
Edisun Heliostats



Heliogen Heliostat

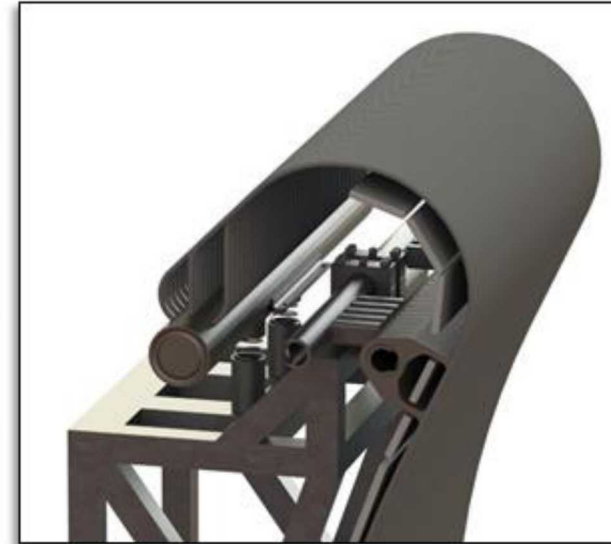
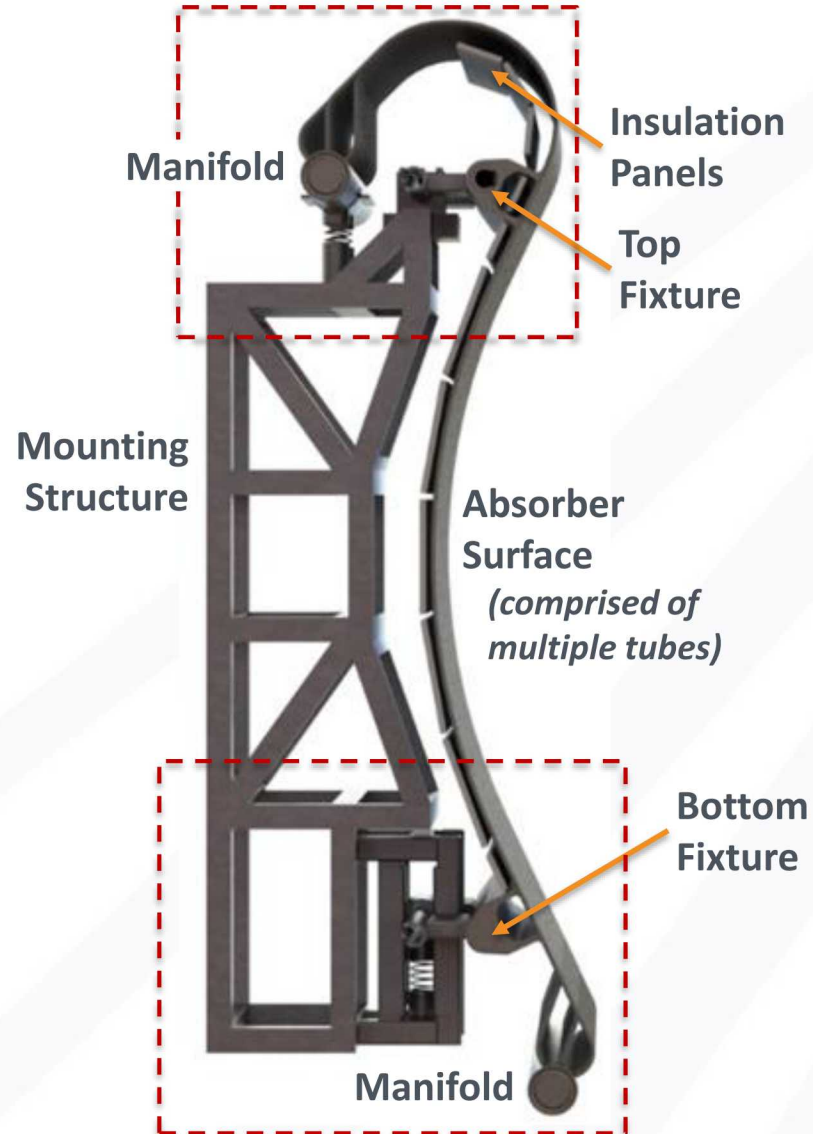
- $\sim 1.5 \text{ m}^2$ Mirrored Area each
 - approaching $\$100/\text{m}^2$, targeting $\$75/\text{m}^2$
- 1 mrad slope error
- 1 mrad aiming error
- Closed loop control

Heliogen Test Facility in Lancaster, CA

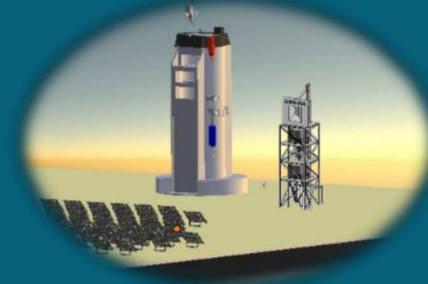


Receiver Layout: Commercial Panel

- Each modular absorber panel is factory built
- Each receiver is comprised of multiple panels



Overview and Design Basis for the Gen 3 Particle Pilot Plant (G3P3)



SolarPACES 2019, October 1 – 4, 2019, Daegu, South Korea

SAND2019-11615 C

Clifford K. Ho, Kevin J. Albrecht, Lindsey Yue, Brantley Mills, Jeremy Sment, Joshua Christian, and Matthew Carlson

Concentrating Solar Technologies
Sandia National Laboratories, Albuquerque, New Mexico, USA

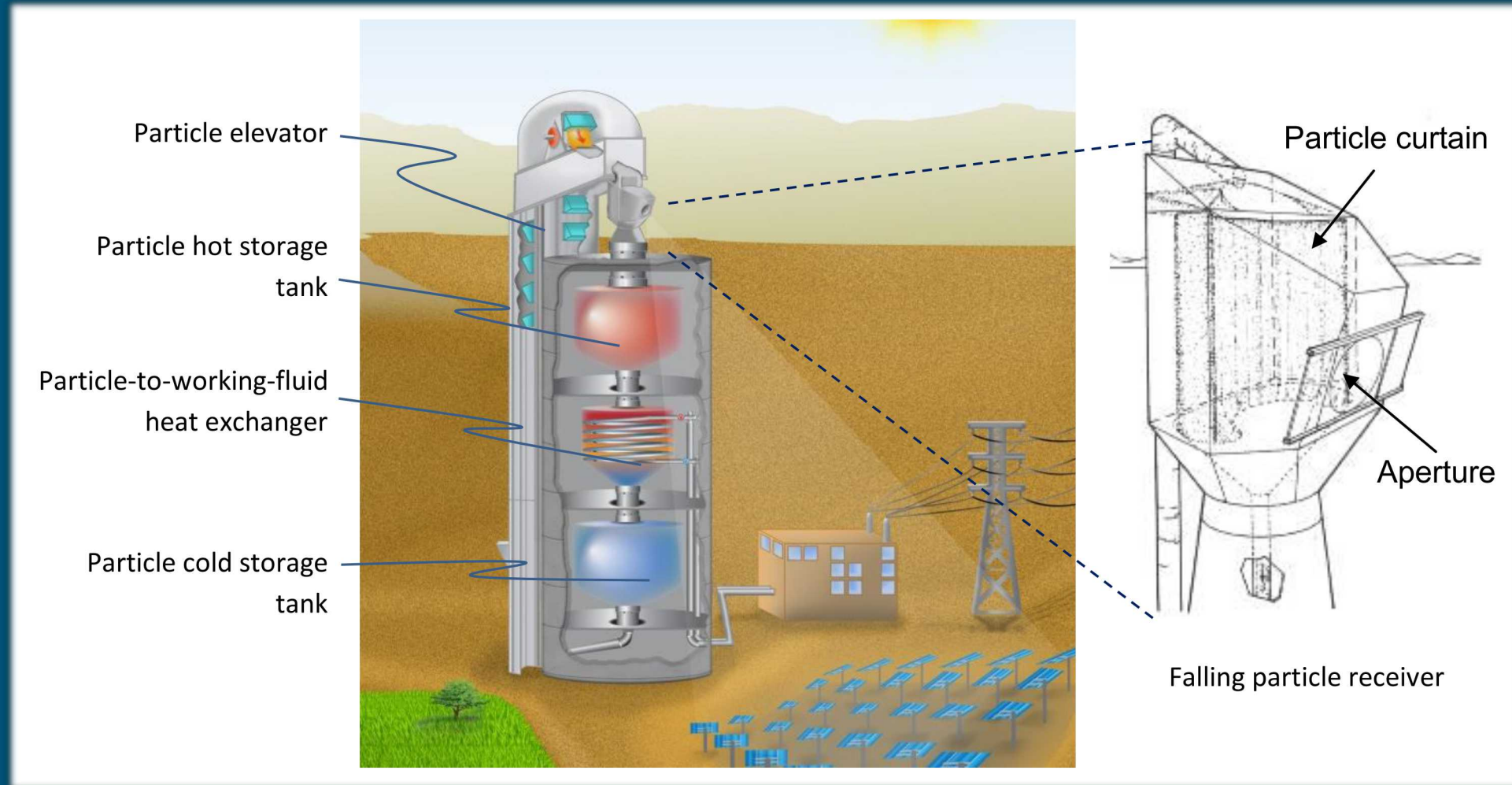
Contributors: Georgia Tech, King Saud University, DLR, CSIRO, U. Adelaide, Australian National University, CNRS-PROMES, EPRI, Bridgers & Paxton, Bohannon Huston, Solar Dynamics, CARBO Ceramics, Solex Thermal Science, Vacuum Process Engineering, Allied Mineral Products, Matrix PDM, Saudi Electricity Company

Large International Team

Role	Team Members	
PI / Management	<ul style="list-style-type: none"> Sandia National Laboratories 	
R&D / Engineering	<ul style="list-style-type: none"> Sandia National Laboratories Georgia Institute of Technology* King Saud University** German Aerospace Center (DLR)** 	<ul style="list-style-type: none"> CSIRO** U. Adelaide** Australian National University** CNRS-PROMES**
Integrators / EPC	<ul style="list-style-type: none"> EPRI* Bridgers & Paxton* / Bohannon Huston 	
CSP Industry	<ul style="list-style-type: none"> SolarDynamics* 	
Component Developers / Industry	<ul style="list-style-type: none"> Carbo Ceramics Solex Thermal Science** Vacuum Process Engineering* FLSmidth 	<ul style="list-style-type: none"> Materials Handling Equipment Allied Mineral Products* Matrix PDM*
Utility	<ul style="list-style-type: none"> Saudi Electricity Company** 	

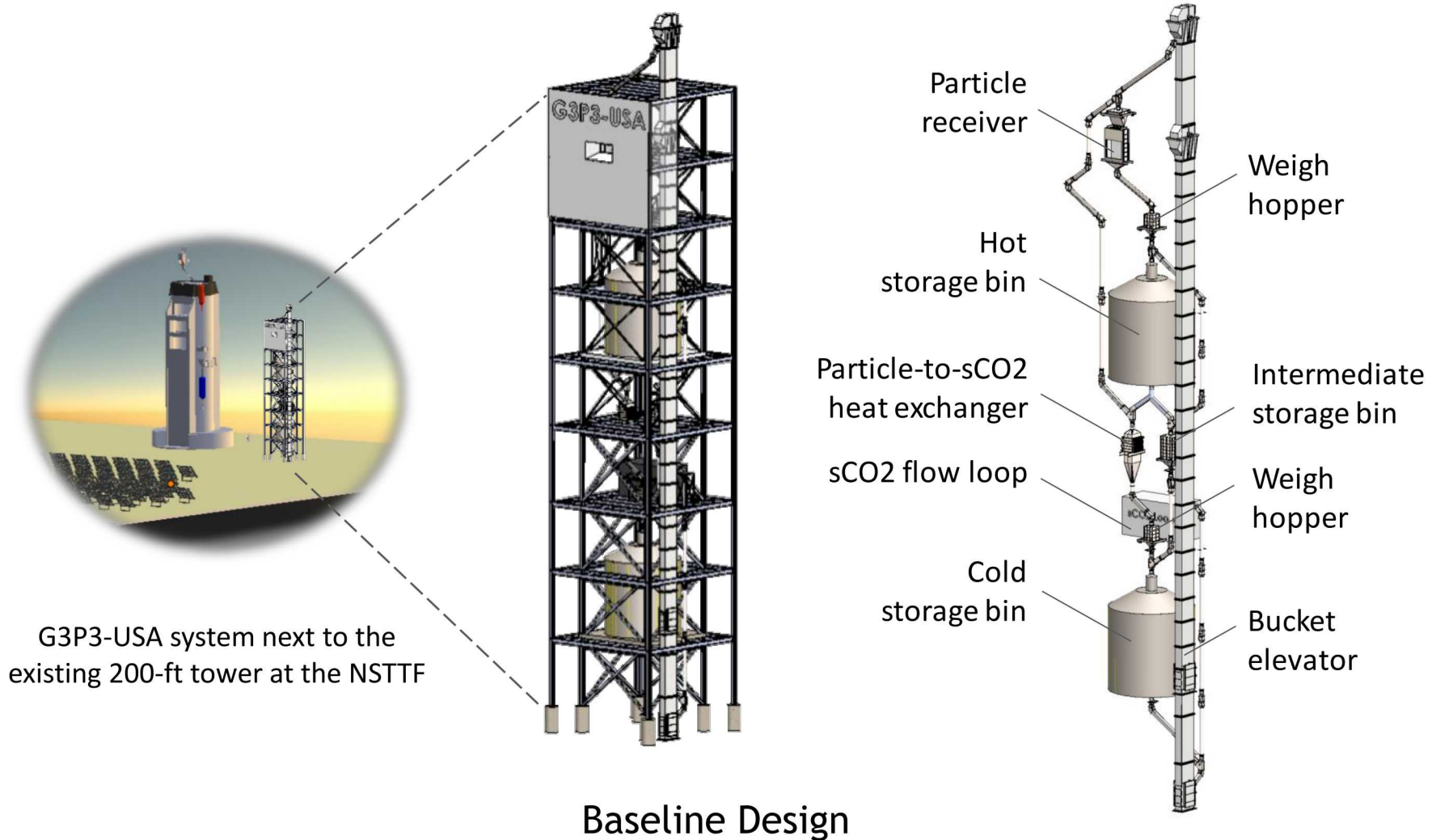
*15 subcontracts (**8 international)

High-Temperature Falling Particle Receiver



Goal: Achieve higher temperatures, higher efficiencies, and lower costs

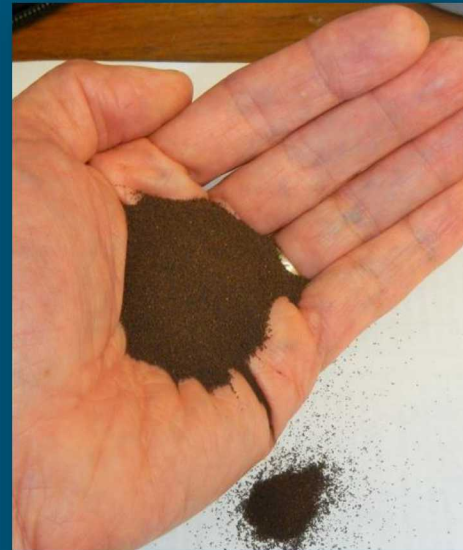
Gen 3 Particle Pilot Plant (G3P3) Integrated System



Particles

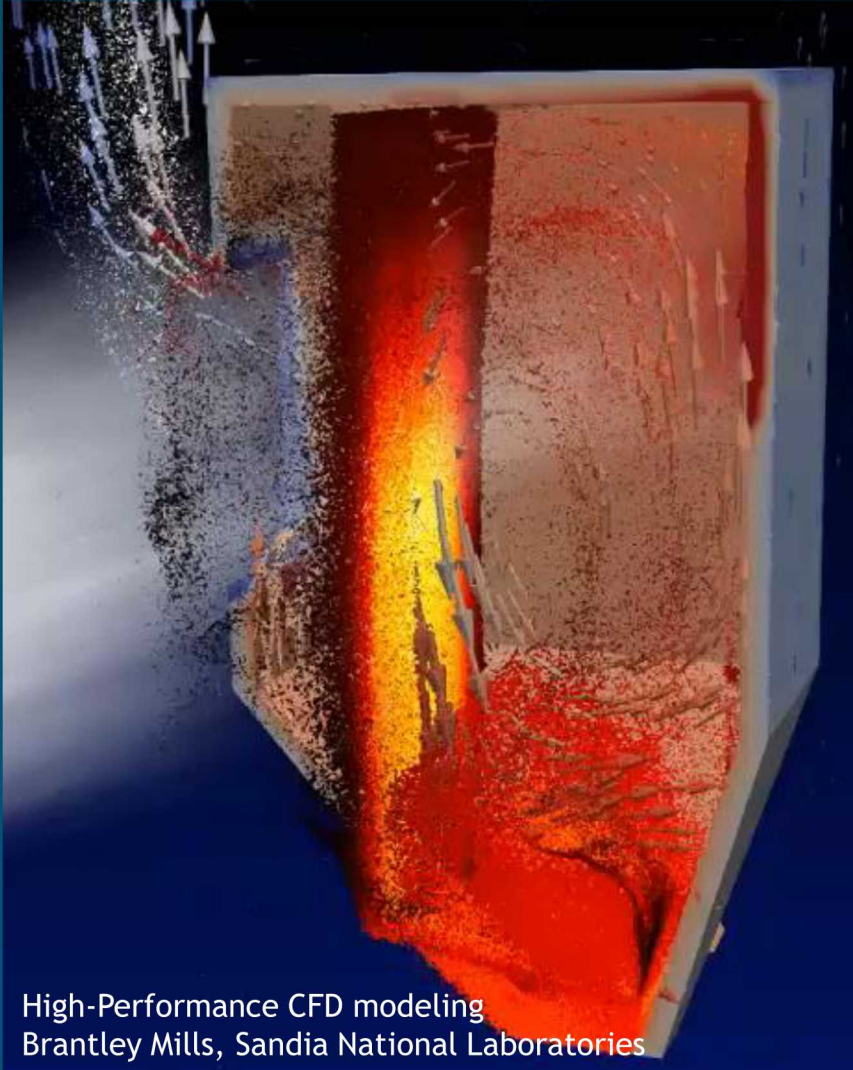


- Cost
 - $\leq \$1/\text{kg}$
- Durability
 - Low wear/attrition
- Optical properties
 - High solar absorptance
- Flowability, low erosion
- Inhalation hazards (e.g., silica, PM2.5)



CARBO HSP 40/70

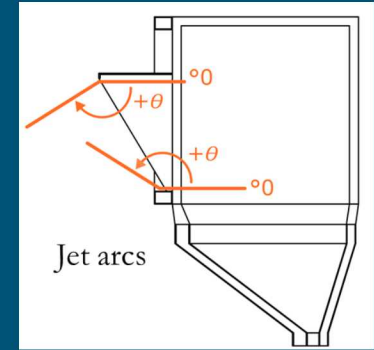
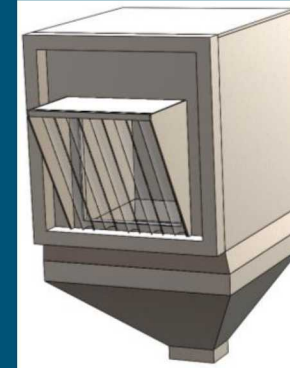
Other Receiver Innovations



High-Performance CFD modeling
Brantley Mills, Sandia National Laboratories



Quartz aperture covers
(SNL, DLR; Yue et al., 2019)

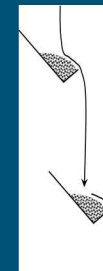
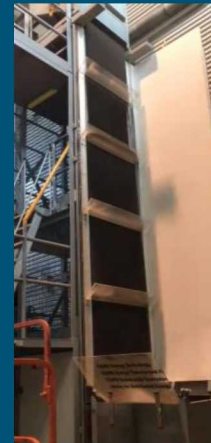


Active airflow (SNL, ANU,
Adelaide; Yue et al., 2019)

Free Falling

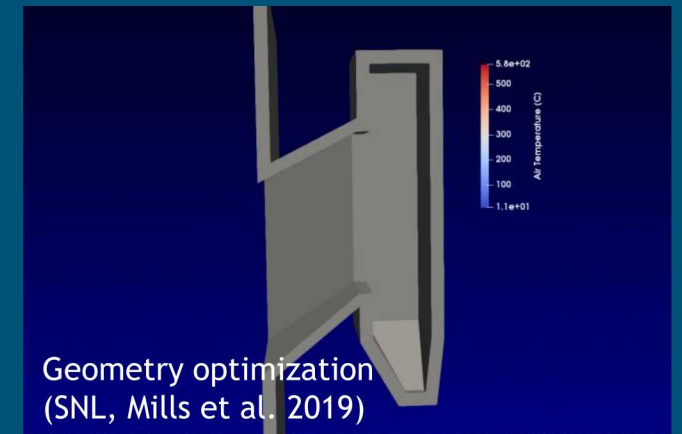
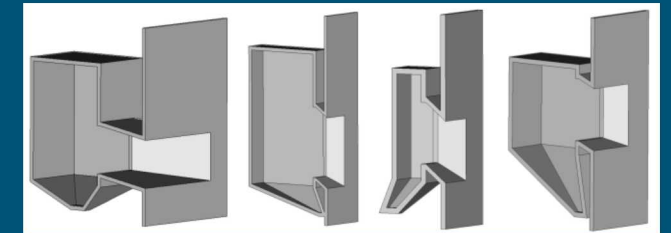


Catch-and-Release



Multi-stage release
(CSIRO, SNL, Adelaide, ANU; Kim et al., 2019)

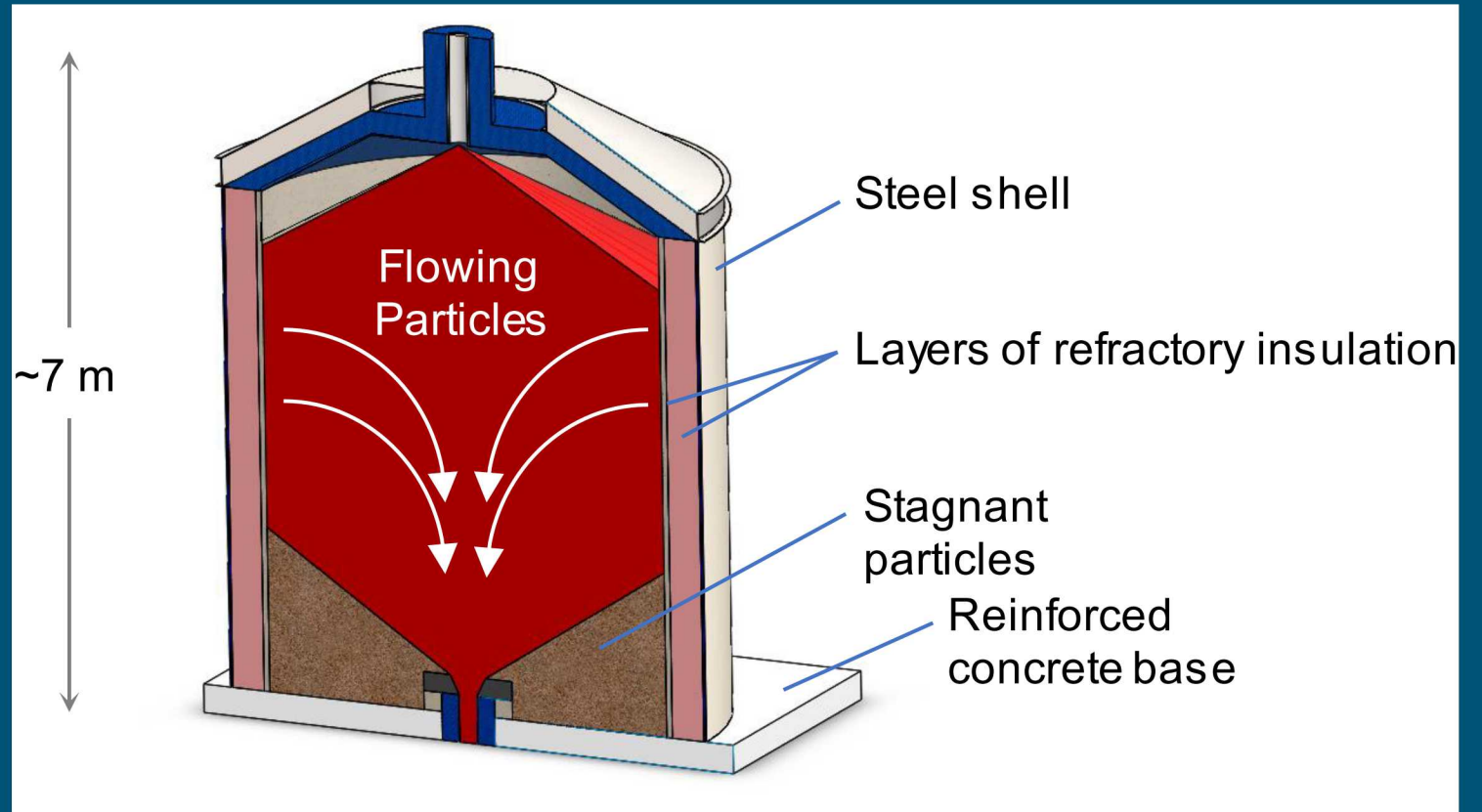
Videos from Jin-Soo Kim (CSIRO)



Geometry optimization
(SNL, Mills et al. 2019)

G3P3 Storage Tank Design

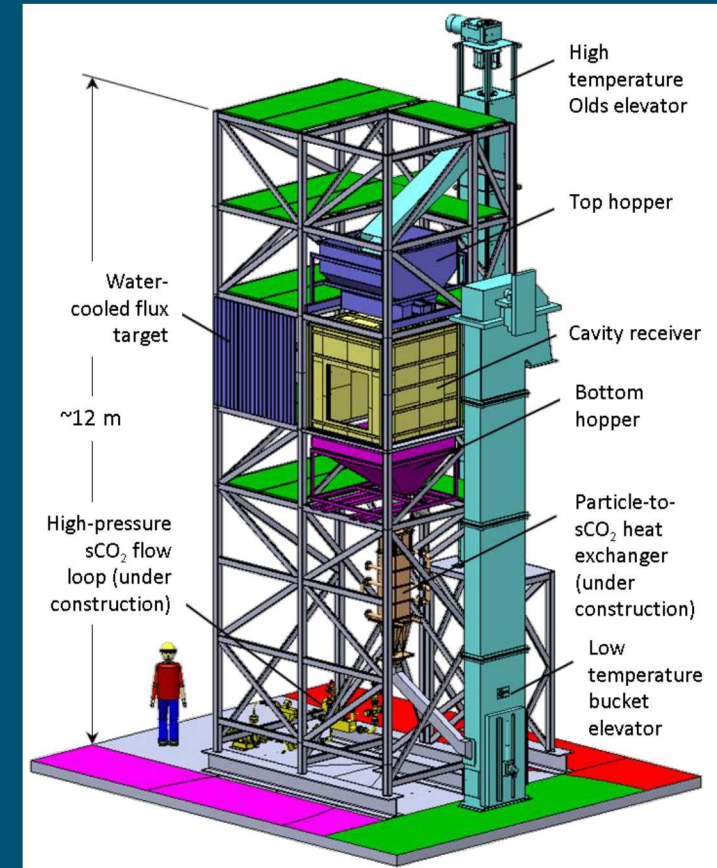
- 160,000 kg of particles
 - 40,000 kg stagnant
 - $\sim 80 \text{ m}^3$ volume
- Goal is $< 10^\circ \text{C}$ temperature drop over 10 hours



Design intended to reduce heat losses, minimize wall erosion, and reduce costs

G3P3 Summary

- Significant advantages
 - Direct heating of particles
 - Wide temperature range (sub-zero to $>1000\text{ }^{\circ}\text{C}$)
 - Inexpensive, durable, non-corrosive, inert
 - Demonstrated ability to achieve $>700\text{ }^{\circ}\text{C}$ on-sun with hundreds of hours of operation
- Gaps and risks being addressed
 - Heat loss (receiver, storage, heat exchanger, lift)
 - Particle-to-working-fluid heat transfer
 - Particle attrition and wear
 - Thermomechanical stresses and erosion in heat exchanger and storage tanks
 - Scale-up to commercial applications



On-sun testing of the falling particle receiver at Sandia National Laboratories

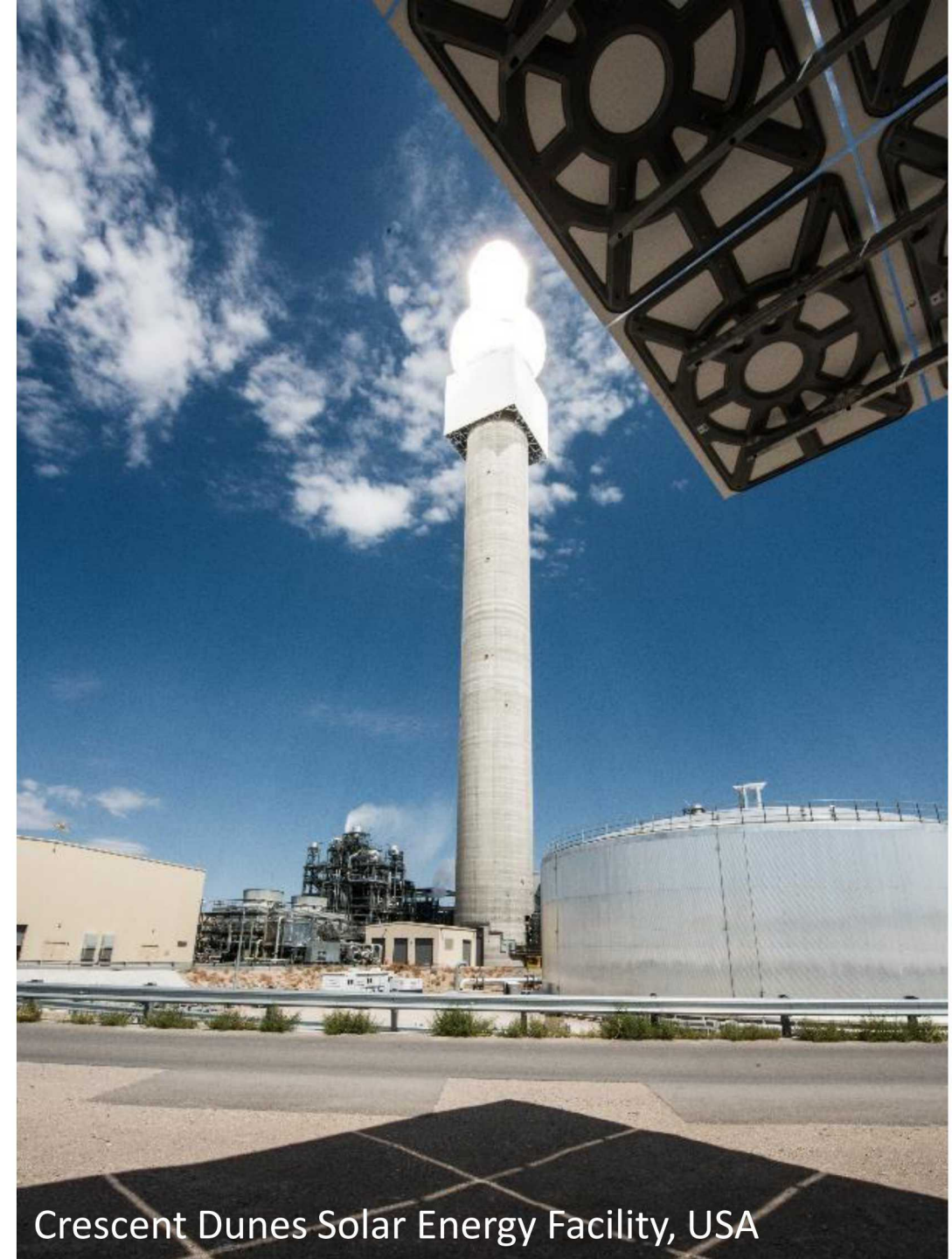
Molten Chloride Salts for Thermal Energy Storage

Heat Storage for Gen IV Reactors for Variable Electrify
from Base-Load Reactors

Idaho Falls, ID

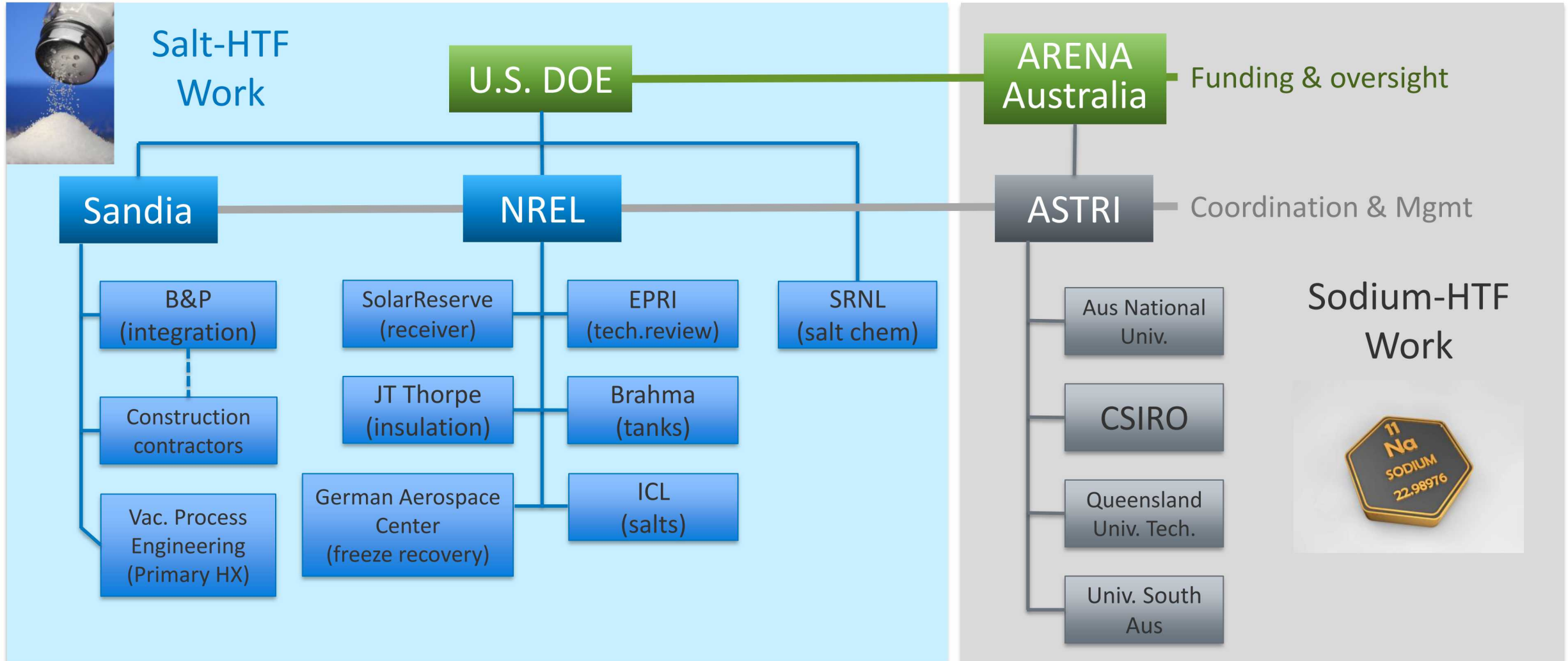
July 23-24, 2019

Craig Turchi, PhD
Thermal Sciences Group
National Renewable Energy Laboratory
craig.turchi@nrel.gov



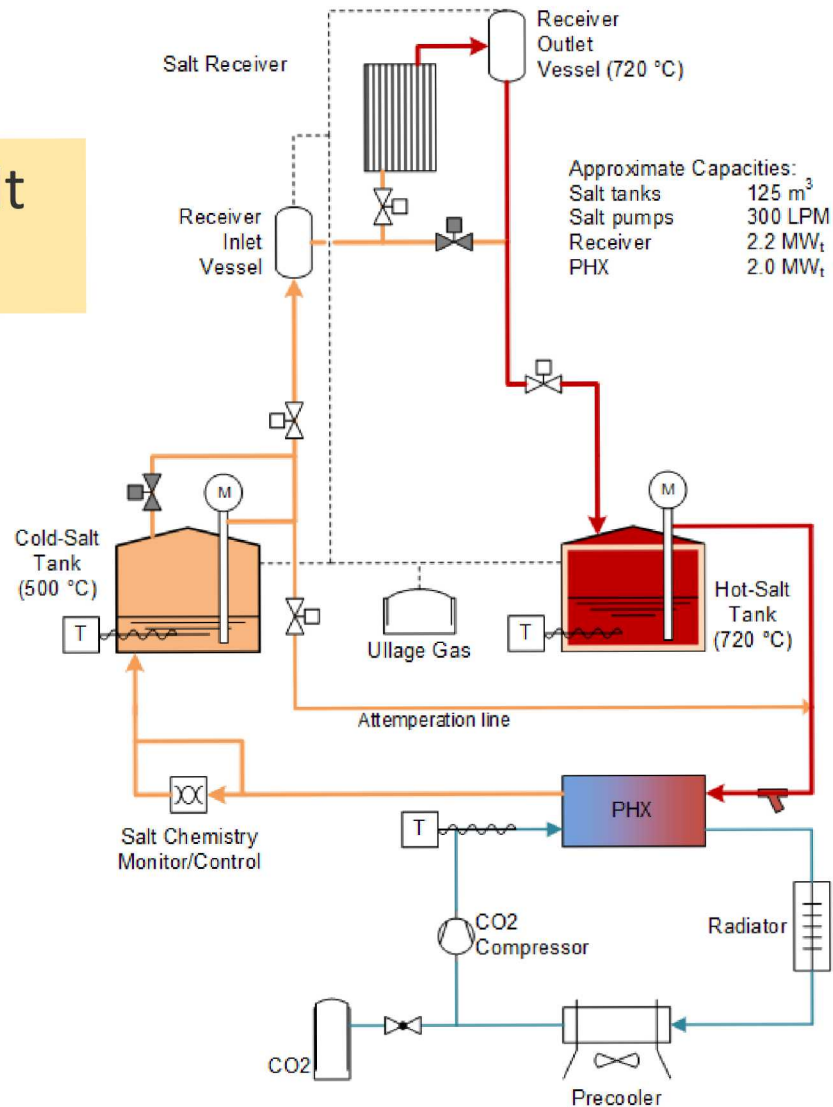
Crescent Dunes Solar Energy Facility, USA

Liquid Pathway Team

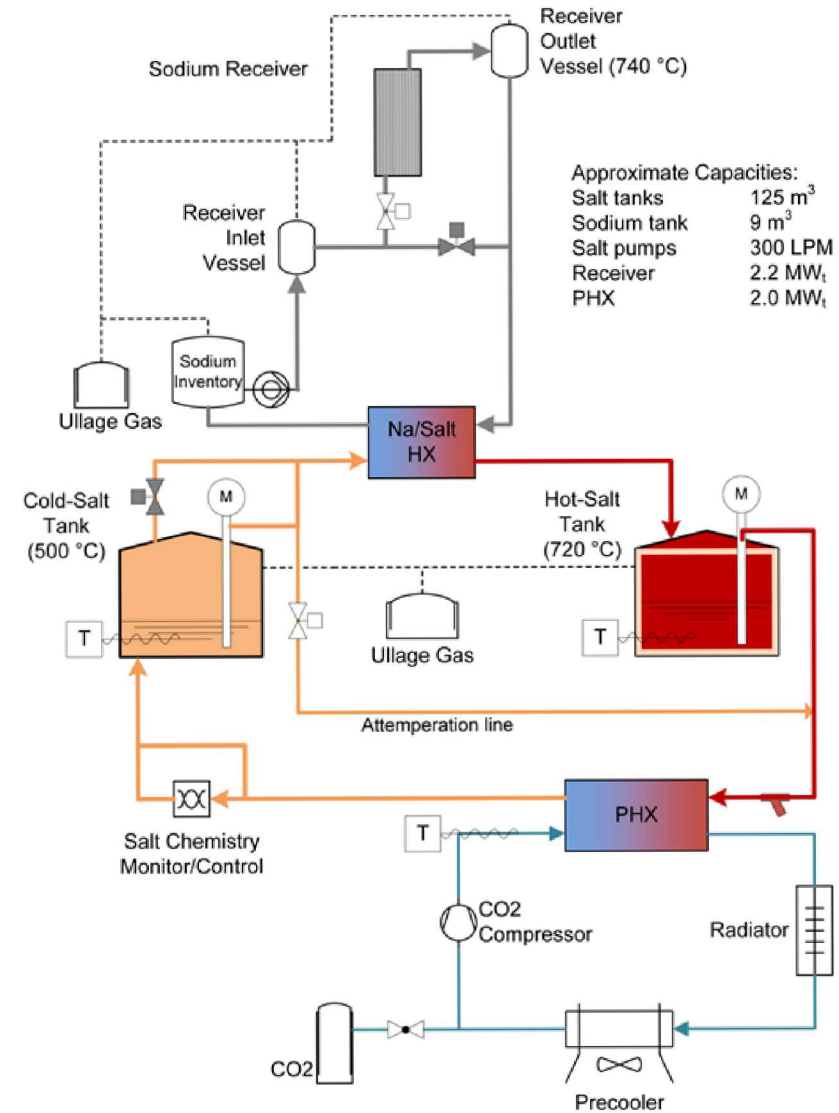


Liquid-HTF Pilot System Alternatives

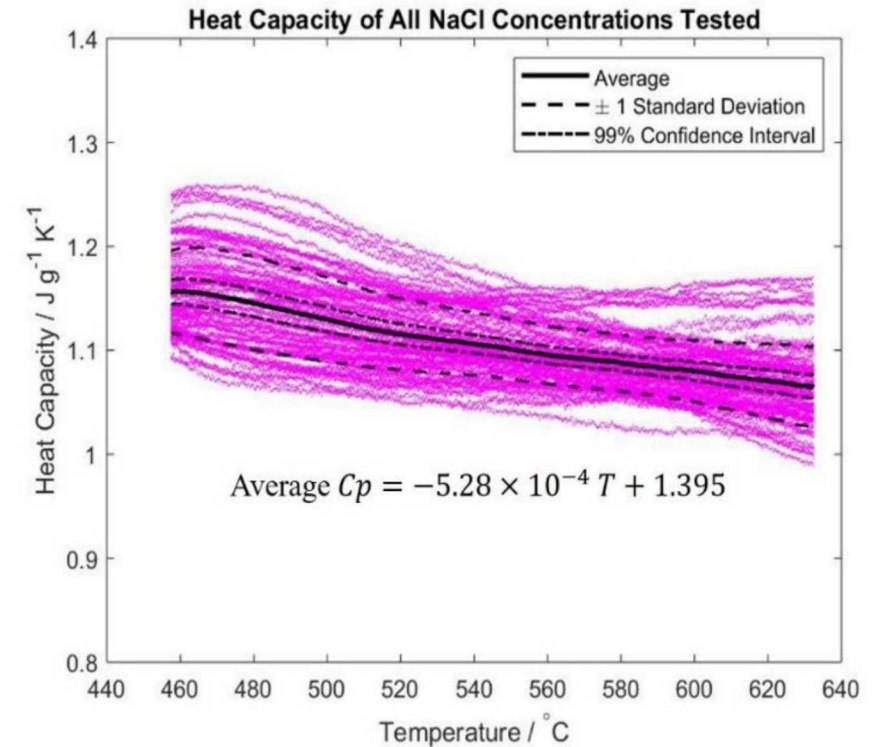
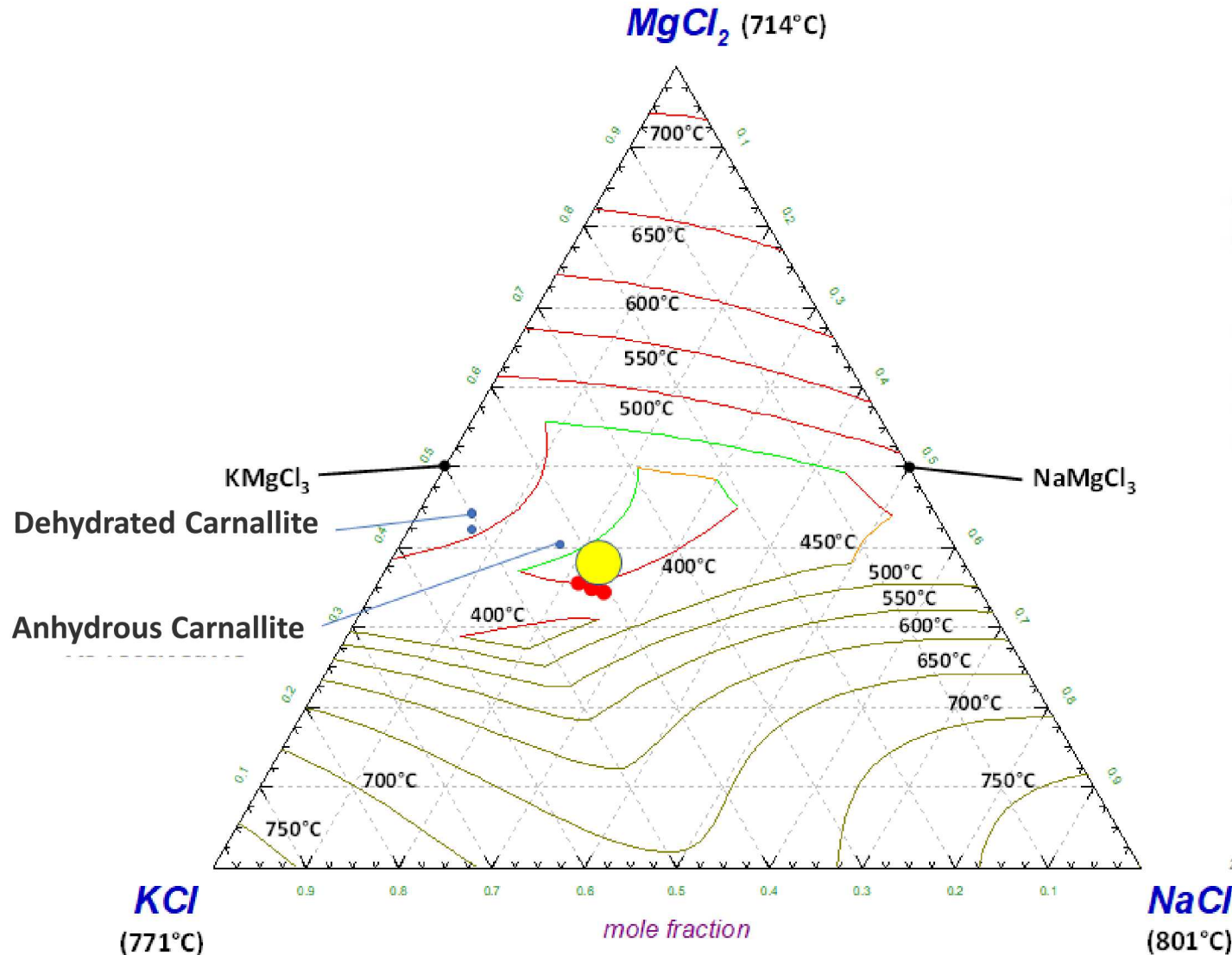
Cl-Salt HTF



Sodium HTF



Optimizing Chloride-Salt Formulation



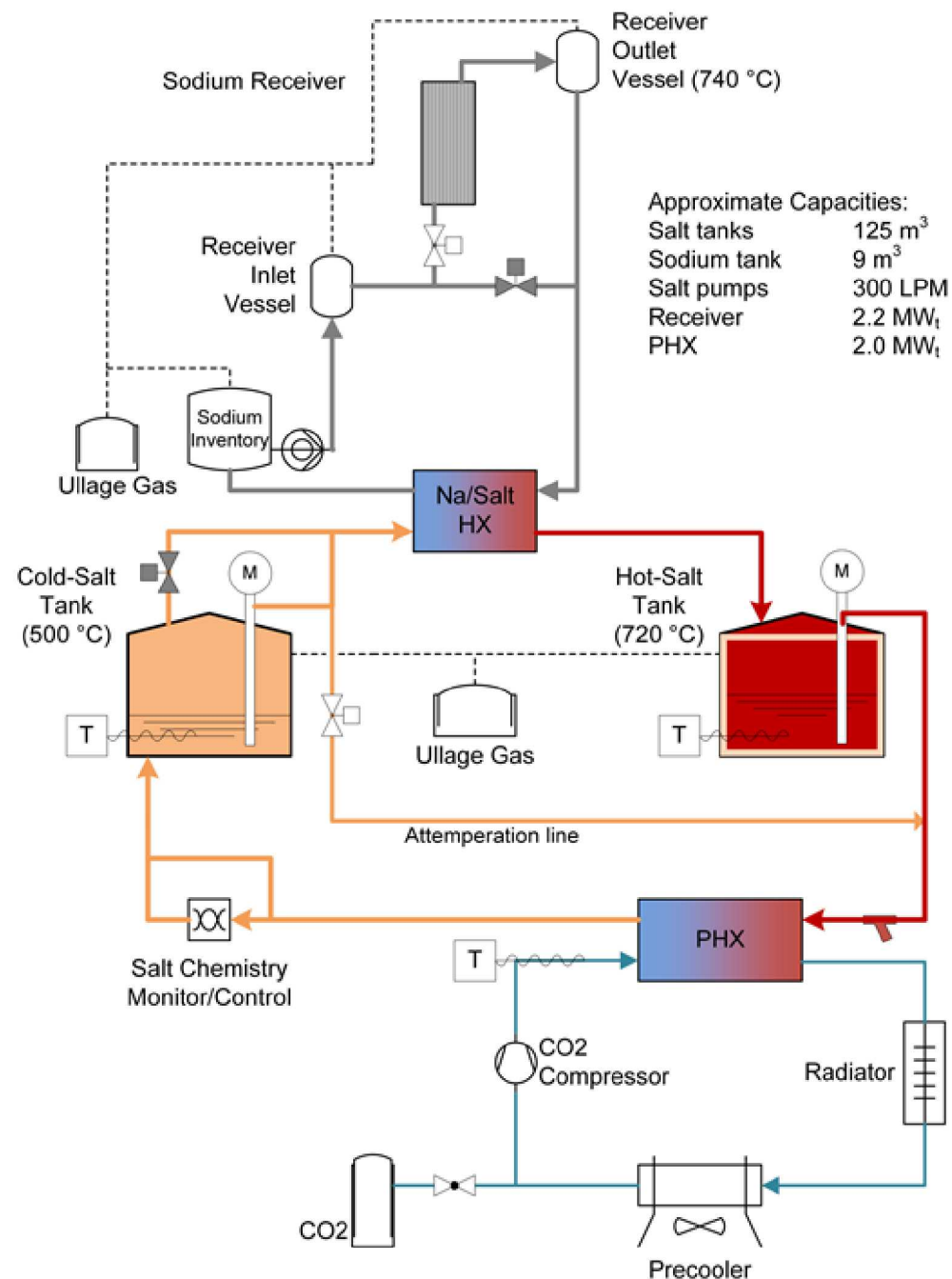
Phase diagram of Na/K/Mg-Chloride modeled with FactSage [Mohan et al., Energy Conversion and Management 167 (2018).



The Case for Sodium

CSP considering the use of liquid sodium for the solar receiver:

- ✓ >100x higher thermal conductivity
- ✓ $T_{mp} = 98\text{ }^{\circ}\text{C}$ vs. $420\text{ }^{\circ}\text{C}$ for salt
- ✓ Lower corrosivity





Optics and autonomy

Progress Toward Commercial Deployment of sCO₂ Brayton Power Cycles

New autonomous in-situ optics tools



Sandia
National
Laboratories

Near-Field Target (UFACET)

Develop algorithm to measure:

- Canting error at multiple points
- Slope error at multiple lines

Far-Field Target (NIO)

Develop algorithm to measure:

- Slope error over the surface
- Canting errors relative to a reference mirror facet
- Tracking error of heliostats



Validate both methods on slope error and canting error.

Integrated Application Steps

3. Perform canting correction on the identified heliostats in the field.

1. Survey over the field
 - Slope error, canting error
2. Ensure design conditions of neighboring heliostats and derive best canting strategy

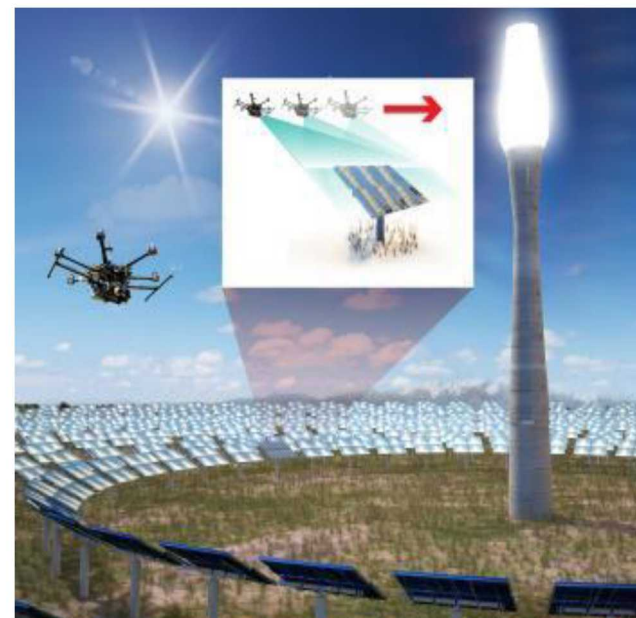
4. Survey over the field for tracking error

5. Validate and monitor solar field performance

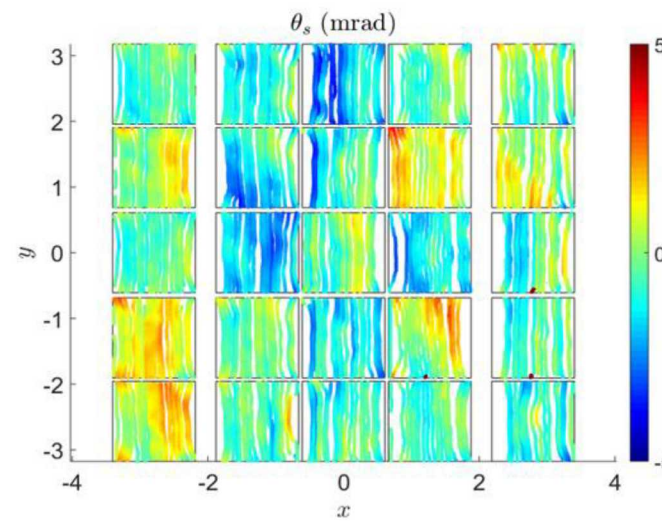
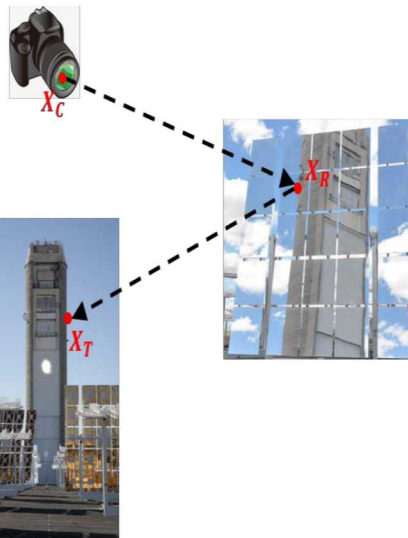
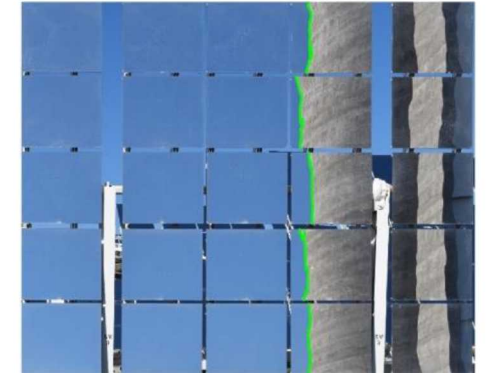
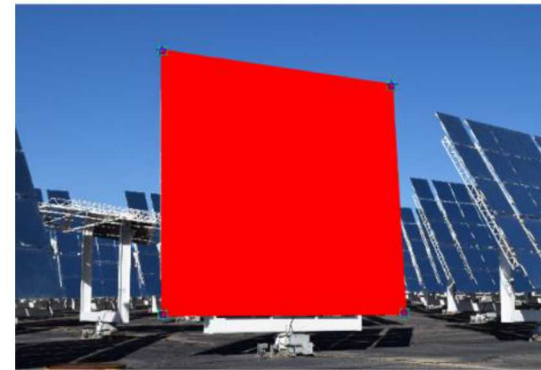
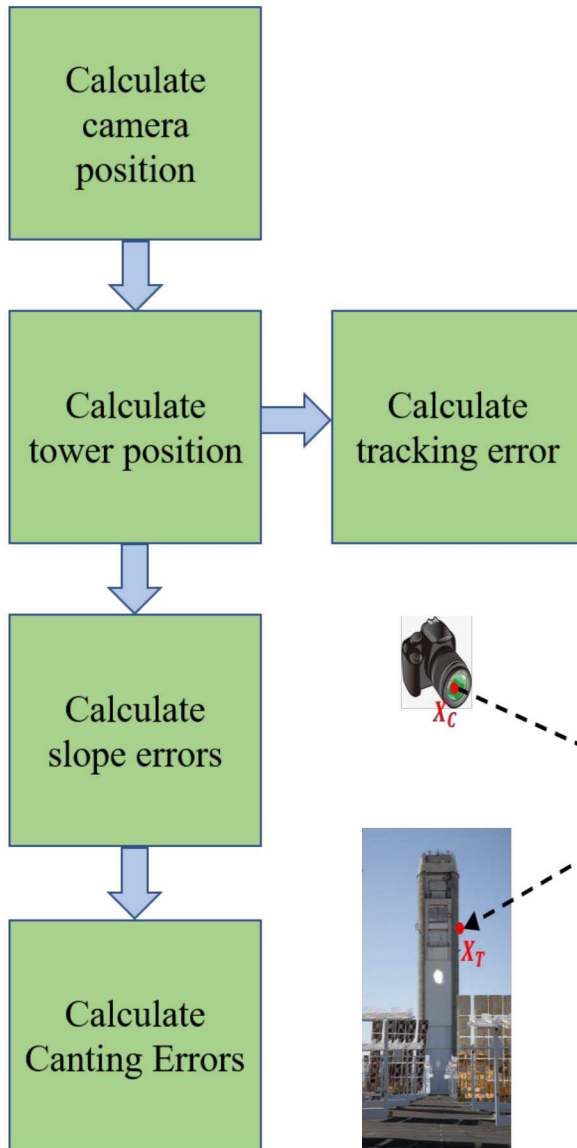
6. Investigate temporal effects of heliostat optical errors, due to installation errors, temperature, partial illumination, gravity, wind, etc.

Non-Intrusive Optical (NIO) Method

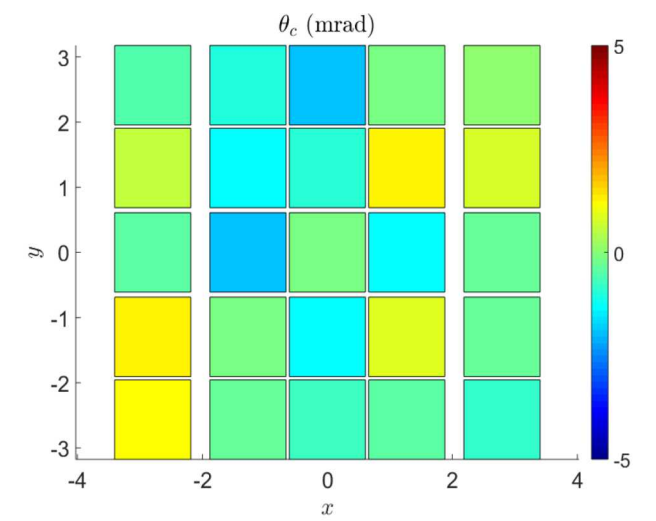
- Use a drone-driven camera to collect reflection images.
- Use photogrammetry and image-processing (coupled with machine learning) techniques to calculate
 - mirror slope error,
 - mirror-facet canting error
 - heliostat tracking error.



Approach



Slope Error Map

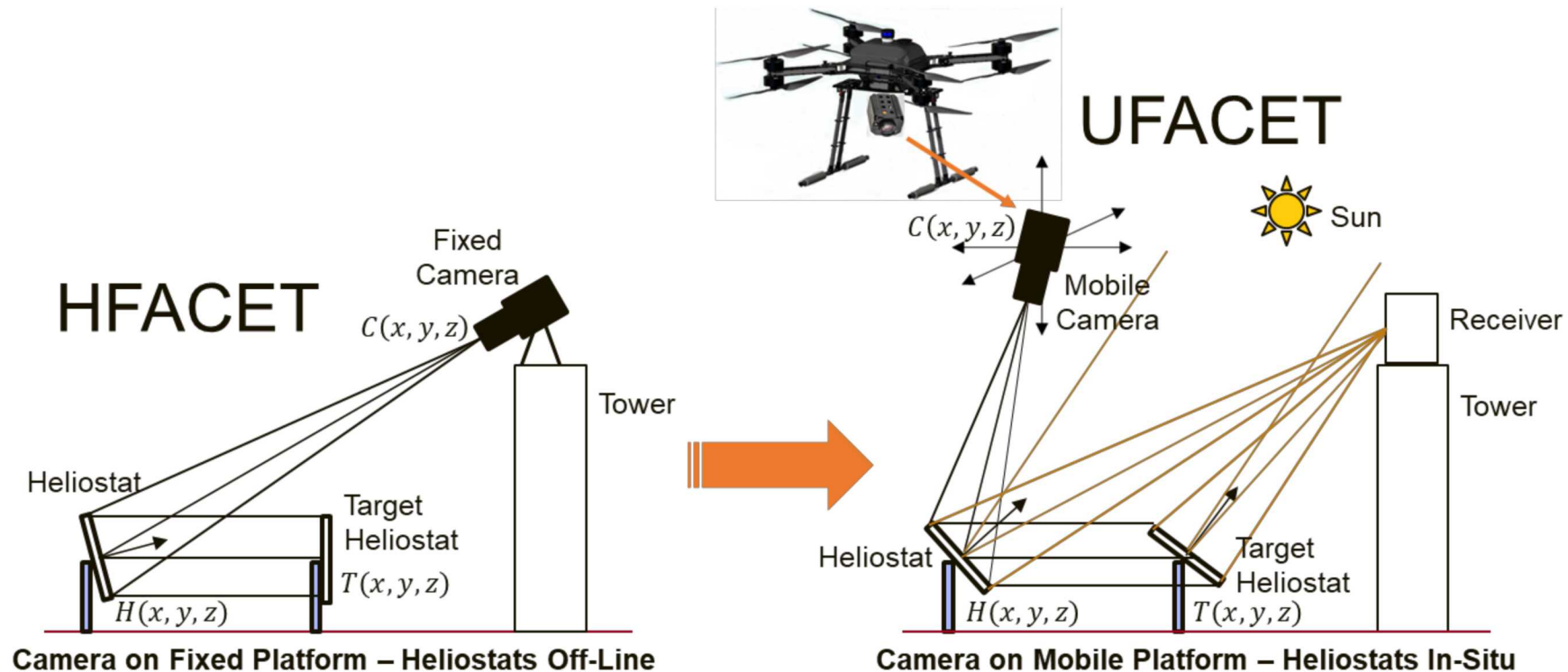


Canting Error Map

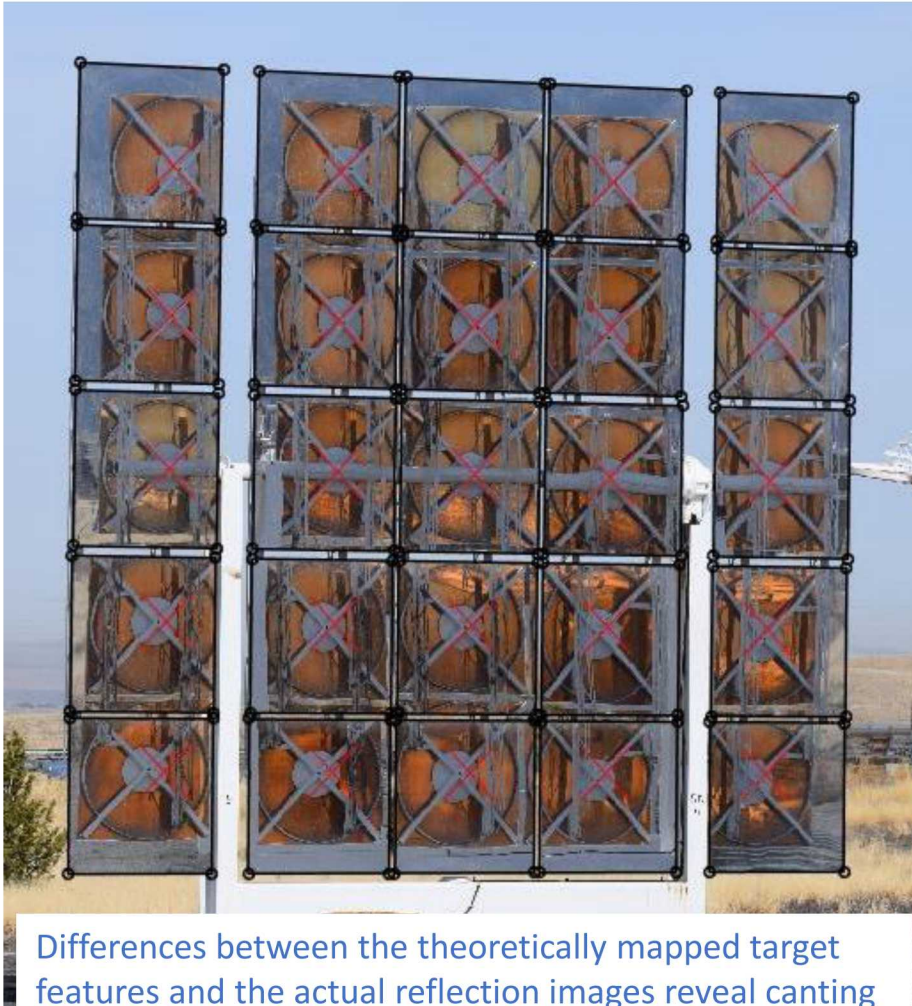
HFACET + UAS = UFACET



- **UFACET** builds on **HFACET**, which is a heliostat assessment tool that was developed at Sandia and successfully implemented at the NSTTF.
- New innovations include attaching the camera to a mobile platform (UAS), which can follow pre-determined paths to assess optical performance parameters of the field, and developing new methods to measure mirror reflectance and slope error on in-situ heliostats.

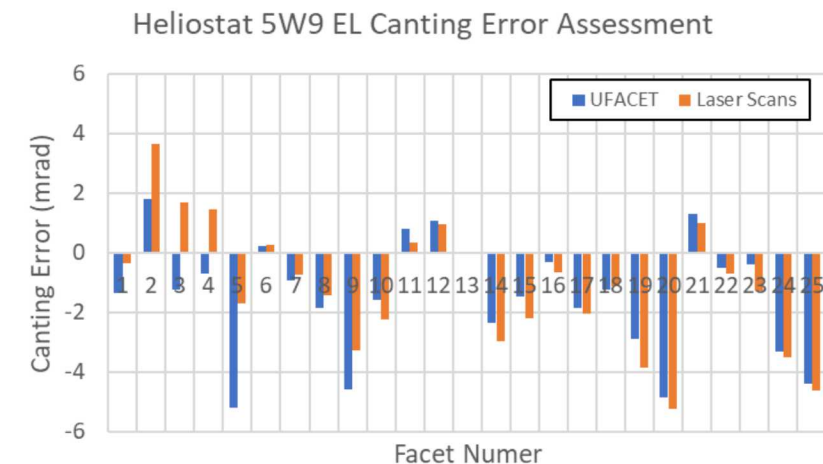
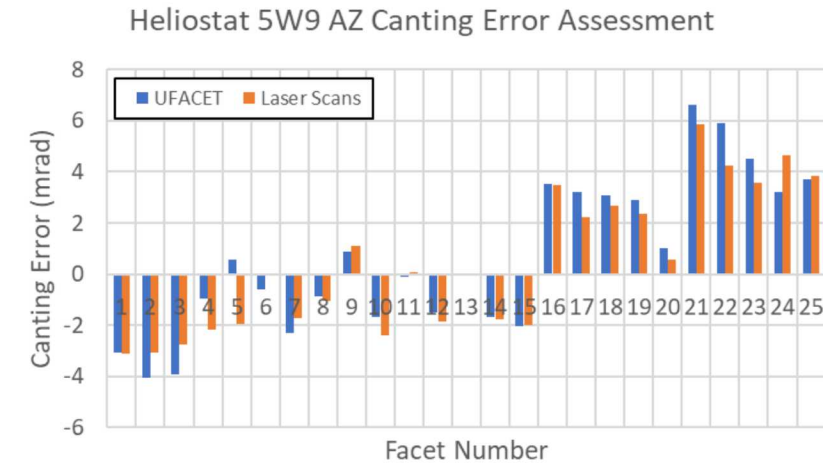


Canting Error Assessments on 5W9



Differences between the theoretically mapped target features and the actual reflection images reveal canting errors.

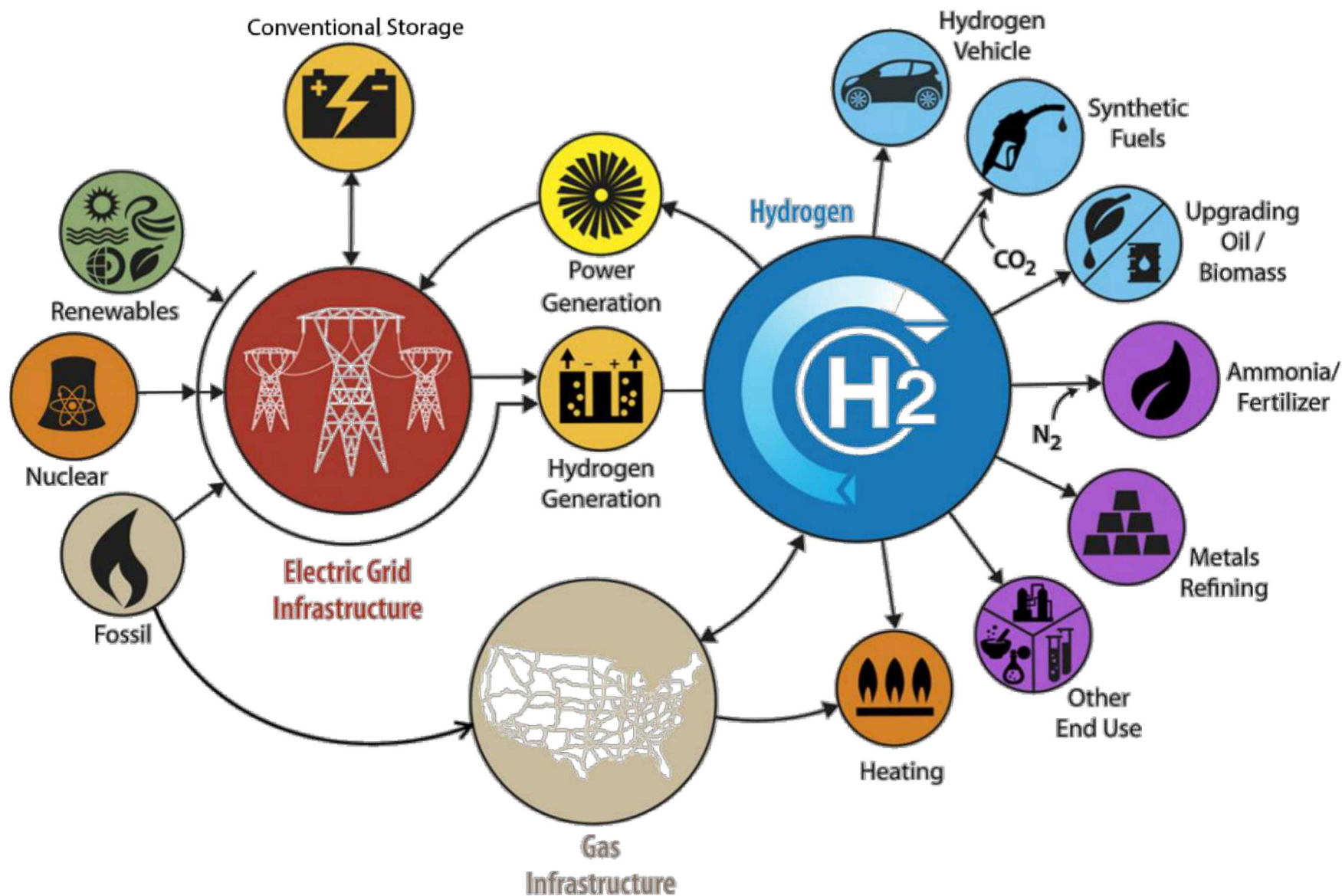
Measured AZ and EL Canting Errors



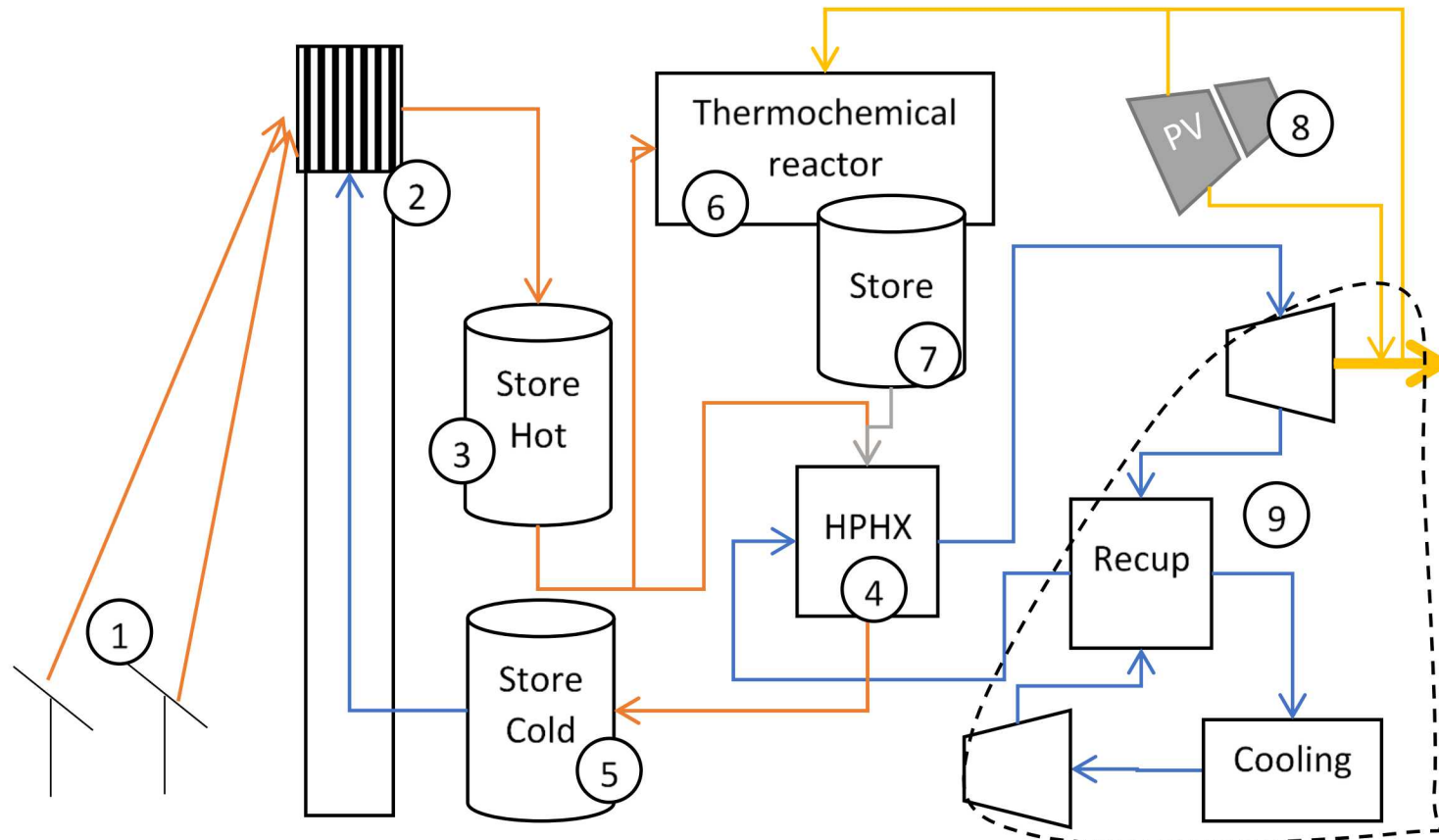


Fuels and long duration storage

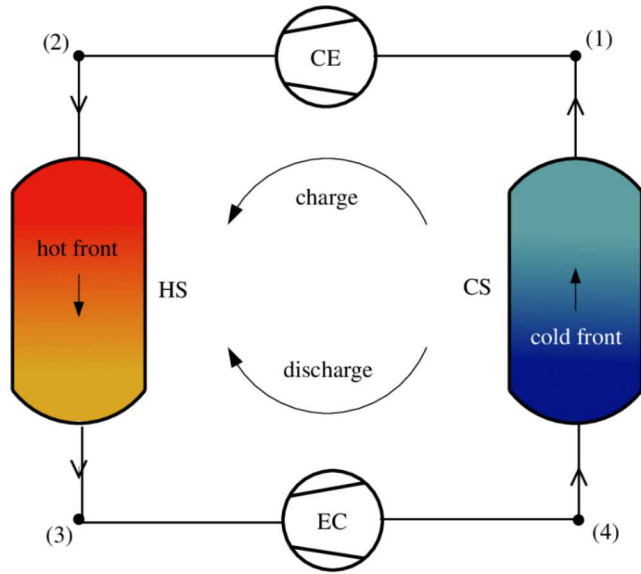
Progress Toward Commercial Deployment of sCO₂ Brayton Power Cycles



Dual storage concepts: Thermal + Solar Fuels



Integrated heat pump thermal storage and power cycle for CSP



Award

- SETO Lab Call Award



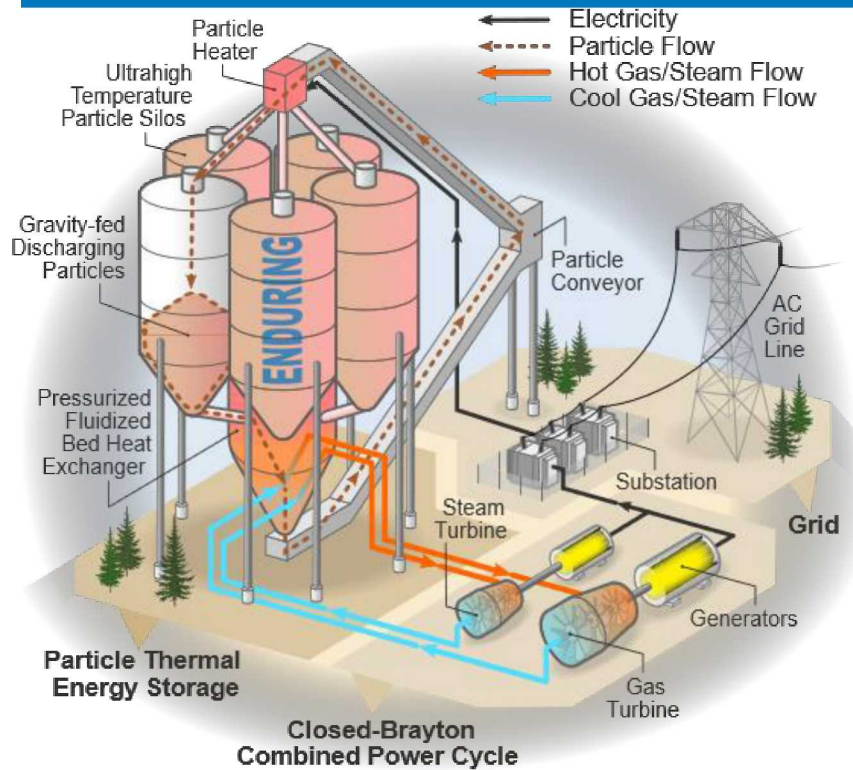
Significance & Impact

- CSP is inherently intermittent and storage tanks may be under-utilized (especially in the winter).
- Heat pump charges store - *decouple* storage from solar availability.
- 'Sub-ambient heat rejection' to reduce effect of high ambient temperatures.
- Combine CSP power cycles with novel storage system – "Pumped Thermal Energy Storage".
- Develop transient thermodynamic and economic models, and assess 'value' with grid analysis tools.

Project Objective

Increase efficiency, dispatchability, and flexibility of CSP through integration with a novel storage system.

Economic Long-Duration Electricity Storage by Using Low-Cost Thermal Energy Storage and High-Efficiency Power Cycle (ENDURING)



Award

- DOE ARPA-E DAYS



Project Objectives:

1. Develop the ENDURING system and components for long-duration energy storage (LDES) to support grid resilience and security.
2. The ENDURING LDES system is designed to be deployed economically anywhere in the United States.

Significance & Impact

- The project team will develop the ENDURING system and verify the component designs to meet the cost and performance targets for demonstration and technology to market.
- The ENDURING LDES system addresses grid storage needs, provides power for several days by low-cost, high-performance storage cycle, allow integration of large amounts of renewable sources like wind and solar, and increase their value to the grid.

Project Team Members:

- General Electric Company
- Greenway Energy
- Allied Mineral Products, Inc.
- Purdue University
- Colorado School of Mines
- POWER Engineers

Acknowledgements



To **SASEC** for inviting me to present this summary of U.S. CSP R&D

Primary contributors to this presentation

- **Dr Avi Shultz**, DOE CSP Program Manager
- **Matthew D. Carlson**, Sandia National Laboratories
- **David Stapp**, CEO/CTO, Peregrine Turbine Technologies, LLC
- **Shaun Sullivan**, Principal Engineer, Renewable Energy R&D Program Mgr., Brayton Energy
- **Dr Clifford K. Ho**, Senior Scientist, Sandia National Laboratories
- **Dr Craig Turchi**, Principal Engineer, National Renewable Energy Laboratory
- **Dr Guangdong Zhu**, Sr Researcher, National Renewable Energy Laboratory
- **Dr Julius Yellowhair**, Principal Engineer, Sandia National Laboratories
- **Mark Mehos**, Group Manager, Thermal Systems R&D, National Renewable Energy Laboratory

Thank you and visit us in 2020!

Paul Gauche

pgauche@sandia.gov

csp.sandia.gov

2020 SolarPACES Conference

29 September – 2 October 2020,
Albuquerque, New Mexico, USA

