-FINAL DRAFT- SAND2014-15559R

April 9, 2019

SAND2014-XXXX
Unlimited Release
Submitted July 8, 2014

Request for Information:
DE-SOL-0006998

Supercritical Carbon Dioxide Brayton Cycle Energy Conversion Research and Development Program

Sandia National Laboratories

Federally Funded Research and Development Center

P.O. Box 5800
Albuquerque, NM 87185

Technical Point of Contact:
Evaristo J. Bonano
Phone: (505) 844-9720
e-mail: ejbonan@sandia.gov

Business Point of Contact:
Alyssa J. Christy
Phone: (505) 844-4542
e-mail: ajchris@sandia.gov

Role in sCO_2 Technology:
Leverage our technical knowledge and operating s-CO_2 Brayton cycle facility, combined with industry participation and our science-based engineering/system engineering approach, to retire technical, developmental, and maturation risks to create a commercial viable s-CO_2 Brayton cycle power conversion system.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Executive Summary

A closed Brayton cycle recirculates the working fluid, and 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, such as supercritical carbon dioxide (s-CO_2), is maintained near the critical point during the compression phase of the cycle. 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 results in thermal efficiency that is significantly improved over the efficiency attainable in an ideal-gas Brayton cycle.

Another advantage of using a supercritical cycle is that the overall footprint of the power-conversion system can be significantly reduced, as compared to the same power output of a steam-Rankine cycle, due to the high pressure in the system and resulting low volumetric flow rate. This allows for the heat-rejection heat exchanger and turbine to be orders of magnitude smaller than for similar power output steam-Rankine systems. Other potential advantages are the reduced use of water, not only due to the increased efficiency, but due 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.

In 2006, Sandia National Laboratories (SNL), recognizing these potentially significant advantages of a higher efficiency power cycle, used internal funds to establish a testing capability and began partnering with the U.S. Department of Energy Office of Nuclear Energy to develop a laboratory-scale test assembly to show the viability of the underlying science and demonstrate system performance. Since that time, SNL has generated over 100 kW-hours of energy, verified cycle performance, and developed cycle controls and maintenance procedures. The test assembly has successfully operated in different configurations (simple Brayton, waste heat cycle, and recompression) and tested additives to the s-CO_2 working fluid. However, challenges remain to confirm viability of existing components and suitability of materials, demonstrate that theoretical efficiencies are achievable, and integrate and scale up existing technologies to be suitable for a range of applications. To establish a clear direction for its Brayton cycle effort, the SNL Brayton team recently adopted this mission statement:

> *By the end of FY 2019, Sandia National Laboratories shall develop, with industry, a fully operational 550˚C, 10 MWe R&D Demonstration s-CO_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.*

In late 2013, SNL conducted an internal review of its technical progress on s-CO_2 closed Brayton cycle technology. That review helps inform this response to the questions regarding technical issues, challenges, and gaps and R&D needs. The technical issues and challenges identified by that review can be generally categorized as system design and efficiency of the system; reliability of the hardware; the need for improved physical models and computer simulation; and gaps in the underlying scientific foundation. In addition to these four technical issues, operations and safety issues should be recognized among the important technical challenges affecting scale-up and commercial deployment of power conversion system based on the s-CO_2 Brayton cycle.

Also 2013, SNL conducted an internal commercialization review for s-CO_2 Brayton cycle technology. The results of this review demonstrate that the technology has applicability across various power generation applications and may offer significant economic advantages over current technologies once fully developed. The results also showed that the development of this technology involves a long-term process, and significant technical challenges must be overcome prior to market adoption of a full system. Due to these uncertainties, market projections are highly speculative and additional research is required to better understand initial applications and applications where industry demand will be highest. SNL is committed to conducting an extensive market review that will leverage market/economic data and participation with industry stakeholders to identify early adopters and determine future market projections. Market demand and initial applications will likely be a result of advantages relative to existing technologies, such as improved energy conversion efficiency, reduced water use, lowered greenhouse gas emissions, and lower cost. In addition, there may be demands for technologies at the component level improved as a result of system level R&D, such as advanced heat exchangers and turbomachinery.

Commercialization of s-CO_2 Brayton cycle technology will depend on various financial, technical, regulatory, social, and value chain factors. These must be properly understood and addressed before commercialization and market risks are alleviated. In order to reduce the risks associated with these factors, it will be essential to support smaller scale projects that mitigate potential risk elements.

Demonstrating the technology at a level that is acceptable for commercialization will require national coordination of research and development activities that involve offices within DOE, national laboratories, academic institutions, industry partners, and other stakeholders. These participants will be involved at varying levels and at different stages within the R&D process. This interaction will be complicated due to the number of stakeholders involved, but can be addressed by considering structural/organization options and considerations for program management. In addition to R&D coordination, information sharing and program feedback will be critical elements of an initial s-CO_2 Brayton cycle technology development program and long-term commercialization success. Many participants have proprietary processes which prevent them from open sharing and communication. Approaches can be taken, though, to manage information sharing risks and constraints to ensure information is properly protected in order to optimize the interactions.

Contents

Nomenclature

ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
DOE	U.S. Department of Energy
EPC	engineering, procurement, and construction
ORNL	Oak Ridge National Laboratory
R&D	research and development
s-CO_2	supercritical carbon dioxide
SNL	Sandia National Laboratories

1 R&D NEEDS

Introduction—A closed Brayton cycle recirculates the working fluid, and the turbine exhaust is used in a recuperating heat exchanger to preheat the feed to the heat source before the turbine feed. A "supercritical cycle" is a closed Brayton cycle in which the working fluid, such as supercritical carbon dioxide (s-CO_2), is maintained near the critical point during the compression phase of the cycle. 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 results in thermal efficiency that is significantly improved over the efficiency attainable in an ideal-gas Brayton cycle.

Another advantage of using a supercritical cycle is that the overall footprint of the power-conversion system can be significantly reduced, as compared to the same power output of a steam-Rankine cycle, due to the high pressure in the system and resulting low volumetric flow rate. This allows for the heat-rejection heat exchanger and turbine to be orders of magnitude smaller than for similar power output steam-Rankine systems. Other potential advantages are the reduced use of water, not only due to the increased efficiency, but also due to the fact that the heat rejection temperature is significantly higher than for steam-Rankine systems, allowing for significant heat rejection directly to air.

In 2006, Sandia National Laboratories (SNL), recognizing these potentially significant advantages of a higher efficiency power cycle, used internal funds to establish a testing capability and began partnering with the DOE Office of Nuclear Energy to develop a laboratory-scale test assembly to show the viability of the underlying science and demonstrate system performance. Since that time, SNL has generated over 100 kW-hours of energy, verified cycle performance, and developed cycle controls and maintenance procedures. The test assembly has successfully operated in different configurations (simple Brayton, waste heat cycle, and recompression) and tested additives and alternatives to the s-CO_2 working fluid. The s-CO_2 closed Brayton cycle is shown schematically in Figure 1, and Figure 2 shows photographs of the SNL Brayton Laboratory test assembly with some of the major components labeled.

However, challenges remain to confirm viability of existing components and suitability of materials, to demonstrate that theoretical efficiencies are achievable, and to integrate and scale up existing technologies to be suitable for a range of applications.

A research and development effort including a medium-to-large-scale supercritical closed Brayton cycle demonstration could help solve these challenges and reduce technological and commercial risks, resulting in a cross-cutting energy solution that contributes to meeting national climate and clean energy goals and facilitates industrial competitiveness.

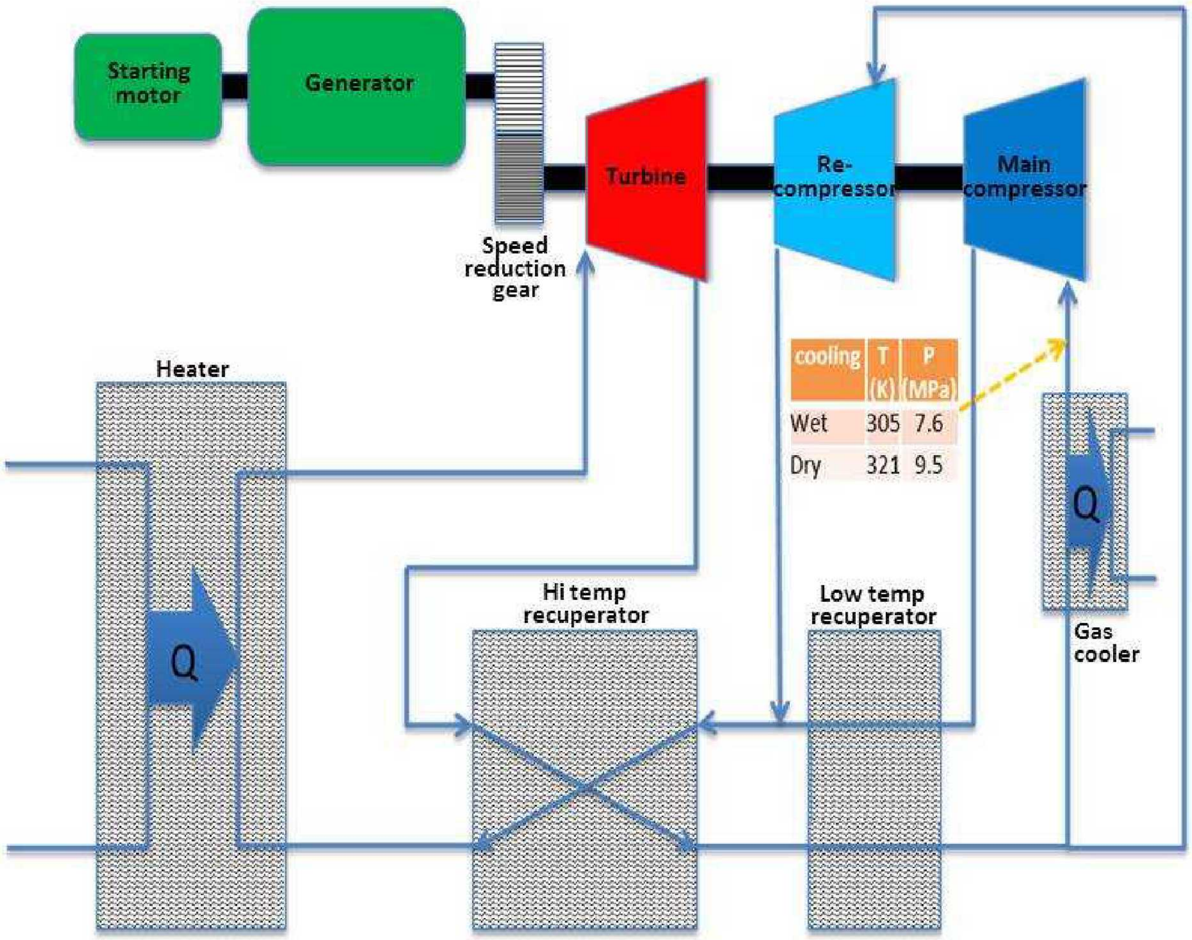
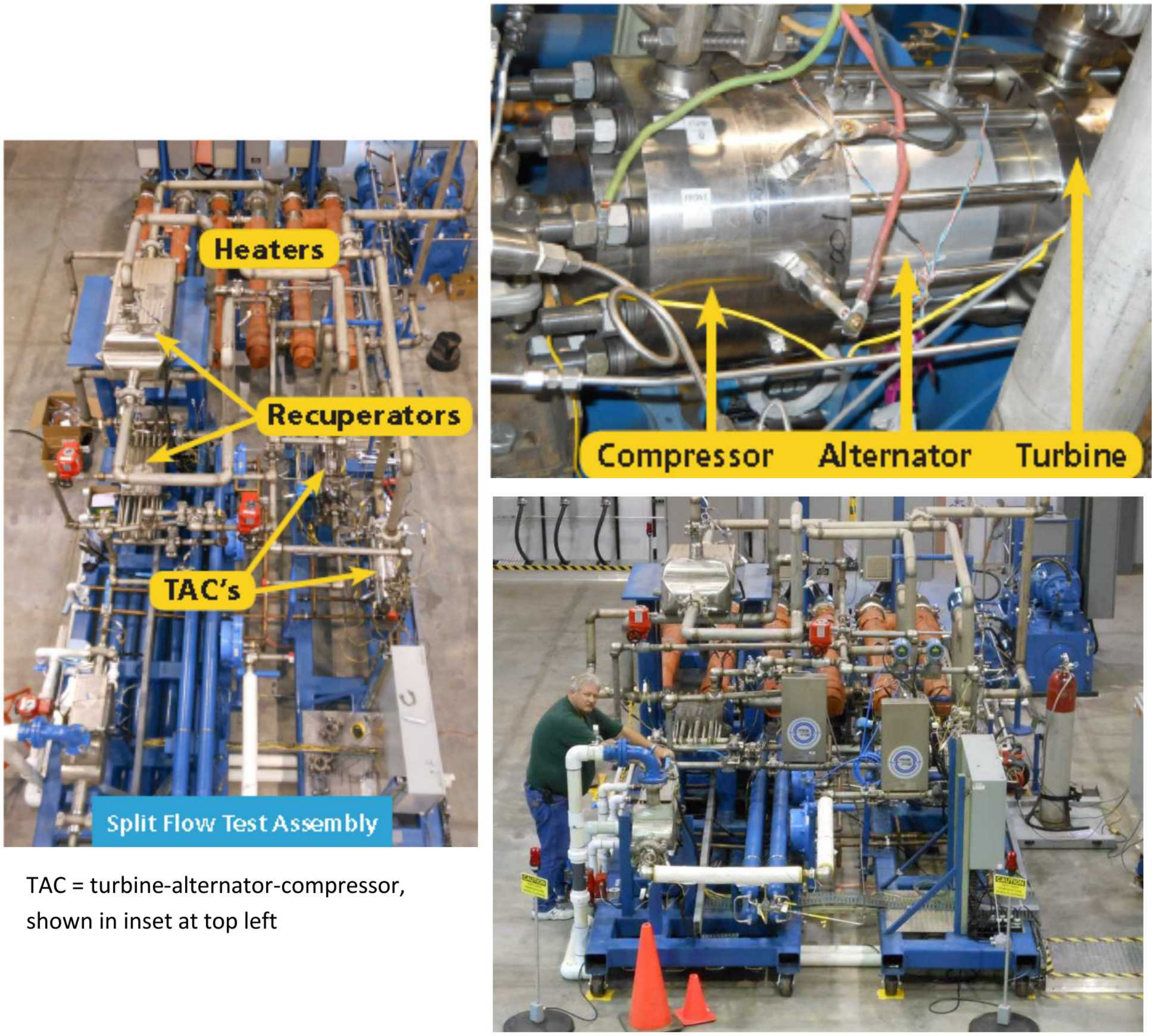


Figure 1. Recompression Closed Brayton Cycle: Schematic illustration



TAC = turbine-alternator-compressor,
shown in inset at top left

Figure 2. Recompression Closed Brayton Cycle: photos of the SNL Brayton Laboratory test assembly, with major components labeled

1.1 Technical Issues: Technical Issues, Challenges, and Technology Gaps Affecting the Scale-Up and Commercial Deployment of the s-CO_2 Brayton Cycle

SNL is investigating s-CO_2 Brayton cycles for power conversion with solar, geothermal, nuclear, fossil, or waste heat sources, which has the potential for greatly increased efficiency and also, due to its reduced size, lower capital costs for electrical power generation. The investigations use SNL's reconfigurable 150 kWe, 550°C s-CO_2 recompression closed Brayton cycle test article (750 kW heat source, generating capacity of 250 kWe), which was manufactured and assembled in 2008 and commissioned in 2009. These investigations serve as the basis for our understanding of the technical issues, challenges, and technology gaps affecting the scale-up and commercial deployment of this technology.

In late 2013, SNL conducted an internal review of its technical progress on s-CO_2 closed Brayton cycle technology. The issues and challenges related to scale-up and commercial deployment identified by that review can be generally summarized as system design and efficiency of the system (Section 1.1.1); component reliability and degradation (Section 1.1.2); the need for improved physical models and computer simulation (Section 1.1.3); and gaps in the underlying scientific foundation, which are addressed throughout this section as relevant. In addition, operations and safety issues (Section 1.1.4) should also be recognized as challenges affecting the scale-up and commercial deployment of the s-CO_2 Brayton cycle.

The components that will not contact the working fluid are mature technologies. Design optimization appropriate for a given application would be required, but none of these components appear to present an obstacle to commercial deployment, and they can be assumed to be predictable in their cost, reliability, and performance. These subsystems and components (which are not discussed further except in the context of their system functions) include:

- Electrical generation subsystem
- Gearbox
- Heat rejection subsystem
- Heat source subsystem
- s-CO_2 inventory control
- Plant controls
- Instrumentation.

1.1.1 System Design and Efficiency

Closed Brayton cycle systems have yet to achieve their theoretical efficiency. s-CO_2 systems must achieve greater than 35% to be commercially competitive with existing steam-Rankine systems. To achieve this system efficiency, two advances must occur. First, a higher-power and larger-scale system must be built so as to overcome the windage, thermal, and other losses inherent in smaller scale systems. Second, each of the components in the system must be designed to operate at near peak performance, and must overcome the additional challenges that arise in integrating subsystems and components together. SNL's system model (Brayton SC) predicts that an efficiency of 48% for a 550°C, 10-MWe system could be achieved if all the components perform at efficiencies or effectiveness above 90% and the pressure drops through the loop are kept very low. Figure 3 shows an example of specific steps that can be taken to improve on the demonstrated cycle efficiency to date. The specific set of operational parameters, component designs, and system geometric configuration that results in adequate efficiency for commercialization is a major uncertainty at this point that needs to be resolved by modeling, component research, and sound systems engineering practices.

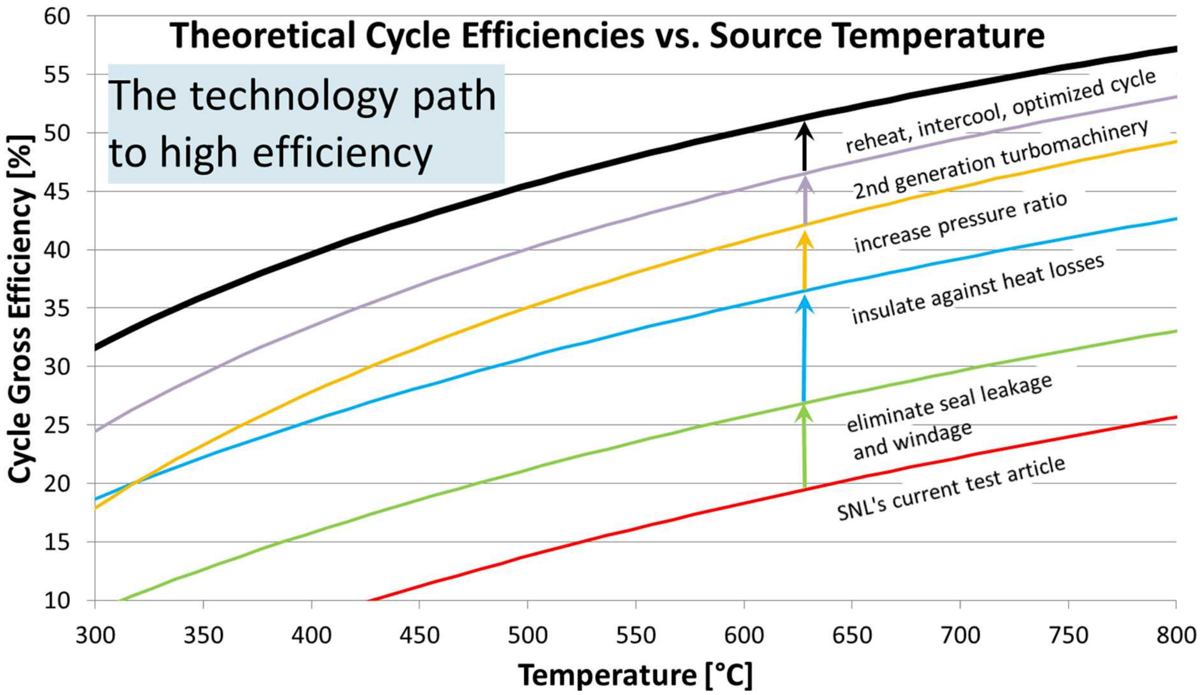


Figure 3. Example of predicted improvements leading to high conversion efficiency

The subsequent sections describe the system components where significant design and performance uncertainty remains and the primary issues they face. In addition to addressing the engineering challenges described there, fundamental science investigations are needed in the following areas:

- The effects of unavoidable impurities in the s-CO_2 working fluid such as carbon monoxide and water vapor on the critical properties of pure carbon dioxide
- Dynamic processes within the system, such as pressure surging, heat transfer and convection, and turbulent flow conditions
- Pressure waves and acoustics.

1.1.1.1 Seals

For an s-CO_2 system that is scalable to power levels required by industry (10 MWe to 1,000 MWe), turbine and compressor shafts must both penetrate a high pressure boundary and provide minimum friction to the rotation of the shafts. This has not been demonstrated at the pressures and temperature needed for this application. Use of shaft seals isolates the generator, radial and thrust bearings, and any necessary starter motors from the high pressure/high temperature CO_2 environment. Placing these components outside of the environment allows the use of industry standard bearings.

Seal designs can be grouped into: (1) contacting seals such as lip seals, mechanical face seals, and brush seals; and (2) non-contacting types including labyrinth seals, gas film-riding face seals (or 'dry gas' seals), and magnetic seals, among others. Each solution carries advantages and disadvantages with respect to leakage rates, cost, lifetime, maintenance, and durability, and pressure, temperature, and speed capabilities.[1] System efficiency is extremely sensitive to volumetric leakage due to the high density s-CO_2 fluid. High surface velocity of rotating parts also poses a challenge. Temperature of the seals will need to be actively maintained to prevent overheating.

Commercial experience with s-CO_2 shaft seals to date is largely based upon CO_2 transport and injection operations in support of enhanced oil recovery. This application has been successfully met in a range of low temperature supercritical fluid conditions at low to moderate speeds (3,600 to 8,000 rpm) by non-contacting CO_2-film dry-gas seals. Off-the-shelf solutions for high pressure s-CO_2 sealing do not presently meet the requirements for the high temperatures that would be required at the turbine end of an s-CO_2 power cycle.[2]

1.1.1.2 Bearings

Proper design and selection of bearings is frequently one of the most important factors to turbomachinery system performance and reliability. The technical challenge here is to determine the approach that is suitable for the mid-scale conversion system and develop a specific configuration that results in acceptably low frictional loss and also survives the corrosion and erosion environment. A number of different technologies may be considered, but, for high-speed, high-load applications such as power production turbomachinery, fluid film (hydrodynamic) bearings and rolling element bearings have historically been the industry workhorse.

In comparison to hydrodynamic oil bearings, magnetic bearings systems typically present a larger upfront cost, which over system lifetime may be recovered in the form of reduced maintenance needs. Magnetic bearings have the added advantage of allowing an extremely detailed level of bearings health monitoring.

In light of these preliminary considerations, a mid-scale (~10 MWe) s-CO_2 power application is most likely aligned with hydrodynamic oil bearings or magnetic bearings. To this point, the main experience with s-CO_2 turbine bearings has been a product of microturbine testing based at SNL, in concert with specialty turbomachinery developer Barber-Nichols Inc. Bearings on this test platform were fluid film gas foil bearings, which actually use the process high pressure CO_2 for lubrication. This design choice was made on the basis of the small size and high speed requirement for this machine, and the limited development of high pressure s-CO_2 gas seals.

---

[1] J. Pasch, M. Carlson, T. Conboy, D.W. Fleming, A. Kruizenga, J. Neely, and G. Rochau, *Supercritical CO2 Power Conversion System (10MW Class): Level 2 Milestone Completion.* (Official use only, commercial proprietary), 2014.
[2] Pasch, J.; M. Carlson; T. Conboy; D.W. Fleming; A. Kruizenga; J. Neely; and G. Rochau, *Supercritical CO2 Power Conversion System (10MW Class): Level 2 Milestone Completion.* (Official use only, commercial proprietary), 2014.

Therefore, the observations on bearing performance derived from the SNL Brayton experiments do not inform likely bearing performance in larger systems where other bearing types would be utilized. Bearings performance on this test article was characterized by high frictional losses, though with significant thrust and radial load support capability.

1.1.1.3 Turbomachinery

Turbomachinery includes turbines, compressors, and associated pressure vessel housings. While the bearings and seals are an integral part of the subsystem, specific attention is dedicated to these components elsewhere in this report. The compressor elevates the working fluid pressure from the cycle minimum at the inlet to the cycle maximum at the discharge. All other pressures around the loop lay within this pressure range. The turbine extracts energy from the hot, expanding working fluid from a pressure slightly lower than compressor discharge down to a pressure slightly higher than the compressor inlet pressure. Therefore, the turbine pressure ratio will always be slightly less than that of the compressor.

Good and precise design of both the compressor wheel and turbine wheel is essential to achieving high component efficiency and resulting high system efficiency. The high density, high pressure, and rapidly changing material properties of CO_2 near the critical point is relatively new and very different regime for turbomachinery design, but the fundamental scientific basis and engineering tools for turbine and compressor design are fairly mature and reliable. The s-CO_2 turbines and compressors in the SNL Brayton Laboratory system have performed very close to the design maps generated from first principles and have operated effectively above and below the critical temperature without the typical mechanical slugging that occurs with steam. Therefore, it is anticipated that there will not be major surprises in the turbomachinery design and operating efficiency as one scales up to higher powers.

1.1.1.4 Heat Exchangers

Recuperation is essential to achieve the highest efficiencies from a closed Brayton cycle. This cycle maximizes turbine work by expanding the working fluid at high temperature and pressure and compressing it at near-liquid conditions in order to minimize the back work ratio. This leaves a large enthalpy difference between compressor outlet and turbine inlet conditions that must be bridged using some combination of external and internal heat transfer (heating, cooling, and recuperation). Internal heat transfer through recuperation significantly increases the efficiency of a cycle with fixed turbomachinery conditions by reducing the amount of external heating and cooling required by the cycle. The technical challenge is determining the optimal cycle design, balancing increases in efficiency with the increased system costs as more recuperation is added.

The recompression Brayton cycle utilizes two recuperators, as shown previously in Figure 1 and Figure 2. Splitting the recuperation process into two parts allows for more effective heat transfer and overall higher system efficiency as discussed further in the subsystem details. A major constraint to the design is to avoid a large pressure drop along each leg of the heat exchanger, while pursuing high heat transfer effectiveness. In addition, the design must accommodate both high operating temperatures and pressures. Figure 4 presents curves of maximum allowable stress from the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel

Code for pressure vessel materials. Overlaid on these curves are operational regions for air Brayton components, s-CO_2 Brayton cycle components, and steam boilers based on a pressure containment factor of 0.22. All materials show a dramatic reduction in allowable stress over a range of temperatures from 550°C to 650°C, suggesting the initial mid-scale demonstration be limited to 550°C.

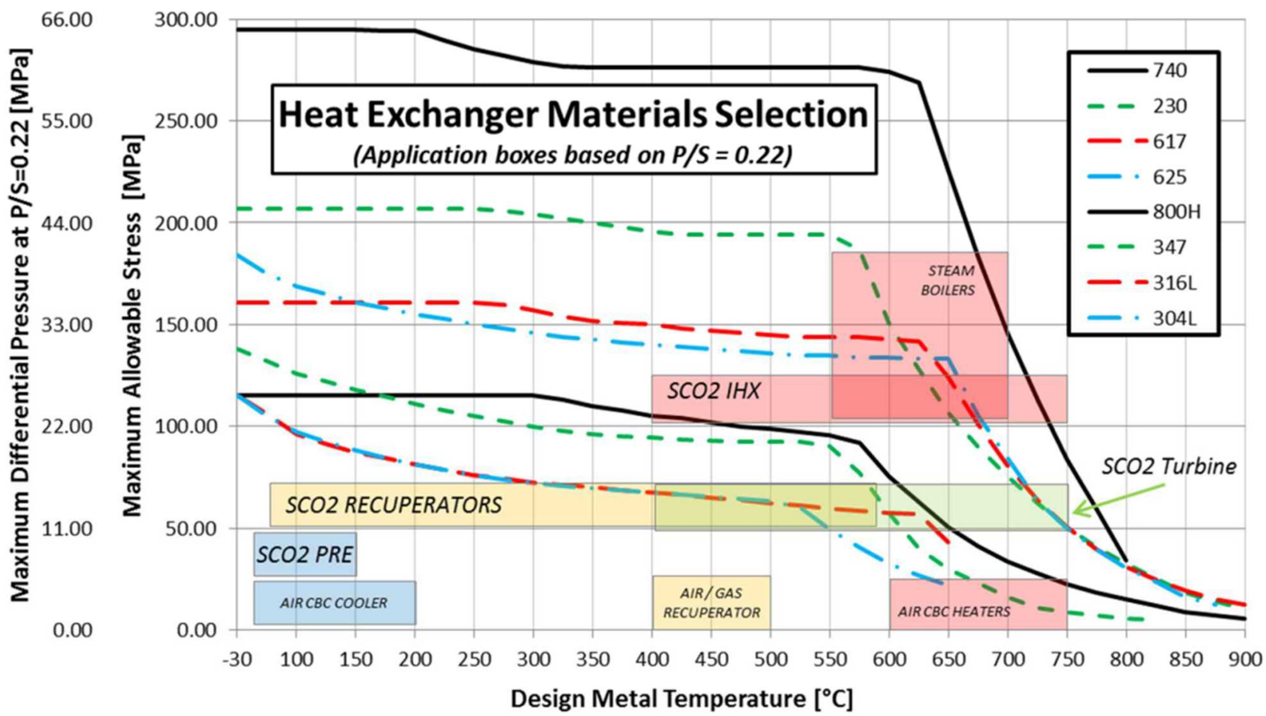


Figure 4. Allowable stresses for several materials relevant to s-CO_2 closed Brayton cycles, with conditions for several different heat exchange applications overlaid based on a pressure containment factor of 0.22.

1.1.1.5 Valves

Any recompression closed Brayton cycle will require three valve functions: isolation, modulating/throttling, and pressure relief. The isolation and throttling valves are highly engineered and are, therefore, the highest cost valves. Operating mechanisms for these systems exist, but the valve body, internal components, and seat will be immersed in hot s-CO_2 and subject to materials effects that create uncertainty regarding the design of the valves. The valve actuator seals will require R&D to demonstrate that they can survive the hot s-CO_2 environment. However, the gate seal does not need to be an absolute seal. This supports metal to metal seating in the main flow channel.

1.1.2 Reliability

There are three areas where reliability is seen to be a technical issue or challenge to scale-up and commercial deployment of the s-CO_2 Brayton cycle:

- Materials Interactions
- Erosion
- Creep.

1.1.2.1 Materials Interactions

Materials reliability uncertainties include: carburization and sensitization and high-temperature corrosion, and erosion. The effects of material interactions can impact the design, reliability, and lifetime of essentially all of the system components. These uncertainties are discussed below.

Carburization and Sensitization— Even though numerous Magnox nuclear reactors have operated with CO_2 coolant at 336°C and 7 atm pressure for over 30 years, there are potential issues that must be resolved at higher temperatures. Formation of metal carbides can result in changes in alloy chemistry and may exhibit erosion, abrasion, or corrosion of the materials or brittle fracture of piping and components during operation. Carburization and sensitization, even in stabilized grades of steel such as 321 and 347, are of concern for long term performance. Carburization of ferric-martensitic steels has occurred at 550°C, and, while this has been observed with 304 at elevated temperatures,[3] the relatively short duration (less than 3,000 hours) of testing and scarce data available make future testing a priority to assess long-term impact on both ferric-martensitic and austenitic steels.

At temperatures above 550°C, a limited number of alloys can be considered to accommodate aggressive temperature and pressure requirements. As was shown in Figure 4, allowable stress falls significantly for most alloys over a range of temperatures from 550°C to 650°C.[4] Alloys 740, 230, 625, and 617 have the highest strength, but they also have the highest costs and most complex fabrication procedures, require long lead time, and are not widely available in required standard forms. Of these alloys, to date, only 625 and 230 have been tested up to 3,000 hours in pure CO_2.[5] Carburization of Inconel (also called Alloy 600) was observed, but the data is limited. Clearly, more research is needed in order to understand and develop measures that can mitigate or avoid long-term effects of carburization and sensitization on system operation.

High Temperature Corrosion—Materials with high chromium content (i.e., typical austenitic alloys) tend to perform well in s-CO_2 due to the formation of a protective chromia scale, which acts as diffusion barriers inhibiting oxidation of the base metal. Past research indicates that chromia and potentially alumina may be suitable for corrosion protection. Up to this point,

---

[3] H.E. McCoy, "Type 304 Stainless Steel vs Flowing CO_2 at Atmospheric Pressure and 1100–1800F." *Corrosion*, *21* (3): p. 84–94. 1965.

[4] M. Carlson, T. Conboy, D. Fleming, and J. Pasch. "Scaling Considerations for SCO2 Cycle Heat Exchangers," Paper GT2014-27233. ASME TurboExpo, 2014.

[5] V. Firouzdor, K. Sridharan, G. Cao, M. Anderson, T.R. Allen. "Corrosion of a Stainless Steel and Nickel-Based Alloys in High Temperature Supercritical Carbon Dioxide Environment." *Corrosion Science*, *69*: p. 281–291. 2013.

relatively little information is available to determine expected corrosion rates in relatively pure CO_2.

1.1.2.2 Erosion

Erosion is a significant issue being encountered in the SNL recompression closed Brayton cycle experiment. Substantial erosion in the turbine blade and inlet nozzle has been observed.[6] It is believed that this is caused by small particulates that originate from the spallation of corrosion products of different materials and at different locations within the loop. These particles are entrained through the nozzle vane and turbine, thus causing erosion. Owing to turbine speeds remaining constant, the issue of erosion is expected to be encountered in scale-up. In addition, inspection of the printed circuit heat exchanger within the recompression closed Brayton cycle loop found an agglomeration of hydrocarbons and erosion products at the inlet.

To address the erosion issues in gas turbines, a wide variety of coating systems has been explored by SNL,[7] and some coatings are in commercial use today. The selection of an appropriate coating system depends on the underlying substrate metal as well as (perhaps more importantly) on the properties of the particulate causing the erosion.

1.1.2.3 Creep

Creep, the tendency of a solid material to move slowly or deform permanently as a result of mechanical stresses, is a primary potential limitation that must be accommodated in the design. In the turbomachinery, the gaps between the turbine and compressor wheels and their housings are small, the tip speeds are large, and the temperature (in the turbine) is high. Thus creep becomes a lifetime issue. In the heat exchangers (recuperators), the pressure difference between the hot and cold legs is large, and the design goal is to minimize the wall thickness between them while keeping flow passages small and numerous. Again, creep becomes a lifetime issue. Once designed for a particular operational time, lifetime extension becomes problematic. If the system design constraints drive one to exotic materials (e.g., due to CO_2 interactions), one may need to obtain creep rate date for that material. There may be some uncertainty in how carburization affects the creep rate.

1.1.3 Physical Models and Computer Simulation

There are mass balance and thermodynamic models used for analysis of results from SNL's closed Brayton cycle experiments, and the current modeling capabilities are adequate to meet current requirements. SNL has created a steady state model (Brayton SC) and Argonne National Laboratory (ANL) has created a dynamic model[8] of the SNL Brayton cycle test assembly, and the prediction of steady state operating conditions for a split-flow closed Brayton cycle thermal-

---

[6] D. Fleming; J. Pasch; T. Conboy; D. Fleming; A. Kruizenga; and M. Carlson. "Corrosion and Erosion Behavior in Supercritical CO2 Power Cycles," Paper GT2014-285136. ASME TurboExpo, 2014.

[7] J. Pasch, M. Carlson, T. Conboy, D.W. Fleming, A. Kruizenga, J. Neely, and G. Rochau, *Supercritical CO2 Power Conversion System (10MW Class): Level 2 Milestone Completion.* (Official use only, commercial proprietary), 2014.

[8] A. Moisseytsev and J.J. Sienicki. *Supercritical Carbon Dioxide Brayton Cycle Control Strategy Development for Sodium-Cooled Fast Reactor Plants: Investigation of Active Reactor Control and Minimum Cycle Temperature Control*. Argonne National Laboratories, ANL-ARC-258, 2013.

to-electrical power conversion system is an area of active development at SNL. Improvements to the Brayton SC model continue to be implemented as knowledge is gained about the behavior of the system from testing experience. Brayton SC generates predictions for steady state operating points and that lends itself to easy modifications and distribution. The program has been independently verified to have the correct physics and to flow logically, and all trade studies performed to date yield reasonable results. Brayton SC is continuously updated as SNL continues to expand into new operational and performance conditions.

However, the existing models do not yet have the predictive power sufficient for use as the operations, physics, and engineering tools needed for full commercial deployment of s-CO_2 Brayton cycle technology. Commercialization of s-CO_2 Brayton cycle technology will require the availability of a detailed systems model that addresses both steady-state and dynamic behavior. A system model is needed for computational experiments to, for example, identify optimal or near optimal conditions for a variety of applications. A fully predictive model, able to capture both steady state and transient effects, thereby capable of challenging and informing test results, is needed to give confidence that the underlying science is adequately understood. As indicated in Section 1.1.1, there are gaps in the fundamental scientific understanding of some of the dynamic processes within the system, such as heat transfer and convection and turbulent flow conditions, and results from scientific investigations into those processes must be translated into predictive modeling capabilities.

1.1.4 Operations/Safety

Safe operation would be an inflexible requirement of any commercial application of the s-CO_2 Brayton cycle. The experience gained in operating the SNL closed Brayton cycle experiment, both in the simple configuration and the recompression configuration, provides a basis for understanding scaled-up, commercial operation of s-CO_2 Brayton cycle systems. A great deal of operational know-how has accrued over the years of safe testing at SNL. Our experience suggests areas of concern for higher power systems are:

- Understanding the potential ramifications of abrupt changes in heat rejection while operating near the critical point. Compressor surging events have occurred in the small-scale system as a result of this phenomenon.
- Methods to prevent the two compressors in a parallel compression system from surging.
- Instrumentation and data processing which are useful to understand the operating point and margin to surge of the two parallel flow compressors real-time.
- Understanding the response and performance of the compressor while operating with two-phase flow.

While the SNL Brayton Laboratory has provided preliminary insights into the above issues, the scale-up and commercial deployment of s-CO_2 Brayton cycle presents these remaining uncertainties:

- Safe heating ramp rates for all components to avoid immediate damage at one extreme, and avoid the less obvious but equally important reduction in service life by unnecessarily high cycle fatiguing at the other extreme.

- While transient management operations may be established for the engineering scale SNL loop, confidence in the applicability of these operations to a much larger scale system will come only through experience.

1.2 Potential R&D Activities to Address s-CO_2 Brayton Cycle Challenges

The R&D activities outlined in this section would address the issues, challenges, and technology gaps described in Section 1.1. To guide that R&D, the first step is establishing rigorous systems engineering process consistent with the guidance of DOE 413.3, starting with a Program Plan, to help identify critical decisions, guide decision-making, and set priorities toward the development of a system design for a scalable, mid-scale (~10 MWe) system. Examples of initial, high-priority testing, investigation, and design efforts are provided in Section 1.3. Generally, these R&D activities would include:

- Preliminary materials research and design activities (see Section 1.3 for details)

- Testing subsystems, components, and materials with a dedicated test rig(s) (Section 1.2.1)

- A full system demonstration of a scalable s-CO_2 closed Brayton cycle system (Section 1.2.2)

- Operations and performance mapping studies on the system demonstration to optimize performance and efficiency under varying environmental conditions and for different applications, including investigation of the effect of additives to the s-CO_2 (Section 1.2.3)

- Determination of reliability and degradation rates (Section 1.2.4)

- Continued development of codes, models, and simulation (Section 1.2.5)

To a large degree, SNL's experience with its closed Brayton cycle test article indicates that a scalable, reconfigurable, full system demonstration program can be initiated soon. However, before an overall system demonstration is designed and built, a comprehensive system design study using systems engineering principles must be performed to identify initial estimates of component designs and identify the primary technical and programmatic risks. Individual components and subsystems should be evaluated to guide these design decisions and identify what component testing is needed. Materials compatibility issues must be identified, and testing in high temperature CO_2 environment must be performed as needed. It is important to establish sufficient confidence that the materials are reliable for the required duration before initiating a scalable system demonstration program. These prioritization issues are discussed further in Section 1.3.

1.2.1 Testing Subsystems, Components, and Materials with Dedicated Test Rigs

The most significant sources of uncertainty, which include seals, bearings, and general materials (metals and soft goods) performance in CO_2, are the highest priority for component testing. Of particular importance will be materials that vendors use in the design of components for other applications but for which the performance in a CO_2 environment is not completely understood. Dedicated component testing would increase confidence in these subsystems and components, and it can also serve to address some of the remaining uncertainties in the fundamental science.

Test rigs need to be developed for most of these components that can reproduce the relevant conditions, as identified by the top-level systems model and operational experience from the small-scale SNL Brayton Laboratory. For the bearings and seals, these will include, for example, shaft rotational speed, ambient pressure, pressure differential across the seal, ambient temperature, appropriate CO_2 conditions, vibrations, shock, and, in the case of magnetic bearings, the electromagnetic environment.

The test rigs noted in the previous section are available for assessing reliability and degradation rates for each of their respective components.

Even though application of this working fluid is relatively new, the fundamental scientific basis and engineering tools for turbine design are mature and reliable. The turbines in the SNL s-CO_2 Brayton Laboratory system have performed very close to the design maps generated from first principles. Therefore, our view is that a dedicated test rig is not necessary for the turbomachinery. A full demonstration system as described in Section 1.2.2 would effectively serve as the "test rig" for the turbomachinery.

1.2.2 Full System Demonstration

A scalable, mid-scale (~10 MWe) s-CO_2 closed Brayton cycle demonstration should be constructed in such a manner as to: (1) allow reconfiguration of the subsystem elements to allow incorporation of R&D results as they improve performance; (2) allow the demonstration to be a test bed for components proposed by manufacturers of subsystem components; and (3) provide an upgradeable infrastructure that can support the increased temperature needs of future demonstrations. In addition to the fundamental objective of demonstrating system efficiency beyond that provided by existing steam-Rankine systems, the full system demonstration should include:

- Operations and performance mapping to explore system performance in various environmental conditions and for various potential applications, including, for example, dry air cooling applicable to power generation in deserts, passive reactor power down, and efficiency vs. turbine inlet temperature (Section 1.2.3).

- Characterizing the change in performance in system, subsystem, components, and materials and investigating materials degradation and reliability of components over extended operational time (Section 1.2.4)

- Continued development and validation of codes, models, and simulation tools that would be used for preliminary designs of even higher power systems and for commercial deployment of s-CO_2 closed Brayton cycle systems (Section 1.2.5).

In addition, the system demonstration would serve to investigate remaining uncertainties in fundamental science issues, including those identified in Section 1.1.1, and to continue investigation of the effect of additives to the s-CO_2.

Although many potential system layouts could be considered, as a preliminary design concept, SNL would recommend a system layout with a single turbine-generator and a separate turbine-driven unit with two compressors sharing a common shaft, which allows compressor speed to be optimized independently of the power turbine. As discussed in Section 1.1 and shown in Figure 4, most alloys show a dramatic reduction in allowable stress over a range of temperatures from 550°C to 650°C, suggesting the initial mid-scale system demonstration be limited to 550°C. Most codes and standards are well understood for a demonstration project like this one. All components for up to 600°C can be code certified with some ease. The components for scalable 550°C demonstration system would follow all applicable ASME, American Petroleum Institute, and American Gear Manufacturers Association code certifications. The integration of these components to a demonstration system would follow ASME B31.1 power piping code certification, yielding a complete code-certified Brayton demonstration. For Brayton cycle systems above 600°C, additional mechanical and/or corrosion test data would be needed to support ASME code approval for use in Brayton cycle heat exchangers. Other process conditions besides temperature will also necessitate additional research and development activity. A reconfigurable Brayton cycle demonstration system, in collaboration with smaller test rigs, could be critical to achieve code certification and commercial confidence in advanced materials for higher temperature operation and compatibility with novel heat transfer fluids.

1.2.3 Operations and Performance Mapping

As part of the demonstration of a scalable s-CO_2 closed Brayton cycle system, performance mapping studies at steady state conditions at various environmental conditions (e.g., wet cooling, dry cooling conditions) should be performed to investigate system performance. Among the goals of such studies would be the identification for optimized operational parameters for different applications of s-CO_2 closed Brayton cycle technology as well as geographically and seasonally varying environmental conditions. Monitoring objectives would include performance and stability as a function of system CO_2 loading, main compressor inlet temperature, turbine inlet temperature, and pressure ratio. Such studies would help establish optimum operating conditions for the various environmental (boundary) conditions. In addition, those trade studies should be performed during rapid, non-emergency transients, as well.

In addition to determining optimum operating conditions, the development of safe and reliable operating procedures for these various transients should be viewed as an important step in preparation for scaled-up commercial application of s-CO_2 Brayton cycle technology for energy production. Operating procedures based on the procedures already developed for the SNL Brayton Laboratory could be completed prior to initial startup of a full system demonstration, after the demonstration unit design is evaluated to identify necessary changes. These procedures would evolve through continuous improvement efforts as experience is gained on a demonstration project, serving as documentation of operational experience for future use.

Operations and performance mapping studies would also investigate the use of additives to the s-CO_2 working fluid. Engineering of the working fluid with CO_2-based mixtures appear to be best suited to cycles operating in the low temperature ranges characteristic of, for example, geothermal power, but additives can be investigated as a means to enable operation with a heat rejection temperature tailored to local climates or day/night cycle, boosting overall conversion efficiency without the need for custom turbomachinery.

1.2.4 Determination of Reliability and Degradation Rates

Addressing the reliability and degradation uncertainties related to materials interactions, erosion, and creep (as discussed in Section 1.1.2) is a key objective of R&D to address s-CO_2 Brayton cycle challenges. The test rigs noted in the Section 1.2.1 are available for assessing reliability and degradation rates for each of their respective components. Much of this reliability research will be performed prior to final component design or component integration. In addition, following assembly of the system, the energy conversion loop can be inspected after various periods of operation to look for degradation effects. For example, turbine nozzle erosion was discovered in the small-scale s-CO_2 Brayton cycle system in the SNL Brayton Laboratory only after operation of the integrated system. Finally, long-term degradation or reliability studies can continue using the test rigs even after final demonstration assembly is complete.

1.2.5 Continued Development of Codes, Models, and Simulation

A key element of an R&D program to support commercial deployment of s-CO_2 Brayton cycle technology is the development of detailed and validated computer models that can simulate the cycle behavior under various conditions and also predict the behavior of larger-scale systems. A validated system model also can be used for computational experiments to identify optimal or near optimal conditions. A fully predictive model, able to capture both steady state and transient effects, thereby capable of challenging and informing test results, is needed to give confidence that the underlying science is adequately understood. Detailed component models can be used to address thermal hydraulics, corrosion, aging and carburization.

As noted in Section 1.1.3, SNL has developed and will continue to improve first-generation system models and component models. Development of these models would continue using insights and validation data from the component test rigs and system hardware. For early modeling needs associated with the existing Brayton Laboratory and the preliminary needs of R&D activities including subsystem and component testing and development of a scalable, full system demonstration, current modeling capabilities are sufficient. Additional, dedicated modeling of components that are relatively new to this application would help to demonstrate a full understanding of performance.

Once a full system demonstration is built, the existing models would be used to improve system thermodynamic efficiency and understand potential materials and system efficiency and reliability concerns relevant to both the mid-scale system demonstration and full-scale commercial applications. For example, challenges are expected regarding the corrosiveness of s-

CO_2 at high temperatures and its performance as a carrier fluid, and addressing those challenges will need to be supported by new codes, models, and simulation methods.

1.3 Relative Priority, Estimated Timeframe, and Estimated Cost for Conducting Needed Research

Recognizing a full system demonstration of an operational mid-scale s-CO_2 Brayton power conversion system as a key milestone toward commercial deployment of the technology, the first priority for scale-up must be the R&D needed as preparation for such a full system demonstration. R&D that is either prerequisite to or would otherwise serve as productive preparation for a full system demonstration would include, for example:

- Continuing research on the small-scale SNL Brayton Laboratory to establish benchmarked models for design, operations, and upset conditions.

- Continuing research on corrosion/erosion and on purity requirements for s-CO_2 on Brayton cycle components.

- Continuing research on compact, high efficiency, low cost heat exchangers to establish a code case for future deployment.

- Designing and testing a durable seal for a 10 MWe s-CO_2 Brayton cycle operating at a maximum temperature of 650°C.

- Initiating a trade study to define the scaling principles from low power test articles (like the current Brayton Laboratory test assembly) to an operational 550°C, 10 MWe s-CO_2 Brayton power conversion system for full system demonstration.

The initial R&D needed prior to a full system demonstration is estimated to take about a year (though development and assembly of the demonstration system itself will take longer). At the start of such an R&D program, a rigorous systems engineering process, consistent with the guidance of DOE 413.3 and starting with a Program Plan, should be used to help identify critical decisions, guide decision-making, and set priorities. Key decisions defining the purpose of the program to be guided by the systems engineering approach include, for example:

- Operational strategy—A "normally off" demonstration system can be used to demonstrate cycle performance and to develop operational procedures (e.g., start-up, steady state, transient); however, if, in addition to these objectives, demonstration of system and subsystem long-term reliability and accumulation of operational time on components and materials is an important objective, then "normally on" is necessary, but entails additional costs and time involved in establishing utility connections.

- Heat rejection system—Wet cooling is typically used for power plant heat rejection, but dry cooling could be advantageous in arid environments and wherever water conservation is important. A key decision in scale-up of s-CO_2 Brayton cycle technology is whether the demonstration should use the common heat-rejection system, or whether it should focus on dry-cooling technologies that have potentially environmental benefits.

The timeline presented in Figure 5 presents one possible timeframe for an R&D program for scale-up of s-CO_2 Brayton cycle technology. This example approach uses the existing SNL Brayton Laboratory to continue work supporting modeling and operations studies. The demonstration system assumed in this example is a 10 MWe recompression closed Brayton cycle system, with wet cooling, maximum pressure and temperature of 20 MPa and 550°C, and a utility interface to a new power generation substation. Other configuration options would change activities suggested here. Using this approach, dry cooling would be tested with using simulated conditions, for example, and this grid-connected configuration will allow "normally on" operation of the demonstration system (the approach necessary for long-term demonstration of system reliability and operations. The initial timeframe SNL set for itself in its Brayton mission goal to develop a fully operational 550°C, 10 MWe s-CO_2 Brayton power conversion system for first demonstration is about five years.

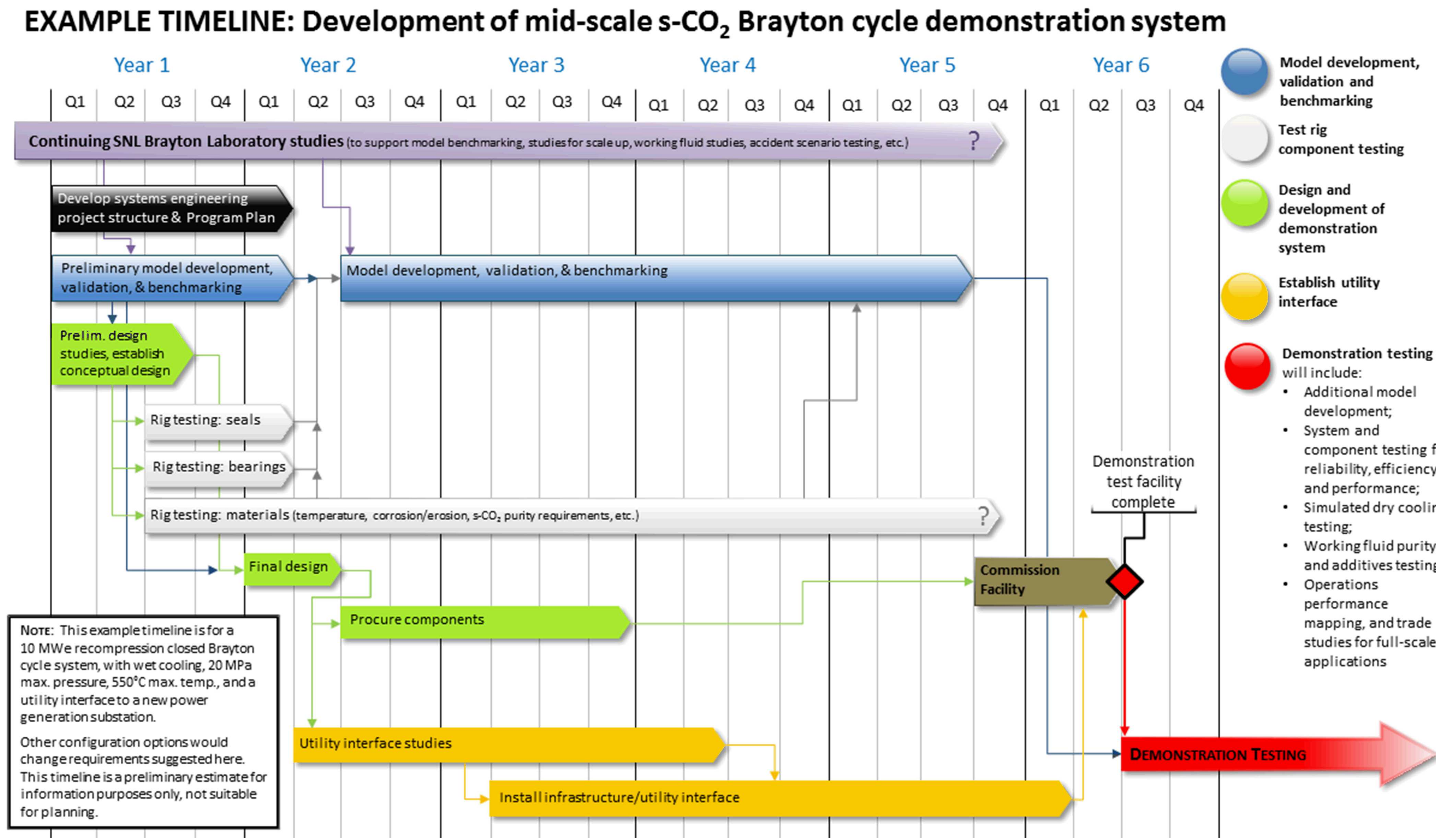


Figure 5. Example timeline for preliminary R&D and development and demonstration testing using a 10 MWe s-CO_2 Brayton cycle power conversion system

Once the 10 MWe 550°C s-CO_2 Brayton cycle demonstration system is commissioned, its testing program should include the objectives outlined in Section 1.2.2:

- Operations and performance mapping to explore system performance and efficiency in various environmental conditions and for various potential applications.
- Characterizing the change in performance and investigating materials degradation and reliability of components over extended operational time
- Continued development and validation of codes, models, and simulation tools that would be used for designs for commercial deployment of s-CO_2 closed Brayton cycle systems
- Investigate remaining uncertainties in fundamental science issues
- Continue investigation of the effect of additives to the s-CO_2.

SNL has developed a rough estimate of costs for development of the demonstration 10 MWe 550°C s-CO_2 Brayton cycle system, including the turbogenerator; turbocompressors; high-temperature recuperator; low-temperature recuperator; furnace; open-cooler heat rejection; turbine stop valve; turbine governor valve; gear box; turbomachinery controls; other instrumentation (two flow meters, instruments); inventory control; two-pole generator and starting motor; load bank; general building facilities and infrastructure; and contracting costs and fees. For this basic s-CO_2 Brayton cycle demonstration system, using load banking and without grid connections (a "normally off" system, as discussed above), the preliminary estimated costs are $29.3M. For a system capable of "normally on" operation, a facility could be connected to the grid using existing utility connections (such as those in place already at SNL) for an additional cost of about $0.4M (and a total cost of $29.8M). Using entirely new utility connections (i.e., a new gas line, a new power generation substation) would add about $5M to the cost, for a total cost of $34.3M (note that this is the set of options illustrated in Figure 5). These ROM cost estimates were developed informally, for general information purposes only.

1.4 Optimum Parameters for Specific Applications

The key differentiating characteristics of an s-CO_2 Brayton power cycle from small size to high efficiency at high turbine inlet temperatures make s-CO_2 Brayton power cycles applicable to many different power generation applications. Different applications are chiefly characterized by the operating characteristics of the heat source.

Nuclear—The very highly recuperated nature of the s-CO_2 Brayton cycle lends itself ideally to closed heat cycle sources, such as a nuclear reactor. The power cycle can be configured for either direct conversion using the CO_2 as the heat transfer fluid or for indirect conversion with molten salt or light gas as the primary heat transfer fluid. Such configurations would provide very high pressure (~35 MPa) operation with turbine inlet temperatures in the range of 500°C to 700°C. Typical nuclear reactor applications would be large generating facilities in the range of 300 to 1,000 MW.

Concentrating Solar Power—Both direct and indirect heating options are available for integration of an s-CO_2 Brayton power cycle into concentrating solar power applications. The small size of the s-CO_2 turbomachinery enables placement in the receiver to provide direct heating by concentrated sunlight. Such a configuration would operate at pressures of 20 to 25 MPa and very high turbine inlet temperatures on the order of 1,000°C. Direct conversion in the receiver minimizes losses due to high temperature gas transport. Alternatively, indirect receivers using either molten salts or solid particles could be used with subsequent heat transfer to the s-CO_2 working fluid. Such indirect receiver designs allow for thermal storage to decouple the power generation cycle from the solar cycle. Indirect receivers would operate over range of temperatures from 600°C for molten salt to 1,000°C for solid particle designs. Generating capacity for concentrating solar power applications would most likely be in the 10 to 100 MW range although applications above and below this range are possible under special circumstances.

Fossil Fuel—A large variety of fossil fuel combustion processes are compatible with the s-CO_2 Brayton power cycle. The operating temperatures of these combustion processes and the resultant turbine inlet temperature cover a wide range from 550°C to 900°C with operating pressures ranging from 15 to 35 MPa. Size and output of such systems reflect the size range in existing fossil fuel plants and could range from 50 MW to greater than 2 GW. The auxiliary benefits of reduced water demand and potentially smaller capital costs due to the size efficiency of s-CO_2 Brayton power plants along with the cycle efficiencies at higher temperatures drive integration of s-CO_2 Brayton power cycles into fossil fuel generation systems. The s-CO_2 Brayton power cycle may also find application in the bottoming cycle of conventional power plants because of these auxiliary benefits.

Geothermal—The typical temperature range for geothermal applications are at the low end of the efficiency profile for s-CO_2 Brayton cycles. Depending on the geologic conditions, this can range from 100°C to 300°C. Pressures are typically in the 15 MPa range. Despite the low efficiencies on the order of 7% to 21% for these inlet temperatures, the potential advantages of not requiring large quantities of water and the possibility of carbon sequestration make s-CO_2 Brayton cycle power systems an option for geothermal applications.

Waste Heat Recovery—These applications are characterized by lower quality temperature sources with typical temperatures in the range of 230°C to 650°C and operating pressure likely to be in the 15 to 35 MPa range. The lower efficiency of the s-CO_2 Brayton cycle for these input temperatures is offset by the small size of the needed turbo machinery and the relative simplicity of the cycle layout compared to conventional heat recovery systems. Installations of this type are typically small and usually generate power in the range of 1 to 10 MW.

1.5 Existing Codes, Models, and Simulation Methods to Support s-CO_2 Development and Specific Improvements Needed

As described in Section 1.1.3, there are existing codes, models, and simulation methods adequate to support the current state of s-CO_2 closed Brayton cycle development. Current modeling capabilities provide a good start for preliminary R&D activities, including subsystem and component testing and modeling to support development of a scalable, full system demonstration. Dynamic systems models presently exist that can function as predictive models. SNL and ANL have created steady state and dynamic models of the SNL Brayton cycle test assembly, and the prediction of steady state operating conditions for a split-flow closed Brayton cycle thermal-to-electrical power conversion system is an area of active development at SNL. SNL's steady state model, Brayton SC, is a useful, robust, stable, modular program that quickly generates predictions for steady state operating points and that lends itself to easy modifications and distribution. The program has been independently verified to have the correct physics and to flow logically, and all trade studies performed to date yield reasonable results. The model is continuously updated as SNL continues to expand into new operational and performance conditions.

The work related to improvements of codes, models, and simulation that SNL has identified as potential R&D activities needed for s-CO_2 closed Brayton cycle development are described in Section 1.2.5.

1.6 Non-technical Constraints and Risks

There are three key non-technical commercialization risks or constraints that should be considered as potentially limiting factors in the commercial deployment of the s-CO_2 Brayton cycle technology:

- Programmatic commitment
- Regulatory risk
- Supply chain limitations

Long-term lifecycle funding and programmatic commitment and continuity will be essential to ensure full development of the technology and necessary engagement of stakeholders. Both of these are critical to the success of the program. In addition, although not currently anticipated to be an issue, social acceptance of the technology should be monitored throughout the program to ensure challenges, resistance, and roadblocks that can contribute to funding and other constraints are identified and managed as early as possible.

Regulatory risks will vary by application, but demonstration of safety and reliability that meets regulatory requirements will be a major milestone in commercial deployment of new technology for power generation, and it can be challenging. Development of robust validated models and simulation capability along with detailed hazard analyses will be needed.

Supply of unique materials and components required for high temperature/high pressure boundaries may require significant lead time (perhaps measured in years). Where design innovations are a design requirement, there will necessarily be supply chain uncertainties. Testing of components and materials during R&D demonstration will help retire some of these uncertainties, but it may also introduce new ones. (It is worth noting, however, that SNL's current understanding is that there is an ample supply of CO_2 with sufficient sources to provide the inventories needed.)

Each of these nontechnical risks requires their own mitigation strategies. In addition to them, management of broad stakeholder involvement that engages industry, national laboratories, academia, materials and component suppliers, regulators, and the public, as appropriate, will be an important part of nontechnical risk mitigation. Aspects of this broad approach to stakeholder involvement are discussed in Sections 2.4 and 2.5.

1.7 Alternative Supercritical Fluids to Support the Brayton Cycle

Numerous alternative supercritical fluids have been proposed for use in Brayton cycles, but to maximize efficiency for a target environment the fluid selection is driven by compression work. Although alternate fluids have been considered for space applications[9] to raise the heat rejection temperature, for terrestrial applications, the CO_2 rejection temperature (88°F) is ideal. There are several hydrocarbons with comparable critical temperatures, but these also come with considerable safety and development risks. Therefore, no alternative supercritical fluids can be recommended for commercial application as alternatives to s-CO_2.

However, careful engineering of the working fluid enables the cycle to operate with a heat rejection temperature that is tailored to the local climate or day/night cycle, boosting overall conversion efficiency without the need for custom turbomachinery. SNL has also studied the introduction of CO_2 additives,[10] and the SNL Brayton Laboratory test assembly includes the capability to inject varying levels of additives. SNL research in this area has shown that the use of CO_2-based mixtures may be best suited to cycles operating in the low temperature ranges characteristic of, for example, geothermal power.

1.8 Proposed Next Steps to Resolve Technical Challenges and Facilitate Commercial Deployment of the s-CO_2 Brayton Cycle

It is the mission goal of the SNL Brayton project to develop, with industry, a fully operational 550°C, 10 MWe s-CO_2 Brayton power conversion system for R&D demonstration that will enable the systematic identification and retirement of technical risks and testing of components for the commercial application of this technology.

To reach that longer term goal, the next steps would be to:

1. Initiate a rigorous systems engineering process following the style of DOE 413.3 to construct the full system demonstration. This objective of this process is to construct the demonstration and facility to support the commissioning of equipment and subsystem elements, and be a pilot facility for some limited period of time (i.e., generate power for less than 1,000 hours). Perform trades and system-level design to identify baseline conditions and component configurations along with risk reduction plans.

2. Perform risk-mitigation research on individual components for the mid-scale demonstration. Of particular concern, design a durable seal for a 10 MWe s-CO_2 Brayton cycle operating at a maximum temperature of 650°C.

---

[9] T. Conboy. "An Approach to Turbomachinery for Supercritical Brayton Cycles in Space." SAND2013-1742C. Presented at Nuclear & Emerging Technologies for Space, February 27th, 2013

[10] T.M. Conboy, S.A. Wright, D.E. Ames, T.G. Lewis, *CO_2-Based Mixtures as Working Fluids for Geothermal Turbines*. SAND2012-4905. 2012.

3. Continue research on test articles to establish corrosion/erosion and purity requirements for s-CO_2 on Brayton cycle components.

4. Continue model development and validation to guide the mid-scale demonstration development. In particular, continue research on low power test articles to establish validation data for operations and upset conditions.

5. Procure, assemble, and commission the mid-scale demonstration.

6. Determine reliability and degradation rates for the components and system through prediction and established testing procedures.

7. Continue research on compact, high efficiency, low cost heat exchangers to establish a code case for future deployment.

8. Initiate research to utilize dry heat rejection without efficiency loss with the objective of minimizing the loss of fresh water to the environment.

9. Initiate materials research to identify high temperature materials suitable for high pressure/high temperature s-CO_2 for application at up to 1,000 MWe and 1,000°C operation and bring them to the code case level and establish a manufacturing market.

10. Support standards development for the materials, components, and systems described above to establish commercial confidence with code certification for advanced materials for higher temperature operation and compatibility with novel heat transfer fluids.

2 MARKET

In 2013, SNL conducted an internal commercialization review for s-CO_2 Brayton cycle technology. The results of this review demonstrate that the technology has applicability across various power generation applications and may offer significant economic advantages over current technologies once fully developed. The results also showed that the development of this technology involves a long-term process, and significant technical challenges must be overcome prior to market adoption of a full system. Due to these uncertainties, market projections are highly speculative and additional research is required to better understand initial applications and applications where industry demand will be highest. SNL is committed to conducting an extensive market review that will leverage market/economic data and participation with industry stakeholders to identify early adopters and determine future market projections. Market demand and initial applications will likely be a result of advantages relative to existing technologies, such as improved energy conversion efficiency, reduced water use, lowered greenhouse gas emissions, and lower cost. In addition, there may be demands for technologies at the component level improved as a result of system level R&D, such as advanced heat exchangers and turbomachinery.

Commercialization of s-CO_2 Brayton cycle technology will depend on various financial, technical, regulatory, social, and value chain factors. These must be properly understood and addressed before commercialization and market risks are alleviated. In order to reduce the risks associated with these factors, it will be essential to support smaller scale projects that mitigate potential risk elements.

Demonstrating the technology at a level that is acceptable for commercialization will require national coordination of research and development activities that involve offices within DOE, national laboratories, academic institutions, industry partners, and other stakeholders. These participants will be involved at varying levels and at different stages within the R&D process. This interaction will be complicated due to the number of stakeholders involved, but can be addressed by considering structural/organization options and considerations for program management. In addition to R&D coordination, information sharing and program feedback will be critical elements of an initial s-CO_2 Brayton cycle technology development program and long-term commercialization success. Many participants have proprietary processes which prevent them from open sharing and communication. Approaches can be taken, though, to manage information sharing risks and constraints to ensure information is properly protected in order to optimize the interactions.

2.1 Current and Anticipated Future Market for the s-CO_2 Brayton Cycle

Market Overview—The current and anticipated future market for the s-CO_2 Brayton cycle is expected to extend across various applications. As R&D activities advance, we expect the s-CO_2 Brayton cycle to achieve higher operating temperatures, allowing for increased potential market opportunities. This progress should be measured on a long-term timescale, with various factors (technical progress, economics, etc.) affecting the rate of deployment within given applications. Initial market opportunities for complete systems (offering 5 to 10 MWe) will likely be realized after concerns about technical risks have been addressed through demonstration. While the main focus of our economic analysis to date is in terms of complete systems, contacts with our industry partners suggest there may also be initial market opportunities in adjacent/tangential areas. In the near-term development stages, industry will be most interested in the advancements of subsystems and components (see advanced heat exchanger example in Section 2.2) for various industry applications, including some unrelated to power generation.

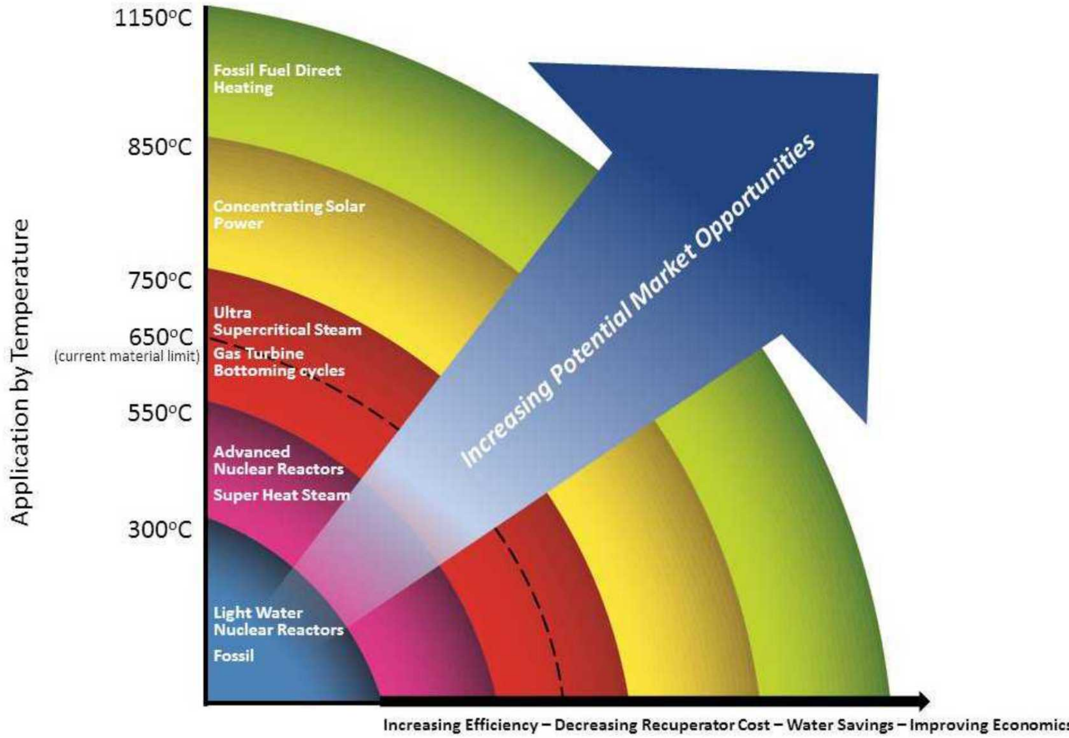


Figure 6. s-CO_2 Brayton cycle value proposition

As discussed in Section 1.4 and demonstrated in **Error! Reference source not found.** above, as technical challenges are overcome and allow for increased operating temperatures, the s-CO_2 Brayton Cycle will have potential applicability for different types of power generation, demonstrating the cross-cut potential of the technology. The potential market opportunities expand as the technology leverages previous R&D accomplishments to establish operational capabilities at higher temperatures. It should be noted that each form of power generation provides a different set of technical challenges, in addition to achieving proper operating temperature, which are not addressed in **Error! Reference source not found.**. As temperature rises (above 300°C), the system is expected to improving benefits, exceeding those of currently deployed technologies, including:

- Increasing efficiencies (see Figure 3)
- Decreasing recuperator costs
- Reduced water use
- Improving overall economics.

R&D advancements will occur in stages, and so too will market development for the s-CO_2 Brayton Cycle technology. In the early stages of complete system deployment, the market opportunities are for small (~10 MWe) installations that operate at temperatures of 100°C to 550°C. Initial applications that meet this criteria include small geothermal facilities or the installation of a s-CO_2 Brayton cycle as a bottoming cycle for small (less than 100 MW) turbine systems. We envision bottoming cycle opportunities for both new plants and in retrofits. At this level, the technology will be able to compete with traditional cycles based on expected cost advantages associated with efficiency, capital costs (at temperatures exceeding 300°C), and operating costs, particularly for applications in arid regions such as the southwestern U.S. or Middle East. Other applications at this point include small fossil plants, light water reactors/pressurized water reactors, and industrial facilities (various fuel considerations).

Over the longer term, as operating temperatures and scalability increase, leading to increased efficiency, the potential market opportunities grow to include large nuclear and fossil fuel plant designs (100 MWe and larger). The critical point for wide-scale adoption is likely a demonstration of an operational model that operates at about 550°C and no longer holds substantial technical risks associated with scaling up. At this point, the technology is expected to offer efficiency and $/kWh advantages over widely deployed steam and gas turbine technologies (thousands of deployed units) which operate at a similar temperature. This configuration defines SNL's Brayton mission goal proposal to develop a fully operational demonstration project at 550°C. As the technology continues to advance, enabling operational temperatures to increase beyond 750°C, potential market opportunities expand further to include concentrating solar power and fossil fuel direct heating.

Global Market—Once an operational design is achieved and technical risks are reduced, a likely market scenario exists in which industry will adopt the technology and establish domestic manufacturing and engineering capabilities that allow for s-CO_2 Brayton cycle systems to be sold and deployed overseas. For a variety of reasons, including rapid growth in power demand and less rigorous regulatory environments in countries such as China and India, overseas opportunities will likely be the first significant market for this technology. U.S. industry could become a leader in this technology and capture a significant share of international markets.

Additional Research—While the potential market share for the s-CO_2 Brayton cycle is quite large, the eventual market will, of course, be heavily dependent on whether the technology is economically competitive with other cycles. Part of the research agenda at SNL is to carefully consider the likely economics of this overall system. While we expect significant capital savings due to scaling considerations, we recognize that a more sophisticated engineering cost analysis will be required before we can estimate ultimate market opportunities. Our economic analysis will utilize SNL's Power System Lifecycle Cost Analysis Tool, which calculates the levelized cost of energy for a wide range of existing and anticipated electricity generation options and allows for a solid understanding of the economic and environmental (greenhouse gas emissions, criteria pollutants, water usage) tradeoffs associated with each option.

Any new technology faces market hurdles. We recognize that while the potential market opportunities for this technology are very large, market acceptance will take time. Market diffusion theory suggests that new technologies face an S-shape (logistic) adoption curve (Figure 7), characterized by innovators, early adopters, market followers (early majority and late majority) and the market laggards;[11,] application of this traditional market diffusion theory to the energy sector suggests that once new technologies capture about 10% to 15% of the market share, diffusion increases rapidly. This is partially attributable to declining costs for the new technology due to economies of scale and technological "learning by doing", meaning processes become more efficient and hence economical as manufacturing increases.[12] Costs for new technologies typically decline in two distinct phases. The first phase corresponds to a pre-commercial, or technical demonstration phase, where costs typically decline by approximately 20% per doubling of capacity. This phase is followed by an incremental phase, where the technology is on the verge of widespread application. During this phase, costs decline at approximately half the rate of the first phase, or 10% per doubling of capacity. [13]

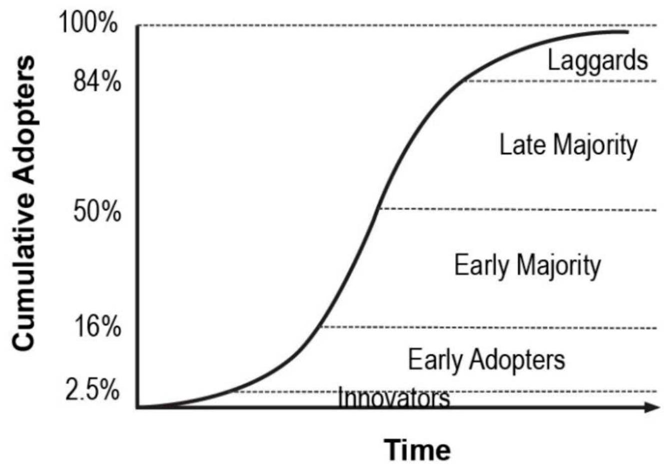


Figure 7. Innovation diffusion theory: technology adoption curve

We expect the situation for the s-CO_2 Brayton cycle to follow a similar commercialization path. Innovators and early adopters could include installations in arid regions of the U.S. and other countries, where adopters may be willing to pay a price premium to deploy a technology that allows construction of new electricity generation facilities in areas where traditional plants could not be located due to lack of cooling water resources. As costs decrease, the market followers may include those needing to meet the proposed new guidelines for greenhouse gas emissions from power plants, particularly those utilizing coal. Finally, the market laggards may include developers of high-efficiency natural gas facilities who are able to further increase efficiencies through the addition of an s-CO_2 bottoming cycle to recuperate heat for large (100+ MWe) systems.

As noted in our research needs, our next steps include a techno-economic analysis of the likely capital costs for this technology. Additional analysis should include quantifying the potential market size over time as a function of process temperatures, costs, and known constraints, such as water and emission restrictions. This effort will help to identify the key market and cost sensitivities for various subcomponents of this technology, which can then be addressed by

[11] J. Fisher and R. Pry. "A Simple Substitution Model of Technological Change," *Technological Forecasting and Social Change 3*, pp. 25–88. 1971.

[12] P.H. Kobos, J. Erickson, and T. Drennen. "Technological Learning And Renewable Energy Costs: Implications For US Renewable Energy Policy," *Energy Policy*, *34,* 1645–1658. 2006

[13] A. Grubler, N. Nakicenovic, and D. Victor. "Dynamics of Energy Technologies and Global Change," *Energy Policy, 27*, pp. 247–280. 1998.

technical teams.

Summary of recommended R&D needs—

- Develop bounded estimates of potential capital costs for s-CO_2 Brayton cycle power conversion

- Demonstrate potential market opportunities at different operating temperatures built with s-CO_2 Brayton cycle technology. Key metrics to quantify include:
  - Increased efficiency and effects on production cost, water use, and greenhouse gas emissions
  - Ability of s-CO_2 Brayton cycle technology to allow plants to meet proposed New Source Performance Standards (40 CFR Part 60)
  - Effect of carbon taxes on overall economics of the s-CO_2 Brayton cycle compared to alternatives.

2.2 Industry Demand

In the near-term, we anticipate that industrial interest in this technology will be in adopting sub-systems and components developed for this technology. Once technical risks are addressed and eliminated, there will be increased industrial interest for adoption of the full system.

Subsystems and components—As mentioned in Section 2.1, industry interests and needs are segmented. Industry (suppliers, manufacturers, etc.) will initially be interested in improved subsystems and components with applications that may not relate to power generation. For example, advanced heat exchanger technology will need to be improved for a full system to operate at anticipated commercial levels. An industry partner who possesses expertise (R&D, manufacturing, etc.) in heat exchanger technology will need to be involved in the R&D process in order to advance capabilities for a scaled s-CO_2 Brayton system. The resulting improvements may be attractive to heat exchanger suppliers/manufacturers for deployment within the companies' existing markets and customer bases. Adoption of these components will hold far less technical risk than a full system, and technology advancements in these areas would provide industry with improved capabilities that could be applied in the near term.

Full-scale system—In order to develop demand from the power generation sector, there is a need to demonstrate the viability of s-CO_2 Brayton cycle technology, while working with industry partners to develop it into a full-scale, commercially viable option. Once a full demonstration system is established, technical risks are properly analyzed/addressed, and costs are shown to be competitive, we anticipate that there will be industry pull demand for a full system within initial niche markets (e.g., arid regions). SNL describes this demonstration system within its s-CO_2 Brayton cycle mission statement:

> *By the end of FY 2019, Sandia National Laboratories shall develop, with industry, a fully operational 550˚C, 10 MWe R&D Demonstration s-CO_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.

At the level described within the mission statement, industry demand will be based on the technology's demonstrated ability to provide improved efficiency relative to existing state-of-the-art technologies, while offering flexibility and cost reductions for power producers. As a cross-cutting technology, the s-CO_2 Brayton cycle addresses growing industry needs across a broad range of applications and a variety of heat sources. A commercially operational model of the s-CO2 Brayton Cycle will offer the following advantages over alternatives across many potential applications:

- Energy efficiency: increased electricity production for same thermal input resulting in lower cost of electricity ($/KWhr). With potential efficiencies at around 50% for currently achievable operating temperatures (see Figure 3), s-CO_2 Brayton technology could provide efficiency advantages that exceed those of existing simple and combined cycles.

- Reduced capital, start up, and operational costs: smaller size, plant siting flexibility, and decreased expenses for water rights.

- Environmental improvement: greenhouse gas reduction; reduced water consumption; dry cooling/suitable for arid environments.

A critical advantage for initial adoption and industry demand for s-CO_2 Brayton cycle technology may be the low water consumption due its ability to utilize dry cooling. The technology is well suited for dry cooling because it is expected to maintain high levels of thermal efficiency over a range of ambient temperatures.[14] Currently, dry cooling is only installed in an estimated 1% of U.S. steam plants due to economic challenges and fundamental limits of air-cooled condensation. Although wet cooling will likely remain the dominant option for most plants in the near-term (even when deploying a Brayton cycle), rising energy needs and increasing concern over water and other environmental impacts position dry cooling to play an increased role in the future. Due in large part to drought conditions in recent years, local governments and operators of power plants have increasingly sought opportunities to reduce challenges related to water consumption and discharge.

Water has become an increasing concern for energy security in the U.S. With about 143 billion gallons of freshwater being withdrawn every day, power plants accounted for more than 40% of U.S. freshwater withdrawals in 2005.[15] Water supplies continue to face regional challenges due to drought conditions and demand from agriculture and water-intensive industrial processes. Figure 8 is a graphic from a study conducted by Oak Ridge National Laboratory (ORNL), showing areas of insufficient water supply for a small nuclear reactor using wet cooling(less than

[14] T. Conboy, M. Carlson, and G. Rochau, "Dry-Cooled Supercritical CO2 Power for Advanced Nuclear Reactors." Paper GT2014-25079. ASME TurboExpo, 2014.
[15] J.F. Kenny, N.L. Barber, , S.S. Hutson, , K.S. Linsey, , J.K. Lovelace, , and M.A. Maupin. *Estimated Use of Water in the United States in 2005.* U.S. Geological Survey Circular 1344. 2009

350 MWe; requires at least 50,000 gpm of water).[16] This shows that large areas of the U.S. are limited in terms of power generation options due to water resources, among other limitations (e.g., population density, proximity to faults, and wide open free space around the site). The s-CO_2 Brayton Cycle's dry-cooling system has limited water consumption demands, providing flexibility in operations and plant siting in some of the areas currently precluded from use today.

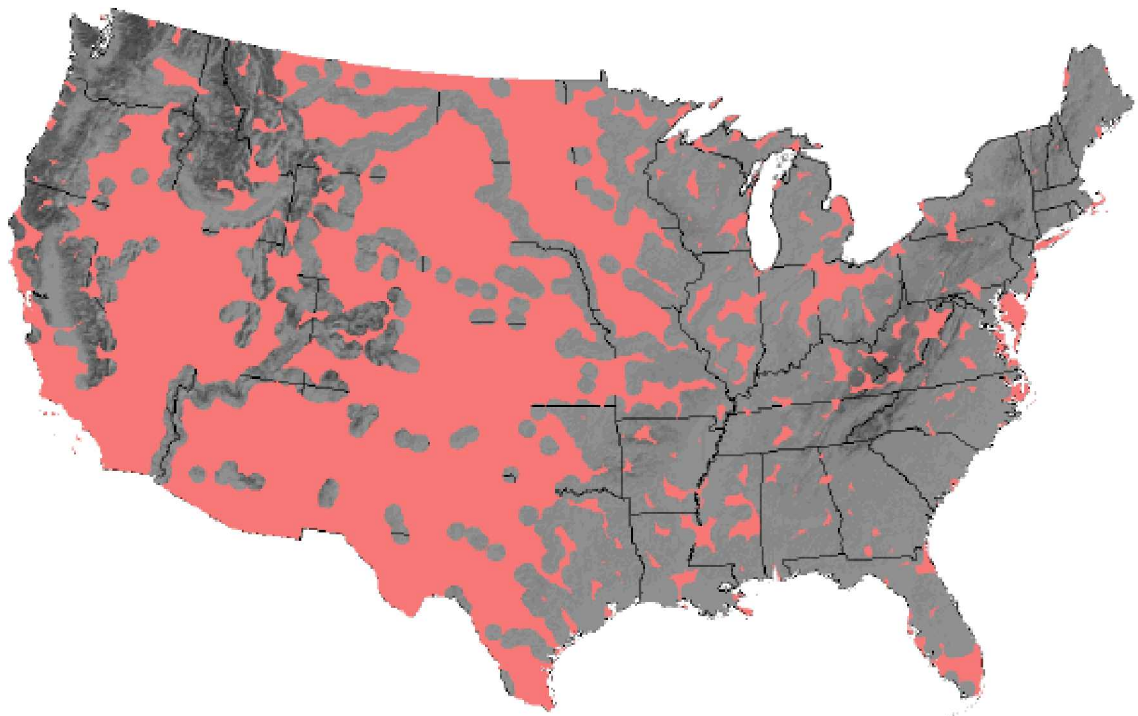


Figure 8. Map of areas with current excluded from siting a small nuclear reactor using wet cooling based on insufficient water resources (and other limitations)

Additional considerations—We anticipate that the changing energy landscape will also contribute to industry demand. The U.S. is facing increasing environmental, public policy, and economic challenges related to power generation and achieving a sustainable domestic energy supply. Commercial deployment of a scalable version of the s-CO_2 Brayton cycle technology may provide an opportunity to address some of these challenges.

As discussed in Section 2.1, the initial markets for deploying this technology will likely be overseas in companies such as China and India. In the longer term, there may also be significant opportunities in the U.S. based on near term changes in the country's power sector. For example, coal-fired power plants, which make up 37% of U.S. generation capacity (2012), remain under significant economic pressure due, in large part, to lower natural gas prices, stagnant demand for new electricity, and the approaching requirements under the upcoming Mercury and Air Toxics Standards and Environmental Protection Agency's proposed Clean

[16] G.T. Mays, R. Belles, B.R. Blevins, S.W. Hadley, W.C. Jochem, O.A. Omitaomu, and A.N. Rose. *Applications of Spatial Data Modeling and Geographical Information Systems (GIS) for Identification of Potential Siting Options for Various Electrical Generation Sources*. Oak Ridge National Laboratory ORNL/TM-2011/157. 2012.

Power Plan..[17,18] At the end of 2012, less than 65% of the coal-fired generators in the U.S. met requirements of the Mercury and Air Toxics Standards. The remaining plants are faced with the decision of costly retrofit activities or plant retirement. For reasons such as these, it is expected that between 50 and 60 gigawatts of coal-fired capacity in the U.S. will retire by 2020, requiring replacement by an alternate power source.[19]

Estimated timeframe for wide-scale commercial deployment—Due to the s-CO_2 Brayton cycle's application across a variety of heat sources, temperatures, and cycle configurations, there are several key system components and technologies that will be shared across applications. R&D and operational activities will jointly address shared challenges, allowing for accelerated commercial deployment of s-CO_2 Brayton cycle power cycles, regardless of heat source and pressure demand. Initial deployment will occur in applications with lower operating temperatures. As temperature requirements increase, so too will timeframes for wide-scale deployment due to advanced R&D demands for both s-CO_2 and other technologies (e.g., fossil fuel direct heating).

As with any new technology, there is considerable uncertainty related to the timescale of commercial deployment based on a variety of factors. For Brayton cycle technology, components and subsystems will first be transitioned from R&D stages to commercial deployment. Once operational stability of a full-system has been achieved, a timeframe for wide-scale adoption (based on the expected market deployment discussed in Section 2.1) can be better understood. As previously discussed, we anticipate that wide-scale adoption in the U.S. may take longer than that of various international markets.

2.3 Factors Most Important for Successful Commercialization

The factors most important to successful commercialization are:

- Financial
- Technical
- Value chain
- Regulatory
- Social

Financial factors—A solid understanding of costs; both capital and operational is a critical factor for commercial adoption of this technology. Given the lifetime and capital expenditure for a new power plant or of a replacement/upgrade of an existing plant to utilize s-CO_2 Brayton cycle technology, it is essential to accurately predict the cost such an installation. Any uncertainty in costing will be reflected in higher projected costs as a hedge against the uncertainty. This will then impact the calculation of levelized cost of energy and will drive investment decisions. While this is a financial decision, the underlying expertise is technical and is based on confidence in the underlying technology.

[17] http://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states#tab1
[18] http://www.eia.gov/forecasts/aeo/power_plant.cfm
[19] http://www.eia.gov/todayinenergy/detail.cfm?id=15031

Technical factors—The only way to accurately determine the costs is to have a solid understanding of the technical factors necessary to design and operate such a system. Some of the critical factors include:

- Solid understanding of operational characteristics of the system
  - Normal operations
  - Startup/shutdown
  - Error and abnormal conditions recovery
- System design and component availability
- Validation of efficiency claims
- Long term operation demonstration
  - Materials lifetime validation
- Connection to grid
  - Frequency regulation
  - Heat rejection temperature regulation.

These factors will determine the confidence in the operational integrity of the system and will allow stakeholders beyond the company to accept the technology. For example, there will need to be confidence in the stability and regulation of the output of a plant utilizing s-CO_2 power conversion before such a plant is connected to the grid, especially at scale.

Value chain factors—The entire value chain for s-CO_2 systems has to be in place in order for the successful commercialization. In order to be successful, the majority of the value chain will need to be populated by suppliers of technology that can be repurposed for use in s-CO_2 applications. Limiting the amount of custom s-CO_2 equipment and materials is an essential element in keeping the overall costs down. In addition, there will need to be expertise available from engineering, procurement, and construction (EPC) contractors who can manage construction of the whole system. Given the nature of EPC contracts, developing a body of expertise within the EPC market is critical. Without it, EPC contractors would not bid on a s-CO_2 power plant contract or would charge a high premium impacting the likelihood of adoption.

Regulatory factors—Beyond the regulatory issues common to all power plants, there will need to be an understanding of the unique regulations that apply to a s-CO_2 plant. With any new technology there is going to be uncertainty about the required regulatory approvals for its use. The approval process for all necessary licenses for installation and operation of a s-CO_2 Brayton cycle power conversion system will need to be clear both for the applicant and the regulatory agency. Uncertainty in the regulatory process could easily kill a planned installation, especially when compared against the incumbent technologies. This may mean that early adoption will occur in places where regulatory requirements are less stringent. An example of this effect can be seen in the construction of ultra-supercritical steam power plants in regions with less regulation such as India and other parts of Asia.

Conversely, the commercial deployment of s-CO_2 Brayton technology could be fostered through implementation of certain regulatory policies. For example, regulations limiting greenhouse gas emissions or promoting increased efficiency, such as the proposed New Source Performance Standards (40 CFR Part 60) or potential cap and trade regulations or carbon taxes, or policies intended to reduce water consumption in arid regions or drought-affected areas could be key factors for selection of this technology.

Social factors—One aspect that may be unique to a s-CO_2 Brayton cycle power plant is the perception of CO_2 use. Public and social acceptance will have to be managed with regard to the use of CO_2 and to distinguish this use from the role of CO_2 as a greenhouse gas. The public perception of the "danger" of accidental release of CO_2 could play a significant role in public acceptance and siting of a s-CO_2 plant.

Recommendation—To reduce the risk associated with these key factors for commercial adoption of s-CO_2 technology, smaller scale projects that mitigate these risk elements are essential. The investment is much smaller for such projects but the technology can be proven thus increasing the confidence and the likelihood of commercial acceptance.

2.4 Entities Needed to Advance the R&D of the s-CO_2 Brayton Cycle

National Coordination of Research and Development Activities—A single organization cannot appropriately address the technical challenges associated with scale-up and cross application configurations of the s-CO_2 Brayton cycle. To date, research efforts between entities have been coordinated at varying levels in order to investigate common problems and develop strategies to advance the system technology to an appropriate state for operational demonstration. Ongoing R&D activities range from design and utilization of kW-scale s-CO_2 Brayton cycles (e.g., collaboration between Sandia National Laboratories and Knolls Atomic Power Laboratory) to leveraged testing of a multi-megawatt turbine in an open cycle for concentrating solar power applications (e.g., Southwest Research Institute collaboration with industry and academia as part of the SunShot project). Industry involvement, such as Echogen partnering with Dresser-Rand (turbomachinery) and GE Marine (shipboard applications), has also addressed development and commercialization challenges. These research efforts are still in the early stages, and various technical and economic challenges must be overcome prior to commercial deployment and scalability.

Advancing the R&D of the technology will require partnerships with defined roles across multiple sectors, including Federally Funded Research and Development Centers, industry, academia, regulators, other research labs, and various stakeholders. This interaction presents challenges due to the number of stakeholders involved, and the diversity of their contributions and interests. This can be addressed by considering structural/organization options and considerations for program management. One such consideration would include DOE executive and technical team management (including members from offices such as the Office of Energy Efficiency & Renewable Energy, Office of Fossil Energy, Office of Nuclear Energy, and the Advanced Research Projects Agency–Energy) of the cross-cut at varying levels, ranging from active program participation/involvement to engagement of the broader potential "user" community that is not actively involved in the program. Additional information on interactions of participants is presented in Section 2.5.

DOE, along with industry, would also guide research directions through project identification and funding. Industry partners will play a key role in informing research and identifying the appropriate application space for the technology (systems and subsystems). Industry will also play a large role in coordinating efforts (e.g. supply chain and manufacturing) to ensure that resulting technologies and systems are cost-competitive and economically viable for commercial deployment. Throughout the process, regulating agencies such as Federal Energy Regulatory Commission, the U.S. Nuclear Regulatory Commission and the U.S. Environmental Protection Agency will also need to be engaged in order to ensure that regulatory issues are well understood prior to deployment.

Each of the partners involved will offer capabilities and application knowledge to overcome varying levels of uncertainty. The extent to which each partner will be utilized is dependent on their available infrastructure, expertise, and other capabilities. The majority of near-term activities will be completed by national labs and academic institutions, with industry playing a more significant role at the engineering-scale system level.

As they relate to existing technical challenges, entities needed to advance the R&D can be separated into three categories within the R&D process: (1) the full-scale system; (2) high uncertainty components; and (3) low uncertainty or commercially available components.

Full-Scale System—Investing in a demonstration-level system will help showcase this technology and resolve technical risks. Potential investors will require minimized risks associated with a new system and with scaling to larger systems. The role of a national laboratory could be leveraging existing s-CO_2 Brayton cycle R&D resources (e.g., laboratory infrastructure and other advanced resources) to provide technical leadership and participate with industry in the definition, design, construction, and operation of a full-scale s-CO_2 Brayton cycle demonstration. A national laboratory's experience could be utilized in a leadership capacity on a "Steering Committee" and through project management/systems engineering in support of system integration and fielding.

Proximity and access to other advanced R&D facilities (e.g., Thermal Test Complex and Materials Test Labs) makes SNL an advantageous host site for advanced Brayton cycle testing and, eventually, a full-scale demonstration. This would allow a Federally Funded Research and Development Center to retain government-owned infrastructure for potential future demonstration while avoiding long-term "mortgage" issues. Experience with existing Brayton test loops (see Section 3) would also provide a suitable foundation for improving the technology readiness of critical components and materials. This experience is also critical to a demonstration system for reasons of safety. SNL has thousands of hours of operating experience with its test loops without a safety incident.

High Uncertainty Components—Some of the components and materials required for a full system are not commercially available and remain unproven at or within:

- Multi-megawatt scales
- Operational industry settings
- Advanced/amplified environments
- Integrated power generation systems.

Further development of these high uncertainty components such as turbomachinery, bearings, and seals and their designs relative to a full-scale system will require early stage materials R&D

and computer modeling that utilizes the capabilities of national laboratories and academic institutions. For example, national laboratories (e.g., SNL, ANL, and ORNL) and academia (e.g., Massachusetts Institute of Technology and University of Wisconsin-Madison) could contribute to materials research to address high-temperature capabilities and erosion/corrosion issues. As a more specific example, ORNL could offer expertise in materials for valves used in supercritical steam systems, and steady state and dynamic models from SNL and ANL can be used to predict operating conditions.

Industry manufacturers/suppliers would leverage the results of this R&D to develop design and manufacturing capabilities in order to deploy these subsystems. As mentioned in Sections 2.1 and 2.2, industry partners will likely express initial interest in deploying these improvements at the subsystem level. Industry partners will be leveraged based on particular strengths in approaching these issues and will focus on different aspects or subsystems. For example, materials that can withstand 700°C are currently available, but there exists a lack of understanding related to long-term erosion potential and valve interaction. By leveraging the capabilities of the labs and academic institutions previously mentioned, this challenge can be addressed and knowledge can be transferred to industry suppliers to develop manufacturing processes for power piping and valves that could reduce overall system costs.

These advancements will lead to unique advantages that offer benefits when compared to existing systems. As the full system is demonstrated at improved capabilities, venture capital firms or companies with advanced R&D structures (e.g., GE) may invest in further development and commercialization.

Commercially Available Components—Participation will also be required from industry for the advancement of commercially available components that may exhibit new uncertainties when utilized in a s-CO_2 environment. For example, manufacturers of turbomachinery and advanced heat exchangers will be needed to contribute to the design of advanced subsystems that have new requirements based on size, temperature, and pressure requirements. Bearings and seals will also require participation from manufacturers who possess competencies in these areas. These industry partners will be leveraged to improve existing designs or create new designs which address the demands of a s-CO_2 system.

Development activities for components that are better understood or commercially available, but that still require modifications for specific applications, will leverage industry partners that possess relevant subject-matter expertise and engineering capabilities. Other subsystems, such as CO_2 storage tanks, possess little uncertainty and are well defined and understood. Industry will supply these subsystems based on existing design specifications and delivery estimations.

2.5 Information Sharing and Soliciting Feedback

Information sharing and program feedback are critical elements of s-CO_2 Brayton cycle R&D program and long-term commercialization success. The challenge to be successful is complicated by the number and diversity of stakeholders involved. The group includes a number of DOE program groups, national laboratories, academia, regulators, potential industry users of the Brayton cycle, and associated suppliers. Many are willing to communicate in a very transparent manner; however, many have proprietary processes and equipment that prevents them from sharing or communicating openly. The regulators involvement is important to ensure program success but their involvement may be limited because of long term responsibilities. All suggested approaches for communication outlined here must be managed in recognition of information sharing constraints and risks to ensure information is properly protected in order to optimize the interactions and to provide fair opportunity for participation to qualified stakeholders.

This section focuses on communication needs and possible approaches that allow for information sharing and feedback with early program participants (e.g., government, utility and other industry stakeholders, etc.) and other stakeholders with immediate and longer-term interest in commercialization of the s-CO_2 Brayton cycle. This information is presented in tandem with Section 1.6.

2.5.1 Communication with Active Program Participants

Communication with active participants in this initial program must allow for regular and urgent sharing of information related to all aspect of managing this cross-entity effort. Examples include normal program management meetings, working sessions for planning and addressing issues, and status reporting. In addition to direct interactions, electronic means allowing for collaborative activities and sharing of information amongst participants in disperse locations will be essential (e.g., use of teleconferencing, videoconferencing, and interactive multi-user access to documents).

2.5.2 Communications with Other Interested Stakeholders

Brayton Website—A website can be used to communicate general information about the Brayton cycle technology and more specific information about the program development and deployment activities to commercialize the technology. The website should include technical information, much like SNL's current Brayton website does, and provide a user-friendly interface that allows for interactive and open feedback and suggestions from all stakeholders.

Engage Commercial Interest Group through Periodic Conferences—Periodic information sharing conferences (e.g., annual or semi-annual) can be used to keep the broad community of stakeholders (a commercial interest group) informed about progress and, where possible, elicit input from them that can enhance the probability of successful immediate and long-term commercialization of the Brayton cycle. Where useful and workable (e.g., considering information sharing constraints), break-out sessions could be included to engage the attendees in forums focused on specific issues and risks (technical and non-technical) related to furthering program progress and ultimate commercialization. This early and direct involvement of potential users of the technology and associated potential suppliers can help ensure more fully-informed decision making while enticing longer-term participation and adoption of the technology.

Focused Ad Hoc Technical Workshops—As work on the program progresses, there may be opportunities and need for engaging stakeholders, including those not currently involved directly in the program and other technical experts, in "technical workshops" focused on a specific aspect of development needed for the program. These workshops can allow for collaboration among and engagement of critical technical talent to work significant technology development challenges. Contractual agreements may be needed with these additional contributors to address information sharing constraints and risks that might inhibit their full participation.

2.5.3 Executive Stakeholder Engagement with DOE

In addition to current DOE advisory groups/boards, an executive advisory board specifically focused on the Brayton cycle program (technology and commercialization) could provide executive-level and strategic input and feedback to the associated DOE management, including Assistant Secretary Lyons, and the DOE technical team. The board membership would include executives from interested major stakeholder groups (industry, utilities, national laboratories, etc.) and could meet on a regular periodically scheduled basis (e.g., annually or semi-annually).

3 Resources Available at Sandia National Laboratories

One of the questions posed in the RFI is what role national laboratories could play in the DOE's "Supercritical Carbon Dioxide Brayton Cycle Energy Conversion Research and Development Program", and in this section we offer an SNL perspective the role it can play in this program.

As a national security laboratory, SNL has built a strong foundation from our work in the nuclear weapons program with an emphasis on integration of fundamental scientific research using rigorous systems engineering methods and tools to deliver solutions to complex engineering problems. This foundation has resulted in the generation of unique technical competencies, facilities, and tools, such as our capabilities in high-reliability and reverse engineering; sensors and sensing systems; modeling, simulation and experiments; natural and engineered materials; and safety, risk, and vulnerability analysis.

We also have built and maintained facilities that are unique within the DOE Complex; some of these are:

- **Brayton Laboratory** with over 20,000 ft^2 of high bay space and infrastructure to support: electrical heat sources >400 kWth at 550°C; cooling systems >1 MWth to <ambient temperature; 15 T overhead crane; grid connect (currently under construction); and access to a natural gas pipeline. Within this facility the following test loops that allow for the conduct of specialized testing will be available: s-CO_2 control valve calibration loop; heat exchanger test loop for efficiency measurement and failure modes (currently under construction); low-pressure closed Brayton cycle at 25 kWe; high-pressure s-CO_2 natural circulation, dry heat exchanger test loop (currently being commissioned); high-pressure s-CO_2 compressor loop operating at ambient temperature up to 80°C; high-pressure s-CO_2 bearing and seal test loop operating at ambient temperature to 80°C; supercritical fluid compression loop operating near critical point for evaluating custom fluids and mixtures; and 150 kWe, 550°C s-CO_2 recompression closed Brayton cycle test article (750 kW heat source, generating capacity of 250 kWe, reconfigurable). At this facility, SNL has capabilities for turbine design/construction; compressor design/construction; heat exchanger/recuperator design/construction; cycle design, modeling, safety, and component integration; operational commissioning and performance verification; instrumentation and controls; mechanical engineering of supercritical fluid systems; and high-speed rotational balancing (currently under construction).

- **Thermal Test Complex** for ultra-high temperature testing of components, and design of high temperature/high pressure heat sources. This facility will provide a capability for the testing of s-CO_2 Brayton cycle system components under the high temperatures and high pressures envisioned for some of the potential applications of the s-CO_2 Brayton cycle.

- **Materials Test Laboratories** which include high-temperature and pressure corrosion testing facility (max 650°C at 4,500 psi) (currently under construction) and in situ corrosion screening facilities that uses methods to rapidly down-select materials (currently under construction). These facilities will allow for investigation of the aging behavior and corrosion of materials in the presence of s-CO_2 with expected contaminants and varying gas quality; testing of long-term materials performance; determination of materials compatibility; and detailed understanding of materials behavior under a variety of extreme conditions.

- **Materials Reliability** testing facilities for the investigation of materials aging, lifetime, compatibility; corrosion science and engineering; brittle materials fracture and failure analysis; gas analyses and engineering; failure modes and effects analysis; and tribology, wear coatings, and electrical contacts. These facilities will allow testing of specialized materials from which s-CO_2 Brayton cycle system components could be built to reliably perform under a wide range of extreme conditions for extended periods of time. The information that could be developed from these testing activities could provide the technical basis for the development of materials code and standards (see Section 1.8)

- **National Solar Thermal Test Facility** designed to provide experimental data for the design, construction, and operation of unique components and systems in proposed solar thermal electrical plants planned for large-scale power generation. The concentrating solar power facility provides an existing thermal source that can be directly tied to a Brayton cycle test loop.

- **Combustion Research Facility**, recognized as a national and international leader in combustion science and technology for more than 30 years, provides capabilities for the investigation of direct fossil fuel combustion as a potential heat source for a s-CO_2 Brayton cycle.

- **Secure Scalable Microgrid Testbed** for research and development of advanced power electronic systems. This testbed provides the opportunity to explore energy storage and microgrid applications for s-CO_2 Brayton cycles.

SNL also has expertise in state-of-the-art advanced modeling and simulation in a number of areas relevant to the fundamental understanding of a s-CO_2 Brayton cycle system and its components, including computational fluid dynamics (e.g., thermal hydraulics, turbulent flow), mechanical behavior (e.g., stress/strain and thermal expansion), operational modeling (e.g., hot/cold startup and thermal shock), and s-CO_2 thermodynamic properties and equation of state, among others. SNL has an active, ongoing research program on geothermal applications, with a particular emphasis on drilling technology.

In addition to our in-house capabilities, since beginning our research and development program in the s-CO_2 Brayton cycle in 2006, SNL has engaged in an extensive set of external collaborative research activities germane to some of the key technical issues to be addressed to increase the commercial attractiveness of this energy conversion technology. Some salient examples are:

- SNL and the Knolls Atomic Power Laboratory (KAPL) have collaborated on their respective closed Brayton cycle programs from the time of initial design in 2007. As a result, the basic design of the turbo-alternator-compressor and motor controller approach are almost identical as a result. This collaboration continues, focusing on the investigation of common problems, discussions on development of heat exchangers, loaning of components, comparison of operating procedures, and strategies to advance the system technology to commercialization.

- Cooperative Research and Development Agreement with a U.S. company to develop a U.S.-based printed-circuit heat exchanger fabrication capability. SNL's expertise with high-quality pinch and upset welds and capabilities for metallography and mechanical testing have provided that company with insight into material cleaning techniques and grain growth characterization needed to produce diffusion bonds that can be certified under the ASME Boiler and Pressure Vessel Code.

- SNL is investigating advanced materials for s-CO_2 Brayton cycles in collaboration other national labs, universities, and international partners. We collaborate with ORNL to understand current corrosion risks, stand-up in-house testing capabilities to support ongoing inspection of our SNL's Brayton test loop, and to select materials for future Brayton test loops. SNL advised the University of Wisconsin–Madison on two successful Nuclear Energy University Program proposals in 2013, now part of the program supporting nuclear reactor technologies in the consolidated innovative nuclear research funding opportunity announcement, focusing on materials compatibility with s-CO_2 and sodium. Through our collaboration with University of Wisconsin–Madison, SNL has leveraged insight from ongoing work at the French Alternative Energies and Atomic Energy Commission on materials for s-CO_2 cycles.

- Compact, high performance, and affordable heat exchangers are a critical technology component for s-CO_2 Brayton cycle commercial viability, and SNL has been working with industrial and university partners to reduce the cost of current high-TRL units while concurrently developing novel patent-pending heat exchanger technology for future applications. Printed-circuit heat exchangers represent the current state-of-the-art for s-CO_2 Brayton applications. SNL has collaborated with the Ohio State University and University of Wisconsin–Madison on their successful Nuclear Energy University Program proposal to optimize printed-circuit heat exchangers for s-CO_2 Brayton cycles applied to advanced nuclear reactors. SNL is leveraging its experience in high-quality metal casting to develop a patent-pending cast metal heat exchanger concept that could provide performance equivalent or superior to printed-circuit heat exchangers at a fraction of the cost across a broad range of power generation and industrial applications.

The unique set of facilities, capabilities, staff and external collaborations make SNL a good potential host for developing and establishing, jointly with industry, a fully operational 550°C 10 MWe demonstration s-CO_2 Brayton cycle 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. The system will be reconfigurable to allow the testing of commercially attractive configurations and system components that can be transferred to industry. SNL will formally apply systems engineering in the identification and retirement of technical risks to first proceed from the currently existing 150 KWe system to the 10 MWe 550°C system, and eventually to higher power levels and temperatures with the necessary scientific and engineering rigor.