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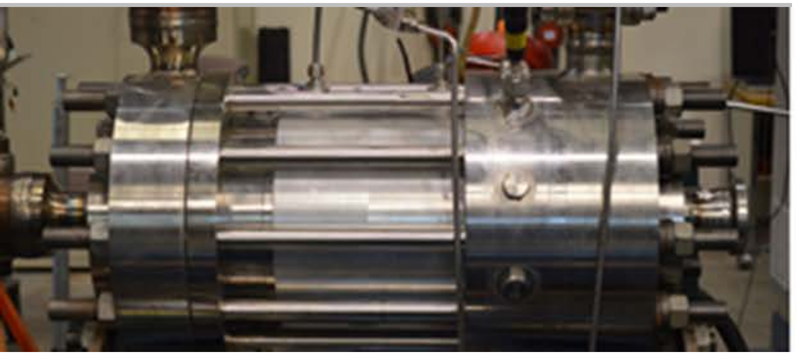
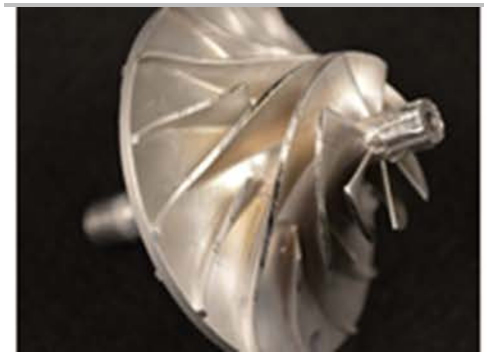


Demonstration testing and facility requirements for sCO2 Brayton Commercialization

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Topics

- Technology Readiness Levels Defined
- Proposed Testing Activities sCO2 Brayton
- Integrated Timeline for Commercialization
- Facility Considerations
- Recommendations

TRL Definition

- 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.
- TRLs are based on a scale from 1 to 9 with 9 being the most mature technology.

TRL Descriptions / Proposed Activities (1 of 6)

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 during TRL 1 work.	**Note that this is currently the TRL for some Brayton cycles and related components.**

Need to clarify cycle configuration and operating temperatures when discussing technology readiness!

TRL Descriptions / Proposed Activities (2 of 6)

Technology readiness level	Description	Proposed Testing Activities sCO2 Brayton
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].**

TRL Descriptions / Proposed Activities (3 of 6)

Technology readiness level	Description	Proposed Testing Activities sCO2 Brayton
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.

TRL Descriptions / Proposed Activities (4 of 6)

Technology readiness level	Description	Proposed Testing Activities sCO2 Brayton
5. Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system **configuration is similar to (matches) the final application in almost all respects**. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants and actual waste. Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.	Complete component testing using 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 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.).**

Note new definition, **application-specific product**

TRL Descriptions / Proposed Activities (5 of 6)

Technology readiness level	Description	Proposed Testing Activities sCO2 Brayton
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.**

TRL Descriptions / Proposed Activities (6 of 6)

Technology readiness level	Description	Proposed Testing Activities sCO2 Brayton
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. Supporting information includes operational procedures that are virtually complete. An operational readiness report has been successfully completed prior to the start of hot testing.	Complete installation and startup of an application-specific product, ready for commercial demonstration.
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**.

Note new definitions of a **Pilot Test** and **Commercial Demonstration**!

Key Testing Activities

- Materials (*critical for high temperatures*)
- **Manufacturing Readiness Assessment**
- Component Rig Testing
- 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
- Commercial Demonstration testing for longer duration tests operated by utility personnel.

Integrated Timeline for Commercialization

TRL	1	2	3	4	5	6	7	8	9
	Basic principles	Technology concept	Proof of concept	Validation lab	Validation field	Prototype	Prototype real environment	Qualified and tested	Operation

Research

Applied research and development

Pilot Testing

Commercial Demo

Model development, Validation, & benchmarking

Materials testing (corrosion, sCO2 purity, temps, etc.)

Component testing (Seals, etc.)

Manufacturing Readiness testing

Specify Product

Integration and Operations Testing in relevant environment at design conditions with specified configuration (prototype)

Complete System

Industry Pilot

Foundational Research

Component Development – Shared investment

Pilot testing, Investment shifts of industry

Facility Considerations for Pilot (1 of 2)

- 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*.

Facility Considerations for Pilot (2 of 2)

- 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 550C and, later when qualified heat exchanger modules are available, increased operating temperature.

Site Considerations

- 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*.

Conclusions

- Common terminology and goals will help clarify success.
- Developing sCO2 Brayton technologies is more than a disruptive component or technology it is a disruptive **ecosystem**.
- **All parties** are benefited by high-confidence TRL assessment - can be accomplished in the form of **testing plans and results** while protecting proprietary information.