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sCO_2 Brayton Energy Conversion Customer Discovery

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EXECUTIVE SUMMARY

All energy production systems need efficient energy conversion systems. Current Rankine cycles use water to generate steam at temperatures where efficiency is limited to around 40%. As existing fossil and nuclear power plants are decommissioned due to end of effective life and/or societies' desire for cleaner generation options, more efficient energy conversion is needed to keep up with increasing electricity demands. Modern energy generation technologies, such as advanced nuclear reactors and concentrated solar, coupled to high efficiency sCO_2 conversion systems provide a solution to efficient, clean energy systems. Leading R&D communities worldwide agree that the successful development of sCO_2 Brayton power cycle technology will eventually bring about large-scale changes to existing multi-billion-dollar global markets and enable power applications not currently possible or economically justifiable.

However, all new technologies face challenges in the path to commercialization and the electricity sector is distinctively risk averse. The Sandia sCO_2 Brayton team needs to better understand what the electricity sector needs in terms of new technology risk mitigation, generation efficiency, reliability improvements above current technology, and cost requirements which would make new technology adoption worthwhile.

Relying on the R&D community consensus that a sCO_2 power cycle will increase the revenue of the electrical industry, without addressing the electrical industry's concerns, significantly decreases the potential for adoption at commercial scale. With a clear understanding of the market perspectives on technology adoption, including military, private sector, and utilities customers, the Sandia Brayton Team can resolve industry concerns for smoother development and faster transition to commercialization.

An extensive customer discovery process, similar to that executed through the NSF's I-Corp program, is necessary in order to understand the pain points of the market and articulate the value proposition of Brayton systems in terms that engage decision makers and facilitate commercialization of the technology.

ACRONYMS

Abbreviation	Definition
SNL	Sandia National Laboratories
DOE	Department of Energy
RCBC	Recompression Closed Brayton Cycle
DP	Development Platform
sCO_2	Supercritical Carbon Dioxide
SFR	Sodium Fast Reactor
RFI	Request for Information
TAC	Turbo-Alternator-compressors (TAC)
FFRDC	Federally Funded Research and Development Centers
R&D	Research and Development
NESL	Nuclear Energy Systems Laboratory
NSF I-Corps	National Science Foundation's Innovation Corps
SMR	Small Modular Reactor
DAQ	Data Acquisition
STEP	Supercritical Transformational Electric Power
CoP	Community of Practice

1. BACKGROUND: SANDIA'S sCO_2 ADVANCED ENERGY CONVERSION PROGRAM

Energy production systems require efficient energy conversion systems. As existing power plants are decommissioned, increasingly efficient energy conversion is needed to meet increasing electricity and energy resilience and security demands. Advanced energy conversion systems that utilize sCO_2 Brayton cycles can provide heat source agnostic, secure, reliable, and deployable power generation for the grid, military applications, continuity of operations, and emergency backup for grid disruptions.

A "supercritical Brayton cycle" is a closed Brayton cycle where the working fluid, supercritical carbon dioxide (sCO_2), is maintained near the critical point during the compression phase. At this point, sCO_2 can adopt properties midway between a gas and a liquid. The closed cycle consists of five components: compressors; turbines; heat input; heat rejection; and recuperation. Optimization of each component contributes to the overall cycle efficiency.

The properties of sCO_2 systems suggest several benefits over traditional steam plants: higher plant efficiency, reduced fuel use, lowered greenhouse gas emissions, smaller physical footprint, and suitability for dry cooling in arid climates. The benefits make the technology very attractive for multiple applications, from energy resiliency for remote military locations to on-the-grid power generation. However, to ensure successful commercial deployment of the technology, these benefits need to be discussed and positioned in a way that demonstrate value to the customers. With the distinctly risk adverse nature of the energy sector, engaging in conversations that highlight the value and identify the concerns and limiting factors is essential.

1.1. The Role of Sandia

For years, Sandia National Laboratories has been working towards mitigating the technical risks involved in Brayton systems. SNL's Brayton Energy Conversion Team ("Brayton team") mission statement, revised in 2020, states: "… *Sandia National Laboratories, in collaboration with government and industry partners, shall investigate the science, develop the test capabilities, and experimentally validate a grid compatible sCO_2 Brayton Power System to transition laboratory technologies to domestic energy commercial applications through the incremental development and testing of components and sub-systems relevant to sCO_2 Brayton power cycles."* [1]

"Successful development of sCO_2 Brayton systems supports overarching Department of Energy (DOE) drivers, including:

- meeting national climate and energy goals
- promoting domestic job creation
- facilitating domestic industrial competitiveness
- maintaining U.S. technology leadership
- providing the nation with cleaner and more affordable power, and
- increasing energy resiliency and surety" [1]

1.2. History and Capabilities

Sandia's history and capabilities developed through the advanced energy conversion program demonstrate it is the right lab for this task. Sandia's work was initially focused on the application of heat from a Sodium Fast Reactor (SFR) to a sCO_2 Brayton power cycle. The team was able to install a complete Recompression Closed Brayton Cycle (RCBC) system, performing tests to demonstrate its operational and performance viability, with maximum turbine inlet temperature of 550 °C and expected thermal efficiency of 45%. The first achieved configuration was a laboratory scale demonstration of a sCO_2 RCBC at 250 kWe. In 2017, Sandia procured the world's first turbocompressor designed to operate at 750°C for 1 MWe generation. The Turbomachinery Development Platform was reconfigured in 2018 to allow for testing of the turbocompressor through 2021. Sandia now intends to return to power cycle configurations, implementing lessons learned from the initial RCBC to include upgrades to the motor controllers and the ability to reject power to the grid. [1] Capabilities have been added to SNL's Brayton Lab. Development Platforms (DPs) include the Turbomachinery Development Platform, sCO_2 bearings, seals and compressor research platforms, sCO_2 Natural Circulation Test rig, 700°C materials testing autoclave, 100 kW heat exchanger testing platform, and sCO_2 turbomachinery mechanical research station. Some capabilities are shown in Figure 1 and summarized on Table 1.

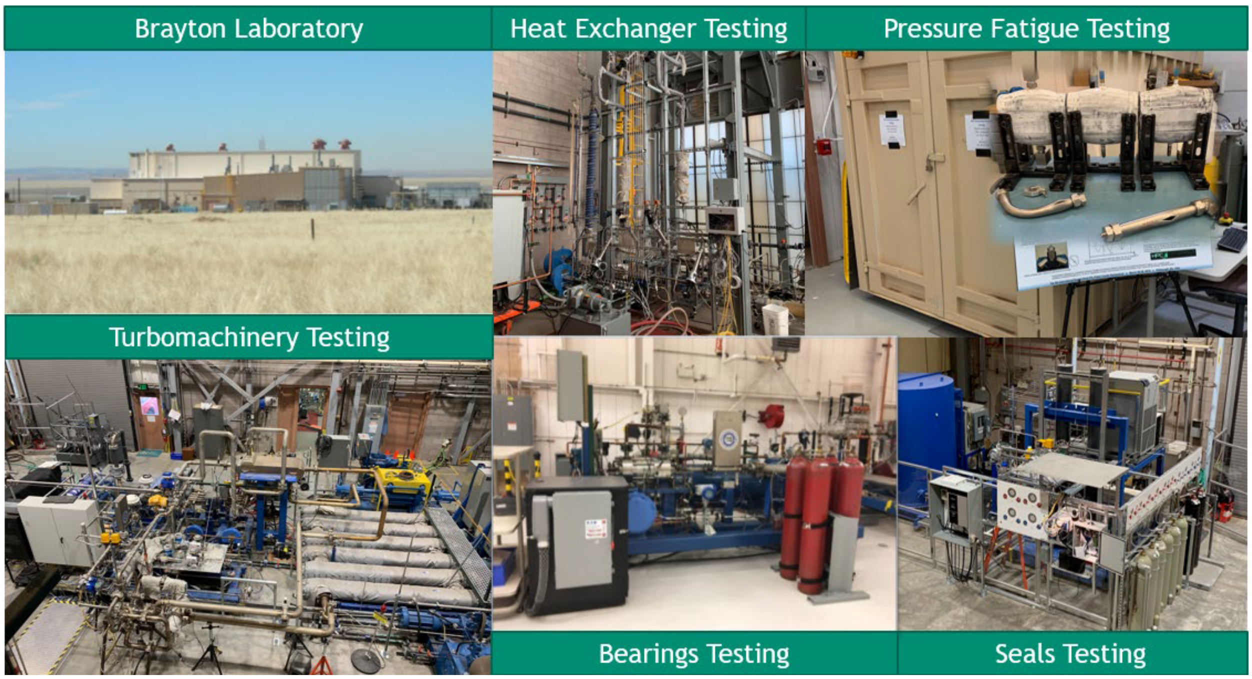

Figure 1: Sandia National Laboratories Brayton Cycle Development Platforms

Table 1: Sandia National Laboratories' sCO_2 Component and System Development Platforms

TEST RIGS	DESCRIPTION
Turbomachinery Development Platform	A reconfigurable testing rig with two turbo-alternator-compressors (TAC) rated at 125 kWe, motor controllers, 780 kW of heating power, 560 kW of heat rejection capacity, recuperators, extensive state of the art data acquisition (DAQ) and controls, rated for 538 °C (1000 °F) and 13.8 MPa (2000 psi) operation. The turbomachinery development platform is currently being used to test a sCO_2 turbocompressor, and there are plans to re-configure to a simple cycle configuration using a TAC.
Bearings Test Rig	The bearings test rig has the capability to test up to 121°C (250 °F) and 11 MPa (1600 psi) to test a variety of bearing types. Most recently this test rig was used to experimentally validate the performance of motor controllers for the TAC. This will enable improved accuracy and performance for bearings tests.
Seals Test Rig	The seals test rig has the capability to test seals ranging from 1" to 8" in diameter at 700 °C (1292 °F) and 30.3 MPa (4595 psi).
High Pressure Fatigue / Hydrostatic Test Platform	75 ksi hydrostatic and fatigue test facility to measure the mechanical performance of compact heat exchangers and other equipment.

1.3. Strategy

Sandia has been pursuing commercial development of sCO_2 Brayton systems through collaboration with industry partners funded by the DOE-NE Supercritical Transformational Electric Power (STEP) R&D program. These partners share a common goal of technology development with Sandia that simultaneously supports their longer-term individual goals. Thus, these partnerships do not need to encompass the full extent of the R&D cycle until the final application is achieved, but rather allow flexibility to optimize resources and capacity towards a faster common goal, while simultaneously freeing up time and resources to achieve individual goals. Sandia is now at the stage where those collaborations, which so far have centered on components, need to be expanded to look at integrated, deployable systems and the applications they will serve.

1.3.1. Commercial Partner Engagement through Testing Capabilities

In July of 2020, Sandia's Brayton team released an official Request for Information (RFI) to "the U.S sCO_2 power cycle industry for recommendations on what sCO_2 development platforms, test rigs and/or facilities are needed to expedite the commercialization of sCO_2 technology." [2] The RFI targeted commercial companies and vendors working on sCO_2 Brayton product development. The RFI specifically asked for:

- Description of the technical problem and proposed solution.
- The need for Sandia National Laboratories' expertise and resources to solve the technical problem.
- Description of the relevant experience, expertise, and capabilities of the interested party.
- Description of any experience partnering with Research and Development (R&D) organizations such as Federally Funded Research and Development Centers (FFRDC), Universities, National Laboratories, or Government Laboratories.

The information received was instrumental in developing Sandia's Brayton Teams 3-year plan. This plan focuses on the technical advances needed to move Brayton systems to commercialization through component development to successfully operate an integrated sCO_2 Brayton system. While this is important it does not identify or address concerns or issues of new technology adoption for the end user, such as utilities, power producers, and/or large consumers.

1.3.2. Customer Engagement through Communities of Practice

Sandia's sCO_2 Brayton efforts on technology development have focused on lining up test loops and rigs, controls, testing and model validation to support industry needs. Projects have supported understanding the science of different components and functions of the system: bearings, SMR applications and risks, turbomachinery, heat exchangers, and most recently the economics of the system and understanding of sCO_2 systems value for commercial purposes [3], with a smaller but consistent effort on assessment of economics and the market.

Sandia's preliminary assessment of the economics of the system and environmental factors of the energy sector indicates the first likely commercial application of sCO_2 Brayton cycles will not be nuclear. Thus, while the Brayton team's target goal is to ready the technology for nuclear applications, supporting the development of other applications through collaboration with partners is a critical part of the effort to expedite technology development. Some potential applications include waste heat recovery, concentrated solar, and distributed energy among others. Potential scenarios for deployment include hybrid grids and microgrids, remote and isolated communities, military bases, shipboard propulsion, and emergency response. To proceed down this path, it is necessary to inventory the needs and requirements of these and other applications, and what those customers need. In addition, the latest update from the economic and market assessment highlighted the need to develop common understanding, and common language around the metrics and value of advanced energy conversion systems in a way that speaks to those making decision on whether or not to adopt the new technology.

The current proposed path forward is to engage the sCO_2 technical community including research and development, manufacturers, component vendors, and interested commercial industries through the use of a Community of Practice (CoP). This would be the third CoP that Sandia has engaged to support Brayton systems, and the online infrastructure is already in place to support it. [3]

CoP's are a great tool to rally around a common problem or achieving common goals, but they are not without limitations. Challenges and lessons learned from previous CoP implementations hover around community management, sustaining relevant discussions, and maintaining an engaged membership. Without a common task to achieve, the community tends to disperse to other responsibilities. Recruiting industry representatives that have expertise on the subject matter, interest in the discussion, and willingness to engage is instrumental. The effort should include the industries within which this technology would have the greatest impact in order to identify the value proposition and relevant metrics most likely to impact decision making to allow a new technology into the mainstream.

2. NEED FOR CUSTOMER DISCOVERY

Advanced energy conversion systems such as the sCO_2 Brayton cycle are critical to the next generation of US energy infrastructure. The current push for decarbonization and resilient sources could greatly benefit from the efficiencies and footprint, as well as the many other advantages identified. However, the risk adverse nature of the energy sector, tied with the safety and resiliency needs of the community, make it so that new technologies need to be demonstrated before serious consideration is given to their adoption. The value proposition of sCO_2 Brayton system needs to be articulated in ways that speak to the needs and requirements of the decision makers.

A solid, proven path forward is needed to ensure the value proposition of sCO_2 Brayton systems is communicated in terms that foster commercial adoption. The NSF iCorp program [4] teaches an approach for "true customer discovery" that could be utilized for this purpose. The basic idea is to conduct a significant number of customer discovery interviews (at least 50 is recommended). The customer, in this case, would be utilities and potential power producers or large consumers. The interviews are not focused on the particular technology, but rather to draw out the customer on things like main customer requirements for a technology, pains with existing technologies, hopes for new technologies, etc. It is an extensive process, but well worth the effort as it allows the team to collect sufficient information to makes the case on how this new technology can alleviate those "pains" and provide true "gains."

The goal for this effort is to develop the relationship and interactions with the relevant end-customer industries, utilities, potential power producers, and/or large power consumers, who will ultimately make the determination of technology adoption. This will allow the Sandia Brayton team to gain understanding of customer needs and perspectives on the new technology. It is assumed, new technologies in the electric industry must be well demonstrated for efficiency, cost, and operations in order to drive adoption. This needs to be verified.

This effort would aim to draw out the customer views on things like main requirements for a technology, pains with existing technologies, and hopes/needs for new technologies. Customer discovery interviews will focus on:

- Understanding potential applications of the technology and which customers will likely be the first adopters and perspectives of utilities, the target commercial customer.
- Defining the requirements of a commercially ready, grid resilient power generation replacement system, which can be used to update, replace, or complement the existing power on the grid in cases of grid failures (i.e., Puerto Rico, remote military facilities)

  Power generation for isolated communities that are remote from the electrical grid, or facilities that desire a dedicated power source.

The Sandia Brayton team aims to identify and engage relevant stakeholders and generate open discussion regarding the requirements and barriers to technology adoption in their markets, leading to understanding their concerns for practical applications. The interviews and business canvas will identify the needs and requirements for successful commercial deployment.

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