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Demonstration testing and facility requirements for sCO2 Brayton Commercialization

Lon Dawson and Matthew Carlson

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Demonstration testing and facility requirements for sCO2 Brayton Commercialization

Lon Dawson and Matthew Carlson
Advanced Nuclear Concepts
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS1136

Abstract

A critical aspect of sCO2 Brayton commercialization is confidence that the technology is viable and sufficiently mature. This confidence comes from systematic testing at the level of individual components to full system demonstrations. The characteristics for testing vary based on the testing goals. This paper is a review of testing philosophy, including component and system testing requirements and facility considerations supporting the research and development (R&D) strategy for commercialization. It was prepared for the 5th International Symposium - Supercritical CO2 Power Cycles March 28-31, 2016 in San Antonio, Texas.

Once the underlying science is proven by foundational research and development, the testing process begins with an evaluation of the technology readiness levels of individual components for a specific process and/or flow. Once the individual components are specified and proven, the focus shifts to integrated system testing in an appropriate facility. This paper proposes some considerations for such a facility. The outcome of integrated system demonstration (Pilot Testing) is a power block ready for a subsequent commercial demonstration focused on extended operation to confirm performance, maintainability, reliability and economics. The dedicated components of the demonstration testing facility (i.e., those excluding the power block: the modular heat source, heat rejection, control and instrumentation infrastructure, and electrical load) may serve as a national asset whose enduring mission is to develop the sCO2 Brayton technology for alternate configurations and applications. (Abstract SAND2015-6409 A)

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TABLES

NOMENCLATURE

DOE	Department of Energy
SNL	Sandia National Laboratories
TRL	Technology Readiness Level
TRA	Technology Readiness Assessment
TMP	Technology Maturation Plan
CTE	Critical Technology Elements
TRA	Technology Readiness Assessment
sCO2	supercritical Carbon Dioxide
R&D	Research and Development
MRA	Manufacturing Readiness Assessment

1. EXECUTIVE SUMMARY

The Supercritical CO2 Power Cycles Symposium is organized to advance supercritical Carbon Dioxide (sCO2) power cycles technology. Such technology advancement is benefited by 1) a strong understanding of current technology readiness, 2) a clear and reachable technology goal and 3) a path to reach that goal.

This paper references the common taxonomy of Technology Readiness Levels (TRLs) which are helpful in estimating technology maturity, and then proposes a series of testing activities to guide further technical development culminating in a commercially ready product. Section 2 defines TRLs and the Brayton testing which, when successful, would justify a given TRL. We propose that in the many parallel development activities, collaboration on the highest technical risks is necessary and possible in the form of sharing testing results. This can be accomplished while still protecting proprietary technology. A benefit for one can help the entire community build confidence! We also propose that a specific system design is necessary for technology advancement of a unique layout beyond TRL 4.

Section 3 describes different types of testing activities and includes a conceptual relationship between TRL, testing phases and testing activities. Section 3 proposes a path for how cost sharing may transition from primarily government to primarily commercial/industrial.

Brayton testing needs to consider that a power cycle is a complex system-of-systems and a successful commercialization will result in replacing a *mature technology application*. So final system integrated testing is conducted in two separate phases: 1) Pilot Testing at a dedicated testing facility to show that the system works and meets performance goals and 2) Commercial Demonstration which is a long duration test at the industrial facility conducted by industry personnel. Section 4 presents these critical phases of technology advancement - why they are needed, what testing must be accomplished and considerations for the supporting facility.

2. BACKGROUND

2.1 Technology Readiness Levels (TRLs) – What and Why

From [1]: "Technology Readiness Levels (TRLs) are a method of estimating technology maturity of the Critical Technology Elements (CTE) of a program during the acquisition process. They are determined during a Technology Readiness Assessment (TRA) that examines program concepts, technology requirements, and demonstrated technology capabilities. TRL are based on a scale from 1 to 9 with 9 being the most mature technology." There are many TRL definitions and potential sources of readiness descriptors for example the US Department of Defense, European Space Agency, Biomedical, Oil & Gas and the European Commission.

The TRL definitions described in Table 1 are defined by the Department of Energy [2]. Table 1 defines the TRL and the DOE description is shown in column 2. Further, specific to sCO2 Brayton technology this paper proposes the testing activities which would satisfy each TRL level in column 3. The hope here is to clarify exactly what *successful* activities and testing will justify a given TRL level and facilitate consensus on both the current technology status and what activities should be done to deliver a commercially-ready technology.

Table 1. TRL Descriptions and Testing Activities

Technology readiness level	Description	Proposed Testing Activities sCO2 Brayton
1. Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology.	Testing is focused on basic principles and foundational science is still being explored. **Note that this is currently in progress for some aspects of sCO2 Brayton technology such as material for high-temperature components.**
2. Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made	**Note that this is currently the TRL for some Brayton cycles and related components.**

	during TRL 1 work.	
3. Analytical and experimental critical function and/or characteristic proof of concept	Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants. Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.	Proof-of-concept testing of applications/concepts is completed. Computer modeling exists and proven valid. Fabrication processes are validated. **Note that this is considered accomplished for the sCO2 recompression closed Brayton Cycle at 500C [3].**
4. Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.	Component rig testing at bench-scale is completed. High risk component integration is completed.
5. Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants and actual waste. Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual	Complete component testing using sCO2 working fluid at design conditions. **Note that to achieve TRL 5 and beyond, the application-specific product must have been chosen and its design specified so that component**

	operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.	**configuration and any system integration is relevant.** **To achieve TRL5, high risk technical issues must be addressed (e. g., material concerns for corrosion, seals, bearings, etc.).**
6. Engineering /pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants. Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.	<u>Subscale</u> testing of an integrated system at design conditions. System and component configuration is targeted to application-specific product.
7. Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning. Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.	Complete pilot testing - All components integrated into an application-specific product, demonstrated at design conditions.
8. Actual system completed and qualified through test and demonstration	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning.	Complete installation and startup of an application-specific product, ready for commercial demonstration.

	Supporting information includes operational procedures that are virtually complete. An operational readiness report has been successfully completed prior to the start of hot testing.	
9. Actual system operated over the full range of expected conditions.	The technology is in its final form and operated under the full range of operating conditions. Examples include using the actual system with the full range of wastes in hot operations.	Complete long term commercial demonstration of an application-specific product at commercial site by utility stakeholder.

2.2 Current Technology Readiness

Specific to sCO2 Brayton technology and working fluid temperatures less than 500C, the general consensus is that the TRL is approximately 3 - Analytical and experimental critical function and/or characteristic proof of concept as demonstrated by the SNL test article testing among others [3]. However higher max temperatures have not been successfully demonstrated to date and the TRL is even lower.

2.3 Pilot System Selection

It is an important consideration in increasing technology readiness above TRL 4 that "validation … should also be consistent with the *requirements of potential system applications*" (emphasis added). The point here is that although an integrated system is not fully tested, testing should be targeted at the *design and configuration of the final system*. Sandia hosted a sCO2 Brayton industry day in August of 2014 [4] and among the takeaways were two specific points:

1. The electric generation industry is not homogeneous. They have many different product offerings each tailored to a specific market need. Each product offering has specific attributes, for example, size, efficiency, emissions, etc. It is not adequate to develop a generic cycle. Rather our development needs to target a specific application and thus facilitate the competitive comparison.

2. The electric generation market is mature and will not tolerate an unproven technology. Specifically, "you should not expect strong industry investment or interest until the technology is piloted for 8000 hours!"

In summary, we propose that for testing to prove TRL4 or above "the application-specific product must have been chosen and its design specified so that component configuration and any system integration is relevant". Although this seems very limiting, it is important to realize that any research and development progress will likely be transferrable to other applications and the confidence will help the entire industry.

2.4 Addressing the highest technical risks

Lastly, we propose that the breadth of sCO2 Brayton development and testing activities to date have identified several areas of technical risk that must be solved and successfully proven before we can have confidence in an integrated prototype demonstration in a relevant environment (TRL6). High technical risks include corrosion, turbine erosion, turbine control, thrust management and seals among others. There is real need to communicate on such important risks and an opportunity for collaboration that could ultimately facilitate new commercial products and confidence in a pilot-ready system! The Department of Energy recommends an assessment of the maturity level of a new proposed technology prior to insertion into the project design and execution phases to reduce technical risk and uncertainty. A Technology Readiness Assessment (TRA) provides a snapshot in time of the maturity of technologies and their readiness for insertion into the project design and execution schedule. A Technology Maturation Plan (TMP) is a planning document that details the steps necessary for developing technologies that are less mature than desired to the point where they are ready for project insertion. TRAs and TMPs are effective management tools for reducing technical risk and minimizing potential for technology driven cost increases and schedule delays [5].

2.5 Sustaining vs Disruptive technologies

Given a good understanding of TRLs, testing requirements for very simple products might be derived. However in power cycle technology we must consider that we are not just proposing to replace a certain component or machine. Indeed an organization seeking acceptance of a novel power cycle must realize that electricity generation might be considered an *ecosystem* (a group of interconnected elements, formed by the interaction of a community of organisms with their environment) which includes component manufacturers, system vendors, cycle integrators, specialized facility design considerations, operators (utilities) and regulators. This ecosystem has had decades of success in delivering power and this success results in strong patterns of behavior. In introducing a disruptive technology, C.M. Christensen noted in *The Innovators Dilemma* (Boston, MA: Harvard Business Review Press, [1997, 2000]) that “The capabilities of most organizations are far more specialized and context-specific than most managers are inclined to believe. This is because capabilities are forged within a value network. Hence organizations have capabilities to take certain new technologies into certain markets. They have disabilities in taking technology to market in other ways.”

Often improved product performance comes from sustaining technologies in the form of *incremental* improvement. “What all sustaining technologies have in common is that they improve the performance of established products, also in the dimension of performance that mainstream customers in major markets have historically valued. Disruptive technologies bring to a market a very different value proposition than had been available previously. Successful companies have a practiced capability in taking sustaining technologies to market, routinely giving their customers more and better version of what they say they want. This is a valued capability for handling sustaining innovation, but it will not serve the purpose when handling disruptive technologies.” [6]

The energy ecosystem has resolved into specific niches based on market needs and so any potential offering will have to address the current baseline performance attributes (relative to that specific niche). This could imply specific performance requirements for cost, efficiency, water use, foot print, load following performance, etc.

3. TESTING ACTIVITIES

In this paper we have used the term testing activities generically for all TRL activities from 1 to 9. Such activities encompass many different disciplines from foundational materials testing, administrative auditing to ensure supply chain robustness, component testing of various natures and integration testing for both pilot testing and commercial demonstration.

Lastly, we compile the various testing activities into a notional sequence as related to key milestones and TRLs.

3.1 Materials

Material testing activities include materials selection for given subcomponents at specified system conditions and proving material characteristics (such as corrosion, creep, carburization, etc.) in the high-temperature sCO2 environment. Although many commercially-available subcomponents exist for sCO2 systems, their performance may have to be re-established for higher temperatures.

3.2 Manufacturing Readiness Assessment

The maturity of the electric generation industry dictates that not only must we deliver an application with improved performance (for some attributes), proven reliable for an extended duration, we must also ensure that the supply chain will robustly deliver future systems to facilitate economies of scale and maximize industry investment. Disruptive technologies imply new / unproven vendors and manufacturing processes! At Sandia our nuclear weapons processes dictate unique product sources with impeccable quality that cannot rely on commodity components so our product realization processes couple a Manufacturing Readiness Assessment (MRA) and maturity process to technology readiness. MRAs define the Manufacturing Readiness level and provide a common language to communicate maturity of the manufacturing system (Tooling, Processes, People, Quality and Safety systems, etc.).

3.3 Component Rig Testing

Component testing is where testing of each component is done separately. Clearly, component function and reliability must be established for all cycle CTEs at design conditions in a relative (sCO2 environment). Component testing may also include source acceptance to facilitate the understanding and validating the manufacturing process and vendor inspections.

Test rigs can perform a variety of key functions from component validation through to the training and development of operators. Component testing may be done in isolation from the rest of the system but rig testing should also include integration of components for high-risk system functions. For example the recompression closed Brayton cycle has been proposed for higher system conversion efficiency but system behavior is decidedly more complex than the simple Brayton cycle. Interactions between turbines, compressors, and other equipment must be well understood for all system conditions (i.e., startup, steady state, design excursion, etc.).

3.4 Pilot Testing

The Pilot Testing will prove TRL 7 - All components integrated into an application-specific product, demonstrated at design conditions in a relevant (sCO2) environment. It should consider all previous component, system and subscale prototype testing and ready the system for a high-confidence commercial demonstration. In addition to testing component control and interaction against pre-determined system requirements, pilot testing will include Operation Readiness Testing to ensure the system can be monitored, operated and maintained, and is functional, resilient, recoverable and reliable in all design conditions (startup, design transient and in emergency).

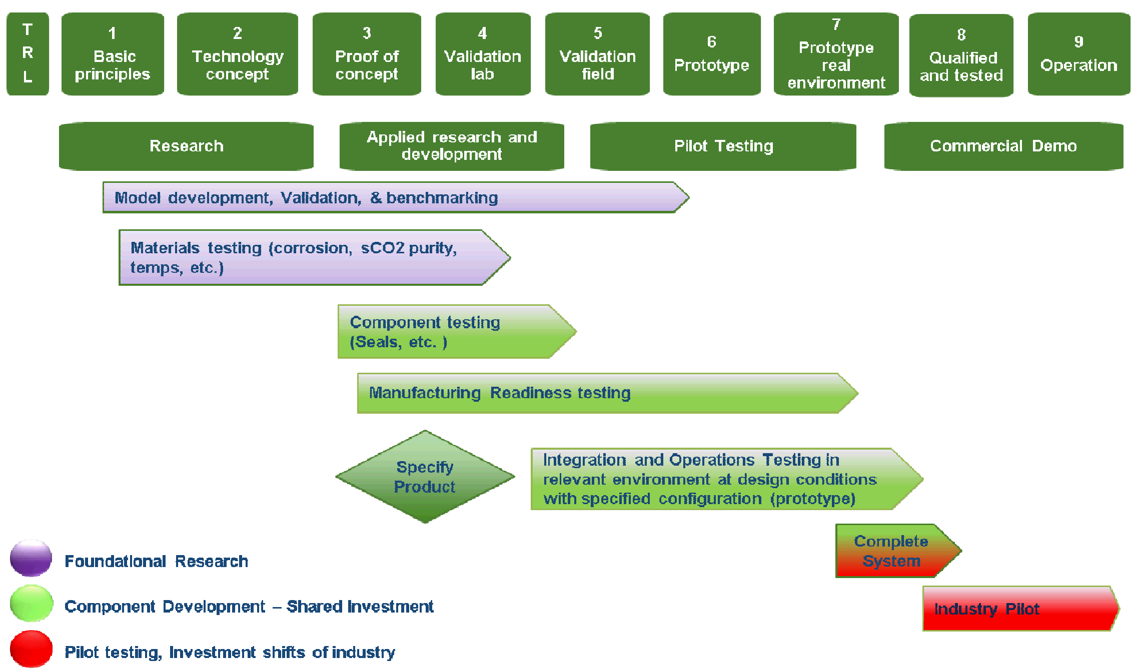
3.5 Commercial Demonstration testing

As previously noted the electric generation industry is mature. Even when pilot testing has been completed a long-term (for example, >8000 hour) commercial demonstration is required. The commercial demonstration will be conducted by stakeholder (e.g., utility) personnel, at a stakeholder facility. For the commercial demonstration, the focus shifts to system reliability and maintenance/operations.

3.6 Integrated Lifecycle Development and Testing

Figure 1 presents the proposed relationship of different testing activities to TRL and separate testing phases from research to pilot and commercial demonstration. A key node is the selection of the specific commercial product which is targeted for pilot. Without this selection the exact design cannot be completed and targeted testing is not possible. Manufacturing readiness should be considered and integrated into the technology readiness planning to ensure the supply chain is reliable and robust.

Figure 1. Lifecycle Development and Testing



A complete technology plan must include not only what is done but who does it, where it happens and who pays for it. Figure 1 activities are color coded with a proposal on how testing activities are likely to be funded. Foundational research (purple) is expected to be completed primarily by and at universities and national laboratories and is expected to be funded in large part by the government because technical risk is high and industry has existing products which are meeting current needs. This paradigm will begin to shift with component testing as there may be derivative benefits from industry collaboration – although the final Brayton product is not purchased at this point, there may be confidence in future investment or alternative markets where components are sold. An example of this is the printed circuit heat exchanger work currently in progress. Heat exchangers can be sold for non-Brayton applications. Clearly manufacturing readiness assessments will be conducted in collaboration with component and system vendors. As the pilot testing progresses there should be increasingly stronger engagement with industry both because technology confidence is growing and the commercial demonstration must be targeted to specific industry use.

4. TESTING FACILITY CONSIDERATIONS [7]

As previously described, we propose that integrated system testing be conducted in two discrete phases:

1) Pilot testing to establish core SCO2 Brayton technology (in a relevant environment, at design conditions and in a configuration targeted to a specific commercial product) to demonstrate performance and operability of the sCO2 Brayton Cycle, and

2) Commercial demonstration with the power block received from the demonstration testing phase for longer duration tests operated by utility personnel.

Our concept for a cost-shared, public-private partnership utilizes existing facilities to house these experiments. The development facility is envisioned to be a national asset whose mission is to develop the sCO2 Brayton cycle, associated components, and after the first demonstration serve as a development/test facility for subsequent systems targeted at other sections of the power generation ecosystem (higher temperature, higher power, etc.).

The pilot testing should leverage all previous component testing and while it begins with validating system requirements and performance, it must also continue with Operational Readiness Testing to prepare for the subsequent pilot. Here are some recommendations for the pilot testing facility:

- Modular design for reconfiguration and component changes,
- Capable of integrating components and technologies from different sources while protecting intellectual property.
- Dedicated development facility with heat source, heat rejection, control and instrumentation infrastructure, and power dissipation.
- Normally "off" system supporting activities which are predominantly short term experiments or transient operations.
- Staffed by independent, unbiased experts with appropriate sCO2 Brayton experience, a proven safety record and capable of continued development and validation of codes, models, and simulation tools for subsequent systems.
- Power block components will be configured to facilitate subsequent transportation to the Pilot Facility (e.g., as a skid-mounted unit).
- A natural gas fired heater with modular stacked heat exchangers that allow initial operation at 550°C and, later when qualified heat exchanger modules are available, increased operating temperature.

Beyond the facility-specific function, some considerations should be given to the pilot testing location. Site considerations include:

- Located where the surrounding R&D capability is accessible and supportive, including advance materials characterization and testing labs.
- In consideration of surrounding infrastructure a remote location is desired – for safety purposes until “certified” for pilot.
- NEPA ready (and other administrative processes such as air quality, construction permitting, biological surveys and fugitive dust permits, etc.).
- Access to natural gas line with sufficient capacity.
- Other necessary infrastructure includes: existing basic structures and open space to support development testing; emergency Services; offices, support labs.
- Capability to protect Commercial Proprietary technology as dictated by stakeholder agreements.

5. CONCLUSIONS

The paper defines the activities which justify technology readiness and proposes a path for development concluding with a commercial offering. This path includes testing activities and objectives and an expected transition from government to commercial funds. As noted in section 2, we propose that sCO2 Brayton technology is currently at TRL3 with technical risks that pose a great opportunity for collaboration. In order to facilitate more focused design and testing, a specific product should be chosen for pilot testing and commercial demonstration. Considering cost, component availability and ease of testing this should be the smallest cycle with a viable commercial market.

Brayton development is supported by the US Department of Energy Supercritical CO2 Tech Team [8] which recognizes the cross-cutting nature of this technology. Technology development is supported by a firm understanding of technical readiness and this can be accomplished in the form of sharing testing plans and results while still protecting proprietary information. The clear understanding of technical readiness then lays the base for developing a prioritized list of technical development risks and the collaborative plans to address these risks.

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APPENDIX A. AUTHOR BIOGRAPHY

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Lon A. Dawson
Principal Member of the Technical Staff
Sandia National Laboratories, Organization 6221 - Advanced Nuclear Concepts
ladawso@sandia.gov
(505) 844 – 5220 or (505) 270-7308 (mobile)
PO Box 5800 MS 1136
Albuquerque, NM 87185-1136

MS and BS in Chemical Engineering. Qualified Submarine Nuclear Engineering Officer by US Navy.

Expert in Project Management, Red Teaming. Process Development, Statistical Process Control, Ramp, Design of Experiment, Statistical Data Analysis, Model-based Problem Solving, Operations Strategy, Process metrology, feedback and control
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