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sCO_2 Power Cycles Summit Summary November 2017

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sCO_2 Power Cycles Summit Summary, November 2017

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Abstract

Over the past ten years, the Department of Energy (DOE) has helped to develop components and technologies for the Supercritical Carbon Dioxide (sCO_2) power cycle capable of efficient operation at high temperatures and high efficiency. The DOE Offices of Fossil Energy, Nuclear Energy, and Energy Efficiency and Renewable Energy collaborated in the planning and execution of the sCO_2 Power Cycle Summit conducted in Albuquerque, NM in November 2017. The summit brought together participants from government, national laboratories, research, and industry to engage in discussions regarding the future of sCO_2 Power Cycles Technology. This report summarizes the work involved in summit planning and execution, before, during, and after the event, including the coordination between three DOE offices and technical content presented at the event.

Contents

Figures

Tables

NOMENCLATURE

ARC	Advanced Reactor Concepts
ART	Advanced Reactor Technologies
ARPA-E	Advanced Research Projects Agency-Energy
ASMR	Advanced Small Modular Reactor
CapEx	Capital Expenditure
CBC	Closed Brayton Cycle
COE	Cost of Electricity
CoP	Community of Practice
CSP	Concentrated Solar Power
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
EERE	U.S. Department of Energy Office of Energy Efficiency and Renewable Energy
EPRI	Electric Power Research Institute
FE	U.S. Department of Energy Office of Fossil Energy
FOA	Federal Opportunity Announcement
GE	General Electric
GTI	Gas Technology Institute
IPOC	Innovation Parkway Office Center
KAFB	Kirtland Air Force Base
LCOE	Levelized Cost of Electricity
NE	U.S. Department of Energy Office of Nuclear Energy
NESL	Nuclear Energy Systems Lab
NETL	National Energy Technology Laboratory
NGNP	Next Generation Nuclear Plant
NREL	National Renewable Energy Laboratory
NSTTF	National Solar Thermal Test Facility
ORNL	Oak Ridge National Laboratory
PCHE	Printed Circuit Heat Exchanger
PIV	Particle Imaging Velocimetry
PTT	Peregrine Turbine Technologies
PV	Photovoltaic
R&D	Research and Development
RCBC	Recompression Closed Brayton Cycle
sCO_2	Supercritical Carbon Dioxide
SCS	Southern Company Services, Inc.
SETO	Solar Energy Technologies Office
SFR	Sodium Fast Reactor
SNL	Sandia National Laboratories
STEP	Supercritical Transformational Electric Power

STP	Standard Temperature and Pressure
SwRI	Southwest Research Institute
TA	Sandia sCO_2 Brayton Laboratory Test Article
TRL	Technology Readiness Level
UW	University of Wisconsin

Introduction

Over the past ten years, the Department of Energy (DOE) has helped to develop components and technologies for the supercritical carbon dioxide (sCO_2) power cycle capable of efficient operation at high temperatures and high efficiency. With recent research and development R&D efforts supported by the DOE offices of Fossil Energy (FE), Nuclear Energy (NE), and Energy Efficiency and Renewable Energy (EERE), the state of sCO_2 power cycle research shows great potential.

The DOE offices collaborated in the planning and execution of the sCO_2 Power Cycles Summit to enable the sCO_2 community to engage in discussions regarding the future of sCO_2 power technology. Topics highlighted the research and development needs to promote energy independence/dominance, economic prosperity, and U.S. technology leadership, including collaborations needed for the sCO_2 power cycle research community to improve efficiency and deliver products that can transition to working power plants.

The sCO_2 Power Cycle Summit highlighted R&D technical achievements in DOE-supported programs, covering past and present research directions, with a vision towards future needs. Invited speakers from industry, utilities, and national laboratories presented their R&D progress. The objective of the meeting was to exchange information on the state-of-the-art in sCO_2 power cycle technology development under DOE aegis, to facilitate networking among technology developers, as well as with utilities and other industrial interests, and to inform technology analysts and private sector investors of this new generation of power cycle technology.

The summit was deemed export controlled, with participation by invitation only. The event took place on Tuesday through Thursday, November 14–16, 2017 in Albuquerque, NM.

This report summarizes the work involved in summit planning and execution, before, during, and after the event, including the coordination between three DOE offices, as well as event highlights and follow-up action items. The report includes:

- Summit Planning: speaker selection, participants list, communications strategy, logistics
- Event Summary: facilities tour, poster sessions, speaker presentations
- Post-Event and Follow-up Actions: community of practice (CoP) and other engagements.

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Background

Benefits of sCO_2 Power Cycles for Energy Conversion

Supercritical carbon dioxide (sCO_2) is a fluid state of carbon dioxide (CO_2) held at or above its critical temperature and critical pressure. Carbon dioxide usually behaves as a gas in air at standard temperature and pressure (STP), or as a solid (called dry ice) when frozen. If the temperature and pressure are increased from STP to be at or above the CO_2 critical point, CO_2 can adopt properties midway between a gas and a liquid. At this state, sCO_2 can be used efficiently throughout the entire Brayton cycle. [1]

Figure 1 illustrates a brief history of sCO_2 Brayton cycles and its forecasted plan for future development.

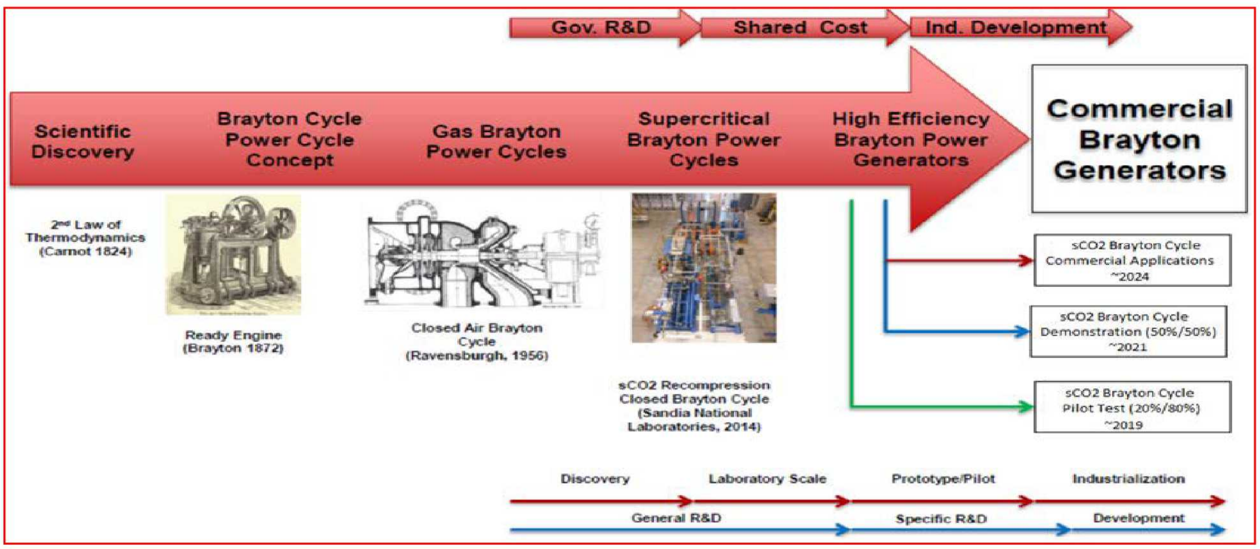


Figure 1: Brief History of sCO_2 Brayton Cycles.

A closed Brayton cycle (CBC) recirculates the working fluid. The turbine exhaust is used in a recuperating heat exchanger to heat the turbine feed. A "supercritical cycle" is a closed Brayton cycle in which the working fluid (sCO_2) is maintained near the critical point during the compression phase of the cycle. The higher gas density of the fluid near its critical point is closer to that of a liquid than of a gas, allowing the pumping power in the compressor to be significantly reduced, which in turn increases the thermal-to-electric energy conversion efficiency [2]. The resulting higher conversion efficiency (up to 50%) translates to increased electricity production for the same thermal input.

The successful development of sCO_2 Brayton cycles promises many benefits for energy conversion, including broad applicability to a variety of heat sources, higher plant efficiency, reduced fuel consumption, smaller size relative to steam system (reduced capital cost), environmental improvement from greenhouse gas reduction, reduction of water consumption, and dry cooling, which makes it suitable for arid environments [1, 3]. In addition, the high pressure in the supercritical cycle and resulting low volumetric flow rate allow for a significant reduction in the overall footprint of the power-conversion system, when compared to the same power output of a steam-Rankine cycle. This in turn allows the heat-rejection heat exchanger and turbine to be smaller than for similar power output steam-Rankine systems.

The benefits can further translate into lower installed costs [3]. In general, increased efficiency represents increased output for the same thermal input, regardless of the thermal source (natural gas, nuclear, solar, or coal). Where fuel costs are a significant portion of overall costs (coal- and natural gas-fired plants), the benefit is reduced fuel costs. Where capital investments are high (nuclear and concentrating solar power), the benefit is increased output for the initial investment.

In addition, sCO_2 Brayton cycle greatly reduces fresh water consumption, not only due to the increased efficiency, but also to the significantly higher heat-rejection temperatures for steam-Rankine systems, allowing for significant heat rejection directly to air. The cycle also provides environmental improvement from greenhouse gas reduction while its dry cooling makes it suitable for arid environments.

sCO_2 Research at the Department of Energy

Brayton cycles are applicable to heat sources championed by the DOE FE, NE and EERE offices. As the offices share a common interest, they support a coordinated R&D approach to help reduce the technical barriers and risks to the commercialization of cycles that use sCO_2 as the working fluid.

The technology development risk for a large scaled sCO_2 power cycle is high, and while the private sector has pursued a few configurations [4], a higher temperature, high-efficiency system has never been tested at design conditions applicable for commercial scale. sCO_2 development and deployment work has largely been limited to small-scale, government-funded initiatives. Work is needed to develop the system characterization for large-scale sCO_2 power conversion, including designs, materials, components, operation and control systems, and sensors, amongst others. It is expected that collaboration across offices, across laboratories, and with industry will mature the technology at the pilot scale to facilitate commercialization. The DOE offices collaboration draws from work completed within each of the office programs to achieve the highest efficiencies offered by the sCO_2 Brayton cycle (compared to the widely used steam turbine Rankin Cycle [1].)

Successful development of the technology supports overarching DOE drivers, including:

- meeting national climate and energy goals,
- promoting domestic job creation,
- facilitating industrial competitiveness,
- maintaining U.S. technology leadership,
- providing the nation with cleaner and more affordable power, and
- increasing energy resiliency and surety.

Office of Nuclear Energy

Within the Office of NE, the Office of Advanced Reactor Technologies (ART) sponsors research, development, and deployment (RD&D) activities through its Next Generation Nuclear Plant (NGNP), Advanced Reactor Concepts (ARC), and Advanced Small Modular Reactor (ASMR) programs to promote safety, technical, economical, and environmental advancements of innovative Generation IV nuclear energy technologies. One of the efforts supported by ARC is exploration and development of supercritical CO_2 Brayton thermal cycle for diverse reactor applications that couple nuclear reactors to power generation with much improved conversion efficiency and reduced plant size. [5]

NE has been involved in Brayton technology development for over 10 years, sponsoring work conducted through the Sandia National Laboratories and Argonne National Laboratory. The NE office supports a collaborative approach with industry that enables short and mid-term collaborations of specific technologies that can be leveraged in the path towards the cycle development for nuclear applications.

Office of Fossil Energy

The FE Advanced Energy Systems program focuses on improving the efficiency of coal-based power systems, enabling affordable CO_2 capture, increasing plant availability, and maintaining the highest environmental standards. Within this program, the sCO_2 Power Cycles for Fossil Fuels supports research and development of supercritical carbon dioxide power cycles that surpass the performance of advanced, ultra-supercritical steam. For FE, developing highly efficient and lower-cost, indirectly heated sCO_2 cycles will provide the technology base for more advanced, directly heated sCO_2 cycles for clean fossil energy conversion. In addition, these direct-fired cycles can produce a high-purity stream of carbon dioxide for use, reuse, or storage.

FE investments in this technology leverage the world-class capabilities of the DOE National Laboratories and those of private industry to accelerate the delivery of sCO_2 power cycle benefits to U.S. industry and the nation [6]. FE has maintained a sCO_2 technology project portfolio for several years, supported through the National Energy Technology Laboratory (NETL).

Office of Energy Efficiency and Renewable Energy

The EERE Solar Energy Technologies Office (SETO) supports R&D seeking to reduce the cost of solar energy. The SunShot initiative launched in 2011 with the goal of making solar electricity cost-competitive with conventionally generated electricity by 2020. The original SunShot's cost target of $0.06 per kilowatt-hour for utility-scale photovoltaic (PV) solar power was achieved in 2017.

While concentrated solar power (CSP) is already deployed globally, using molten salt as the heat transfer fluid and the storage medium enables a CSP plant to be highly efficient and significantly reduce costs. Future advanced molten-salt power tower designs envision higher salt temperatures with a sCO_2-Brayton power cycle [7]. Power cycles using sCO_2 as the working fluid have been identified as the most promising advanced power cycles for integration with CSP, which is aligned with FE and NE priorities [8].

sCO_2 Stakeholder Engagement Events

Given the broad areas off shared interest around the development of sCO_2 power cycles, and the potential for collaboration among R&D entities, several events have been conducted since 2013 (Figure 2) to encourage discussion and support collaboration amongst sCO_2 community stakeholders.

Most recently, events in 2016 and 2017 were organized through the combined DOE offices to engage industry and streamline R&D through collaboration. The most recent event, 2017 sCO_2 Power Cycles Summit, is summarized in this report.

2013	2014	2015	2016	2017
• SwRI sCO_2 Power Cycle Technology Roadmapping Workshop, Feb. 13–14 • Navy Energy Recovery Workshop, March 13–14, Arlington, VA	• sCO_2 Development Workshop, June 23–24, 2014, Washington DC; • Sandia Industry Days, Brayton Cycle Industrial Engagement Workshop, Aug. 26–27, Albuquerque, NM • Workshop on sCO_2 Energy Conversion R&D, Sept. 11, 2014, Pittsburgh, PA		• DOE sCO_2 Industry Days, Nov. 1–2, 2016, Chicago, IL	• sCO_2 Power Cycles Summit, Nov. 14–16, 2017, Albuquerque, NM

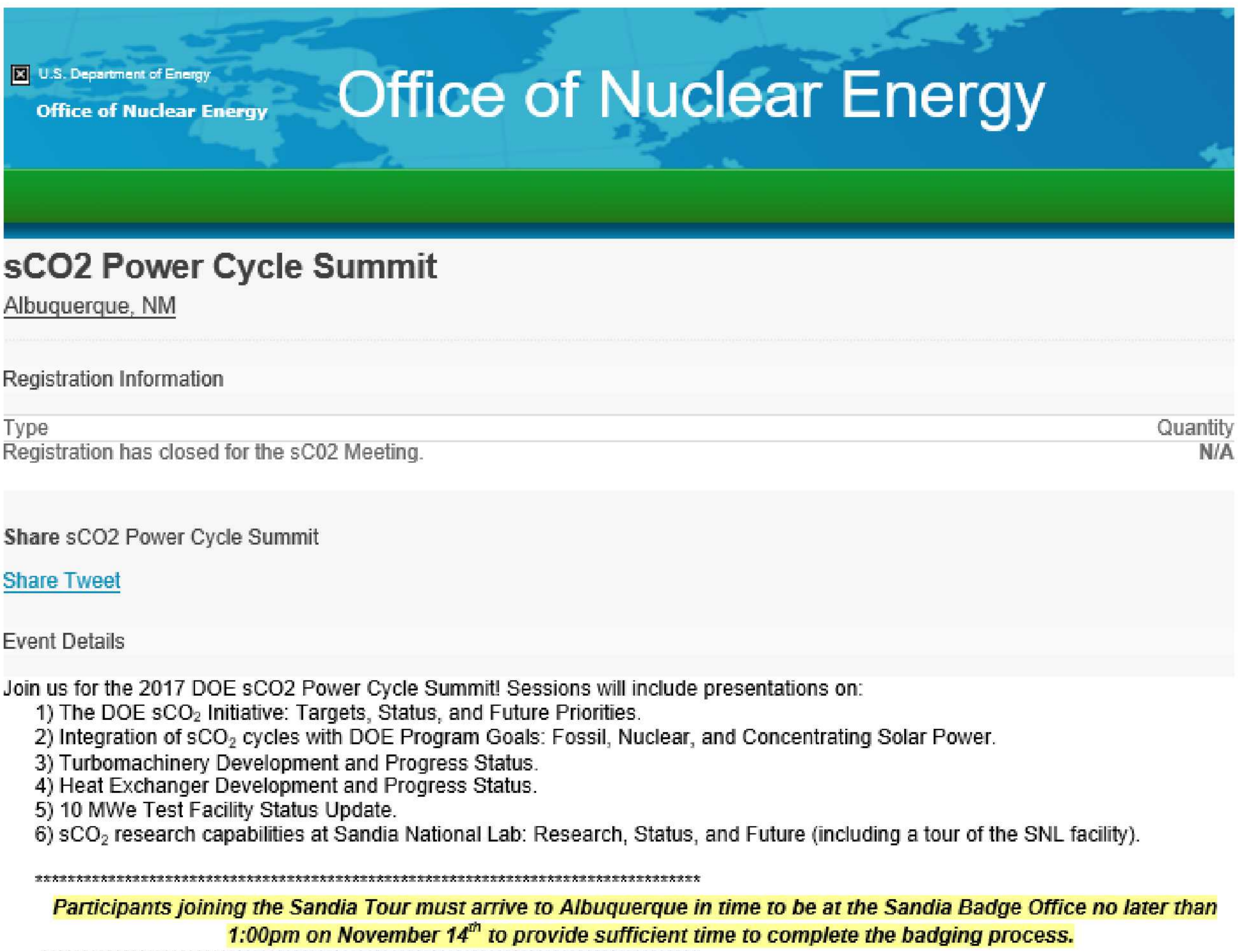
Figure 2: sCO_2 Community Events Timeline.

Summit Planning

The NE, FE, and EERE offices worked together in the coordination of the 2017 sCO_2 Power Cycles Summit. The offices secured support from SNL Advanced Nuclear Concepts (8841) group as local hosts for the event, and Allegheny Science & Technology for event logistics. The event took place on Tuesday through Thursday, November 14–16, 2017 in Albuquerque, New Mexico (NM). The following activities were executed during event planning.

Event Logistics and Registration

A determination was made by DOE to hold the event in Albuquerque, New Mexico, with interest in including a facilities tour of the Sandia National Laboratories (SNL) Brayton NESL Laboratory and Solar Tower. An Eventbrite registration site (Figure 3) was set up, providing information about the event and collecting official information from participants for registration, including name, company name and address, phone number, email, emergency contact, days attending the event, interest in SNL facilities tour, and interest in the group dinner.



U.S. Department of Energy
Office of Nuclear Energy
Office of Nuclear Energy

sCO2 Power Cycle Summit
Albuquerque, NM

Registration Information

Type	Quantity
Registration has closed for the sC02 Meeting.	N/A

Share sCO2 Power Cycle Summit

Share Tweet

Event Details

Join us for the 2017 DOE sCO2 Power Cycle Summit! Sessions will include presentations on:

1) The DOE sCO_2 Initiative: Targets, Status, and Future Priorities.
2) Integration of sCO_2 cycles with DOE Program Goals: Fossil, Nuclear, and Concentrating Solar Power.
3) Turbomachinery Development and Progress Status.
4) Heat Exchanger Development and Progress Status.
5) 10 MWe Test Facility Status Update.
6) sCO_2 research capabilities at Sandia National Lab: Research, Status, and Future (including a tour of the SNL facility).

****

Participants joining the Sandia Tour must arrive to Albuquerque in time to be at the Sandia Badge Office no later than 1:00pm on November 14th to provide sufficient time to complete the badging process.

****

Figure 3: Event Information and Registration Website.

The Marriott Hotel in Albuquerque Uptown (2101 Louisiana Blvd NE, 87110) was selected as the venue because of its close location to the SNL facilities, availability of conference space, and preferred conference pricing negotiated. Marriott provided an exclusive online reservations site (Figure 4) for participants to secure the preferential conference rate for their hotel booking. This site link was provided to participants once their registration to attend the event was completed.

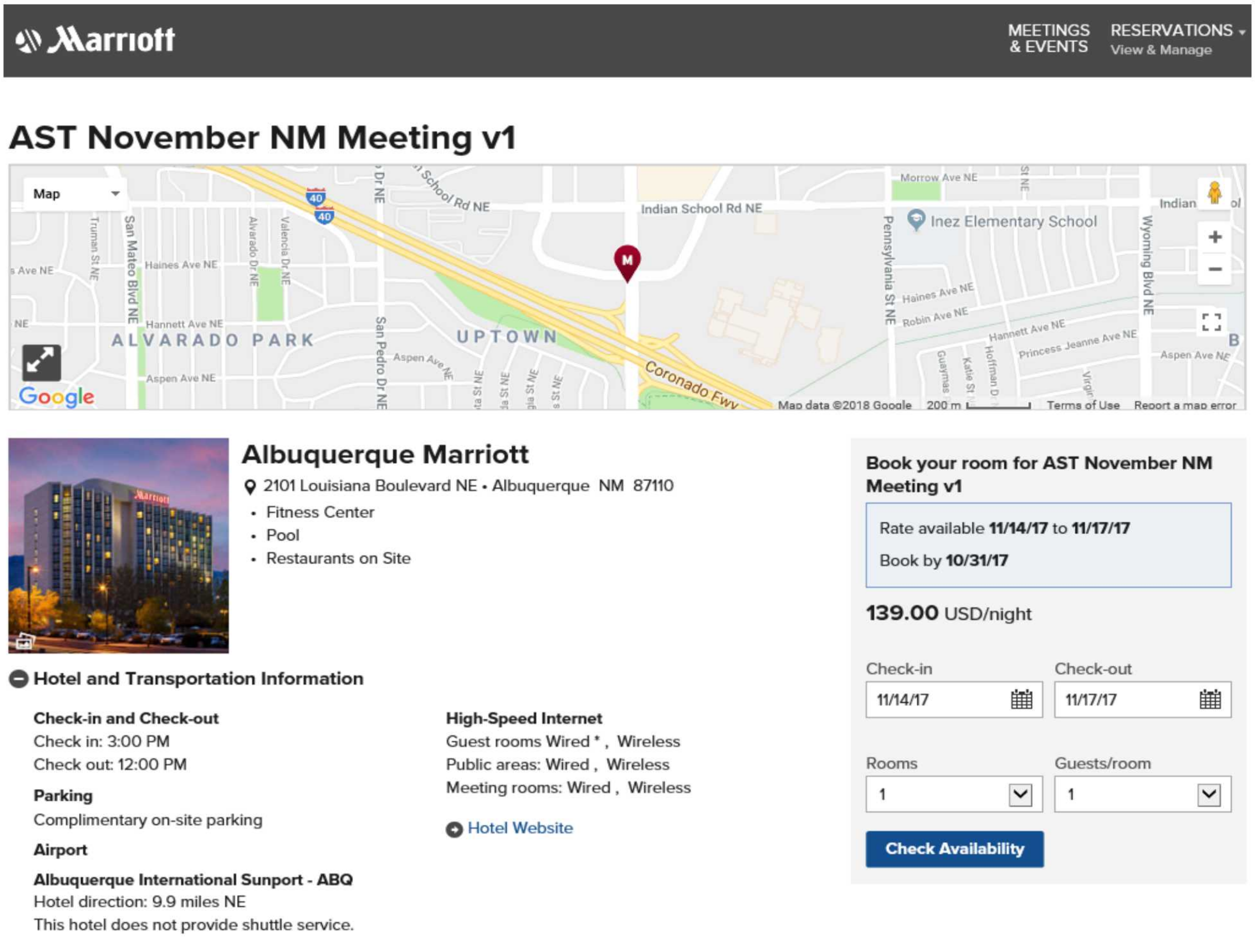


Figure 4: Marriott's Event Rate Booking Website.

Event Communication Strategy

Planning for the sCO_2 Power Cycles Summit started in July 2017, with a target event date of November. The Summit was deemed export controlled, with participation by invitation only. As such, only U.S. entities (i.e., government representatives, national laboratories, U.S.-based companies) were cleared to attend the event. University contacts are considered exports, so the only university representatives invited had current active sCO_2 engagements with the DOE offices or the national laboratories. An initial participant list was drafted based on the list of attendance to the 2016 Industry Days event (Chicago, IL) and reviewed by DOE and SNL for completeness and new partner additions.

A “Save the Date” announcement was developed (Figure 5) and mailed out to the participant list in August. The communication was sent via email, which also served as confirmation of the contact information for individuals. Email addresses were revised when needed.

Figure 5: Save the Date Announcement.

The event announcement was also posted on the DOE sCO_2 Power Cycles website, https://energy.gov/under-secretary-science-and-energy/sco2-power-cycles[1] (Figure 6) for public information. Individuals who wanted information about the event, or were seeking an invitation, were asked to email the event contact. Invitation requests were redirected to the DOE NE office for evaluation and discussion with the other three offices prior to a determination.

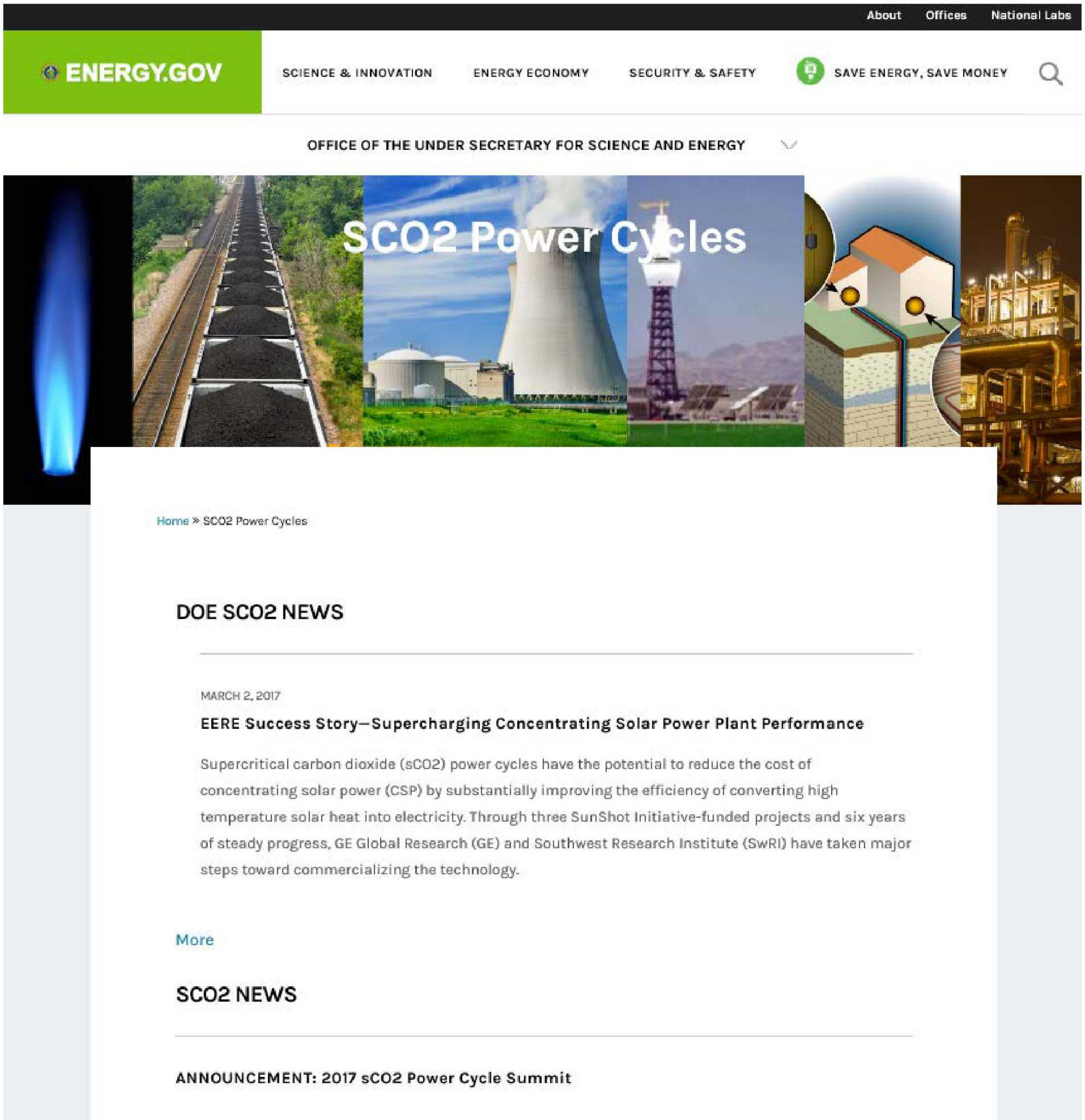


Figure 6: Department of Energy sCO_2 Power Cycles Open Website.

[1] This website launched in July 2017 with collaboration from NE, FE, and EERE, with support from NETL, SNL, and DOE website administration, to support sCO_2 information sharing with the general community.

Tours to Sandia locations and Access to the Kirtland Air Force Base

The tours to Sandia's Solar Tower and Brayton Testing Lab were coordinated with the leadership of both locations. Both facilities are located within the Sandia National laboratories campus inside the Kirtland Air Force Base (KAFB) in Albuquerque, NM. Access to KAFB is strictly controlled and requires photograph badges be issued to all visitors. A bus was booked to transport tour participants from the SNL badging office (Innovation Parkway Office Center [IPOC] building outside the base) to the tour facilities and back.

For KAFB access, registrants to the event were grouped in three categories:

- *HSPD12 badge holders* do not require advance notice or previous processing for access to the base. These participants were asked to bring their current badge and notify the event coordinators of their interest to join the tour to reserve space on the tour bus.

- *U.S. Citizens or Permanent Residents* were asked to complete a Visitor Information Form.

- *International visitors* were not allowed to join the tour due to long processing time required to conduct due diligence on international visitor access requests.

Tour access was limited to U.S. Citizens or Permanent Residents only. Event registration was closed on October 15 to ensure sufficient time to process all tour access requests. A Sandia HSPD12 badge holder was required as escort for every eight non-HSPD12 visitors at all times, including bus rides.

The tours were conducted on Tuesday, November 14, 2017, prior to the official start of the summit sessions on November 15 and 16.

Securing Content Relevant Agenda

An ambitious agenda was prepared to establish support for sCO_2 R&D from all areas of government, laboratories, and industry represented at the summit. The DOE Offices worked on several fronts, securing participation from several parties:

- **Keynote Speakers**

  The dates and topic of the summit were communicated to Senators King (Washington, DC), Heinrich (New Mexico), and Murkowski (Alaska), through DOE and SNL Government Relations offices. Each received an invitation to address summit participants, and varieties of options were made available (in person, live videoconference, recorded video remarks.) Senator Murkowski accepted the invitation and issued a video statement for event participants. Logistics were addressed with the conference venue to confirm AV transmission.

  Representatives from the DOE Office of FE, Office of NE, and Office of EERE were scheduled to issue opening remarks outlining the efforts, path and goals of each of the offices sCO_2 programs.

Sandia management was invited to issue the event welcome in their role as local hosts for the summit.

- **R&D Content Presentations and Poster Session**

  The DOE offices identified principal investigators and program managers to discuss their DOE funded programs history and R&D status. Topics covered several areas of the sCO_2 power cycle development, including materials, component development, and power system applications. Content presentations featured representatives from national laboratories, academia, and industry currently engaged in sCO_2 R&D efforts and collaborations at multiple levels.

  Posters were invited from specific R&D topics that were introduced but not discussed in detail during the content presentations or panel sessions. To facilitate the poster session, presenters were given the option of submitting their poster in high-resolution format via email to have it reviewed and printed on site at SNL.

  Individual invitations were issued to all parties, followed by follow-up confirmation of attendance from each participant.

Event Agenda

The full agenda for the 3-day event, including laboratory tours, is presented here.

sCO2 Power Cycle Summit

Location:	Sandia National Labs
Date:	Nov. 14, 2017
Time:	1.00 PM to 5.00 PM

Agenda

1:00 - 2:30 PM	Arrival at IPOC for badging - tour bus departs at 2:30pm
2:30 - 5:00 PM	Tour of Sandia Brayton Laboratory and Solar Tower
5:00 PM	Return to IPOC

sCO2 Power Cycle Summit

Location: Albuquerque Marriott
Date: Nov. 15, 2017
Time: 8.00 AM to 5.10 PM

Agenda

8.00 – 8.30 AM	Introduction and Welcome - *Explanation of Summit*	Robinson, NE
8.30 – 8.50 AM	Federal Senator/staff (awaiting confirmation)	
8.50 – 9.10 AM	Welcome	Bonano, SNL
9.10 – 9.30 AM	Keynote	Golub, NE
9.30 – 10.00 AM	BREAK & Poster Session* (3hr)	Salon A-D
10.0 – 11.00 AM	NE, Energy Conversion Program - *Program Summary, Status, and Vision of Future*	Robinson, NE Rochau, SNL
11.0 – 12.00 PM	FE, sCO2 Program - *Program Summary, Status, and Vision of Future*	Bhima, FE Weiland, NETL Stanislowski, UND Ohadi, ARPAE
12.00 – 1.30 PM	Lunch	Local Establishments
1.30 – 1.50 PM	Concentrating Solar Thermal Power (CSP) Overview, Solar Energy Technologies Office - Program Summary, Status, and Vision of Future	Shultz, EE
1.50 – 2.10 PM	Turbo Machinery and Testing	Blunk, Siemens
2.10 – 2.30 PM	Status of Sunshot Expander Testing	Moore, SWRI
2.30 – 2.50 PM	Design, Fabrication and Testing of Apollo Compressor	Mortzheim, GE
2.50– 3.30 PM	STEP Facility Development - *Status and Future*	Kutin, GTI
3.30 – 3.50 PM	Break	
3.50 – 4.10 PM	Integral Geared Compressor: Design, Fabrication and Testing	Wygant, Hanhwa
4.10 – 4.30 PM	Turbomachinery Topics (Peregrine)	Pasch, SNL Stapp, Peregrine
4.30 – 4.50 PM	Distributed Energy Systems	Brooks, Peregrine Rochau, SNL
4.50 – 5.10 PM	Status of development of EPS power systems (Echogen)	Held, Echogen
5.10 PM	Adjourn	
6.00 PM	Group Dinner at Local Restaurant	

*Poster displays will run concurrent with Plenary Session

sCO_2 Power Cycle Summit

Location: Albuquerque Marriott
Date: Nov. 16, 2017
Time: 8.00 AM to 5.15 PM

Agenda

8.00 – 8.10 AM	Introduction - Plan of the day	Robinson, NE
8.10 – 8.40 AM	Research Needs and Development Status for the SCO2 Cycle; CSP Perspective	Vijaykumar, EE
8.40 – 9.10 AM	Research and Development Needs for the SCO2 Cycles: Fossil Energy Perspective	Dennis, NETL
9.10 – 9.40 AM	Research and Development Needs for SO2 Cycles: Nuclear Energy perspective	Rochau, SNL
9.40 – 10.00 AM	BREAK & Poster Session begins* (3hr)	
10.00 – 10.30 AM	Development of a basic and applied R&D plan for the Recompression Brayton Cycle	Rochau, SNL
	****** sCO2 Component Technology Review Section******	
10.30 – 12.00 PM	Heat Exchanger Development (EE, NE, FE) - EE "Regenerator as Replacement for Recuperators in SCO2 Power cycles - EE/FE "Status of development of the Brayton Recuperator" - NE "State of art in PCHE development and associated research in Sandia" - FE "Microtube Recuperators"	Wildberger, VPE Anderson, UW Sullivan, Brayton Carlson, SNL Portnoff, THAR
12.00 – 1.00 PM	Lunch	Local Establishments
1.00 - 1:20 PM	Invited Industry Presentations - "Advanced alloys for the SCO2 Power Cycle"	Dennis, NETL Deodeshmukh, Haynes
1.20 – 2.20 PM	Materials Development - EE "State of the art in SCO2 corrosion and mechanical testing - NE "Overcoming Materials Challenges for NE sCO2 Energy Conversion Systems" - FE sCO2 corrosion materials	Carlson, SNL Pint, ORNL Walker, SNL Kung, EPRI
2.20 – 3.05 PM	Industry Engagement Panel: Utility Representatives Questioned by Industry - What is the industry expectations on SCO2 cycles? - What is industry approach to implementing SCO2 cycles? - What research should DOE and industry be funding in near future? - Applications needs for; CC, coal, nuclear, CSP	Stekli, EPRI Panelists: Barron, SCS Blunk, Siemens Julius, Duke Mann, Tristate Generation
3.05 – 3.20 PM	BREAK	
3.20 – 4.00 PM	Invited Industry Presentations - "Google X's thermal energy storage project (Project Malta)" - "Status of Net Power50 MWt Allam Cycle Demonstration Plant"	Dennis, NETL Apte, GoogleX Dimmig, Net Power
4.00 – 4.45 PM	Industry Engagement Panel: Laboratories Questioned by Industry - Each panelist to give brief overview of sCO2 current and planned activities - What does the industry expect the national labs to develop? - What would the utilities need from national labs to incorporate SCO2 cycles within their plants? - What form of research should component and power cycle developers expect from national labs?	Mollot, FE Panelists: Turchi, NREL Rochau, SNL Dennis, NETL
4.45 – 5.15 PM	DOE Wrap Up and Close Out	DOE

*Poster displays will run concurrent with Plenary Session

2

Attendance and Participation

The sCO_2 Power Cycles Summit was completed successfully with attendance from 100 representatives from government, national laboratories, industry, universities, and contractors (Figure 7). The full list of attendees and contact information is included on the OUO Addendum A: Presentations report.

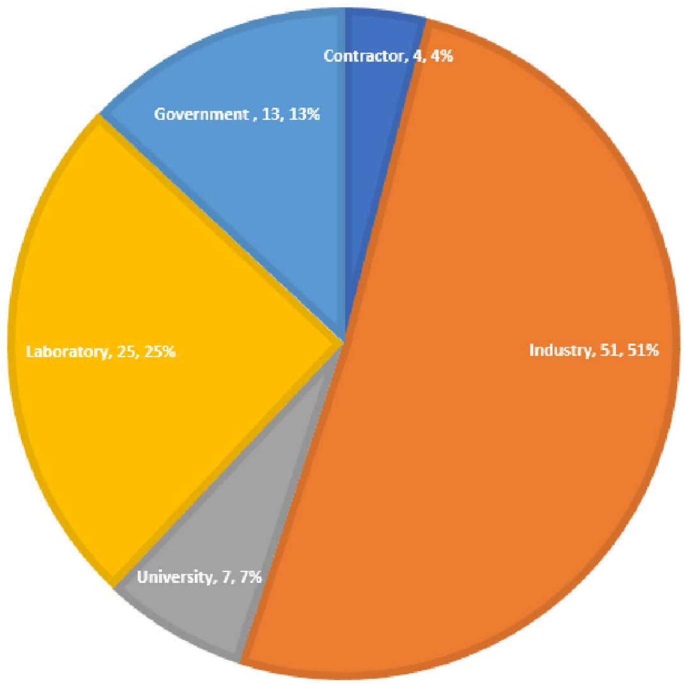


Figure 7: sCO_2 Power Cycles Summit Participation.

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Event Summary

Tour of the Sandia Brayton Laboratory and Sandia National Laboratories Solar Tower

The sCO_2 Summit included a tour of experimental facilities at SNL related to the sCO_2 field on the afternoon of November 14, 2017. The tour included two locations—the Nuclear Energy Systems Laboratory (NESL) and the National Solar Thermal Test Facility (NSTTF). Approximately 45 people participated in the tour, including DOE employees from the offices of Nuclear Energy (NE), Fossil Energy (FE), and Energy Efficiency and Renewable Energy (EERE). Visitors also came from other DOE national labs, private research institutions, large and small businesses, and universities.

The NESL is focused on sCO_2 cycle and component development and demonstration. It is a large high-bay facility with amble heating and cooling capabilities. Visitors to the NESL were able to see the breadth of sCO_2-specific experimental capabilities that were described by Sandia staff including:

- Main Test Assembly
- Bearings Test Rig
- Natural Convection Loop
- Optical Diagnostics Lab
- Burst and Fatigue Rig
- Heat Exchanger Rig.

The Main Test Assembly is a pioneering sCO_2 loop for the field with which many researchers are familiar. Other component test capabilities were less well known but visitors asked many questions about technical specifications and applications and were very engaged. This part of the tour was very effective at showing the community SNL experimental capabilities for all aspects of sCO_2 Brayton cycle development likely to lead to future collaborative opportunities. Figure 8 to Figure 13 show NESL and its various test capabilities.

Figure 8: Heat Exchanger Test Loop.

Figure 9: Compressor/Seal Test Loop.

Figure 10: Low-Pressure Brayton Loop.

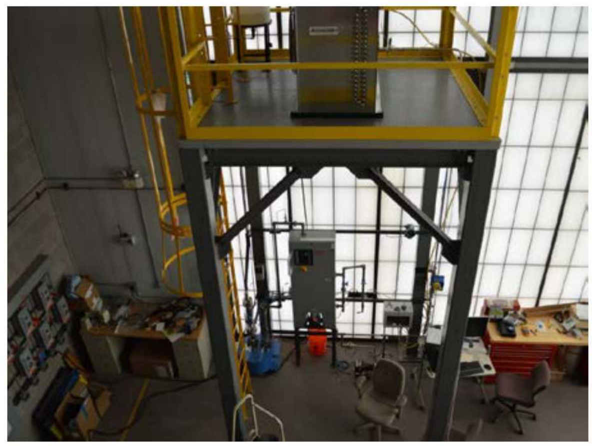
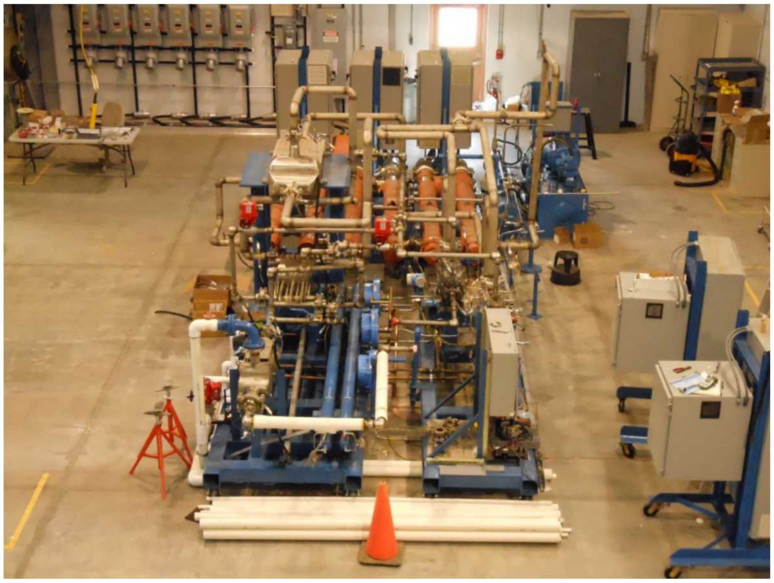


Figure 11: Dry Natural Circulation Loop.



- 2 × 125 kWe TAC Units
- 6 × 130 kW Heaters (Electric)
- 500 kW Gas Cooler (PCHE)
- 1.7 MW Recuperator (PCHE)
- 2.3 MW Recuperator (PCHE)

Figure 12: 1 MW_{th} Brayton Test Loop.

Figure 13: Nuclear Energy Systems Laboratory Facility.

The NSTTF is focused on CSP research and demonstration for energy production. Solar energy is reflected in a field of 218 mirrors or heliostats and focused on a 200-foot-tall tower (Figure 14) for a total thermal power of 6 MWth [9]. This energy input is then transferred into a power cycle, where the sCO_2 Brayton cycle is the primary pathway to convert thermal energy into electrical energy.

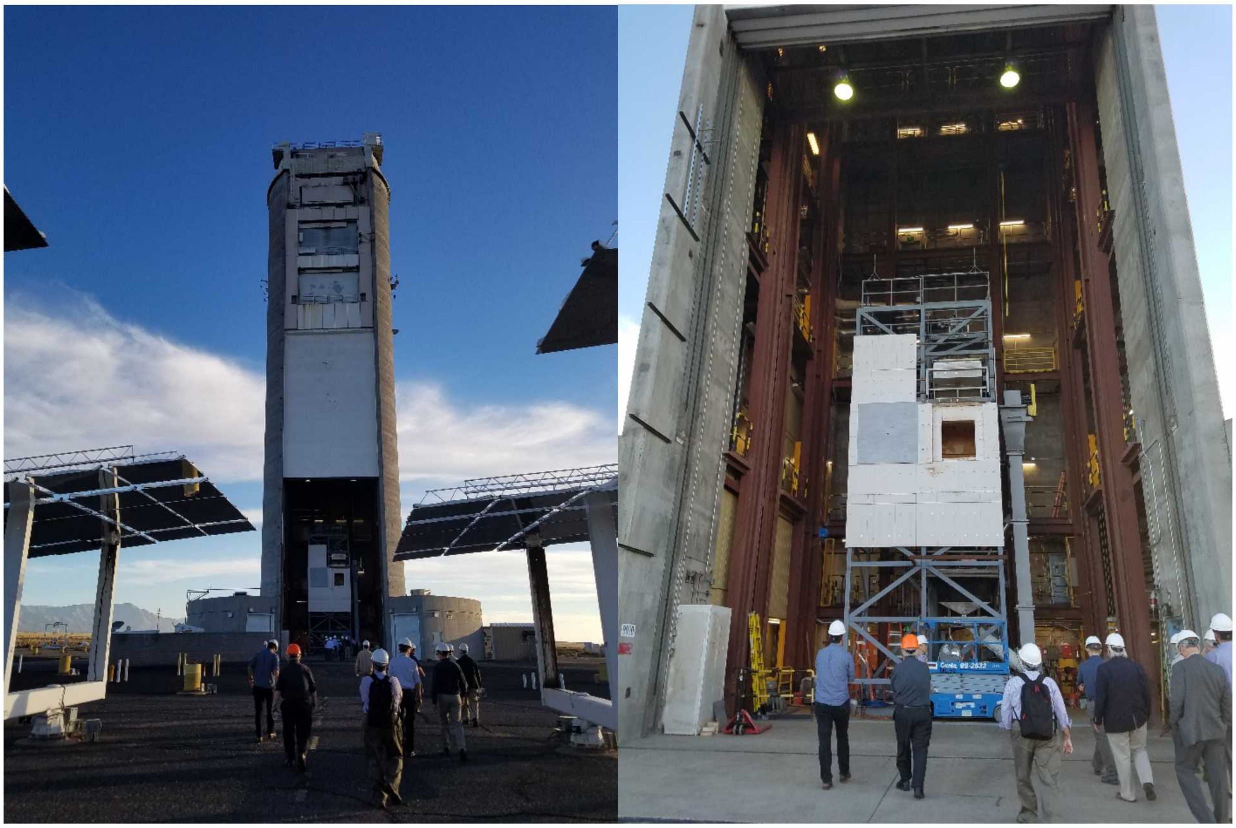


Figure 14. National Solar Thermal Test Facility Visit Photographs.

At left in Figure 14, the SNL Concentrating Solar Tower and heliostat field. At right, falling particle receiver temporarily at the ground level for upgrades. Typically, this tower is raised to the top by a 100-ton elevator.

Visitors viewed several test capabilities described by SNL staff, including the Heliostat Field, Solar Tower, Solar Furnace, and Control Tower. They were also allowed to walk around the top of the tower to view the local facilities and across the valley. This was an engaging visit as researchers were able to discuss collaborative opportunities, especially in light of EERE's recent Federal Opportunity Announcement (FOA) to fund large-scale CSP demonstrations attached to energy conversion cycles.

Keynote Speakers

The remarks issued by keynote speakers are included in their entirety in the Addendum A: Presentations report, including.

- Senator Murkowski video remarks – transcribed
- Welcome by SNL local host
- Keynote message by DOE NE host.

R&D Content Presentations

DOE Program Summary, Status, and Vision for the Future

Office of Nuclear Energy

The NE office supports a collaborative approach with industry that enables short and mid-term collaborations of specific technologies that can be leveraged in the path towards the cycle development for nuclear applications. Major activities identified in the program support a collaborative approach with industry to develop and test RCBC components.

The ART Energy Conversion Team focuses on Sodium Fast Reactor (SFR) Application. Activities include:

- Development of the Technology Roadmap/Project Management Plan/System Engineering Model to support the Systematic Risk Identification and Retirement from components to system configuration.
- Commercialization of the sCO_2 system by 2030, by pursuing the goal of operating a Recompression Closed Brayton Cycle (RCBC) at a turbine inlet of 550°C. Currently working on Brayton Development Platforms and engaging industry to advance technology readiness level (TRL) of components to 550°C and 750°C
- Development of Intermediate Sodium to CO_2 Heat Exchanger (primary heat exchanger) supported by Sodium Drain, Fill, Plug in Printed Circuit Heat Exchanger (PCHE), and Sodium CO_2 interactions R&D efforts.

The ART Energy Conversion Team is procuring the world's first 1 MW turbocompressor at 750°C though design/build process by SNL, and standing up eight additional test configurations in addition to the RCBC Test Article. New configurations will address heat exchanger (SEARCH), particle imaging velocimetry (PIV), seals, bearings, turbcompressor (core), dry heat rejection (tall loop), and parallel compression.

The ART Energy Conversion program goals are summarized in Figure 15. The full NE-ART Energy Conversion (EC) presentation is included in the Addendum A: Presentations report.

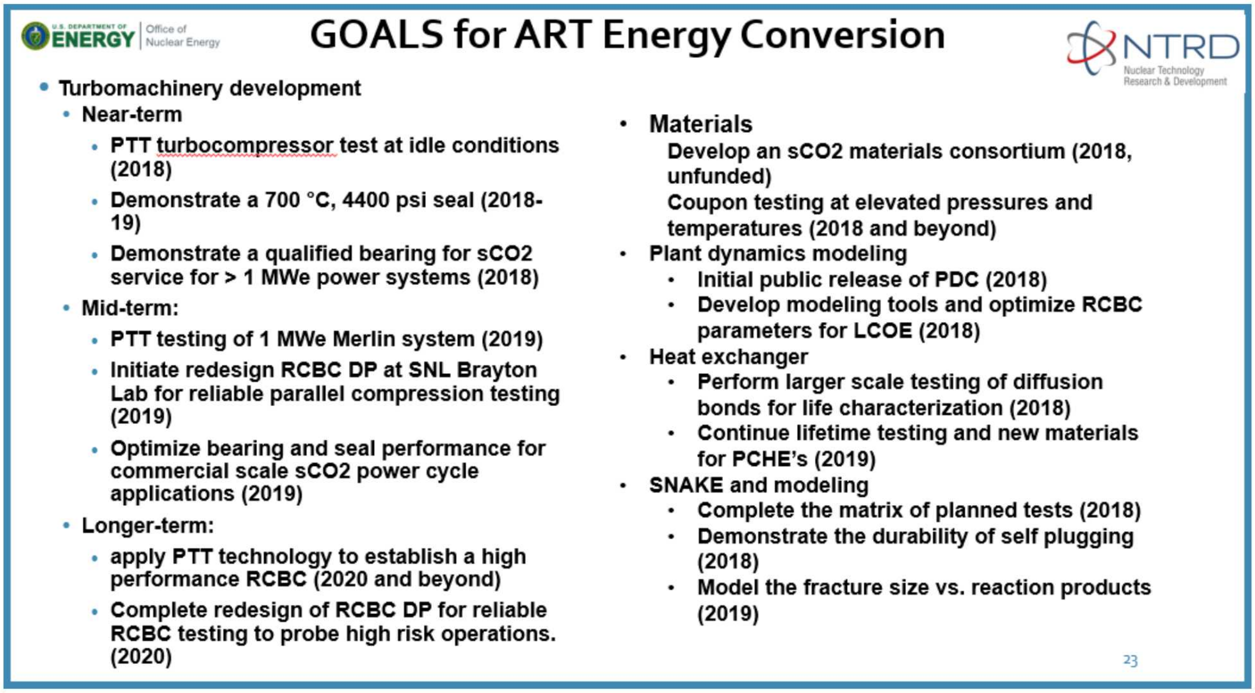


Figure 15: Nuclear Energy-Advanced Reactor Tecnologies Energy Conversion Program Goals.

Office of Fossil Energy

The office of FE Advanced Energy Systems program focuses on improving the efficiency of coal-based power systems, enabling affordable CO_2 capture, increasing plant availability, and maintaining the highest environmental standards. Within this program, the sCO_2 Power Cycles for Fossil Fuels supports research and development of supercritical carbon dioxide power cycles that surpass the performance of advanced, ultra-supercritical steam.

Developing highly efficient and lower-cost, indirectly heated sCO_2 cycles will provide the technology base for more advanced, directly heated sCO_2 cycles for clean fossil energy conversion. In addition, these direct-fired cycles can produce a high-purity stream of carbon dioxide for use, reuse, or storage.

FE is pursuing technology development for indirectly and directly heated cycles, as seen in Figure 16.

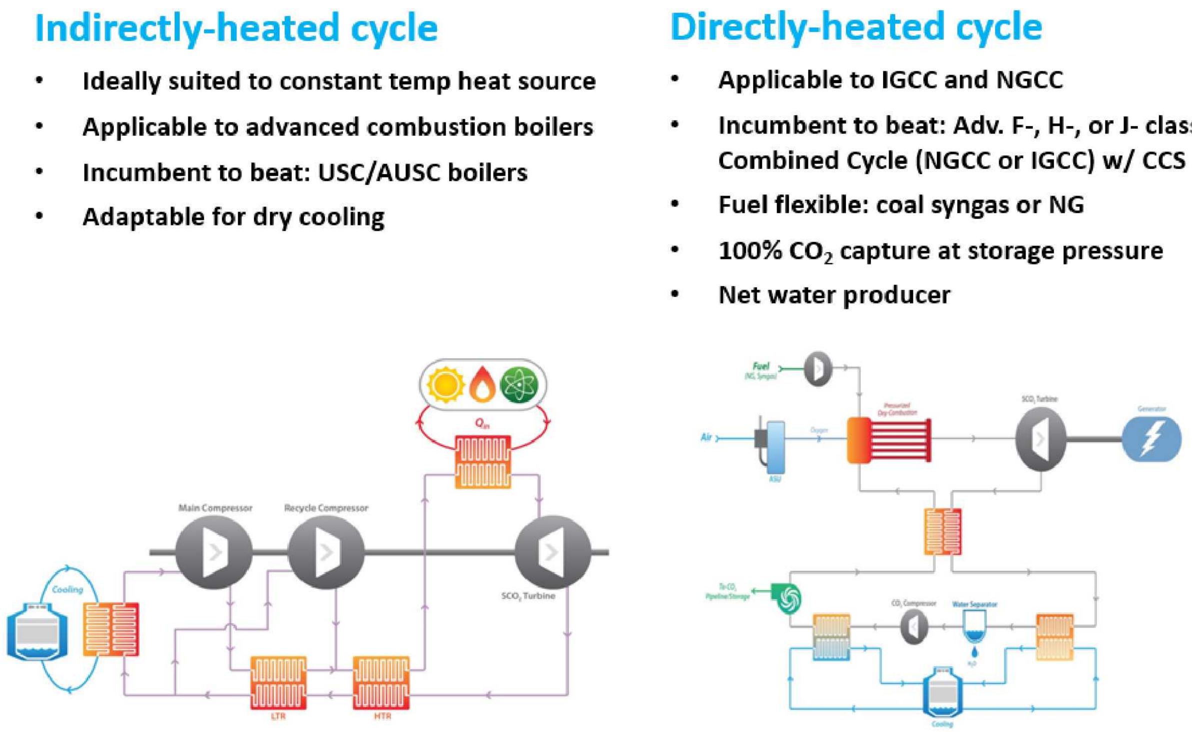


Figure 16: Fossil Energy sCO_2 Cycles for Fossil Energy Applications.

The office of FE investments in this technology leverage the world-class capabilities of the DOE national laboratories and those of private industry to accelerate the delivery of sCO_2 power cycle benefits to U.S. industry and the nation [6]. FE has maintained a sCO_2 technology project portfolio for several years, supported through NETL. Figure 17 summarizes the current NETL approach to sCO_2 cycle development.

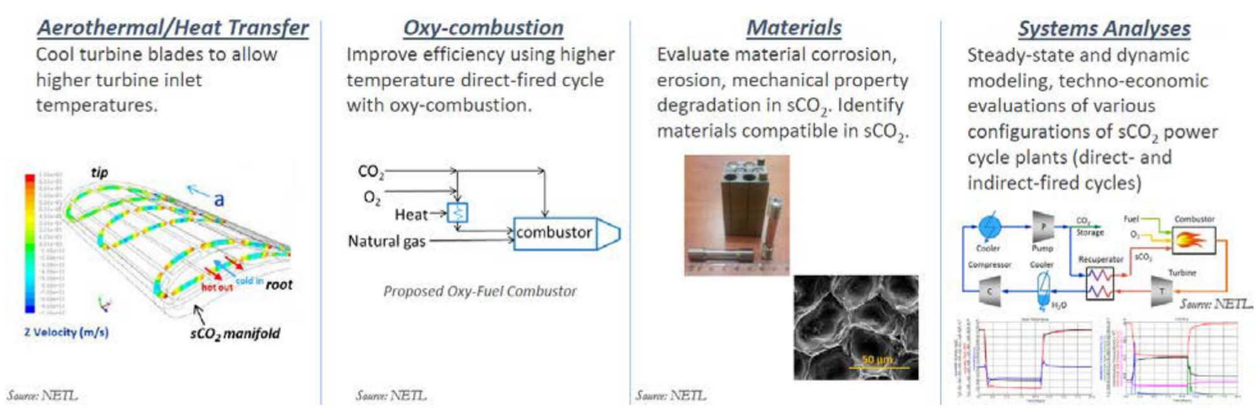


Figure 17: National Energy Technology Laboratory Research and Innovation Center Approach to sCO_2 Development.

NETL selected Gas Technology Institute (GTI), together with partners Southwest Research Institute (SwRI) and General Electric (GE) Global Research, to design, build, and operate a 10 MWe sCO_2 pilot demonstration power plant—known as the Supercritical Transformational

Electric Power (STEP) Facility—with the purpose of advancing the technology development of sCO_2 Brayton power cycles.

Full NE-ART EC presentations are included in the Addendum A: Presentations report.

Office of Energy Efficiency and Renewable Energy

The EERE seeks to reduce the cost of solar energy. While CSP is already deployed globally, using molten salt as both the heat transfer fluid and storage medium enables a CSP plant to be highly efficient and significantly reduce costs. By choosing the size of the solar field and thermal energy storage, the same CSP technology can be configured to meet evolving demands of the future grid. Current flexible designs for an evolving grid are characterized as Peaker (with <6 hours of storage), Intermediate (with 9 hours of storage), and Baseload (with >12 hours of storage).

Future advanced molten-salt power tower designs envision higher salt temperatures with a sCO_2-Brayton power cycle [7]. Power cycles using sCO_2 as the working fluid have been identified as the most promising advanced power cycles for integration with CSP, which is aligned with FE and NE priorities [8]. Illustrations of the CSP Program technical targets are in Figure 18.

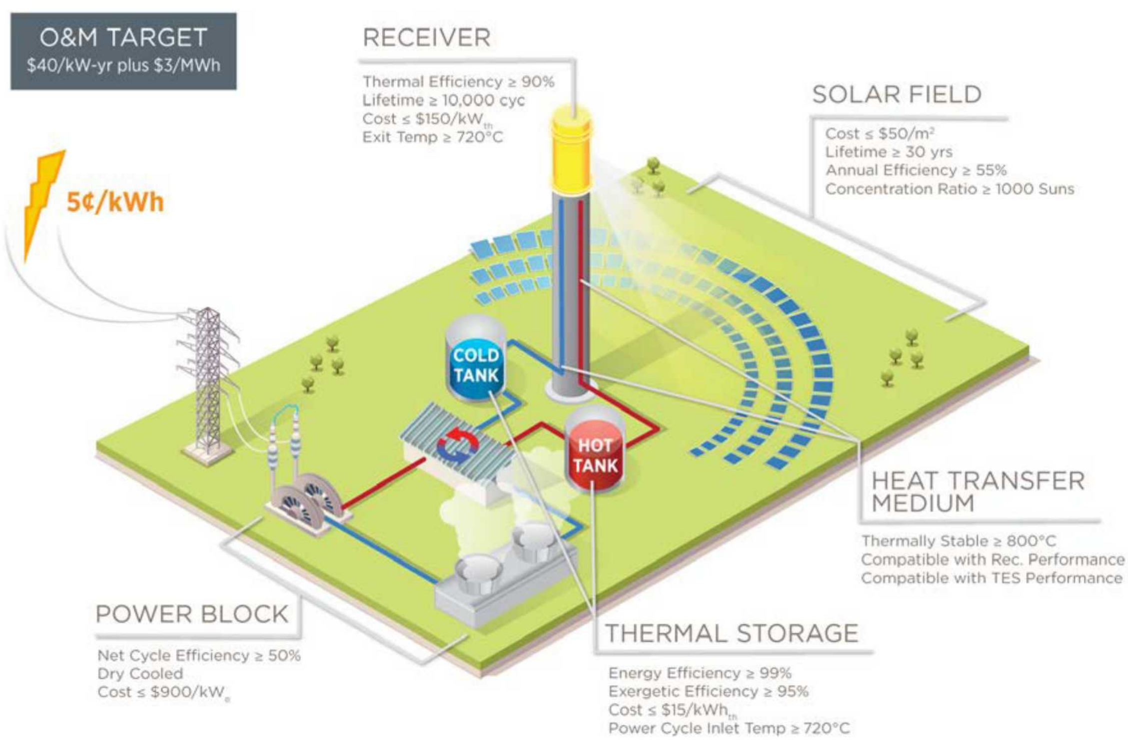


Figure 18: Concentrated Solar Power Program Technical Targets.

Supercritical CO_2 Brayton-cycle energy conversion systems transform heat energy to electrical energy using sCO_2 rather than through steam-Rankine cycle systems commonly used in current CSP, coal, nuclear, and combined-cycle gas plants. Cycle configurations such as the partial-cooling cycle and recompression with main compression intercooling, together with reheat; appear able to reach the SunShot target of 50% efficiency, even when combined with dry cooling.

To achieve the SunShot target of 50% efficiency, high temperatures (≥700°C) are required. The temperatures will require alternative heat transfer fluids (HTF) to currently used molten nitrate salts, which are limited to temperatures less than 600°C. The technology pathways with potential to deliver the high temperatures include particle, advanced molten-salt, and/or gas-phase HTFs and associated receivers.

The EERE Program Overview is included in the Addendum A: Presentations report.

Technical Development Status Presentations

Summit sessions included presentations addressing several topics. The presentation titles and presenters are listed in Table 1. The full content of all these presentations is included in the Addendum A: Presentations report.

Table 1: sCO_2 Power Cycle Summit Presentations

Development, Testing, R&D Needs	Speaker
Dresser-Rand / Siemens / Echogen Supercritical CO_2 Commercialization Update	Blunk, Siemens
Development of a High-Efficiency Hot Gas Turbo-Expander and Low-Cost Heat Exchangers for Optimized CSP sCO_2 Operation	Moore, SwRI
Design, Fabrication and Testing of Apollo Compressor	Mortzheim, GE
Integrally Geared Compressor-Expander	Wygant, Hanwha
Power Generation Reinvented – Echogen sCO_2 Technology	Held, Echogen
sCO_2 Turbomachinery Design Topics	Stapp, Peregrine
Near-Term Applications for 1 to 20 MW sCO_2 Power Blocks	Brooks, Peregrine
Supercritical CO_2 Pilot Plant Test Facility Project	Kutin, GTI
Research Needs and Development Status for the sCO_2 Cycle	
Grid Modernization Research at Sandia	Rochau, SNL
A Concentrated Solar Power Perspective	Vijaykumar, EERE
Fossil Energy Perspective	Dennis, FE
Development of a Basic and Applied R&D Plan for the Recompression Closed Brayton Cycle (RCBC)	Rochau, SNL
Invited Industry Presentations	
HAYNES® 282® Alloy for sCO_2 Power Cycle	Deodeshmukh, Haynes
Net Power, Truly Clean, Cheaper Energy	Dimmig, Net Power
Malta: a PHES Moonshot	Apte, GoogleX
sCO_2 Component Technology Review	
Heat Exchanger Development (EERE, NE, FE) - EERE “Periodic Flow Regenerators for sCO_2 Brayton Cycles” - EERE/FE “Development Status of the Brayton Recuperator”	Wildberger, VPE Anderson, UW Sullivan, Brayton

- NE "State of Art in PCHE Development and Associated Research at Sandia" - FE "sCO_2 High-Temperature Microtube Recuperators for the sCO_2 Power Cycles"	Carlson, SNL Portnoff, THAR
Materials Development - EERE "State of the Art in SCO_2 Corrosion and Mechanical Testing" - NE "Overcoming Materials Challenges for NE sCO_2 Energy Conversion Systems" - FE "DOE FE Materials R&D on Supercritical CO_2 Corrosion"	Carlson, SNL - Pint, ORNL - Walker, SNL - Kung, EPRI

Panel Sessions

Two panel discussion sessions were conducted during the event to grant industry the opportunity to question utility representatives on their views and needs for technology adoption and to question the national laboratories on the future path and progression of sCO_2 R&D programs.

Panel Topic	
Industry Engagement Panel: Utility Representatives Questioned by Industry - What are the industry expectations on SCO_2 cycles? - What is industry approach to implementing SCO_2 cycles? - What research should DOE and industry be funding in near future? - Applications needs for CC, coal, nuclear, CSP	Panelists: Barron, SCS Blunk, Siemens Julius, Duke Mann, Tri-State
Industry Engagement Panel: Laboratories Questioned by Industry - What does the industry expect the national labs to develop? - What would the utilities need from national labs to incorporate SCO_2 cycles within their plants? - What form of research should component and power cycle developers expect from national labs?	Panelists: Rochau, SNL Dennis, NETL Turchi, NREL

Panel Discussion Highlights: Utility Representatives Questioned by Industry

This panel focused on sCO_2 and scale in the utility market, with questions addressed by industry representatives.

1. The potential market for sCO_2 is assumed to be a complete replacement for any application where the steam Rankine cycle is in. Is that the total market in terms of the utility case? Out of the potential applications, what do you see as the first opportunity for sCO_2 system to be deployed in a utility application?

   The utility industry is very risk averse. Utilities will look at the technology as it is and compare it to where they are in supporting customer needs. Utilities are looking for efficiency improvements, but operations will always prefer to go back to where their comfort is. sCO_2 has to be a big step change to drive utilities to the next technology iteration. Utilities do not seem interested in being the first to market, but would rather see demonstrated benefits in efficiency and cost.

However, there might be a regulation established in terms of emissions that forces the industry to go a specific route. sCO_2 could also be an opportunity where other cycles do not make sense.

2. What do utilities have to see before they can adopt technology? What is the scale that utilities want?

   A useful corollary is the wind industry. They started in the 1 kW utility scale, and "several million deployments later," a few utilities have started to own them. Maybe that is a realistic expectation.

   Multiple things need to be well understood before utilities go out and buy an sCO_2 system. It is necessary to really understand how to operate the system, startup, shutdown, load-follow, maintenance over the lifespan of 30 years or longer, and what will be the costs of that maintenance. Basically, technology development needs to eliminate not just the technical risk, but also the economic risk over the lifespan of the plant, not just up-front costs. Training programs for operators under different conditions may need to be part of the deployment strategy.

   There is a big difference between first-to-market "plant one" versus following plants. As the plants increase, the industry develops a marketplace so the costs go down. This applies not only for the economics of the plant, but also for developing the labor force that can support it from both operations and maintenance sides. Many uncertainties and positions that will need to be trained are not there today.

3. Operational characteristics of sCO_2 are important. What are the key operational characteristics that utilities would like to see proven before they are ready to buy a sCO_2 system?

   It will depend on the application. Operational flexibility encompasses a lot of different things, including how long does it take to start up, shut down, whether you can ramp up and down a load, impact of renewables on the grid, and how the system can respond to quick changes in load, what is the minimum load, etc. A nuclear application will be different from CSP. However, with the operational environment that exists today, transient conditions are the norm. Utilities need a general understanding of system operations on transient conditions for each application.

4. Do utilities have any sort of boundary conditions in ramp-up times, turndown conditions that they would like to see demonstrated out of a machine like this?

   The facility would need to be flexible enough to adjust very quickly. Right now, utilities are not putting a number on what that ramp-up or shut down should be, but it needs to be able to adjust transient conditions very quickly.

5. Assuming the most likely first system will probably be a stand-alone, gas fired, 10 MWe system. Are utilities going to buy that? Do they need it?

There might be some interest looking at distributed generation applications. As far as integrating it to the regulated environment, where utilities need to recoup those costs from customers at the utility regulatory commissions in various states, it will be an uphill challenge. It might be more open on the most unregulated states.

In places where there are no reasonable choices because of the regulatory environment, it would make sense to use an open cycle (if the technology existed) to reduce the electricity bill. The ability to self-supply would make an interesting option. This is the market until the other areas come down in price, or the need is there, and operational requirements and costs are met.

6. Do you, as representatives of the user community, potential future utility operators, feel adequately engaged in defining your needs and priorities?

   Utilities feel engaged as they have been approached by the different technology developers and innovative research leaders. The technology has not been selected yet because it is not developed, but they feel that as the technology gets there, utilities will be engaging it. However, it is not something that is in the forefront of their planning to include the technology in the next generation facility.

   One of the reasons why utilities attended the event is that part of their role is to provide information and stay engaged with all the different technologies through forums like the summit. They also communicated with other utilities to understand how their needs may be different.

7. Out of the results seen thus far, are there any technical challenges that concern you, that maybe have not been addressed by this community? Or, are there areas that we (the labs) seem overly worried about that you are not so concerned about?

   A lot of the technical challenges are well understood. One of the things utilities might be concerned about more is the potential for how to manufacture, build, and construct these plants, especially since facilities 1, 2, 3, and 4 are not going to be well understood to begin with. The R&D side needs to understand how the technology and utilities get to the point where they feel confident about manufacturing processes, fabrication, etc. All these things can tie into financial risks and increase costs.

   Utilities recommend being realistic about cost expectations. Plants being built today are under $1,000/kWe and they are already over 62% efficient (although maybe not on the same device); they are relatively efficient and inexpensive. So, if the result of sCO_2 ends up being similar efficiency but more expensive, there is really no benefit to the change. Facilities need to make sure it is affordable to manufacture, but the procedures to manufacture with specific materials will also have a learning curve. Once the first deployment is done, then you can consider advanced tuning. For example, stronger cutting tools might be needed for the stronger materials; welding machines might need to be made for the higher strengths. There are several manufacturing unknowns.

R&D must also realize sCO_2 is in competition with other technologies out there. Solar is getting increasingly efficient since the mid-80s. Same with wind technology. Utilities will evaluate all the technologies to determine what they will put on the grid next. They are waiting for the economics to add to their models to decide along with operations and maintenance.

8. Other countries have different fuel expenses, regulatory issues, etc. Would it be possible to do the first units there? What other places would be able to build this technology? Would demonstrations in other countries be something you would consider or does it have to be something you have to physically visit and see it on the ground?

   A potential country interested in the technology is probably Japan. They are concerned with efficiency and CO_2.

   As long as the demonstration is relevant to what the utility wants to do, it will meet their needs. Utilities do like to see the technology and talk to the people that operate and maintain it, but they can and do travel around the world to see other technologies.

9. The science says that for about 700°C, there is typically a 1 to 4% point efficiency to be gained. It is not clear whether the electricity is cost competitive or not. Is that percentage efficiency gain enough?

   Ultimately, what matters is the total lifecycle cost of the plant. All things being equal, utilities will always choose the more mature technology. The new technology must have a significant cost advantage, especially on the early stages of the technology, for utilities to choose it over something more mature.

   Alternatively, coal is cheap, efficiency is important for regulatory reasons, but not for cost. The open cycle is more important because it eliminates the regulatory risk from a CO_2 perspective whereas the 4% efficiency increase just decreases the size of the plant.

10. Where is your sensitivity in terms of scale? How large a demonstration base and what size level would you be comfortable to integrate a system to your grid?

    There are a lot of unknowns to make that determination, because you need to consider not just the demonstration but also the level of comfort of operations, maintenance, and engineering staff with the specific technology and technology readiness, and that they have matured not only through testing but through other markets. It depends on the technology and how it matures its TRL. Events like the summit do help utilities become more comfortable with where the technologies are. It also depends on what the perceived risk is, and who is going to take on that risk.

11. Do you see any value in being able to locate generation closer to load? Putting aside concerns such as first of a kind, configuration, etc.? Is that something we should be focusing on?

Historically, generation dictated where generation would be placed in the plant. However, some of the utilities' research is now looking at distribution/transmission dictating where to place generation. It is necessary to consider the transmission/distribution congestion in specific areas, and other factions that need to be accounted in the calculation. It is already possible to do that with reciprocating engines that are ~50% efficient, but they do not do it, so that might give an indication of interest.

There is some potential value to have a more distributed application, not just in substations but also even at customer sites. This has been a trend in recent years.

12. How much do you see the renewables portfolio standards or IRPs of renewables and renewables with storage playing a role in the next 5 to 10 years, and how that plays into a solarized sCO_2 system?

    It is not a major factor in the immediate future, but it is becoming a part of the toolbox.

Panel Discussion Highlights: Laboratories Questioned by Industry

Given SNL and NETL had presented the status of their programs during the technical presentations, the National Renewable Energy Laboratory (NREL) opened the panel discussion with an overview of its focus and progress. NREL is not heavily involved in the development of the power cycle, but dedicated in looking at the constraints of the power cycle and how CSP must interface with those constraints. The future of CSP is predicated on the ability to integrate storage and add value to the grid. The slides presented discuss the areas of R&D being pursued, and are included in the Addendum: Presentations report.

NETL supports FE in pursuing a 10 Mwe power cycle. Its program was developed by incorporating the development of the power cycle into specific areas of the FE programs, such as combustion, turbines, fuel cells, gasification, among others, to divide the scope and budget to develop the technology. FE has realized a more integrated approach and funding to support the programs is needed. Currently, its focus is on the turbine area while encouraging the advanced combustor group to engage in the recuperator. Simultaneously, the crosscutting effort is working on the materials R&D need. For technology development, NETL advocates the need for a more comprehensive strategic plan, including additional studies for what will really be the first application for this technology.

SNL is working on supercritical CO_2 power generation for nuclear systems. They are charged to come up with a cost-effective technology that could enhance safety and include waterless power generation of the systems. SNL is currently trying to develop the technology for sodium fast reactors and all the technology associated with that, including going to higher temperatures for conversion efficiency. SNL is also doing work in CSP to develop the power block. Time dependency is short for CSP, much longer for nuclear reactors.

SNL is also working on technology for Advanced Small Modular Reactors (ASMR). As comparison, for pressurized water reactors at 300°C, CO_2 generates about the same energy conversion difference as steam plants. The big distinction is that CO_2 would not require water or condensing the liquid to be put back in, so there might be a big advantage for SMRs ease of operation. In general, SNL expects to see sCO_2 systems that have much simpler operations.

Panel Questions addressed by representatives from NETL, SNL, and NREL:

1. What can industry expect the labs to do when it comes to component design? And what will they not be able to pay for?

   Industry may be more interested in focusing on lower capital expenditures (CapEx) versus high efficiency, which basically rolls up to cost of electricity. We do try to focus on lowering cost of electricity (COE).

   FE is focused on large stationary power systems, but we do not get the sense that people think this would be the first starter.

   One of the things labs can help the most given resources at SNL is distributed energy technology. The market of 1 to 20 MWe level looks like a sweet spot working in partnership with industry through collaborative R&D agreements. The goal would be to improve the technology and get it to market quickly, with the PCHE as an example.

   NREL work is geared towards the solar industry rather than the power block. As an applied laboratory, NREL is engaged with industry lab partnerships, and has a number of useful tools that are generally applicable, such as high-performance computing and virtual 3D simulations. NREL has worked on CSP development for field layout, grid simulations, and quantification of hours of storage and how that brings value to the grid for regional areas.

2. On the materials and design side, allowable stress versus temperature is falling significantly between 700°C and 790°C. Based on the primary heater design for our version of the STEP facility, the through-wall temperature gradient drives the limit of the fluid temperature that you can attain. There is a tradeoff on wall thickness, temperature, and high pressure. Understanding the design barriers better would be a big help to the primary heat exchanger design. Would the labs work on how that impacts that important, very expensive component?

   This is a very important point. The temperature was set to try to get the equation right for CapEx, efficiency, and lower COE, but the 620°C lower temperature was also looked at, and presumably, it is possible to use different materials, thinner walls, etc. There is a lot that can be done to advance the technology without going all the way to the highest temperatures right away and still achieve benefits compared to supercritical steam at the same temperatures.

3. Understanding the economic tradeoff of materials selection versus the operating conditions will have a big effect on the levelized cost of electricity (LCOE) and CapEx vs efficiency, there still needs to be better fidelity for the materials cost. Basing cost on elemental composition is a good start, but engaging with the suppliers in understanding materials is needed. Can we pick a few materials and get some real costs to help decide how we choose materials?

It is a good idea to put a group like this together, but maybe more specialized on the materials side in order to cue the data to make decisions and reporting baselines. The data is only as good as the data that was collected. Assuming that production ramps up with materials demand, that is going to affect the prices as well, so some sort of ongoing basis is needed. The focus would be to be able to determine what materials to pick for a specific type of conditions. Cost may change the design of the cycle.

From a systems engineering perspective, a concurrent engineering approach has allowed us to discover pockets of information outside of the labs. There is a lot of information and databases of materials that come from NASA and other places. Looking into that information by getting together people who know where the information is should be something the labs would be able to do fairly readily.

The labs have also done a lot of work on the area, and are reporting the information as it is gathered and analyzed.

Poster Session

A poster session was planned for exhibit during both days of the event. Posters were invited from specific R&D topics that were introduced but not discussed in detail during the content presentations or panel sessions. The scope of the poster sessions was to allow participants exposure to the full range of R&D and the principal investigators working on those areas, to establish first contact in many cases.

To facilitate the poster session planning, presenters were given the option of mailing the poster in high-resolution format to have it reviewed and printed on site at SNL. Thirty-six (36) posters were on display at the event, as detailed in Table 2. Previews of the posters are included in the Addendum B: Posters report.

Table 2: sCO_2 Power Cycle Summit Posters

Title of Poster	Last Name	Affiliation
Materials Corrosion in Supercritical CO_2	Anderson	University of Wisconsin - Madison
Low-leakage Seals for Utility-scale sCO_2 Turbines	Bidkar	GE Global Research
Near Term Applications of 1-20 MW sCO_2 Power Blocks: A National Imperative	Brooks	Peregrine Turbine Technologies, LLC
Near Term Applications of 1-20 MW sCO_2 Power Blocks: A new Era Emerging	Brooks	Peregrine Turbine Technologies, LLC
Near Term Applications of 1-20 MW sCO_2 Power Blocks: Collaborative Advancement of Fossil Fueled Fired sCO_2 Power Cycles	Brooks	Peregrine Turbine Technologies, LLC
Near Term Applications of 1-20 MW sCO_2 Power Blocks: Global Market Applications	Brooks	Peregrine Turbine Technologies, LLC
Advanced Heat Exchanger Development for sCO_2 Brayton Cycles	Carlson	Sandia National Laboratories

Title of Poster	Last Name	Affiliation
Cost Estimation of sCO_2 Brayton Power Cycles	Carlson	Sandia National Laboratories
An Advanced Gas Foil Bearing Design Using Supercritical CO_2 as the Working Fluid	Chapman, Jr.	Mechanical Solutions, Inc.
Physics-based Reliability Models of Supercritical CO_2 Turbomachinery Components	Moore	SwRI
Brayton Cycle Economic Tool	Lance	Sandia National Laboratories
High-Temperature Micro-pin sCO_2 Solar Receiver Development	Fronk	Oregon State University
Development of Process Lubricated Bearings for sCO_2 Cycles	Ertas	GE Global Research
Bearing Development Platform	Fleming	Sandia National Laboratories
Seal Development Platform	Fleming	Sandia National Laboratories
Particle-to-sCO_2 Heat Exchanger Designs for Concentrating Solar Power	Ho	Sandia National Laboratories
Investigation of Auto ignition for High Pressure Supercritical Carbon Dioxide Oxy-combustion	Karimi	Georgia Institute of Technology
Low-Cost Recuperative Heat Exchanger for Supercritical Carbon Dioxide Power Systems	Kelly	Altex Technologies Corporation
The 10 MWe sCO_2 Pilot Plant Project	Kutin	Gas Technology Institute (GTI)
High Resolution Optical Measurements for sCO_2	Lance	Sandia National Laboratories
High-Efficiency Thermal Integration of Supercritical CO_2 Brayton Power Cycles for Oxy-fired Heaters	Maxson	EPRI
Technology Roadmap and Systems Engineering Model for sCO_2 Power Cycle Development	Mendez	Sandia National Laboratories
Plant Dynamic Modeling at Argonne	Moisseytsev	Argonne National Laboratory
Source-to-$C0_2$ HX	Sienicki	Argonne National Laboratory
Four Access Controlled Test Cells Supported by a Fully Capable Services Infrastructure	Morris	Notre Dame Turbomachinery Lab
High-Temperature Calcium-Based Thermochemical Energy Storage System for Use with CSP Facilities	Muto	Southern Research Institute
sCO2 Power Cycles with Integrated Thermochemical Energy Storage Using an MgO-based sCO_2 Sorbent in Direct Contact with Working Fluid	Muto	Southern Research Institute
sCO_2 Power Cycle Development	Pasch	Sandia National Laboratories
Advanced Materials Issues in Supercritical Carbon Dioxide	Pint	Oak Ridge National Laboratory

Title of Poster	Last Name	Affiliation
Experiments and Modeling to Aid the Development of Supercritical CO_2 Oxy-fuel Combustor	Vasu	University of Central Florida
sCO_2 Turbomachinery and Heat Exchanger Development	Stapp	Peregrine Turbine Technologies, LLC
Manufacturing Process Development for Lower-Cost Heat Exchangers for High-Temperature/Pressure Applications	Sullivan	Brayton Energy
Overcoming Materials Challenges for SFR sCO_2 Energy Conversion Systems	Walker	Sandia National Laboratories
NE sCO_2 Power Cycle Technology	Pasch	SNL
Fossil Energy sCO_2 Power Cycle Technology	Weiland	NETL
Absorption/Desorption Based Supercritical Carbon Dioxide Power Cycles	McClung	SwRI
Robust ZrC/W Composites for High-Temperature (>750°C) sCO_2 Heat Exchangers[2]	Sandhage	Purdue University

[2] Poster by Sandhage is not available for publication, and is not included in this report.

Post-Event and Follow-up Actions

Various activities were identified during the summit, either for immediate action or for follow-up resulting from the relationships established during the event.

Communities of Practice

A community of practice (CoP) is a group of people interacting, sharing, and working together toward common goals. A CoP is targeted to connect people in conversation around relevant content in a way that advances common goals. Communities may serve many purposes, such as providing stakeholders a forum for discussion, sharing resources and practices, and coordination and strategy [10], and have been shown to deliver positive, unexpected results across several industries [11].

The key tool is to have a common platform constituents can consistently monitor. The biggest challenge is ensuring people are engaged. It is recommended to “meet them where they are,” so it is good to understand which platforms this community already uses. Some organic communities (online and offline) have already formed within sCO_2 research groups, so they could be tapped to be supported and expanded based on common goals.

SNL established the online infrastructure to support two communities of practice, depending on the type of information and discussions to be enabled (Figure 19).

Password Protected Community — Enable continuous communication and collaboration

- Unclassified Unlimited Release (UUR) Information ONLY
- Password Protected
- Access requires DOE Offices sponsor

SNL External Collaboration Network — Enable collaboration and work with proprietary information

- UUR, Official Use Only (OUO), and Proprietary Information
- Password-Protected, SNL External Collaboration Network
- Access requires DOE Offices sponsor, onboarding to SNL org 8841, and registration with SNL ECN

Figure 19: Sandia National Laboratories-Hosted sCO_2 Communities of Practice.

The password-protected community was launched within a week of the summit as a means to support follow-up conversation between summit participants. The sCO_2 Power Cycles CoP is hosted by SNL and features UUR information only. Initial content includes all the presentations, posters, and pictures from the event, as well as a list of participants with relevant contact information.

Access to this community was granted to all participants of the summit and their authorized representatives. Additional access can be requested for new members by emailing the primary community contact. Sponsoring from the DOE offices supporting the CoP effort is required to obtain access. Ongoing management is conducted on the community, which currently exceeds 45 registered users.

Merlin Proposals to DOE-NE

Three proposals were prepared for NE outlining incorporation of a sCO_2 Power Cycle at 1 MWe capability. Two of the proposals focused on a Concentrated Solar Heat Source and one for demonstration of grid compatibility of the Peregrine Turbine Technologies (PTT)[3] *Merlin* at 1 MWe and linking it to the SNL grid.

Merlin is a 1 MWe simple recuperated Brayton cycle engine with a 750°C turbine inlet temperature. This product is at the lower end of the high value of power ratings within the core distributed energy (DE) market and is well positioned for multiple military and civilian DE applications. The initial unit will serve as proof-of-concept for the *Maverick*. *Maverick* is a 6 MWe combustion turbine of similar design to that of *Merlin*. *Maverick* and *Merlin* share a highly efficient modular design and hence many of the same components.

Negotiations with Siemens on Support of Advanced Concepts for Naval Power and Waste Heat

Discussions with Siemens have focused on support of a waste heat recovery system for the local grid of a natural gas compressor station and the potential of a 25 MWe sCO_2 power system for the electric ships 1000 V power bus. Also discussed was support of the Siemens Grid on a Skid concept.

Heat Pipe Reactor with sCO_2 Power Conversion for Department of Defense Applications

Discussions have been held with LANL on coupling a heat pipe reactor of 3 to 10 MW to a sCO_2 that would be hardened, transportable, and autonomous for Department of Defense (DoD) applications.

Advanced Research Projects Agency-Energy Concepts for He Reactor with sCO_2 Power Conversion with General Atomics

An Advanced Research Projects Agency-Energy (ARPAe) MEITNER (partnership with General Atomics and SNL) concept paper was developed and a full proposal invited to support the EM2 helium reactor coupled to a sCO_2 power cycle.

Advanced Research Projects Agency-Energy Concept for Load Following sCO_2 Power System with Peregrine Turbine

An ARPAe OPEN (partnership with PTT and SNL) concept paper was developed to demonstrate load following capability with a sCO_2 power cycle with essentially an instantaneous up to 90% power swing.

[3] SNL has been collaborating with Peregrine Turbine Technologies (PTT) on the development and testing of sCO_2 Brayton technologies that will likely have early applications for distributed energy and waste heat recovery markets.

Kirtland 1st Initiative

A concept paper was developed to couple a 1 MWe sCO_2 power cycle to a SMART microgrid at KAFB with integrated renewables as a demonstration of DoD base energy resiliency.

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Conclusions

The benefits of sCO_2 cycles for energy conversion are clear. However, the challenges presented to develop the technology cannot be underestimated. There is much interest and willingness between the DOE offices, laboratories, and industry to develop collaborative agreements supporting sCO_2 R&D. The large scope and complexity of R&D needed to achieve technology readiness in a timely manner call for this type of integrated collaboration. Tools, means, and strategies that can be implemented to support these collaborations are welcome.

There is increased interest in engaging the utilities industry to understand its demands for technology adoption. There is uncertainty in determining the commercialization goal, technology readiness criteria, and risk levels for utilities and insurers, among others. The sCO_2 community is currently working with the understanding that the primary challenges towards commercialization are proving reliability of the system, meeting standards of utility, and understanding all the risks associated with writing a contract between vendor and utility. These need to be validated, allocating success metrics via a market analysis and other relevant means. The market analysis also needs to understand the policies in place for utilities, and the implications for their operations in terms of revisiting permissions or acquiring new permissions that would otherwise not be needed if they implement the existing technology instead.

Utilities at the summit highlighted several areas of need before they could consider implementing new technologies. First, the risk-averse nature of the industry makes being *first-to-market* not necessarily a priority, rather seeing real benefits on a proven technology. Second, technology development needs to eliminate not only the technical risk, but the economic risk of the new facility, including operations and maintenance for the lifespan of the system (~30 years) beyond the initial acquisition. And third, the training needed for the new positions and personnel that do not currently exist because they are not needed for contemporary systems.

Similarly, in regards to technology development, there is a need to engage with materials suppliers to understand the cost of materials based on specific criteria, including demand and price change over time.

Industry interest is tangible, but engagement needs to be supported financially and operationally. Some areas to consider include easing collaborations with the labs, facilitating information sharing that protects commercial intellectual property, supporting technology development economically and via policies and programs, among others. Research partners and industry need to come into a collaboration with an understanding of the risk they are willing to undertake for the potential benefits of the new technology.

This type of summit event provides great networking opportunities and can result in any number of collaboration projects with industry (as seen on the follow-up actions). The poster session provides participants the visibility to meet and interact with principal investigators in areas more relevant to their needs. However, developing genuine collaborations requires ongoing contact. Although the CoP was set up to enable that type of ongoing relationship, response and participation has been limited.

The U.S. community ability to collaborate allows much faster advances than other countries. The sCO_2 community is demonstrating that integration is possible; recognizing one group cannot do everything and the input from industry, vendors, suppliers, government, and labs is critical. sCO_2 is real technology innovation. The area has provided many examples for collaboration and integration, but the opportunity to leverage resources remains. It takes a lot of effort to form effective partnerships, but the results are worthwhile for everyone, and the DOE offices are committed to supporting this effort.

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