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sCO_2 Brayton Cycle: Roadmap to sCO_2 Power Cycles NE Commercial Applications

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sCO_2 Brayton Cycle: Roadmap to sCO_2 Commercial Power Cycles

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Abstract

The mission of the Energy Conversion (EC) area of the Advanced Reactor Technology (ART) program is to commercialize the sCO_2 Brayton cycle for Advance Reactors and for the Supercritical Transformational Electric Production (STEP) program. The near-term objective of the EC team efforts is to support the development of a commercially scalable Recompression Closed Brayton Cycle (RCBC) to be constructed for the first STEP demonstration system with the lowest risk possible. This document details the status of technology, policy and market considerations, documentation of gaps and needs, and outlines the steps necessary for the successful development and deployment of commercial sCO2 Brayton Power Systems along the path to nuclear reactor applications.

Document Control

Version	Creation Date	Revisions	Created By	Release Date
1.0	2/29/2016	Preliminary Draft	Mendez, C.	3/2/2016
2.0	7/29/2016	Preliminary/Partial Report – updated Focus Area structure, added commercial path forward	Mendez, C.	8/10/16
3.0	5/1/2018	Updated Roadmap supports timeline changes and inclusion of grid qualification goals	Mendez, C.	6/6/18

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Executive Summary

The mission of the Office of Nuclear Energy (NE) Energy Conversion (EC) area of the Advanced Reactor Technology (ART) Program is to develop the supercritical carbon dioxide ($sCO_{2)}$ Brayton cycle for application in Advanced Reactors while supporting the Supercritical Transformational Electric Production (STEP) program. The near-term objective of STEP to establish an operating, commercially scalable Recompression Closed Brayton cycle (RCBC) pilot facility to be constructed in collaboration with the DOE Offices of Nuclear Energy (NE), Fossil Energy (FE), and Energy Efficiency and Renewable Energy (EERE). The STEP Pilot Facility should be established with the lowest risk possible, to be achieved by strategic, incremental development and testing of the components that make up the sCO_2 Brayton energy conversion power system.

Sandia National Laboratory (SNL)'s Brayton Energy Conversion Team original mission statement, developed in 2014, called for the development "with industry, of a fully operational 550°C 10 MWe R&D demonstration sCO_2 Brayton Power Conversion System that will allow the systematic identification and retirement of technical risks and testing of components for the commercial application of this technology." This statement was revised in May 2018, to support the understanding that retirement of risks for commercial ready technologies translates into the qualification of components for grid compatibility. The new mission statement states that:

> *"By April 2020, 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 that transitions laboratory technologies to domestic energy commercial applications."*

Since before 2010, SNL and others have been working towards mitigating some of the risks involved in Brayton systems. SNL, for example, has focused on the demonstration of an RCBC Test Article focused on developing the technology to make it available for commercialization in nuclear applications. Current research lines include the development and demonstration of components such as turbo machinery, heat exchanger, and recuperators, bearings and seals, materials work, and development of common understanding on the technology readiness levels for TRL management.

Notwithstanding current efforts, there are still multiple areas that need to be addressed along the path to commercial readiness. SNL and the STEP collaboration (supported by NE, FE, and EERE DOE offices) have now initiated an overarching program R&D plan to support the development of Brayton R&D coordination that optimizes resources and ensure teams are working towards commercially viable goals. The STEP program R&D plan is focused on supporting three goals:

1- To ensure component readiness for the successful launch of sCO_2 Brayton Cycle Pilot Facility, supporting Brayton systems applications for FE, NE, and EERE applications.

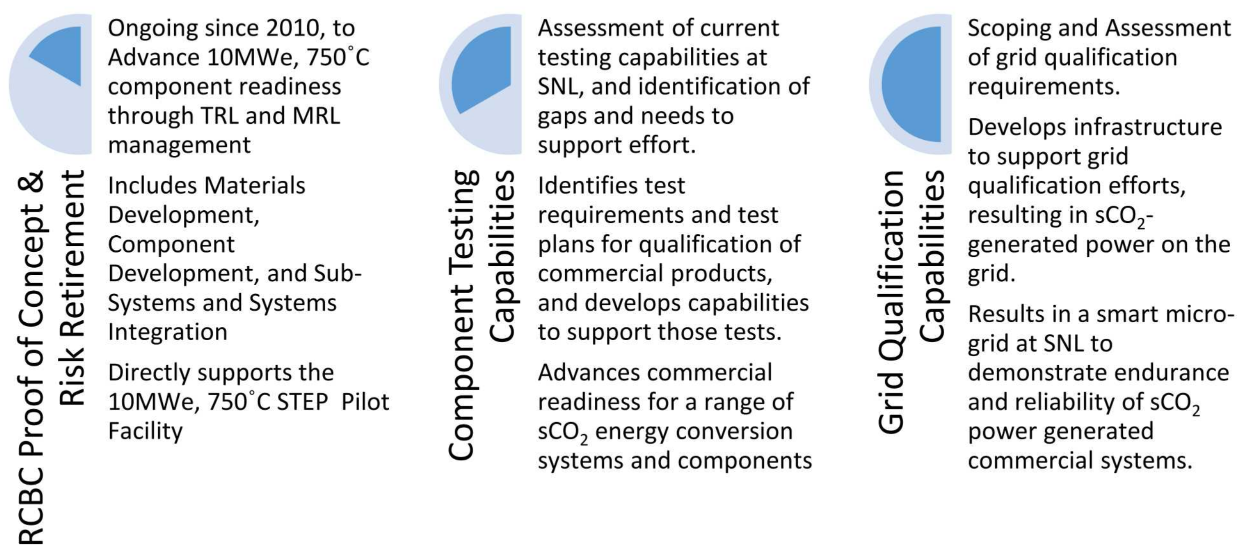
2- To support the development of a system that is re-configurable and scalable, allowing the testing of commercially attractive configurations and system components that can be transferred to industry, and

3- To establish the foundations for successful commercialization of the technology inclusive of elements that enable means to increase the reliability and resiliency of electric power systems.

This ART-NE program roadmap proposes the use of combined ART and NE - STEP efforts, along with partnerships with commercial entities, to achieve the development of 10MWe cycle components aligned with the DOE STEP Pilot facility to achieve commercial applications, and market-ready sCO_2 systems, both of which support NE goals to develop sCO_2 Brayton Energy Conversion technologies applicable to advanced nuclear reactors. For these purposes, *commercial Brayton Energy Conversion systems* ready is assumed to mean *power on-the-grid*.

For example, the plan calls for using facilities at Argonne National Laboratory (ANL) for the development of the Na-sCO_2 intermediate heat exchanger for the SFR at 550˚C, and the Development Platform (DP) of the SNL Brayton Laboratory to develop components for the Pilot Demonstration, raising the individual components' Technology Readiness Level (TRL)[1] and the System TRL. Simultaneously, SNL Brayton Laboratory will work to advance the ART and NE-STEP common technology to higher temperatures of 700˚C, supporting commercial products development that would be ready for market as the result of this collaboration path, while the Pilot evolves to the higher temperature goals envisioned for advance reactors. The plan also calls for the development of a micro-grid at SNL, achieving grid qualification capabilities to demonstrate power on-the-grid of upcoming commercial systems.

This roadmap outlines three R&D lanes to support SNL's Brayton Mission, as seen below:



While the *RCBC Proof of Concept and Risk Retirement* area has been ongoing since 2010, when the program was initiated at SNL, two new lines of work have been identified as critical to support successful commercial-ready systems. The *Component Testing Capabilities* builds from the

[1] TRL is a method of estimating technology maturity of critical technology elements.

existing work in risk retirement, by upgrading and expanding capabilities to support the testing of various sub-systems and components likely to result from the multiple identified sCO_2 Brayton applications beyond nuclear reactors. The *Grid Qualification Capabilities* aims to address the need to demonstrate reliability and safety of Brayton systems to put power on the grid, as a necessary requirement for successful commercial applications (via distributed energy or utilities markets, among others.) These stages are added to the roadmap towards the development of commercial applications of sCO_2 Brayton Systems as part of the larger commercialization goal, to be pursued through the STEP Pilot Facility at 700-715 C for 10MWe off grid, currently scheduled for the end of FY21.

The situation analysis for the development of sCO_2 Brayton technologies has identified further R&D work needed on the following critical areas:

Scientific basis of Brayton systems – The important questions that surround development of this technology are based less in fundamental science and more in application of the known science, design techniques, and operational processes to a well-known fluid in a well-known thermodynamic cycle and well-known machinery that has not been combined before. A concise integration is necessary with questions revolving around demonstrating that this novel combination of fluid and machinery work together as expected and perform as predicted, to baseline system computer models, and to develop control algorithms. These efforts are ongoing at SNL and ANL.

Cycle configurations and potential applications – Cycle configurations must be matched to heat sources in a manner that achieves the highest thermal to electrical conversion efficiency in balance with economic objectives and operational, safety, and emission requirements. Since Demo is envisioned to be energy input agnostic and various cycle configurations could contain common components, it is necessary to stay abreast of all potential DOE Collaboration applications regardless of heat source. SNL will continue to progress the development of the RCBC in FY18 for the office of NE and will continue to support other cycles and applications where commonality exists for STEP NE interests.

Systems design, scalability and modeling – In order to advance on component readiness, it is necessary to define the specific target application to pursue. SNL has made assumptions regarding DOE-NE target applications and the most likely commercial applications to market. Additionally, the operational longevity of the system needs to be understood and preventative maintenance programs should be developed. These efforts require understanding of the full system design, so progress should be initiated to document the current status of knowledge on these areas.

Component readiness (and market/manufacture readiness) of those components –Working towards a target TRL for common components, it is important to develop a common understanding of TRL definitions and what constitutes a "relevant environment", "laboratory" scale and "engineering" scale. Work is also needed to assess and/or validate the current TRL for common components across the DOE Collaboration for a specific application and to determine what is the TRL threshold that each component must achieve prior to a pilot facility demonstration. This determination must consider the readiness, behavior, and availability of materials used in components and systems interfaces, the manufacturability of the components and sub-systems, as well as the economic and operational implications of defining and creating a "relevant" environment for the different components. In addition, further component readiness work needs to be completed on specific components to ensure they are at the specified TRL for demonstration and MRL for commercialization. This task should not be underestimated and likely carries a major portion of the success of the pilot facility and commercial deployment of Brayton systems. These components/sub-components include heat exchanger, recuperator, heat rejection, turbine and turbomachinery, bearings and seals, and others.

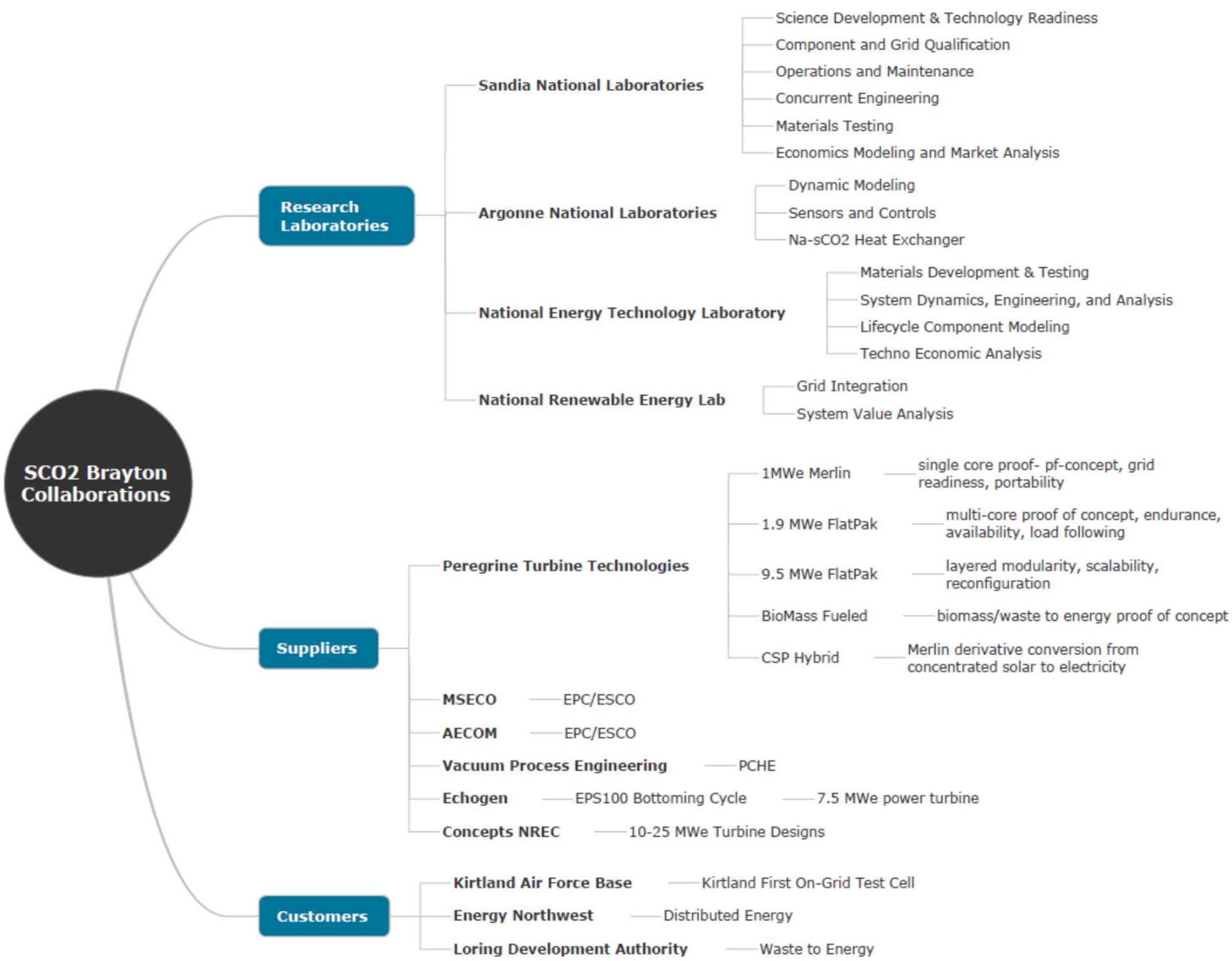
Safe/reliable/efficient grid connectivity - sCO_2 Brayton technologies for commercial applications need to be able to demonstrate the capability to meet requirements that put power on the grid safely, reliably and efficiently. Because of the risk aversion of the industry, the system must be tested and demonstrated before engaging potential utilities at an actual installation.

Facilities design, planning and operations – Significant progress towards a facility design that meets guidelines and can support maximum performance within demo definitions, leading to a preliminary design of the facility, would be critical to achieve the rapid timeline that is expected once demo proposals are awarded. A comprehensive work system analysis that develops a comparison of operations will help identify disruptive areas that may become detractors for a potential sCO_2 commercial interest. This study must include not only the impact on technology components but rather the impact of the technology on other elements of the work system (organization, environment, personnel, and tasks) including on the roles and responsibilities of personnel.

Scalability and Modularity by design - In addition to scaling the system to commercial levels, it is important to consider scalability to support the interests of the DOE Collaboration. Modularity for the design could facilitate the use of the facility over time to test a range of commercial applications and operating conditions. A potential modular approach would expand on and benefit from the potential for collaboration across the DOE Collaboration. A pilot facility that incorporates concurrent engineering principles into the design could enable modular configurations on both the system and the facility to allow for re-configuration when needed. However, such a design needs to be validated for viability based on both technology and cost. This type of design will have implications in lifetime of the system components and the operating procedures of the facility, which needs to be understood as part of the design.

Similarly, the market analysis calls for a comprehensive understanding of the energy industry to address stakeholder requirements, address concerns and mitigate risks. This requires the engagement of commercial industry partners, including research laboratories, parts/technology suppliers, and providers/consumers of commercial applications. Identified needs include ensuring that R&D efforts result in the development of a competitive alternative that provides solutions that are comparable or better than the current industry standard, and understanding, developing, measuring and analyzing metrics of technology adoption, including methods to communicate demonstrated and perceived value of the technology to stakeholders.

The path to the development of commercial Brayton applications calls for collaboration with industry partners. These partners share a common goal of development of the technology along the path towards their longer-term individual goals. As opportunities to expedite the RD&D process are presented, new collaborations may be created. 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. A preliminary outline of potential partners is shown below.



For example, SNL has been collaborating with Peregrine Turbine Technologies (PTT) on their novel approach for developing a commercially available technology. PTT is working towards the development of the *Merlin*, a 1 MWe sCO_2 power cycle at 750C. While the cycle itself is proprietary, it uses RCBC relevant components at 750C, supporting the advancement of components and the temperature increase needed for NE reactor applications. *Merlin* also builds up to the development of the *FlatPak*, which provides scalability, modularity, and load-following capabilities, all of which have been identified as requirements for commercial applications.

The partnership with PTT supports commercial readiness for a variety of products and applications in an expedited timeline. The progression of the PTT partnership resulting in desired ART-NE and STEP capabilities includes:

- *1.0 MWe "Merlin", single core, skid based (portable) sCO_2 Power Generation System:* Demonstration of sCO_2 Power Conversion operating on air combustible fuels (specifically NG). Accomplishes 1) Validation of Proof of Concept, 2) Grid Readiness, and 3) Endurance/Availability.
- *1.9MWe "FlatPak" multi-core, sCO_2 Power Generation System:* Demonstration of Dual Core System Capability: Accomplishes 1) Validation of Multi-core Concept, 2) Grid Readiness, 3) Endurance/Availability, 4) Demonstrate "dual core load-following" capability.
- *9.5 MWe "FlatPak" multicore, sCO_2 Power Generation System:* Demonstration of Multi-core, Layered Modularity. Accomplishes 1) Validation of Grid Readiness, 2) Endurance/availability, 3) Scalability of multi-core, layered system configuration, 4) Demonstration of multicore load following capability.
- *1.0 MWe Biomass Fueled, (single core, skid based portable) sCO_2 Power Generation System:* Demonstration of sCO_2 Power Conversion operating on air combustible fuels (specifically Kirtland or SNL generated biomass/waste-to-energy). Accomplishes 1) Validation of Proof of Concept, 2) Grid Readiness, 3) Endurance/Availability, 4) Biomass efficiency @ 2X current best available steam technology.
- *1.0 MWe CSP Hybrid (Merlin derivative) sCO_2 Power Conversion System:* Demonstration of sCO_2 conversion of concentrated solar to electricity and dispatchability.

To support grid qualification, a proposal is in place to develop the Kirtland First initiative, coupling a 1 MWe sCO_2 power cycle (*Merlin*) to a SMART microgrid on Kirtland Air Force Base, with integrated renewables as a demonstration of DoD base energy resiliency.

Merlin and *FlatPak*, once qualified through the Kirtland First effort, could be commercially relevant to utilities that need a strong and reliable power portfolio. However, the initial commercial market targeted for this 1.0 MWe to 19.0 MWe system is applications requiring distributed energy, such as isolated communities that are remote from the electrical grid, and facilities that desire a dedicated power source. *Merlin* and *FlatPak*'s ability to use heat from a wide variety of fuel sources, including waste heat and natural gas, make them candidates for near-term fossil fuel fired market as well.

A comprehensive Systems Engineering approach has been established to support and monitor the progress of the EC Effort through the multiple collaborations, ensuring that the work is not duplicated and achieves progress towards the primary ART-NE and STEP mission. The ART-NE Systems Engineering model (below) incorporates the principles of project management, requirements management for testing and validation, concurrent engineering, and balance modeling into a comprehensive program management approach to organize and validate R&D efforts and milestones.

The development needs identified from the analysis and leading to this roadmap are categorized in 9 focus areas for research opportunities. These are summarized as follows:

1. Management and Integration

- Identification, analysis and support of program functions for succesful sCO2 program planning and project management.
- Development, advancement, and coordination of punblic-private collaborations.

2. sCO2 Materials Development

- Identification/ validation of materials that will satisfy the performance requirements for each component in a commercial scale system, using commercial purity grade sCO2.

3. Component Development

- Facilitate commercialization of domestic heat exchanger, Turbomachinery, Cycle Development, Bearings and Seals technology and other components and systems.

4. Sub-System Test

- Facilitate the integration of materials, components and programmatic research into commercially viable Brayton system applications, including prototyping, commissioning and piloting operations.

5. Development Platform Operations and Maintenance

- Upgrade and maintain the Development Platform (DP) with new subsystems and upgraded infrstructure, including spare parts inventory to ensure continued DP operational readiness.

6. Systems Engineering

- Systems and concurrent engineering, systems modeling, requirements testing and validation, TRL and MRL management, system metrics, technology roadmapping.

7. Economics

- Economics modeling for component, system, and lifecycle. Market assessment for successful commercialization.

8. Advanced sCO2 Development

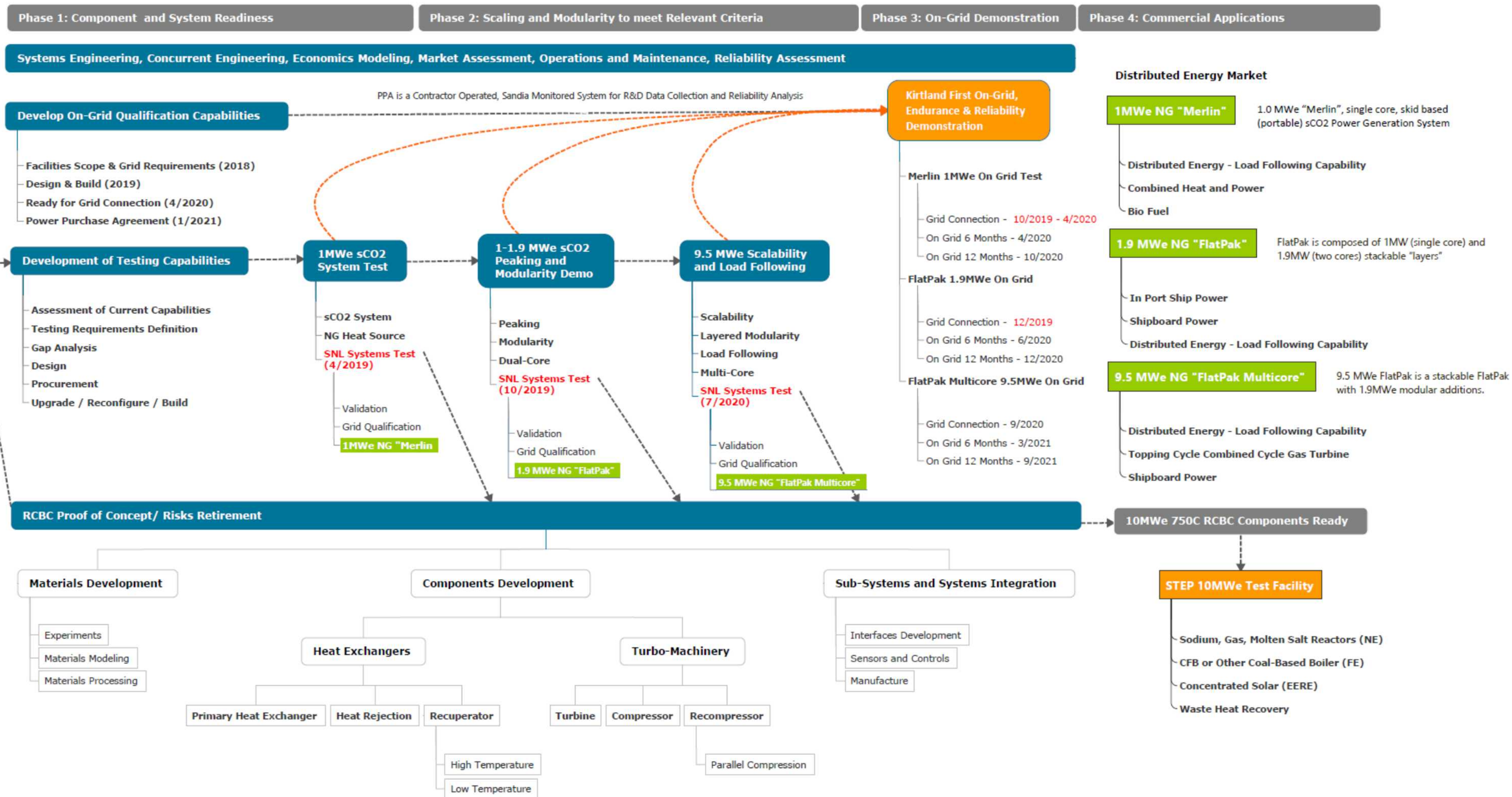
- Advanced Development of Brayton Engines exploiting the benefits of Supercritical Fluids, Compact Heat Exchangers, and associated cycle variations with a goal of clean coal power production.

9. Integrated System Test

- Demonstrate viability for sCO2 Power System validation for grid connection. Must support eventual 10MWe grid connection.

The roadmap shown below illustrates how the three main areas of work come together to support on-the grid endurance and reliability demonstrations, the STEP 10MWe Pilot Facility Demonstration, and various ready-to-market products available for commercial applications.

Preliminary Roadmap to Commercial, On-the-Grid sCO_2 Power Cycles Demonstration



Major milestones and path forward leading to and through Brayton Systems commercialization include:

CY18	sCO_2 test article (TA) reconfiguration complete Merlin construction and acceptance testing Begin turbocompressor test on idle conditions Demonstration of high temperature (700C) and high pressure (4400 psi) operations for seals and bearings On-Grid Qualifications Scope and Requirements Study STEP Facility design completed
CY19	sCO_2 TA will bring the 1MWe system online Begin full-scale testing and operation Kirtland First - Qualification for grid connectivity MSR begin to achieve >700C applications.
CY20	Integrate recompression into the closed Brayton Cycle Kirtland First - Test grid qualification capabilities ready, Merlin on-grid test integration STEP Facility construction completed, CBC 550C, 10MWe, Off-Grid Testing
CY21	STEP RCBC reconfiguration, RCBC 550 Testing High Temperature Component and Cycle definition at TRL7.
CY22	Proof of Concept evolves to higher temperatures. STEP RCBC 750 Testing
CY23	High Temperature and Power Pilot-Test complete.
CY24	Commissioning to commercial applications. System completed and qualified through test and demonstration at TRL8[2].
CY25	Commercial interests are expected to apply the technology without DOE support. TRL9[3]

[2] TRL8 is designated when the actual system has been completed and qualified through test and demonstration.
[3] TRL9 is designated when the actual system operated over the full range of expected conditions.

Acronyms and Abbreviations

AMC	U.S. Army Materiel Command
ANSI	American National Standards Institute
ARC	Advanced Reactor Concepts
ART	Advanced Reactor Technologies
ASMR	Advanced Small Modular Reactor
BMPC	Bechtel Marine Propulsion Corporation
BPA	Bonneville Power Administration
CBC	Closed Brayton Cycle
CCBC	Combustion Closed Brayton Cycle
CRADA	Cooperative Research and Development Agreement
CTE	Critical Technology Elements
DOE	U.S. Department of Energy
DP	Sandia sCO_2 Brayton Laboratory Development Platform
EC	Energy Conversion
EERE	U.S. Department of Energy Office of Energy Efficiency and Renewable Energy
EH	Energy Huntsville
ENW	Energy Northwest
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
FBO	Federal Business Opportunities
FE	U.S. Department of Energy Office of Fossil Energy
GA	General Atomics
GFR	Gas Fast Reactor
HGFR	Helium Gas Fast Reactor
HTR	High Temperature Reactor
KAPL	Knolls Atomic Power Laboratory
LCAT	Life Cycle System Analysis Tool
LFR	Lead Fast Reactor
MSR	Molten Salt Reactor
NAVSEA	Naval Sea Systems Command
NE	U.S. Department of Energy Office of Nuclear Energy
NEC	National Electrical Code
NFPA	National Fire Protection Agency
NGNP	Next Generation Nuclear Plant
NPP	Nuclear Power Plant
OSHA	Occupational Safety and Health Administration
PCHE	Printed Circuit Heat Exchanger
PIH	Public Information Hearing
PSD	Prevention of Significant Deterioration
PTT	Peregrine Turbine Technologies

R&D	Research and Development
RCBC	Recompression Closed Brayton Cycle
SCBC	Simple Closed Brayton Cycle
sCO_2	Supercritical Carbon Dioxide
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
TIT	Turbine Inlet Temperature
TRL	Technology Readiness Level
UBC	United Building Code
VCBC	Variant Closed Brayton Cycle
VPE	Vacuum Process Engineering

Organization of this Document

This preliminary roadmap is formatted for ease of reading in identifying relevant points as follows:

	Objectives, Guidelines, and Target Areas – identifies the programmatic objectives, guidelines, and target areas defined on this roadmap in support of sCO_2 Brayton Cycle development.
	Assumptions – identifies any assumptions that are made through the roadmap in regard to the policies and capabilities guiding the development process.
	Open questions - identifies open questions identified through the analysis. These questions represent critical areas of the roadmap where decision points need to be addressed.
	Development Needs – identifies clear development needs in the progression towards achieving roadmap goals.
	Collaboration Opportunities – identifies opportunities for collaboration among a diverse number of potential entities, including researchers, government, and industry.

Background

The mission of the Department of Energy (DOE) Office of Nuclear Energy (NE) Energy Conversion (EC) area of the Advanced Reactor Technology (ART) Program is to develop the supercritical carbon dioxide (sCO_2) Brayton cycle for application in Advanced Reactors while supporting the Supercritical Transformational Electric Production (STEP) program. The near-term objective of STEP to establish an operating, commercially scalable Recompression Closed Brayton Cycle (RCBC) pilot facility to be constructed in collaboration with the DOE Offices of Nuclear Energy, Fossil Energy (FE), and Energy Efficiency and Renewable Energy (EERE). To achieve the lowest risk possible, the STEP Pilot Facility should be established through the strategic, incremental development and testing of the components that make up the sCO_2 Brayton energy conversion power system.

Successful development of this technology supports the overarching 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.

Sandia National Laboratories (SNL) Brayton Team supports the DOE-NE energy conversion research and development (R&D) programs, pursuing the successful advancement of sCO_2 Brayton Cycle technologies.

What is the sCO_2 Brayton Cycle?

Supercritical carbon dioxide is a fluid state of carbon dioxide (CO_2) where CO_2 is 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 both increased from STP to be at or above the CO_2 critical point, it 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]

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. This cycle is a thermal-to-shaft power cycle consists of five basic components; compressors, turbines, heat input, heat rejection, and recuperation. Each component offers unique challenges to improvements, and consequent cycle thermal-to-shaft power conversion efficiency. Optimization of each of these components contributes to the overall optimization of the cycle efficiency. As with any engineered system, performance and economic considerations present an engineering optimization problem.

Cycle efficiency increases with temperature monotonically and rapidly. Current goals seek to achieve temperatures of approximately 450 °C for waste heat applications at the low end, up to 700 – 750 °C for high temperature primary cycles. Cycle efficiency also improves with pressure ratio, but only to a point. In general, the lower the maximum temperature of the cycle, the lower the optimum pressure ratio.

sCO_2 Benefits and Challenges

The benefits of sCO_2 Brayton Cycle for power conversion [1, 2] include:

- 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,
- Vastly reduces water consumption, and
- Dry cooling/suitable for arid environments.

The key property of the fluid near its critical point is its higher gas density, closer to that of a liquid than of a gas, allowing for the pumping power in the compressor to be significantly reduced, which in turn increases the thermal-to-electric energy conversion efficiency [3]. The resulting higher conversion efficiency (up to 50%) translates to in increased electricity production for same thermal input.

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 [4]. 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 fact that the heat rejection temperature is significantly higher than for steam-Rankine systems, allowing for significant heat rejection directly to air.

Other benefits include environmental improvement from greenhouse gas reduction, and dry cooling, making the system suitable for arid environments.

However, there are still technical and non-technical challenges that need to be further investigated. First and foremost, the technology needs to be proven ready. Commercial viability requires a demonstration of performance, cost, operability, and reliability [2]. Energy is a highly regulated industry with significant public interest where plant owners tend to be "conservative" with respect to emerging technologies [2, 5].

A few of the challenges that have been identified for the implementation of sCO_2 at commercial scales are outlined below as examples:

- Material performance and code qualification need to be addressed [2], and materials need to be developed to withstand the pressures and temperatures over economically meaningful product lifetimes [6].
- Turbo-expanders for sCO_2 service are unique to sCO_2 power cycles and face design challenges associated with high power densities and the differences between ideal gas models and real gas behaviors [6]. These factors need to be considered in design.
- Heat exchanger design has a significant influence on cycle performance, physical layout, and capital costs [6] that need to be understood and addressed during design.
- Controlling the cycle under various environmental conditions requires further exploration of the critical parameters and adjustment options [6].
- Design must ensure that system interaction does not impact the safety basis (on normal, transient, and load following conditions) [2].

Figure 1 illustrates the brief history and expected pathway to commercialization of sCO_2 Brayton systems across multiple applications [7]. Target dates have been modified from the original to reflect current progression timelines.

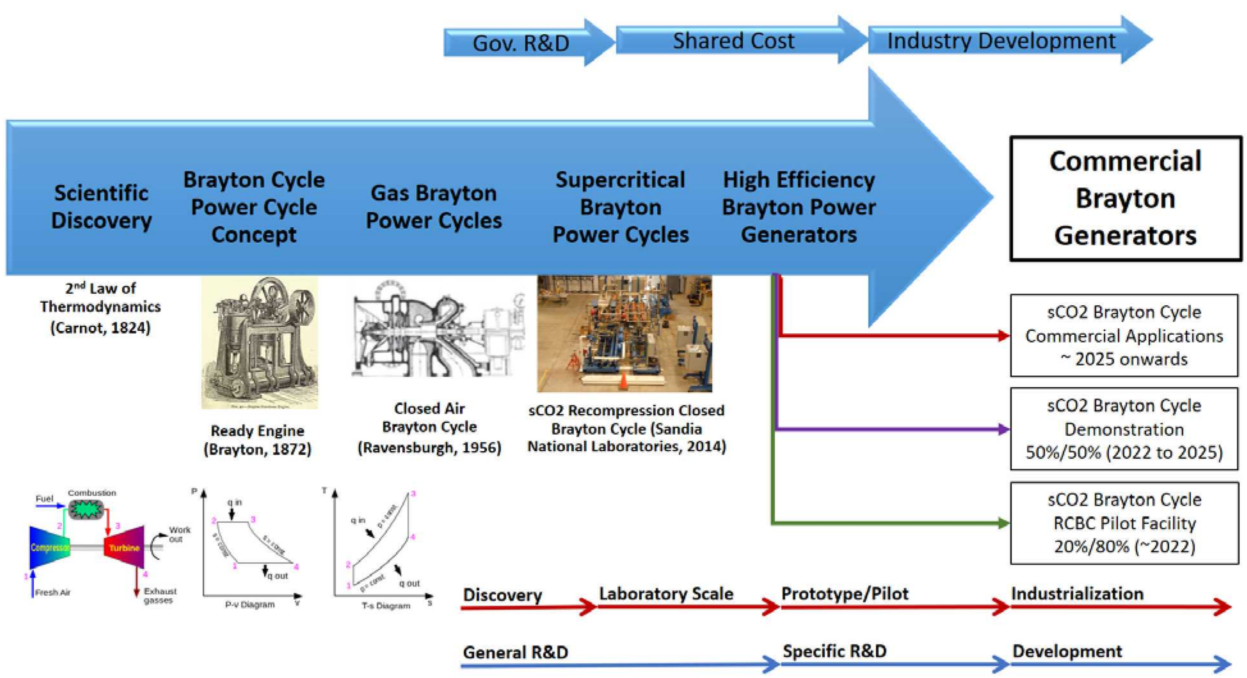


Figure 1: Pathway to Technology Commercialization

Potential applications

sCO2 Brayton power cycles provide potential solutions to a wide variety of power-generation applications. Nuclear power, concentrated solar thermal power, fossil fuel boilers, geothermal, and shipboard propulsion systems are considered potential favorable applications that could replace traditional steam Rankine cycles [4]. Table 1 describes applications that may be relevant to Brayton Cycle commercialization efforts.

A preliminary assessment of the economics of the system and environmental factors of the energy sector indicates that the first likely commercial application of sCO2 Brayton cycles will not be nuclear. Thus, while this roadmap is focused on a sodium fast reactor sCO2 RCBC demonstration, supporting the development of other applications through collaboration with partners is a critical part of the effort to expedite technology development.

Table 1: sCO_2 Potential Applications and Configurations

Application	Motivation	Size [MWe]	Temperature [C]	Pressure [MPa]
Advanced Reactor Designs **(Includes Sodium and High Temp Reactors (gas, molten salts)**	Efficiency, Size, Water Reduction	10 - 300	350 – 800 +	20 - 35
Advanced Small Modular Reactors	Compact size, Dry Cooling, Distributed applications	10 - 300	550 - 700	25 - 40
Gas turbine Bottoming	Replace Steam HRSG of Combined Cycle Gas Turbine	10-100	750C	
Shipboard Propulsion	Efficiency, Size	10 - 100	500 - 1000	35
Shipboard House Power	Efficiency, Size	< 1 - 10	230 - 650	15 – 35
Waste Heat Recovery	Efficiency, Size, Simple Cycles	1 - 10	< 230 - 650	15 - 35
Concentrated Solar Power	Efficiency 50%, Size, Dry Cooling	3	700	35
Geothermal	Efficiency	1 - 50	100 - 300	15
Natural Gas fuel cycle, targeting distributed energy	Dry Cooling	6		
Fossil Fuel (indirect heating)	Efficiency, Water Reduction	300 – 600	550 - 900	15 – 35
Fossil Fuel (direct heating)	Efficiency, Water Reduction, Facilitates CO_2 capture	300 – 600	1100 - 1500	35

Gen IV Reactors

In 2002, sCO_2 Brayton cycles re-surfaced as part of a roadmap for the next generation of nuclear reactors (Gen IV reactors) beginning construction after 2030 [8], and were seen as the primary power conversion system option for moderate-temperature lead fast reactors (LFRs) as well as a secondary option for both sodium fast reactors (SFRs) and high-temperature lead fast reactors as shown in Table 2 . Other leading cycle options included the supercritical Rankine water cycle (also called ultra-supercritical or advanced ultrasupercritical steam Rankine), and the helium gas Brayton cycle. It is important to highlight the temperature range on these reactors, as shown on Table 2. Considering these ranges, the modularity and reconfiguration of the SNL test facility will be critical to the scalability for commercial applications.

Table 2: Crosscutting energy research and development proposed by the Generation IV International Forum [8]

Generation IV System (T_{outlet})	Hydrogen Production		Heat Delivery		Advanced Cycles for Electricity Production		
	I-S Process	Ca-Br Process	Process Heat	Desali-nation	Supercritical CO_2 Brayton	Water Rankine Supercritical	Helium Brayton
GFR (850°C)	P	S	S	O			P
MSR (700-850°C)	P	S	S	O			P
SFR (550°C)				O	S		
LFR (550°C)				O	P	S	
(800°C)		P	S	O	S[1]	S[1]	
SCWR (550°C)				O		P	
VHTR (1000°C)	P		S	O			P

P: Primary option
S: Secondary option
O: Option for all systems

[1] Bottoming cycle using heat at lower temperatures available after higher temperature heat has been used for hydrogen production.

While Rankine systems had the most usage experience, they were limited to a moderate temperature range of approximately 350 C. Helium Brayton cycles could easily achieve higher temperatures and had other benefits to the neutronics of a reactor by avoiding the possibility of activation and subsequent contamination from leaks of reactor coolant. However, containment of high-temperature helium, in addition to the cost of replacing the fluid (as it necessarily leaked out over time) and historic difficulties with fabricating efficient helium turbines, continued to be major research challenges.

sCO_2 Brayton seemed to promise both the high efficiency of the Brayton system with the high-temperature and low activation concerns of helium, but had only previously been explored in paper studies and never tested experimentally due to challenges associated with designing near-critical compressors and compact heat exchangers.

Since the original roadmap, research has progressed rapidly to envision applications for the sCO_2 Brayton power system for the molten salt reactor (MSR), gas fast reactor (GFR), and the very high temperature reactor (VHTR also known as the helium gas fast reactor or HGTR).

The recompression configuration has long been recognized to complement closed cycle heat sources, such as nuclear reactors and solar thermal energy fields, because of the extensive heat recovery from the turbine exhaust prior to heat rejection that the cycle achieves [9]. Depending on operating conditions and heat exchanger performance, 60 – 70% of working fluid heating comes from cycle internal heat recuperation, with the remaining 30 – 40% of heat addition provided by an external source. An important consequence of extensive recuperation is that the sCO_2 enters the heat source heat exchanger at a high temperature, and thus extracts a relatively small portion of the external heating fluid thermal energy which results in a gross inefficiency in fuel usage for open heat source applications that exhaust the effluent. However, for closed heat source cycles, particularly nuclear reactors, this consequence is highly beneficial. The benefits of this significant degree of recuperation, and other benefits discussed elsewhere (such as reduced compression work), lead to predicted thermal conversion efficiencies on the order of 50% for turbine inlet temperatures around 700 °C and reasonable assumptions of various component performances.

Distributed Energy

Distributed energy consists of a range of smaller-scale and modular devices designed to provide electricity in locations close to consumers. Conventional power stations, such as coal-fired, gas and nuclear powered plants, hydroelectric dams, large-scale solar power stations, some wind turbine farms, are centralized and often require electricity to be transmitted over long distances. By contrast, distributed energy systems are decentralized, modular and more flexible technologies, that are located close to the load they serve, with capacities ranging from 1 to 100 MWe. Power supply configurations enabled/enhanced by advanced forms of DE generation including include Behind the Fence/Single customer with or without grid interconnect, Partial Feeder/Multiple customers in close proximity with or without grid interconnection, Full Feeder/Regional serving Multiple customers with grid interconnection, and Full Substation/Regional Grid Integrated.

Distributed energy offers solutions to many of the nation's most pressing energy and electric power problems, including blackouts and brownouts, energy security concerns, power quality issues, tighter emissions standards, transmission bottlenecks, and the desire for greater control over energy costs. The modality takes load off the national grid and operated by utilities, such as Northwest Utilities (a hydroelectric provider currently building a small modular reactor at Idaho). The initial likely application of sCO_2 Brayton technologies for distributed energy is driven by fossil fuels. Most of these applications also have the potential of providing combined heating/cooling in conjunction with power production (tri-generation). Combined efficiencies can approach 90% in those applications where CHP requirements are ideally matched.

Waste to Energy

Waste-to-energy is the process of generating energy in the form of electricity and/or heat from the primary treatment of waste. It is a form of energy recovery. Most processes produce electricity and/or heat directly through combustion, or produce a combustible fuel commodity, such as methane, methanol, ethanol or synthetic fuels. The power generation efficiency of these operations are generally low and require an additional revenue stream from waste handling/management and/or subsidies to be economically viable. The increased efficiency of sCO_2 Brayton power generation systems in combination with advanced combustion, gasification or pyrolytic processes promise to significantly increase the efficiency of power generated from waste fuels.

Energy generated and/or recovered from waste holds significant environmental, commercial and social benefits, including waste minimization and environmentally sound waste management, larger efficiency due to the reuse of waste material, and emissions reduction. Applications for sCO_2 Brayton technologies for waste-to-energy are likely, such as combusting municipal waste to produce electricity.

Combined Heat and Power (Waste Heat Recovery)

An alternative to improving overall energy efficiency is to capture and reuse the lost or "waste heat". A waste heat recovery unit is an energy recovery heat exchanger that recovers heat from hot streams with potential high energy content.

A bottoming cycle has the primary energy source applied to a useful heating process. The reject heat from the process is then used to generate electrical power. The typical bottoming cycle directs waste heat from a process to a waste-heat-recovery boiler that converts this thermal energy to steam which is supplied to a steam turbine, extracting steam to the process and also generating electrical power.

The Brayton cycle can be used as a bottoming cycle for the gas turbine by means of a gas–gas heat exchanger. In contrast to the conventional combined cycle, this alternative does not require bulky steam equipment (boiler, steam turbine, condenser, etc.), and allows unmanned operation. An increase in power of 18–30% and in efficiency of up to 10%-units is expected in a gas turbine with a Brayton bottoming cycle depending on the number of intercoolers [10].

Concentrated Solar

The SunShot vision study [11], released in 2012, laid out an ambitious path toward increasing the deployment of solar energy technologies up to 14% and 27% of total electricity demand by 2030 and 2050, respectively, at a cost-competitive levelized cost of electricity of 6 cents/kWh in line with other generation technologies instead of relying on government subsidies. While much of this path focused on photovoltaic power systems and other “soft costs” of solar generation, concentrating solar power (CSP) technologies including trough, Fresnel, and power tower embodiments required advancement in power conversion systems.

Similar to the cycles proposed for nuclear applications, the SunShot vision study suggested supercritical steam Rankine, sCO_2 Brayton, and gas Brayton cycles as leading candidates to improve the cost and performance of both the power block and overall system.

In the SunShot case however, air is the gas of choice rather than helium because there is need for a hermetically-sealed power block or concern of radioactive activation. Steam Rankine systems used for CSP face a significant challenge of either scaling down from 400 MWe or larger options used in the coal in nuclear industry, or scaling up from 50 MWe or smaller systems used at lower temperatures in steam bottoming applications for natural gas combined cycle power plants to a 150 MWe-scale anticipated with CSP power towers.

By the time this study had been released both sCO_2 Brayton and air Brayton cycles had been demonstrated at lab or prototype scales, however sCO_2 Brayton cycles still require research into several scientific challenges including turbomachinery, heat exchangers, and bearings and seals, while both systems required significant improvement in power block cost confidence.

An example of an early market for this technology exists at the Crescent Dunes Solar Energy Project, which is a 110 MW concentrated solar power plant located near Tonopah, NV. All of the electricity generated will be purchased by the Nevada Power Company under a power purchase agreement with the developer, SolarReserve, at the rate of $0.135/kWhr [12]. The plant began operations in September, 2015, too early to implement an sCO_2 power conversion cycle. However, once this technology is available commercially, it is these types of CSP plants that will realize the significant benefits of improved conversion efficiencies and an expected lower capital cost.

Fossil Fuel Primary Cycle (CFB boiler or other coal based "boiler")

An example of the near-term market for fossil fuel fired applications is the Peregrine Turbine Technologies Merlin cycle. This power cycle can use heat from a wide variety of fuel sources, including waste heat, biomass, and natural gas. The initial market targeted for this 1 – 2 MWe system is applications requiring distributed energy, such as isolated communities that are remote from the electrical grid, often with limited or expensive access to conventional fuel sources, and facilities that desire a dedicated power source. Customers include typical private consumers whose only investment is paying for electricity, heat generating operations that seek to improve economic efficiencies by converting their waste heat stream into electricity, and operations that generate waste products that have significant heating value. The technology is highly scalable, up to 100 MW, where it can be deployed for transmission and distribution support.

Shipboard Power

Future U.S. Navy ships will require power systems that meet more stringent agility, efficiency, scalability, controllability and resiliency requirements. Modularity and the ability to interconnect power systems having their own energy storage, generation, and loads is an enabling capability [13]. The Navy is interested in the development and manufacture of gas turbine-generator sets with an output rating of between 20 to 30 Megawatts electrical (MWe) (nominally about 25 MWe), for use on Naval vessels. The Navy is looking for potential gas turbine generator sets; the generator's electrical interface requirements; the impacts of those requirements on turbine-generator set performance and size; the availability of a marinized and militarized turbine-generator sets; and the estimated costs for any development steps needed to bring the turbine-generator set to an advanced/engineering development model state of maturity (e.g. Technology

Readiness Level (TRL) of 6 or higher and the gas turbine is fully ready for qualification/performance testing [14]). A sCO_2 Brayton cycle, due to its high-speed operation, compact size, fuel economy, and minimal heat rejection is ideal for the electric ship applications, particularly for the medium voltage DC bus.

Department of Energy sCO_2 Brayton Power Cycles Programs

DOE-NE ART Energy Conversion

Within DOE-NE, the Advanced Reactor Technologies (ART) program 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 ART 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. [15]

NE has been involved in Brayton technology development for over 10 years, sponsoring work conducted through Sandia National Laboratories (SNL) and Argonne National Laboratory (ANL). The NE office supports a collaborative approach with industry that enables short and mid-term collaborations on specific sCO_2 technologies that can be leveraged in the path towards the sCO_2 Brayton cycle development for nuclear applications.

The ART-NE targets for Research and Development efforts are outlined below:

Applications: The NE office is exploring the sCO_2 Brayton cycle for several potential applications. Of primary interest is the Recompression Closed Brayton Cycle (RCBC) for advanced nuclear reactors (MSR, GFR, and the very high temperature HGTR). Other applications are supported because of their ability to advance sCO_2 Brayton systems for nuclear applications, including distributed energy (for small and very small SMRS), concentrated solar (because of the common power cycle with distributed energy), fossil fuel primary cycle (since the high temperature leverages to high temperature reactors), shipboard power, and waste heat recovery.

Target Date: NE would like to see a commercial demonstration at 10 MWe by 2020 and deployed products by 2025 to support commercial, off-the-shelf (COTS) products for SFRs. Future nuclear power must be integrated with renewables; thus NE is also pursuing power on the grid, with an on-grid demonstration expected by April 2020.

Size: 50-100MWe

Temperature: 550 ˚C to 750 ˚C

Configuration: RCBC and/or RCBC with dry heat injection.

Technical R&D Themes:

- Component Development for system and sub-systems, including Heat Exchanger, Turbomachinery, Heater, Recuperators, Compressor/Recompressor, Bearings, Seals, and system interfaces.
- Systems Integration, from reactors to utilities
- Materials compatible for 40 years of operation
- Operations and Maintenance procedures supporting deployment readiness
- Technology Readiness Levels (TRL) and Manufacturing Readiness Levels (MRL)
- Applied Systems Engineering and Concurrent Engineering for system requirements modeling, test and validation, and commercialization readiness.

Development Targets:

- RCBC applications for advanced reactors
- System level operations, stability, and optimization
- Safe and reliable system level performance
- Materials integrity
- Cost and economic viability competitive with NG turbines
- Performance demonstration scalable for small and large applications
- TRL and MRL advancement for components and subsystems for risk reduction at demonstration and beyond commercialization

Criteria for R&D scope definition:

- Optimally designed for operation with an SMR at 550°C TIT to 750°C TIT (turbine inlet temperature)
- Commercial scale turbine targeting an isentropic efficiency in the upper 80's%
- Commercial scale compressor targeting an isentropic efficiency in the mid 80's%
- Low cost recuperation devices with effectiveness optimized for low COE (cost of electricity)
- Acceptable corrosion / erosion resistance for 30-40 year life with affordable materials (life comparable to steam based systems)
- Operations optimization for efficiency, and stability throughout range of normal boundary conditions
- Reliable, repeatable, and safe cycle operations for transient events including startup, shutdown, load following, and emergency
- Effective sensor network design, system control, condition monitoring, and fault diagnosis to enhance maintenance planning and cycle response to plant disturbances, malfunctions, safety-critical tasks, and infrequent abnormal and emergency situations
- Collaboration that advances sCO_2 technology development for application to advanced SMRs

Work is still needed to develop the system characterization for large scale sCO2 power conversion, including designs, materials, components, operation and control systems, and sensors, amongst others. It has been proposed that a path forward for technology development leading to reactor applications is to continue the ART-NE base R&D program, to work across DOE through STEP to integrate/coordinate related efforts in Fossil Energy and Energy Efficiency/Renewable Energy, and to continue stakeholder engagement to establish effective partnerships with industry [2].

Coordination between DOE Offices through STEP

The Supercritical Transformational Electric Power (STEP) program, co-sponsored by the offices of Nuclear Energy (NE), Fossil Energy (FE) and Energy Efficiency and Renewable Energy (EERE), constitutes a DOE coordinated effort that seeks to facilitate the commercialization of sCO_2 technologies. The DOE-STEP mission is to reduce the technical barriers and risks to the commercialization of the sCO_2 power cycle by working with industry to develop and mature the technology at the pilot scale in order to facilitate commercialization.

To this end, the DOE sCO_2 Technology Team (Tech Team) is charged with using a coordinated, collaborative approach to develop and facilitate commercialization of sCO_2 energy conversion technology. This is would be achieved by drawing from the NE, FE, and EERE programs, working together to achieve the highest efficiencies offered by sCO_2 Brayton Cycle technology (compared to the widely-used steam turbine Rankine Cycle.) [1]

There are still multiple areas that need to be addressed along the path to commercial readiness. The technology development risk for a large scaled sCO_2 power cycle is high, and while the private sector has pursued a few configurations [7], a higher temperature, high efficiency system has never been tested at design conditions applicable for commercial scale. Currently, sCO_2 development and deployment work has largely been limited to small-scale, government-funded initiatives. For example, SNL's RCBC Test Article (TA) supports 250kwe -1 MWth at 550 °C and 14 MPa max. There is currently no integrated sCO_2 facility that can manage temperatures greater than 700 ˚C and pressures higher than 35 MPa, which are likely characteristics necessary for commercial applications.

The DOE coordinated effort is structured around a common goal to establish a 10 MWe STEP Pilot facility for evaluating power cycle and component performance over a range of operating conditions. To that end, the STEP Tech Team (supported by NE, FE, and EERE DOE offices) have initiated an overarching program R&D plan [16] to support the development of Brayton R&D coordination that optimizes resources and ensure teams are working towards commercially viable goals. The SNL STEP program R&D plan is focused on supporting three goals:

1- To ensure component readiness for the successful launch of sCO_2 Brayton Cycle Pilot Facility, supporting Brayton systems applications for FE, NE, and EERE applications.

2- To support the development of a system that is re-configurable and scalable, allowing the testing of commercially attractive configurations and system components that can be transferred to industry, and

3- To establish the foundations for successful commercialization of the technology inclusive of elements that enable means to increase the reliability and resiliency of electric power systems.

STEP Pilot Facility

In October 2016, DOE-FE awarded a 6-year project to design, build, and operate a 10 MWe Supercritical Carbon Dioxide Pilot Facility. The project team is composed by Gas Technology Institute (GTI), Southwest Research Institute® (SwRI®), and General Electric Global Research (GE-GR). This facility will aim to advance the state of the art for high temperature sCO_2 power cycle performance from an estimated current TRL of 3, Proof of Concept, to a TRL of 7, System Prototype Validated in an Operational System.

To ensure timely and focused technology development towards the specific goals, the target configuration of the cycle and additional characteristics for a likely commercial application need to be clearly stated. Table 3 summarizes *SNL's best understanding* of the pilot facility configuration, based on the expectation that the facility will approach commercial scales as much as possible, and assuming a demonstration of the sCO_2 Indirect Cycle[4], Circulating Fluidized Bed boiler or other coal based "boiler" will be the first to market. The table also shows a side-by-side comparison of characteristics needed to advance DOE-NE target goals for nuclear applications.

Table 3: Current best understanding of demo configuration, compared to the NE target application

		STEP	***NE***
Overview	**Scope**	Design, construct, commission, and operate a 10 MWe Supercritical Carbon Dioxide (sCO_2) Pilot Plant Test Facility	Commercial demonstration at 10 MWe by 2020. Deployed commercial cycles by 2025 to support SFR applications by 2030
	Application	sCO_2 Brayton cycle for ***CFB boiler or other coal based "boiler"***	sCO_2 Brayton cycle for **Sodium Fast Reactor**
System	**Size**	10 MWe net power	10MWe initially, ***50-100 MWe target***
	Temperature	***700˚C - 715˚C***	***550˚C -750˚C***
	Configuration	RCBC	RCBC
Performance	**Pressure Ratio**		~3.0
	Operating Speed		10 krpm
	Power Conversion Efficiency	50%	45%- 50%[5]
Operational	**Processes**	Almost completely automated	Almost completely automated
	Normally on/Off	On	On
	Connected to Grid?	Yes, but not for distribution	Yes

[4] *Indirect Cycle* is another name for the Brayton Cycle used by the Office of Fossil Energy meaning the heat source is coupled to the power cycle via a heat exchanger. This term differentiates the Brayton initiative from another FE cycle of interest, the Allam Cycle (also known as direct cycle) where the heat of combustion is mixed with the sCO_2 fluid.

[5] 45% efficiency is required for the lower temperature SFR, 750C is required for 50% efficiency.

If the goal for the STEP facility is to prove the sCO_2 power cycle by testing common components to reduce risk on the commercial system, the facility should be as energy input agnostic as possible, in order to test various heat inputs of interest to the DOE offices. It must also provide capabilities for modularity, scalability, and reconfiguration.

Notwithstanding these capabilities, since the facility design started in late 2016, it is now likely to be in an advanced state that might limit the flexibility of incorporating cycle or application specific requirements for testing. A comprehensive effort is underway to document and understand the potential applications across the DOE offices including their target configurations and applications of interest [16].

Additional work is needed to identify the applications' **requirements to demonstrate a commercially viable solution**, and to identify the **commonalities in the system components and interfaces requirements** to clearly define where the systems differ for each application.

This information is critical to ensure that research offices can coordinate efforts, appropriately focus resources to maximize opportunities for collaboration, and reduce duplicated/concurrent development efforts while ensuring the needs of each individual office are being met.

In the meantime, a preliminary report for the Program Definition of a 10 MWe sCO_2 RCBC Demonstration Power System [18] was developed by SNL and anticipates that much of the cycle topics, both technical and operational, will follow industry standard architecture. The preliminary report summarizes technical and operational issues from the perspective of the power generation industry while highlighting aspects of this facility that are unique to the sCO_2 application and may be useful to support the STEP facility design.

The DOE cross-offices coordination has the potential to expedite the development of the technology. A **concurrent engineering team** is needed to manage R&D coordination, while supporting both STEP and individual office goals.

Laboratory Capabilities Supporting the Office of Nuclear Energy

The DOE National Laboratories Complex is the primary source of R&D to pursue sCO_2 energy conversion technology development. Sandia National Laboratories (SNL) and Argonne National Laboratory (ANL) have been engaged with the DOE-NE office through both NE-ART and STEP to support sCO_2 Brayton Power Cycles technology development for reactor applications. Their participation to date and capabilities are summarized below.

Argonne National Lab (ANL)

Argonne National Laboratory has been involved in the sCO_2 Brayton Cycle program continuously since 2002. Most recent experimental work has supported the development of Sodium Heat Exchangers, and the development and maintenance of the Plant Dynamics Code, which features worldwide leading capability for system level plant dynamic analysis. ANL has also supported industry collaborative studies, which are expected to possibly result in new ANL testing facilities for (1) heat exchanger testing of CO_2-to-CO_2 and sodium-to-CO_2 HXs under prototypical conditions, and (2) testing of small-scale TES system with prototypical materials.

sCO_2 laboratory capabilities include:
- Development and maintenance of the Plant Dynamics Code
- Whole plant dynamic analysis for Gen IV reactors including SFRs utilizing sCO_2 power conversion
- Steady-state and dynamic analysis of integral sCO_2 test loops
- Development and optimization of control strategies for sCO_2 cycles including those with dry air cooling
- Conceptual design of optimized sCO_2 cycle power converters for nuclear reactors especially SFRs
- Model Predictive Control for sCO_2 cycles
- Cycle analysis and optimization to reduce cycle cost
- Modeling and analysis and optimization of dry air cooling for sCO_2 power cycles
- Cost estimation for sCO_2 power cycles
- Thermal hydraulic modeling of compact diffusion-bonded heat exchangers
- Transient analysis of thermal shock loadings
- Identification of testing needs and conceptual design of testing facilities for sCO_2 power cycle development
- History of sCO_2 cycle development especially for nuclear power applications
- Experiment testing and analysis of compact diffusion-bonded heat exchanger performance

Test Rigs:
- Sodium-CO_2 interaction facility (SNAKE) – Injection of CO_2 into sodium column or channel under prototypical conditions
- Sodium Plugging Phenomena Loop - Examines plugging by precipitated sodium oxide in sodium-to-CO_2 heat exchanger channels
- Sodium Freezing and Melting facility – Determine stresses when sodium freezes inside sodium-to CO_2 heat exchanger channels
- Sodium Draining and Refilling facility – Demonstrate that sodium channels inside sodium-to-CO_2 heat exchangers are large enough for efficient sodium draining
- Thermal shock testing facility for compact diffusion-bonded heat exchangers – Under development

Potential Applications of Interest:

- Nuclear
- Concentrated Solar high temperature liquid salt-to-CO_2 heat exchangers and HX phenomena
- Distributed Energy Sources
- Fossil Fuel Primary Cycle
- Direct sCO_2 Cycles to extend the Plant Dynamics Code
- Use of sCO_2 power cycles with Thermal Energy Storage.

ANL supports NE in the development of a 550°C, 100 MWe and larger RCBC for the AFR-100 power converter[6]. Work has been focused upon applications of sCO_2 Brayton cycles to Sodium-Cooled Fast Reactors (SFRs), but has also worked on applications to Lead-Cooled Fast Reactors (LFRs) and High Temperature Gas-Cooled Reactors (HTGRs).

ANL current efforts focus on the development of Intermediate Sodium to CO_2 Heat Exchanger (Primary Heat Exchanger) along two major tasks: Sodium Drain, Fill, Plug in PCHE, and Sodium/CO_2 Interactions. Fundamental phenomena crucial to the reliable design of compact diffusion-bonded sodium-to-CO_2 heat exchangers include sodium-CO_2 interactions, draining of sodium from compact diffusion-bonded sodium channels, and the ability to refill the channels, inadvertent sodium freezing and remelting, and inadvertent plugging of compact diffusion-bonded sodium channels due to oxide plug formation. Data is being generated in Sodium-CO_2 Interaction tests, Sodium Draining and Refilling tests, Sodium Freezing and Remelting tests, and Sodium Plugging Phenomena tests.

The Sodium-CO_2 Interaction tests are providing insights into the self-plugging phenomena that might seal a leak at high sodium temperatures, solid reaction product formation, and safe removal of sodium-CO_2 reaction products at low sodium temperatures. The sodium portion of the Sodium Plugging Phenomena Loop is being redesigned and built to incorporate lessons learned to avoid accidental plugging.

ANL has also developed the Plant Dynamics Code (PDC) for steady state and dynamic sCO_2 cycle analysis since 2006. PDC is current worldwide state-of-the art capability for system level plant dynamic analysis of sCO_2 Brayton cycle power converters. It is coupled to SAS4A/SASSYS-1 LMR code. PDC is being used to investigate dry air cooling for the sCO_2 cycle, showing an increase in plant $/kWe of only about 2% over water cooling and with commercially available technology [19]. This code is currently being updated and documented to make it more accessible to users, and continues to be validated with available data from sCO_2 cycle facilities.

Other accomplishments include the development and optimization of sCO_2 Brayton cycle conceptual design for the AFR-100 SFR, development of combined control strategies for the sCO_2

[6] 100 MWe is the electrical power of the AFR-100 SFR that is 250 MWt (105 MWe). 550 °C is the core outlet temperature for a SFR. The intermediate sodium and turbine inlet temperatures might be somewhat lower; for example, 528 and 524 °C with dry air cooling, respectively.

Brayton cycle power converter and the SFR, testing and validation of steady state and dynamic modeling in the PDC against the PCHE testing data, and development of a Technology Gap Analysis for the sCO_2 Brayton cycle for SFR applications, by Christopher Grady, updated in April 2017[7].

The Gap Analysis is a section of the sCO_2 Brayton Cycle for SFR Applications for covers the integrated sCO_2 Brayton cycle, turbomachinery, and heat exchangers. Each subsection covers: Functions and requirements; Historical experience; State of the art; Technology gap analysis that includes Gap definition, R&D requirements, and Fabrication and/or testing requirements; and References. Also identified are needs for new testing facilities to reach commercial scale relevant to SFR applications (e.g., 100 MWe).

Sandia National Laboratories (SNL)

Sandia National Laboratories has been working on the sCO_2 Brayton Energy Conversion program since before 2010. The team is researching a thermal-to-electric power conversion technology in a configuration called the Recompression Closed Brayton Cycle (RCBC), using supercritical carbon dioxide as the working fluid, rather than steam, thereby dramatically increasing conversion efficiency compared to the steam Rankine cycle.

<u>sCO_2 laboratory capabilities include</u>:
- Thermodynamics
- Cycle Design
- Commercial Component Development
- Systems Integration
- Materials
- Operations and Maintenance
- Economics Modeling
- Systems and Concurrent Engineering
- Roadmapping

<u>Test Rigs:</u>
- **sCO_2 Brayton Laboratory Component and System Development Platform:** sCO_2 Component and System Development Platform: a reconfigurable testing rig with 2 turbo-alternator-compressors rated at 125 kWe, motor controllers, 780 kW of heating power, 560 kW of heat rejection capacity, recuperators, extensive state of the art DAQ and controls, rated for 538 °C and 13.8 MPa operation. The DP is used to test components and systems, one of which is the RCBC.
- **Bearings Test Rig:** The bearings test rig has the capability to test up to 250F and 1600 psi bearings environments.

[7] Efforts to obtain a copy of this Gap Analysis to complement this report were unsuccessful.

- **Seals Test Rig:** The seals test rig has the capability to test seals that range from 1" to 8" in diameter @700C and 4500 psi.
- **Sandia Particle Test Loop (SPTL)**: A 1 MWt falling particle receiver using concentrated solar energy that can heat particles to over 700 °C. The hot particles can then be used to heat sCO_2 in a particle-to-sCO_2 heat exchanger from 550 °C to 700 °C. A 100 kWt sCO_2 test loop is being integrated with the SPTL to test the world's first solarized sCO_2 system.
- **Solar Tower:** a 200-ft tall tower surrounded by 200+ heliostats that can produce 6 MW of thermal energy from the sun. The particle test loop is situated on top of the tower to receive the concentrated sunlight from the heliostats.
- **SuNLaMP High Temperature Loop**: 200 kWth input, 700 C, compact and reconfigurable test loop for measure the performance the operation of primary heat exchangers.
- **sCO_2 Tall Loop:** High pressure thermosyphon loop to measure natural convection effects in supercritical fluids.
- **APOLLO Loop:** Modification of the sCO_2 Tall Loop to measure the performance of regenerators as a possible replacement for recuperators.
- **UNM NEUP Loop:** Modification of the sCO_2 Tall Loop to measure the performance of twisted tube heat exchangers for Fluoride salt-cooled High-temperature Reactor (FHR) applications.
- **Heat Exchanger Test Loop:** 100 kW water-water loop to measure the performance of compact heat exchangers.
- **Mobile Heat Exchanger Test Loop:** 25 kW water-water loop to measure the performance of compact heat exchangers.
- **High Pressure Test Facility:** 60 ksi hydrostatic and fatigue test facility to measure the mechanical performance of compact heat exchangers and other equipment.
- **Low Pressure Gas Brayton Loop:** 30 kW, 700 C low pressure gas Brayton test loop to investigate the system dynamics of a coupled pin-type nuclear reactor and gas Brayton cycle and alternative gas Brayton cycle operating fluids.
- **sCO_2 Visualization Loop:** Optical facility to measure flow and density distributions of sCO_2
- **MCHE Visualization Loop:** Optical facility to measure flow distributions in water for MCHE and other geometries

<u>Potential Applications of Interest:</u>
Aligned with the NE office interest of exploring collaborations that support an expedited R&D path to nuclear applications, SNL is considering a variety of applications of interest:
- Sodium Fast Reactor nuclear application
- Distributed Energy (for small and very small SMRS)
- Concentrated Solar Power
- Fossil fuel primary cycle
- Shipboard power
- Waste heat recovery
- Bottoming cycle for gas turbine

The ultimate goal of the sCO_2 Energy Conversion program is technology transfer and commercialization. SNL's Brayton Team worked through 2017 focused on fulfilling the original mission statement, developed in 2014, which called for the development "with industry, of a fully operational 550°C 10 MWe R&D demonstration sCO_2 Brayton Power Conversion System that will allow the systematic identification and retirement of technical risks and testing of components for the commercial application of this technology."[8]

SNL's work on sCO_2 systems for NE is focused on the application of heat from a Sodium Fast Reactor (SFR) to a sCO_2 Brayton power cycle. Maximum turbine inlet temperature is 550° C and expected thermal efficiency is 45%. The current state of the sCO_2 technology is a laboratory scale demonstration of a sCO_2 RCBC at 250 kWe.

To achieve commercial interest, R&D is necessary to reduce the technological and economic risks for: materials that can handle the temperature and pressures without serious corrosion from the sCO_2; component technology that demonstrates scalability to commercial levels; system level testing to demonstrate performance and develop operating procedures; technology readiness level (TRL) risk management, systems engineering and economic models guided by a technology roadmap to support early engagement with industry to leverage knowledge and transfer technology.

The strategy is to perform basic and applied R&D to develop the sCO_2 RCBC to support the energy conversion of the SFR by 2030 at commercial off-the-shelf scale. To that end, SNL projects include:

- Developing and testing materials suitable to supporting the sCO2 RCBC for the SFR for the lifetime of the plant.
- Developing heat exchangers for the SFR coupling the sodium to the sCO2 and understanding the consequences of sodium and sCO2 interactions.
- Developing the sCO2 components for the RCBC demonstration: including turbines, compressors, recuperators, seals, bearings, control valves, control systems, high speed electrical generators, and waterless heat rejection.
- Testing sCO2 components within a complete system to investigate performance trades, assess effects of design features such as fluid additives, and develop operating procedures.
- Developing and maintaining technology roadmaps, system engineering and economic models, science based steady state and dynamic models for specifying requirements and developing operating procedures, tracking results, and planning futures.

[8] This statement was revised in May 2018, to support the understanding that retirement of risks for commercial ready technologies translates into the qualification of components for grid compatibility. The new mission is introduced in the next chapter of this report.

SNL's RCBC Test Assembly (TA) focused on developing the technology to make it available for commercialization in nuclear applications. The characteristics of the TA are described on Table 4 and shown in Figure 3.

Table 4: RCBC Test Article Description

Heater – 780 kWth, 550°C	Load Bank – 0.75 MWe
Max Pressure - 14 MPa	Gas Compressor to scavenge TAC gas
TACs – 2 ea., 125 kWe @ 75 kRPM, 2 power turbines, 2 compressors	Inventory Control
	Turbine Bypass (Remote controlled)
High Temp Recuperator – 2.3 MW duty	ASME B31.1 Designed Pipe, 6 Kg/s flow rate
Low Temp Recuperator – 1.7 MW duty	Engineered Safety Controlling Hazards
Gas Chiller – 0.6 MW duty	Remotely Operated

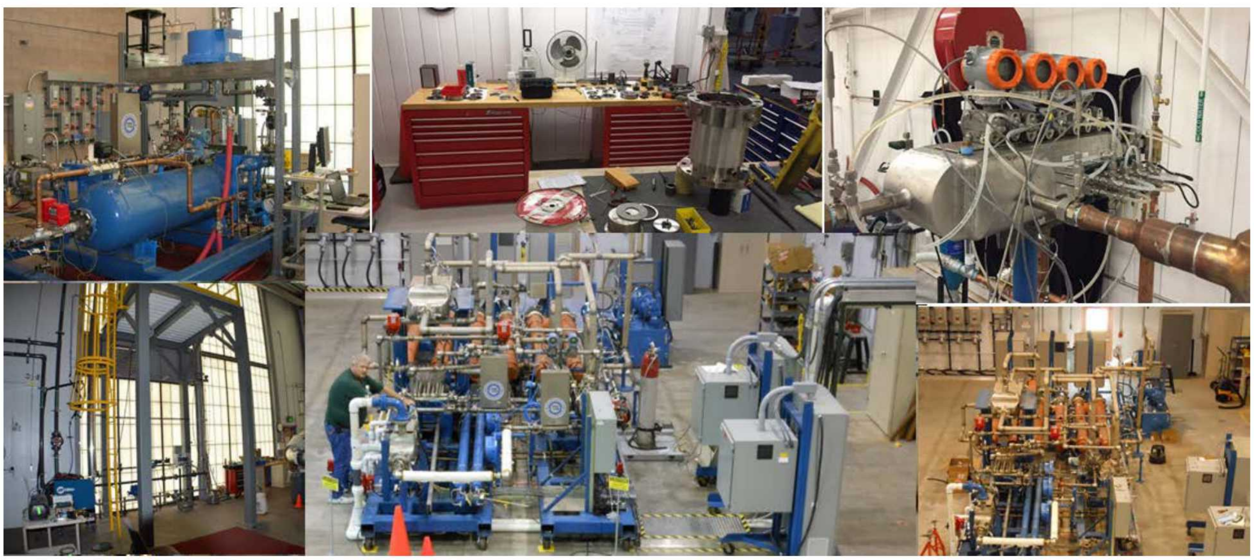


Figure 2: RCBC Test Article Description

As R&D has progressed, other components have been added to SNL's sCO_2 capabilities into the Brayton Laboratory Development Platform (DP). The capabilities available on the DP include 780 kW Recompression Closed Brayton Cycle, sCO_2 Bearings, Seals and Compressor research platform, sCO_2 Natural Circulation Test rig, 700C Materials testing autoclave, 100 kW Heat Exchanger testing platform, and sCO_2 Turbomachinery mechanical research station.

In addition, SNL is procuring the world's first 1 MW turbo compressor at 750°C though Design/Build process and standing up 8 additional test configurations in addition to the RCBC Development Platform to address:

- Heat Exchanger (SEARCH© design tool), optimized Printed Circuit Heat Exchanger Design
- Heat Exchanger test rig (thermal hydraulics)
- Particle Imaging Velocimetry (PIV), flow distribution measurement on HX headers

- High Pressure Test Facility (Pressure/thermal fatigue)
- sCO2 Seals test rig
- sCO2 Bearings test rig
- Turbocompressor test rig
- Dry Heat Rejection with Natural Circulation (Tall Loop), waterless power production
- Parallel Compression, combining compressor fluid output under different conditions
- APOLLO Regenerator Test Facility
- Twisted-Tube Heat Exchanger Test Facility
- SuNLaMP Compact High-Temperature sCO2 Test Platform

To date, SNL has been able to install a complete, operational RCBC, forming tests to demonstrate its operational and performance viability. Current work focuses on improving components readiness, including bearings, seals, materials performance, heat exchangers, and evaluation subcomponents integration and system level operations. SNL milestones reports are available at http://energy.sandia.gov/energy/renewable-energy/supercritical-co2/ and document progress in specific areas[9]. Most recent accomplishments include:

- Technology Roadmap/Project Management Plan/System Engineering Model completed with Systematic Risk Identification and Retirement from components to system configuration.
- Commercialization of the sCO2 system components to a higher TRL level to support sCO2 system commercialization.
- Operation Recompression Closed Brayton Cycle at a turbine inlet of 550C, working with industry to achieve high TRL components for system integration.
- Development of cross-cutting economic model identifying value engineering opportunities.
- Development and deployment of collaborative sCO2 Power Cycles Community of Practice
- Development of compact high-performance heat exchangers.

These activities attempted to advance the TRL level of components of the RCBC to 550°C and begin to move to 750°C turbine inlet temperature by engaging in Federal Business Opportunities (FBO) to Cooperative Research and Development Agreement (CRADA) Processes, yielding lab/industry collaborations with patents, copyrights, and national awards.

SNL believes the biggest challenges for technology development and deployment are in proving reliability of the system, economics, and meeting standards of utility, including the contracting requirements between vendor and utility companies. The sCO_2 system must be at least as economical as the current alternative – with valid arguments supporting a requirement for much cheaper alternatives - and be able to demonstrate enough value in benefits to offset the risk and cost of introducing the new technology.

[9] Repository site is in the process of being updated with latest reports, but is the permanent location for SNL sCO2 publications.

To this end, SNL is supported by a concurrent engineering and integrated project management approach [20], addressing the identification and analysis of relevant challenges, both to the technical development and commercial deployment of sCO_2 power cycles. To achieve the commercialization and technology transfer objectives, a preliminary roadmap was developed in 2016 [21] illustrating interim stages of technology development and demonstration leading up to a commercialization goal. This staged approach develops the technology by focusing on specific requirements at a time. **That preliminary roadmap is updated and replaced with the present document**, which recognizes the importance of on-grid qualification of components and systems to support market-ready sCO_2 commercial applications.

For these purposes, *market-ready sCO_2 energy conversion* is assumed to mean *power on-the-grid*.

Roadmap Foundations

SNL Brayton Team

Mission and Objectives

Sandia National Laboratory (SNL)'s Brayton Energy Conversion Team original mission statement, developed in 2014, called for the development "with industry, of a fully operational 550°C 10 MWe R&D demonstration sCO_2 Brayton Power Conversion System that will allow the systematic identification and retirement of technical risks and testing of components for the commercial application of this technology." This statement was revised in May 2018, to support the understanding that retirement of risks for commercial ready technologies translates into the qualification of components for grid compatibility. The new mission statement states that:

> *"By April 2020, Sandia National Laboratories, with government and industry partners, shall investigate the science, develop the test capabilities, and experimentally validate a grid compatible sCO_2 Brayton Power System that transitions laboratory technologies to domestic energy commercial applications."*
>
> SNL Brayton Team Mission, May 2018

This revised mission outlines the **objectives** of the program as seen in Figure 3 and below:

1 **"with government and industry partners"**: establishes the commitment *to support coordination and collaboration across labs and with industry* that meet stated common goals.

2 **"investigate the science, develop the test capabilities, and experimentally validate":** outlines the comprehensive spectrum of the R&D that must be accomplished, *to lead R&D that ensures systematic identification and retirement of risks to ensure component readiness* for the successful deployment of commercial applications.

- including concepts and/or criteria that may still be theoretical in nature, and advancing the knowledge base beyond scientific theory,
- through the development and achievement of testing capabilities to assess component, sub-systems, and systems performance at established criteria,
- to experimental validation of requirements that result in practical applications, through documented and demonstrated test results.

3 **"grid compatible sCO2 Brayton Power System"**: supports the industry need for grid qualification as a requirement for successful deployment of RCBC commercial applications, guiding SNL *to lead R&D that is inclusive of elements that increase the reliability and resiliency of electric power systems.*

4 **"transitions laboratory technology to domestic energy commercial applications"**: aims *to establish the foundations for successful commercialization of the technology* while recognizing that R&D goal is not fulfilled until 1) the technology has reached a readiness level that is accepted by industry and 2) knowledge is transferred to domestic industry for commercial use.

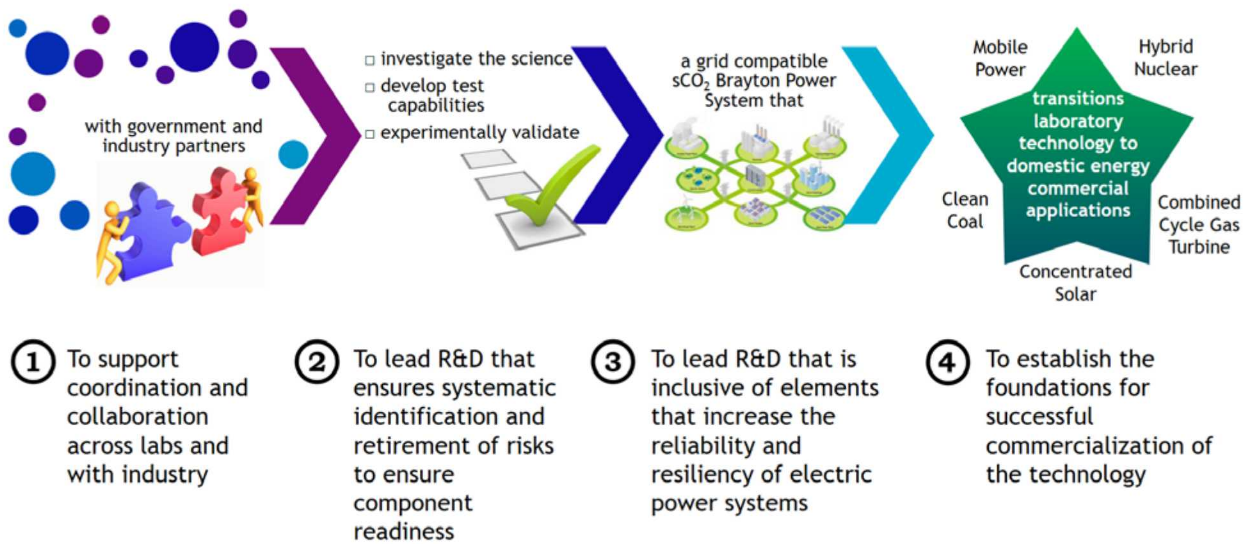


Figure 3: Objectives identified from SNL Mission Statement

Vision and Program Guidelines

The vision for sCO_2 power cycles development is
technology transfer that supports domestic energy applications.
SNL Brayton Team Vision, 2018

SNL's Brayton Team defined three program guidelines to support its mission:

1. **Deliberate design and development of scalable, modular, and reconfigurable test capabilities**, to allow the testing of a variety of commercially attractive configurations, system components, and sCO_2 Brayton products that can be transferred to industry.

2. **Deliberate planning, execution, and monitoring of systems engineering principles** in the identification and retirement of technical risks to:
   - pursue TRL advancement utilizing SNL's existing 150KWe system, through upgrades and additional capabilities, to reach the 10 MWe-750˚C system in support of the STEP test facility.

- demonstrate commercially relevant grid connection capabilities identifying the challenges and barriers for commercial applications.
- proceed to higher power levels and temperatures past the 2022 STEP demonstration in support of ART-NE nuclear application goals.

3. Deliberate demonstration of SNL's capability to systematically:

- Apply graded approach using applicable scientific and engineering rigor
- Address development and maturation risks of commercially viable technologies.

Roadmap to sCO_2 Commercial Applications

Roadmap Phases – staging to success

The roadmap is divided into interim phases aligned with stages of technology development. This approach develops the technology by focusing on progressive metrics, identification of gaps and their mitigation strategies, and addressing barriers that may delay progress in future phases. This allows the R&D scope, milestones, actions, and timelines to be focused on the short-term objectives while the concurrent engineering approach outlines and monitors the end-goal requirements for programmatic success.

The roadmap turns each demonstration milestone into the primary objective for that phase. The characteristics that define each phase are defined below.

Phase 1: Component Readiness

SNL has been working on sCO_2 science development since 2007. Previous work has included development of the Supercritical CO_2 Brayton Cycle Test-Loop, Controls, Testing, and Model Validation. The Recompression Brayton Cycle (RCBC) model or test article (TA) was developed to explore the sCO_2 Brayton Cycle and explore components focused on a sodium fast reactor. However, the design is limited to up to 250kwe and 1 MWth at 550C maximum.

This stage includes all the previous work done in the technology and components up to **reaching a readiness level** that is considered adequate for the demonstration scale. To demonstrate readiness for commercialization, it is necessary to achieve **commercial scale configurations** that will facilitate the retirement of risks associated with sCO_2.

This stage also integrates the two new lanes, Component Testing Capabilities and Grid Qualification Capabilities, which provide the foundation for an accelerated timeline. As previously stated, the three R&D lanes individually support at least one of the program goals but, when pursued together, they have the potential to generate an accelerated timeline to the commercialization of Brayton systems that support domestic energy applications. Such is the case for Product Grid Qualification, which can qualify systems smaller than the 10MWe STEP to demonstrate endurance, reliability, and safety on the grid. After such qualification, it is assumed that the product would be market-ready, and could begin commercialization for a segment of the market (Figure 4).

Phase 2: Pilot through the STEP Facility

The RCBC TA has limitations that make it impossible to demonstrate commercial scale. The STEP Pilot aims to establish a 10MWe RCBC 700˚C-715˚C facility capable of demonstrating the technology is as close to commercial scale as possible, considering actual applications of the system. However, this facility will not be connected to the grid (although it can include simulation of the scenario) and is expected to be normally "off". The Pilot Facility would be capable of being turned on for multiple days at a time, allowing experiments to demonstrate the system effects on the environment.

Phase 3: Demonstration

The demonstration phase would take the pilot application and configuration even closer to commercial scale. It is expected that a demonstration would be connected to the grid and will be normally "on", operating for a minimum of 1000 hours. However, it would still be a research facility operated by engineers and scientists.

Phase 4: Commercialization

The main differentiator between the demonstration phase and reaching commercial scale is that during the commercial phase the operation of the facility is transferred and fully owned by industry and in continuous, or near continuous, commercial power generation operation.

R&D Roadmap Lanes

At the current phase, this roadmap outlines three primary R&D Lanes to be pursued at SNL, as seen in Figure 4.

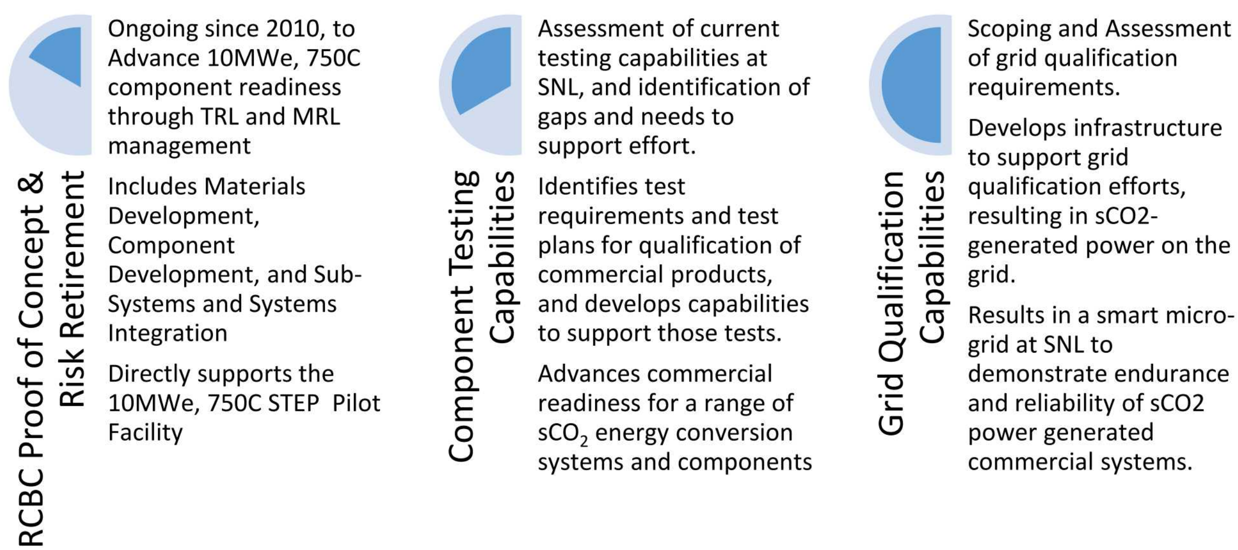


Figure 4: Primary R&D Lanes for SNL's sCO_2 Energy Conversion Technology Roadmap

While the *RCBC Proof of Concept and Risk Retirement* area has been ongoing since 2010, when the program was initiated at SNL, two new lines of work have been identified as critical to support successful commercial-ready systems. Each of these lanes individually support at least one of the program objectives.

- **RCBC Proof of Concept and Risk Retirement** directly supports the 10MWe, 750˚C STEP Pilot Facility by testing and retiring risks on components, advancing component readiness at varied temperatures leading up to the STEP Facility criteria.
- **Component Testing Capabilities** builds from the existing work in risk retirement effort, by upgrading and expanding capabilities to support testing the likely commercial derivative solutions (sub-systems and components) resulting from the requirements presented by the STEP Facility and the many identified commercial applications.
- **Grid Qualification Capabilities** aim to address the need to demonstrate reliability and safety of Brayton systems to put power on the grid, as a necessary requirement for successful commercial applications (via distributed energy or utilities markets, among others.)

Figure 5 shows a path to technology commercialization that illustrates the interim stages of the roadmap leading up to a commercialization goal. The highlighted section identifies the current scope of work.

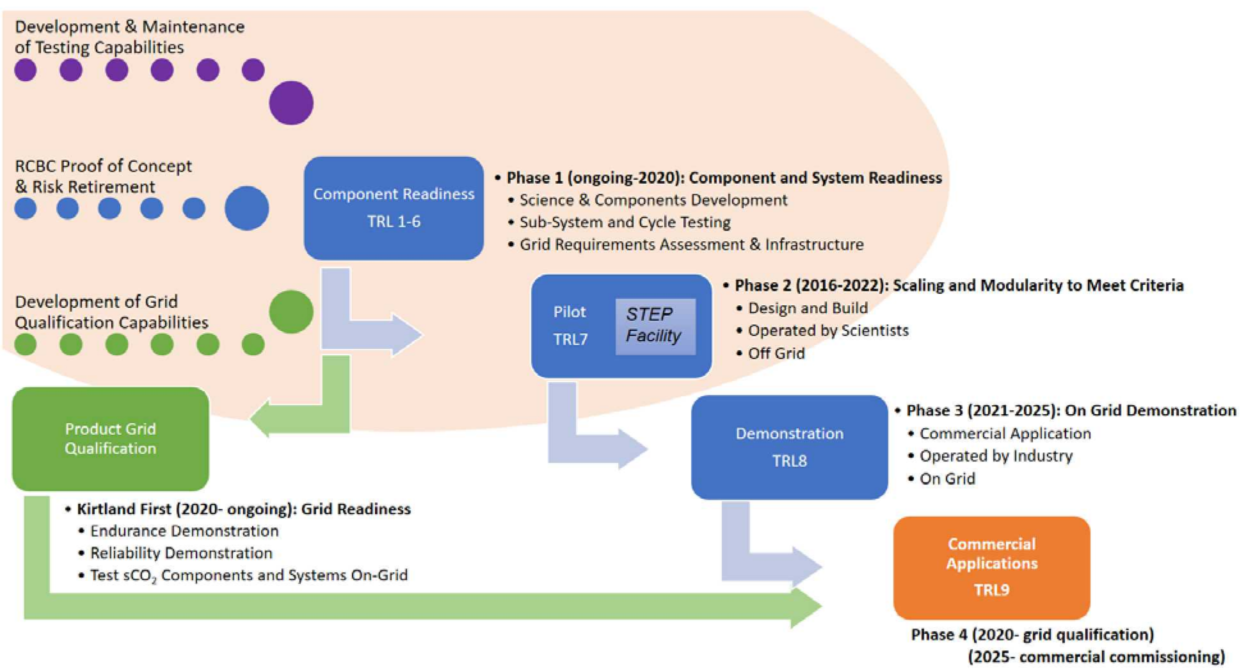


Figure 5: Roadmap Phases for sCO2 Commercialization

R&D Collaboration

This program roadmap proposes the use of combined ART and NE-STEP efforts, along with partnerships with universities and commercial entities, 1) to advance the development of 10MWe sCO_2 Brayton Cycle components, in alignment with the DOE STEP Pilot facility; and 2) to develop market-ready sCO_2 energy conversion systems relevant to commercial applications. Both targets support NE goals to develop sCO2 Brayton Energy Conversion technologies applicable to advanced nuclear reactors.

For example, the plan calls for using facilities at Argonne National Laboratory (ANL) for the development of the Na-sCO_2 intermediate heat exchanger for the SFR at 550˚C, and the Development Platform (DP) of the SNL Brayton Laboratory to develop components for the Pilot Demonstration, raising the individual components' Technology Readiness Level (TRL)[10] and the System TRL. Simultaneously, SNL Brayton Laboratory will work to advance the ART and NE-STEP common technology to higher temperatures of 700C, supporting commercial products development that would be ready for market as the result of this collaboration path, while the Pilot evolves to the higher temperature goals envisioned for advance reactors. The plan also calls for the development of a micro-grid at SNL, achieving grid qualification capabilities to demonstrate power on-the-grid of upcoming commercial systems.

Metrics

Stage 1 spans from the initial science development through current and future efforts of cycle testing utilizing the RCBC Test Article. **Stage 2** is the successful execution of a demonstration to show the scale of the commercial application on a system that is controllable and largely problem free, and where the technology performs as expected.

In essence, the aim of Stage 1 is to develop component readiness to a level where it can be said with confidence that Stage 2 (through the STEP Pilot Facility) will be successful at "Go".

Making this assessment while simultaneously supporting the development of a scalable technology that is commercially attractive requires a definition of metrics to measure progress. This section identifies the metrics that will be used to monitor and evaluate progress towards the stated milestones and objectives.

Technology Readiness Levels

DOE utilizes Technology Readiness Levels (TRL) to assess the readiness of systems components. "Technology Readiness Levels (TRLs) are a method of estimating technology maturity of the Critical Technology Elements (CTE) of a program during the acquisition process. They are determined during a Technology Readiness Assessment (TRA) that examines program concepts, technology requirements, and demonstrated technology capabilities. TRL are based on a scale from 1 to 9 with 9 being the most mature technology." [22]

In 2017, SNL proposed that to prove TRL4 or above the application-specific product must have been chosen and its design specified so that component configuration and any system integration is relevant. Although this seems very limiting, it is important to realize that any research and development progress will likely be transferrable to other applications, and the ensuing confidence will help the entire industry. [23]

[10] TRL is a method of estimating technology maturity of critical technology elements.

Table 5 summarizes the definition of TRL levels according to the Department of Energy (DOE) [24] and proposes testing activities specific to sCO_2 that would satisfy each TRL level [25].

Work is needed to validate the proposal of testing activities, seeking consensus from stakeholders on exactly what activities will demonstrate a given TRL level.

Table 5: TRL Definitions

	TRL	Level	DOE Definitions	Proposed Testing Activities sCO_2 Brayton
Basic Technology Research	1	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology.	Testing is focused on basic principles and foundational science is still being explored. **Currently in progress for some aspects of sCO_2 Brayton.**
	2	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.	Component TRL and System TRL must be assessed separately. Technology readiness for components can progress individually. **System TRL must demonstrate components integrated at system performance levels.**
Research to Prove Feasibility	3	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants. Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.	Proof-of-concept testing of applications/concepts is completed. Computer modeling exists and proven valid. Fabrication processes are validated. **System TRL can only be as high as its lowest rated component, and system integration needs to be completed to move beyond TRL 3.**
Technology Development	4	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small-scale tests on actual waste. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.	Component rig testing at bench-scale is completed. High risk component integration is completed. **To achieve TRL 4 and beyond, the application-specific product must be selected and its design specified so that component configuration and any system integration is relevant.**

	TRL	Level	DOE Definitions	Proposed Testing Activities sCO_2 Brayton
	5	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants and actual waste. Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/ environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.	Complete component testing using sCO_2 working fluid at design conditions. **To achieve TRL5, high risk technical issues must be addressed (e. g., material concerns for corrosion, seals, bearings, etc.).**
Technology Demonstration	6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants. Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, protot ypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.	Subscale testing of an integrated system at design conditions. System and component configuration is targeted to application-specific product.
System Commissioning	7	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning. Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.	Complete demonstration testing - All components integrated into an application-specific product, demonstrated at design conditions.
	8	Actual system completed and qualified through test and demonstration.	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An Operational Readiness Review (ORR) has been successfully completed prior to the start of hot testing.	Complete installation and startup of an application-specific product, ready for pilot testing.
Operations	9	Actual system operated over the full range of expected conditions.	The technology is in its final form and operated under the full range of operating conditions. Examples include using the actual system with the full range of wastes in hot operations.	Complete pilot testing of an application-specific product at commercial site by utility stakeholder for >= 8000 hours.

SNL developed a preliminary TRL assessment of components based on Principal Investigators' input on several areas [26, 23], seen in Table 6.

Table 6: Preliminary Component TRL Assessment

Tech type	EERE CSP	FE	Nuclear		Preliminary TRL Estimate									
Approx. Temp. (°C)	H	L	L											
MWe	3 to 10	10	10		TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9	
	CSP Indirect	GT bottoming cycle power	Sodium SFRs	CTE Result	Basic technology process principles been observed?	Equipment and process concept been formulated?	Demonstrated in a simulated environment?	Laboratory-scale testing in a simulated environment?	Bench-scale testing in a relevant environment?	Prototypical engineering scale testing in a relevant environment?	Successfully operated in operational environment?	Successfully operated in a limited environment?	Successfully operated in the full environment?	Risk
Heater														
Exhaust gas/sCO2 heat exchanger		x		Y	X	X	X	X						L
liquid/sCO2 heat exchanger			x	Y	X	X								M
solid/sCO2 heat exchanger	x			Y	X	X	X							H
Recuperator(s) (Including recompression)														
below 600 above 400	x	x	x	Y	X	X	X	X	X	X	X	X	X	L
Heat rejection														
dry cooling type	x	x	x	Y	X	X	X	X	X	X	X	X		L
Pipes and Flanges														
Low Temperature Heat Source		x	x	N	X	X	X	X	X	X	X	X	X	L
Higher Temperature Heat Source (>650)	x			Y	X	X	X	X						L
Valves														
Low Temperature Heat Source		x	x	N	X	X	X	X	X	X	X	X	X	L
High Temperature Heat Source	x			Y	X	X	X	X						M
Insulation	x	x	x	N	X	X	X	X	X	X	X	X	X	L
Turbine	x	x	x	Y	X	X	X	X						M
Compressors				N										
Near critical	x	x	x		X	X	X	X	X					L
Gas compression			x		X	X	X	X	X	X	X	X	X	L
Bearings & Seals				Y	X	X	X	X						M
Hydrodynamic oil bearings (~5 to 900 MWe)	x	x	x		X	X	X	X	X	X	X	X	X	L
Gas Foil Bearings	x	x	x	Y	X	X	X	X	X					M
Advanced labyrinth seals (up to 10 MWe)	x	x	x		X	X	X	X						M
Dry lift-off seals (~3 to 1000 MWe), <450F	x	x	x		X	X	X	X	X	X	X	X	X	L
Dry lift-off seals (~3 to 1000 MWe), >450F	x	x	x		X	X								M
Generator	x	x	x	N	X	X	X	X	X	X	X	X	X	L
Gear Boxes				N										
Lower speed (3MW-300MW)	x	x	x		X	X	X	X	X	X	X	X	X	L
Motor	x	x	x	N	X	X	X	X	X	X	X	X	X	L
Instrumentation	x	x	x	N	X	X	X	X	X	X	X	X	X	L
Controller Hardware - Low Speed	x	x	x	N	X	X	X	X	X	X	X	X	X	L
Controller Software	x	x	x	N	X	X	X	X	X	X	X	X	X	L
System Modeling				Y										
Steady State	x	x	x		X	X	X	X	X					L
Transient	x	x	x		X	X	X	X	X					M
Startup	x	x	x		X	X	X	X	X					M
Facilities Design	x	x	x	N	X	X	X	X	X	X	X	X	X	L
CO2 Supply Systems	x	x	x	N	X	X	X	X	X	X	X	X	X	L
Electrical Power	x	x	x	N	X	X	X	X	X	X	X	X	X	L
Energy Storage (Electrical)	a		a	Y	X	X	X	X						H
Waste Heat Rejection	x	x	x	N	X	X	X	X	X	X	X	X	X	L
Inventory Control	x	x	x	N	X	X	X	X	X	X	X	X	X	L

This estimate served to prioritize SNL's component development R&D program. The assessment identified high technical risks including corrosion, turbine erosion, turbine control, thrust management, and seals, among others [23]. The assessment also concluded that there is a high opportunity for component development synergy across the DOE offices. It is important to note that when this preliminary assessment was completed, it was developed for NE Sodium SMR's applications. High-temperature gas reactors, molten-salt reactors, and FE and EERE applications were not within scope at the time.

Within those limitations, work is still needed to validate the preliminary nature of the TRL estimates, and to simultaneously expand it to the more recent scope of NE potential applications and FE/ EERE combined interests on alternative applications.

The preliminary **component TRL assessment** needs to be reviewed and updated across the national laboratories to bring together the expertise of researchers across the multiple applications, and validated based on the time elapsed since the initial baseline.

However, component TRL is not an indicator for system TRL. The Brayton system TRL cannot be higher than the lowest rated individual component and/or the system interfaces. By this assessment, a full RCBC could be estimated to be at TRL 1-2 while some individual components could be assessed much higher based on the target application. SNL is working on a systems model to support system TRL assessment.

A **comprehensive system assessment** needs to be completed for the most likely applications based on the individual component TRL assessment and system modeling of component interfaces.

To move forward with Stage 1 Component Readiness specifications, it is necessary to explore and detail two critical decision points:

1- Identify and communicate a final **desired demo configuration** for NE. The crosscut's common goal is to establish a 10MWe facility capable of evaluating a range of conditions. However, the initial set of conditions needs to be articulated for NE in order to make progress towards the specific NE goal.

2- The **component technology readiness level required** to confidently support a move of the component from RCBC TA to integration into the pilot scale, and to commercial levels, including respective testing plans (assumed to be TRL 7-9 depending on application).

3- The **system technology readiness level required** to confidently support a commercial RCBC application (assumed to be TRL 9 for public, environmental, and operational safety), as well as acceptable TRL required for technology transfer from DOE to commercial entities.

Manufacturing Readiness

Manufacturing readiness level (MRL) is a measure developed by the United States Department of Defense (DOD) to assess the maturity and risk of manufacturing, much in the same way that TRL is used for technology readiness [27]. MRL is applicable to assess the capabilities of potential component manufacturers and suppliers, as well as to assess the readiness of manufacturing processes for materials that support sCO_2 Brayton temperatures and pressures. MRL is critical to support the successful commercialization of the technology, as it is capable of addressing both safety and demand risks. The basic definition of MRL levels is shown in Table 7.

The possible use of MRL applied to sCO_2 Brayton component development needs to be studied based on relevant systems criteria. The definitions outlined in Table 7 must be aligned to the specific Brayton requirements that reduce manufacturing risk in order to be applied to supplier selection.

Table 7: Manufacturing Readiness Level (MRL) Definitions

MRL	Description	Definition
1	Basic manufacturing implications identified	This is the lowest level of manufacturing readiness. The focus is to address manufacturing shortfalls and opportunities needed to achieve program objectives. Basic research (i.e., budget activity 6.1 funds) begins in the form of studies.
2	Manufacturing concepts identified	This level is characterized by describing the application of new manufacturing concepts. Applied research (i.e., budget activity 6.2 funds) translates basic research into solutions for broadly defined military needs. Typically, this level of readiness in the science and technology environment includes identification, paper studies, and analysis of material and process approaches. An understanding of manufacturing feasibility and risk is emerging.
3	Manufacturing proof of concept developed	This level begins the validation of the manufacturing concepts through analytical or laboratory experiments. This level of readiness is typical of technologies in the science and technology funding categories of Applied Research and Advanced Development (i.e., budget activity 6.3 funds). Materials or processes, or both, have been characterized for manufacturability and availability but further evaluation and demonstration is required. Experimental hardware models have been developed in a laboratory environment that may possess limited functionality.
4	Capability to produce the technology in a laboratory environment	This level of readiness is typical for science and technology programs in the budget activity 6.2 and 6.3 categories and acts as exit criteria for the materiel solution analysis phase approaching a milestone A decision. Technologies should have matured to at least technology readiness level 4. This level indicates that the technologies are ready for the technology-development phase of acquisition. At this point, required investments, such as manufacturing technology development, have been identified. Processes to ensure manufacturability, producibility, and quality are in place and are sufficient to produce technology demonstrators. Manufacturing risks have been identified for prototype build, and mitigation plans are in place. Target cost objectives have been established and manufacturing cost drivers have been identified. Producibility assessments of design concepts have been completed. Key

MRL	Description	Definition
		design performance parameters have been identified as well as any special tooling, facilities, material handling, and skills required.
5	Capability to produce prototype components in a production-relevant environment	This level of maturity is typical of the midpoint in the technology-development phase of acquisition, or in the case of key technologies, near the midpoint of an advanced technology-demonstration project. Technologies should have matured to at least technology readiness level 5. The industrial base has been assessed to identify potential manufacturing sources. A manufacturing strategy has been refined and integrated with the risk-management plan. Identification of enabling/critical technologies and components is complete. Prototype materials, tooling and test equipment, as well as personnel skills, have been demonstrated on components in a production-relevant environment, but many manufacturing processes and procedures are still in development. Manufacturing technology development efforts have been initiated or are ongoing. Producibility assessments of key technologies and components are ongoing. A cost model has been constructed to assess projected manufacturing cost.
6	Capability to produce a prototype system or subsystem in a production-relevant environment	This MRL is associated with readiness for a milestone B decision to initiate an acquisition program by entering into the engineering and manufacturing development phase of acquisition. Technologies should have matured to at least technology readiness level 6. It is normally seen as the level of manufacturing readiness that denotes completion of science and technology development and acceptance into a preliminary system design. An initial manufacturing approach has been developed. The majority of manufacturing processes have been defined and characterized, but there are still significant engineering or design changes, or both, in the system itself. However, preliminary design of critical components has been completed and producibility assessments of key technologies are complete. Prototype materials, tooling and test equipment, as well as personnel skills have been demonstrated on systems or subsystems, or both, in a production-relevant environment. A cost analysis has been performed to assess projected manufacturing cost versus target cost objectives and the program has in place appropriate risk reduction to achieve cost requirements or establish a new baseline. This analysis should include design trades. Producibility considerations have shaped system-development plans. Industrial capabilities assessment for milestone B has been completed. Long-lead and key supply-chain elements have been identified. All subcontractors have been identified.
7	Capability to produce systems, subsystems, or components in a production-representative environment	This level of manufacturing readiness is typical for the midpoint of the engineering and manufacturing-development phase leading to the post-critical design review assessment. Technologies should be maturing to at least technology readiness level 7. System detailed design activity is underway. Material specifications have been approved and materials are available to meet the planned pilot-line build schedule. Manufacturing processes and procedures have been demonstrated in a production-representative environment. Detailed producibility trade studies and risk assessments are underway. The cost model has been updated with detailed designs, rolled up to system level, and tracked against allocated targets. Unit-cost reduction efforts have been prioritized and are underway. The supply chain and supplier quality assurance have been assessed and long-lead procurement plans are in place. Production tooling and test equipment design and development have been initiated.

MRL	Description	Definition
8	Pilot line capability demonstrated; ready to begin low-rate initial production	This level is associated with readiness for a milestone C decision, and entry into low-rate initial production. Technologies should have matured to at least technology readiness level 7. Detailed system design is essentially complete and sufficiently stable to enter low-rate production. All materials are available to meet the planned low-rate production schedule. Manufacturing and quality processes and procedures have been proven in a pilot-line environment and are under control and ready for low-rate production. Known producibility risks pose no significant challenges for low-rate production. The engineering cost model is driven by detailed design and has been validated with actual data. The Industrial Capability Assessment for milestone C has been completed and shows that the supply chain is established and stable.
9	Low-rate production demonstrated; capability in place to begin full-rate production	At this level, the system, component, or item has been previously produced, is in production, or has successfully achieved low-rate initial production. Technologies should have matured to at least technology readiness level 9. This level of readiness is normally associated with readiness for entry into full-rate production. All systems-engineering/design requirements should have been met such that there are minimal system changes. Major system design features are stable and have been proven in test and evaluation. Materials are available to meet planned rate production schedules. Manufacturing process capability in a low-rate production environment is at an appropriate quality level to meet design key-characteristic tolerances. Production risk monitoring is ongoing. Low-rate initial production cost targets have been met, with learning curves validated. The cost model has been developed for the full-rate production environment and reflects the effect of continuous improvement.
10	Full-rate production demonstrated, and lean production practices in place	This is the highest level of production readiness. Technologies should have matured to at least technology readiness level 9. This level of manufacturing is normally associated with the production or sustainment phases of the acquisition life cycle. Engineering/design changes are few and generally limited to quality and cost improvements. System, components, or items are in full-rate production and meet all engineering, performance, quality, and reliability requirements. Manufacturing process capability is at the appropriate quality level. All materials, tooling, inspection and test equipment, facilities, and manpower are in place and have met full-rate production requirements. Rate production unit costs meet goals, and funding is sufficient for production at required rates. Lean practices are well established and continuous process improvements are ongoing.

Economic Indicators

The development of a technology for commercial applications requires an understanding of the economic environment and conditions in which the technology will be adopted and deployed. Monitoring the economic environment will highlight issues of relevance in timing and cost of development, allowing R&D teams to take these considerations into account as the technology develops.

Wide scale adoption requires a sCO_2 Brayton systems that is economically competitive. For commercialization, it is necessary to consider the economics of technology development and operation. This may present a challenge if achieving higher efficiencies may require higher temperatures and special materials, which may come at a higher cost. For example, as reported on [5], Pasch demonstrated the tradeoffs between system pressure ratio, component size, wall thickness, efficiency, and operating costs (Figure 6).

Operating sCO_2 systems at higher temperatures increases efficiency but may require more expensive materials. SNL is developing tools to assess the economic tradeoffs associated with various design parameters. For example, we know that a 10 MW natural gas system with an overall efficiency of 45% would have fuel savings of $15 million per year over a system with an overall efficiency of 40%. Achieving the higher efficiency will require additional capital cost expenditures. Our analysis shows that as long as the additional costs are less than $350 per installed kW, the overall savings will be positive. This type of analysis will help engineers understand the economic constraints associated with various design considerations. [28]

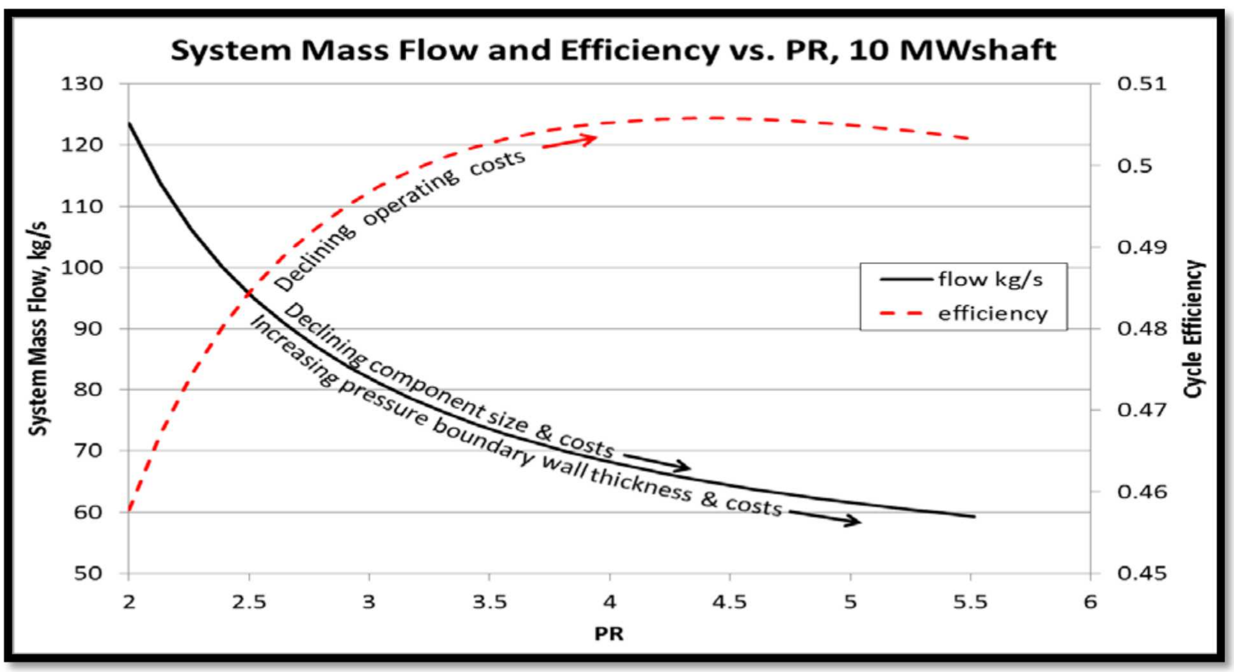


Figure 6: Economics of System Tradeoffs

SNL has developed and is optimizing an economic tool that helps cost Brayton systems components. This tool helps SNL's technical team understand value of various design points. Maintaining abreast of this type of considerations as the technology is developed influences the decisions made during development and supports that technology solutions remain attractive for commercialization.

Some metrics that could be used to continually assess the economics of the system include:

- **Increased cost** of higher-cost materials vs. savings due to efficiency improvements
- **Installed cost** and **energy cost to market**
- Market comparisons on **energy capacity additions**

DOE Collaboration stakeholders must agree on the economic indicators that will support the system development, and develop a schedule for monitoring and sharing economic information.

The cost of development of the system can have a significant impact on the economic competitiveness of solutions. Cost considerations, including the cost of materials used, should be included in the assessment of component readiness, to complement the more technical TRL and MRL metrics.

The optimization of an economic tool for Evaluating Brayton Systems is ongoing. This tool will refine existing costing tools to help technical team understand value of various design points (value engineering). Specific detailed data is needed from utilities and supplier to reduce uncertainty in the models.

Environmental Impact

Environmental impact plays a significant role in the successful deployment of energy technologies. The implications of environmental impact are easily identified in both policy and public perception considerations. Considering the current environmental policy concerns, it is important to quantify, monitor, and document the system's potential impact on the environment, in order to be prepared to highlight the benefits of the new technology and the steps taken to address issues or concerns.

The improved efficiency that is expected from sCO_2 system results in **lower greenhouse gases**. This is a significant benefit to the technology, that should be quantified and documented as a measure of environmental impact.

Additionally, sCO_2 systems can use air cooling rather than water cooling. Given the increasing concerns about water scarcity and quality, dry-cooling and water savings can also be considered measures for successful environmental impact, when applicable. These include **gallons of water saved** per year and **value of water savings** [29].

Technology Value and Impact

Valuation of the technology, and the impact of development decisions on that valuation, should be considered through every stage of the science, component and facility development actions. While commercial viability requires a demonstration of performance, cost, operability, and reliability [2], the energy industry is highly regulated with significant public interest [2, 5].

A comprehensive strategy for valuation of the technology and quantification of its impact may be created. For components, the implicit in-system achievements, performance and optimization must be documented. For the technology as a system, the value of improved efficiencies that the system brings to the energy industry must be considered in comparison to both the current best-in-market and the mainstream alternatives.

It is critical to understand the end-customers value system for new technology adoption. This includes utilities, government, and other potential application users.

Perceived technology value and impact

Perceptions of the technology value and impact are just as important as the measured reality of these variables. While perceptions may be less critical for the component readiness stage, it becomes more relevant as the discussion progresses to commercialization, including investment cycles and even site licensing for a facility. Plant owners tend to be “conservative” with respect to emerging technologies [2, 5], so perceptions on the technology alone may significantly impact adoption. It has been stated by utilities that, all things being equal, operators will always revert to the technology they are familiar and comfortable with. [30]

Measurements of perception, climate, and culture can be designed specifically for the system being studied. It will be necessary to design, evaluate and implement methods to measure perceived value and impact of sCO_2 Brayton technology on several groups: operators, maintenance, utility engineers, community leaders, application interests, suppliers and industry leaders, and the scientific community. The results of this analysis will raise relevant information to support technology transfer and commercialization strategy.

Situation Analysis

The situation analysis considers key factors that need to be explored to identify their impact on the roadmap objectives. Following the IEA guide [31], this roadmap categorizes the information on three key areas: Technology, Market and Policies.

Technology

The situation analysis of the technology identifies the status of the critical components that need to be developed.

Scientific Basis

Thermodynamics is a very well understood science. It has been studied for hundreds of years, and has been successfully applied to understand and optimize numerous thermodynamic processes, in particular, many power conversion cycles. The Brayton cycle was first proposed and patented by John Barber in 1791, and further developed by George Brayton in the mid-1800's [32]. The physics has been applied to closed Brayton cycle system development and operation as early as 1939, using air as the process fluid. Over 750,000 hours of operation with closed air Brayton cycle power plants have accrued since that time [33], and many millions of hours on open air Brayton cycles (jet engines) [34]. The primary unique feature of the current program is the application of carbon dioxide as the process fluid. The thermodynamics and benefits of this specific fluid were developed by Gianfranco Angelino [35, 36, 37]

Primary component differences between the closed air cycles documented by Frutschi [33] and closed sCO_2 cycles exist in the turbomachinery – turbines and compressors. The design, manufacture, and operation of turbomachinery is a well understood process [38] for many fluids. It is expected that the first principles physics commonly applied in this process will work for sCO_2 as well. The investigation and demonstration of this expectation is being pursued by the sCO_2 Brayton team at SNL, with very favorable results to date [39].
Thermo-physical properties of CO_2 have been thoroughly studied for many decades. High quality property routines are maintained at the National Institute of Standards and Technology [40], are readily incorporated into computer models, and have proven to be robust and easy to use. These routines are based on extensive research over a very broad range of fluid conditions [41].

Materials

To achieve the highest efficiencies, sCO_2 Brayton systems must perform at high temperatures (>700°C turbine inlet). In this regime, material performance has not been proven. Even at nominal operating temperatures, in support of a commercially viable solution, it is important to develop understanding of materials behavior for meaningful product lifetimes. Materials solutions must be explored while keeping in mind the cost impact because excessively high cost could prevent industry from integrating sCO_2 into their energy conversion portfolios.

Materials limit the existing technology. Fluid/materials questions being investigated primarily revolve around material compatibility with CO_2. This work includes testing of bearings and component materials and various metals. The investigation employs both traditional elevated temperature and pressure oven testing, as well as application of fundamental science to characterize the chemical processes involved between the metals and CO_2.

The erosive and/or corrosive degradation of materials in the sCO_2 Brayton cycle present a significant hindrance to commercial adoption. Challenges have already been identified on the hot side of the CBC, including:

- primary heat exchanger – thick walled, corrosion resistant tubing with large surface area exposure to heat source
- turbine inlet piping and castings – structurally sound castings, creep resistant piping all resistant to sCO_2 corrosion
- high temperature recuperator and associated inlet piping; this represents the same issues presented in the turbine inlet piping and castings, but at the lower turbine outlet temperature
- erosion and corrosion impact to material lifetime and failure modes.

In support for a commercially viable solution, it is important to develop understanding of **materials properties, behavior, and performance** under real power cycle operating conditions for meaningful product lifetimes. Materials for long duration performance are yet to be identified. Durability studies for materials R&D are needed, in particular to demonstrate PCHE applicability to these power cycles.

The **materials erosion** issues observed in the sCO_2 cycles must be understood and overcome to realize a successful commercial scale system. SNL has made significant progress in understanding and resolving turbine degradation by performing a systematic root cause analysis (RCA), where hypotheses have been identified and tested through a series of experiments. Through this work, stainless steel particulate in the loop has been identified as the leading cause for turbine degradation. However, additional experimental work is needed to (1) prove that this particulate material is definitely causing the observed erosion, (2) identify the source for the particulate material within the system, and finally to (3) prove that the placement of particulate filters into the system successfully eliminates the observed erosion.

A high purity CO_2 environment is not likely to be present in a commercial scale system. Instead, a commercial scale system is likely to use commercial grade CO_2 with higher impurity concentrations. Commercial grade CO_2 is likely to contain impurities common to commercial grade gases (O_2, H2O, N_2, S, etc.) as well as other contaminant gas species resulting from component outgassing and/or surface contaminants from within the Brayton cycle.

A critical shortcoming in the **available experimental data** on sCO_2 induced **material corrosion**, is that high purity CO_2 has exclusively been used in these studies. It is necessary to gain a sense of the chemical harm that a base CO_2 with minor constituents might have on materials. Testing would be needed, but the cost could be very expensive because of the wide range of components that could be in an industrial fluid.

There has been work completed on how impurities impact **corrosion** of the materials at 550C. The issue is picking the right material to develop the system at the lower cost.

There is a critical need to understand how the composition of sCO_2 (impurity concentration) in the system changes over time. While work has been done to understand the impact that impurities can have in the system, as more knowledge is developed on sCO_2 composition over time, new work may be required on the impact of corrosion in the system.

Materials solutions must be explored keeping in mind the cost impact in the system, since too high of cost could preclude industry from integrating sCO_2 into their energy conversion portfolios. The cost of components and material alternatives should be part of the component readiness assessment. To achieve this, it is necessary to establish component materials requirements for commercial scale system components and to identify the materials that will satisfy those component performance requirements during the lifetime for a commercial system. This begins with a clear understanding, from the available literature, of the performance of structural alloys and seals and bearings materials.

There is also a need for study and guidance regarding where conventional or advanced stainless steel should be used, and what is the max temperature they operate at. While some **cheaper steels** might work, the decision could come down to the lifetime of these materials, which needs to be studied under specific system conditions.

Mixtures in cycles can provide new possibilities for the system. There is need for trade studies of the effects of mixtures on component and cycle performance. For example, a mixture of sCO_2 with 10% of something else could help move critical stuff around the cycle. Theoretical studies and experiments to determine what that "something else" should be would be needed to create a realistic model, with the expectation that confidence level will vary greatly from mixture to mixture. Evaluation of whether these mixtures will improve the overall performance of the cycle requires accurate thermos-physical properties (especially thermodynamic properties) for the mixture; the most important conditions will be the region near the critical point of CO_2. There is need for data that correlates fluid chemistry with thermodynamic and transport properties, to provide verification and/or improvement of fluid and mixture equations of state.

Joining metals is a critical issue for sCO_2 applications due to the use of advanced, high-strength alloys for welding and a variety of materials for diffusion bonding. For both welding and diffusion bonding, there is a significant need to develop procedures for every expected material combination. Specifically, welding procedures for stainless steels are well-known and diffusion bonding has been conducted to ASME BPV code requirements by several vendors, but advanced nickel alloys have limited development and experience and need more work. Requirements exist in the ASME BPV code that welding and diffusion bonding procedures must meet for commercial applications, and code requirements for nuclear applications are under active development. Some joining techniques will result in compositional gradients even between like materials which should be investigated for corrosion concerns.

Materials joined by **welding, diffusion bonding, and brazing** may be affected by the sCO_2 environment. There is need to understand the mechanics of materials, and determine the best **adequate tools for lasting manufacturing**. Effective welding, brazing for mechanical properties also needs to be studied.

Diffusion bonding procedures for advanced nickel alloys must be verified and exercised in order to avoid the costs of using secondary containment vessels.

There is need for R&D of materials for coatings in order to support component development and system integration.

There is also a need to understand if scale formation and potential liberation can lead to plugging and erosion.

Cycle Configuration

Aside from the individual components, different configurations of these main components are preferred for specific applications. In general, the sCO_2 CBC offers the following benefits compared to current steam Rankine cycles.

- Higher cycle efficiency than the Rankine Cycle for a given Heat Transfer Fluid (HTF) outlet temperature
- Good load following capabilities
- A very wide array of conceivable designs to match requirements and conditions
- Excellent scalability while remaining efficient
- Ability to incorporate air cooling as ultimate heat sink, with small impact on cycle efficiency
- Ease of build, installation and operation
- High fluid density, low pressure ratio yields compact turbomachinery
- Ability to interface better with the high temperature HTF at smaller scale
- Potential to reduce the cost of the power block.
- Operational simplicity compared to steam generation that can possibly lead to reduced O&M cost

However, each configuration provides application-specific benefits to achieve the objectives of energy conversion with diverse power sources. Several efforts have been made to compare the performance of various configurations [37, 42], with forty-two configurations already identified and catalogued [42]. In general, the optimal configuration depends primarily upon the maximum and minimum sCO_2 temperatures, pressure ratio, type of heat source, energy storage requirements, turn down ratio, and economics.

Cycle configurations must be matched to heat sources in a manner that achieves the highest thermal to electrical conversion efficiency in balance with economic objectives and operational, safety, and emission requirements. There are several configurations of the supercritical Carbon Dioxide Brayton Cycle being explored by DOE and the national laboratories. These include the simple, recompression, and partial cooling cycles. Because of DOE Collaboration goals, the STEP facility is envisioned to be energy input agnostic.

Outlined below are the three Close Brayton Cycle configurations currently considered in the combined ART/Energy Conversion & STEP program.

Simple Closed Brayton Cycle (CBC)

The Simple Closed Brayton Cycle (Figure 7) is, as the name implies, the simplest form of the closed Brayton cycle. The SCBC, or CBC, utilizes the fewest components to achieve the baseline efficiency improvements This cycle, and minor variations of it, are the basic configuration expected for implementation in bottoming cycle applications.

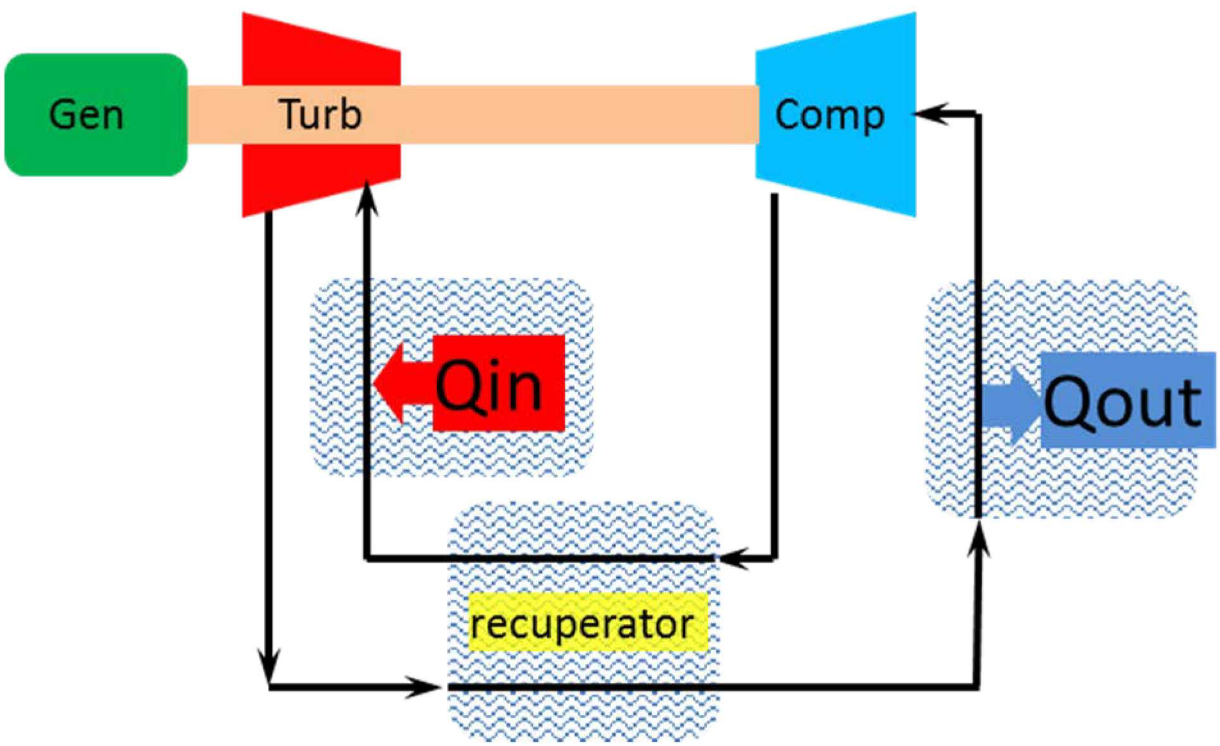


Figure 7: Closed Brayton Cycle

- Also known as "waste heat to power," is a process whereby waste heat from an existing process is used to produce electricity.
- Relatively simple to implement and operate

While efficiency is still an objective, it is in general less important to maximize efficiency compared with installing a simple system to recover energy from a waste heat stream for modest, cost effective electrical output and possibly combined heat and power applications. The primary heat exchanger is designed to transfer the heat from the facility waste heat stream into the sCO_2, and optimally minimizes impact to the primary operations of the facility.

Recompression Closed Brayton Cycle (RCBC)

The Recompression Closed Brayton Cycle (Figure 8) has several design improvements over the simple cycle. It adds an additional stage of compression and recuperation to the SCBC for additional efficiency improvements at the expense of additional hardware and complexity. This cycle configuration is optimized for closed heat sources like concentrated solar and nuclear power where the highest efficiency is obtained with the smallest temperature change to the heat source working fluid. The benefits arise from better recuperation practices. This configuration is the basis for SNL's TA.

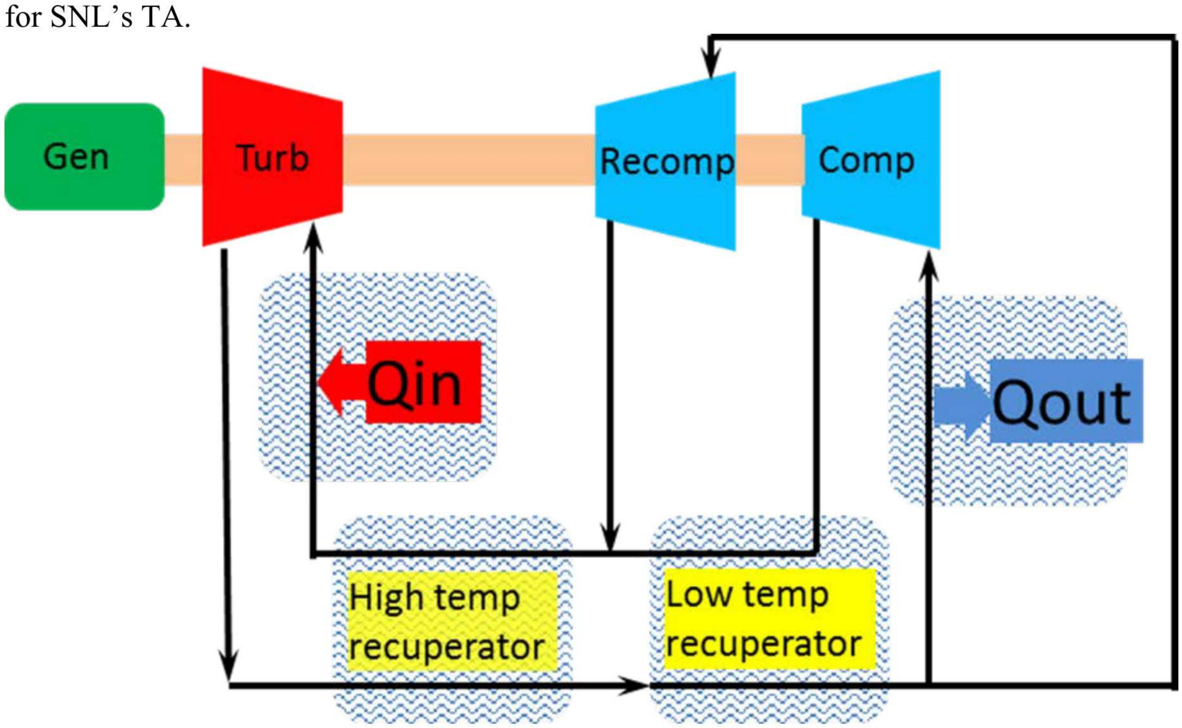


Figure 8: Recompression Closed Brayton Cycle

- Ideally suited to constant temp closed heat sources (NE, CSP)
- Applicable to advanced combustion boilers
- Incumbent to beat: USC/AUSC boilers
- Adaptable for dry cooling
- Cycle to be used for 10 MW sCO_2 pilot plant
- >50% cycle eff. (work out/heat in) possible

First, the specific heat of CO_2 in the vicinity of the critical temperature is a strong function of pressure – a dependency not observed in ideal gases that exist away from the critical point. This dependency strongly affects heat transfer from the warm, low pressure flow from the turbine to the colder, high pressure flow from the compressor. To optimize this heat transfer operation, recuperation is split between two recuperators – a high temperature (HTR) and low temperature recuperator (LTR). The total flow stream on the low-pressure side goes through both recuperators, but only a portion of the total flow stream rejects heat, is compressed, then receives heat in the LTR. The flow split occurs between the LTR low pressure discharge and heat rejection, as is show in the figure below. Flow recombination occurs on the high-pressure side between the LTR and the HTR. The flow heat capacities of the two flow streams in the LTR are much better matched in this way compared to a simple cycle, and coupled with having a second recuperator (HTR), greater heat recuperation is possible, but at the expense of an additional recuperator, compressor, and operational complexity. The great extent of recuperation yields a fluid at the external heat source heat exchanger that is only at a modestly lower temperature than the desired TIT. Therefore, the external heat source can be considered to be a source for 'topping off' the enthalpy of the flow. Also, as a result, the heat source working fluid is only modestly cooled in the heat transfer process. Rejecting this high temperature fluid to the atmosphere would result in very low thermal-to-electric conversion efficiency. For this reason, RCBC's are really only practical for closed heat sources. Efficiency increase relative to the simple cycle, for comparable operating conditions, is on the order of 5 – 8 percentage points, which is significant.

RCBC Partial Cooling Cycle

Energy storage is an important feature, even an economically enabling feature, in some applications, particularly for solar thermal heat sources. The RCBC described above is predicted to be less amenable to these applications since the 'topping off' aspect of the cycle works to the economic detriment of the overall plant efficiency where energy storage mechanisms are applied. That is, the small temperature drop across the power turbine in the RCBC renders sensible heat storage designs less economically efficient than in a cycle that has a larger temperature drop across the turbine. To overcome this challenge, the RCBC Partial Cooling Cycle (Figure 9) incorporates an additional heat rejection and compression component that allows gas expansion in the turbine to a lower pressure and temperature, which consequently allows for better utilization of the energy storage devices. The additional compressor elevates the fluid pressure back to that which is optimal for the remaining heat rejection and compression processes, which is the same as that for the RCBC.

- More efficiently integrates with 2-tank thermal energy storage (TES)
- Expands heat source temp. differential, increases storage energy density and reduces cost of TES.
- Absorbs heat from sCO_2 recuperator exit
- Lowers returning temperature back to the solar receiver.

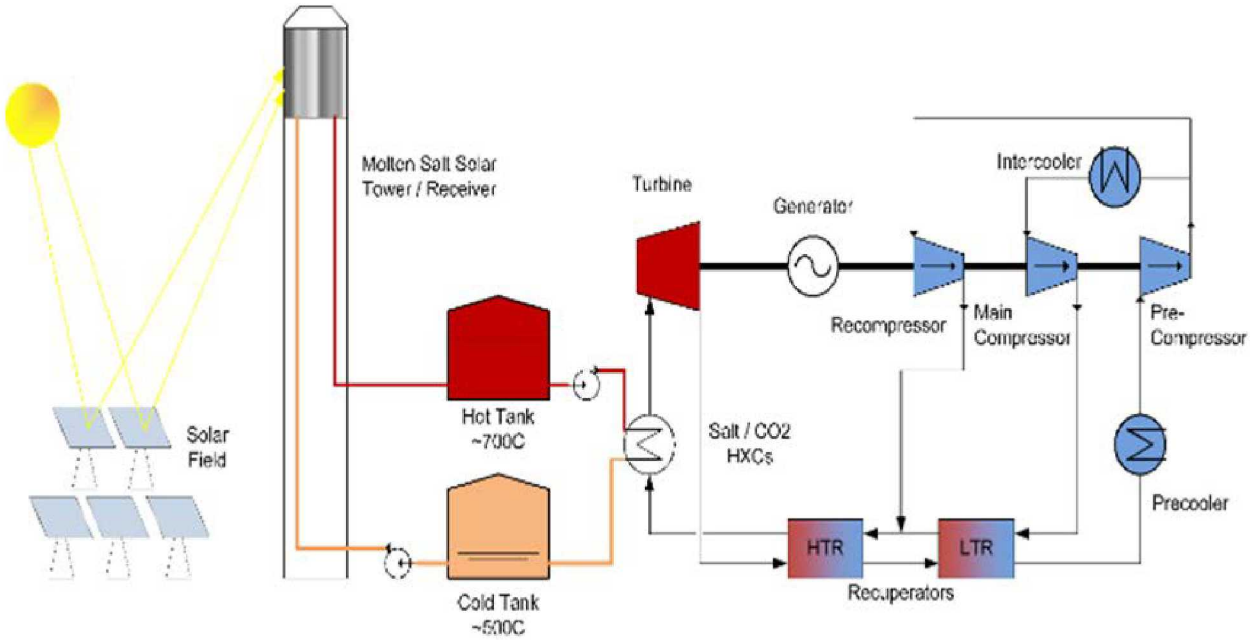


Figure 9: RCBC Partial Cooling Cycle

Cycle design improvements to the base designs

Two commonly cited improvements to the systems described above are turbine reheat and compressor interstage cooling.

The **turbine reheat** method is common in steam plants, and will require additional plumbing and an additional turbine. The sCO_2 is expanded through the high-pressure turbine only to a point somewhat prior to full expansion to low pressure. The intermediate pressure fluid is then routed through a heat source to elevate its temperature to a higher energy state. This reheated flow is then routed to a low-pressure turbine for expansion to the system low pressure. Additional stages of reheat can be added for incremental improvements in efficiency, but at additional cost for the extra turbines and high temperature piping.

- One stage of reheat increases RCBC efficiency by nominally 1 percentage point
- Additional stages of reheat realize diminishing returns due to the limited cumulative pressure ratio across the expansion process

Compressor interstage intercooling reduces compressor work by increasing the density and reducing the compressibility of the working fluid by cooling it during the compression process. This method is implemented by routing the partially compressed flow from the first stage of compression into a cooler to reject heat prior to the subsequent compression stage. The method requires additional plumbing, an additional cooler, and perhaps additional stages of compressors, depending on whether the compressor design was already multistage or not. As with reheat, multiple stages of intercooling are possible, but with diminishing returns. In previous applications of this method, the waste heat has sometimes been used for other applications, such as facility heating as in a combined heat and power design.

- One stage of intercooling increases RCBC efficiency by nominally 1 percentage point
- Additional stages of intercooling realize diminishing returns due to the limited cumulative pressure ratio across the compression process
- Rejected heat can be used for other purposes, such as facility heating.

Because various cycle configurations could contain common components it is necessary to stay abreast of all applications regardless of heat source. SNL will continue to progress the development of RCBC in focus to support the STEP Facility and ART-NE applications.

Component Readiness

The general assessment based on SNL's test article is that TRL for sCO_2 Brayton Cycles at working fluid temperatures less than 550C is approximately TRL 2-3 (i.e. "analytical and experimental critical function and/or characteristic proof of concept"). However higher maximum temperatures have not yet been successfully demonstrated and the TRL on those conditions may be even lower. Overall Technology Readiness Levels could be improved by focusing on advancements at the component level.

Compressors operate with declining power requirements as CO_2 density increases. For common cooling techniques that reduce the fluid to the vicinity of its critical temperature of 88 °F, the compressor is processing a fluid with very dynamic properties, particularly density, which presents challenges for stable operation. Turbines generate greater mass specific power with higher fluid inlet temperatures, which present material challenges, especially with the relatively high mass flow rate and subsequent aerodynamic loading on the turbine blades. To provide the turbine with higher temperatures, the heat input device must also operate at high temperatures. The pressure boundary between the heating fluid and the sCO_2 must provide adequate heat transfer characteristics while maintaining the pressure boundary integrity at the elevated temperatures. The heat rejection device must cool the CO_2 to the required compressor inlet temperature while minimizing pressure drop and thermal transients. The recuperators must provide excellent heat transfer performance across a pressure boundary that maintains integrity between two fluid streams that are at the extremes of the cycle pressure range.

Compressor is a mechanical device that increases the pressure of a gas by reducing its volume. A simple closed Brayton cycle includes a single stream of process fluid, so compression work is accomplished by one or more compressors in series. The recompression cycle operates with two parallel flow paths at the cold end, one of which rejects heat from the cycle and is compressed in the main compressor, and the other flow stream is compressed in the recompressor (hence, the name of the cycle). These parallel flow streams require parallel compression, which introduces an added level of control complexity to maintain proper pressure and flow balance between the two compressors. Compression of CO_2 is well understood, primarily from the gas and oil industry operations. The *sCO_2 RCBC control complication is in the parallel operation*, not the actual process of compression.

Generator converts mechanical energy to electrical energy in the form of alternating current. A commercial RCBC can conceivably use an alternator to provide starting power during power-up and then to convert excess shaft power to electrical power. A more likely scenario will separate these functions into a starting motor and a generator.

Turbine is a rotary mechanical device that extracts energy from a fluid flow and converts it into useful work. A turbine is a turbomachine with at least one moving part called a rotor assembly, which is a shaft or drum with blades attached. Moving fluid acts on the blades so that they move and impart rotational energy to the rotor. This component *needs to be tested for practical applications, which requires a full system test rig* to advance, but its development is expected to advance rapidly with testing.

Primary Heat Exchanger is used to transfer heat between a primary heat source and the power cycle sCO_2 working fluid. The classic example of a heat exchanger is found in an internal combustion engine in which a circulating fluid known as engine coolant flows through radiator coils and air flows past the coils, which cools the coolant and heats the incoming air. In the RCBC application, the primary heat exchanger will be either a fired furnace with tube bundles through which the sCO_2 flows and picks up heat from the burning fuel, or it will be a heat exchanger with the heat source fluid transferring its heat to the sCO_2, as in a nuclear reactor.

Recuperator is a special purpose energy recovery heat exchanger positioned within the supply and exhaust air streams of an air handling system, or in the exhaust gases of an industrial process, in order to recover the waste heat. For the RCBC, the recuperator transfers heat from the exhaust of the turbine into the compressor discharge, prior to applying heat from an external source. On the order of 50% of the heat addition to the compressor discharge is achieved through recuperation, with the external heat source making up the balance.

Heat Rejection is a heat rejection system used to maintain the thermodynamic operating point of the cycle. This technology is very well understood, with a variety of configurations in use since the beginning of heat engine use. SNL's Brayton Lab has demonstrated viable operation of a CBC with both wet and dry heat rejection conditions at compressor inlet.

The focus of component readiness is to retire risks of system components individually, to increase the probability of a successful demo that can demonstrate the potential and viability of the technology at commercial levels. As established on the Metrics section, component readiness is measured according to Technology Readiness Levels. The current TRL Level for components, based on SNL's assessment is shown in Figure 10.

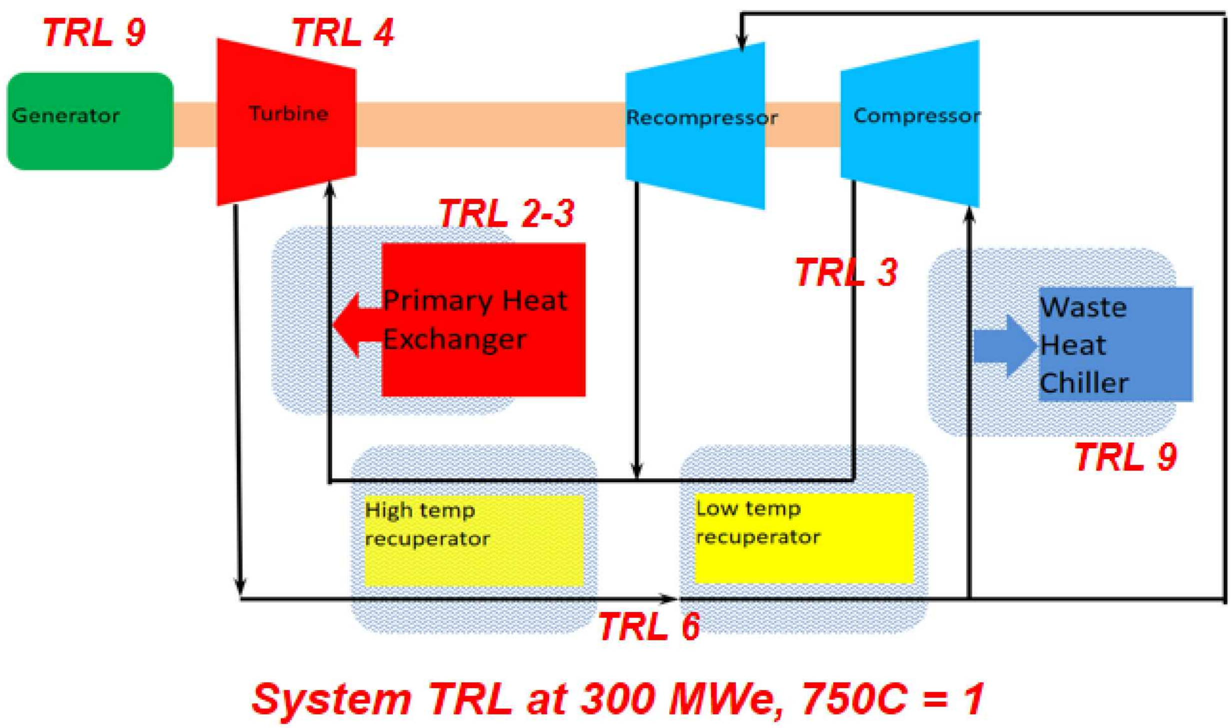


Figure 10: Preliminary Component and System TRL Assessment

To ensure component readiness, all components must be at a **TRL Level high enough to guarantee start-up success** for the chosen demo configuration. The relevant levels are defined below, based on DOE TRL categories Table 5.

TRL 4, Component and/or system validation in laboratory environment, is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.

TRL 5, Laboratory scale, similar system validation in relevant environment. Almost all aspects of test system match commercial system. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application.

TRL 6, Engineering scale, similar (prototypical) system validation in relevant environment. Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system.

Based on these definitions, in order to move from technology development (TRL 4-5) to technology demonstration (TRL 6) high risk technical issues must be addressed (e. g., material concerns for corrosion, seals, bearings, etc.), the application-specific product must be chosen, and its design must be specified so that component configuration and any system integration is relevant.

Working towards a target TRL for common components, and distributing the work among multiple research groups, it will be important to develop a common understanding of these definitions and what constitutes a “relevant environment”, “laboratory” scale and “engineering” scale.

Work is also needed to assess and/or validate the current TRL for common components across the DOE Collaboration for a specific application and to determine what is the TRL threshold that each component must achieve prior to demo. This determination must consider the economic and operational implications of defining and creating a “relevant” environment for the different components.

This is relevant for the assessment of specific components, for which the creation of a test rig is intrinsically the creation of the full system. For those cases, it can be argued that the relevant environment for such components or subsystem should be the demo itself. Therefore, although TRL6 is considered the readiness threshold for technology demonstrations [24], TRL for Pilot readiness of those components may be acceptable at a lower TRL.

While these determinations and agreements are reached, SNL is assuming the DOE definitions for technology readiness, and working towards a TRL6 threshold for technology readiness.

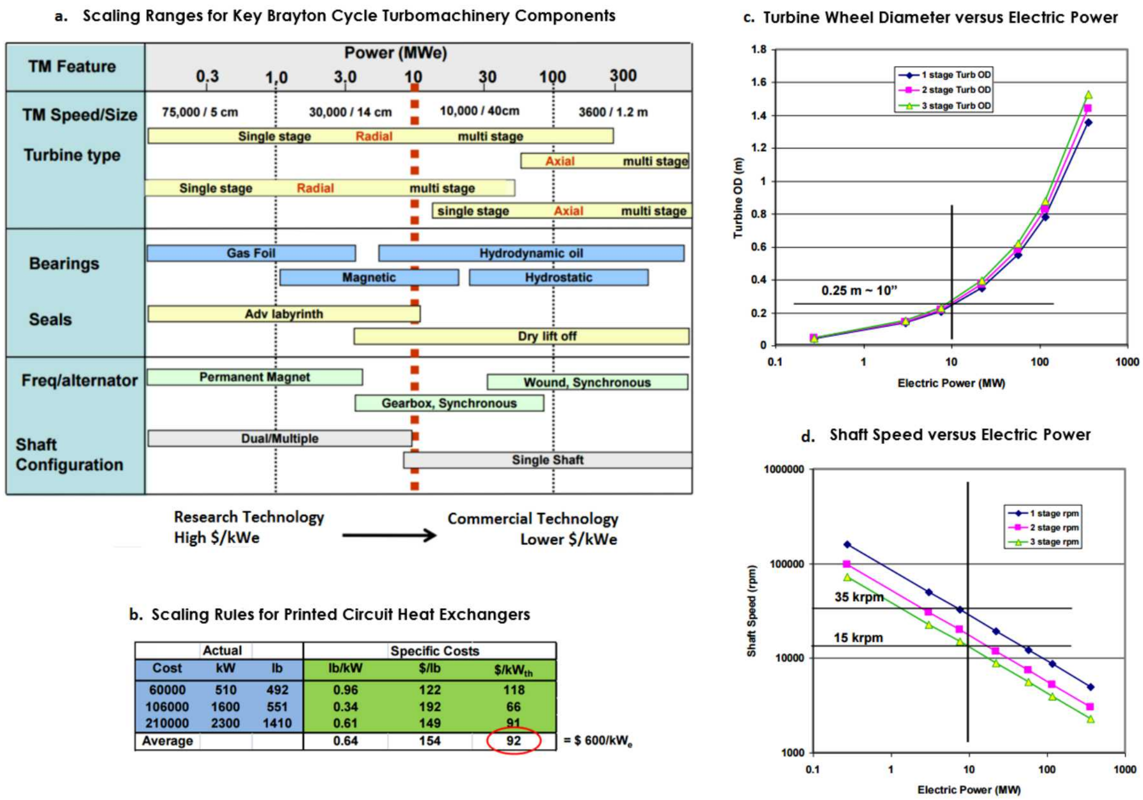
To move forward with Stage 1 Component Readiness, it is necessary to provide guidance regarding the minimum technology readiness level required to confidently support a move from RCBC TA to a demo scale model. Specific characteristics of the system, as explained above, make the definitions DOE TRL Guide [14] open to interpretation, making TRL level decisions relevant based on cost, capabilities, and practicality.

SNL’s preliminary estimate of TRL levels for several sCO_2 applications [23] as the first step in identifying the components that needed further development in the roadmap for NE applications. However, it is important to note a few caveats:

- This table introduces a **preliminary estimate**, created on expert knowledge assessments.
- Work for NE application is based on the **assessment of Sodium SMR’s**
- When work was completed, high-temperature gas reactors and molten-salt reactors were **not within the scope** of the NE program.

Within those limitations, work is still needed to validate the preliminary nature of the TRL estimates, and simultaneously to expand it to the more recent scope of NE potential applications as well as other alternative applications of the DOE Collaboration.

Component readiness must also consider scaling on the system design as it moves from laboratory scale to a 10MWe design for demo, which would allow the use of commercial technologies. Metrics from a scaling study by SNL [43] are summarized on Figure 11, including turbomachinery components (a), printed circuit heat exchangers (b), and turbine (c, d).



Actual			Specific Costs		
Cost	kW	lb	lb/kW	$/lb	$/kW$_{th}$
60000	510	492	0.96	122	118
106000	1600	551	0.34	192	66
210000	2300	1410	0.61	149	91
Average			0.64	154	92 = $ 600/kW$_e$

Figure 11: Scaling Ranges for Key Brayton Cycle Components

Component Development

An RCBC cycle is described by several primary components, primarily the turbomachinery and heat exchanger applications.

- **Turbomachinery**: Formed by the turbine and compressor, the turbomachinery is the most influential portion of the system. The turbomachine as a whole must be operated, researched, and developed to understand thrust and thrust management, address rotordynamics issues, methods to reduce windage losses, and development and proving of internal bearings and seals.
- **Heat exchangers**: Several Brayton cycle components fall within the general category of heat exchanger applications, including the primary heat exchanger, recuperator, and heat rejection. Figure 12 summarizes current technology readiness levels for Heat Exchanger applications, to illustrate where there are R&D needs related to the primary heat exchanger, recuperators (at different temperatures), and heat rejection (both wet and dry). Although there are a lot of common issues between different applications, each one of these boxes represents past, current, and/or future work that still needs to be developed to achieve acceptable TRL for commercialization.

Technology Readiness Levels		from Direct Gas Combustion	from Exhaust Gas	from 3 MPa Helium	from Steam	from floride molten salts	from nitrate molten salts	from liquid sodium	from liquid lead-bismuth	from Heat Transfer Oil	from Combusting Particles	from Inert Solid Particles	from Geothermal Resources	from sunlight	Yet To Be Identified Materials	Advanced Nickel Alloys	Conventional Nickel Alloys	Austenitic Stainless Steels	to Water	to Humidified Air	to Dry Air	TIT / °C
Molten Salt Reactor	NE					3											4-5	6-8	6-8	2	2-4	700 to 850
Sodium Fast Reactor (SFR)	NE							3										6-8	6-8	2	2-4	550
Lead Fast Reactor (LFR)	NE								3								4-5	6-8	6-8	2	2-4	550 to 800
Helium Gas Reactor (GFR, VHTR)	NE			4-5											2	3	4-5	6-8	6-8	2	2-4	700 to 1000
Nuclear Shipboard Propulsion	NE																	6-8	6-8			200 to 300
Direct CSP Tower	EE													4			4-5	6-8	6-8	2	2-4	500 to 1000
CSP Tower with Thermal Storage	EE						8	2		2		4		4			4-5	6-8	6-8	2	2-4	500 to 1000
CSP Trough with Thermal Storage	EE						8			2								6-8	6-8	2	2-4	300 to 600
CSP Dish Generator	EE							2		2				4-5			4-5	6-8			2-4	500 to 1000
Direct Geothermal Plant	GT												2					6-8	6-8	2	2-4	100 to 300
Indirect Geothermal Plant	GT				4-5													6-8	6-8	2	2-4	100 to 300
Direct Natural Gas Combustion	FE	3-5	4												2	3	4-5	6-8	6-8	2	2-4	1100 to 1500
Integrated Gasification Coal	FE	3-5													2	3	4-5	6-8	6-8	2	2-4	1100 to 1500
Pulverized Coal Fluidized Bed	FE										4					3	4-5	6-8	6-8	2	2-4	550 to 900
Waste Heat Recovery	FE		4-5															6-8	6-8	2	2-4	230 to 650
Gas Turbine Bottoming	FE		4-5															6-8	6-8	2	2-4	230 to 650
Municipal waste to energy	FE		4-5															6-8	6-8	2	2-4	230 to 650
10 MWe Pilot	FE		4-5														4-5	6-8	6-8	2	2-4	550 to 700
50 MWe Demonstration	FE		4-5														4-5	6-8	6-8	2	2-4	550 to 700
		N/A	Gas			Liquid					Solid				>750	750	650	550	sCO2 Cooling			
		sCO2 Heating from Various Sources													Recuperation MDMT / °C							

Figure 12: TRL Levels for Heat Exchanger Applications

From a component development point of view, and for dynamic modeling, it is important to understand the performance of components, such as the heat exchanger and recuperator, and their status at different states. Several technical challenges for modeling have already been identified, including modeling the physics of the main compressor, modeling operations near critical point, with scenarios where inlet conditions change, or a system beyond the operating temperature or beyond critical.

Primary Heat Exchanger

Data is needed to validate performance of primary heat exchangers. For the pilot facility, the primary heat exchanger must be capable of producing sCO_2 at 550˚C and higher depending on potential applications. The specific development of the primary heat exchanger may need to be based on the targeted application. As the technology develops, issues have been identified with heat exchangers due to cost for compact printed circuit heat exchangers, possible issues with pressure drop and the impact to overall cycle efficiency, as well as designs for sodium-to-CO_2 heat exchangers.

Additional work is needed to support the development of primary heat exchangers that can withstand rapid start-ups and transients during operation, as well as the identification of low-cost materials in the heat exchanger that can withstand thermal cycling and fatigue.

Printed Circuit Heat Exchangers

Printed circuit heat exchangers (PCHEs) have been essential in the advancement of sCO_2 Brayton cycles due to the need for compact, low-cost, and high-performance recuperative heat exchange.

However, issues remain with PCHEs including their high capital cost and significant uncertainty around mechanical performance and thermal fatigue. Fouling is a constant issue for heat exchangers in all applications and some scope is provided to continue work on this under an IRP. SNL has identified several ways to address these issues through a CRADA partnership with Vacuum Process Engineering (VPE).

Previous activities with VPE have established an "industry community" that made substantial advancements in heat exchanger design and manufacturing. The CRADA process has loosely aligned industry interest in establishing a US-based source for PCHE's. Further development is necessary to form a consortium to support collaboration and provide a coordinated response to technology development.

There is a lack of data to demonstrate that printed heat exchangers are durable above 700C, especially in creep. EPRI is currently trying to model this to understand the limitations.

It is important to look at thin wall components. HTHX have thin wall components, and depending on how thin those components are they might have a significant effect in the system.

Compact diffusion-bonded HXs are monolithic and inherently mechanically stiff. There is a need for thermal shock testing for compact HXs in order to provide design and operational guidelines.

Sodium to sCO_2 Heat Exchangers

There are currently ongoing efforts by ANL to obtain fundamental data required for reliable design of compact sodium-to-CO_2 heat exchangers, in order to successfully deploy the sCO_2 Brayton cycle is to be successfully together with SFRs. These efforts include:

- Sodium-CO_2 interactions under prototypical release conditions of CO_2 inside of compact HXs.
- Timescale for draining of sodium from compact HX sodium channels and sodium retention inside of compact HX sodium channels following deliberate draining of intermediate sodium.
- Stresses resulting from freezing or melting of sodium inadvertently trapped inside of compact HX sodium channels.
- Plugging of sodium channels due to precipitation of oxygen impurities on sodium channel walls at cold end of HX.

These experiments lead to understanding the phenomena in the tests, which is needed to identify a reliable safe value for the minimum sodium channel size will not be known without the data. The incentive for HX designers to minimize the sodium channel size to make the HX more compact and economical must be balanced against the above phenomena.

Recuperators

The objectives of recuperator research is to maximize heat transfer efficiency, minimize pressure drop, ensure even flow distribution, and minimize cost. Challenges on this area include heat transfer performance, pressure containment, materials strength and stability at high temperature, diffusion bonding procedures, oxidation resistance, and fouling effects. Data is needed to validate the performance of recuperators.

Commercially available recuperators are predominantly diffusion bonded monolithic structures which can experience high thermal stresses and unknown thermal fatigue lifetime. Several concepts have been proposed that may feature greater thermal compliance to mitigate thermal stress issues. Given the variety of geometries proposed increased test capabilities are needed to validate the impact of trading off thermal compliance for corrosion lifetime and manufacturability.

The recuperator needs to be tested to retire the risks and validate the many concepts for specific applications, advancing their readiness from TRL3. Furthermore, recuperators account for a substantial portion of the power system cost. The value of this cost needs to be demonstrated for commercialization. Work on this area could validate novel recuperator concepts and facilitate the deployment of high efficiency sCO_2 cycles and accelerate the commercialization of sCO_2 systems.

Because SNL's development platform is highly reconfigurable, high and low temperature recuperators are easily replaced with new designs brought in by external interests for development. This presents an opportunity to engage commercial interests and collaborate, developing common understanding of the needs and capabilities of the commercial applications.

There is a need to optimize recuperator effectiveness, pressure drop, and approach temperature for optimum cycle preference at a low CAPX and COE.

Heat Rejection

The overall efficiency of air coolers also needs to be understood. The heat rejection system for SNL's development platform has been shown to provide dynamic and controllable heat rejection functionality [44]. Conditions that represent both wet and dry cooling can be established within this infrastructure.

The heat rejection system needs to be better understood in preparation for demo. Performance characteristics for both wet and dry cooling conditions are needed to closely control the compressor inlet temperature to minimize the compressor work needed to achieve the required compression ratio.

Although tube-fin heat exchangers are available and affordable, the large field size resulting from their use can impose large pressure drops and increased fluid inventory in an sCO_2 cycle.

Development of compact dry heat rejection systems is necessary for commercialization in order to avoid the cost and complexity of a wet-cooling system and the system trade-offs resulting from using current technology.

There is need to understand the trades for two compressors operating at optimal performance. To support this, there is interested in having the STEP pilot facility operate at higher temperatures, with swappable, independent motor-driven compressors.

There is need to develop and demonstrate advanced cooling control methods for efficient compressor inlet temperatures while considering real-world effects. This requires the development, implementation, and testing of advanced cooling controls.

Turbine

The turbine is the prime mover of the generator. Research on turbine must demonstrate efficient, flexible and reliable operation. The turbine design is a critical variable to the overall cycle design. Turbine test rig requires the loop and access to the flowing working fluid. Since building a turbine test rig essentially requires building the system almost completely, it is expected that the demo system will be the test rig for the turbine. Turbine operating tests must also run a long time to get realistic results.

The design process for turbines is well understood and the conditions brought forth by sCO_2 simply introduce a new working fluid to the turbine design. A turbine designed to accept sCO_2 at specific conditions, as determined by the application, may have a number of issues to be addressed.
To date, tests performed on turbomachinery at laboratory/engineering scale to compare turbine performance and compression performance with predictions show that (for the laboratory scale) the designs work as expected. However, there is still a lot more work to be done to complete this verification process. Echogen has presented some data for verification, but it is proprietary to them. SNL has also presented data, but at only a very limited range of operation.

In CO_2 turbines, the gas remains dense when compared to steam. As the system scales up there may be issues related to density, that affect system performance and must be addressed by design:

- Materials work due to the high temperatures of the process fluid and working with a novel fluid.
- Specific designs for axial bearings, thrust bearings and seals may be required.
- Rotor weight and rotational speed will affect balance, vibration, thrust management and will need to be defined by the turbine design.
- Startup and shutdown and operational procedures will include specific variables to be defined by the turbine manufacturer.

- Methods to determine wear patterns, material evaluation techniques, efficiency calculations, maintenance schedules and operational longevity.
- The operating ranges of the process will need to be defined and checked against the turbine's operating capabilities, including fluid path audit (Steam Path Audit) techniques to determine long-term operability.

Extremely little data exist in the open literature that demonstrate measured turbine performance matches predictions. Therefore, a lot of work needs to be done to verify designs by comparing predicted and measured performance. Pasch et al. published results of such comparisons for a turbine and compressor [45] in a very limited range of conditions, but a great deal more data are necessary to conclusively state that standard turbine design and performance prediction methods apply to sCO_2 specific designs.

Verification efforts at SNL are currently funded using the legacy BNI turbomachinery, which has been limited to date due to turbomachinery and motor controller problems, and also by the transition of the development platform to support testing of the Peregrine turbocompressor. Some verification can be achieved during this testing campaign, but only to a limited extent due to testing over only a very limited range relative to the design of that turbocompressor.

Materials for high temperature applications need to be developed. It is well understood that cycle energy conversion efficiency increases strongly with turbine inlet temperature. Therefore, there will always be a strong drive to operate at higher temperatures.

Prevention of turbine nozzle and blade erosion must also be researched. Experience with the SNL and the KAPL/Bettis test loops have shown erosion on these parts.

Maximizing performance of turbines is also strongly desired. This can be achieved mainly by minimizing flow leakages and other design losses. This can be particularly challenging at lower power levels (~ 1MWe) where smaller turbines commonly have higher leakage rates as a percentage of total flow, simply because running clearances are a larger fraction of overall dimensions as compared with larger machines.

In preparation for a successful test, it is necessary to develop the scientific basis for an sCO_2 system that leads to a 10 MWe system design for construction by industry. As the first application where the turbine has been designed to operate with sCO_2, the specific turbine design must meet a 10 MW up to 550C and 700C RCBC system.

Compressor

The recompression cycle operates with two parallel flow paths at the cold end, one of which rejects heat from the cycle and is compressed in the main compressor, and the other flow stream is compressed in the recompressor (hence, the name of the cycle). These parallel flow streams require parallel compression, which introduces an added level of control complexity to maintain proper pressure and flow balance between the two compressors.

Compression of CO_2 is well understood, primarily from the gas and oil industry operations. The sCO_2 RCBC control complication is in the parallel operation, not the actual process of compression. Testing with the SNL RCBC has consistently demonstrated the high sensitivity of the fluid density and pressure to small perturbations in heat rejection in the flow stream processed by the main compressor. This sensitivity manifests as instabilities in the operation of the two compressors, which can lead to damaging compressor surge events and exceedances of thrust bearing response capacity.

The previous discussion on turbines addressing the dearth of and need for data for turbine performance applies to compressors as well. An additional difficulty for measuring compressor performance is the fact that it operates very close to the critical point, so that uncertainties in temperature measurements can have a dramatically greater effect on calculated performance as compared with turbine measurements. As with turbines, maximizing performance of compressors is also strongly desired.

These are the two primary avenues of research – stable operation of the two compressors and thrusting actions – that would greatly benefit from a robust rig dedicated for this purpose that can safely operate at and beyond normally safe conditions.

There is a need to investigate compressor inlet temperature effects from CO_2 phase distribution and bearing loading. This requires development of unique testing capability for high fidelity CO_2 diagnostics with compressor bearing load measurements.

There is need to operate the main compressor at sub-critical, transcritical, and supercritical conditions, compressor intercooling, turbine reheat, economizers, partial cooling cycles, effects of flow bypasses at various locations.

It will be useful to develop compressor designs that provide acceptable performance over the range of conditions that are possible while operating near the critical point. These conditions could include cavitation, strong perturbations in axial thrust and ways to manage or prevent them, and variations in fluid conditions from more gas-like to more liquid-like that far exceed the variations at the turbine. This issue is peculiar to sCO_2 CBC systems compared with the vast majority of other power cycles in existence. As such, little is understood about operating a compressor in this range of conditions, and therefore much must be learned.

System Scalability

In order to support a fully reliable commercial solution, the sCO_2 cycle must be fully understood. A unique aspect of this work is the scalability to any size Brayton Cycle and broad application to various heat sources.

Since 2007, SNL has created and used a laboratory scale platform to develop sCO_2 Brayton technology. One purpose of the demo is to advance the science by scaling the system to demonstrate commercial viability. Table 8 shows a comparison of the development platform against expected demo characteristics, which illustrates the need for scaling from the TA.

Table 8: Comparison of development platform and demo system characteristics

Sodium Fast Reactor RCBC SCO_2 Brayton Cycle Configuration

		TA	**Pilot Facility**
Objective		Demonstrate sCO_2 feasibility at lab scale	Demonstrate scalability to 300 MWe, Reliability to 8000 hrs., and dispatchable power.
System	Size	250 kWe	10 MWe
	Temperature	550	550
	Configuration	Recompression Closed Brayton Cycle (RCBC)	Recompression Closed Brayton Cycle (RCBC)
Performance	Pressure Ratio	1.8	~3.0
	Operating Speed	75 krpm	10 krpm
	Power Conversion Efficiency	20%	50%
Operational	Processes	Manually controlled	Almost completely automated
	Normally on/Off	Off	Off
	Connected to Grid?	No	No

In addition to scaling the system to commercial levels, it is important to consider scalability to support the interests of the DOE Tech Team. The sCO_2 DOE offices defined a common goal to establish a facility for evaluating power cycle and component performance over a range of operating conditions. While this preliminary roadmap is aligned to NE applications, Table 1 introduced some of the requirements for EERE and FE applications.

The pilot system and facility need to be designed for scalability on two fronts: scale to commercial levels and scale to a range of operating conditions.

Furthermore, there is interest in modularity for the design, which could facilitate the use of the facility over time to test a range of commercial applications and operating conditions. A modular approach would expand on and benefit from the potential for collaboration across the DOE Collaboration.

Based on current knowledge of the technology and system design methods, we assume that it might be possible for a single facility to be reconfigured for multiple conditions, including multiple heat sources, as long as the modularity is incorporated into the design of the facility and the multiple operating conditions are known during the design. This assumption needs to be validated to ensure viability of the model at a reasonable cost.

To explore the viability of this model, Figure 14 shows the operating temperature range and sCO_2 power conversion efficiency for various heat sources [43]. While sCO_2 power conversion operating temperatures are applicable to all heat sources, optimum design requires different approaches to each heat source.

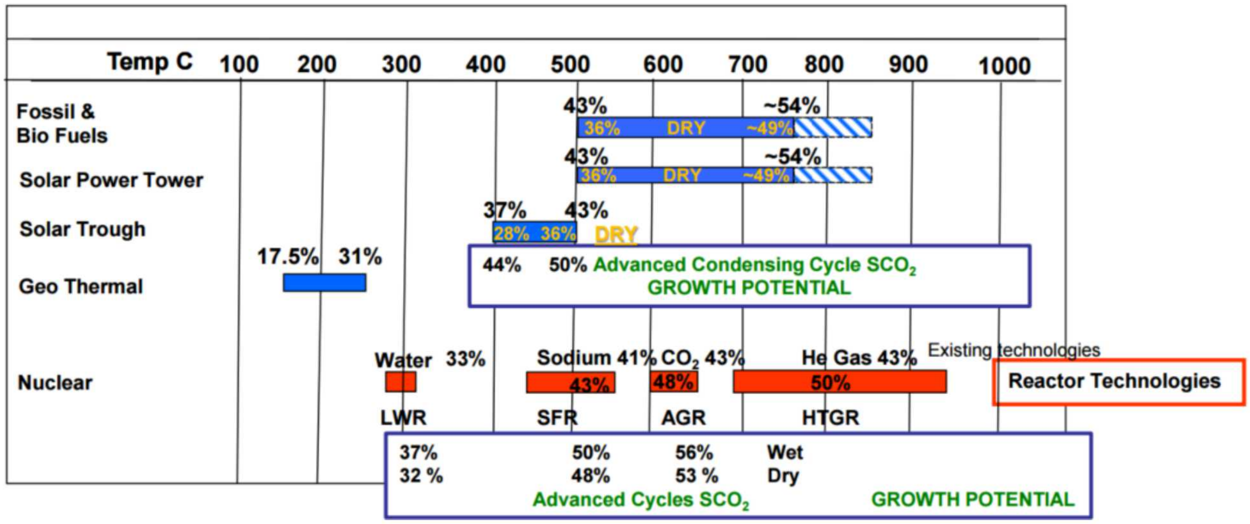


Figure 13: Temperature Range and Efficiency for various Heat Sources [43]

A demo that incorporates concurrent engineering principles into the design could enable modular configurations on both the system and the facility to allow for re-configuration when needed. An effort to establish a concurrent engineering approach to the modular design of demo is needed to explore viability and scope of this model. This type of design will have implications in lifetime of the system components and the operating procedures of the facility, which needs to be understood as part of the design.

System Interfaces

The focus of sub-system integration is to retire risks of interfaces between components, to increase the probability of a successful demonstration that can show viability of the technology at commercial levels. A system is only as strong as the integration between its components, since two perfectly designed components can fail as a system is there are not properly interfaced.

Subsystems integration research is needed for component integration, such as the turbomachinery, Leak detection in Sodium-to-CO_2 Heat Exchangers and Removal of Reaction Products, Radiolytic Decomposition of CO_2, Tritium Removal with sCO_2 Brayton Cycles, Impurities and impurity effects in CO_2 working fluid in sCO_2 Brayton cycles, and sCO_2 inventory management.

A comprehensive inventory of component interfaces, design criteria, and parameter requirements is needed to develop the appropriate test scenarios and plans for system integration. This effort is currently underway at SNL, and targets the identification of system and interface requirements as the component testing progresses.

The effort will benefit greatly from a Model Based Systems Engineering effort to support comprehensive development across all components and variables of the system. SNL is currently working on this effort, but is limited by the available information regarding requirements for multiple applications.

It is necessary to obtain **data** where it is lacking in order to demonstrate the functioning and reliability of components, subsystems, and integrated power converters.

Turbomachinery Integration

Thrust force predictions are known to be extremely uncertain. This appears to be true for sCO_2 cycles as well. The ability to measure these forces in compressors and turbines with all the available techniques (direct force measurements with load cells, static pressure measurements, etc) will help to understand this phenomenon in both transient and steady state conditions.

There is need to verify rotor dynamics predictions associated with operating with a highly dense fluid throughout the full range of operation.

There is need to assess cycle performance as a function of loading. Data are needed to calculate turbine and compressor performance in order to validate performance maps.

Data is needed to firmly understand the magnitude of windage losses in CO_2 turbomachinery. Quantifying turbine performance requires quantifying each type of loss. Test data indicates that heat losses from the turbine area could be a significant contributing loss.

Pipes, Bearings, Seals

Bearings and seals must be developed and tested to show acceptable performance. Based on TRL analysis, work should include the following:

- Advanced labyrinth seals (up to 10 MWe)
- Dry lift-off seals (~3 to 1000 MWe)
- Hole Pattern seals

In general bearings & seals need to be qualified for supercritical CO_2 conditions, to be run at temperatures and pressures that are relevant to the cycles, scaling up to 10 MWe. The focus of the analysis is to guide decisions for the system design based on speed, power, temperature and shaft diameter.

SNL is currently identifying companies to partner with, using the SNL test rig to test their designs.

For turbines and compressors, the dense sCO_2 working fluid coupled with power transients requires a robust thrust management system with proven bearings. Lateral and axial force-management requirements need to be identified Specific designs for axial bearings, thrust bearings and seals may be required.

There is need for reliable, high performance bearings to allow higher turbine inlet Temperature and Pressure.

There is need for research & development of radial and thrust bearings.

There is need for development of low-leakage shaft end seals for turbo expanders.

Pipe and fittings at low temperatures, below 600°C, are already commercially available although with a limited selection of materials. Above 600°C, however, the strength of any piping material currently approved under ASME B31.1 Power Piping code requirements quickly drops, and pipe and fittings are not readily available in relevant sizes. There is need to test pipes and fittings by creating a relevant sCO_2 environment at the scale of pipe and fittings needed. This requires a very large sCO_2 test loop to validate their performance.

Controls

Controlling an RCBC for optimal operation requires a great deal of R&D [46]. Control operations to safely start, stop, and operate at steady state under varying boundary conditions has yet to be explored to any meaningful extent.

A detailed set of instrumentation requirements is necessary to provide information of system state: erosion, leaks, inventory control, detection of impurities, condition monitoring, etc.

Different applications of sCO_2 technologies may have unique optimal control schemes. For example, nuclear, solar, waste heat, topping/bottoming applications, shipboard, etc. R&D teams should develop a control scheme and criteria necessary to support their primary application. The STEP facility power cycle control architecture may be designed to accommodate control scheme testing, allowing for significant changes to test different control strategies.

Development of process controls is needed, and can be expected to range from off-the-shelf technology to highly customized solutions depending on the specified parameters and functions needed to ensure safety and security of the process. NETL has produced a preliminary recommendation that needs to be validated for NE applications.

Other control features, such as effective and efficient way to follow load demand, need to be investigated.

Parallel compression control with two compressors has had very little attention, but is an area of great need, especially as one of the two flow streams in an RCBC undergoes dramatic density change at heat rejection, then also increased pressure loss due to flow through the LTR [46].

System Integration

System Design and Configuration

Systems integration is critical to determine the System TRL for specific applications. Achieving a specific system design for each application is critical to advance system readiness. To that end, it is necessary to define the specific application, configuration and characteristics desired for the application. Table 9 summarizes the design criteria that need to be defined.

Table 9: Primary Design Criteria for System Application

Heat source characteristics	Conversion cycle configuration	Conversion cycle specs	Other significant features
• Temperature (influences materials selection) • Available heat energy (determines max power available for conversion to electricity) • Primary heat source or waste heat stream (influences intermediate heat exchanger (IHX) design.	• Simple • Recompression	• Electrical power output (influences component sizes) • Pressure ratio (influences component sizes and system efficiency) • Max temperature (influences system efficiency and materials selection)	• Dry/wet cooling • Connected to grid? • Normally off/on

Once the demo characteristics are identified, research stakeholders can work to define the common components characteristics, and to establish the preliminary readiness levels of those components so a coordinated effort can be implemented. Then a complete system and facility design can be developed, once the current situation and clear end goal are established.

SNL's current understanding is that NE's focus is the development of a 10MW, 550C, RCBC sCO_2 Brayton cycle system. However, other criteria for NE target goals are yet to be determined.

Table 3 (page 34) summarizes SNL's best understanding of the NE application configuration needs. The SNL team defined this configuration based on the expectation that STEP will approach commercial scales as much as possible and assuming that the

Pilot Facility will initially address a CFB boiler or other coal based “boiler” application of the sCO_2 Brayton Cycle, while NE’s target configuration addresses Sodium Fast Reactors applications.

Meanwhile, research teams can continue to make progress on the system design and integration by supporting the development of sub-systems based on the characteristics that have already been established, and by further working on system operations that may be independent of the specific configuration.

There should be testing in precompression and partial cooling configurations, with repeated startup and shutdown procedures for the different heat sources, including studies on how rapidly these operations can be done.

It needs to be demonstrated that the cycle can be operated and controlled at low heat input levels corresponding to about 1 % nominal thermal power or less, such that the cycle can be utilized for at least some portion of shutdown heat removal.

SNL is working on a systems model to support system TRL assessment and requirements documentation. A comprehensive system assessment needs to be completed for the most likely applications based on revised component TRL assessment and system modeling of their interfaces.

System Modeling

A flexible cycle is needed for commercial applications. This work is supported by continued development of steady state and transient computer models.

New models need to be generated to support the development of operational procedures. Furthermore, because the demo facility will be used primarily for testing and development, data acquisition and validation will be extremely important.

The aim of the models is to develop control strategies for the system. Current models will be used to baseline the performance/operations of the new models that need to be designed.

Steady state: Steady state models are needed to identify the best cycle configuration on the basis of thermodynamics and expected component performance, and to execute performance trade studies among other needs, which is necessary to communicate advancements to the industry community.

Transient: Transient models are useful for identifying the effect of off-normal conditions that put mechanical and thermal stress on the cycle components and transient system responses that have time-relevant effects. Such models are useful when coupling the power cycle in a safety significant system such as a nuclear reactor.

The RCBC Test Article has proven to generate quality data necessary to baseline computer models. More expansive data will be generated in the near term and must be analyzed.

Startup: System modeling for startup conditions are needed.

Extension and validation of ANL's Plant Dynamics Code are needed to provide a dynamic analysis capability for the design and verification of operating and control strategies for sCO_2 Brayton cycle power converters. This includes strategies for cycle control during postulated accidents that need to be included for NPP applications.

There is need to develop dynamic modeling of the RCBC, including process control and operational strategies. There is a need to develop detailed model of the RCBC components and system lifetime models.

SNL's Economic modeling tool is currently operational to investigate economics to predict the Levelized Cost of Electricity (LCOE) for sCO_2 power cycles to determine market feasibility.

Future economics modeling to reduce LCOE requires understanding and application of optimal operating parameters.

There is a need to develop the economics tool for LCOE predictions that are benchmarked with vendor cost estimates. The current model needs to be updated with vendors cost estimates, and piping considerations, but designs for these temperatures are not mature.

Develop economics optimization capabilities for minimum LCOE (not maximum efficiency). Thermodynamic and economics models need to be integrated in an optimization routine.

Uncertainties exist in several areas of costing, such as commercial scale component costs (500 MWe power plant nominally). Estimating component costs for this size system is difficult and uncertain. Depending on component, information is obtained from other studies that include vendor quotes for components, or direct vendor quotes for sCO_2 compressors, cooling systems, etc. Better validated costs from vendors are needed.

It would be beneficial to facilitate a national lab consortium for sCO_2 economics for the sharing of information to improve prediction accuracy. This effort is being started from scratch at SNL, but needs coordination, collaboration, and sizeable time to mature.

Grid

sCO_2 Brayton technologies for commercial applications need to be able to demonstrate the capability to meet requirements that put power on the grid safely, reliably and efficiently. Because of the risk aversion of the industry, the system must be tested and demonstrated before engaging potential utilities at an actual installation.

The role/configuration and capabilities of "the Grid" are going to be/are being re-defined, and will be very different than it has been for the past 100 years. The performance of sCO_2 power generation sources will impact the grid and must be designed and tested with grid resiliency and reliability as priorities. Grid interconnection/interfaces will become very different and all will be influenced by the many different sources "sharing" it and their abilities to be, or not to be, integrated. sCO_2 technologies, if designed and tested appropriately, will have the ability to enable marginal/limited technologies with dispatchability issues.

A micro-grid test bed is needed to support grid qualification of components and market products. SNL has proposed a Kirtland-First initiative, to develop such a grid at the Kirtland Air Force Base (KAFB) and put sCO_2-generated power on the grid. To achieve this endeavor, it is first necessary to scope out the work needed to support the on-the-grid Kirtland First milestone, to include all timeline, activities, policies, and costs of mission. This effort must have the capabilities for an eventual 10MWe grid connection.

Demonstrated and reliable ability to follow rapid load changes is necessary for grid-connection. There is need to test and develop conceivable load following techniques, such as turbine flow bypass, turbine upstream and downstream control valves to manipulate turbine power, etc.

SNL Energy Surety Design Methodology should be expanded to accommodate for these factors in the rapidly changing grid. Power generation and transmission & distribution resources can no longer effectively be designed, tested and commercialized in isolation of each other and expect to be viable.

Policies

Several policies and regulations impact the creation of any commercial facility ready for deployment. These include environmental and occupational safety regulations, building codes and standards, and operational/organizational readiness. The impact of policies, procedures and regulations must be understood and addressed as part of the component readiness stage in order to mitigate the risk of barriers closer to commercialization.

Siting and Licensing

Commercial facilities for utilities will likely need to be built anew, rather than retrofitted. However, utilities have already commented that they are less likely to pursue new technology facilities if the cost or time involved in licensing is not greatly offset by the benefits of the new system [30]. It has also been stated that unless external policies or politics intervene in pushing the adoption of a specific technology, utilities' operators are more likely to revert to their known technology [30].

While siting and licensing procedures and requirements will vary by location, it is important to gain a general understanding of the criteria, expectations, and complexity of the process, and ensure proper value-added is presented by the system based on potential baseline scenarios.

Facilities Design

The design of the facility will be impacted by several codes, standards and requirements by multiple organizations and regulators. SNL completed a Pilot Facility Program Definition effort [18] which identified that in addition to adhering to the local building regulations and the United Building Code (UBC), the facility will need to address:

- Risks associated with the sCO_2 CBC development.
- Personnel issues of system isolation and restricted access to energized areas and rooms under CO_2 fire mitigation.
- Fugitive process fluid release and fire alarming.
- Potential for catastrophic equipment failure.
- The potential for object liberation, pipe failure, or process fluid release should be give more attention due to the use of prototype equipment. The areas that house the turbo machinery should have a blast wall and part liberation studies should be complete to evaluate the danger.
- A comprehensive cathodic protection program to address a potential for corrosion and induced currents generated by process fluids or equipment. A site study will determine the type and locations of various protection techniques.
- Fire and CO_2 monitoring are part of the NFPA 72 code and should be carefully designed. A continuous process monitor with alarming and automatic shutdown that reports to the DCS is available.
- Physical and virtual protections against terrorists, saboteurs, and vandals. The 10 MWe test facility is not considered a critical asset to grid stability. However, these issues should be considered for a 100 MWe base load unit that will be a critical asset.

Utilities have experience in the facilities design process, but the Brayton system and environmental interfaces may bring about new challenges and variables that need to be understood and addressed. It is necessary to develop a comprehensive understanding of the impact that the use of sCO_2 will have on the design of the system, the facility, and the operations.

For STEP, it is necessary for DOE to provide guidance on the extent of coordination that the DOE Tech Team expects during the design and execution of Pilot planning, especially in light of scalability and modularity interests that will significantly impact facility design. DOE Collaboration offices should consider designating a centralized leadership and coordination effort for the initiative. The Preliminary Basic and Applied R&D Plan [16] currently under review introduces this need as a recommendation.

Operations and Maintenance

For the technology to be commercially viable, demonstrations should aim to understand the impact of the new system on the current operation of a mainstream, currently commercially operated system. Operational flexibility encompasses a lot of different things, including how long does it take to start up, shut down, can you 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. With the operational environment that exists today, transient conditions are the norm.

The impact of sCO_2 on system and facility operations must be documented to facilitate safe adoption of the solution. Without this work, a first-of-a-kind operating system will be exposed to high risk operations and potential damage to high-cost components. The RCBC TA can be configured as a scaled version of the anticipated demo. It would then behave similarly to the demo during operational evolutions (startup, shutdown, transient, boundary condition variation changes) and can guide the development of operating procedures. Procedures have already been developed for the nominal operation of the TA [47].

Understanding of operations for rapid heat input/heat rejection transients, whether emergency or standard, need to be investigated to develop control responses. Development of these types of procedures are a fundamental requirement for any grid-connected power cycle. System operation must be analyzed, and operational procedures developed for startup, steady state, transient, shutdown, emergency operations, and emergency shutdown [18].

A comprehensive work system analysis that develops a comparison of operations will help identify disruptive areas that may become detractors for a potential sCO_2 commercial interest. This study must include not only the impact on technology components but rather the impact of the technology on other elements of the work system (organization, environment, personnel, and tasks) including on the roles and responsibilities of personnel.

The operational longevity of the system needs to be understood and preventative maintenance programs should be developed. Although these efforts do require understanding of the full system design, progress should be initiated to document the current status of knowledge on these areas.

There is need to demonstrate, at least at component scale, reliable operation for >1000 hours to gain industry confidence.

Work on the operations has already identified the need for further work in the following areas:

- Operational optimization under various environmental conditions (e.g. heat rejection environment) must also be explored, regarding optimal responses to electric load variations and various unintended perturbations.
- Surge and thrust management issues exist in low flow conditions, which could be caused by two-phased state but further research on this area is needed.
- Need to understand thermal cycling effects on hardware and thermal ramp rate limitations.

- Updating of instrumentation (locations, sensitivity, redundancy, etc.) and control (response time, flow rates, etc.) requirements.
- Repairing or replacing components leads to schedule extensions, increased cost and may challenge the success of the project. The operational plan to support fast and expedient preventive maintenance should be documented, as well as the acquisition of spare parts to maximize the availability of the test system.

Safety

As with any energy facility, safety and integrity of the system, the facility, the environment and personnel is critical. When dealing with new materials and new technologies, safety issues are often unpredictable due to the very nature of experimentation.

Requirements for system operations and maintenance need to be addressed beyond modeling, both for cycle management and facility operations. System level performance and stability while operating near the critical point still require much additional R&D.

Preventive maintenance techniques must be developed to identify degrading components. Understanding how to identify failing parts and components by available instruments must also be researched [48].

Emergency procedures must also be developed, and some aspects of this work will be heat-source and cycle configuration specific.

Other safety requirements need to be considered and addressed during the facility design, construction, and operation. The Environmental Protection Agency (EPA) and the occupational Safety and Health Administration (OSHA) provide both regulation and guidelines that must be considered. Safety research must be embedded in all sCO_2 related materials and technical work to ensure that concerns are documented, including the potential for latent human errors and technical failures that may create incidents at a later stage. Some considerations include fuel and oil spills that will need to be addressed in the environmental application process, impact of seismic activity on the system, and development of safety mechanisms (physical, operational and organizational), impact of flooding on the system, including analysis of flood scenarios during facility design and site selection, and development of safety mechanisms (physical, operational and organizational) to mitigate the risks, occupational safety, and emergency preparedness and emergency response. [18]

Market

It is important to understand the market for which the technology is being developed and deployed. This environment includes the energy supply, demands, commercial interests.

Energy Industry

The proposed demo facility will not be connected to the grid, but the ultimate goal for commercialization will require demonstration and deployment at the grid, contributing to electric additions. The U.S. Energy Information Administration (EIA) reported that projected electric capacity additions are below recent historical levels [49]. Figure 14 and the accompanying text are reported directly from the source.

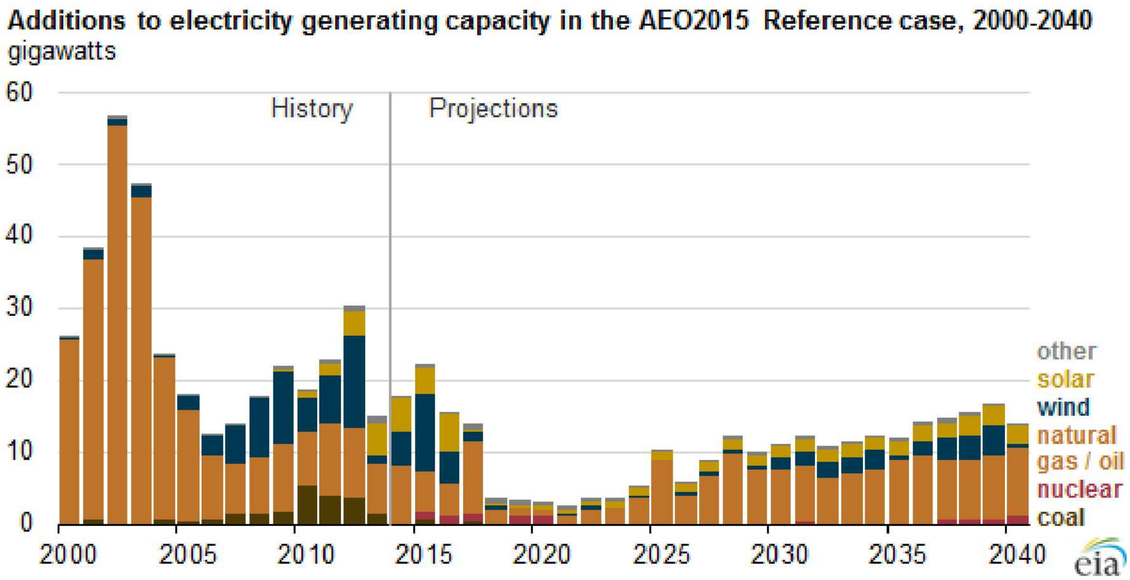


Figure 14: Projected Capacity Additions through 2040 [49]

Natural gas-fired plants account for 58% of the capacity additions through 2040, while renewables provide 38% of the additions, and nuclear 3%. Natural gas-fired combined-cycle plants are relatively inexpensive to build in comparison with new coal, nuclear, or renewable technologies, and are generally more efficient to operate than existing steam plants that may be powered by natural gas, oil, or coal.

Renewable additions are aided in the near term by federal tax credits, and in the longer term by rising natural gas prices and state renewable targets. Nuclear additions total 9 GW, including 6 GW of plants currently under construction and 3 GW projected to come online after 2029. New coal plants total just 1 GW, as high construction costs and uncertainty about future limits on greenhouse gas emissions reduce their competitiveness. Drennen [28] reports that the 15,450 MW of new capacity added in 2015 are distributed as follows:

- 7,902 MW Natural Gas (92% Combined Cycle)
- 3,815 MW Wind
- 3,240 MW Solar

Major commercial providers were Western Electricity Coordinating Council (solar) and ERCOT (natural gas and wind). The largest single addition was by Dominion Resources (three combustion turbines, one steam turbine) at a total cost of $1.1 billion (installed cost: 827 $/kW).

Competitive alternative

Wide scale adoption requires a sCO_2 Brayton systems that is economically competitive. For commercialization, it is necessary to consider the economics of technology development and operation. This may present a challenge if achieving higher efficiencies may require higher temperatures and special materials, which may come at a higher cost. For example, as reported on [5], Pasch demonstrated the tradeoffs between system pressure ratio, component size, wall thickness, efficiency, and operating costs (Figure 6).

For the system to be competitive in the market, it is necessary to design sCO_2 components that are economically feasible and that provide a competitive system lifetime. An economic tool that helps cost Brayton systems components is being refined to help SNL's technical team understand value of various design points.

The utility industry is very risk averse. During sCO_2 community outreach events conducted during 2016 and 2017, utilities have highlighted that they actively evaluate all the technologies to determine what they will put on the grid next, but sCO_2 is in competition with others. Ultimately what matters is the total lifecycle cost of the plant. All things being equal, utilities will always choose the more mature technology. Utilities are looking for efficiency improvements, but demonstrated reliability is the key to adoption. Operations will always prefer to go back to where their comfort is.

Utilities do not seem interested in being the first to market, but rather to see demonstrated benefits in efficiency and cost.

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. 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.

Integrating any sCO_2 system to the regulated environment, where utilities need to recoup those costs from customers at the utility regulatory commissions in various states, will be a challenge. It might be more open on the most unregulated states. Looking at distributed generation might be an easier application, especially in places where there are no reasonable choices because of the regulatory environment. (Ex: 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. Until the other areas come down in price, or the need is there, and operational requirements and costs are met, this is the market

It is necessary to assess and stay abreast of regulatory and political environment for conditions that may trigger sCO_2 adoption.

Commercial Interests

Integrating commercial interests and research partners into the program development plan is key to the acceleration of readiness for Brayton-based subsystems and applications of the technology. Figure 15 outlines the R&D path towards a commercial RCBC application and highlights the potential for collaboration in the development of Brayton-based subsystems that simultaneously support the path towards fulfilling the mission and develop commercial subsystem capabilities.

Commercial interests and research partners may accelerate the R&D process working together in areas where both DOE and the commercial entity benefit on a common goal. Once that common goal is achieved, each entity would progress towards their individual path having achieved accelerated results, optimized resources, and successful collaboration.

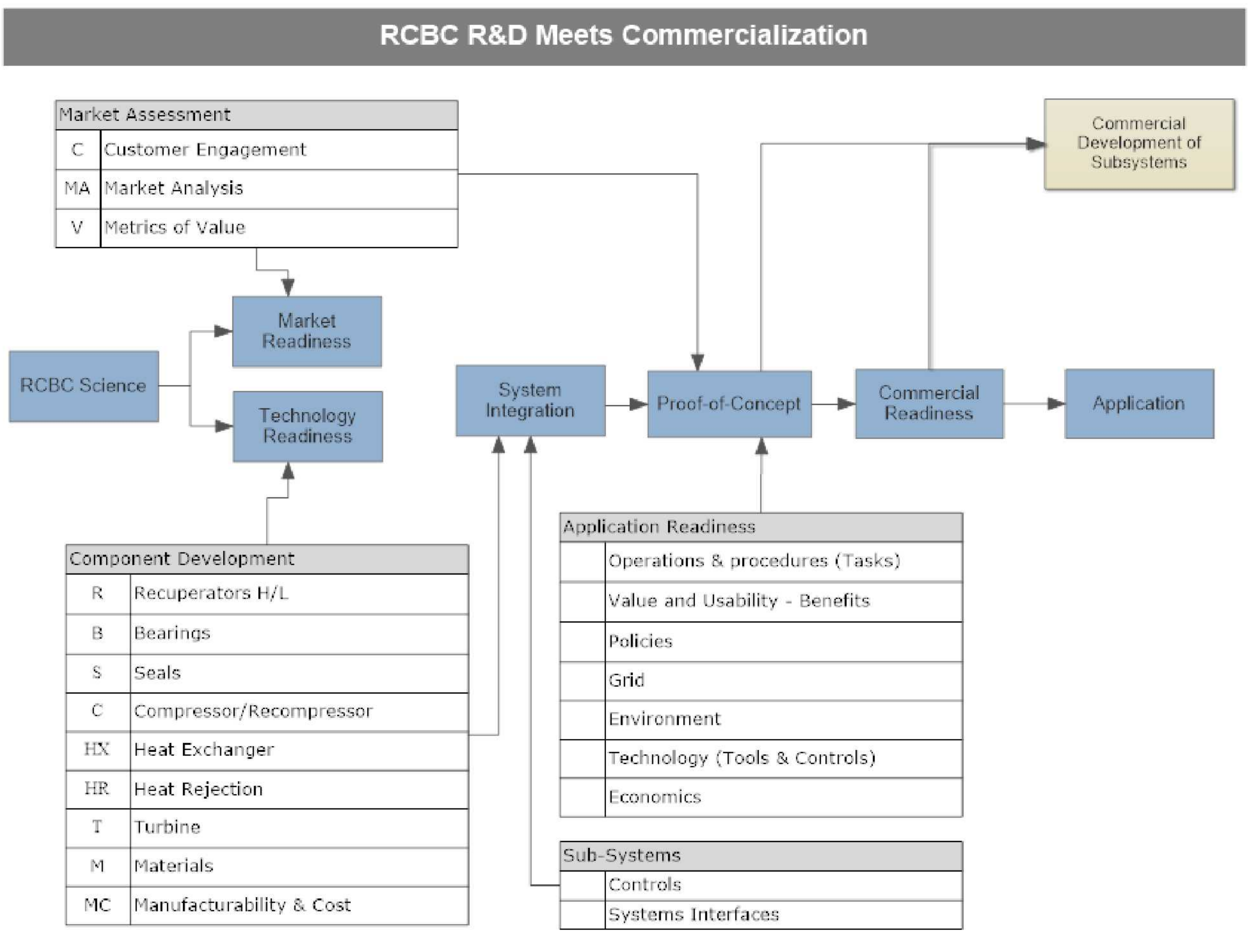


Figure 15: R&D Path Towards Commercial sCO_2 Brayton Applications.

Appendix A: Summary of Potential Commercial Partners reviews relevant commercial interests that have been identified, categorized on three main areas: sCO_2 Brayton research environment, suppliers and applications.

sCO_2 Research Environment

Research on sCO_2 Brayton cycles has generally centered around a few key institutions based on their fabrication and operation of sCO_2 test facilities, with numerous other research programs dove-tailed into the efforts of these institutions to address specific scientific, component, or sub-system technology areas.

In addition, the ARPAe office is interested in High Efficiency High Temperature modular power with a vision towards component and system development for High Temperature High Efficiency Modular Power (<1 MW) that utilizes innovative designs, materials, and manufacturing techniques. This interest is aligned in many areas with the sCO_2 offices path towards sCO_2 power cycles development. It proposes that the potential first users of such systems are in Biomass-to-electricity, Oil and Gas, Marine, Pharmaceuticals, Power Generation, and Industrial (such as transportation, cement, air separation, and process industries.)

Universities that currently partner with the DOE-NE offices and National Laboratories in support of sCO_2 R&D are listed in Table 10.

Table 10: University Partners

	Project
Purdue University	- NEUP – to develop data for nuclear code qualification of diffusion-bonded heat exchangers - IRP – to develop a draft code case for nuclear code qualification of diffusion-bonded heat exchangers and guidelines for high-reliability operation.
North Carolina State University (NCSU)	- IRP – Develop a draft code case for nuclear code qualification of diffusion-bonded heat exchangers and guidelines for high-reliability operation.
Oregon State University	- IRP – to develop a draft code case for nuclear code qualification of diffusion-bonded heat exchangers and guidelines for high-reliability operation.
University of Idaho	- IRP – Develop a draft code case for nuclear code qualification of diffusion-bonded heat exchangers and guidelines for high-reliability operation.
University of Michigan	- IRP – Develop a draft code case for nuclear code qualification of diffusion-bonded heat exchangers and guidelines for high-reliability operation. - NEUP – Technical point of contact for compact heat exchanger research.
University of New Mexico	- NEUP – Develop and demonstrate twisted-tube heat exchangers for Fluoride salt-cooled High-temperature Reactor (FHR) applications.
University of Wisconsin	- NEUP – to develop data for nuclear code qualification of diffusion-bonded heat exchangers. - IRP – to develop a draft code case for nuclear code qualification of diffusion-bonded heat exchangers and guidelines for high-reliability operation. - NEUP – Technical point of contact for compact heat exchanger research.

In addition, international interests in sCO_2 research have been noted by both Tokyo Institute of Technology and Korean Atomic Energy Research Institute (KAERI), among others. For the purposes of this roadmap, SNL believes it is important to stay abreast of sCO_2 technologies development globally, but has no intention of engaging international partnerships at this point. The intent is to keep the technology a US owned and constructed technology. Designs are considered Export Controlled – Commercial.

Commercial Partners

In the U.S., there are several companies pushing early commercialization, ranging from Net Power (fossil fuel generation with carbon sequestration using the Allam cycle), Echogen (waste heat applications), and Peregrine Turbine Technologies (direct fired, air combustible fuels in simple cycle via gas turbine). While each of these companies is moving forward with commercialization, they are facing typical hurdles confronting new technologies, including securing investor financing for an unproven technology. The sCO_2 CBC represents a high technology risk to the commercial power industry. While there are technical risks associated with this technology, there is a perceived risk that must be addressed and understood by industry and national laboratories.

Potential customers and investors want to see demonstration facilities and assurances that the technology can deliver on its potential. SNL predicts that near-term markets such as waste heat recovery and distributed energy generation for a frail power grid will generate the "market pull" warranting the advancement of the technology readiness levels of the components and cycles, but industry validation is needed.

SNL's preliminary SDD [50] pointed to a need for US government investment in pre-commercialization activities for the sCO_2 cycle. Reaching out and engaging industry through the FBO/CRADA process creates industry interest by providing a pathway to address technical risk, provides a better understanding of industry needs and most importantly, consolidate information at the national laboratory advancing the development process of energy conversion systems.

The engagement of suppliers and other stakeholders in the process is a key stage in expediting technology commercialization. The creation of an industry consortia would facilitate the coordination of sCO_2 Brayton R&D development efforts and response in a way that maximizes the strengths and interests of stakeholders. Appendix A: Summary of Potential Commercial Partners provides a list of all the commercial stakeholders that have been identified to the date of this report.

A market assessment must include regular monitoring checkpoints on the market to ensure that both component and ultimately system design remain competitive with the latest market information. It is also expected that stakeholders from the industry who actively participate on the Brayton effort will be able to raise market change concerns in a timely manner. The following suppliers, including private research organizations, have been engaged by and working with the DOE offices and National Laboratories network

Customers

Potential customers that have been identified are listed in Appendix A: Summary of Potential Commercial Partners and Customers, and summarized in Table 11.

Table 11: Potential Customers

Customers	Field
Air Force Research Lab/ Air Force Space Command/ Kirtland Air Force Base	Government
ARMY Corp of Engineers	Government
Army Materiel Command	Government
Bonneville Power Administration	Utilities
Duke Energy	Utilities
Energy Huntsville	Utilities
Energy Northwest	Utilities
Loring Development Authority	Industry
Naval Nuclear Laboratory	Government
NAVSEA	Government
Southern Company	Utilities
Tristate Generation	Utilities

The potential end customers for the different cycles have not expressed their criteria for technology adoption. The next and critical step in the market analysis is to establish contact with the customers to engage them in the conversation.

While all new technologies face challenges in the path to commercialization, the electricity sector is distinctively risk averse [28]. The System Design Description (SDD) for Sandia National Laboratories Supercritical Carbon Dioxide Closed Brayton Cycle states that "Any new technology, whether it is a consumer electronic product or an advanced energy generation source, needs to capture at 10 – 15% of the potential market before it can aggressively capture market share. Helping an industry convince potential early adopters requires technology demonstration and validation." [50]

With this in mind, it is important to develop a comprehensive commercialization plan and define strategies to communicate the benefits of Brayton and clearly articulate what the technology can offer that differentiates it from the alternatives. These include higher efficiency, a smaller footprint, potential of dry cooling, and reductions in key greenhouse gases. Transferring this response into commercial benefits will be important when communicating with business and community stakeholders.

Past, Present and Future Efforts

This section summarizes the activities that have been completed, are in progress, and have been proposed for continued development of the sCO_2 Brayton technology in preparation for demo testing.

Program History

SNL has been working on the development of sCO_2 Brayton technology since 2007, with the development of the test loop, controls, testing and model validation. Since then, projects have been focused on 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, amongst others. A series of projects that support sCO_2 technology are currently in progress. Figure 17 summarizes the timeline for sCO_2 previous and current program development at SNL, including efforts up to last Fiscal Year FY2017. The projects are further documented on Appendix B: Projects History for clarity of scope, objectives and achievements.

A comprehensive Systems Engineering model [20] has been established to support and monitor the progress of the EC and STEP effort through the multiple collaborations, ensuring that the work is not duplicated and that progress is achieved towards the primary ART-NE and STEP missions. The ART-NE Systems Engineering *Reinforced V Model* (Figure 16) incorporates the principles of project management, requirements management for testing and validation, concurrent engineering, and balance modeling into a comprehensive program management approach to organize and validate R&D efforts and milestones.

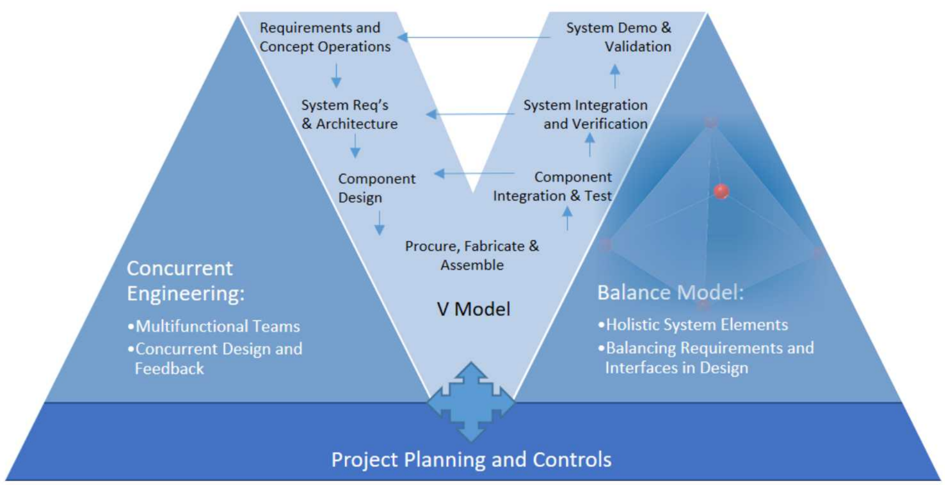


Figure 16: SNL Energy Conversion Reinforced V Model

Roadmap

Guided by the systems engineering model, the roadmap shown on Figure 18 illustrates how the three R&D lanes come together to support on-the grid endurance and reliability demonstrations, the STEP 10MWe Pilot Facility Demonstration, and various ready-to-market products available for commercial applications.

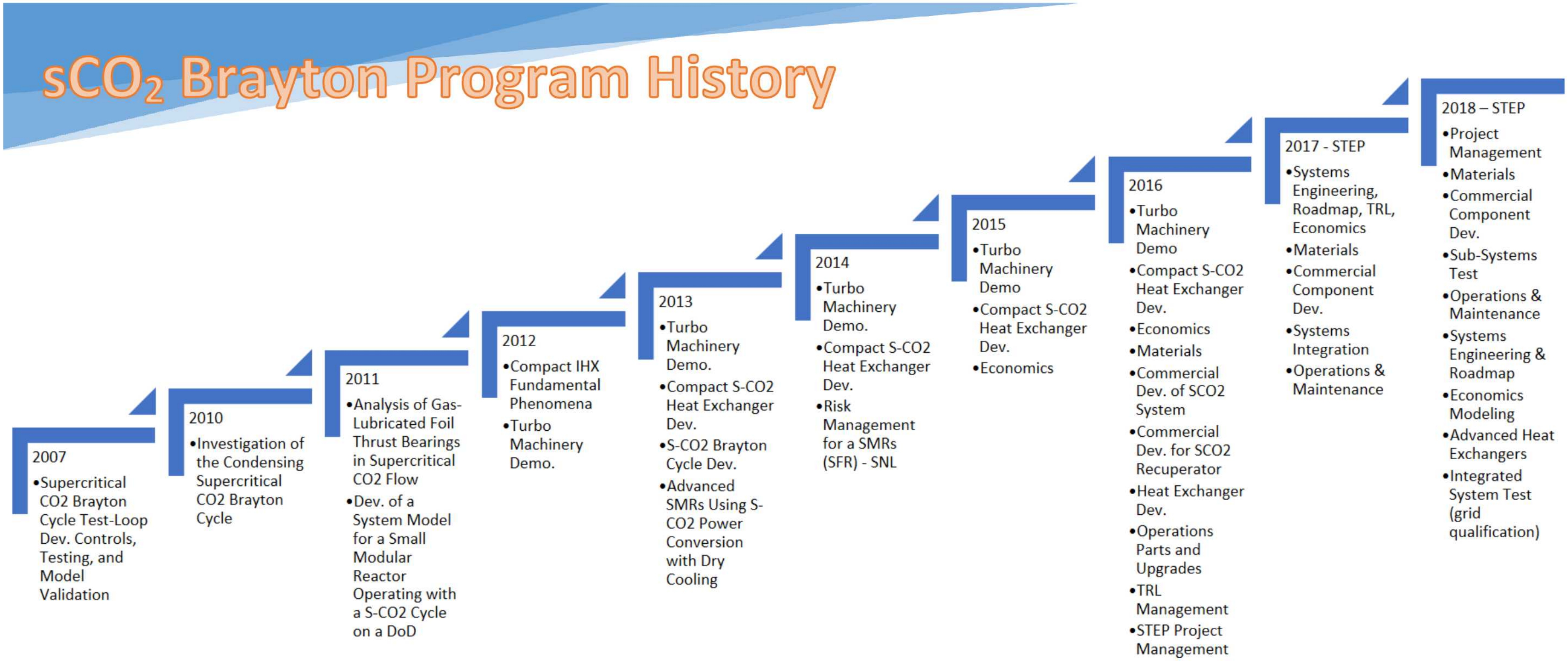


Figure 17: Projects History Timeline

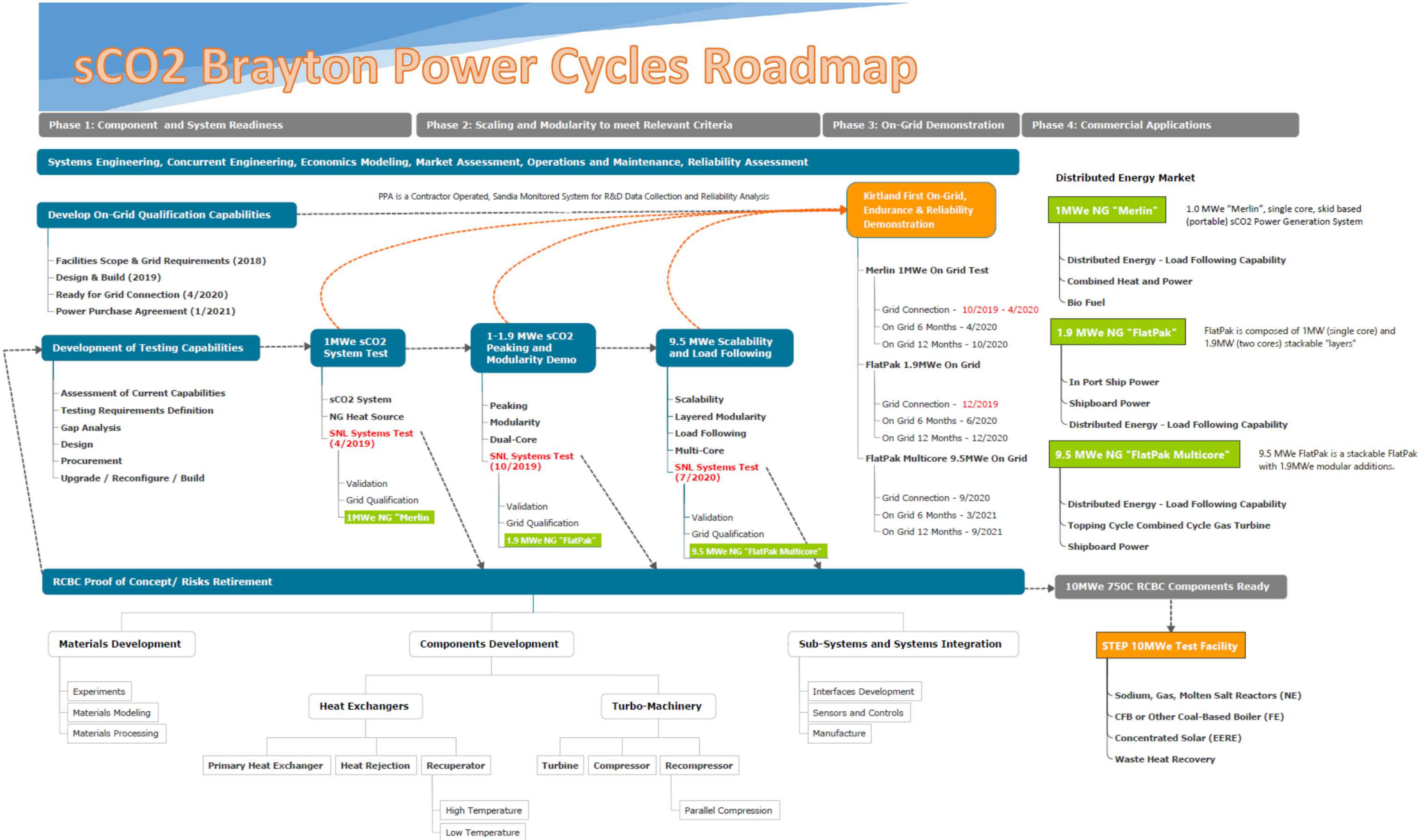


Figure 18: Roadmap to sCO2 Power Cycles Commercialization

Path Forward

Focus Areas

The development needs identified during the situation analysis and leading to the roadmap are categorized in 9 R&D focus areas (Figure 19).

1. Management and Integration

- Identification, analysis and support of program functions for succesful sCO2 program planning and project management.
- Development, advancement, and coordination of punblic-private collaborations.

2. sCO2 Materials Development

- Identification/ validation of materials that will satisfy the performance requirements for each component in a commercial scale system, using commercial purity grade sCO2.

3. Component Development

- Facilitate commercialization of domestic heat exchanger, Turbomachinery, Cycle Development, Bearings and Seals technology and other components and systems.

4. Sub-System Test

- Facilitate the integration of materials, components and programmatic research into commercially viable Brayton system applications, including prototyping, commissioning and piloting operations.

5. Development Platform Operations and Maintenance

- Upgrade and maintain the Development Platform (DP) with new subsystems and upgraded infrstructure, including spare parts inventory to ensure continued DP operational readiness.

6. Systems Engineering

- Systems and concurrent engineering, systems modeling, requirements testing and validation, TRL and MRL management, system metrics, technology roadmapping.

7. Economics

- Economics modeling for component, system, and lifecycle. Market assessment for successful commercialization.

8. Advanced sCO2 Development

- Advanced Development of Brayton Engines exploiting the benefits of Supercritical Fluids, Compact Heat Exchangers, and associated cycle variations with a goal of clean coal power production.

9. Integrated System Test

- Demonstrate viability for sCO2 Power System validation for grid connection. Must support eventual 10MWe grid connection.

Figure 19: Programmatic R&D Focus Areas

2018-2020 Action Plan

The immediate scope and timeline for each focus area is outlined in Table 12. For this purpose, the goal is a *mature energy conversion system for nuclear reactors that will be deployed as early as 2030.* With interim goals of *power on the grid by 2020* and *an assembled RCBC for test at the STEP pilot facility by 2023.*

Table 12: SNL 2018-2020 High Level Action Plan

WP	Objective	FY18	FY19	FY20
1. *Project Management*	Planning, Procurement, Business development with multiple DOE Offices and Industrial Partners.	Business operations, collaboration management.	Business operations. Engagement with Kirtland negotiating PPA	Business operations. Engagement with Kirtland.
2. *Materials*	Characterization for 40 years of reliability on a reactor.	Identification of materials used for Merlin, begin studies on corrosion and durability.	Predictions of durability of materials and identification of maintenance needs.	Operational monitoring of materials in Merlin to and identify lifetime issues.
3. *Components*	Reliable, durable operation for 90% capacity factor operation on grid	Identify Merlin components, perform FMEA, design test cell, component test plan on Merlin rig.	Operational testing of Merlin and component evaluation. Begin grid qualification testing.	Complete Merlin Grid Qualification and install at Operations site. Component qualification analysis at 1 MWe. Prepare for modular system demonstration.
4. *Sub-System Test*	Technology Identification, test and evaluation of system components leading to RCBC testing in 2023 at 10 MWe	Seals, Bearing, HX testing and qualification for Merlin, compressor testing, preparation for turbine testing.	Advance seals and bearings R&D, supporting durability, maintainability.	Prepare component designs for RCBC testing at 10 MWe.
5. *Operations and Maintenance*	Upgrades, maintenance, and operations of SNL capabilities	Construction of Test Cell Operations and maintenance of SNL capabilities.	Qualification Testing support. Infrastructure construction. Operations and maintenance of SNL capabilities.	Ready for on-grid operations. Operations and maintenance of SNL capabilities.

WP	Objective	FY18	FY19	FY20
6. *Systems Engineering*	Define the component requirements to achieve a RCBC integrated with an advanced reactor	Comprehensive R&D plan for coordination and collaboration in STEP Facility target. Establish Concurrent Engineering team for requirements definition and validation, grid qualification, and quality planning.	Develop System test criteria and test plans for grid qualification and establish TRL and MRL levels for RCBC components.	Testing and validation of grid connection. Document impact of sCO2 subsystems on Work System for Staffing, Safety and Operation/Mainten ance considerations.
7. *Economics*	Approach to achieve <1000$/KWe overnight cost	Engage industry to drive down costs on components and couple model. to grid compatability	Model PPA for Merlin at 1 MWe, market analysis for application to nuclear, fossil, solar, biopower, combined heat and power.	SMART Grid Value Proposition. Viabili ty of Energy Storage.
8. *Heat Exchangers*	Primary and Recuperator technology for the lifetime of the plant	Evaluate PTT technology as candidate technology for RCBC and Solar applications. FMEA Analysis	Evaluation of PTT heat exchangers performance and durability.	Selection and design of components for nuclear application.
9. *Integrated system Test*	1. Integrated system testing using fossil fuel heat source for power generation at 1 MWe supporting future 10 MWe Demonstration. 2. Coupling a "Duck Curve" Power demand with a baseload reactor.	Assessment, Planning, Timeline, Business contacts and engagement. Design of q MWe Test Cell, System Studies, Infrastructure development.	Develop Infrastructure, qualification of grid connection. Commissioning of Test Cell and begin Merlin Testing.	Connect to Grid. Merlin on-grid test integration and grid qualification complete.

Collaborative Partnerships

The path to the development of commercial Brayton applications calls for collaboration with industry partners. These partners share a common goal of development of the technology along the path towards their longer-term individual goals. As opportunities to expedite the RD&D process are presented, new collaborations may be created. 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. A preliminary outline of potential partners is shown on Figure 20.

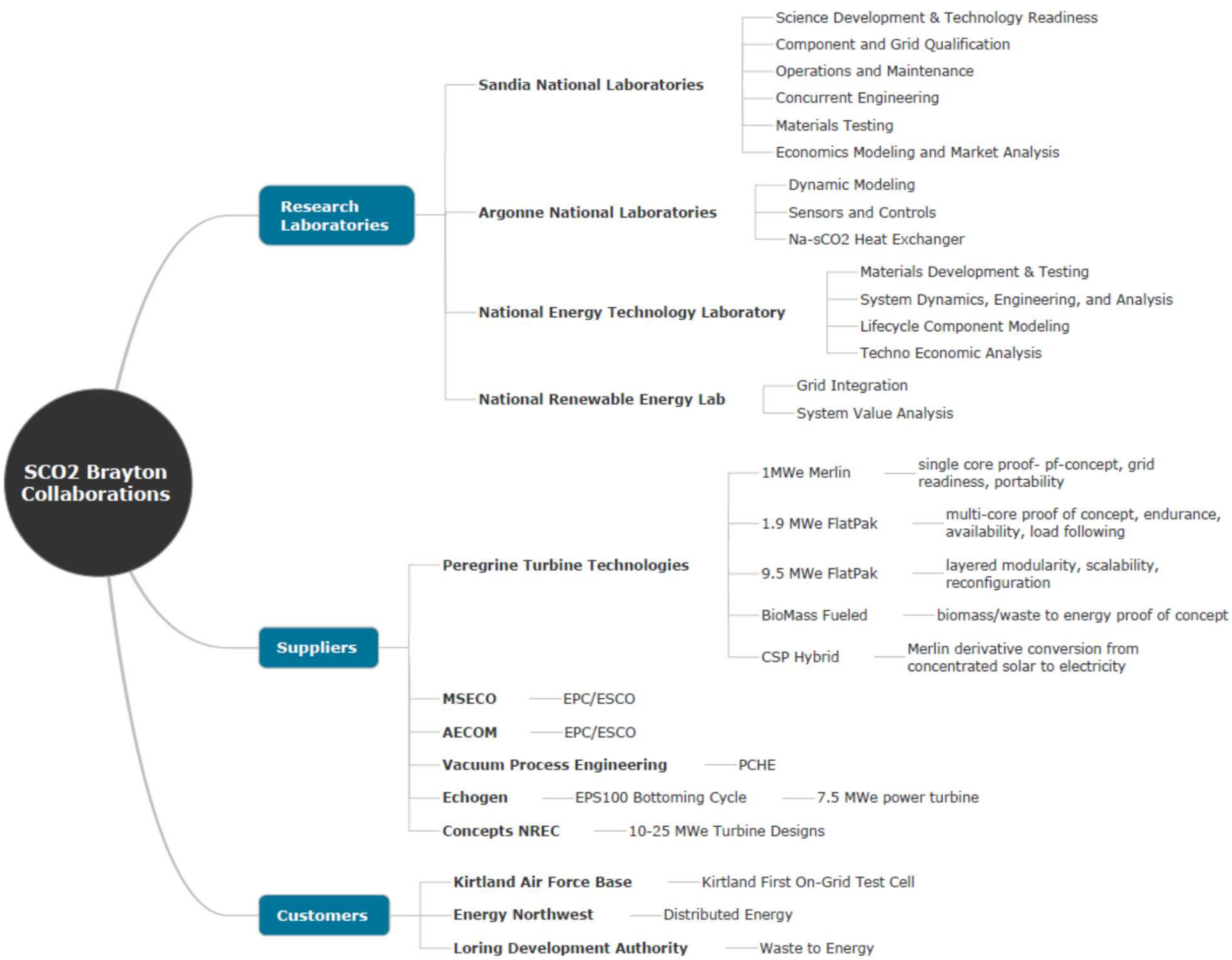


Figure 20: Commercial Partners Network

Collaborative Opportunities Currently Proposed

The following activities support development of the sCO_2 technology building up to the nuclear reactor application requirements.

<u>*Merlin* Proposals to DOE-NE</u>

Three proposals were prepared for NE outlining incorporation of a sCO_2 Power Cycle at 1 MWe capability. Two of the proposals were focused on a Concentrated Solar Heat Source and One Proposal for demonstration of grid compatibility of the Peregrine Turbine Technologies (PTT)[11] *Merlin* at 1MWe and linking it to the SNL grid.

[11] SNL has been collaborating with Peregrine Turbine Technologies (PTT) on the development and testing of sCO2 Brayton technologies that will likely have early applications for distributed energy and waste heat recovery markets.

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 sCO2 power conversion for DoD applications

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

ARPAe Concepts for He Reactor with sCO2 Power Conversion with General Atomics

An 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.

ARPAe Concept for load following sCO2 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.

Kirtland 1st initiative

A concept paper was developed to couple a 1 MWe sCO_2 power cycle to a SMART microgrid on Kirtland Air Force Base with integrated renewables as a demonstration of DoD base energy resiliency.

Case Study for collaborative work supporting multiple R&D lanes

The products and uses arising from these activities are spinoffs of the roadmap (which might be funded by a different program) while the main target continues to be advanced reactors for ART-NE. For example,

For example, SNL has been collaborating with Peregrine Turbine Technologies (PTT) on their novel approach for developing a commercially available technology. PTT is working towards the development of the *Merlin*, a 1 MWe sCO2 power cycle at 750C. While the cycle itself is proprietary, it uses RCBC relevant components at 750C, supporting the advancement of components and the temperature increase needed for NE reactor applications. *Merlin* also builds up to the development of the *FlatPak*, which provides scalability, modularity, and load-following capabilities, all of which have been identified as requirements for commercial applications. While *Merlin* components support the development of the 1MWe RCBC needed to adapt to reactors (NE goal), it functions as a reactor simulator on a micro grid at 1MWe, *FlatPak* is a modular spin-off that supports scalable ready-to-market commercial applications.

The partnership with PTT supports commercial readiness for a variety of products and applications in an expedited timeline. The progression of the PTT partnership resulting in desired ART-NE and STEP capabilities includes:

- *1.0 MWe "Merlin", single core, skid based (portable) sCO_2 Power Generation System:* Demonstration of sCO_2 Power Conversion operating on air combustible fuels (specifically NG). Accomplishes 1) Validation of Proof of Concept, 2) Grid Readiness, and 3) Endurance/Availability.
- *1.9MWe "FlatPak" multi-core, sCO_2 Power Generation System:* Demonstration of Dual Core System Capability: Accomplishes 1) Validation of Multi-core Concept, 2) Grid Readiness, 3) Endurance/Availability, 4) Demonstrate "dual core load-following" capability.
- *9.5 MWe "FlatPak" multicore, sCO_2 Power Generation System:* Demonstration of Multi-core, Layered Modularity. Accomplishes 1) Validation of Grid Readiness, 2) Endurance/availability, 3) Scalability of multi-core, layered system configuration, 4) Demonstration of multicore load following capability.
- *1.0 MWe Biomass Fueled, (single core, skid based portable) sCO_2 Power Generation System:* Demonstration of sCO_2 Power Conversion operating on air combustible fuels (specifically Kirtland or SNL generated biomass/waste-to-energy). Accomplishes 1) Validation of Proof of Concept, 2) Grid Readiness, 3) Endurance/Availability, 4) Biomass efficiency @ 2X current best available steam technology.
- *1.0 MWe CSP Hybrid (Merlin derivative) sCO_2 Power Conversion System:* Demonstration of sCO_2 conversion of concentrated solar to electricity and dispatchability.

To support grid qualification, a proposal is in place to develop the Kirtland First initiative, coupling a 1 MWe sCO_2 power cycle (*Merlin*) to a SMART microgrid on Kirtland Air Force Base, with integrated renewables as a demonstration of DoD base energy resiliency. Once qualified through the Kirtland First effort, *Merlin* and *FlatPak*, would be commercially relevant to utilities that need a strong and reliable power portfolio.

Furthermore, since *FlatPak* is a layered system of 1.0MW or 1.9 MWe (multi-core) layers, it achieves a 19.0 MWe from 10 layers of 1.9 MWe (Figure 21). 70% to 80% of Near Term Market Value for sCO2 Power Generation Systems is in 1 MWe to 20 MWe Systems [51]. This meets the initial commercial market targeted for applications requiring distributed energy, such as isolated communities that are remote from the electrical grid, and facilities that desire a dedicated power source. *Merlin* and *FlatPak*'s ability to use heat from a wide variety of fuel sources, including waste heat and natural gas, also make them candidates for near-term fossil fuel fired market.

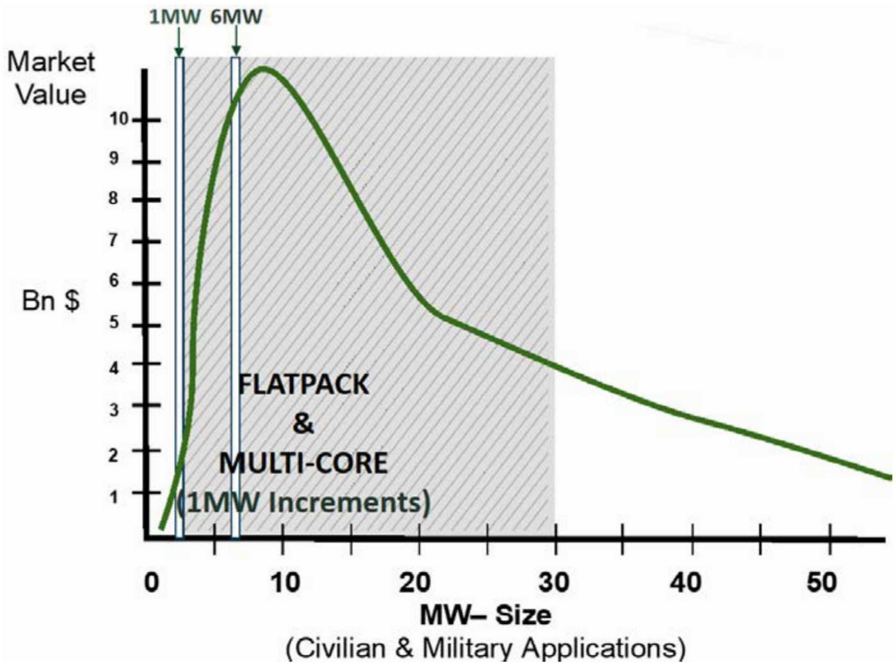


Figure 21: Target Market for *Merlin* and *FlatPak* [51]

Action items

Action items for sCO_2 Brayton technologies commercialization can be categorized into either staged demonstration supporting the 3 R&D lanes or programmatic development.

Staged Demonstration

Action items that support staged demonstration are to be accomplished during the natural progression of scaling current capabilities to support the 10MWe, 750C STEP Facility. Currently, SNL's TA has the capabilities to demonstrate a 250kWe RCBC at 550C with 1.8 pressure ratio (Table 4: RCBC Test Article Description, page 41). To support STEP, the RCBC Risk Retirement lane must demonstrate increased capacity to 1MWe, and incrementally to 10MWe, and demonstrate increased temperature to 550C followed by 750C.

Upgrading capabilities to test commercial RCBC applications requires an incremental plan that supports change management without negatively impacting risk retirement activities. The immediate actions to support the staged demonstration are outlined in Figure 22.

RCBC Proof of Concept and Risk Retirement

- Develop practical plan to 1) demonstrate increased capacity to 1MWe, progressing incrementally to 10MWe 2)demonstrate increased temperature to 750C.
- Match incremental plan to R&D needs and timeline for known RCBC component testing ahead of STEP Facility needs.

Develop Testing Capabilities

- Identify and document partners' timeline
- Develop integrated schedule that supports testing needs while progressing towards STEP scale and temperature parameters
- Develop test plans and validation criteria that meet partners' needs.

Develop Grid Qualification Capabilities

- Assessment of requirements for grid qualification
- Address policies and procedures to remove potential barriers
- Address Political and Business concerns, establish contacts and contracts with pertinent stakeholders
- Design, Build, and Validate Grid Connection

Figure 22: Immediate Actions to Plan Incremental Development of Capabilities

Programmatic Development

Action items that support programmatic development include strategic initiatives that help overcome the gaps and barriers to successful commercial applications. These include:

- Continue performance on FY18 funded projects towards technology readiness.
- Identify and engage stakeholders, primarily utilities, military customers, and power generation/distribution markets. Establish consortia with sCO_2 commercial interests.
- Establish TRL thresholds. Validate the TRL preliminary estimates.
- Analyze MRL thresholds, apply to sCO_2 Technologies and perform initial assessment.
- Initiate Work System Analysis. Develop concurrent engineering model for systems integration.
- Validate roadmap progress metrics, including system value and perceived value. Develop communication strategy to articulate the benefits of the technology for industry.
- Develop value engineering to maintain, monitor and prioritize system economies and costs.

Milestones and Barriers

Milestones

Table 13 identifies major project **milestones** and their associated timelines towards DOE-NE project objectives. Each milestone is related to at least one primary objective, but may tie to several. The same is true for the identified R&D Lanes. For easy reference, the program objectives and R&D lanes are revisited in Figure 23.

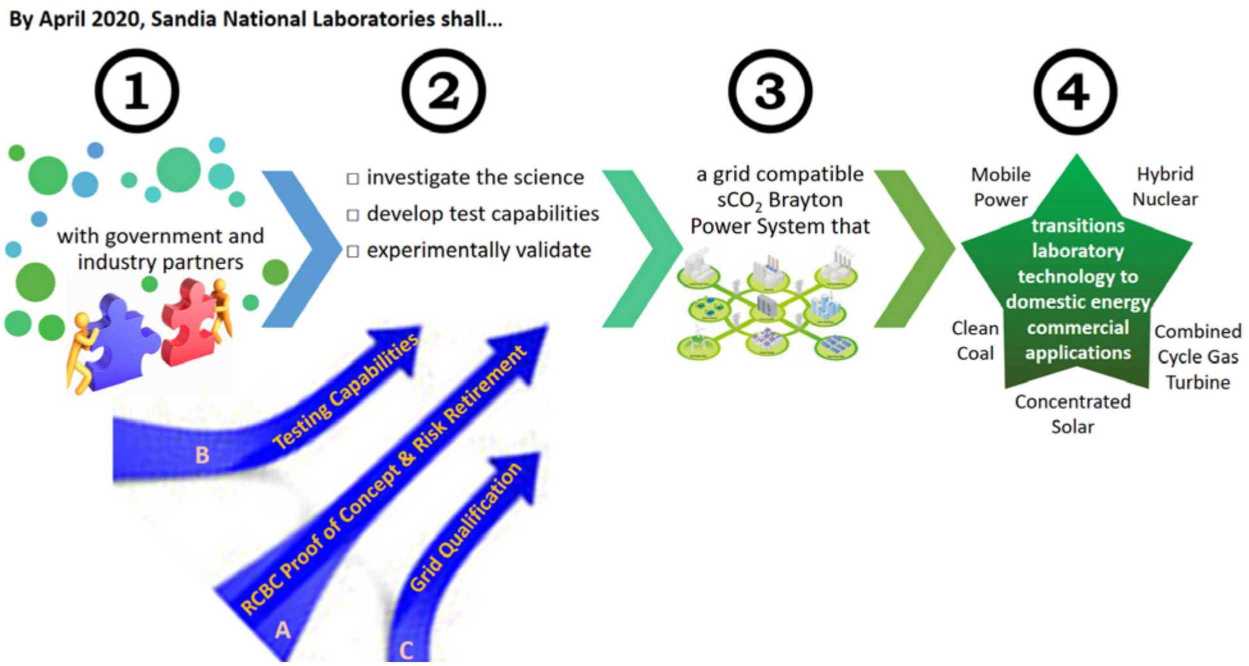


Figure 23: Mission and R&D Lanes Revisited

Table 13: Primary Milestones to Brayton Systems Commercialization

Year	Objective	R&D Lane	Milestone
CY18	2	A, B	sCO_2 test article (TA) reconfiguration complete
	1, 2	A	Merlin construction and acceptance testing
	2	A	Begin turbocompressor test on idle conditions
	1, 2	A	Demonstration of high temperature (700C) and high pressure (4400 psi) operations for seals and bearings
	3	C	On-Grid Qualifications Scope and Requirements Study
	1	A	STEP Facility design completed
CY19[12]	2	B	sCO_2 TA will bring the 1MWe (Merlin) system online
	2	A	Begin 1MWe full-scale testing and operation
	1, 3, 4	C	Kirtland First - Qualification for grid connectivity.
	2	A	MSR begin to achieve >700C applications.
CY20[13]	2	A, B	Integrate recompression into the closed Brayton Cycle
	1, 2, 3	C	Kirtland First - Test grid qualification capabilities ready,
	1, 2, 3, 4	C	Merlin on-grid test integration
	1, 2	A	STEP Facility construction completed, CBC 550C, 10MWe, Off-Grid Testing
CY21	1, 2	A	STEP RCBC reconfiguration, RCBC 550 Testing

[12] By 4/2019, set up a test cell for 1 MWe system (Merlin). This test will include the turbo compressor at full power, the 1 MWe sCO2 power turbine, and electric generator to commission all for grid connection.
[13] By 4/2020, 1MWe system (Merlin) to be grid ready

Year	Objective	R&D Lane	Milestone
	1, 2	A	High Temperature Component and Cycle definition at TRL7.
CY22	1, 2	A	Proof of Concept evolves to higher temperatures.
	1, 2	A	STEP RCBC 750 Testing
CY23	1, 2	A	High Temperature and Power Pilot-Test complete.
CY24	1, 2, 4	A	Commissioning to commercial applications.
	1, 2, 4	A	System completed and qualified through test and demonstration at TRL8.
CY25	1, 4	A	Commercial interests are expected to apply the technology without DOE support.

Barriers

Barriers identify obstacles on the way to reaching the objectives, and often related to knowledge, technology, market, regulations and public acceptance. Preliminary barriers to the commercialization of sCO_2 Brayton Cycles are identified on Figure 24 highlighting the estimated year in which they are expected to become issues for a successful system. Strategies to eliminate or mitigate these barriers need to be identified well in advance of the specified timeframes to ensure timely implementation and the possible evaluation of alternative protocols being built into the system.

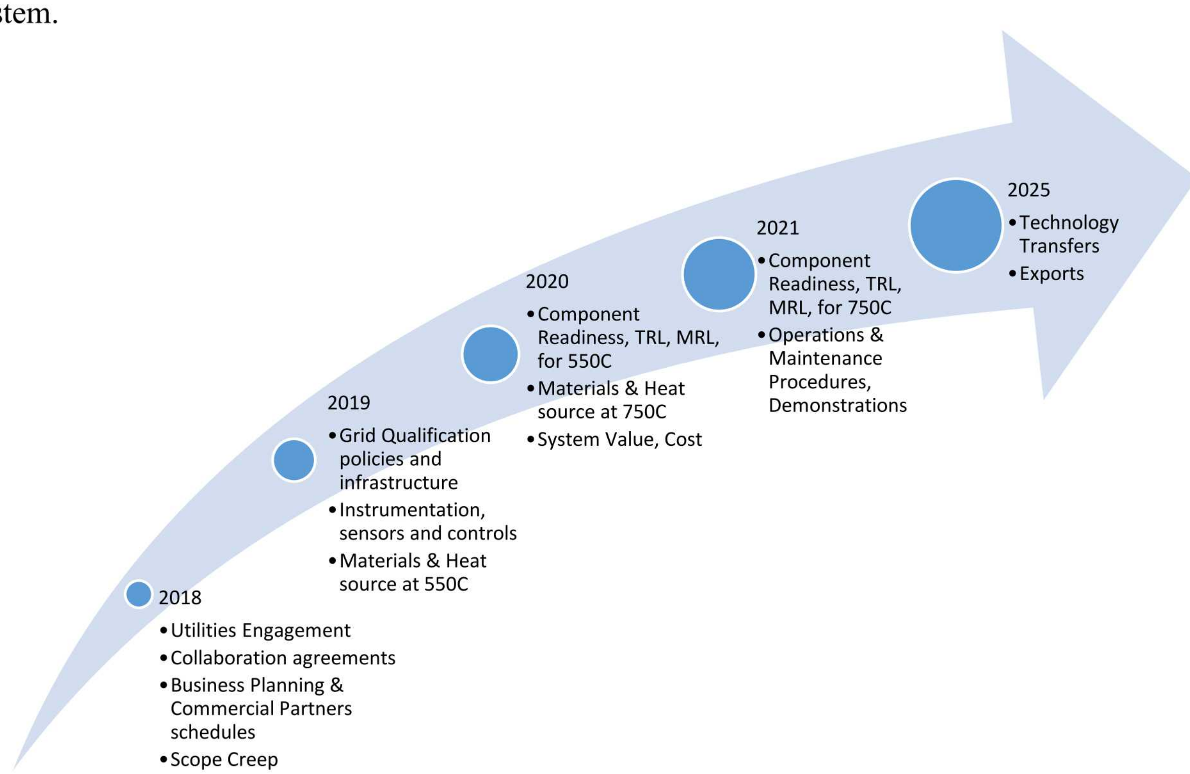


Figure 24: Preliminary Barriers to Commercialization

Conclusion

Several benefits to the development of Supercritical CO_2 Brayton Cycle technology have been identified. The broad applicability to a variety of heat sources, higher plant efficiency and reduced fuel consumption, smaller size, reduction in water consumption, and environmental improvement make it an attractive alternative. However, there are still significant challenges on the way to successful commercialization and deployment to this technology.

DOE's ART and STEP Programs are interested in developing sCO_2 capabilities, with STEP's DOE Collaboration (NE, FE, EERE) supporting a demonstration to reduce the technical barriers and risks to the commercialization of the technology while encouraging collaboration among the offices and with industry.

This document analyzed the status of the technology development, the market, and the policies to derive a preliminary roadmap to guide R&D efforts. The primary focus was to establish a path to evaluate component readiness in preparation for demo and pilot test, and to do this while taking into consideration the scalability of the system and establishing the foundations for a path to commercialization.

Commercialization is not an after-thought. Successful deployment is impacted by the market and the policies surrounding the technology. For sCO_2, these form a very strong argument in favor of commercialization, considering that the benefits include cost savings, environmental impact, system efficiencies, and reduced footprint. Furthermore, sCO_2 Brayton cycles have applications for both military and commercial interests. This, tied to the DOE coordination effort, provides enormous potential to establish a solid collaboration strategy that can support a more rapid R&D timeline and a direct pathway to commercialization. This is achieved by establishing common goals and coordinating efforts to ensure that resources are optimized for the development of common components.

Furthermore, as new knowledge is developed, the roadmap must be updated to ensure that additional R&D needs are met. That is the case in this roadmap revision. Upon preliminary conversations with utilities, it was decided that market-ready applications translate into power on-the-grid. To address that need, SNL's Brayton mission was revised, and two new lines of research were added to the original Risk Retirement goal. The new lines, to develop incremental testing capabilities, and to develop grid qualification capabilities, support ART-NE and STEP Pilot facility goals while simultaneously providing an accelerated path to testing and the ability to qualify sCO2 technologies for grid connection.

Several challenges have been identified during the creation of this roadmap.

The specific configuration for the Pilot Facility, or any other relevant DOE-NE demonstration, must be decided soon to ensure that technology readiness levels can be assessed and further developed for the relevant environment. While progress can continue to be made without a specific system configuration, the question that must be asked is "to what end?" Without a definitive end-goal application that the technology can be developed towards, R&D is only relevant to the progress of science and does not directly contribute to the commercialization of the technology.

SNL has assumed that an RCBC for Sodium Fast Reactor is the primate application of interest for NE but will likely not be the first commercial application. With this in mind, SNL adopted a collaborative approach that supports other applications (such as Fossil Energy for the STEP facility, and Distributed Energy for commercial partners) while moving the technology forward towards the ART-NE target goals.

This preliminary roadmap is built on a hypothesis regarding technology readiness levels of the individual components. While previous work on the development of the technology allows us to make informed assumptions about the status of components, it is important to undertake a formal effort to determine each component baseline TRL and define the TRL threshold and test rig for each, both pre- and during pilot testing. A validation of preliminary TRLs, by either demonstrated science or peer-expert reviews, will set the foundation to establish a solid roadmap for the development of the components, system and facility with requirements specific to the chosen demo application.

There are several stakeholders working on and/or interested in the technology. This translates into multiple possible applications, directions to commercialization, and R&D progress opportunities. Available data (on knowledge, capabilities, and needs) must be consolidated across the DOE Collaboration, science and industry partners. To support scalability and collaboration goals, it will be important to identify the commonalities among the applications. A concurrent engineering approach could consider the commonalities as scenarios, building modularity into the design of the facility and components' testing specifications.

The timeline for the STEP demonstration presents a challenge to other stakeholders with already established demand from the distributed energy market and military applications, who are ready to acquire the technology for immediate use. Commercial suppliers also have interest, with several ready to collaborate towards in a faster development timeline. However, challenges with supplier timelines and manufacturability of components have already been experienced.

Several activities can be undertaken to support coordinated R&D plans, not the least of which is the formal adoption of a roadmap process by the DOE Collaboration. A collaborative R&D plan was commissioned in FY17 and is currently under review. The next step following the R&D plan is to develop a Concurrent Engineering Team to manage the uncertainties and conflicts encountered between the target applications of the three DOE offices, the suppliers, and the potential customers. The roadmap process calls for the identification and collaboration of stakeholders across the entire work system, which in turn facilitates and supports early engagement of stakeholders for the eventual commercialization. Furthermore, the roadmap process would ensure that the input of the stakeholders (their needs, interests and concerns) are addressed during R&D, increasing the likelihood of technology adoption.

Lastly, a roadmap is a living document. This document constitutes a preliminary path to commercialization, but information must be complemented with additional sources and updated regularly to ensure the plan remains current towards specific goals.

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Appendix A: Summary of Potential Commercial Partners and Customers

Suppliers

AECOM	AECOM is an engineering procurement contractor headquartered in Los Angeles, CA with a global footprint. AECOM manages the installation of large-scale power plants, and works extensively with DOE projects. [52] They have completed work with SNL to determine what the EPC cost would be for them to be able to take the contract to build the EPC for the pilot facility during construction. SNL and AECOM collaborated on a recent RFP for the facility design. AECOM is ready to start immediately. **Website:** http://www.aecom.com/solutions/engineering
Aerojet Rocketdyne	Aerojet Rocketdyne is a leader in aerospace and defense, providing propulsion and energetics to the space, missile defense and strategic systems, tactical systems and armaments areas, in support of domestic and international markets. Aerojet Rocketdyne worked with FE in the development of Advanced Turbomachinery Components for Supercritical CO_2 Power Cycles. Website: http://www.rocket.com/
Alfa Laval	Alfa Laval is the largest single original equipment manufacturing for industrial heat exchangers with an interest in the future needs for sCO_2 heat exchangers. Website: https://www.alfalaval.com/
Altex Technologies Corporation	Altex Technologies Corporation uses special analysis and testing tools to provide innovative energy technology solutions needed to attain energy security and address climate change, at a lower cost, for industry and the public. Altex worked with FE on Low Cost Recuperative Heat Exchanger for Supercritical Carbon Dioxide Power Systems, and through SBIR on Corrosion and Erosion Resistant Surface Features for High Pressure Supercritical Carbon Dioxide Heat Exchangers Website: http://www.altextech.com/
Barber-Nichols Incorporated	Barber-Nichols Incorporated (BNI) specializes in the design and production of turbomachinery; products include compressors, fans, pumps, turbines, generators, motors, and controllers for aerospace, cryogenic, defense, and energy applications. In addition to specialty hardware, BNI also provides engineering consulting and contract manufacturing. BNI interest in sCO_2 technologies appears limited to designing and selling turbomachinery. BNI helped to design the component and system development platform resident at the Brayton Lab at SNL. Their specialty is designing turbomachinery for various applications. This includes all aspects of machine design, from mechanical, rotordynamics, and operations. They also helped design and build the KAPL/Bettis CBC, and they have been involved with the motor controller acquisition for the bearings test rig. Website: https://www.barber-nichols.com/
BgtL	BgtL is a compact solution provider for high temperature and high pressure applications. They specialize in the provision of turnkey solutions, incorporating compact technology for high temperature and high pressure processes. BgtL has developed unique proprietary technology for Thermal Energy Storage (TES) utilizing molten aluminum alloy as a phase change material and vacuum insulation to minimize heat losses. In collaboration with ANL, they are developing a proprietary design that can be used with different heat sources including nuclear (SFR, LFR, Liquid Salt, HTGR) and concentrating solar power, and electricity sources including photovoltaic (PV) power plants. Website: https://bgtl-inc.com/

Brayton Energy	Brayton Energy works in the design, prototyping, and testing of turbomachinery and gas turbine systems in support of responsible, sustainable energy production. Brayton Energy collaborated in the CSP: Apollo (2015) and SunShot (2012) efforts on solar receiver with integrated thermal storage for sCO_2. They also collaborated with FE on the manufacturing process development for lower-cost heat exchangers in high-temperature/pressure applications. Website: http://www.braytonenergy.com/
Calabazas Creek Research	Calabazas Creek Research, Inc. develops advanced, innovative technologies for high power RF generation and transmission, including components and applications. CCR specializes in UHF, microwave, millimeter-wave and Terahertz high power sources and components using vacuum electron devices. The company focuses on new, innovative technologies for the next generation of RF sources and systems. Calabazas Creek Research worked with FE through SBIR on Nanoscale Metal Oxide Coatings for Corrosion Protection of Superalloy Materials. Website: http://calcreek.com/
Cascade Technologies Inc	Cascade Technologies Inc (CTi) is a provider of information technology and professional services for the Federal Government. CTI worked with FE through SBIR on Highly Scalable Large-Eddy Simulations of Oxy-Fuel Combustors for Direct-Fired Supercritical CO_2 Power Website: http://www.cascadestech.com/default.aspx
Combustion Research and Flow Technology	Combustion Research and Flow Technology (CRAFT Tech) offers computing resources to perform simulations and modeling for consulting projects. CRAFT Tech worked with FE through SBIR in Combustion Modeling for Direct Fired Supercritical CO_2 Power Cycles, and Simulation Tool for Turbomachinery Operating with Trans-Critical Real Fluids Website: https://www.craft-tech.com/
CompRex	CompRex designs and sells compact diffusion-bonded heat exchangers for high temperature and high pressure applications. They have delivered and successfully tested a pilot-scale heat exchanger to the Naval Nuclear Laboratory for sCO_2 cycle development. HX footprint was reduced by up to 10 times compared with S&T and 15 to 20 % compared with PCHE. With assistance of ANL, CompRex is developing a new proprietary design that improves upon their existing product. It is expected that commercialization of CompRex's commercially viable HX technology supports power industries and military applications Website: http://www.comprex-llc.com/#comprex-solutions
Concepts NREC	Concepts NREC are experts in turbomachinery, maintaining an in-house research and development program, and over 70 patents worldwide. Their work focuses on improving the performance and manufacturability of turbomachines. Concepts NREC worked with FE through SBIR in improving efficiency and reducing costs for the Supercritical CO_2 design process. Website: http://www.conceptsnrec.com/home

Echogen	Echogen focuses on waste heat applications. They develop and market an sCO_2 bottoming cycle, the EPS100, which has been under development for 6+ years. The EPS100 heat engine uses industrial grade liquid CO_2 as the working fluid, without practical temperature or pressure working limits [53]. Echogen has constructed and is testing a 7.5 MWe power turbine at 450 ˚C (funded by Dresser-Rand). Echogen is also working with GE Marine to develop a 1 MW power system for marine applications. They have no primary heat exchanger. And have not demonstrated high temperatures because they do not have the proper facility to perform a high temperature testing. Echogen worked with EERE on the Tech-to-Market (2017) sCO2Power Cycle with Integrated Thermochemical Energy Storage. Echogen worked with FE through SBIR on the Demonstration of a Compact Heat Exchanger for SCO_2 Heat Recovery Systems. **Website:** http://www.echogen.com/our-solution/product-series/eps100
Gas Technology Institute	GTI is the leading research, development and training organization addressing energy and environmental challenges to enable a secure, abundant, and affordable energy future. research initiatives address issues impacting the natural gas and energy markets across the industry's value chain—supply, delivery, and end use. GTI was selected by FE and NETL to lead the sCO_2 Pilot Plant Test Facility. Website: http://www.gastechnology.org/About/Pages/default.aspx
GE Global Research	GE Global Research is a major developer, manufacturer, and marketer of power systems who appears to have some interest in researching the development of sCO_2 technology. NE worked with GE Global Research to test their proprietary cycle – SNL built and tested it for them. They also funded a $450k WFO with SNL several years ago but nothing has happened ever since. GE has worked on multiple efforts with EERE, including Development of High Efficiency Expander and 1 MW test loop, Physics-Based Reliability Models for sc-CO_2 Turbomachinery Components, Development of an Integrally-Geared sCO2Compander, and Compression System Design and Testing for sCO2CSP Operation. GE also worked with FE in the Development of Low-Leakage Shaft End Seals for Utility-Scale Supercritical Carbon Dioxide (SCO_2) Turbo Expanders Website: http://www.geglobalresearch.com/about
General Atomics	General Atomics (GA) is a major developer, manufacturer, and marketer of power systems, particularly nuclear. GA is interested in developing a High Temperature Gas Reactor (HTGR), and to use sCO_2 as the working fluid in a RCBC. GA is interested in collaborating with SNL to develop their idea and their intent is to start a development program immediately. Website: http://www.ga.com/about
Hanwha Techwin	Hanwha Techwin supports high tech technology development. They are experts in precision machining (based on their development and manufacture aircraft engines), high tech automation, and security solutions. Hanwha Techwin worked with EERE as part of the CSP: APOLLO (2015) effort to develop an Integrally-Geared sCO_2 Compander Website: http://www.hanwhatechwin.com/
Hexces	HEXCES designs, develops, manufactures, and services compact platelet heat exchangers (CPHXs) for numerous market applications. These diffusion bonded heat exchangers, also known as printed circuit heat exchangers (PCHEs), or microchannel heat exchangers (MCHEs), provide high pressure, temperature, and thermal capabilities within a small footprint. HEXCES is a spin-out of Clean Energy Systems with a primary interest in molten salt to sCO_2 heat exchangers for CSP applications. Website: http://www.hexces.com/

Heatric	Heatric manufactures printed circuit heat exchangers using diffusion bonding, resulting in PCHEs that are up to 85% smaller and lighter than traditional technologies. They are well-established in the upstream hydrocarbon processing, petrochemical and refining industries. Heatric has provided the majority of PCHEs in-use for sCO_2 applications to date, including those used at SNL, KAPL, Echogen, and NET Power. Heatric is primarily interested in commercial applications for heat exchangers and has limited interest in research or nuclear applications. Website: https://www.heatric.com/index.html
Illinois Rocstar LLC	Illinois Rocstar is a research institute that performs simulation science. They are experts in modeling & simulation to improve processes and products. Illinois Rocstar worked with FE through SBIR on PIV-Validated RANS Turbulence Modeling for Buoyant Supercritical CO_2 Flows Website: http://www.illinoisrocstar.com/
Knolls Atomic Power Lab (KAPL)	Knolls Atomic Power Laboratory (KAPL) is a research and development facility dedicated to the support of the US Naval Nuclear Propulsion Program. KAPL is operated for the DOE by Bechtel Marine Propulsion Corporation. KAPL employees develop advanced nuclear propulsion technology, provide technical support for the safe and reliable operation of existing naval reactors, and provide training to naval personnel who operate them. [54] Bechtel Marine Propulsion Corporation (BMPC) is testing a supercritical carbon dioxide (sCO_2) Brayton system since 2012. The 100 kWe Integrated System Test (IST) is a two shaft recuperated closed Brayton cycle with a variable speed turbine driven compressor and a constant speed turbine driven generator using sCO_2 as the working fluid. The IST design includes comprehensive instrumentation and control system to facilitate precise control of loop operations and to allow detailed evaluation of component and system performance. [55] Website: http://www.knollslab.com/
Mechanical Solutions, Inc.	Mechanical Solutions, Inc (MSI) specializes in field vibration testing and troubleshooting of critical service rotating and reciprocating machinery; turnkey machinery design and development; computer simulation and analysis including computational fluid dynamics (CFD) and finite element analysis (FEA); high-speed video and 3D spatial tracking; and others. Mechanical Solutions worked with FE through SBIR in the study of an advanced gas foil bearing using Supercritical Carbon Dioxide as the working fluid. Website: http://www.mechsol.com/
Mid-South Engineering Company	Mid-South provides engineering services for all areas of power plants, with experience with commercial and industrial boilers using a wide range of fuels: biomass, liquor, natural gas, compressed natural gas, oil, and alternative fuels. Website: http://www.mseco.com/markets/energy/
Net Power	Net Power is an organization promoting high-temperature and high-efficiency oxy-fuel combustion cycle that includes a form of the closed Brayton cycle and CO_2 sequestration components. There is no current involvement with SNL. Net Power claims that a production/development timeline is near/mid-term, but this is still several years away. Website: https://netpower.com/about-us
New Way Air Bearing	New Way Air Bearings works on the design and manufacture of modular air bearings, and is a provider of integrated porous media air bearing solutions for OEM applications. They are interested in the development of high temperature bearings and seals, and currently manufacture a bearing that can be used as a bearing or a seal. Website: https://www.newwayairbearings.com/

Peregrine Turbine Technologies	Peregrine Turbine Technologies is a developer and marketer of the Merlin and Flatpak sCO2 power generation systems. Merlin is a 1 MWe simple recuperated Brayton cycle engine with a 750C turbine inlet temperature. This product is at the lower end of the high value of power ratings within the core DE market and is well positioned for multiple military and civilian DE applications. The initial unit will serve as proof-of-concept for the FlatPak modular product family (1.0 to 9.5 MWe. FlatPak, which provides scalability, modularity, and load-following capabilities, all of which have been identified as requirements for commercial applications. FlatPak is well placed in the high value segment of the DE market and is also well positioned for WTE and Biomass applications. The 1.0 and 1.9 MWe "Paks/layers" can be assembled into 1 to 9.5 MWE power islands, ganged and networked to 50 MWe and beyond. SNL has been collaborating with PTT and their novel approach for developing a commercially available technology. The Maverick is in design stage. However, it needs funds to build and test. If funded, they could get something built well within 3 years. Currently working on developing and testing their heat exchanger. Both an MOU and NDA have been signed. Website: http://peregrineturbine.com/about_us
Siemens Government Technologies	Siemens Government Technologies is a U.S. Government's solution provider of technology and services for energy, infrastructure, automation and marine platforms, in all 50 U.S. states and its territories, and in many countries at U.S. Government locations. SGT sCO_2 work is focused on commercialization, interested in "bridging the bridge of risk." Siemens is interested in risk reduction, focused on the smaller scale, and working on an energy service performance model, where Siemens bears the risk of first to market. They are not expecting to have a 50MW machine, but rather a 1-10MWe. They are willing to bring in new partners and new technology into the project, but those partners need to identify the risk (price tag) they are willing to bring to development. Website: http://www.siemensgovt.com/
Southwest Research Institute	Southwest Research Institute (SwRI) is a nonprofit organization providing R&D services to government and industry. They develop innovative solutions that advance the state of the art in a broad variety of subject areas. SwRI contributed with EERE on the following efforts: Development of High Efficiency Expander and 1 MW test loop, Physics-Based Reliability Models for sc-CO_2 Turbomachinery Components, Development of an Integrally-Geared sCO2Compander, Compression System Design and Testing for sCO2CSP Operation SwRI also contributed with FE on the following efforts: High Inlet Temperature Combustor for Direct Fired Supercritical Oxy-Combustion, Development of a Thin Film Primary Surface Heat Exchanger for Advanced Power Cycles, Absorption/Desorption Based High Efficiency Supercritical Carbon Dioxide Power Cycles Website: https://www.swri.org/
Thar Energy	Thar Energy LLC works in delivering green energy solutions for biofuels and advanced heating and cooling system, including advanced heating/cooling technologies, novel biofuel manufacturing process, drop-in replacement for distillation/dehydration, and conversion of agricultural residues into liquid fuel. Thar Energy collaborated in the CSP: SunShot (2012) efforts to develop a High Efficiency Expander and 1 MW test loop. Thar Energy also worked with FE on several projects, including High Temperature Heat Exchange Design and Fabrication for Systems with Large Pressure Differentials, and Technology Development of Modular, Low-Cost, High-Temperature Recuperators for SCO_2 Power Cycles Website: http://www.thargeo.com/

Vacuum Process Engineering	Vacuum Process Engineering (VPE) is a US-based manufacturer of high pressure heat exchangers and custom diffusion bonding. VPE is interested in manufacturing and selling heat exchangers for CBC systems. VPE made substantial advancements in heat exchanger design and manufacturing. They are experts on fusion bonding heat exchangers. SNL helped VPE develop a PCHE. SNL designed a tool for them to use in order to design their own heat exchangers. VPE heat exchangers can be produced immediately. Website: http://www.vpei.com/about-vpe
Xdot Engineering and Analysis	Xdot is a small company dedicated to rotordynamics, foil bearing application assistance, analysis tool development, bearing shape optimization, and friction damping. Xdot is interested in designing, fabricating and testing bearings solutions for sCO_2 systems. The company manufactures gas foil bearings. Their involvement in the coating materials comes as a need to identify the best coating materials to use with their bearing designs. Xdot has worked with SNL on a range of coating material vendors (LiquidMetal Technologies, General Magnaplate, TurboCAM, Hohman Plating, Everlube, and Endura) to provide coated foil samples. These coated foil samples have been used in 500-hour CO_2 exposure tests at two temperatures (315oC/550oC), to identify chemical compatibility and behavior in environments relevant to gas foil bearings for sCO_2 turbomachinery. Currently, they are engaged by SNL to complete a second phase of bearing foil coating material evaluations, including preparing and evaluating coating materials at higher temperatures (750oC), and also in sCO_2 (550oC). Website: https://www.xdotea.com/home.html
Customers	
Air Force Research Lab/ Air Force Space Command/ Kirtland Air Force Base	In order to align with the three strategic goals of the Air Force Energy Flight Plan14 - improve resiliency, optimize demand, and assure supply – the Office of Energy Assurance (OEA) partners with defense and federal agencies, industry, and communities to develop innovative solutions that defend against cyber, natural, and physical challenges. This includes integrating more resilient, cost-effective and cleaner energy resources to ensure the Air Force is using resources efficiently and productively while accomplishing the mission. Website: http://www.safie.hq.af.mil/Programs/Energy/Office-of-Energy-Assurance/
Army Corp of Engineers	The mission of the 249th Engineer Battalion Prime Power is to: On order, deploy worldwide to provide prime electrical power and electrical systems expertise in support of military operations and the National Response Framework. The 249th EN BN reports directly to HQ, USACE. The battalion offers a variety of services including: electrical power requirement assessment, power production; transformer inspection and test analysis; maintenance and repair of power plants, substations, and government owned or managed transmission and distribution systems, circuit breaker and relay maintenance; infrared surveys, medium-voltage electrical contractor oversight, and training for personnel to operate and maintain prime power distribution and generation equipment. Website: http://www.usace.army.mil/
Army Materiel Command	The U.S. Army Materiel Command (AMC) is the Army's premier provider of materiel readiness across the spectrum of joint military operations [56]. The AMC develops new technology to meet the needs for Army Bases. The AMC is interested in sCO_2 given that they supply independent power for US bases and are looking for green power for nominal 10 MWe blocks. The AMC is involved with SNL since they are a target of the Energy Huntsville Consortium. AMC is looking to purchase a system that operate independently of the commercial grid. They need it now to meet Presidential orders. Website: http://www.amc.army.mil/amc/about.html

[14] Air Force Energy Flight Plan: http://www.safie.hq.af.mil/Portals/78/AFEnergyFlightPlan2017.pdf?ver=2017-01-13-133958-503

Bonneville Power Administration	The Bonneville Power Administration is a federal nonprofit that markets wholesale electrical power from 31 federal hydro projects in the Columbia River Basin, one nonfederal nuclear plant and several other small nonfederal power plants. It operates and maintains about three-fourths of the high-voltage transmission in its service territory. BPA's service territory, which includes Idaho, Oregon, Washington, western Montana and small parts of eastern Montana, California, Nevada, Utah and Wyoming. As part of its responsibilities, BPA promotes energy efficiency, renewable resources and new technologies. Website: https://www.bpa.gov/Pages/home.aspx
Duke Energy	Duke Energy is one of the largest electric power holding companies in the United States, supplying and delivering electricity to approximately 7.4 million U.S. customers. They have approximately 52,700 megawatts of electric generating capacity in the Carolinas, the Midwest and Florida – and natural gas distribution services serving more than 1.5 million customers in Ohio, Kentucky, Tennessee and the Carolinas. Our commercial business owns and operates diverse power generation assets in North America, including a portfolio of renewable energy assets, natural gas, nuclear and coal. Website: https://www.duke-energy.com/home
Energy Huntsville	Energy Huntsville (EH) is a loose consortium of energy interests in Huntsville, AL. Organized by Mayor Tommy Battle, Energy Huntsville seeks to promote energy-related interests from local, state, and national entities within the Huntsville community. The members of Energy Huntsville are active across the spectrum of energy sectors including: renewables, fossil fuels, power generation, energy storage, transportation, building energy efficiency and energy management. [57] Energy Huntsville finds sCO_2 to be a new, innovative and exciting power generation technology and are therefore very interested in working with SNL as they want to be at the forefront of innovative energy programs. For example, Energy Huntsville is exploring the burning of biofuels with closed heat source driving the RCBC as a likely waste to energy application. No timeline has been defined for a production environment. Website: http://energyhuntsville.com/about
Energy Northwest	Energy Northwest (ENW) provides energy services and generates electricity in Washington state. It owns and operates four electricity generating facilities, develops new power generation facilities to meet growing demand, and provides operations and maintenance services for generating facilities owned by other utilities. The agency's vision is to be the region's leader in energy generation and public power solutions. Achieving this calls for a strong power portfolio that includes a variety of electricity generating operations and professional and technical services. Energy Northwest is a likely site for the 1 to 5 MWe Pilot Facility featuring Peregrine's Merlin and FlatPak technologies. Website: http://www.energy-northwest.com/whoweare/Pages/default.aspx
Loring Development Authority	Loring Commerce Centre, once the Loring Air Force Base, is now a busy commercial, industrial and aviation park, priding businesses with building space, developable sites, and infrastructure for business development. It is a potential pilot site for Peregrine's biomass fueled Merlin. Website: https://www.loring.org/

Naval Nuclear Laboratory	The Naval Nuclear Laboratory includes the Bettis and Knolls Atomic Power Laboratories, the Kenneth A. Kesselring Site, and the Naval Reactors Facility which have proudly supported the nation since 1946. The Naval Nuclear Laboratory has nearly 7,000 employees working at primary locations in Pennsylvania, New York, South Carolina, and Idaho. The Naval Nuclear Laboratory also has an established presence at numerous shipyards and vendor locations around the globe. The Naval Nuclear Laboratory is dedicated solely to the support of the United States Naval Nuclear Propulsion Program, and is operated by Bechtel Marine Propulsion Corporation, a wholly owned subsidiary of Bechtel National, Inc. Bettis and Knolls Atomic Power Laboratories investigate sCO_2 power cycles as an alternative to steam power cycles for nuclear propulsion. Website: https://navalnuclearlab.energy.gov/
NAVSEA	The Naval Sea Systems Command (NAVSEA) engineers, builds, buys and maintains ships, submarines and combat systems that meet the Fleet's current and future operational requirements. The NAVSEA is interested in sCO_2 for a 25 MWe shipboard power operating on fossil fuel to generate shipboard power for electronics in parallel with gas turbine propulsion systems. They are involved with SNL since the Brayton Consortium submitted a response to an RFI and have been requested to brief them. Website: http://www.navsea.navy.mil/WhoWeAre.aspx
Southern Company	Southern Company is an electric utility has about 46GW of electric generating capacity, nuclear, fossil and renewables. They are interested in sCO_2 deployed for those applications, “sooner rather than later.” Website: https://www.southerncompany.com/about-us.html
Tristate Generation	Tristate Generation Transmission is an “electric cooperative of cooperatives”. It generates and transmits electricity to 43 electric cooperatives in various states. The source is mostly coal-fired. Website: https://tristategt.org/content/about-us

Appendix B: Projects History

	Project	*Objectives*
(2007)	Supercritical CO_2 Brayton Cycle Test-Loop Development, Controls, Testing, and Model Validation	The objectives of this effort were to: 1) develop the world's first supercritical carbon-dioxide Brayton cycle test-loop, 2) operate the loop to validate simulation models and to study control methods and supercritical phenomena, and 3) develop integrated dynamic simulation models for the supercritical Brayton cycle and simulation models for compression near the critical point as well as effective control methods for the sCO_2 Brayton cycle.
(2010)	Investigation of the Condensing Supercritical CO_2 Brayton Cycle	This project aimed to evaluate the potential improvement in cycle efficiency and power upgrades that can be obtained with existing and future LWRs by using advanced supercritical CO_2 (sCO_2) power cycles.
(2011)	Analysis of Gas-Lubricated Foil Thrust Bearings in Supercritical CO_2 Flow	A semi-empirical thrust bearing model was developed using data acquired during previous tests. Analysis of this data taken at high rotation speeds and temperatures, using supercritical CO_2 fluid flow as a lubricant, served as the basis for a model tailored to Brayton cycle technologies developed at SNL. This provided a useful tool to experimenters in preparation for and during future test runs. As a second part of this study, SNL's supercritical CO_2 compression test loop was modified to incorporate instrumentation for measurement of thrust load. Further research into instrumentation methods is needed. This new test rig provided SNL with a facility for generating source data for model validation and thrust bearings R&D.
(2011)	Development of a System Model for a Small Modular Reactor Operating with a sCO_2 Cycle on a DoD Installation that Utilizes a Smart/Micro-Grid	The first component was the modeling of a temporal stochastic micro-grid, capable of producing accurate predictions of a micro-grid behavior under. The second part of the model was the expansion of the super-critical CO_2 Brayton power cycle analysis tools developed into a temporal fluid dynamics code for sCO_2 Brayton closed loops. The third part of the model used SNL's RPCSIM code updated to accurately model several advanced reactors. The final component was testing with sCO_2 experimental loops.
(2012-2013)	Compact IHX Fundamental Phenomena	As the technology develops for the sCO_2 Brayton Cycle as an advanced energy conversion technology, issues have been identified with heat exchangers due to corrosion by sCO_2 and sodium. Three objectives are identified in FY12: 1) Complete literature review on high temperature supercritical carbon dioxide and sodium corrosion; 2) A plan detailing an experimental sCO_2 and sodium corrosion testing program to develop advanced heat exchangers; and 3) Initiate small scale experiments in sCO_2 and sodium that address gaps in research.
(2012)	Turbomachinery Demonstration	The specific scope was to develop the necessary scientific basis for an sCO_2 system that leads to a 10 MWe system design for construction by industry. In support of this objective, 3 tasks have been identified:

	Project	Objectives
		1) Completed the construction of the fully recuperated split flow supercritical CO_2 loop and ship to SNL. Final testing and installation of new parts completed the loop in early 2012, closed the contract with Barber-Nichols, and delivered the loop for installation at SNL's Brayton Laboratory. 2) Commissioned the split flow loop at SNL in preparation for engineering testing. Commissioning testing involved performance checks of the components to verify readiness for engineering tests to begin 3) Began testing to verify Brayton Cycle technology, developed accurate scaling codes to commercial scale systems, and demonstrated power generation. These tests looked at the start-up, shut-down modes, as well as steady state operation. Codes were bench-marked and engineering issues resolved. 4) Began development of a domestic source of high performance heat exchangers. This task surveyed US capabilities and identified vendors who will work with SNL to manufacture small devices for engineering testing. The highest thermal/electrical conversion efficiency is one way to improve the economics of any power system. Advanced Reactors benefit with a Super-Critical Carbon Dioxide (sCO_2) Brayton cycle electrical generation systems by matching the compact turbomachinery to the temperature of the reactor to approach up to 50% conversion efficiency in 1/10 of the size and 1/100th of the cost of conventional steam driven systems. In FY12 we expected to demonstrate the path to 50% efficiency in 1/10 size and being to address the cost issues primarily associated with heat exchangers.
(2013-2016)	Turbo Machinery Demonstration (Brayton Cycle)	Energy conversion technology is important for both alternative energy products and distributed power applications. Heat exchanges are also a key component for the economic and reliable operation of SMR systems. One option for advanced SMR R&D to continue the demonstration of supercritical CO_2 turbomachinery (1.5M), shorter term, and ARC R&D to continue activities on the design of compact heat exchanges for low/high pressure coupled systems (2M), longer term. 2013 1) Develop and benchmark steady state test assembly performance to include relevant loss factors. Validate and Verify prediction codes. 2) Identify sources of inefficiencies during the testing process and impediments to safe and reliable testing. Implement corrective actions to mitigate these effects. Possible upgrades include acquiring all materials needed to enable timely repairs to testing hardware, modifying the current system cooling architecture to improve system performance and extend component lifetime, and installing a comprehensive insulation system. 3) Summarize R&D findings for FY13. Extend the knowledge base in operating an sCO_2 split flow Brayton loop, and identify the remaining obstacles to achieving the operating conditions of the original design. 4) Research costing issues related to advanced heat exchangers in sCO_2 Brayton cycles, to focus on the economic trade-offs of capital costs of heat exchangers and power plant economics. 2014 1) Achieve the original design point of the RCBC in pressure ratio and temperature. Validate and Verify prediction codes using data from the design point tests. 2) Develop a detailed plan to establish a 10 MWe-class RCBC. Interface with industry partners to identify risks. 3) Summarize R&D findings for FY14. Extend the knowledge base in operating an sCO_2 RCBC loop, and specifically complete performance trade studies as a function of pressure ratio, turbine inlet temperature, compressor inlet temperature, and mass loading. 2015

	Project	Objectives
		1) Progress towards the original design point of the RCBC in pressure ratio and temperature. Validate and Verify prediction codes using data from the design point tests. 2) Identify root cause motor controller problems and causes for elevated temperatures within the TAC that prevent attaining the design operating point. Implement improvements to existing TAC and motor controller designs to overcome identified limiting causes. 3) Summarize R&D findings for FY15. Extend the knowledge base in operating an sCO_2 RCBC loop, and specifically complete performance trade studies as a function of pressure ratio, turbine inlet temperature, compressor inlet temperature, and mass loading. 2016 1) Description of RCBC TA Design Status and Path Forward. Characterize current capability of the RCBC TA. Develop options to improve performance and achieve the design point (PR 1.8, 1000 °F max temp, 75 krpm speed). Develop cost/benefit analysis. 2) Identify primary processes required for routine RCBC operations. Develop automated control algorithms for these processes. 3) Present and discuss current status associated with the SNL CBC R&D. Include improvements in design, operations, DAQ and data processing, modeling, degree of automation potential, and understanding of cycle potential
(2013-2016)	sCO_2 Heat Exchanger Development	As the technology develops for the sCO_2 Brayton Cycle as an advanced energy conversion technology, issues have been identified with heat exchangers due to cost for compact printed circuit heat exchangers and possible high temperature corrosion of diffusion bonded stainless steel under stress. Currently there are two project initiatives that address the development of sCO_2 heat exchangers. **The first project is focused on compact heat exchanger development.** 2013 Implemented the testing program developed in FY12 to examine the corrosion of stainless steels under stress at 550 degrees C. Began the study of developing a more economic heat exchanger that scales to large power levels. 2014 Continued implementing the testing program developed in FY12 to examine the corrosion of stainless steels under stress at 550 degrees C. Continued the study of developing a more economic heat exchanger that scales to large power levels. 2015 Implement the testing program develop in FY14 to examine the corrosion of stainless steels under stress at 550 degrees C. Continued the study of developing a more economic heat exchanger that scales to large power levels. 2016 The current objectives are to (1) create a testing program to examine the contaminate that is causing the increase in pressure drop and reducing overall cycle efficiency in the RCBC testing facility, and to (2) continue studying new and immerging advanced heat exchanger that scale to large power levels, generating an update on new innovative/commercialized advanced heat exchangers. Will implement a testing program in FY17 to examine the contaminate that is causing the increase in pressure drop thus reducing overall cycle efficiency in the RCBC testing facility. Will continue the studying of new and immerging advanced heat exchanger that scale to large power levels. **The second project is focused on addressing major issues with Heatric PCHEs** including their high capital cost and significant uncertainty around thermal fatigue lifetime. PCHEs have been essential in the advancement of sCO_2 Brayton cycles due to the need

	Project	Objectives
		for compact, low-cost, and high-performance recuperative heat exchange. For this effort, SNL has been working with Vacuum Process Engineering (VPE) to advance this technology and address the issues. Work on this area is divided by the following tasks: 1. Flow Optimization 2. Shim Fabrication 3. Alternate Headers 4. Failure Modes 5. HT Enhancement 6. Geometric Strength 7. High-Temp Bonds 8. Dissimilar Metals FY16 work includes tasks 1 through 6, focusing primarily on tasks 1 and 3 for optimization and alternative headers in line with needs discussed with industry. The first three activities cover optimization of flow configurations for PCHEs including additional testing of the SNL prototype PCHE, the VPE show device, and incorporation of these results into the SEARCH PCHE design code, investigation of improved shim fabrication techniques including area optimization, mechanical forming, and additive manufacturing, and development of alternative header designs. The fourth activity will address PCHE failure modes in collaboration with any awardees of the FY16 CINR RC-2.1 mission to establish high power-level pressure and thermal fatigue modeling and experimental capabilities for real-world devices at SNL in order to guide the basic science occurring under the NEUP and to accelerate research findings out of the lab and into prototype devices fabricated by VPE and tested at SNL. Activities five and six provide continued support for supervision of NEUPs 13-5101 and 14-6670 into the following years. These activities ensure basic science research into advanced PCHE surface geometries progress smoothly, to provide advice and real-world experience, and assist in moving results from the laboratory to heat exchanger vendors. Activities seven and eight advance diffusion bonding technology in collaboration with VPE to certify advanced nickel alloys with high creep and corrosion resistance at high temperatures, as well as dissimilar metal bonding for primary, intermediate, and secondary heat exchangers of next generation nuclear plants (NGNPs) where materials compatibility suggest very different alloy compositions are required for long-life components.
(2013)	sCO_2 Brayton Cycle Development	A new, patent-pending configuration for the recompression closed Brayton cycle (RCBC) concept, called the cascaded RCBC (CRCBC) was evaluated for the benefits of building and testing. The feasibility of and requirements for standing up a new testing platform for new heat exchanger designs was completed. The objectives are to: Evaluate benefits of the CRCBC, design the testing architecture, and purchase a new printed circuit heat exchanger to support this testing. Evaluate the benefits of and needs for a heat exchanger test platform. Complete the work and acquire the components necessary to stand up the test platform.
(2013)	Advanced SMRs Using sCO_2 Power Conversion with Dry Cooling	Initial tests aimed at investigating the ability of CO_2 to provide adequate flow and heat transfer under conditions simulating emergency shutdown in a CO_2 system. Testing also examined in detail the CO_2-to-air heat transfer process by contracting vendors to build advanced air coolers for this purpose.

	Project	Objectives
(2015)	Risk Management for SMRs	Support the “Integration of risk results and insights” work area for the prototype Probabilistic Risk Assessment (PRA). Specifically, falling under the “Risk Management (RM) to provide Incident Management Guidelines (IMG)” sub-area. Addressed selected critical safety and licensing gaps that were identified in the DOE Sodium Fast Reactor Safety and Licensing Research Plan (SAND2012-4260), specifically tools that can assess seismic transients and EM pump performances. Output presented a collection of accident progressions that represents the spectrum of potential accident plant conditions and instrumented variables that could confront plant operators.
(2015-2016)	Economics	Economics greatly impact the viability for commercialization of any new technology. Previous work used Power LCAT (Power Life Cycle System Analysis Tool) for identifying the high-level tradeoffs associated with technical and economic performance. Efforts to focus on refining this tool to help technical team understand value of various design points (value engineering tool). Will also update market analysis for Brayton technology for designs ranging from 10 MW to 300 MW+. The objective is to identify various pathways to commercialization of Brayton and the associated technical and economic challenges for each pathway. 2015 FY15 efforts included: Near-term market analysis for Brayton Cycle Technology - Initial economic estimates using Power LCAT (Life Cycle Analysis Tool) - Useful for identifying the high-level tradeoffs associated with technical and economic performance 2016 FY16 efforts will focus on refining this tool for use in evaluating longer- term pathways to commercialization for Brayton for nuclear and other sectors. Specific questions/goals: - Could integration of Brayton technology in NE, EERE, and FE-sponsored technologies strengthen the economic case commercialization of these technologies? - What are the key sensitivities? - Identifying these tradeoffs will help technical team understand value of various design points. For example, what are the economic tradeoffs of using specialized materials to achieve higher temps and higher efficiencies? It is expected that beyond FY16 the work will be focused on value engineering and further market analysis, using this tool as Brayton team reaches design decision points as a value engineering tool (Examples: heat exchangers, materials, operating conditions, plant and component sizing.) As economics become clearer, will continually update market analysis with goal of identifying potential customers and markets worldwide for technology.
(2016)	Materials	It is clear from work completed in the RCBC test assembly that there are implications to the use of sCO_2 in this kind of environment. The work aims to move sCO_2 technology towards commercialization by identifying/validating materials (structural alloys as well as seal/bearing materials) that will satisfy the performance requirements for each component in a commercial scale system, using commercial purity grade sCO_2. This effort started on November 2015 and focuses on: Providing structural alloy and seal/bearing materials solutions for a future commercial scale sCO_2 Brayton Cycle. Understanding and resolving component erosion. Task 1 is focused on establishing clear component materials requirements (or targets) for a commercial scale system. These are needed for both structural alloy components as well as for seal and bearing materials. This task will also develop a clear

	Project	Objectives
		understanding, from the available literature, of the performance of structural alloys and seal/bearing materials. These will be used collectively to identify component material solutions and/or gaps where additional development is needed. Task 2 is focused on understanding and resolving component erosion through a Root Cause Analysis (RCA) and using experiments/modeling to characterize gas composition evolution in closed sCO2 systems. This task will also determine the impact of gas impurities on structural alloy corrosion, develop surface models to achieve an understanding of sCO_2 degradation mechanisms, and gain a preliminary understanding of sCO_2 on seal and bearing materials.
(2016)	Commercial Development for sCO_2 System	While sCO_2 has shown considerable promise as an efficient and flexible working fluid, outstanding engineering challenges remain a barrier to commercial implementation. SNL expertise in the development of sCO_2 recompression closed Brayton cycle (RCBC) systems up to 1 MWth can be leveraged to enable U.S. manufacturers to develop marketable system components. The Brayton Team at SNL is positioned to facilitate commercialization of domestic heat exchanger, Turbomachinery, Cycle Development, Bearings and Seals technology via vendor engagement. Four Federal Business Opportunities (FBO) will be constructed to ensure fairness of opportunity with private industry. This effort is expected to begin on March 2016. The work is focused exclusively on the development and execution of CRADA's with private industry to retire technical risks of specific components, advancing the TRL, in preparation for the pilot demonstration. The focus of the FBO's will be on: • Bearings development for sCO_2 applications. • Seals development for sCO_2 applications. • Heat exchanger development for sCO_2 applications. • Cycle development for sCO_2 applications.
(2016)	Commercial Development for sCO_2 Recuperator	Commercially available recuperators are predominantly diffusion bonded monolithic structures that are unsuitable for high thermal transients such as those that will occur in sCO_2 power cycles. Peregrine Turbine Technologies is developing an externally fired advanced modular sCO_2 Brayton cycle. A key component of the technology is its sCO_2 recuperator that returns otherwise waste heat back into the cycle, thereby reducing the fuel consumption and increasing the efficiency. The Peregrine design is unique in its construction, and is designed to accommodate large thermal transients and mitigate many of the failure mechanisms associated with high temperature sCO_2 components. However, while the design has been highly engineered and undergone rigorous mechanical and thermal analysis, it has never been tested. The objective of this effort is to validate this novel recuperator concept to facilitate the deployment of high efficiency sCO_2 cycles and accelerate the commercialization of sCO_2 systems. This effort is expected to begin on March 2016 and will focus on: • Retiring the mechanical and analytical technical risk, and • Validating the concept for release to field-testing and application to other cycles (advancing its readiness from TRL3 to TRL6.)
(2016)	Operations Upgrades and Parts	Two current projects address the continuity of operations on the current TA as progress is made for scalability. The scope of the **upgrades** effort is to modify the SNL RCBC Test Assembly to achieve the original operating design point of 1000 F, 1.8 pressure ratio, 75 krpm. This facilitates trade studies and establishing operating procedures at relevant conditions for an RCBC results in TA performance.

	Project	Objectives
		The scope of the **parts** effort is to obtain and maintain a substantial spare parts inventory for the RCBC Test Assembly to expedite the maintenance and rebuild processes by eliminating parts delivery delay. Both of these efforts started on November 2015.
(2016)	TRL Management	The strategic objectives of this effort are to identify common block requirements and interfaces for a system, identify overlap and synergies between potential sCO_2 Brayton technology applications, maintain a comprehensive estimate of outstanding technical risks and uncertainties for these potential applications, and reveal how advances in one implementation (e.g., a 10 MWe 550C demonstration) accrue to other applications. The work will be completed in two steps: Step 1 – Document TRL. Develop and maintain a comprehensive estimate of component readiness and technical risks tracking ALL relevant research. Step 2 – Develop Plans for TRL demonstration or improvement. Once a TRL baseline is established it can be used to retire risks by identifying alternate approaches to either prove the baseline design or modify it to achieve the desired performance. The process starts with establishing Critical Technology Elements (CTEs) for a given application. In fact, this has already been done for the Advanced Reactor application (10 MWe, 550C). Later the system can be expanded to support other applications for sCO_2 Brayton technology. For each CTE an estimate of technology readiness level (TRL) is documented. This includes interactions with potential suppliers (and partners) identifying their capabilities and limitations. This effort started on November 2015.
(2016)	STEP Project Management	This effort is focused on developing a technology roadmap for the NE-STEP activities that lead to the formation of a prototype recompression closed Brayton Cycle suitable for a sodium cooled fast reactor. Additionally, the roadmap will establish a systems engineering model to develop the necessary components to a suitable Technology readiness for a successful demonstration.
(2017)	Management and Integration	Roadmapping - Develop and manage integrated roadmap and collaborations for STEP. Systems engineering – Develop Systems model and document system requirements for SFR RCBC, CSP and Fossil Heat Recovery to develop components to a suitable TRL for a successful demonstration. Economics - Systems decision-making guided by economic analysis to support commercialization pathways. Project Management in support of Brayton Mission
(2017)	sCO_2 Materials Development	Materials support for a future commercial scale sCO_2 power system - Integral component to the system development efforts in SNL-NM, providing timely materials analyses support / troubleshooting & evaluating the performance of materials used in piping, heat exchangers, and bearings for sCO_2 systems. Development of NE-Focused sCO_2 Structural Materials Consortium and Experimental Program - Identify and Resolve structural materials issues involved in the development of sCO_2 energy conversion systems for Advanced Nuclear Reactor Technologies.
(2017)	Commercial Component Development	This effort combines previous component development efforts into one work package that supports system development for commercial applications, including: Turbine - Industry led sCO_2 Turbine designs for 10MWe RCBC @550C Compressor - Industry developed sCO_2 Compressor Designs

	Project	Objectives
		Recuperators - sCO_2 Recuperator Designs Primary Heat Exchanger - Development of Primary Heat Exchanger for sCO_2 System Coupling to heat source Heat Rejection - Low cost heat rejection for maximum net conversion efficiency Bearings - Bearing design and qualification for sCO_2 service Seals - Seal design and qualification for sCO_2 service
(2017)	System Integration	Development of Process, O&M, and Maintenance Protocols. 01. Develop operating processes, valves, and controls for RCBC at Lab Scale, integrating all components on system. Demonstration of Operability and Generation of complete data sets for Dynamic Modeling. 02. RCBC characterization, model verification and turbine control. 03. Prototype system controls design and development. 04. Analysis and decision on turbomachinery (turbine and compressor) design configuration for commercial system. 05. Design, Construction and Testing of Parallel Compression Test Fixture
(2017)	Development Platform Operations and Maintenance	Continued operations of DP to conduct experiments and testing. Continued upgrading and maintenance of DP in support of Brayton technology development needs at higher temperature and power. Installation and maintenance of adequate infrastructure to support technical work

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