

DIRECT SUPERCRITICAL CO₂ POWER CYCLE TECHNOLOGY RESEARCH AND DEVELOPMENT

TECHNOLOGY GAPS AND RESEARCH NEEDS

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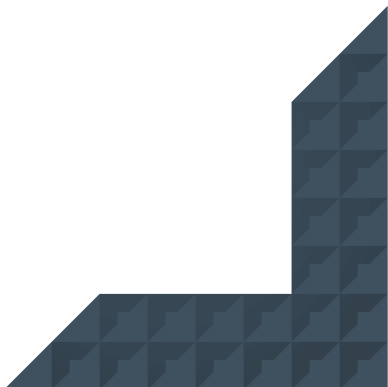
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EXECUTIVE SUMMARY

This research and development (R&D) plan aims to identify technology gaps and research needs to help enable the commercialization of the direct supercritical carbon dioxide (sCO₂) power cycle technology by 2025. The goal of the plan is to help reduce technical risks to commercialization of the technology by providing guidance to United States (U.S.) national laboratories for closing the technology gaps.

After a brief introduction in Chapter 1, Chapter 2 of this document gives an overview of the direct sCO₂ cycle technology. It describes the major components of the system and discusses cycle performance and cost.

Chapter 3 categorizes the identified technology gaps under five technological groups: (1) system analysis and dynamics, (2) combustion and turbomachinery, (3) heat exchangers, (4) materials, and (5) pollution control. For each technology gap, research needs are listed. Technology readiness level (TRL) is also assessed for each technology discussed.

Chapter 4 provides a timeline for the entire direct sCO₂ power cycle technology assessed through 2025, based on the TRLs assigned to the component technologies.

Chapter 5 provides a list of capabilities relevant to the direct sCO₂ power cycle technology compiled from the U.S. national laboratories.

Chapter 6 provides a list of organizations involved in the direct sCO₂ power cycle technology.



1.0 INTRODUCTION

Interest in supercritical carbon dioxide (sCO₂) Brayton cycles is gaining momentum for a variety of power generation applications including fossil, nuclear, concentrated solar, and waste heat. The majority of these applications utilize indirectly heated sCO₂ cycles in which carbon dioxide (CO₂) in a closed loop is compressed, heated, and expanded to generate power. Compared to the steam Rankine cycles, the primary drivers for the sCO₂ cycles are (1) increased power generation efficiency, (2) potential reduction in capital cost due to compact and simple plant configurations, and (3) reduction in water use.

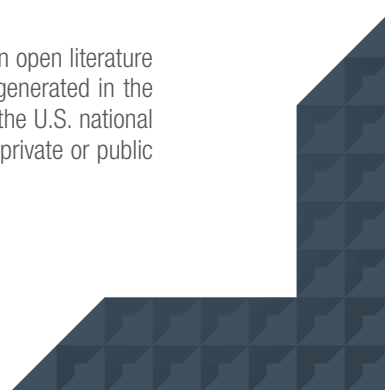
A direct sCO₂ cycle (also called Allam cycle or open cycle or semi-closed cycle or direct-fired cycle) burns fossil fuel in an oxyfuel combustor to produce a supercritical fluid composed of primarily CO₂ with water (H₂O) and oxygen (O₂), which is expanded in a turbine to generate electricity. While most of the CO₂ is recycled as diluent in the combustor, a steady stream of CO₂ is produced ready for sequestration or utilization for other applications, resulting in zero-emission power generation using fossil fuels. A description and status of the direct sCO₂ power cycle technology are given in the following chapters, including a timeline for the commercialization of the technology.

This research and development (R&D) plan identifies technology gaps and research needs to help enable the deployment and commercialization of direct sCO₂ power cycle technology. The goal of the plan is to help reduce technical risks to commercialization of the technology by providing guidance to United States (U.S.) national laboratories for closing the technology gaps.

This document can be utilized to maximize the value of the government investment in this technology by providing a roadmap to reduce the technical risks, decreasing the likelihood of duplicated efforts, and enhancing the collaboration across U.S. national laboratories and other Department of Energy (DOE) facilities.

In addition to identifying technology gaps and research needs, the R&D plan provides a summary of existing capabilities relevant to the direct sCO₂ cycle research in the U.S. national laboratory complex. However, no attempt was made to match these capabilities to the specific research needs.

Overall, the information presented in this report is based on the data in open literature and the data presented in open conferences in addition to the data generated in the authors' own research. The capability information was collected from the U.S. national laboratories. None of the information in this report was solicited from private or public companies.



2.0 OVERVIEW OF DIRECT sCO₂ POWER CYCLE TECHNOLOGY

In the open-cycle or direct sCO₂ system, natural gas or syngas fuel is burned with oxygen (O₂) in a combustor and recycled CO₂ is used as a diluent to control the turbine inlet temperature. Various film and convection cooling approaches are used with the combustor and turbine components, similar to what is done in Brayton cycles. The maximum firing temperature of these systems is typically limited by metallurgical constraints of the high-temperature recuperator, currently about 760°C for wrought, polycrystalline nickel-based alloys. With the relatively low-pressure ratio at which these systems optimize (Pr ≈ 3-10), the turbine inlet temperature and pressure end up around 1,150°C and 30 MPa respectively. This leads to a high-power density cycle with a reduced footprint relative to conventional power generation technologies. Resulting capital cost reductions are somewhat offset by the need to contain the high pressures, but combined with the high efficiencies, direct sCO₂ power plants are expected to be comparable to, or better than, conventional combined cycle plants with carbon capture and storage (CCS) on a cost of electricity (COE) basis.

A simple, direct-fired Brayton cycle with oxy-fuel combustion and carbon sequestration is shown in Figure 2.1 (Strakey, 2014). In this cycle, all of the low-pressure flow leaving the low temperature recuperator is cooled to near ambient temperatures in order to remove the water from the system. The benefit of this approach is that the output of the compressor is a nearly pure stream of CO₂ that can be recycled to the combustor for temperature control with the remainder being ready for purification and storage. In this sense, the cycle permits carbon capture at no “additional” cost. In this cycle, additional heat from elsewhere in the cycle is required to overcome a heat and temperature imbalance in the recuperation train. One way to deal with this is to integrate the waste heat from the air separation unit (ASU) into the recuperator (Allam, 2013 & 2014a).

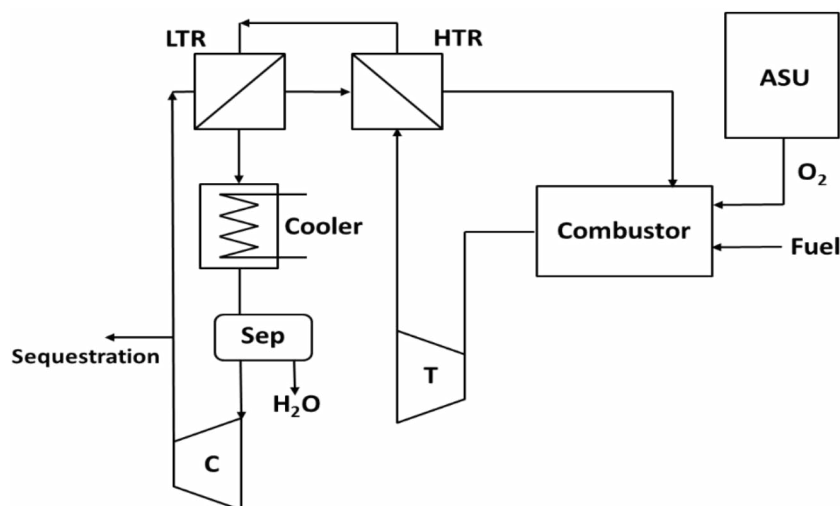


Figure 2.1. Direct-fired simple sCO₂ Brayton cycle. LTR and HTR are low and high temperature recuperators, ASU is an air separation unit, Sep is the CO₂/H₂O separator, C is a compressor, and T is the turbine (Strakey, 2014).

2.1 NATURAL GAS-FIRED CYCLES

Natural gas is an attractive fuel because it allows for the development and demonstration of various aspects of the technology with a clean burning fuel as opposed to coal-derived syngas. The potential thermal efficiency is also high (in excess of 58%) based on the lower heating value (LHV) of natural gas (Allam, 2013). In a system analysis carried out by Allam et al. (2013), the turbine was assumed to operate at an inlet pressure of about 30 MPa with a pressure ratio of 10 and an inlet temperature of 1,150°C. The turbine exit temperature was roughly 750°C. At the bottom end of the cycle, the working fluid is cooled to near ambient temperature and the pressure is roughly 3 MPa. After water separation, the working fluid is compressed back up to 30 MPa in a multi-stage, intercooled compressor train. As noted in their study, the recuperator pinch-point problem is overcome through the integration of waste heat from the ASU, which is introduced into the 30 MPa working fluid in the recuperator. The pinch point is a result of the fact that the specific heat capacity of sCO₂ has a pressure dependence, increasing from 1.06 to 1.47 kJ/kg-K as pressure is increased from 3 to 30 MPa around 225°C. As was noted earlier, one of the main benefits of this cycle configuration for power production from natural gas is that the cycle naturally allows for CO₂ transportation and sequestration at pipeline ready pressures with minimal additional compression work (Figure 2.1). CO₂ separation and compression in conventional air-fired Brayton cycle gas turbine combined cycle power plants typically incurs a thermal efficiency penalty as much as 6 percentage points (NETL, 2015a). Additional studies of the natural gas-fired cycle have been undertaken by the National Energy Technology Laboratory (NETL) (White, 2018) and the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG) (2015), and are discussed in Section 2.10.

2.2 COAL-FIRED CYCLES

Coal can also be considered as a fossil fuel for direct sCO₂ cycles; however, due to its inherent ash content, direct combustion of coal within the sCO₂ cycle is technically difficult due to the need for complete particulate removal at high temperature and pressure. Typically, the coal is first gasified and cleaned of its ash content, with combustion of the resulting syngas occurring within the sCO₂ combustor. Coal also contains other impurities such as sulfur, nitrogen (N₂), and chlorine that may also be cleaned from the syngas before entering the sCO₂ cycle using conventional gasification technologies, though an efficiency benefit may result if these can be cleaned within the sCO₂ cycle (Lu, 2014). This is discussed in more detail below.

NET Power has also developed a coal-fired version of their direct sCO₂ cycle, in which coal is first gasified and cleaned before syngas is burned in the sCO₂ cycle combustor (Allam, 2013). In the baseline system, an entrained flow, dry-fed, slagging gasifier is used with a water quench, which produces a claimed net plant thermal efficiency of 47.8% (higher heating value [HHV]) on bituminous coal (Lu, 2014). Variations in coal type, gasifier type, and heat recovery processes yield a range of HHV efficiencies from 43.3% to 49.7% (Lu, 2014).

The Electric Power Research Institute (EPRI) has also studied a syngas-fired direct sCO₂ power plant based on coal gasification in a slagging, entrained flow gasifier (EPRI, 2014b; Hume, 2016). The study includes Shell's dry-fed gasifier design (including a steam bottoming cycle powered by the syngas cooler's thermal output) and investigates the effects of O₂ purity and coal feed carrier gas on the purity of the CO₂ in the power cycle's turbomachinery. The study concludes that high-O₂ purity (99.5%) and CO₂ coal feed carrier gas are required to produce a storage-ready stream with sufficient CO₂ purity (98.1%) for permanent sequestration (EPRI, 2014b).

A similar study was undertaken by NETL, also utilizing a Shell gasifier and gas cleanup train prior to introduction of syngas to the sCO₂ combustor (Weiland, 2016a). The syngas cooler is used to raise steam for the coal drying, ASU, and sulfur removal processes, but is not used to power a steam bottoming cycle, as with the EPRI study (2014b). Additional heat is harvested in the syngas cooler by preheating compressed syngas prior to introduction to the sCO₂ combustor, and to provide additional preheating of recycle sCO₂ for the oxy-combustor. This study yields a plant HHV thermal efficiency of 40.6%, with high purity CO₂ separation and a 20% reduction in COE relative to a Shell-based integrated gasification combined cycle (IGCC) plant with CCS (Weiland, 2018).

2.3 CONDENSING OPTION

While most of the proposed CO₂ power cycles operate solely in the supercritical regime, there are variations that employ condensation of the CO₂ before compression. At a pressure of 6 MPa, the condensation point of CO₂ is 20°C. The benefit of condensation is that the higher density of the CO₂ requires less compression power, thereby increasing cycle efficiency. In general, any effort to reduce the cold temperature of the sCO₂ cycle, short of adding a refrigeration system, will more than pay for itself through improved cycle efficiency (IEAGHG, 2015).

Also, condensing cycles offer the potential for reduced recuperation demand. This occurs because lower CO₂ temperatures require lower saturation pressures at the pump inlet, raising the turbine pressure ratio and lowering the turbine outlet/recuperator inlet temperature. The drawback of condensing cycles is that at temperature below about 100°C, the differences in specific heat between the low-pressure and high-pressure sides of the recuperator increases significantly, which aggravates the pinch point problem and introduces large irreversibilities (Kim, 2012).

Another issue for condensing cycles is the need for very cold cooling water (10-15°C) and small temperature approaches in the sCO₂ cooler. Cooling towers are another alternative to once-through cooling, where mechanical draft cooling towers are preferred to natural draft towers due to their reduced approach temperature (4°C vs. 7°C for natural draft) and smaller size. This allows for lower sCO₂ temperatures and higher densities at the compressor inlet, such that the reduction in compression power more than offsets the fan power requirements of the mechanical draft cooling towers (IEAGHG, 2015).

2.4 THERMAL INTEGRATION OPTIONS

In the natural gas-fired direct sCO₂ systems, thermal integration of the sCO₂ cycle is possible with the ASU and CO₂ purification unit (CPU), particularly with their compressors. NET Power's cycle requires thermal integration with the ASU compressor to help balance the heat duties on either side of the recuperator. To increase the amount of heat available for integration, the ASU main air compressor is not intercooled. Although this increases the ASU power requirement, its effect is offset by improved sCO₂ cycle recuperation, leading to higher overall plant efficiency (Allam, 2013).

In coal-fired systems, there are additional thermal integration opportunities with the gasification train. In particular, there is a considerable amount of heat that can be recovered from the syngas exiting the gasifier, which must be cooled prior to ash removal and syngas cleaning. In typical gasification systems, this heat is recovered in a syngas cooler, which raises steam for power and thermal duty elsewhere in the gasifier train. This can also be used for syngas preheating or additional CO₂ preheating prior to combustion, though preheating O₂-containing streams is discouraged for safety reasons (Weiland, 2016a). The sulfur recovery plant and syngas compressor also provide sources of thermal energy for integration with the sCO₂ cycle, though this is a topic that has not yet been explored in current studies.

2.5 WORKING FLUID

One of the unique challenges for direct sCO₂ cycles is that the working fluid is no longer pure CO₂ as it is in indirect cycles. Depending on whether the cycle uses natural gas or syngas as fuel, the working fluid composition passing through the turbine will be different, as shown in Table 1. Furthermore, the working fluid impurities are a function of the temperature rise required in the combustor, thereby dictating the fuel and oxidizer requirements. This, in turn, is a function of the turbine pressure ratio, and the approach temperature at the hot end of the recuperator, which both determine the temperature of the recycle CO₂ entering the combustor.

TABLE 2.1. TURBINE INLET FLUID COMPOSITIONS (VOLUME %).

COMPONENT	NATURAL GAS (IEAGHG, 2015)	COAL/SYNGAS (EPRI, 2014b)
CO ₂	91.80	95.61
H ₂ O	6.36	2.68
O ₂	0.20	0.57
N ₂	1.11	0.66
Ar	0.53	0.47

Impurities in the working fluid as defined by anything other than CO₂ can have a detrimental effect on the cycle performance as shown in a system study by Hume (2016). For a compressor operating near the critical point of CO₂, the compressor power was found to increase by roughly 6% as the working fluid purity dropped from 100% CO₂ to 95.6% CO₂ with the balance comprising O₂, N₂, H₂O and argon (Ar). A further drop to 90.9% CO₂ purity resulted in an increase in compressor power of roughly 34% over the pure CO₂ case. The increase in compressor power is a result of the decreased fluid density arising from gaseous impurities.

2.6 SOURCES OF sCO₂ IMPURITIES

Impurities can enter the sCO₂ cycle through the fuel, oxidizer, or other internal processes. Oxidizer impurities are either N₂ or Ar, the quantities of which depend upon the level of effort expended to separate O₂ from air in the ASU. Further, use of more O₂ than is needed for combustion can result in O₂ impurities downstream of the combustor. Fuel impurities derived from natural gas include N₂ at 0.9-1.6 volume %, depending on location, and should be accounted for in systems studies (NETL, 2012a; IEAGHG, 2015). In syngas-fired combustors, impurities are a function of the coal gasification process and syngas cleanup train. N₂ from the coal may be passed along to the syngas, as well as other sulfur, chlorine, and N₂ containing species that are not fully cleaned from the syngas. The syngas itself mostly comprises carbon monoxide (CO), which is converted to CO₂ in the combustor, and hydrogen (H₂), which is converted to H₂O. In general, H₂O is typically condensed from the sCO₂ cycle after the recuperator, though its concentration in the sCO₂ can affect its condensation temperature, potentially affecting the recuperator heat balance. Even after a condensation-based water removal system, however, water vapor will always be present to some degree in the system.

The water content is an example of a process-dependent impurity, since it is generated from the internal combustion process. This H₂O may also combine with CO₂ or other gaseous impurities to generate carbonic acid (H₂CO₃), sulfuric acid, and other acids. Other process impurities may come from coal transport fluids in the gasifier (EPRI, 2014b), syngas quench water, and incomplete combustion products (White, 2018). Further, since the combustion process is occurring at near stoichiometric conditions, CO can be expected to form in significant quantities. Camou (2014) measured CO concentration at the exit of a 10 MPa oxy-combustor on the order of 150 ppm. Much of the CO formed in the combustor may shift to CO₂ as the combustion gases cool in the turbine and recuperators, but this is very much dependent on the rate of expansion and cooling. For a very rapid expansion, the CO may essentially be “frozen” in place and not able to reach chemical equilibrium. Since these factors are system dependent, it is not clear how much CO can be expected at the low-temperature end of the cycle. One modeling study by Strakey suggests that reactions effectively cease after the first turbine stage, and only allow about 10% of the CO recombines to CO₂ (2018). Another study on the effects of incomplete combustion suggest that the plant efficiency decreases by about 0.75 percentage points per mole % of CO in the combustor exhaust (White, 2018).

2.7 WATER AND POLLUTANT REMOVAL

Aside from the immediate issues any of these pollutants may raise for the cycle efficiency or hardware life and reliability, there is also the need to reduce pollutants to acceptable levels before the exhaust gases can be released to the atmosphere or sequestered. Oxy-combustion of syngas will produce many of the contaminants present in the products from a coal oxy-combustion process including O₂, N₂, and Ar from the ASU, as well as acid gases such as sulfur trioxide (SO₃), sulfur dioxide (SO₂), hydrogen chloride (HCl), and nitrogen oxides (NOx) (Murciano, 2011). Both pre-combustion and post-combustion sulfur removal techniques have been considered for direct sCO₂ cycles utilizing syngas from coal gasification (Lu, 2016). McClung et al., (2014) concluded that desulfurization using limestone slurry with recovery of gypsum byproduct is the preferred flue gas desulfurization method. On the other hand, post-combustion removal techniques may have efficiency benefits for direct cycles in theory (Lu, 2016). One factor important to consider for the post-combustion sulfur removal option is that hot corrosion from sulfur in the syngas combustion

products can have detrimental effects on turbine and recuperator materials (Lai, 2007). Acid gasses such as sulfur oxides (SO_x) and NO_x will be formed in the combustion process and are likely to condense out in either the low-temperature recuperator or the water removal system. These corrosive effects can critically shorten the life of nickel-based alloy components that will be required for use in the turboexpander as well as the recuperator. The capital cost as well as maintenance costs of the recuperators could prove to be a limiting factor in the realization of large-scale commercial application (Strakey, 2014). Mercury is also a concern but is expected to fall out with the nitric acid (Allam, 2013).

Water vapor in the combustion exhaust remains in the working fluid through the turboexpander and recuperator, but must be removed prior to CO₂ compression. For a direct sCO₂ cycle with a low-pressure side operating at 3 MPa, the condensation point for water is about 117°C. As the working fluid cools through the recuperator, it begins to condense. After exiting the recuperator, cooling water is used to condense the remaining water vapor, then liquid water is removed in a water separator (Allam et al., 2014a). Where liquid water exists in the presence of CO₂, from the recuperator through the water separator, materials must be resistant to H₂CO₃ corrosion. Therefore, corrosion resistant stainless steels must be used (Allam et al., 2014a).

2.8 CARBON CAPTURE AND STORAGE

One of the primary benefits of direct sCO₂ cycles is its ease of CO₂ capture—CO₂ is relatively pure and at higher pressures. Underground storage of CO₂ requires that the CO₂ be pumped to high pressures for transport underground and to drive dispersion of the CO₂ into the bedrock or dissolution of the CO₂ into the brine formation. The pressure for storage is typically 2,200 psig (15.08 MPa) for most system studies (NETL, 2013).

In addition, existing CO₂ pipelines that are used for enhanced oil recovery (EOR) have purity specifications for CO₂ that are in place to protect the pipeline hardware. These specs are listed in an NETL Quality Guidelines for Energy System Studies (QGESS) report (NETL, 2013) and in Table 2. Meeting these specs typically requires the use of a CPU, which utilizes cryogenic distillation columns to reject impurities from the CO₂ storage stream (Jin, 2015).

TABLE 2.2. CO₂ PURITY SPECIFICATIONS PER END USE (NETL, 2013).

IMPURITY	UNITS	CARBON STEEL PIPELINE, SALINE RESERVOIR STORAGE	ENHANCED OIL RECOVERY	VENTING CONCERNS
H ₂ O	ppmv	500	500	N
N ₂	vol%	4	1	N
O ₂	vol%	0.001	0.001	N
Ar	vol%	4	1	N
CH ₄	vol%	4	1	Y
H ₂	vol%	4	1	Y
CO	ppmv	35	35	Y
H ₂ S	vol%	0.01	0.01	Y
SO ₂	ppmv	100	100	Y
NO _x	ppmv	100	100	Y

A study by the IEAGHG (2015) compares the performance of a base sCO₂ system with a distillation column CPU (90% CO₂ capture rate at 99.8% purity) against a case without the use of a CPU (100% CO₂ capture at 98% purity), and against a case utilizing an additional membrane to improve capture rate in the base case CPU (98% CO₂ capture at 99.8% purity). The study found that in the case of no CPU, resulting in low CO₂ storage purity, lower auxiliary power consumption leads to an increase of about 0.2% in the plant's net thermal efficiency over the base case. For the high-purity, high-capture rate case including the membrane in the CPU, a higher compression power requirement reduces the plant's efficiency 0.4% relative to the base case. This underscores the need to consider CO₂ capture rates and CO₂ purity when comparing direct sCO₂ cycles against one another, or against competing technologies.

2.9 COMPONENT CHALLENGES

While many of the component challenges associated with indirectly heated sCO₂ cycles also exist for direct cycles, there are a host of additional challenges unique to direct sCO₂ power cycles. This section discusses those component challenges unique to direct cycles.

2.9.1 OXY-COMBUSTOR

At pressures on the order of 30 MPa, a direct-fired sCO₂ combustor is more likely to resemble a rocket engine than any type of conventional gas turbine combustor. At these very high pressures and energy release densities, issues such as injector design, wall heat transfer and combustion dynamics may play a challenging role in combustor design. At these conditions, combustor design is an area where there is very little experience (Strakey, 2014).

Also, since these pressures are well beyond current design experience, Computational Fluid Dynamics (CFD) modeling will not only be useful, but may be a necessity in the design process. CFD modeling to predict combustion dynamics or just overall mixing and performance requires validated chemical kinetic mechanism for the governing reactions. Typically, for natural gas combustion, GRI Mech (2014) is used, but this mechanism has only been developed and validated for pressure below about 3 MPa, which is an order of magnitude below the typical 30 MPa of direct-fired systems. Reduced mechanisms, as well as simple global reaction mechanisms are usually derived from the more detailed mechanisms like GRI Mech and as such are only valid for combustion below about 3 MPa. At higher pressures, 3-body recombination reactions deplete the pool of combustion radicals such as O, H, and OH, as shown in the equilibrium calculation in Figure 2.2 (Strakey, 2014), which is for a stoichiometric methane (CH₄)/O₂/CO₂ mixture with a nominal temperature of about 2,000 K. Also note the increase in temperature as pressure is increased due to the decrease in radical concentrations and subsequent increase in product gas formation (CO₂ and H₂O).

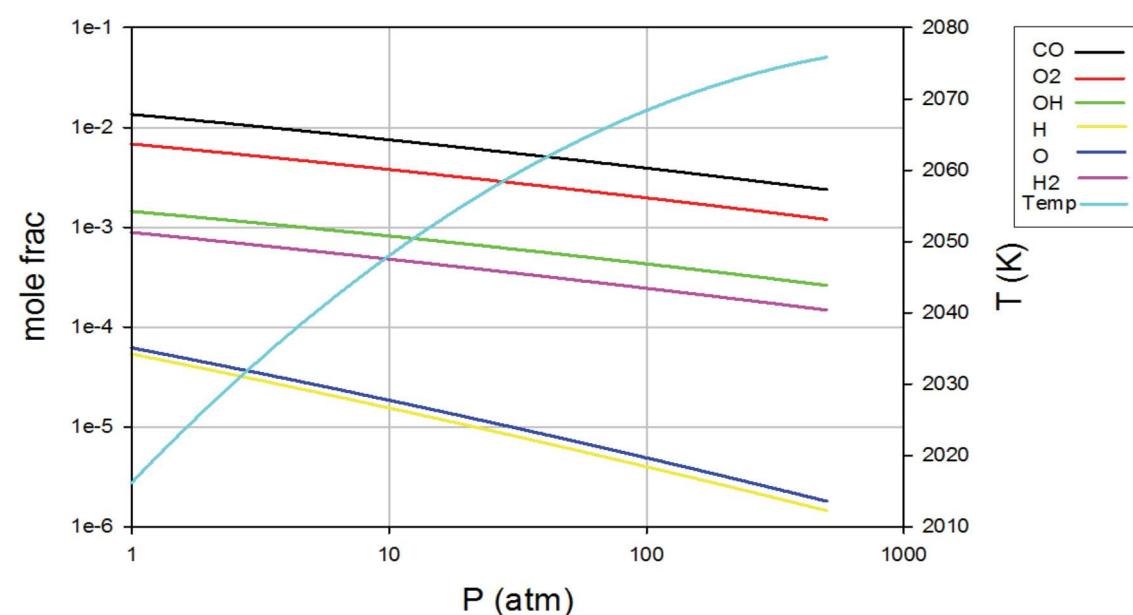


Figure 2.2. Equilibrium calculation for stoichiometric methane-oxygen mixture with carbon dioxide diluent (Strakey, 2014).

The extrapolation of low-pressure kinetic mechanism to the very high pressures of sCO₂ cycles introduces a large uncertainty in reaction rates and heat release. Confidence in CFD and other modeling predictions requires validation of candidate mechanisms using shock tube, combustion bomb and flame speed measurements at high pressure. For coal-based systems operating on coal syngas, even more data is needed for the prediction of high-pressure syngas chemistry with potential contaminants.

For oxy-fired combustion, NO_x formation is not really an issue so the preferred combustion approach is diffusion flame combustion where the fuel and oxidizer are mixed and burnt in the combustion chamber. It is well known in the gas turbine community that diffusion flame combustors are inherently more resistant to combustion dynamics than premixed combustors. However, it is also well known that rocket engine combustors, which are all diffusion based, have a long history of combustion dynamics problems due to the very large pressure and large energy release density, which tends to couple with the resonant acoustic modes of the combustion chamber. Problems with combustion dynamics (Strakey, 2016) are typically discovered and solved with full-scale hardware testing through the use of Helmholtz resonators, baffles, and injector design modifications. Some of the most damaging coupling occurs in the 1-5 kHz range due to combustor tangential acoustic modes and is known as screech in the rocket engine community. Recently, some promise has been shown with CFD modeling using compressible Large Eddy Simulations (LES) to predict combustion dynamics, though this is computationally expensive and far from maturity.

Currently, there is only one known high-pressure oxy-fuel combustion rig that has been fully tested. A 5 MW, 30 MPa combustor has been developed and tested by Parametric Solutions Inc. (PSI) for Toshiba/NetPower (Allam, 2013). The PSI combustor was designed mainly for demonstration purposes, though some data is publicly available (Iwai, 2015; Camou, 2014). Lessons learned from this combustor were applied to the design and development of a 50 MWth combustor, which will undergo testing at the NET Power demo plant in 2018 advance of full-cycle operation (Allam, 2017). A review of the pertinent sCO₂ oxy-combustion literature can be found in Strakey, et al. (2014).

2.9.2 TURBINE

There are a number of design challenges for indirect sCO₂ turboexpanders, including seals, bearings, throttle control valve durability, and erosion in turbomachinery components among others (Weiland, 2017). For direct cycles those challenges all still exist but are even further from being resolved because of the higher operating temperatures expected in a direct cycle. A natural gas-fueled power plant based on the Allam cycle would need to have a turbine inlet temperature of 1,150°C and pressure of 30 MPa to achieve an efficiency comparable with natural gas combined cycle (NGCC) power plants (Allam, 2013). While sCO₂ properties are predictable at these temperatures and pressures, making aerodynamic design less of a challenge, structural design still remains a challenge because of the large blade loading expected from such a dense fluid. With turbine inlet temperatures exceeding 1,150°C, not only will turbines require internal cooling, but they may require film cooling as well. Cooling techniques matured through the development of air breathing gas turbines (Han et al., 2000) should be adaptable for application in sCO₂ direct cycle turboexpanders. A preliminary assessment of sCO₂ turbine blade cooling strategies has been performed by Aerojet Rocketdyne under an ARPA-E program (EPRI, 2015), and the effect of blade cooling flows has been included in the IEAGHG report on the natural-gas fired Allam cycle configuration (IEAGHG, 2015).

The high direct sCO₂ cycle temperatures also preclude the use of turbine throttling valves upstream of the turbine, as would be used in indirect sCO₂ cycles, requiring alternative strategies for turbine throttle control. Similar to gas turbines, this is more easily accomplished via fuel and oxidizer flow control, which can provide rapid modulation of turbine inlet temperature, though the use of cold, high-pressure sCO₂ could also be used for hot sCO₂ attemperation, albeit at a penalty to cycle efficiency. Further, the turbine shaft should also drive one of the cycle's compressors to provide a braking effect in the event of loss of electrical load.

Another complication not present in indirect cycles is the presence of impurities in the hot gas path of the turbomachinery. Downstream of the oxy-combustor, the primary constituents will be CO₂ and H₂O, but depending on the fuel, other impurities such as SO₃, SO₂, HCl, as well as environmental particulates will be present in the hot gas path making erosion, corrosion, and deposition all possible issues for design consideration. Several studies exist in the open literature to report the effects of erosion, corrosion, and deposition in air breathing gas turbines (Hamed and Tabakoff, 2006; Richards, 1992; Wenglarz and Wright, 2003), but little is known about these effects at the high pressures that will exist in direct cycle turboexpanders. Some research has been conducted to better understand the effects of corrosion on stainless steels and nickel-based alloys in sCO₂ environments (Oleksak, 2018a; Mahaffey, 2014; Pint, 2014; Saari, 2014), but little is known about sCO₂ corrosion effects at temperatures exceeding 1,150°C in the presence of water, sulfur, and other impurities, particularly for the long duration exposure times that utility-scale turboexpanders will be expected to operate between maintenance shut downs.

2.9.3 RECUPERATOR

Recuperative heat duty in direct sCO₂ cycles is approximately twice as high as the electrical power output of the cycle (Allam, 2014a). While this recuperative heat duty is not as significant as in indirectly heated sCO₂ cycles, recuperator cost will still be a considerable factor in plant design. All of the recuperator challenges posed by indirect sCO₂ cycle conditions will also apply to direct cycle recuperators, although direct cycle recuperators will be required to operate at temperatures that are 200-300°C higher than even the high-temperature recuperator in an indirect cycle. In fact, as the highest temperature component in the cycle that cannot utilize cooling, the high-temperature and pressure capabilities of the recuperator are the limiting factor that prevents the cycle from operating at more severe, and more efficient, conditions. As turbine inlet temperature in the direct cycle exceeds 1,150°C, turbine exhaust (recuperator inlet) temperature approaches 800°C (Allam, 2014a). To make matters more challenging, the direct cycle turboexpanders are expected to operate at a higher pressure ratio than indirect turboexpanders making the direct cycle recuperator subject to higher pressure differentials than indirect cycle recuperators. These pressure differentials approaching 27 MPa will result in higher stress levels in the recuperator, as well as increased recuperator sizes to accommodate the larger volume flows at the low-pressure side of the cycle, relative to indirect sCO₂ cycles.

To increase turbine inlet temperatures beyond the current limitations of about 1200°C for the purpose of improving cycle efficiency, advanced materials or recuperation strategies will be needed to handle the resulting increase in turbine outlet temperatures. Advances in cost-effective structural metal alloys may make incremental improvements in high-temperature and pressure threshold at the turbine outlet, but ceramic heat exchangers will likely be required for the highest temperature recuperative duty to reach the full potential of these directly heated sCO₂ power cycles. Lewinsohn et al. (2016) are currently developing a ceramic heat exchanger for sCO₂ applications with focus on validation of design tradeoffs, verifying reliability, and verifying manufacturing costs which may approach \$200/kWt. Compact ceramic heat exchangers are immature and costly as compared to their metal counterparts and little is known regarding the effects that exhaust gas species at sCO₂ conditions may have on the ceramics, but ongoing R&D is expected to address these challenges.

2.9.4 COMPRESSOR

The design challenges for indirect sCO₂ cycle compressors (e.g., multiphase flows, condensation, aerodynamic losses) will likely apply to compressors utilized in direct cycle applications (Weiland, 2017).

Diluents (consisting of mainly N₂ and Ar from the syngas and 95 v% pure O₂ streams) entering the sCO₂ working fluid during combustion will likely be discharged throughout the cycle. Thus, studies have shown an increase in the specific power needed to compress the recycled CO₂ containing the impurities vs. a pure sCO₂ case (EPRI, 2014b). Optimization efforts to ensure purity of the CO₂ working fluid will be required to combat large compression power requirements that reduce cycle efficiency.

Additionally, as discussed in Section 2.6, combustion of coal-derived syngas will produce impurities of SO₂ and NO/NO₂. As these impurities will be exposed to condensed liquid H₂O and excess O₂ at later points in the cycle, namely within the heat exchanger, acid conversion (sulfuric acid and nitric acid) is expected to occur (Allam, 2013). These impurities present corrosion challenges to exposed turbomachinery, including the direct cycles CO₂ recycle compressor, depending on the cleanup and separation processes included within the specific cycle. While cycle specifics may vary, careful design selection of corrosion resistant turbomachinery will likely require consideration.

2.10 CYCLE PERFORMANCE, COST, AND PROSPECTS

The significant recent interest in direct sCO₂ power cycles comes largely from the potential for high efficiency cycles with CCS bolstered by NET Power's work to demonstrate the cycle. A summary of the results from the direct sCO₂ systems analyses in the literature is shown in Table 3.

TABLE 2.3. DIRECT sCO₂ PLANT PERFORMANCE RESULTS FROM SELECTED STUDIES.

SOURCE	FUEL	TURBINE INLET		PLANT THERMAL EFF.	CO ₂ CAPTURE
		°C	bar	HHV, %	%
Allam, 2013	Methane	1150	300	53.1	100
McClung, 2015	Methane	1200	200	46.5	
IEAGHG, 2015	Natural Gas	1150	300	49.9	90.0
EPRI, 2017	Natural Gas	1150	300	48.4	90.1
White, 2018	Natural Gas	1204	300	48.2	98.2
NETL, 2015a (NGCC w/CCS)	Natural Gas	1359	17	45.2	90
Allam, 2013	Illinois No. 6 coal	1150	300	48.9	100
Hume, 2016	PRB coal	1123	300	39.6	99.2
Zhao, 2018	Datong coal	1193	300	37.1	100
Weiland, 2018	Illinois No. 6 coal	1204	300	40.6	99.4
NETL, 2015b (IGCC w/CCS)	Illinois No. 6 coal	1337	26	31.2	90

The results in Table 3 show that CH₄ and natural gas-powered direct sCO₂ cycles generally perform better than coal-fired cycles, which is expected due to the added requirement of a coal gasification train. The IEAGHG analysis of the Allam cycle in Table 3 (IEAGHG, 2015) results in about 3 percentage points lower efficiency than that reported by Allam (2013); however, NET Power commentary contained in the IEAGHG report explains that these differences result from improved thermal integration, cooling, overall process optimization relative to the IEAGHG study (2015). The studies by McClung et al. (2015) and EPRI (2017) report similar efficiencies to the IEAGHG study at similar conditions. Further, McClung et al. achieved higher thermal efficiencies in condensing recompression cycles in a direct-fired configuration, though the turbine outlet temperatures of about 1000°C were well beyond the capabilities of existing high temperature recuperators (2015). The study by NETL (White, 2018) yields a slightly lower efficiency than either the EPRI or IEAGHG studies, but achieves a higher CO₂ capture rate at 98.2%.

For coal-fired systems, the high thermal efficiency of 48.9% reported by Allam (2013) falls within the range of thermal efficiencies reported by Lu (2014) (43.3% to 49.7%), which cover several variations in coal type, gasifier type, and heat recovery processes, though turbine inlet and other cycle conditions are not reported. Part of the reason for higher efficiencies than reported in the other coal-fired studies in Table 3 is the use of SO_x and NO_x removal processes that are internal to the sCO₂ cycle, as discussed in Section 2.2 and Section 2.7. This may improve the plant HHV thermal efficiency by about 2 percentage points (Lu, 2014), though the impact of acids in the sCO₂ working fluid will need to be considered from a material compatibility perspective. Further efficiency improvements are reflective of significant thermal integration between the gasifier and sCO₂ cycle and high-pressure (8.5 MPa) gasifier operation (Allam, 2014b). An independent estimation of the HHV efficiency of the in situ syngas cleanup process yields 45.4% (Weiland, 2018), while studies with conventional syngas cleanup predict HHV thermal efficiencies of about 40% (Hume, 2016; Weiland, 2018).

As for plant costs and cost of electricity, very little information is available, and what has been published is highly speculative, given that many of the required components have never been built and are still in development. Further, economic assumptions (e.g., fuel costs, labor costs, financing assumptions, plant lifetime and capacity factor) may vary widely between studies, thus economic comparisons are generally only valid within a given study in which common economic assumptions are made.

In the IEAGHG study of natural gas-fueled plants, the levelized cost of electricity (LCOE) of the direct sCO₂ plant was \$105.3/MWh, while NET Power's analysis in this report gives an LCOE of \$92.9/MWh (IEAGHG, 2015). Other oxy-combustion turbine plant designs were also analyzed in this study, with the direct sCO₂ plant proving to have a 10-12% lower LCOE than the other plant designs. Amec Foster Wheeler, who was contracted by IEAGHG to perform this study, also performed a follow-up analysis for EPRI, utilizing economic assumptions more common to North

America. The direct sCO₂ cycle in this study had an LCOE about 11% lower than the other oxy-combustion turbine plant designs considered, and further showed a 2% lower LCOE relative to an NGCC plant without CCS (EPRI, 2017). A recent NETL study shows that a direct sCO₂ plant has a comparable total plant cost, on a \$/kW basis, to a NGCC plant with CCS, but due to its higher efficiency, the direct sCO₂ plant has first-year COE that is about 4% lower (White, 2018). Natural gas-fueled direct sCO₂ systems are, therefore, competitive with NGCC plants in terms of thermal efficiency and cost, and superior to other oxy-combustion turbine approaches.

For coal-fueled plants, EPRI's 2014 study estimates the total plant cost of a direct sCO₂ plant to be about 3% higher than that of a comparable IGCC plant with CCS on a \$/kW basis (with significant uncertainty noted), but with a 4% lower COE due to its higher efficiency (EPRI, 2014b). A more optimized and thermally-integrated direct sCO₂ plant design considered by NETL yields a 19% lower total plant cost (\$/kW basis) and a 20% lower COE than a comparable IGCC plant with CCS, although IGCC plants with more advanced hydrogen turbines are more competitive (Weiland, 2018).

Coal-fueled direct sCO₂ systems are, therefore, very competitive with IGCC systems with CCS; however, additional competition may come from oxy-fired indirect sCO₂ systems with CCS, which have comparable thermal efficiency and COE, depending on turbine inlet temperature and cycle configuration (NETL, 2017b). Ongoing techno-economic analysis research at NETL is currently pursuing improvements to both direct and indirect sCO₂ plant designs to improve their economic competitiveness with NGCC and IGCC plants with CCS.

2.11 SUMMARY OF THE STATUS

Demonstration of a direct sCO₂ power is proceeding through the development and construction of the NET Power/8 Rivers 25 MWe power plant in Texas. This cycle offers high efficiency with an inherent ability to capture CO₂ at relatively high purity and pressure, with natural gas combustion occurring within the cycle, and coal utilization made possible by gasification of the coal and combustion of the resulting syngas. Specific challenges in these cycles, as discussed above, are related to impurities in the predominantly sCO₂ working fluid, the higher temperatures in the cycle that require combustor and turbine cooling, and specific oxy-combustion challenges at pressures comparable to those in rocket engine combustion.

Future interest in direct sCO₂ cycles will forever be tied to the desire to capture and store/utilize CO₂ emissions from fossil-fueled power generation. Given that greenhouse gas reductions are likely to be a major thrust in power generation research in the coming decades, prospects for continuation of development of direct sCO₂ power cycles seems likely to be strong for the foreseeable future.

3.0 TECHNOLOGY GAPS & RESEARCH NEEDS

This chapter categorizes identified technology gaps under five technological groups: (1) system analysis and dynamics, (2) combustion and turbomachinery, (3) heat exchangers, (4) materials, and (5) pollution control. For each technology gap, research needs are listed. Technology readiness level (TRL) is also assessed for each technology discussed.

3.1 SYSTEM ANALYSIS AND DYNAMICS

3.1.1 COST VS. PERFORMANCE OF DIRECT sCO₂ CYCLE COMPONENTS FOR COE MINIMIZATION

Problem Statement: In order to minimize the COE from a direct sCO₂ power plant, a balance between efficiency (fuel cost) and the prorated capital cost of the plant over its expected lifetime must be achieved. This requires knowledge of the currently unknown component cost and performance tradeoffs that can be used to optimize a plant design for minimum COE. Often, since component costs are unknown for new cycles, cycle designers pursue efficiency as the only figure of merit, although lower-efficiency designs with fewer or less expensive components may ultimately produce the lowest COE plant designs.

For example, as the desired recuperator temperature approach and pressure drops decrease, plant efficiency increases, but the size and cost of the recuperators also increases significantly. Likewise, higher efficiency turbomachinery improves plant efficiency but costs more, with currently unknown scale, performance, and cost relationships for these new components. Capital costs associated with a direct sCO₂ turbine are unknown, as this is a new technology that is closely held by Toshiba. This is needed, as well as its dependence on scale, to accurately assess the techno-economic viability of direct sCO₂ power cycles at different scales. Likewise, costs for compressors and pumps can currently be estimated by vendors, though vendor experience and offerings in this area may not be optimal. Further, the variability in compressor and pump inlet conditions, as a function of variable ambient conditions and cooling system performance, make specification and costing of an appropriate compressor or pump difficult.

Past Work & Progress: Some COE minimization work has likely been performed by 8 Rivers/NET Power and their vendors in the course of their cycle development, though few details of this process have been made public. For coal-fueled direct sCO₂ applications, where the coal is first gasified and the resulting syngas burned in the sCO₂ oxy-combustor, 8 Rivers has favored low-cost quench-style gasifiers without syngas cleanup, instead performing pollutant removal within the sCO₂ cycle using their “DeSNOx” process (8 Rivers, 2014; Lu, 2016). For the commercial-scale natural gas-fired system, 8 Rivers notes that competitive bids were used to determine sCO₂ cycle component costs, and that ongoing discussions with vendors to improve component efficiency and integration with the remainder of the plant are expected to contribute to reductions in COE from first-of-a-kind (FOAK) to nth-of-a-kind (NOAK) plants (IEAGHG, 2015). Another cost-saving measure is seen in the design of the 50 MWth demo plant, where a separate high-temperature recuperator section was produced from nickel-based Alloy 617 to cool the turbine exhaust from 705°C to 550°C, while the remaining recuperator sections were made from lower-cost 316 stainless steel (Allam, 2017).

A study by Amec Foster Wheeler that includes economics of a natural gas-fueled direct sCO₂ power plant does not include detailed cost breakdowns of power cycle components (IEAGHG, 2015; EPRI, 2017). An EPRI study on a gasification-based direct sCO₂ power plant breaks cycle costs down only into compression, turbine, and recuperation/piping accounts, with little detail on their bases (EPRI, 2014b).

The most detailed publicly-available direct sCO₂ cycle component costs are from techno-economic studies by NETL, though cost bases for many components are unvalidated (NETL, 2017a; Weiland, 2018; White, 2018). The oxy-combustor and turbine in these studies are scaled from the combustor and turbine sections of a comparably-sized gas turbine, plus the cost of a high-pressure turbine shell, and may be underestimated. Compressor costs are scaled from quotes received for indirect sCO₂ power cycles, though an effort is currently underway to update these costs for commercial-scale direct sCO₂ power cycle conditions. Recuperator costs are also scaled from indirect sCO₂ power cycle studies, and may not account for the larger recuperator volume resulting from lower direct sCO₂ recuperator pressures (30 bar) relative to recompression sCO₂ cycle recuperator pressures (80 bar). Regardless, COE sensitivities that have been performed using this approach include the following:

- Determining the sensitivity to final high-temperature preheating of recycle CO₂ to the oxy-combustor using a syngas cooler (NETL, 2017a). An alternative approach to this type of thermal integration, as well as implementation of other improvements, improved plant efficiency by 3 percentage points and reduced COE by 10% (Weiland, 2018).
- Increasing the recuperator approach temperature from 10°C to 20°C in the improved gasification/direct sCO₂ system above resulted in reductions to both plant efficiency and capital cost, resulting in a net increase in overall plant COE (Weiland, 2018).
- Investigations of alternative recuperator cost scaling relationships from a second vendor illustrates the effect of sCO₂ component capital cost uncertainty on the overall economics of a natural gas-fueled direct sCO₂ plant (White, 2018).

Finally, it should be noted that cost scaling relationships for sCO₂ cycle components for concentrated solar power applications have been developed by Sandia National Laboratories (SNL) using their database of sCO₂ component costs (Carlson, 2017). While these relationships are mostly for smaller scale, indirect recompression sCO₂ cycle systems, an effort is currently underway to combine sCO₂ component cost databases across DOE national laboratories, for the purposes of expanding these cost scaling relationships to larger scales and additional applications, including direct sCO₂ cycles.

Research Needs: Development of accurate cost scaling relationships are needed for turbomachinery, recuperators, and other direct sCO₂ cycle components as a function of design specifications (e.g., pressure drops, temperature approaches, inlet pressure/temperature/volumetric flow). These scaling relationships need to be validated through vendor quotes and benchmarking against sold equipment, possibly in other applications.

While cost-scaling relationships for recuperators are arguably the most mature, they currently lack scaling as a function of pressure drop, which significantly impacts both sCO₂ cycle efficiency and recuperator size and cost. Likewise, as noted above, recuperator size and cost should also be a function of the lowest pressure in the recuperator, which dictates the volumetric flowrate, and is linked to the pressure drop. Clarification of this relationship will allow for better optimization of direct sCO₂ cycles for minimum COE.

A significant need is a public and independent direct sCO₂ turbine design and cost, as well as scaling relationships for the design. No such design of cost relationship currently exists outside of Toshiba. In 2018, NETL selected a Southwest Research Institute (SwRI)-led project from DE-FOA-0001816 entitled “Development of Oxy-Fuel Combustion Turbines with CO₂ Dilution for sCO₂-Based Power Cycles.” This project may provide the relevant turbine design and cost information needed for system analyses.

Cost-scaling relationships are also needed as a function of shaft power, inlet volumetric flow, and inlet temperature, for centrifugal pumps, centrifugal compressors, and axial compressors. Further, there are situations in which barrel-type centrifugal compressors are preferable to integrally-gearred compressors, and situations where compressor intercooling is needed. These decision metrics need to be determined, as well as the cost relationships for each compressor type and variation.

Finally, once these cost and performance scaling relationships are determined, there is a need for development of a cycle modeling platform that incorporates these relationships as a function of their performance specifications, to enable automated COE minimization of direct sCO₂ plant designs.

Major R&D Challenges

- Component cost models are closely held by component vendors, and are unlikely to be shared externally.
- The potential for interference (whether perceived or real) with Toshiba’s intellectual property on direct sCO₂ turbines may prevent progress.
- Accurate models that incorporate the lowest-cost manufacturing processes are a challenge for non-manufacturers to develop independently.
- Derivation of cost-scaling relationships from multiple quotes (possibly from multiple vendors) is time consuming and inevitably over-simplified.
- Openness of compressor and pump vendors to sharing proprietary information may also be a challenge.

TRL Assessment: This assessment is based on publicly-available knowledge, but maturity of publicly-available direct sCO₂ component costs is significantly variable—from no available costs for oxy-combustors and turbines to reasonable UA-based cost scaling relationships for recuperators. NETL is currently at a TRL-2 for direct sCO₂ cycle, and should improve to TRL-4 by 2020, following planned analysis activities.

It should be noted that higher, unknown TRL levels have likely been achieved by NET Power and Toshiba in the course of their pre-front end engineering design (FEED_ studies and demo plant construction. 8 Rivers/NET Power likely have a good database of sCO₂ component costs for specific operating conditions, though they may not have a good handle on how these costs vary with component performance—this information should reside with the individual component vendors. Toshiba currently has a monopoly on cost information for direct sCO₂ combustors and turbines.

3.1.2 SYSTEM CONTROLS TO OPTIMIZE TRANSIENT DIRECT sCO₂ PLANT PERFORMANCE

Problem Statement: Direct sCO₂ power cycles are a new concept, and little to no work has been done to date on control strategies for startup, shutdown, and load transients, or to maintain high cycle efficiency during part-load or off-design system operation. Plant flexibility is also valued by utilities, thus control strategies that deliver maximum load ramp rates and/or low minimum load are needed

Ambient conditions, particularly temperature, are known to have a significant impact on indirect sCO₂ cycle performance, since the CO₂ critical temperature of 31°C is near ambient temperature. Effects of daily or seasonal temperature variations on direct sCO₂ cycle performance are unknown, as well as potential control strategies to maintain high cycle efficiencies under such variations.

There is a wide array of possible cycle control strategies at the designer’s disposal (e.g., fuel/oxidant input, system pressure, mass flow, compressor inlet guide vane position, cooling rate, pump speed), and little guidance on the likely stable, efficient, and cost-effective approaches.

Past Work & Progress: NET Power has developed their own control strategies for their 25 MWe demonstration plant, though details on these approaches are unknown. A transient system model has been developed with sufficient accuracy to function as a training simulator for plant operators (Allam, 2017). Some of the developmental control strategies relevant to this cycle are available in the patent literature (Fetvedt, 2016; Itoh, 2017). Part load studies on the direct sCO₂ plant are beginning to emerge in the literature (Scaccabarozzi, 2017). NETL will be starting development of a dynamic direct sCO₂ plant model in 2018.

Experimental test loops that are investigating direct sCO₂ cycle components may have relevant information that could assist in developing overall direct sCO₂ cycle controls. In particular, SwRI is developing a closed-loop oxy-combustor test rig, which also includes recuperation, compressors, and a direct contact cooler (Delimont, 2017). Thar Energy has built and run a basic sCO₂ oxy-combustor (Delimont, 2017). EERC has developed and run an experimental facility for a direct contact cooler for gasification-based direct sCO₂ systems (Allam, 2017).

Work is underway by multiple groups (NETL, SwRI, GTI, General Electric [GE]) to develop control strategies for the 10 MWe indirect sCO₂ Supercritical Transformational Electric Power (STEP) plant, though the architecture of the recompression cycle is very different from that of the direct sCO₂ cycle. Echogen has developed automated control strategies for cascade sCO₂ cycles for their 7 MWe EPS100 unit. Controls have also been developed for smaller indirect sCO₂ recompression cycles at SNL, Knolls Atomic Power Lab (KAPL), Bechtel Bettis, among others. Some of these control strategies for indirect sCO₂ cycles may be able to be leveraged for direct sCO₂ power cycle controls.

Research Needs: Detailed models for all direct sCO₂ cycle components need to be developed, including turbomachinery, recuperators, coolers, the combustor, and the ASU. These models need to be capable of predicting part-load or dynamic response of each component. Technology gaps and research needs for off-design turbomachinery performance are discussed further in Section 3.2.7. Heat exchanger data needs include metal masses, pressure drops, and holdup (sizing).

Off-design studies are needed to develop likely strategies for part-load cycle operation. Further, transient system studies that test multiple control approaches are needed to determine the best approach. These may be used to inform the development of controls for direct sCO₂ cycles, though feedback in the form of experimental data from operating test loops is also needed to validate the dynamic system models.

Major R&D Challenges:

- ASUs are a large component of direct sCO₂ power systems, and are not known for their dynamic operation capabilities. In IGCC systems, the ASU is the rate-limiting sub-system for load ramping operations.
- Lack of operating experience with direct sCO₂ power cycles.
- Unknown design and operating challenges at larger scales, where cycle architecture may vary from the early demonstration units.

TRL Assessment: Assessment for this technology gap is based on publicly-available knowledge (Figure 3.1). The most likely pathway for development of direct sCO₂ cycle control systems is through the SwRI oxy-combustion test facility project, as well as their upcoming direct sCO₂ turbine project, which will be integrated with the oxy-combustor in a test loop. The oxy-combustion project is slated to utilize the 1 MWe SunShot test loop, which is undergoing testing at the moment. Control systems for the oxy-combustor are conceptual at this point; however, process instrumentation and test loop layouts have been completed, thus the TRL is at 1-2. Completion and testing of the oxy-combustion test loop in 2020 would likely bring the TRL to 3, while integration with the direct sCO₂ turbine would likely not occur until 2022 or later, raising the TRL to 4. A larger DOE-funded direct sCO₂ demonstration unit would be needed to advance the TRL to the 6-7, though the timeframe for this is uncertain.

Systems Analysis - Dynamics

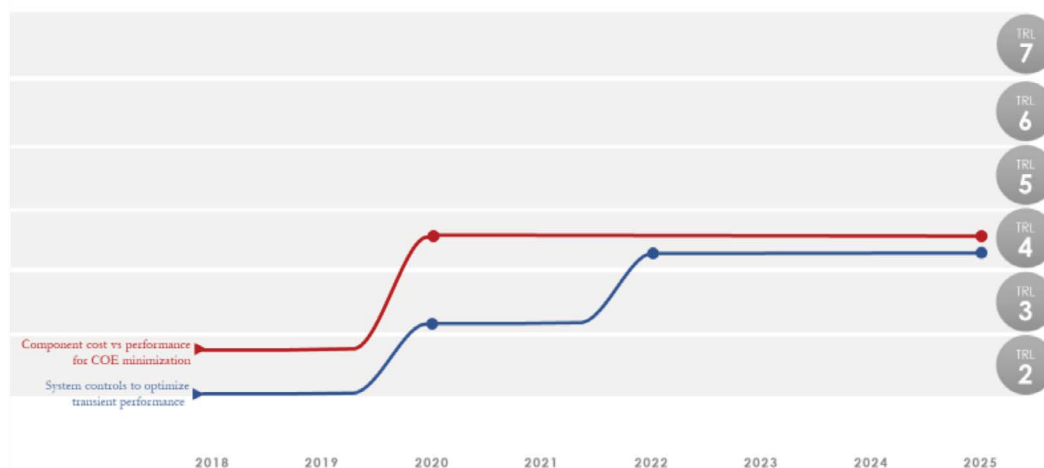


Figure 3.1. Technology readiness level progression for system analysis and dynamics for direct sCO₂ power cycles.

In the meantime, NETL is planning to develop and exercise a dynamic model of a commercial-scale direct sCO₂ power plant in the next two years. Basic control strategies for part-load and off-design operation will be implemented, which could bring this to TRL 4 by 2020 for these control actions, though startup, shutdown, and emergency stop control operations needed for actual plant operation will not be explored.

It should be noted that NET Power has developed control strategies to an unknown TRL for their demonstration plant, though these will be refined in the course of testing and demonstration of the plant. Modifications to the component and cycle design may necessitate changes to control approaches, to be tested and validated in the commercial-scale demonstration around 2022. In addition, the demonstration plant does not include an ASU, thus controls for this unit will be needed for the commercial-scale unit.

3.2 COMBUSTION AND TURBOMACHINERY

3.2.1 COMBUSTION MODELS FOR sCO₂ OXY-COMBUSTION

Problem Statement: Oxy-combustion for direct sCO₂ cycles occurs at very high pressures and with large amounts of CO₂ dilution. Existing combustion models for CFD simulations have not been validated at these conditions and may not be appropriate for these conditions.

Past Work & Progress: There is no current effort to validate or develop combustion models for sCO₂ direct cycles although there has been some recent effort to explore model sensitivity (Strakey, 2018).

Research Needs: In order to validate existing models and/or develop new models, experimental data is needed. This could consist of very small bench-scale experiments at 300 bar to provide fundamental data on things like injector mixing or flame-anchoring. Ultimately, some larger-scale combustor data is needed to validate combustion models through prediction of heat release profiles, flame length, CO production, etc. Once the data is generated, existing combustion models can be exercised to see how well they agree with the data. Several different modeling approaches with varying levels of fidelity are likely needed. Simple models to predict flame length and heat release distribution will be needed as well as more detailed models incorporating finite rate chemistry in order to predict CO or other minor species formation. Fuel flexibility also needs to be addressed as both natural gas and syngas are potential fuels.

Major R&D Challenges: The very high pressures make the experimental measurements challenging. There are very limited experimental facilities that are capable of running experiments at 300 bar. Also, the wide range of potential operating conditions makes it difficult to focus on one single combustion model. Several different modeling approaches may be necessary to cover the entire range of combustor operating conditions.

TRL Assessment: There has been a very limited amount of work in exercising combustion models at direct-fired relevant conditions. While most combustion models will “work” at these conditions, it is difficult to assess the applicability or accuracy of these models without experimental data for validation.

3.2.2 EXPERIMENTAL DATA FOR sCO₂ OXY-COMBUSTION AT DIRECT-FIRED CONDITIONS

Problem Statement: The combustion R&D community has a reasonably good understanding of the physics associated with liquid and gaseous fuel combustion for air breathing gas turbine applications up to pressures of 30 bar. Oxy-combustion for direct sCO₂ power cycles requires that level of understanding to be extrapolated to oxy-combustion conditions reaching 300 bar with CO₂ diluent concentration as high as 95%. Mixing characteristics, reaction kinetics, combustion instability, emissions (CO), and autoignition are some of the critical unknowns that require additional R&D from the bench-scale through full-scale testing. Presently, there are ongoing lab-scale experimental efforts to compliment ongoing numerical/computational efforts. These efforts are beginning to shed light on the uncertainties associated with chemical kinetics at direct sCO₂ oxy-combustion conditions; however, experimental test campaigns utilizing state of the art diagnostic tools to observe combustion behavior at direct-fired conditions are needed to close this technology gap by answering critical questions related to mixing, instability, autoignition, and emissions. This data is also critical for validating and developing CFD models.

Past Work & Progress: In 2014, SwRI was selected for a Phase I award to develop a plan for building and testing an sCO₂ oxy-combustor for testing at lab scale. In 2016, SwRI was selected for a Phase II follow-up award to complete the detailed design, fabrication, and testing of that combustor in an existing sCO₂ loop on the SwRI campus in San Antonio, Texas (Delimont, 2017). SwRI has partnered with the University of Central Florida and Georgia Tech which both have ongoing awards through the University Turbine Systems Research Program to develop reduced order chemical kinetic mechanisms for sCO₂ oxy-combustion. SwRI has also partnered with GE to assist with the oxy-combustor design. They plan to implement state-of-the-art diagnostics (including optical diagnostics) to characterize the combustion behavior during operation.

Toshiba has developed and tested a 5 MW oxy-combustor at pressures up to 300 bar with natural gas as the fuel (Iwai, 2015). Unfortunately, there has been very limited data published or shared with the combustion community on these tests (Camou, 2014).

Thar Energy has also developed a very small-scale oxy-combustor that underwent very limited testing. There has been no published data as of yet from this experiment (Delimont, 2017).

Research Needs: Experimental combustor data at high pressure (~300 bar) with CO₂ dilution is needed. Measurements of heat release distribution, CO formation, operating envelope, ignition, wall heat flux, acoustic stability and basic flowfield data (velocity, temperature, etc.) are needed for validating CFD models.

Major R&D Challenges: The biggest challenge to collecting the necessary data is the lack of existing experimental facilities. The challenge of developing and running a new 300 bar experimental combustor and associated facility is the cost and inherent difficulty and risk of experimentation at such high pressures and temperatures. The high pressures necessitate large flowrates, which increase the scale and cost of such experiments.

The NETL Research and Innovation Center has a team led by Dr. Pete Strakey working on predicting sCO₂ oxy-combustion characteristics through the use of CFD. General conclusions from Strakey's work to date include:

- Accurately predicting CO levels for combustor design to minimize CO at the turbine inlet is critical to maximizing cycle efficiency. For every mole % of CO that enters the turbine a cycle efficiency penalty of 0.75 percentage points is expected (White, 2018).
- Findings suggest that thermo-acoustic instability may be a major issue (Strakey, 2016). Strakey plans to explore the effect of injector O₂ concentration on instability. Hypothesis: The propensity for instability will decrease as O₂ concentration decreases due to a decreased heat release density.
- Because selecting appropriate combustion models is critical to accurately modeling combustion with CFD, there is a need for validated detailed chemical kinetic mechanisms and corresponding reduced mechanisms.
- Perhaps the greatest research need currently is experimental data from oxy-combustion of natural gas and/or syngas at relevant conditions. This data will play a critical role in validating reduced order kinetic mechanisms and CFD models.

TRL Assessment: Combustor experiments have been conducted at bench/laboratory scale to gain a better understanding of the important factors to consider in design of pilot-scale combustor. The present TRL associated with this technology gap is TRL 2/3. Under an award presently funded by DOE (FE0024041), SwRI will test a combustor in relevant conditions using the SunShot test facility pushing the TRL to 4 by 2021. A newly awarded pilot project (FE0031584) with the University of North Dakota Energy & Environmental Research Center (UND EERC) and 8 Rivers Capital could potentially lead to pilot plant construction and testing with syngas at the 25 MWth scale by 2024 advancing the TRL to 7.

3.2.3 REDUCED ORDER CHEMICAL KINETIC MECHANISMS FOR sCO₂ OXY-COMBUSTION

Problem Statement: Chemical kinetic mechanisms are well established for combustion environments that have current commercial applications such as liquid- or gaseous-fueled gas turbine engines. Mechanisms such as GRI Mech 3.0 or Aramco 2.0 are detailed and reasonably accurate up to approximately 30 bar. Mechanisms that can accurately predict combustion characteristics of CH₄ or syngas oxy-combustion at pressures exceeding 30 bar do not currently exist. Additionally, current mechanisms do not accurately account for high concentrations of CO₂ (diluent), which is likely to be required in the CH₄ or syngas oxy-combustion environments expected in sCO₂ direct cycles. The operating envelope of available chemical kinetic mechanisms needs to be expanded to include the operating regime expected for sCO₂ oxy-combustion. Additionally, reduced order versions of these mechanisms must be developed such that they can be integrated with CFD models for practical use in making computational predictions essential for combustor design. Accurate predictions for mixing, autoignition, flowfield temperature, and CO formation and burnout are critical in the design of oxy-combustors for sCO₂ direct cycles. The design of downstream components and ultimately the efficiency of the power cycle are dependent on accurate combustion predictive capabilities.

Past Work & Progress: In Fiscal Year 2015, two University Turbine Systems Research (UTSR) projects were awarded to the University of Central Florida and Georgia Tech Research Corporation to develop reduced order chemical kinetic mechanisms for sCO₂ oxy-combustion. Both projects are using shock tube facilities to measure ignition delay times of syngas or CH₄ mixtures with O₂ and CO₂, and are using this data to develop updated reduced order mechanisms that can be practically integrated with CFD. To date, these two projects have led to a number of important findings, which are documented by Pryor et al. (2017), Manikantachari et al. (2017), Karimi et al. (2018), and Liu et al. (2017).

Research Needs: Experimental data for ignition delay time, laminar flame speed, flame and/or stirred reactor species profiles at direct-cycle relevant conditions are needed (P~300 bar, preheat temp ~ 1000K, CH₄/O₂/CO₂ mixtures). Existing detailed mechanisms such as GRI and Aramco need to be validated against this data and updated as necessary. Reduced order (skeletal) mechanisms then need to be derived from the validated detailed mechanisms.

Major R&D Challenges: The main challenge is the lack of fundamental experimental data on ignition delay time and laminar flame speed at relevant conditions. The very high pressures make the experimental measurements difficult and costly. There are very few shock tubes that can currently run up to 300 bar and sufficient preheat temperature for ignition delay time measurements. Also, there are no laminar flame speed experimental devices currently in existence that can reach 300 bar pressure. This is more challenging than the shock tube measurements.

TRL Assessment: The University of Central Florida (FE0025260) and Georgia Tech (FE0025174) are currently completing projects to validate kinetic mechanisms in a laboratory environment high-pressure shock tube. Therefore, the current TRL for kinetic mechanism development is 3. Georgia Tech will use their reduced order kinetic mechanism for the design and testing of the SwRI oxy-combustor (FE0031620) by 2023 moving the TRL to 4. Reduced order mechanisms are expected to evolve for use in combustor design for the 25 MWth coal-Allam plant or some equivalent by the end of 2025 to achieve TRL 7.

3.2.4 TURBINE COOLING STRATEGIES

Problem Statement: Direct sCO₂ cycles will likely operate at temperatures (>1100°C) that are too high for uncooled turbine blades. The maximum operating temperatures of advanced alloys is usually below 800°C. Cooling approaches using CO₂ as the coolant are needed. This could be either internal cooling or film cooling or some combination of the two. As with conventional air-fired turbines, minimizing cooling flow is key to maximizing cycle performance.

Past Work & Progress: Countless studies have been conducted over decades to develop optimized cooling technologies for vane/blade cooling in air breathing gas turbines. Cooling techniques matured through the development of air breathing gas turbines (Han et al., 2000) should be adaptable for application in sCO₂ direct cycle turboexpanders. In the Toshiba 25 MW direct-fired turbine, Ni- or Co-based materials are used for the vane/blade materials similar to air breathing gas turbines. Cooling for the vanes/blades is provided by cooling passages in the rotor and turbine casing (Iwai et al., 2015). There has been some limited research done on sCO₂ heat transfer, mostly for recuperators. A preliminary assessment of sCO₂ turbine blade cooling strategies has been performed by Aerojet Rocketdyne under an Advanced Research Projects Agency-Energy (ARPA-E) program (EPRI, 2015), and the effect of blade cooling flows has been included in the IEAGHG report on the natural-gas fired Allam cycle configuration (2015). While the turbine cooling model used in this latter report is not tuned to sCO₂ specifically, it demonstrates that the plant efficiency is sensitive to the cooling flow, yielding reduced cycle efficiency at high turbine inlet temperatures for which excessive cooling flow is needed (IEAGHG, 2015). A simple turbine cooling model was developed by NETL and empirically fit to the data on the IEAGHG study in order to account for variations in the required turbine cooling flow as a function of coolant temperature; however, this model remains unvalidated (White, 2018). This model shows that reduced coolant temperatures are beneficial to cycle and plant efficiency, although the NET Power/Toshiba direct sCO₂ demonstration seems to favor turbine coolant inlet temperatures of about 400°C. Further, based on an assumed maximum blade metal temperature of 860°C, the model predicts that 5 of the 7 stages of the Toshiba turbine require cooling, roughly consistent with Toshiba's turbine cooling approach (Sasaki, 2017).

Experimental work on blade and nozzle cooling approaches was performed by Toshiba in the development of their sCO₂ turbine for the NET Power demonstration, though little to no results have been published on this work (Sasaki, 2017). Some information on Toshiba's turbine cooling approach can be gleaned from their recently published patents and patent applications (Maeda, 2016; Mimura, 2017; Onoda, 2014; Okamura, 2016). This approach appears to be fairly conservative and simplistic to facilitate a successful demonstration, thus there may be considerable room for improvement by applying some of the turbine blade cooling strategies that have been pivotal to increasing gas turbine efficiencies in the last decade or so.

Research Needs: Basic heat transfer correlations need to be validated with sCO₂ as the working fluid at conditions relevant for direct sCO₂ cycles (pressure, temperature, heat flux, etc.). CFD models for internal and external flow need to be validated against experimental data. Experimental data with representative cooling passage designs needs to be collected. The effectiveness of film cooling with the high-density fluid and high Reynolds number (Re) flow conditions needs to be determined to assess whether film cooling is a viable option for consideration. sCO₂ boundary layer thicknesses will be thinner, which may impact the effectiveness of film cooling. Heat transfer enhancement parameters for internal cooling features such as pin fins and trip strips used in gas turbine internal cooling design have not been measured at the high Re expected for sCO₂ turbines. Because the density of sCO₂ is closer to H₂O, H₂O-cooled turbine data may be of more use than air-cooled data.

One factor to consider for cooling vanes/blades in the direct cycle turboexpander is the increased operating pressure. Increasing pressure increases heat transfer coefficient on the external and internal surfaces of the turbine vane/blade. This increases the heat flux from the hot gas path to the coolant flow leading to a greater temperature rise in the coolant fluid for a given flowrate. There is a need for detailed modeling effort to determine the most effective methods for cooling turbine vanes/blades at direct cycle operating conditions to minimize the coolant flow required to maintain turbine durability.

The suitability of using rim seal purge correlations developed from gas turbines to determine purge requirements to prevent hot gas ingestion for sCO₂ turbines is uncertain.

The turbine requires design efforts to optimize blade geometry and cooling channels. No real technological barriers are seen since the hot gas path can be designed using the same criteria as air breathing gas turbines; however, this is a need that may not be justified until there is a market for direct sCO₂ power cycles (IEAGHG, 2015).

Major R&D Challenges: Near the critical point, the thermodynamic properties of CO₂ are very sensitive to pressure and temperature making predictions of heat transfer more difficult. The suitability of internal cooling with sophisticated heat transfer features and film cooling commonly practiced in air-fired gas turbines is uncertain with sCO₂ that has an operating density approximately 30 times greater than air with similarly larger Re.

TRL Assessment: This technology is expected to mature quickly because of prior work conducted for cooling industrial gas turbines. The oxy-combustion turbine being developed under a new award with SwRI (FE0031620) has the potential to advance the state of the art to TRL 6 by 2023. Cooling technologies will likely be required and have the potential to be tested at pilot scale by UND EERC (FE0031584) in a 25 MWth pilot scale coal-Allam plant by 2025 advancing the TRL to 7.

3.2.5 RECOVERY OF LEAKAGE AND TURBOMACHINERY SEALS

Problem Statement: sCO₂ power cycles operate at high exhaust pressures reaching 1100 psia. While direct cycles generally have lower turbine exhaust pressures than indirect cycles, turbine end-seal leakage can result in a high recompression load to recover the CO₂. This recompression load to reclaim leakage CO₂ can have a significant negative impact on cycle efficiency. This need for reclaiming lost CO₂ due to leakage requires additional equipment such as smaller machinery for recompressing the CO₂. Because flow rates for ancillary applications are much lower than the main process flows, these machines are more likely to be reciprocating compressors or pumps for smaller applications (Brun et al., 2017). This additional equipment not only adds to the auxiliary load (reducing plant efficiency), but also increases the capital cost of the plant. Additionally, the amount of CO₂ lost from the system (or cost of a leakage recompression system) increases proportionally to the number of shaft end seals, which may be doubled for a dual-shaft configuration (Brun et al., 2017).

Maximizing utility-scale sCO₂ power cycle efficiency requires the development of low-leakage, large-diameter and split-segment face seals. These dry gas face seals are not presently available for the operating environment of utility-scale sCO₂ turbines. In addition to the need for turbine end seals, there is a need for radial turbine seals to reduce leakage at turbine inter-stage locations, which can also lead to inefficient turbine operation.

Presently, there are ongoing sCO₂ turbomachinery development efforts at scales up to 25 MWe. End seals are either not necessary at these small scales or small-scale dry gas (hydrodynamic) seals that are commercially available can be used. End seals are necessary for utility-scale turbines, because bearings must be located outside the turbine, therefore, requiring turbine end seals to shield such bearings from the high-temperature turbine exhaust flow. Dry gas (hydrodynamic) seals are not commercially available at the scales necessary for utility-scale sCO₂ turbomachinery, which is expected to have shafts larger than 20 inches in diameter. Several challenges exist impeding the development of dry gas seals for utility-scale sCO₂ turbomachinery. These challenges are listed below.

Past Work & Progress: In Fiscal Year 2014, NETL awarded a project to GE Global Research, funded through the Office of Fossil Energy Advanced Turbines Program to perform a conceptual design for a utility-scale turbo expander dry gas seal. The project, titled “Development of Low-Leakage Shaft End Seals for Utility-Scale Supercritical Carbon Dioxide Turbo Expanders,” has since been granted a Phase II R&D effort that includes the development of radial hydrodynamic seals. Bidkar et al. (2016) performed a system-level study in the form of a preliminary design of a seal scavenge compressor to show that the end seal leakage cannot be neglected for an indirect cycle utility-scale sCO₂ turbine. A preliminary compressor design resulted in an integrally geared six-stage configuration with intercooling after three stages. The overall predicted efficiency of the compressor was about 83%. The isentropic enthalpy change associated with compressing the leakage flow and the predicted compressor efficiency allowed them to estimate the auxiliary compression load. They found that 0.45% seal leakage flow can result in cycle efficiency loss of about 0.5 percentage points. Compensating for this auxiliary loss by raising the overall indirect cycle efficiency through higher firing temperatures would require at least a 60°C increase in turbine inlet temperature. Bidkar et al. (2016) concluded that the investment required to improve seal designs to minimize leakage would be significantly less than the investment required to increase turbine inlet temperature by 60°C.

The development of hydrodynamic dry gas end seals and radial seals could lead to improvement in utility-scale recompression closed Brayton cycle efficiency of up to 0.65 percentage points (Bidkar et al., 2017). The impact on plant efficiency by using hydrodynamic seals in direct cycle turbomachinery has not been quantified to this extent, but the impact is expected to be similar.

The primary objective of the GE Global Research project is a field-trial-ready face seal design validated with full-scale prototype tests representative of the operating conditions of indirect cycle utility-scale sCO₂ turbine end seals. Additionally, the work will deliver a film-riding radial seal design validated with bench-scale testing to demonstrate the feasibility of this sealing technology for the turbine inter-stage location. If successful, the project will advance the large-diameter sCO₂ face seal component technology from TRL 2/3 (achieved in Phase I effort) to TRL 6, and advance the sCO₂ film-riding radial seal component technology to TRL 4.

Research Needs: In closed-loop steam Rankine cycles, the low-pressure working fluid can be condensed to liquid and recovered through a liquid feed pump. Low-pressure CO₂, on the other hand, cannot be condensed to liquid and recovered through a liquid feed pump because its pressure is below the triple point (5.2 bar) of CO₂ (Bidkar et al., 2016). The CO₂ that has leaked past the end seal in either direct or indirect cycles must be compressed as a vapor from near atmospheric pressure conditions to the lower cycle pressure. Based on the conclusions by Bidkar et al. (2016) challenges associated with reclamation of leakage CO₂ can be mitigated through the development of hydrodynamic seals.

The following specific research needs have been identified:

- Design of seals for large pressure differential capability
- Risk coning of mating faces in large diameter dry gas seals
- Concern for condensed CO₂ in seals reducing effectiveness
- Quantification of the requirement of hydrodynamic seals in direct cycle turbomachinery in terms of impact of leakage on plant efficiency
- Coatings to prevent oxidation as well as wear in dry gas seals at low speed operation
- Uncertainties associated with heat transfer within seal cavities at realistic operating conditions – bearing and seal thermal management

To accompany the development of low-leakage hydrodynamic turbomachinery seals for sCO₂ power cycles (direct or indirect), parallel efforts are needed to develop efficient CO₂ recovery systems, which would most likely need to be integrated with inventory control systems. Additionally, a study similar to the one conducted by Bidkar et al. (2016) is necessary to quantify the impact of leakage, and thus, recovery/recompression of CO₂ on plant efficiency and cost.

TRL Assessment: A subscale dry gas seal specifically designed based on boundary conditions expected in a utility-scale sCO₂ expander has been tested in a bench-scale environment establishing a TRL 3 status. By the end of 2019, a full-scale seal will be tested in sCO₂ at relevant pressures and temperatures, raising the TRL to 5. By 2021, prototypes have the potential to be tested in actual turbomachinery at pilot scale in the 10 MWe STEP facility. By 2024, seals would be required for operating an oxy-combustion turbine in the UND EERC coal-Allam pilot at 25 MW, the scale advancing the TRL to 7.

3.2.6 NEAR- AND TRANS-CRITICAL COMPRESSOR OPERATION

Problem Statement: A significant technical barrier to predictable, reliable, and efficient operation of all sCO₂ power cycles lies in the design of the main compressor. In particular, the main compressor's power requirements are largely a function of the inlet fluid density, which varies considerably in the vicinity of the CO₂ critical point of 31°C and 73.7 bar. With increased inlet fluid density, compression power requirements decrease, leading to higher cycle efficiency. Ideally, compression power is minimized under liquid CO₂ operation, though the ability to condense CO₂ varies with ambient condition and cooling system design. At lower temperatures, lower compressor inlet pressures are required to achieve condensation, thus the pressure ratio expected of the compressor changes. Further, the compressor will likely need to consider widely varying off-design conditions, and little is known about the controllability of the compressor using inlet guide vanes under these conditions.

For direct sCO₂ cycles, the effect of the physical state of impurities (N₂, Ar, O₂, CO, H₂O) in a multi-phase mixture with condensed phase CO₂ has a significant effect on compressor/pump power requirements. Some impurities are in a gas phase, and some are dissolved in the CO₂ liquid—physical property models of these gas mixtures near the CO₂ critical point are inconsistent, and lead to large variations in required compression power, and hence cycle efficiency.

Past Work & Progress: Some work has been done on indirect sCO₂ plants to investigate near- and trans-critical compressor operation. Initial studies at SNL have shown that trans-critical compressor operation is thermodynamically favorable and experimentally feasible, at least for the particular compressor design tested (Wright, 2011). Despite this work, few if any sCO₂ cycle designs propose to operate in this regime, and compressor designers are apprehensive about designing machines to operate in this space. GE has recently performed some CFD modeling studies of one of their compressors for suitability over a wide range of conditions, though this work remains unvalidated due to lack of experimental data (Saxena, 2017). Other studies of near-critical centrifugal compressor operation have recently been performed for indirect sCO₂ cycle applications with pure CO₂ working fluid (Ameli, 2018; Hosangadi, 2018). Experiments at the Massachusetts Institute of Technology (MIT) have recently been performed to provide model validation data at relevant sCO₂ compressor inlet conditions, though again, no data exists for direct sCO₂ working fluids with gaseous impurities (Lettieri, 2015, 2017). Finally, other compressor test loops are under development in Korea and Japan and may experimentally investigate this issue for pure sCO₂ systems.

As noted, little work has been done on this problem for direct sCO₂ power cycles. An EPRI study on a coal-gasification/direct sCO₂ system noted the deleterious effects of ASU- and gasifier-derived gaseous sCO₂ impurities on cycle compressor operation, though these were for steady state compressor operation at a single operating point (EPRI, 2014b). The most extensive work to date has been reported in a recent study by Vesely et al. (2018), which details the effects of various impurities on compressor performance for various compressor inlet temperatures spanning near- and trans-critical CO₂ compressor operation. Their modeling results show significant increases in compressor power requirement with the presence of gaseous impurities, particularly for compressor inlet temperatures in the near-critical region of 30–34°C. Recent work at NETL has highlighted the effect of gaseous impurities derived from oxy-combustion inefficiency on the cycle compressor performance and hence cycle efficiency for a given steady-state operating point (White, 2018). Future studies will investigate other steady-state compressor inlet conditions, and separate dynamic modeling efforts will investigate compressor and cycle control options under these conditions. Finally, it should be noted that Atlas Copco must have done some non-public work on this topic to be able to supply NET Power with compressors for their demo plant. Some of their work has been reported, though details of compressor operation as a function of proximity to the CO₂ critical point or CO₂ impurity levels are not reported (Freed, 2018).

Research Needs: Fundamental studies are needed to determine the solubility and fluid states of impurities within a primarily CO₂ working fluid, as these physical properties have a significant bearing on the compressor under near-critical operation. Both computational and experimental investigations are necessary to understand how compressor and plant performance varies with compressor inlet conditions, which are, in turn, affected by changes in ambient conditions via the cooler immediately upstream of the compressor. Compressor/pump designs that are amenable to condensing operation at high efficiency are needed for both indirect and direct sCO₂ power cycles, as well as an understanding of how to use inlet guide vanes to the control dynamic range of the compressor under these challenging conditions.

Major R&D Challenges

- Size and scale of experimental compressor R&D for utility-scale systems. Are smaller scale results scalable?
- Few test stands capable of generating direct sCO₂ fluid mixtures for compressor testing
- CFD of compressors is challenged by computations of real gas properties for mixtures of near-critical CO₂ with gaseous impurities

TRL Assessment: This assessment is based on publicly-available knowledge. Two main options exist for advancing the TRL of near-critical compressor/pump operation for direct sCO₂ power cycles. First, on the modeling front, NETL's Systems Engineering and Analysis group will investigate steady-state compressor inlet conditions in 2018 and will develop a separate dynamic model to investigate compressor and cycle control options under these conditions. These efforts should yield a TRL 2 by 2019. Second, SwRI's 1 MWth oxy-combustor test loop includes a compressor/pump for recycling CO₂ fluid to the recuperator in the test loop. Data on the operation of this unit for fluids relevant to direct sCO₂ power cycle conditions should be available by 2020, raising the TRL to 4 upon completion.

It should be noted that NET Power has preliminary control strategies for their demo plant, based on a dynamic cycle model they developed, which likely includes the capability to vary compressor and pump inlet conditions, as well as the level of impurity in the CO₂ working fluid. In particular, the design condition for the plant has a pump inlet temperature of 20°C, though the inlet pressure may be above the CO₂ critical pressure, thus condensing operation is not considered. This information is not included in the above TRL Assessment, due to the lack of details in the public domain.

3.2.7 OFF-DESIGN TURBOMACHINERY PERFORMANCE

Problem Statement: Turbomachinery performance maps are needed at utility scales to enable part-load, off-design, and dynamic operation studies of direct sCO₂ power cycles, though these maps do not yet exist. Off-design performance maps are needed to devise control strategies for maintaining efficient cycle operation under transient and off-design operating conditions. This includes startup, shutdown, and load-ramping operations to meet variable power grid demand due to integration of renewables.

The compressor and pump will operate over a wide range of inlet conditions, as a function of the ambient conditions and process cooler operation near the CO₂ critical point. This significantly affects the operational characteristics and compression power requirements, and in turn, the cycle efficiency.

Variation in required turbine cooling flows for off-design conditions are unknown, but may have a significant impact on cycle efficiency

Off-design conditions, particularly at startup and/or shutdown, may include variations in fuel and/or oxidizer flow, creating variability in the primarily CO₂ working fluid, which must also be accounted for in turbomachinery performance estimation.

Past Work & Progress: Transient modeling efforts to date have been for small-scale, low-temperature test loops at KAPL, Bechtel Bettis, and SNL. Research is now underway by NETL, SwRI, and GE to investigate off-design operation of the STEP plant, using turbomachinery performance maps developed by the vendors (Zitney, 2018; Mahapatra, 2018). Echogen also has significant experience with off-design operation, but only for their application (7 MWe system with a centrifugal turbine), and much of their information is not public (Held, 2014). Larger-scale system control efforts were undertaken by Aerojet Rocketdyne, but these likely used assumed maps (Vega, 2014). Further, all of these cases are for indirect sCO₂ power plants, which will differ in turbomachinery configuration from the direct sCO₂ plant. The most comparable component between the two cycles is the main compressor/pump, though in direct sCO₂ cycles, the working fluid is not pure CO₂ as it is in indirect sCO₂ plants.

For direct sCO₂ cycles, a transient model is under development for the NET Power demo plant, and is used as a training simulator, but turbomachinery maps are not public information (Allam, 2017).

Research Needs: Turbomachinery performance maps are needed for both constant and variable speed turbines, compressors, and pumps for direct sCO₂ power cycles. In the NET Power plant, for instance, the turbine is connected to one compressor and a generator, operating at ~6000 rpm (Freed, 2018). The pump is motor driven, and can likely operate at variable speeds. Other designs may favor a turbo-driven compressor that can operate at variable speeds for improved control, with a separate power turbine operating at a single speed. In general, a direct sCO₂ turbine will require connection to at least one compressor to help prevent turbine overspeed in a loss-of-load event, due to the infeasibility of adding turbine stop valves at the turbine inlet conditions.

There is also a need to determine the variability in turbine cooling flow requirements at off-design conditions. In addition, the effect of impurities in the CO₂ working fluid on turbomachinery performance will need to be determined. The direct sCO₂ turbine is far enough from the CO₂ critical point that all impurities behave as an ideal gas mixture, though the real gas effects of CO₂ near the critical point will affect compressor and pump performance, particularly as ideal gas impurities are mixed in.

Major R&D Challenges

- Compressor and pump performance maps are complicated by operation near the CO₂ critical point, and with potential variations in the working fluid phase (at the inlet and potentially within the impeller) at off-design conditions (Saxena, 2017). Inlet guide vanes add another variable to the mix.
- Experimental determination of turbomachinery maps at utility scales is hampered by changes in turbomachinery design at different scales, thus requiring large scale demonstrations:
 - Axial turbines are preferred at scales over 100 MWe (Fleming, 2012). (The NET Power turbine is scaled to 25 MWe with 25% arc admission of a base 100 MWe turbine design (Allam, 2017). Toshiba determined this to be the minimum feasible size for demonstration.)
 - Pumps will likely always be of a centrifugal design due to improved operation for condensing fluids, but the highest-efficiency compressor design may change from centrifugal to axial geometry at ~10 MW shaft power (Fleming, 2012).

- There are several compressor and pump vendors to assist with R&D in this area, but only one turbine vendor (Toshiba). Atlas Copco is supplying the compressor for the NET Power demo plant (Freed, 2018).
- Generic turbomachinery maps can be used for the time being, but will need to be validated at some point, most likely with data from the NET Power demonstration.

TRL Assessment: This assessment is based on publicly-available information only (Figure 3.2). No one apart from Toshiba has designed or built a direct sCO₂ turbine, thus the public pathway TRL is likely at TRL 2, at best. In 2018, NETL selected a SwRI-led project from DE-FOA-0001816 entitled “Development of Oxy-Fuel Combustion Turbines with CO₂ Dilution for sCO₂-Based Power Cycles.” This is the most likely pathway to advancement of the public TRL for the direct sCO₂ turbine, though the timeline and TRL assessment is unknown at this time. As noted above, the CO₂ pre-compressor TRL is fairly advanced at 8-9, and publicly available performance curves that have been benchmarked with operational compressor data are available (Modekurti, 2017). This model was modified to produce a dynamic model of a pure CO₂ compressor for the STEP plant modeling project, and could be further modified to include sCO₂ impurities present in direct sCO₂ cycles, thus this TRL is about 2-3. (Zitney, 2018)

It should be noted that Toshiba has likely developed a performance map for their 50 MWth sCO₂ turbine at the NET Power demo plant, although without prior testing, the map is probably based on turbine modeling efforts. This map will likely be updated following the turbine testing at the demo plant. With unknown TRL levels and timeframe for further TRL advancement, this information has not been included in the TRL Assessment. Likewise, performance mapping of the pre-compressor and pump used in the NET Power facility is also at an unknown TRL level.

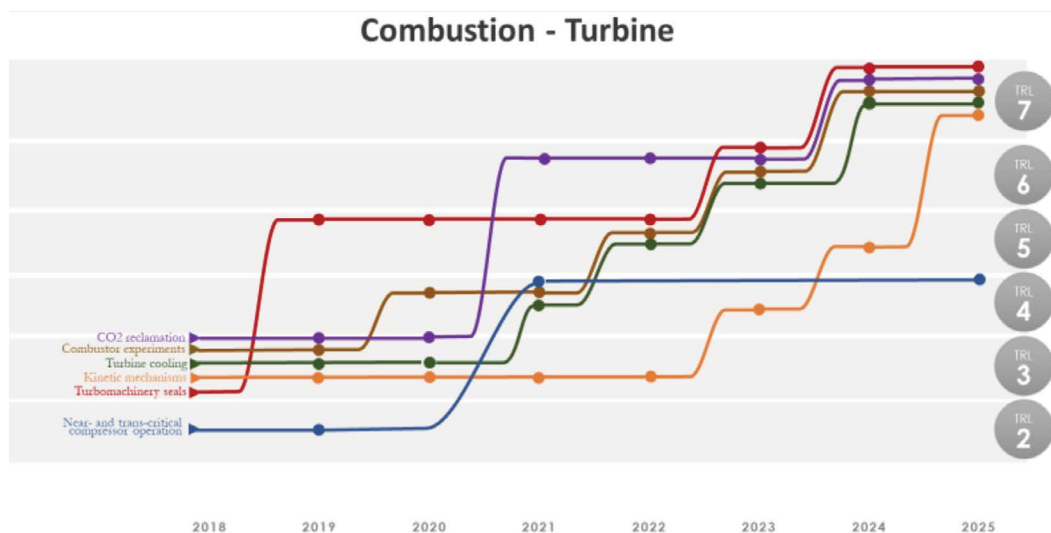


Figure 3.2. Technology readiness level progression for combustion and turbomachinery for direct sCO₂ power cycles.

3.3 HEAT EXCHANGERS

3.3.1 LONG-TERM PERFORMANCE OF HEAT EXCHANGERS IN DIRECT sCO₂ POWER CYCLES

Problem Statement: The capabilities and limitations of heat exchangers in a direct sCO₂ cycle are not understood well in an actual implementation. Direct sCO₂ cycles use the products of high temperature-high-pressure combustion as the working fluid, which are fed from the gasifier or combustor directly into the power turbine. From there, the working fluid enters the hot side of the high-temperature recuperator (HTR) at a temperature from 700-760°C, which is the limit for nickel-based alloys used in exhaust piping at the expected operating pressures (Weiland, 2016). 8 Rivers Capital has developed the Allam cycle, which is a novel CO₂ oxy-fuel power cycle that uses hydrocarbon fuels while capturing nearly 100% of all atmospheric emissions at a comparable cost to non-carbon sequestration power cycles (Allam, 2013). Initial cycle demonstrations are currently under construction, and as a result the only known data on these direct sCO₂ cycles are limited to simulations. Long-term performance and capabilities of recuperators in direct sCO₂ cycles are not known past modeling and simulation. As such, there exists a technology gap on experimental data on recuperator performance. Finally, problems could arise from material degradation or poor material selection when designing the recuperator.

Past Work & Progress: NETL conducted a performance baseline study for direct sCO₂ cycles (Weiland, 2016; White, 2018). 8 Rivers Capital published an update on the progress of the 50 MWth demonstration-scale plant using natural gas as the fuel (Allam, 2017). The HTR was designed and built by Heatric—it consists of 1 section made from Inconel 617 and 3 sections made from 316L stainless steel. The Inconel 617 alloy will withstand high working fluid temperatures, and as it cools down the 316L stainless steel alloy will provide effective heat transfer at a lower capital cost. Currently a demonstration-scale plant is being built to test the Allam cycle.

Research Needs: Both computational and experimental investigations are necessary to understand the following:

- Creep, scaling, and fouling in heat exchangers (TRL 3)
 - Combustion contaminants effects on recuperator
- Heat exchanger type selection and sizing for optimal cost (TRL 4)
- Material selection for high-temperature-high-pressure operation (TRL 3)
- Ceramic recuperators in direct sCO₂ cycles (TRL 2)
- The limit of temperature for preheating the O₂ stream

Major R&D Challenges: There does not exist an appropriate test loop to experimentally test the functionality and performance of the direct sCO₂ cycle recuperator.

3.3.2 HEAT EXCHANGER TYPE SELECTION AND SIZING FOR OPTIMAL COST

Problem Statement: For over a century, engineers have been designing heat exchangers with the objective of manufacturing a heat exchanger with long service life for the least possible life cycle cost. When considering heat exchanger designs it is necessary to compare the relative impacts of heat conductance (heat transfer coefficient times heat transfer area), material requirements (metal mass), and pressure drop (pumping power). Depending on the ultimate objective, the analyses will differ. There are three fundamental objectives that could apply to the analysis. These include the following:

1. Reduce material for equal pumping power and heat duty – This is a probable objective for recuperators for sCO₂ cycles when the pressure drops and approach temperatures have been specified and the objective is to reduce the amount of material as a surrogate for manufacturing cost of the heat exchanger.
2. Increase UA for equal pumping power and heat exchange surface – This would be the case for internal cooling of turbine blades and vanes. The pumping power in the form of available pressure drop will be fixed based on the available system pressures. The heat exchange surface will largely be fixed (not considering internal features) by the gross blade geometry.
3. Reduced pumping power for equal heat duty and surface area – This could apply to recuperators for sCO₂ cycles also if it is determined that increase in efficiency as a result of a better net performance from the rotating equipment (turbine power minus compressor power) is the objective with fixed recuperator cost. This assumes that recuperator cost is directly related to the surface area.

The challenge is to select the fundamental heat exchanger geometry whether it be tried-and-true shell and tube or up-and-coming additively manufactured configurations that accomplish the required process conditions for the lowest cost.

Past Work & Progress: NETL has funded several studies for the development of HTRs for indirect sCO₂ power cycles that focused on plate style, micro-channel, micro-tube, thin film primary surface, and flattened panel heat exchanger geometries. Printed circuit and shell and tube heat exchangers for the required conditions are also possible and commercially available. As this work continues, there is hope and likely an economic requirement to develop heat exchangers that are more cost effective than those that are currently available. The maximum temperature requirement for the HTR for indirect sCO₂ cycles is less than 600°C while it is expected to be 800°C for direct cycles. Even with the higher temperature requirements for the direct cycle, work that was performed for indirect cycle HTR could be relevant with the proper material selection.

ARPA-E recently solicited proposals under the Funding Opportunity Announcement (FOA) for High Intensity Thermal Exchange through Materials and Manufacturing Processes. This solicitation includes thermal hydraulic designs of metallic heat exchangers for temperature > 800°C and ceramic or composite structure heat exchangers for temperatures >1,100°C.

Research Needs: While numerous heat exchanger geometries have been proposed for HTRs, there is no clear winner. The microtube concept seemed the preferred choice, but issues with assembling and bonding the tubes to the tube sheet caused this approach to be abandoned. To date, the most promising configuration appears to be printed circuit heat exchangers. Some additively manufactured concepts have been proposed and are being developed; however, this approach will result in small modules requiring many modules for a commercial size power plant. With many modules, the headering requirements will not be trivial.

Major R&D Challenges:

- Developing or validating a heat exchanger geometry that is efficiently manufactured, durable, and cost effective. This goal is not new as thermal-hydraulic engineers have been working on better heat exchangers for over a century.
- Expecting that many heat exchanger modules will be required for a commercial-size power plant, developing a cost-effective means of headering modules that provides uniform distribution between module without creating excessive pressure drop.

TRL Assessment: Several heat exchanger geometry concepts that have potential to meet economic requirements of <\$100/kW have been demonstrated at prototype scale (TRL 4) (Figure 3.3). Headering of any of these heat exchanger geometry concepts has only been demonstrated analytically (TRL 3).

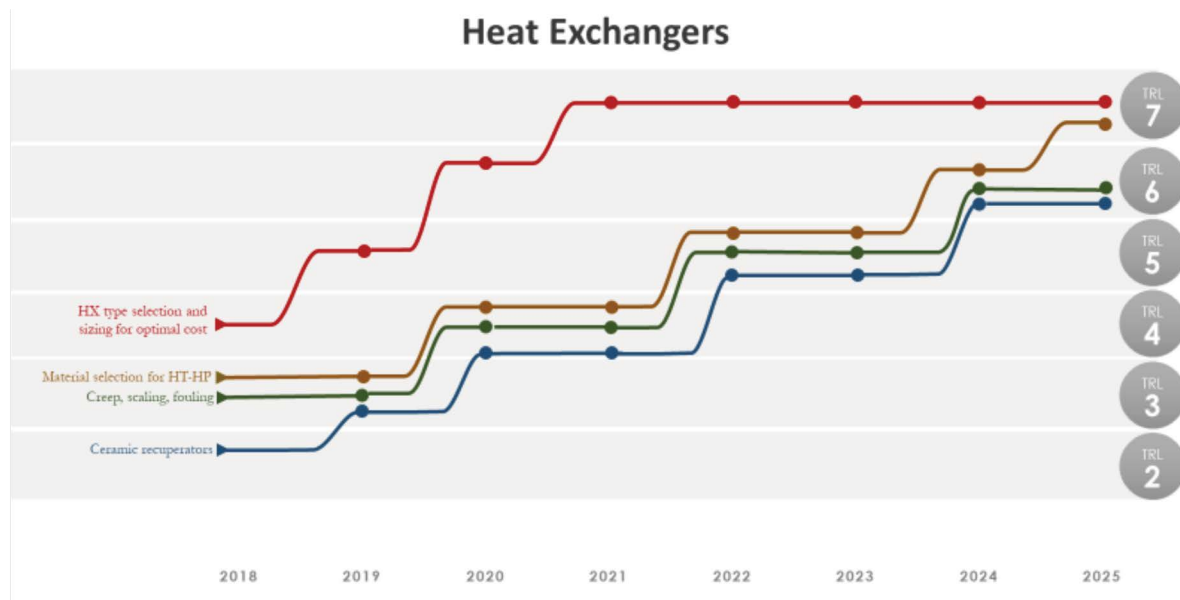


Figure 3.3. Technology readiness level progression for heat exchangers for direct sCO₂ power cycles.

3.4 MATERIALS

3.4.1 AVAILABILITY OF COST-EFFECTIVE STRUCTURAL MATERIALS FOR HIGH-TEMPERATURE COMPONENTS

Problem Statement: Very limited data on high-temperature oxidation of alloys is available in direct sCO₂ cycle environments. The data needs to be generated to demonstrate the viability of the alloys for various components and to reduce the risk for commercialization of this power cycle technology. More data is available on creep life of commercial materials thanks to the advanced ultra-supercritical steam cycle research. However, interactions between CO₂-rich environment and creep processes in thin sections are not well understood.

Past Work & Progress: In general, Ni-based alloys were found to resist oxidation by forming relatively thin protective oxide layers (1-5 μm) at temperatures between 650°C and 750°C for up to 2500 hours in typical direct sCO₂ power cycle environments (Oleksak, 2018a; Tylczak, 2018; Kung, 2018; Pint, 2018a; Lolla, 2018). The oxidation rates found in these investigations were somewhat higher than those found in indirect cycle environments for both Ni-based and Fe-based alloys. In these studies, while it was noted that no carburization was observed in the Ni alloys, some carburization was evident in the Fe-based alloys. Effect of SO₂ was also minimal when included in the test atmosphere. While no sulfur compounds were observed in the Ni alloys, some steels contained sulfur compounds below the oxidation scale (Oleksak, 2018a; Tylczak, 2018). Little or no effect of pressure was observed for Ni and Fe alloys exposed to pure CO₂ (Oleksak, 2018a; Pint 2018b); however, the pressure effect remains to be confirmed in the direct sCO₂ cycle environments.

Research Needs:

- High-temperature oxidation kinetics data for alloys that are important to this application at relevant temperatures and environments. Although oxidation data has started to become available for limited set of conditions, it is hard to extrapolate to other conditions
- Understanding oxidation mechanisms in multi-oxidant (O₂, CO₂, H₂O, SO₂) environments
- Effect of impurities that are introduced from the combustion of fuel on oxidation of alloys
- Effect of pressure on oxidation kinetics in direct sCO₂ cycle environments
- Exfoliation of oxide scale and its effects on the operation of heat exchangers and other components. Exfoliated oxide scales can cause fouling in heat exchangers with small channels and erosion in turbine parts
- Effect of high-temperature oxidation on mechanical properties of thin wall components (compact heat exchangers) (Cedro III, 2018)

Major R&D Challenges: Generating data on materials performance in harsh power generation environments is usually a challenge. The working fluid in direct sCO₂ power cycles poses especially challenging conditions: high-temperature, high-pressure, high-velocity turbulent flows, and corrosive composition. It would be difficult and expensive to include all these effects in a laboratory setting. However, the tests are usually performed in environments that include some of these conditions.

TRL Assessment: While most commercially available high-temperature materials are at TRL 3 or 4 for applications in direct sCO₂ power cycles based on the open literature, a few of them were used to build the components of the recent 25 MWe demonstration plant, which can push their TRL to 7 or 8 if the demonstration plant operates successfully.

3.4.2 AVAILABILITY OF LOW-COST MATERIALS RESISTANT TO AQUEOUS CORROSION IN LOW-TEMPERATURE COMPONENTS

Problem Statement: One of the challenges in direct sCO₂ power cycles is the low-temperature corrosion of materials in components such as low-temperature recuperator and cooler. Water dissolved in sCO₂ at high temperatures begins to condense as temperature of the working fluid decreases. Since the condensing water is saturated with CO₂, acidic conditions are established in the low-temperature recuperators and coolers. In addition, in the case of coal-fired units, if the syngas is not cleaned before combustion, sulfuric acid condensation will take place in the recuperators. For both H₂CO₃ and sulfuric acid cases, aqueous corrosion is severe on the lower Cr containing steels such as Grades 91 and 22, which are traditionally used for lower temperature applications in steam cycles. As a result, higher cost austenitic stainless steels are proposed conservatively to be used in fabrication of lower temperature heat exchangers resulting in higher capital cost.

Past Work & Progress: A corrosion issue unique to the direct sCO₂ power cycles was identified (Teeter, 2016; Repukaiti, 2017; Oleksak, 2018b; Repukaiti, 2018). Water dissolved in sCO₂ at high temperatures begins to condense as temperature of the working fluid decreases. Since the condensing water is saturated with CO₂ (essentially this constitutes H₂CO₃), aqueous corrosion is observed on the surface of steel. The corrosion is severe on the lower Cr containing steels such as Grades 91. A comparison of corrosion rates in terms of mass change reveals two orders of magnitude higher mass loss due to corrosion on Grade 91 compared to 347H in water-rich phase at 50°C (Repukaiti, 2018). Currently, in the absence of any identified low-cost steels with sufficient corrosion resistance, higher-cost austenitic stainless steels are the only option for fabrication of low-temperature recuperators, coolers and piping.

Research Needs: Investigations are necessary to identify

- Corrosion mechanisms and rates for the boiler materials at low temperature region
- Low-cost steels that perform adequately in this environment

Major R&D Challenges: Generating data on materials performance in harsh power generation environments is usually a challenge. The working fluid in direct sCO₂ power cycles poses especially challenging conditions: high-temperature, high-pressure, high-velocity turbulent flows, and corrosive composition. It would be difficult and expensive to include all these effects in a laboratory setting. However, the tests are usually performed in environments that include some of these conditions. Another challenge is to conduct electrochemical measurements (to determine corrosion rates) on metallic samples under pressure at elevated temperatures.

TRL Assessment: Current TRL is assigned as 3. General corrosion mechanisms acting on the low Cr (2-9%Cr) steels have been identified. The low Cr steels are deemed not suitable for the lower temperature components. Medium Cr steels (10-15%Cr) will need to be identified and their suitability need to be shown in the laboratory conditions.

Current research at NETL is aimed to bring this technology to TRL 4 by 2019 by demonstrating the suitability of a few medium Cr steels in the laboratory conditions. TRL 5 and 6 needs a facility that produces oxyfuel combustion fluid with a cooling system where water condensation takes place. This may be a demonstration plant built conservatively (using expensive materials) similar to the Net Power plant. Samples of steels (TRL 4) can be exposed in this facility to bring the technology to TRL 5. Furthermore, testing a component or a part of a component built using the identified material in this facility can bring the technology to TRL 6 or 7. Building and operating a demonstration plant using the steel on the appropriate components will bring the technology to TRL 8. A commercially-operated plant will need to use this steel on the appropriate components to bring the technology to TRL 9.

3.4.3 EROSION

Problem Statement: Erosion of components of sCO₂ power cycles is not understood well. There is evidence that erosion takes place in the sCO₂ test loops (Fleming, 2014; Clementoni, 2014). In the SNL test loop, severe erosion was observed on turbine nozzles and blades (Walker, 2016). Although failure analysis did not yield conclusive results, there was some evidence indicating that the damage was caused by iron-rich particles (possibly oxides) entrained in the sCO₂ flow. It was thought that the particles were introduced from the CO₂ inventory tanks that were manufactured using ferritic-martensitic steels. Even if this conclusion is correct and the problem can be solved by employing various strategies, it is very unsettling that particles entrained in the flow can cause such severe erosion. Particles can be entrained in the flow by other mechanisms. One likely mechanism is the spallation of oxide scale on internal walls of equipment. The bulk velocity of the sCO₂ stream is very high as a result of very high mass flow rates and small component cross sections. Furthermore, very low dynamic viscosity and high density of sCO₂ combined with the high velocity result in very turbulent flows in the sCO₂ cycles. Such turbulent flows can cause spallation of oxide scales forming on the internal surface of the components. Once the oxide particles are entrained in the flow, they can cause severe erosion by high velocity particle impact on the walls of components.

If the erosion is due to flow characteristics of the working fluid in the sCO₂ cycles, it can become a significant barrier for the commercialization of the sCO₂ power cycle technology.

Past Work & Progress: Other than the three reports mentioned above, there is no published work that deals directly with the erosion problem in sCO₂ power cycles. The NETL research papers (Apte, 2016; He, 2018) that were published in the sCO₂ Power Cycles Symposium Proceedings investigated sCO₂ flow characteristics in a pipe with a 90° bend. Computational fluid dynamics (large eddy simulations) was performed at different Re (5000, 27,000, 50,000, and 95,000) to investigate the effect of flow patterns on the component walls to identify the potential causes of the erosion.

Research Needs: Both computational and experimental investigations are necessary to understand

- Flow patterns of working fluid in various components of sCO₂ power cycles
- Mechanisms of hard particle entrainment in working fluid
- Interactions of hard particles with the component walls

Major R&D Challenges: Setting up a test bed for studying erosion requires knowing the mechanism of material removal from the component surface. Without this knowledge, a test system may not yield desired results. It may also be an expensive proposition to set up an erosion test system that may require a recirculating sCO₂ loop. Computational fluid dynamics simulations can become very expensive in terms of computing time for very high Re as is the case in sCO₂ power cycles.

TRL Assessment: There has been a very limited work on this subject. Its TRL is likely to be 1-2.

3.4.4 NEW, AFFORDABLE HIGH-PERFORMANCE MATERIALS

Problem Statement: The direct sCO₂ power cycles will benefit from the development of new, cost-effective structural materials that can withstand higher temperatures and harsher environments. Advanced power plants can realize higher efficiencies if higher temperature materials were available at affordable cost. For example, today direct sCO₂ cycle plants are designed for turbine inlet temperatures of 1150°C and primary heat exchanger inlet temperatures of 750°C due primarily to the materials limitations.

Research Needs: New, phase-stable high-temperature alloys can be developed using following concepts (Cedro III, 2018): (1) new microstructural strengthening features can be incorporated in alloys in order to promote stability and maintain strength at high temperatures, (2) improved control of manufacturing processing parameters can result in enhanced phase stability at high temperatures, and (3) advanced manufacturing methods can be used to create microstructures with improved stability and strength. These and other concepts can be used to develop materials such as

- New metallic alloys for heat exchangers, turbines, and combustors: Oxide dispersion strengthened (ODS) alloys (Klueh, 2005), cermets (Lipke, 2010), refractory metal alloys, and intermetallics are some examples of advanced alloys that can be considered for development for the components of direct sCO₂ power cycles.
- Ceramic materials for heat exchangers: Ceramic materials such as silicon carbide can be used at significantly higher temperatures than the nickel-based alloys (Lewinsohn, 2016)).
- Composites for turbines: Components made of ceramic matrix composites may allow higher turbine inlet temperatures (NETL, 2017b).
- More effective thermal barrier coatings (TBCs) for turbines and combustors: Due to properties of sCO₂ and high pressure of the cycle, higher heat fluxes in the sCO₂ turbine and combustor are expected compared to the conventional gas turbines (Sasaki, 2017). Higher temperature gradients across the TBC will create harsher conditions for the TBC and affect its durability. More on TBCs is discussed in Section 3.4.5.

Major R&D Challenges: It takes a long time to develop new materials and bring them to the market place. However, with the employment of computational tools recently, the development time period may be shortened.

TRL Assessment: The new materials technologies will likely to be at TRL 1-2.

3.4.5 THERMAL BARRIER COATINGS

Problem Statement: Direct sCO₂ cycles are expected to operate at turbine inlet temperatures up to and potentially exceeding 1200°C. To achieve gas temperatures as high as 1200°C, a thermal protection system will be needed to maximize durability of the turbine vanes and blade. TBCs include a low thermal conductivity ceramic top coat, which insulates the vane/blade reducing the temperature of the vane/blade material. The use of TBC in combination with vane/blade cooling will be required for sCO₂ direct cycles. State-of-the-art air breathing gas turbines have been designed to operate at turbine inlet temperatures exceeding 1600°C. These engines employ TBCs in combination with sophisticated internal and external (film) cooling technologies to maintain durability of the nickel-metal superalloy vanes/blades; however, there has been little-to-no research to investigate the independent and combined effects of cooling with TBC in conditions relevant to sCO₂ direct cycles.

Past Work & Progress: Pint et al. (2016) conducted furnace cycle studies of a TBC consisting of a metallic NiCoCrAlY alumina-forming bond coating and a ceramic (Y₂O₃-stabilized ZrO₂) top coating in 0.1 MPa 90% (CO₂-0.15O₂) with 10% H₂O and found no detrimental effect of this environment on coating durability.

Cooling techniques matured through the development of air breathing gas turbines (Han et al., 2000) should be adaptable for application in sCO₂ direct cycle turboexpanders. In the Toshiba 25-MW direct-fired turbine, Ni or Co based materials are used for the vane/blade materials similar to air breathing gas turbines. Cooling for the vanes/blades is provided by cooling passages in the rotor and turbine casing (Iwai et al., 2015). Toshiba used a TBC coating in their 5 MW test combustor, and also in the combustor and turbine of the 25 MWe NET Power demonstration plant. A sample of 0.4 mm Y₂O₃-stabilized ZrO₂ with a 0.1 mm bond coat of MCrAlY overlaying a water-cooled substrate was tested over 1000 thermal cycles with no observed spalling (Sasaki, 2017).

A preliminary assessment of sCO₂ turbine blade cooling strategies has been performed by Aerojet Rocketdyne (EPRI, 2015) and the effect of blade cooling flows has been included in an external report on the natural-gas-fired Allam cycle configuration (see Section 3.2.4) (IEAGHG, 2015).

Research Needs: Downstream of the oxycombustor, the primary constituents will be CO₂ and H₂O, but depending on the fuel, other impurities such as SO₃, SO₂, and HCl, as well as environmental particulates will be present in the hot gas path making erosion, corrosion, and deposition all worth considering when evaluating the applicability of a TBC architecture. Several studies exist in the open literature to report the effects of erosion, corrosion, and deposition in air breathing gas turbines (Hamed and Tabakoff, 2006; Richards et al., 1992; Wenglarze and Wright, 2003), but little is known about these effects at the high pressures that will exist in direct cycle turboexpanders. Some research has been conducted to better understand the effects of corrosion on stainless steels and nickel-based alloys in sCO₂ environments (Oleksak et al. 2018a; Mahaffey et al., 2014; Pint et al., 2014; Saari et al., 2014), but little is known about sCO₂ corrosion effects on and the applicability of TBCs used in air breathing gas turbines at temperatures exceeding 1200°C in the presence of H₂O, sulfur, and other impurities, particularly for the long-duration exposure times that utility-scale turboexpanders will be expected to operate between maintenance shutdowns.

The higher turbine heat loads that will occur with sCO₂ compared to gas turbines would make the TBC more impactful; however, the mechanical integrity with the higher turbine blade loads is also a question that presents an additional design challenge.

Major R&D Challenges: None identified.

TRL Assessment: While available TBC materials are at TRL 3 or 4 for applications in direct sCO₂ power cycles, TBC applied on the components of the recent 25 MWe demonstration plant can push its TRL to 7 or 8 if the demonstration plant operates successfully.

3.4.6 PERFORMANCE OF JOINTS IN DIRECT sCO₂ POWER CYCLES

Problem Statement: Compact heat exchangers are an enabling technology for the sCO₂ power cycles since they can exchange heat very effectively in a much smaller volume-to-surface ratio than the traditional heat exchangers. The smaller volume-to-surface ratio means usage of smaller amount (lower weight) of expensive high-temperature materials in fabrication. The compact heat exchangers also contain a high ratio of bonded regions to bulk material when they are compared to the traditional heat exchangers. For example, up to 20% of volume of a microchannel heat exchanger can have the bond structure. This ratio goes up as thinner sheets are used for the layers. Diffusion bonded or brazed regions of the structure may have different chemical composition and microstructure compared to the rest of the sheet material. Similarly, fusion zones and heat-affected zones (HAZ) of welded materials have different composition and microstructure compared to the bulk material. Therefore, they may be affected differently than the bulk structure when exposed to the sCO₂ cycle environment.

Past Work & Progress: NETL and KAIST have been evaluating joint performance in simulated indirect sCO₂ power cycle environments during the past two years. This work has yielded information on high-temperature oxidation and mechanical behavior of joints. High-temperature oxidation work to date has focused primarily on the effects of indirect sCO₂ cycle environments (Doğan, 2016; Lee, 2018). Environmental stability of diffusion bonded regions of Haynes 230, Haynes 282, and Alloy 600 stacks was investigated by exposing coupons to indirect sCO₂ cycle environments. The diffusion bond regions of Ni alloys did not exhibit an accelerated oxidation.

Research Needs:

- Long-term high-temperature oxidation behavior of joined Ni- and Fe-alloys in direct sCO₂ cycles
- Creep, low-cycle fatigue, and creep-fatigue behavior of joined Ni- and Fe-alloys in direct sCO₂ cycles
- Physics based life modeling of joined sections in direct sCO₂ cycles

Major R&D Challenges: Generating data on materials performance in harsh power generation environments is usually a challenge. The working fluid in direct sCO₂ power cycles poses especially challenging conditions: high-temperature, high-pressure, high-velocity turbulent flows, and corrosive composition. It would be difficult and expensive to include all these effects in a laboratory setting. However, the tests are usually performed in environments that include some of these conditions.

TRL Assessment: Bonds and welds on several components will be exposed to direct sCO₂ cycle conditions at the 25 MWe Net Power demonstration plant. If they perform successfully, their TRL can be deemed as 7. However, most other welds and bonds are at TRL 2-3 since not many of them have been tested under direct sCO₂ cycle conditions.

3.4.7 ADVANCED MANUFACTURING OF COMPONENTS FOR DIRECT sCO₂ POWER CYCLES

Problem Statement: Components of direct sCO₂ power cycles are compact compared to their steam cycle counterparts owing to much higher density of sCO₂ compared to the supercritical steam. However, their compactness and intricacy make them difficult, if not impossible, to manufacture using traditional processes. Compact heat exchangers are a good example. They are an enabling technology for the sCO₂ power cycles since they can exchange heat very effectively in a much smaller volume-to-surface ratio than the traditional heat exchangers. The smaller volume-to-surface ratio means usage of smaller amount (lower weight) of expensive high-temperature materials such as nickel-based superalloys in fabrication. It has not been a customary practice to use methods such as diffusion bonding (including transient liquid phase bonding and brazing) to join these corrosion and heat resistant alloys. The fact that they are extremely corrosion resistant and contain elements with high affinity to O₂ such as aluminum (Al) and titanium (Ti) makes diffusion bonding challenging. Some of the highest performing alloys such as Inconel 740H and Haynes 282 are yet to be demonstrated for diffusion bondability.

Additive manufacturing (AM) may also be applicable to these compact components of sCO₂ cycles. AM may make it possible to manufacture components designed for ultimate performance without the limitations of subtractive manufacturing methods.

Past Work & Progress: Past two years, NETL has worked on diffusion bonding of Haynes 230 and Haynes 282. It has been found that Haynes 230 can be bonded using a technique called transient liquid phase bonding (Kapoor, 2017). On the other hand, Haynes 282 was problematic in bonding and didn't produce acceptable bonds. For Haynes 282, presence of internal oxidation products such as alumina beneath the surface prevented good bonding and more surface preparation techniques will need to be explored.

Research Needs:

- Develop joining methods for high performing alloys such as Inconel 740H and Haynes 282 for use in manufacturing compact heat exchangers.
- Demonstrate additive manufacturing of components of sCO₂ power cycles to enable application of high performing designs not possible to manufacture using other methods.

Major R&D Challenges: None identified.

TRL Assessment: Depending on the materials, TRL of diffusion bonding varies. For example, diffusion bonding of 316 stainless steel is at TRL 9 since it is routinely performed commercially. On the other hand, diffusion bonding of alloys such as Inconel 740H and Haynes 282 are at TRL 2-3. Other nickel-based alloys such as Inconel 625 is diffusion bonded for sCO₂ cycle test loops and demonstration plants. This puts the diffusion bonding of alloy 625 at TRL 7.

In general, AM of most sCO₂ power cycle components are at TRL 2-3 (Figure 3.4).

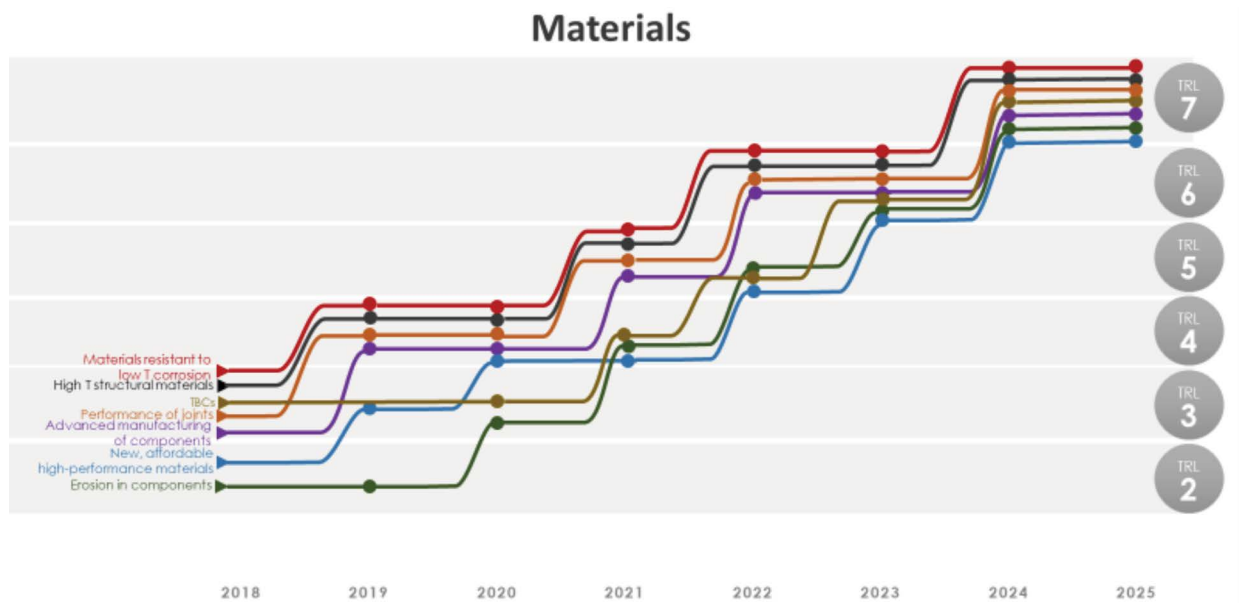


Figure 3.4. Technology readiness level progression for materials for direct sCO₂ power cycles.

3.5 POLLUTION CONTROL

3.5.1 WORKING FLUID POLLUTANT EFFECTS

Problem Statement: Unlike the indirect-fired cycle where the working fluid is primarily pure CO₂, the direct sCO₂ cycle working fluid contains additional impurities coming out of the oxy-combustion process, present in different compositions depending on if the fuel is natural gas or syngas, which can negatively affect cycle performance. These impurities include O₂, N₂, H₂O, SO_x, NO_x, HCl, Ar, and particulates. Impurities may also have effects on the purity of the CO₂ stream exiting the process.

Acid gases present in the direct sCO₂ power cycle (SO₂, SO₃, NO_x) have the potential to condense out in the low-temperature regions of the cycle, specifically the low-temperature recuperator and the cooler. HCl from coal-derived syngas can similarly condense out in the low-temperature sections. The acids formed can cause corrosion in the piping and equipment, shortening their lives. Acids remaining in the power cycle can also cause corrosion concerns in the turboexpander and HTRs as they circulate throughout the entire cycle.

The exhaust gas from the combustor in the direct sCO₂ power cycle contains water vapor, which remains present throughout the cycle. The water vapor is condensed in the cooler downstream from the low-temperature recuperator, and then must be removed in a liquid separator. H₂CO₃ can form and be present anywhere in the process where CO₂ and liquid H₂O are found together, typically in the low-temperature areas of the cycle—from the low temperature recuperator where water could start to condense all the way through the water separator downstream from the cooling heat exchanger. H₂CO₃ can cause corrosion in any of the piping or cycle equipment.

Additionally, particulates, water content, and gas composition coming out of combustion can have effects on turbomachinery performance and on overall cycle performance. Water content in the sCO₂ can also affect the recuperator heat balance. Further information on the effects of sCO₂ impurities can be found in sections 2.5-2.7 above.

Past Work & Progress: Hume (2016) performed systems studies for a 500 MWe IGCC plant modified with a direct-fired oxy-fueled sCO₂ power cycle. Among items investigated, the effect on overall plant performance from the composition of the syngas entering the combustor from the gasifier was evaluated, showing differences in compressor power based on the composition of gas entering the expander (3 test cases ranging from 77.54 to 95.61% CO₂ wet). This resulted in varying CO₂ product purity and slight overall plant efficiency differences.

NETL modeling has shown non-CO₂ components exiting the combustor are detrimental to efficiency, where process and cycle efficiency drops by about 0.75 percentage points per mole percent of CO in the combustor exhaust (White, 2018).

NETL has investigated low-temperature corrosion in direct sCO₂ power cycles, evaluating corrosion of materials in sCO₂ at low temperatures and with or without presence of water.

8 Rivers Capital and NET Power have proposed to remove coal-derived N₂ and sulfur compounds in situ within the sCO₂ cycle using their DeSN_x process, as opposed to employing conventional syngas cleanup processes to remove these impurities upstream of the sCO₂ cycle (Allam, 2013; Lu, 2016). If successful, this process yields cost and efficiency benefits for coal-fueled direct sCO₂ cycles, as the cost and performance of syngas cleanup units, and their associated steam requirements, can be eliminated. However, the process results in very acidic water condensate within the sCO₂ cycle, which must be managed with appropriate material selection. Efforts to refine and demonstrate the DeSN_x process are detailed in papers by Lu (2017) and Laumb (2017).

Research Needs: Regarding pollutant effects on cycle performance, additional systems studies and experimental studies are necessary to understand

- Additional impacts of gas composition out of the gasifier on the combustion
- Impacts of particulates and water content on turbine and other components, as well as overall cycle performance
- Impacts of the gas composition exiting the combustor and entering the turbine
- Impacts on CO₂ product purity
- Impacts of in-cycle gas cleanup
- Evaluate particulate filtering methods
- Modeling combustion, based on combustor configuration and conditions, to determine gas composition out of combustion step

Refinement of these systems studies will be possible using data from actual operating pilot-scale and larger pre-commercial demonstration facilities.

Additional materials performance evaluation in low-temperature sCO₂ condition are necessary at lab- and bench-scale to:

- Evaluate at conditions below 150°C and 80 bar
- Evaluate effects of HCl and SO₂ on material properties
- Evaluate H₂CO₃ on material properties

Further evaluation of materials in an actual operating environment will be possible at pilot-scale and larger direct-fired demos. A timeline for TRL progression for pollutant removal technologies for direct sCO₂ power cycles is given in Figure 3.5.

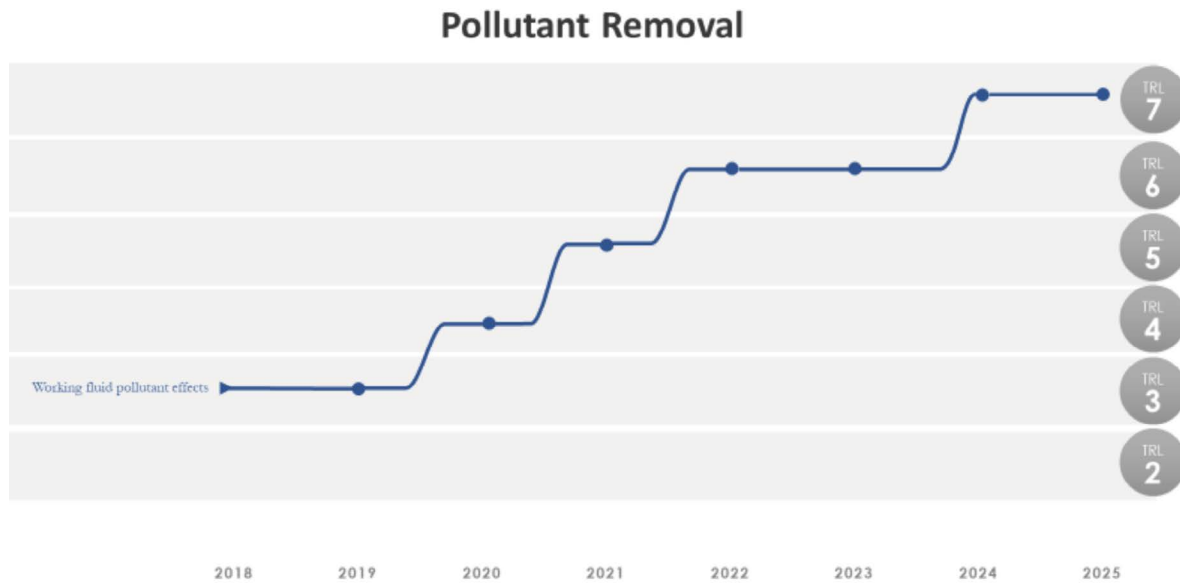


Figure 3.5. Technology readiness level progression for pollutant removal technologies for direct sCO₂ power cycles.

Major R&D Challenges: It will be necessary to develop the test cases to evaluate in system studies to more thoroughly investigate effects of pollutants on cycle performance and identify optimal conditions. Validating performance effects and stream compositions in a combustion test loop would require either developing and setting up a new combustor and test loop or working with an existing loop to test appropriate cases.

A thorough study is needed of the different acids, over wide ranges of relevant concentrations, using a range of potential materials. Studies should include longer term testing to evaluate any potential deterioration of material properties. Additionally, HCl may have corrosive effects on the autoclaves used for the testing, and new approaches/materials for the testing may be required. Challenges include identifying if lower cost materials can be used in the low-temperature areas or if there is a need for more expensive materials due to these potential corrosion concerns.

TRL Assessment: The current TRL is at 3 based on initial modeling and systems studies of pollutant effects on performance. Additional modeling and systems studies along with refinement of these studies based on data from operating pilot plants will take the TRL to 6-7.

4.0 TIMELINE FOR COMMERCIALIZATION

Based on the TRL assigned in the technology gaps and research needs discussion in the previous chapter, a timeline for direct sCO₂ cycle technology development is given in Figure 4.1.

sCO₂ Technology Development Timeline

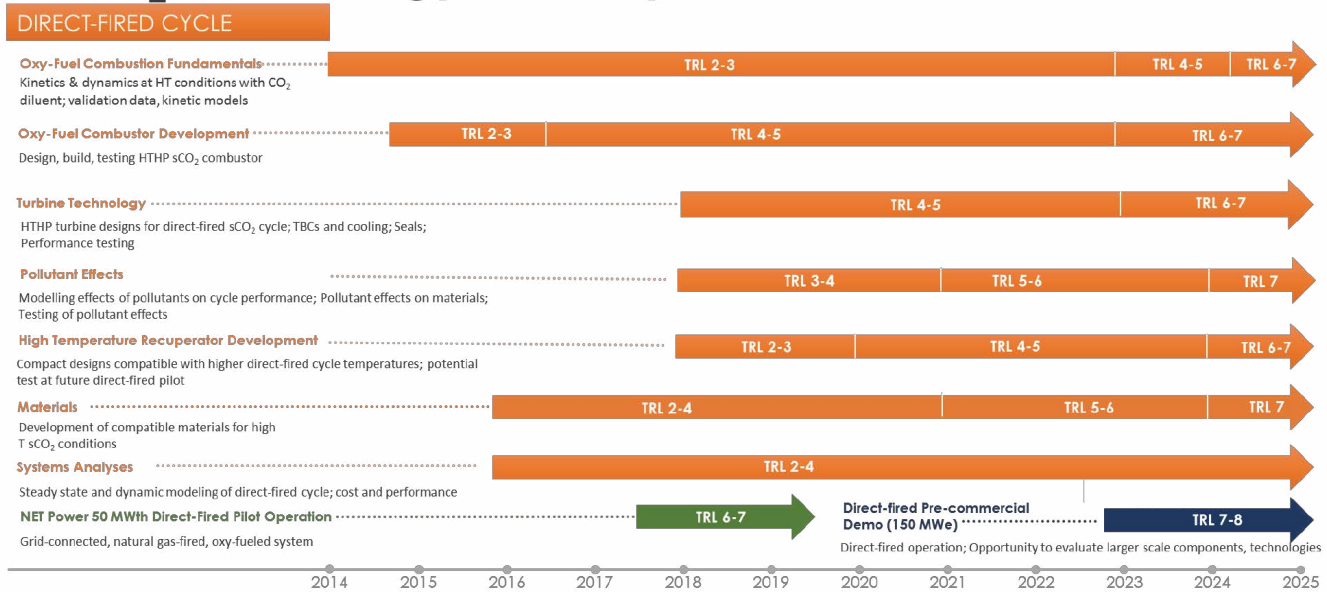


Figure 4.1. Direct sCO₂ cycle technology development

5.0 CAPABILITIES OF U.S. NATIONAL LABORATORIES FOR PERFORMING RESEARCH ON DIRECT sCO₂ POWER CYCLE

5.1 NATIONAL ENERGY TECHNOLOGY LABORATORY (NETL)

Supercritical CO₂ Autoclave

This 1-liter (heated zone volume) autoclave is constructed of Ni-based superalloy Haynes 230, has an inside diameter of 2.25", and is ASME rated and stamped at 4000 psig at 800°C. The design life is 50,000 h. The maximum heating rate is 260°C/h. The design was by Anderson Engineering and it was manufactured by Marks Brothers. It resides inside a Thermcraft 3-zone furnace to control temperature, and has a water-cooled cap. The effective temperature limit inside the autoclave is approximately 750°C. The rate of process fluid flow is controlled by a high-pressure CO₂ pump, and the pressure controlled by a back-flow regulator. Normally it is run at a rate of 2-3 g of CO₂ per minute, but has a maximum rate of 12 g per min. Up to 77 samples (size approximately 0.75 x 0.5 x 0.12 inches) fit on a sample tree within the flat heat zone of the autoclave. Larger samples are possible, but would be more limited in number. Current operations are limited to pure CO₂, which simulate indirect cycle sCO₂ environments. However, it is being refitted for direct cycle sCO₂ environments, with the inclusion of H₂O and O₂.

Supercritical Steam Autoclave

This 1-liter (heated zone volume) autoclave is constructed of Ni-based superalloy Haynes 230, has an inside diameter of 2.5", and is ASME dual-rated and stamped at 3300 psig at 760°C and 5000 psig at 704°C. It was designed and manufactured by Autoclave Engineers. It resides inside a CM 1-zone furnace to control temperature. The insulated top allows the effective temperature limit inside the autoclave to be close to the ASME rating limits. The rate of process fluid flow is controlled by a high-pressure H₂O pump, and the pressure controlled by a back-flow regulator. Normally it is run at a rate of 2-3 g of CO₂ per minute, but has a maximum rate of 12 g per min. Up to 50 samples (size approximately 0.75 x 0.5 x 0.12 inches) fit on a sample tree within the flat heat zone of the autoclave. Larger samples are possible, but would be more limited in number. Current operations are limited to pure H₂O, which simulate supercritical steam boiler environments. Input water consists of deaerated deionized water, which is monitored for dissolved O₂ and conductivity.

Standing Stirred Autoclaves (SSAC)

These units are plumbed and wired to a gas supply system (capable of delivering a variety of pure and mixed gases: air, Ar, N₂, CO₂, O₂, SO₂, hydrogen sulfide [H₂S], CH₄, NH₃), gas venting system, and heating/cooling system. Each autoclave is controlled by a Parr 4875 power controller. A single Parr 4871 process controller controls the four 4875 units. Overall control and data acquisition is performed on a computer from the control room (B26-106). Two types of pumps can be used to supply gas and fluid pressure to the system. In most operations, A Haskel model AGD-62 pneumatic high-pressure pump is used to supply gas for experiments and boost pressure to the required experiment conditions. Alternately a Teledyne isco pump can be used to inject H₂O or pure CO₂ into the autoclave. The operating envelope for the autoclaves is 4,500 psig (designed to 5,000 psig) and 250°C. A variety of configurations (e.g., stirred modes, Teflon/Glass liners, and dip tubes) and autoclave metals (e.g., SS-316, Titanium, and Hastalloy) can be used depending on test conditions.

Electrochemical Reaction Autoclave (ERAC)

This unit consists of a cell enclosed in a Parr Autoclave with capabilities to perform electrochemical measurements for the study of corrosion of metal alloys and advanced materials at temperatures (up to 250°C) and pressures (up to 4,500 psig) under aqueous conditions (including brines) involving the use of pure and mixtures of gases containing: air, Ar, N₂, CO₂, O₂, H₂S, SO₂, and CH₄. This apparatus will allow for closed exposure testing as well as flow-through testing using an ISCO pump with a volumetric flow rate between 0.001 and 80 mL/min. Tests can run from hours to several weeks. Fluid sampling is possible via the fluid sampling port. Electrochemical kinetics will permit the investigation of materials for sCO₂ applications, development of corrosion-resistant metallic coatings, development of corrosion sensing technologies, and gain a comprehensive understanding of the thermodynamics of the system.

Severe Environment Corrosion and Erosion Research Facility (SECERF)

The SECERF has multiple three-zone tube furnaces that can be used for high-temperature exposure testing, including corrosion testing materials for potential sCO₂ power cycle use. The SECERF is special in that there are a variety of gases that can be mixed using precision mass flow controllers and used in the furnaces. The gases include CO₂, N₂, O₂, CO, CH₄, H₂, H₂S, HCl, SO₂, and helium (He), with H₂O as an additional component. This allows for production of multiple possible sCO₂ direct- or indirect-fired gas streams that can be programmed to vary in composition or gas rate during an exposure if needed. These gas streams are typically CO₂ rich with contaminants that include, H₂O, O₂, and as needed SO₂ and HCl. The furnaces have sealed ceramic tubes to contain the flowing gas streams. The tubes are typically about 2 3/4" inner diameter. The 3-zone furnaces allow for adjustment of the various temperature zones to achieve a uniform temperature zone of about 12" in which to position samples. Racks, which are positioned in the tubes, have been constructed that allow many samples to be exposed simultaneously. While the furnaces are limited to atmospheric pressure, the lab and gas supply system is configured to allow long exposure times, with times to 1,000 h being routine. The furnaces can be operated at 900°C routinely and at higher temperatures with additional preparation.

High-Temperature Facility (HTF)

The HTF has multiple 3-zone tube furnaces (three limited to 1,250°C, and one limited to 1,700°C) that can be used for high-temperature exposure testing, including corrosion testing materials for potential sCO₂ power cycle use. Gas supplies to these furnaces can include high purity CO₂, O₂, N₂, and Ar, plus mixtures of these. Water can also be introduced to the furnaces as needed. The gases are metered through metering valves and measured by mass flow meters prior to being mixed and introduced to the furnaces. For sCO₂ work, this allows for conducting high-temperature corrosion tests in indirect high purity CO₂ conditions as well as sCO₂ direct conditions where additional O₂ and H₂O will be present. The furnaces have sealed ceramic tubes to contain the flowing gas streams. The tubes are typically about 2 3/4" inner diameter. The 3-zone furnaces allow for adjustment of the various temperature zones to achieve a uniform temperature zone of about 12" in which to position samples. While the furnaces are limited to atmospheric pressure, the lab and gas system is configured to allow long exposure times, with times to 1,000 h being routine.

Environmental Creep Frame

NETL has a creep frame fitted with a retort tube. This allows for acquisition of creep rates in user selected environments. The frame has temperature capabilities from room temperature up to 900°C. Dual LVDTs measure specimen strain off shoulders. Stress is applied by utilizing weights and a lever arm. Capacity of the frame is rated to 222 kN. Selection of an Ar with H₂ will simulate a low-O₂ environment where baseline data can be generated to compare to a harsher more aggressive environment such as CO₂ gas or steam.

Confocal Scanning Laser Microscope

NETL has a confocal microscope fitted with a sealed tensile stage and a high-temperature furnace. The tensile stage has a capacity of 5kN and maximum strain rate of 20 mm/min. The sealed tensile stage allows for testing to be conducted in vacuum, CO₂ gas or any other desired environment. Stress is applied by a linear actuator and measured by a load cell with capacity of 5 kN. Strain is measured by the confocal optics. The confocal system is ideal for research looking to measure extension in specific environments, particularly tensile extension or crack growth.

Heat Exchange and Experimental Testing (HEET) Rig

The HEET rig is a small-scale closed loop heat exchange testing device designed to measure heat transfer coefficients at conditions relevant to both indirect and direct sCO₂ cycles. The rig is currently being assembled and is expected to be operational by Fall 2018. This rig will have the capability to perform experiments at pressures as high as 3,500 psia, temperatures as high as 1000°F, and Re as high as 1,000,000 at a maximum CO₂ flowrate of about 0.25 kg/s. A draft test matrix has been developed that will enable the study of the impact of Re on the Nusselt number. Additionally, the test rig has the ability to introduce impurities such as N₂ to study their impact on heat transfer coefficient. Impurities will be present in the sCO₂ for the direct cycles.

Systems Engineering and Analysis

The Systems Engineering and Analysis (SEA) directorate possesses an extensive set of power system equipment cost and performance data, including that used in the renowned "Cost and Performance Baseline for Fossil Energy Plants" volumes. Further, SEA has developed a consistent methodology and an extensive set of QGESS reports to ensure high quality, consistent, comparable analysis results.

In addition, SEA researchers have been studying direct sCO₂ power cycles with carbon capture for the past 4-5 years, and have developed efficient and cost-effective direct sCO₂ plant designs. SEA researchers have also developed a historical competency with process dynamic modeling of advanced energy system concepts, such as IGCC and fuel cell hybrid systems. Along with other national laboratory and university partners, NETL also has experience in applying advanced controls to advanced cycle concepts. Finally, NETL's computational capabilities to perform techno-economic analyses and dynamic power plant simulations include licenses for the Aspen Plus and Aspen Dynamics software packages. SEA is also growing internal capability for such analyses on an open source framework with the ongoing development of the Institute for the Design of Advanced Energy Systems (IDAES) software platform.

5.2 OAK RIDGE NATIONAL LABORATORY (ORNL)

1. Three alloy 282 autoclaves capable of the highest temperature and pressure combinations (30 MPa, 800°C)
 - a. One of the autoclaves is equipped with a triple pumping system to inject controlled amounts of sCO₂, O₂ and H₂O to simulate direct-firing. Currently, 30 MPa sCO₂ is being evaluated with 1% O₂ and 0.25% H₂O at 750°C.
 - b. A second autoclave is being upgraded with a similar triple pumping system for studying lower levels of O₂ and H₂O in the 50-100 ppm range at 30 MPa.
2. Three pressurized closed end tube furnace systems ("Keiser" rigs) capable of 0.1-4.3 MPa pressures and 1400°C
 - a. One system is currently being used to simulate the UK Advanced Gas Cooled Reactor conditions of 4.3 MPa CO₂ (600 psi) at an accelerated temperature of 640°C.
 - b. Each system has a controlled gas train capable of mixtures of CO₂, O₂, H₂O, SO₂, etc. and have been used for comparison experiments at 0.1 and 1.7-3.0 MPa to study the role of pressure with two separate tubes in one furnace with the same gas and two pressures.
3. Six tube furnaces with controlled gas capabilities (CO₂, O₂, H₂O, SO₂, etc.) at 0.1 MPa

5.3 SANDIA NATIONAL LABORATORIES (SNL)

SNL is working on an sCO₂ Brayton cycle in support of DOE Office of Nuclear Energy (NE) programs pursuing the development of the technology. SNL is researching a thermal-to-electric power conversion technology in a configuration called the recompression closed Brayton cycle (RCBC) that uses sCO₂ as the working fluid, rather than steam, thereby dramatically increasing conversion efficiency compared to the steam Rankine cycle. sCO₂ laboratory capabilities include the following:

- Thermodynamics
- Cycle Design
- Commercial Component Development
- Systems Integration
- Materials
- Operations and Maintenance
- Economics Modeling
- Systems and Concurrent Engineering
- Roadmapping

Test Rigs include the following:

- **sCO₂ Brayton Laboratory Component and System Development Platform:** sCO₂ Component and System Development Platform: a reconfigurable testing rig with 2 turbo-alternator-compressors rated at 125 kWe, motor controllers, 780 kW of heating power, 560 kW of heat rejection capacity, recuperators, extensive state-of-the-art data acquisition (DAQ) and controls, rated for 538°C and 13.8 MPa operation. The development platform is used to test components and systems, one of which is the RCBC
- **Bearings Test Rig:** The bearings test rig has the capability to test up to 250°F and 1600 psi bearings environments
- **Seals Test Rig:** The seals test rig has the capability to test seals that range from 1" to 8" in diameter @700°C and 4500 psi
- **sCO₂ Tall Loop:** High-pressure thermosyphon loop to measure natural convection effects in supercritical fluids
- **APOLLO Loop:** Modification of the sCO₂ Tall Loop to measure the performance of regenerators as a possible replacement for recuperators
- **UNM NEUP Loop:** Modification of the sCO₂ Tall Loop to measure the performance of twisted tube heat exchangers for Fluoride salt-cooled High-temperature Reactor (FHR) applications
- **Heat Exchanger Test Loop:** 100 kW water-water loop to measure the performance of compact heat exchangers
- **Mobile Heat Exchanger Test Loop:** 25 kW water-water loop to measure the performance of compact heat exchangers
- **High-Pressure Test Facility:** 60 ksi hydrostatic and fatigue test facility to measure the mechanical performance of compact heat exchangers and other equipment
- **Low-Pressure Gas Brayton Loop:** 30 kW, 700°C low-pressure gas Brayton test loop to investigate the system dynamics of a coupled pin-type nuclear reactor and gas Brayton cycle and alternative gas Brayton cycle operating fluids
- **sCO₂ Visualization Loop:** Optical facility to measure flow and density distributions of sCO₂
- **MCHE Visualization Loop:** Optical facility to measure flow distributions in water for MCHE and other geometries

5.4 NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (NIST)

NIST capabilities that can support the direct sCO₂ power cycle technology are all in the category of measurement and modeling of thermophysical properties of the fluids in the power cycle.

1. High-accuracy measurement of fluid density at temperatures from 210-620 K and pressures up to 50 MPa
2. Vibrating-tube densimeter for measurements of density of liquids and compressed gases from 270-470 K at pressures to 50 MPa
3. Measurement of sound speed for gases at temperatures to 500 K and pressures to 10 MPa
4. Measurement of thermal conductivity of liquids, vapors, and supercritical fluids at temperatures from 60 K to 750 K at pressures up to 70 MPa [extensive measurements have already been made on pure CO₂]
5. Measurement of viscosity of fluids from 250 K to 450 K at pressures to 100 MPa

For all of items 1-5, measurements can be made on pure fluids or on well-characterized mixtures (such as CO₂/O₂).

6. Development of reference-quality equations of state for pure fluids (CO₂, O₂, etc.) (A DOE-funded project for pure CO₂ is in progress.)
7. Development of reference-quality correlations for viscosity and thermal conductivity of pure fluids (already measured pure CO₂ viscosity and thermal conductivity)
8. Development of models for thermodynamics of gas mixtures
9. Implementation of thermophysical properties in user-friendly form via the Reference Fluid Thermodynamic and Transport Properties (REFPROP) database, <https://www.nist.gov/srd/refprop>

5.5 PACIFIC NORTHWEST NATIONAL LABORATORY (PNNL)

Extreme Environment Alloy Discovery & Development

- Physics-based multi-scale modeling coupled with machine learning and experimental data to design alloys tailored for specific applications
- Phase field models for microstructure evolution predictions
- High-throughput combinatorial arc melting system for accelerated alloy development
- Combinatorial alloy thin-film deposition system capable of simultaneously depositing up to five elements

Extreme Environment Alloy & Component Manufacture

- Solid Phase Processing approaches to the production of materials and semi-finished parts
 - Shear Assisted Processing & Extrusion (ShAPE™)
 - Ultra High Velocity Cold Spray
 - Friction Processing
- Similar and Dissimilar Materials Joining
 - Friction Stir Welding
 - Friction Stir Scribe
 - Friction Stir Dovetailing
- Coatings & Claddings
 - Ultra High Velocity Cold Spray
 - ShAPE™
 - Slurry-Based Coatings
- Additive Manufacturing by Solid Phase Processing
 - Ultra High Velocity Cold Spray

Materials Characterization

- Microstructural characterization across scales from optical metallography to scanning electron microscopy (SEM), focus ion beam (FIB), electron backscatter diffraction (EBSD), aberration-corrected STEM/TEM, x-ray photoelectron spectroscopy (XPS)
- Chemistry characterization across scales: ICP-S, SIMS, Laser Ablation SIMS, 3-D Atom Probe
- Environmental Molecular Sciences Laboratory (EMSL) – DOE User Facility that includes capabilities like Rutherford Backscatter, Auger, ToF-SIMS, NanoSIMS, XANES, X-Ray Diffraction and Spectroscopy
- In situ Environmental (S)TEM, with capabilities to 900°C, and with reducing gas (H₂, CO), oxidation, methane, neutral gas, steam exposures

- In situ Aqueous Corrosion evaluations via transmission electron microscopy (TEM) and nuclear magnetic resonance (NMR)
- High Energy X-ray Diffraction with Crystal Plasticity Modeling
- Thermal Analysis – High throughput, high-temperature differential scanning calorimetry/thermogravimetric analysis (DSC/TGA) can test up to 32 samples to temperatures up to 1600°C in air or inert gases

Materials Performance Assessment

- Physics-based multi-scale modeling coupled with machine learning and experimental data to predict materials performance
- Corrosion and Stress Corrosion Cracking
- Mechanical Properties – tensile, compression, creep, fracture toughness, hardness

Compact Heat Exchangers

- Microchannel heat exchanger design and manufacturing expertise for compact/efficient applications (in a prior project technology was applied to an air-cooled application for an sCO₂ power cycle)
- Advanced heat pump development and design
- Expertise in catalyzed micro-channel reactor design, manufacturing and systems integrations

Systems Analysis

- Component and process engineering modeling expertise (COMSOL, ChemCad, ASPEN, etc.)
- Process development expertise, including integrated processes for power and/or chemical conversions (e.g., heat integrated solid oxide fuel cell [SOFC]-based power system)
- Complex process development and testing, including system controls

5.6 LAWRENCE LIVERMORE NATIONAL LABORATORY (LLNL)

Additive Manufacturing with Nickel Superalloys

LLNL has a world-class initiative in advanced manufacturing, including a specific capability around method development for metal printing. The facilities include a suite of commercial metal printers as well as several research test beds for developing higher-quality and higher-throughput techniques. LLNL has used its open-platform Powder Bed Fusion printer, supplied by the Fraunhofer Institute, to make a prototype heat exchanger for sCO₂ system in Inconel 625. Prints with additional superalloys are planned in current work. These capabilities can be used to create and test various parts for the sCO₂ power cycle where complex geometry or homogeneous materials properties are desirable.

Multiphysics Models with High-Performance Computing

LLNL has extensive High-Performance Computing (HPC) facilities and experience with multiphysics modeling for a range of energy and materials problems. Commercial codes, like StarCCM and OpenFOAM, as well as in-house codes, like GEOS, are used frequently on complex fluid flow problems and mechanical performance under high-stress conditions, which are each relevant to sCO₂ systems. So far, HPC has been used to simulate flows in sCO₂ heat exchangers with complex, 3D-printed geometries.

6.0 SUPPLIERS AND DEVELOPERS

ORGANIZATION	AREAS OF ACTIVITY FOR DIRECT sCO ₂ POWER CYCLES
Air Liquide	oxy-combustion modeling, oxy-combustor testing, O ₂ production
Altex	recuperators
Atlas Copco	compressor supplier for NET Power demo plant
Brayton Energy	recuperators
Cascade Technologies	oxy-combustion modeling - LES
CB&I	engineering, procurement and construction (EPC) firm building the NET Power demo plant
Combustion Research and Flow Technology	oxy-combustion modeling
CompRex	recuperators
Creative Power Solutions	oxy-combustor designer
Czech Technical University	cycle modeling on effect of impurities
Dena Scientific	oxy-combustion modeling
Dresser-Rand, A Siemens Company	turbomachinery
Echogen Power Systems	sCO ₂ power system developer
Electric Power Research Institute	direct sCO ₂ cycle techno-economic analyses
Exelon Generation	NET Power demo plant operator & power sales
Gas Technology Institute (GTI)	oxy-combustor development and testing
General Electric	turbomachinery
Georgia Institute of Technology	oxy-combustion modeling, oxy-combustion fundamental testing
Hanwha Techwin	sCO ₂ compressor and pump vendor, developer of uncooled direct sCO ₂ turbine
Illinois Rocstar	oxy-combustion modeling
Korea Advanced Institute of Science and Technology (KAIST)	Korean electric utility, generation, transmission, distribution
Meggitt/Heatric	recuperators, supplier for NET Power demo plant
Mezzo Technologies	recuperators
Mohawk Innovative Technology, Inc.	recuperators
National Energy Technology Laboratory	systems analyses, oxy-combustor modeling, oxy-combustion fundamentals, materials development and performance testing
NET Power	direct-cycle power plant developer
Oak Ridge National Laboratory	materials
Ohio State University	recuperators
Oregon State University	microchannel heat exchangers
Peregrine Turbine Technologies	turbomachinery
Praxair	direct sCO ₂ cycle modeling, O ₂ production
Sandia National Laboratories	cycle design, component development, system integration, economic modeling
Siemens	turbomachinery
Southwest Research Institute	oxy-combustor design, oxy-combustion test loop, direct sCO ₂ turbine design and testing
SuperCritical Technologies	modular power system developer
Symplectic Research	oxy-combustion modeling
Thar Energy LLC	recuperator manufacturer, oxy-combustion testing, direct sCO ₂ water & pollutant removal
Toshiba	oxy-combustor testing and development for direct sCO ₂ cycle, turbine for direct cycle, turbine and combustion control systems
University of Central Florida	oxy-combustion modeling, oxy-combustion fundamental testing
University of North Dakota Energy & Environmental Research Center	direct contact cooler for water and pollutant removal, gasification direct sCO ₂ demo plant developer
University of Texas-El Paso	oxy-combustion modeling, oxy-combustor testing
University of Wisconsin-Madison	materials, regenerators as alternative to recuperators for direct sCO ₂ cycle
Vacuum Process Engineering, Inc.	recuperators

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