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Phased Approach to Development of a High Temperature sCO2 Power Cycle Pilot Test Facility

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ABSTRACT

Supercritical CO_2 power cycles have the potential to achieve greater thermodynamic efficiency than current steam power cycles for source temperatures above 700C and in waste heat recovery applications where simpler steam cycles are currently used. Developing and commercializing these power cycles requires research and development programs and associated test facilities to systematically reduce the associated risks. Test facilities must grow in capability and complexity as technical risks are retired and ultimately reach peak temperatures above 700C and thermal conversion efficiency above current SOA steam power cycles. This paper describes a phased approach to test facility development that progresses in a stepwise manner from an initial configuration of a simple recuperated CO_2 Rankine cycle at 550C to a final configuration of a recompression Brayton cycle at 700C or greater. To insure the maximum component re-use the initial facility design must include a master plan for all phases of technology development ensuring a smooth transition between phases and hardware configurations. A detailed approach to facility design including definition of each phase along with associated hardware configuration and specific test goals is presented.

1. INTRODUCTION

CO_2 power cycles have potential efficiency, size, and cost benefits for several power generation applications resulting in substantial research activity. Applications for CO_2 power cycles can be roughly grouped into two categories: primary cycles with heat sources amenable to transferring all of the thermal energy within a narrow temperature band such as concentrated solar, nuclear, or coal fired fossil and bottoming or waste heat recovery cycles where the thermal energy is transferred into the power cycle over a wide temperature band as the exhaust stream from the topping cycle or thermal host cools. Maximum performance for these two different application categories require different CO2 power cycles with primary cycles achieving best performance with the recompression cycle or one of its variants and the bottoming cycles achieving best performance with a cascaded cycle or one of its variants. These cycles universally have turbine inlet conditions that are well above the critical point of CO_2 (31C and 7.3 MPa) but the minimum pressure and temperature in the cycles may be above or below the critical point depending on the ambient conditions and the cycle design

Angelino [1], [2] was one of the earliest researchers to recognize the potential for CO_2 cycle efficiencies to exceed steam cycle efficiencies at elevated turbine inlet temperature. He concluded that at turbine inlet temperatures above 650C a single heating partial condensation CO_2 cycle would exhibit a better efficiency than a reheat steam cycle with the same turbine inlet temperature. In the 1970's, Brown et al [3] studied closed loop CO_2 cycles along with other alternative energy conversion cycles and concluded that recompression CO_2 cycles had the potential to achieve plant efficiencies 4-5 points greater than contemporary state of the art steam cycles but with a capital cost estimated at three times greater than the steam cycle. In 1977, Combs [4] studied CO_2 cycles as an alternative to gas turbines for naval ship propulsion concluding that CO_2 cycles could provide a 25% reduction in fuel consumption although with an increase in powerplant size and weight. After a quarter of a century with no activity, in 2004 Dostal [5] rekindled interest in the CO_2 recompression cycle by showing the benefits of this cycle in an advanced nuclear power application. Since 2004 there has been widespread interest in CO_2 power cycles with hundreds of papers published by researchers from around the world. In 2015, Ahn et al [6] published a review article covering much of this work.

Several small scale cycle test loops for closed loop CO_2 power cycles are in operation or under construction. In the United States, Sandia National Laboratory [7] and the Bechtel Marine Propulsion Company [8] have constructed and operated test loops with output less than 1 MW. In Japan, the Japanese Institute of Applied Energy [9] has constructed and operated a kW scale test loop focused on compressor development. In Korea, the Korean Atomic Energy Research Institute is planning a power cycle test loop with a capacity less than 1 MW which was expected to begin operation in 2015 [6]. Two larger scale test facilities include the Echogen low temperature test of the EPS100 at Dresser Rand [10] and the SwRI/GE test facility [11] currently being constructed to test a scaled version of the 700C class turbine being developed under the SunShot program by GE and SwRI [12]. While there are several closed loop test facilities in operation around the world none has the combination of scale, temperature, and flexibility needed to push the next phase of cycle development. This paper describes a phased approach to developing the next generation of closed cycle CO_2 power cycle test facility to meet the needs of scale, maximum temperature and efficiency, and flexibility while managing cost and risk profiles.

2. APPLICATION SPACE

The application space for CO_2 power cycles can be visualized as a two-dimensional space denoted by plant output in MW on the abscissa and maximum cycle temperature on the ordinate as in Figure 1. The green shaded region underlying the entire space is the versatile incumbent steam cycle which has seen wide application in the past two centuries. The versatility, efficiency, and maturity of the steam cycle and the associated turbomachinery and other equipment pose a significant barrier to entry for new power cycle concepts such as closed loop sCO_2 Brayton cycles. With the exception of the dashed box for direct fired CO2 cycles all of the applications shown in this figure are for externally fired cycles where the primary heat input is transferred to the working fluid in a heat exchanger. The orange colored region in the lower left of Figure 1 indicates the application space for Organic Rankine Cycles (ORC) which have thermodynamic and economic benefits in the low temperature and smaller output region of the application space.

CO_2 cycles have several promising application spaces where they show benefits over the incumbent steam cycle. In the lower power Waste Heat Recovery (WHR) applications such as a bottoming cycle for an aeroderivative gas turbine where two-pressure non-reheat steam cycles are currently employed a cascaded closed loop CO_2 power cycle provides greater thermodynamic efficiency than the steam cycle or an ORC. This is shown by the blue region spaning approximately 5-50 MW and 350-550C in Figure 1.

Bottoming cycles for larger industrial gas turbines typically employ highly optimized three pressure reheat steam cycles which exceed the efficiency of the best CO_2 cycles [13] making the Heavy Duty Gas Turbine Combined Cycle (HDGT CC) a space where steam cycles will continue to be employed. CO_2 power cycles as a bottoming cycle for an aeroderivative represent the most likely initial commercial application of CO_2 power cycle technology.

For power cycles where the heat input comes directly from the primary source CO2 cycles exhibit higher thermodyanmic cycle efficiency relative to steam cycles when the maximum cycle temerpature exceeds 600-650C. For these cycles, a recompression cycle is used to maximize the average heat input temperature and therefore the cycle thermodynamic efficiency. These primary power cycles are represented by the blue regions on Figure 1 that span the temperature range above 600C. The US DOE SunShot initiative [14] has identified high efficiency CO2 power cycles as a potential enabler in their drive to reduce Concetrated Solar Power CSP electricity costs to below $0.06/kW-hr. Programs sponsored under the SunShot initiative have resulted in component designs [12] for turbomachinery and recuperators that could enable pilot plants to be constructed in the next 5-10 years. For fossil applications in the 100-1000MW range, CO2 cycles have a thermodynamic efficiency advantages compared to state of the art steam cycles at high turbine inlet temperatures above 650C. Due to the additional challenges associated with scaling to the larger output and integrating with a fossil boiler, implementation of these cycles is likely 10+ years in the future. Programs sponsored by DOE NETL are providing critical information about the scaling of turbomachinery for these cycles [15], [16].

Further in the future are applications of CO2 power cycles coupled to Gen 4 nuclear reactors. Also further in the future are direct fired oxy-combustion CO2 cycles which offer the potential for much higher turbine inlet temperatures and therefore higher cycle efficiencies. These two applications are shown in the dashed boxes on Figure 1.

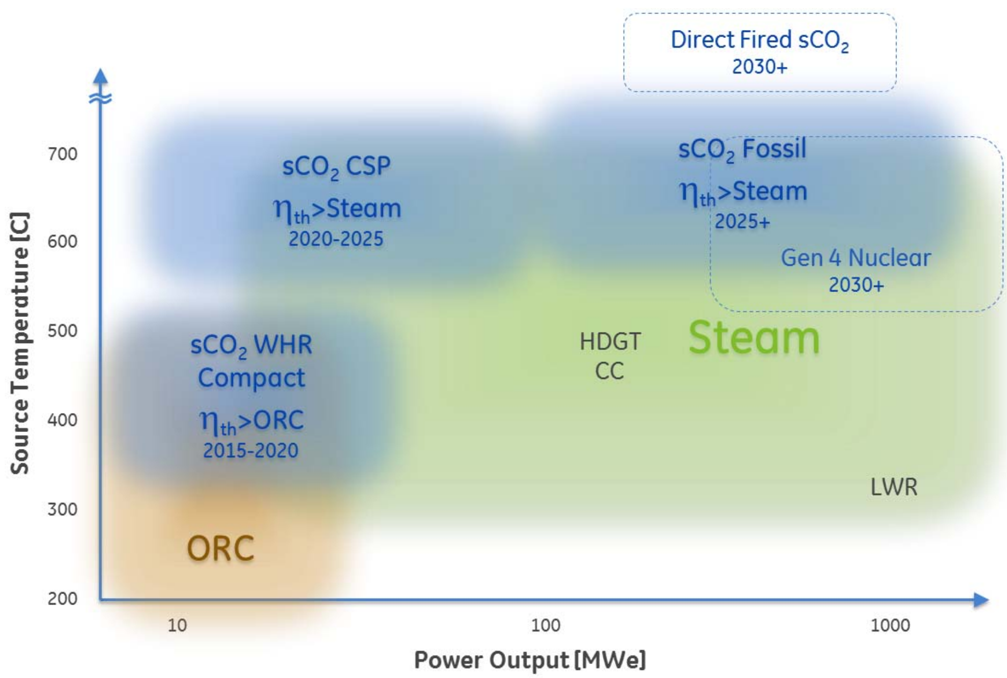

Figure 1 Application space for CO2 power cycles

3. TECHNOLOGY GAPS

Sienicki et al. [17] surveyed the state of the art in CO_2 cycle and component development in 2011 and determined that a 10 MWe scale demonstration and test facility could incorporate nearly all of the essential features of a commercial size power plant. This study was done in the context of a nuclear power cycle and does not address turbine inlet temperatures above 550C as a critical factor. Building on this work, an assessment of technology gaps as a function of turbine inlet temperature was performed to assess the readiness of the major power cycle equipment for a 10 MWe scale pilot facility and a 10-50 MWe scale demonstration plant. An initial assessment was done for a plant operating with a turbine inlet temperature of 550C with results shown in Figure 2. In this assessment, green color indicates minimal risk, yellow indicates a moderate risk, and red indicates a high risk. This assessment shows that the current level of technology readiness is sufficient to allow construction of a 10 MWe scale pilot facility at 550C. The learning from the pilot facility is needed to retire risks in performance of compressors near the critical point, recuperator and system modeling, starting, and controls before construction of a commercial demonstration plant.

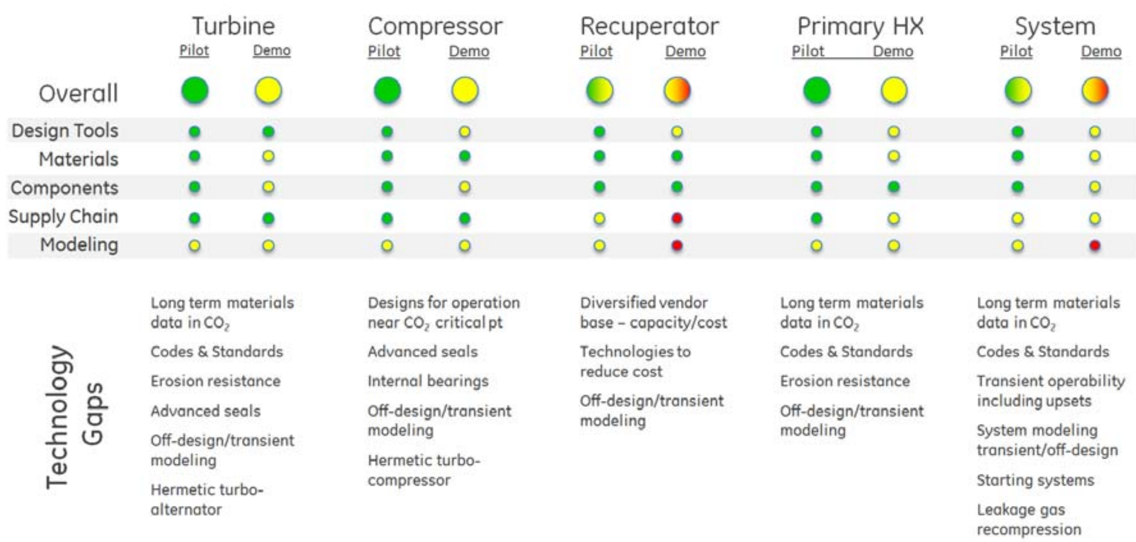

Figure 2 Technology gaps for 550C CO2 power cycles

Assessing the gaps for a 10 MWe scale pilot plant at 700C reveals several additional items that must be considered including availability of high temperature materials for primary heat exchanger and recuperator fabrication, designs for high temperature and pressure components including seals and valves, thermal management of temperature gradients in highly power dense turbines, furnace designs, and material properties. These results are shown for the near term pilot and longer term commercial demo in Figure 3. Extending a 700C power cycle from a pilot to a commercial demo will require additional long term experience with materials in a high temperature CO_2 environment to ensure life targets are met. By adopting the phased approach outlined in the next section, many of the key learning objectives for the facility can be addressed before introducing the additional risks for the high temperature pilot.

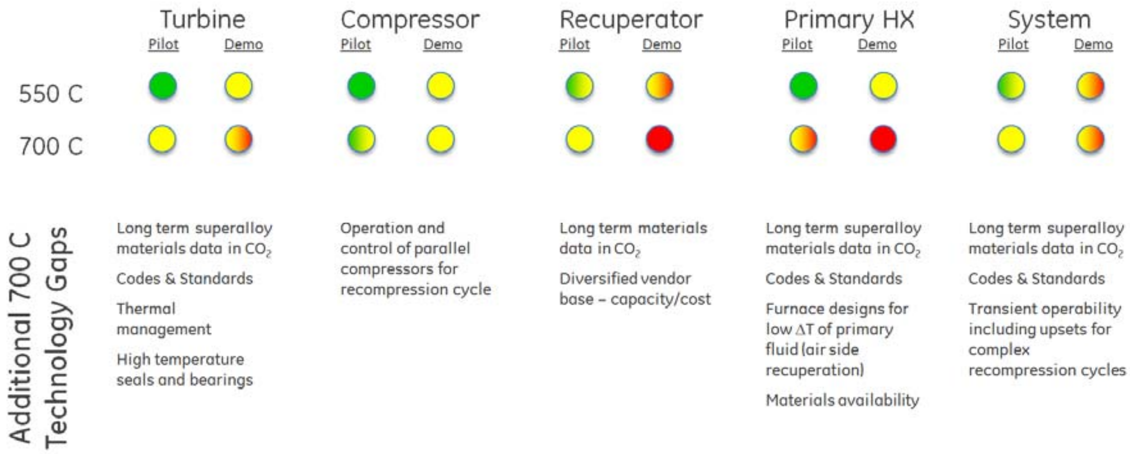

Figure 3 Technology gaps for 700C CO2 power cycles

4. TEST FACILITY APPROACH

A multi-phase test approach aimed at systematically reducing the risks associated with sCO2 power cycles while minimizing programmatic risk inherent in a pilot-scale test facility is proposed. The conceptual design of the test facility will reflect this approach to minimizing systematic and programmatic risks by establishing phased objectives that address specific technical risks while minimizing added complexity at each phase. In this manner, programmatic risk can be minimized by reducing unnecessary complexity at each step and using lessons learned from prior phases to address technical challenges and reduce uncertainties as the cycle and components move from a simplified cycle at lower temperature to a high efficiency recompression Brayton cycle at high temperatures. The technical phases are tied together by a master plan described here that considers the technical requirements and objectives of each phase as a continuous and smooth development towards the final recompression Brayton cycle configuration. This master plan ensures a smooth transition between phases and hardware configurations.

Based on current technology gaps and past evaluation of sCO2 cycles, the facility will progress in a stepwise manner from an initial configuration of a simple recuperated Rankine cycle at 550 °C, shown in Figure 4, to a more complex cycle configuration in a cascaded Brayton cycle at 550 °C suitable for waste heat recovery, shown in Figure 5, to a final configuration of a recompression Brayton cycle at greater than 700 °C, shown in Figure 6, which is anticipated to achieve a thermal efficiency above 50%, exceeding state-of-the-art, externally-fired steam power cycles.

Phase 1: Recuperated Simple Cycle

The phased cycle configurations address specific technical risks at each stage. The simple recuperated sCO_2 Rankine cycle with turbine inlet temperature up to 550 °C incorporates a single motor-driven compressor, recuperator, and single turbine connected to a load bank. Shown schematically in Figure 4, this configuration represents the least complex full sCO_2 power cycle incorporating all major components allowing for development and calibration of control strategies. Test objectives for this simple cycle configuration include:

1. Demonstrate basic operation and control of a simple recuperated sCO_2 Brayton power cycle producing greater than 5 MWe.

2. Implement and test an automated control system for the safe and predictable operation of the basic Brayton cycle through normal operating transients and simulated emergency transients.
3. Obtain component performance data for sCO_2 expander, recuperator, primary heater, and compressor over a range of operating conditions to validate component performance predictions.
4. Obtain cycle performance data to validate steady state and dynamic models and performance predictions.

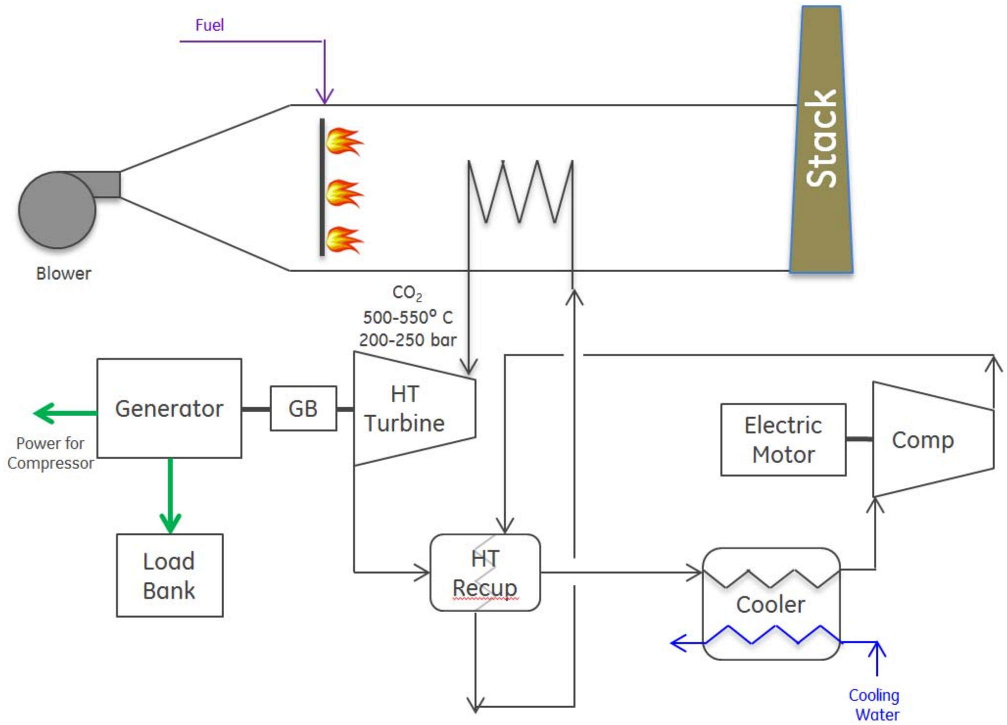

Figure 4 Simple Recuperated Cycle

Phase 2: Cascaded Cycle

Extending the baseline simple recuperated cycle to a cascaded cycle by adding a low temperature recuperator, compressor, and turbine, the cascaded cycle would be operated with turbine inlet temperature up to 550 °C. Adding a second turbine and compressor as shown with heavy lines in Figure 5 allows continued development of control strategies involving multiple turbo-machines. Cycle configurations of this type apply directly to commercial WHR applications. Inclusion of a cascaded cycle variant in the test approach provides needed risk reduction to enable construction of a commercial plant of this type that will provide critical long-term operating data for a CO_2 power cycle. Specific goals for the cascaded configuration include:

1. Test operation and control of a complex cascaded cycle including multiple expanders, recuperators, and compressors producing greater than 8 MWe. Repeat goals 2-4 for the complex cycle.
2. Test compressor operability and obtain performance data over a wide range of ambient conditions including trans-critical operation. Exercise compressor variable geometry.
3. Test inventory management system for closed-loop Brayton cycle including part load operation and starting transients.

4. Use electrical coupling of generators and compressor drive motor to simulate single-shaft and multi-shaft operation including part-load operation and starting transients.

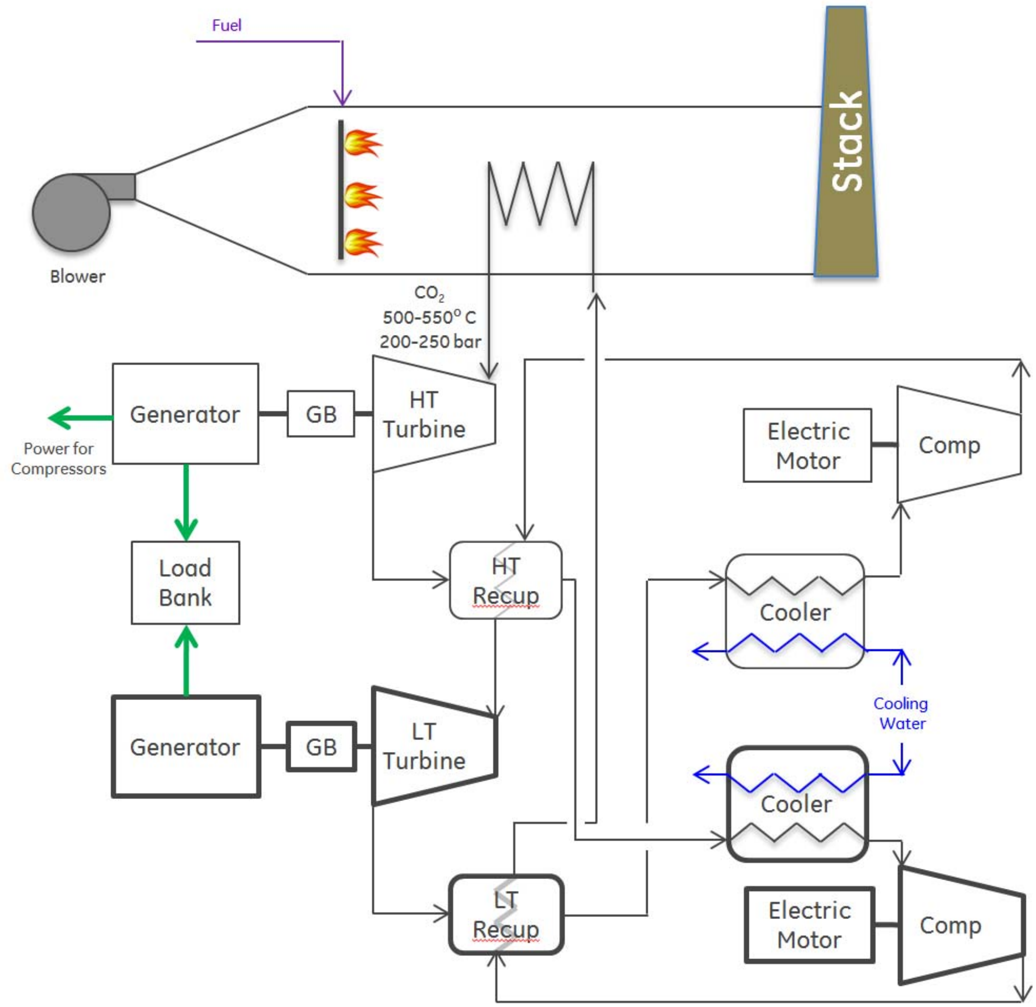

Figure 5 Cascaded Cycle

Phase 3: Recompression Brayton Cycle

Phase 3 of the test facility would reconfigure the cycle to a recompression cycle with a single turbine connected to a load bank and two parallel compressors. This phase would add high-temperature capability to the primary heater, turbine, valves, and recuperator, and increase the turbine inlet temperature to 700 - 750 °C while increasing the temperature of the flow returning to the primary heater to maximize heat input temperature. The recompression cycle provides maximum thermodynamic efficiency for constant temperature heat sources including nuclear, coal, and concentrated solar. Upgrading the highest temperature parts of the cycle, highlighted in red in Figure 6 to allow for temperatures above 700 °C, permits this cycle configuration to demonstrate thermal cycle efficiencies above state-of-the-art steam plants. Specific goals for the recompression cycle in phase 3 of the research program include:

1. Demonstrate safe component operation, controllability, and performance of highly complex recompression cycle with high inlet temperature producing greater than 10 MWe. Repeat goals 2-4 from Phase 1.

2. Perform detailed exploration of parallel compressor operation over a wide range of power cycle and ambient conditions including trans-critical operation of the main compressor. Develop control schemes for parallel compressor operation including scheduling of variable geometry and optimization of fixed vs variable speed operation.
3. Achieve overall cycle performance for high temperature recompression cycle of greater than 50% thermal to electric conversion efficiency.

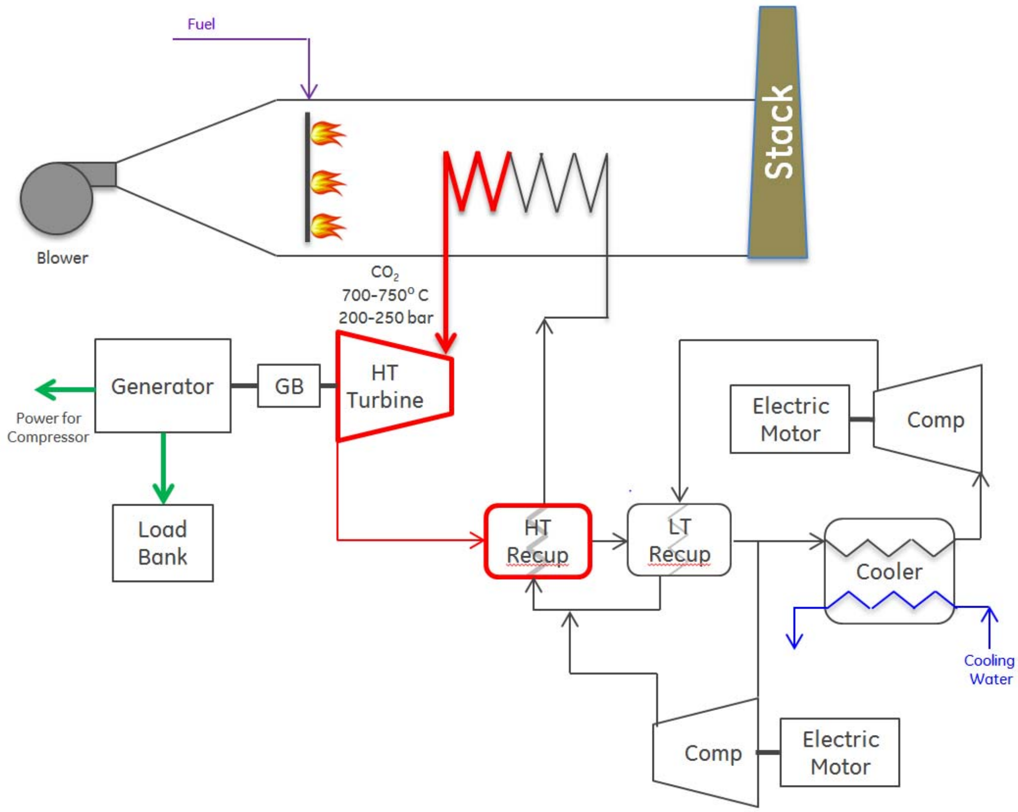

Figure 6 Recompression Cycle

5. ECONOMIC VIABILITY OF THE PHASED APPROACH

To achieve the progressively staged risk reduction targets described in the preceding section at the minimum possible cost a strategy of component re-use is proposed. This strategy includes both re-use between phases and re-use of component designs developed on DOE funded projects including the turbine developed by GE and Southwest Research Institute for the SunShot program and the compressor being developed by GE and Southwest Research Institute for the SunShot Apollo program. This re-use strategy enables the complete phased test program to be completed with major hardware costs similar to those of completing only a high temperature cycle demonstration test and provides significantly better management of cost and risk profiles.

Due to the challenging objective of demonstrating SOA component efficiencies and overall cycle efficiency greater than 50% in phase 3, all components will be optimized for performance in this cycle and then reapplied at moderately off-design conditions in the earlier phases where risk reduction objectives do not require peak performance. A summary showing all of the major components, their design basis, and which phase of the test program is used to set their optimal design point is shown in

Table 1. In anticipation of this type of system demonstration, the turbine designed for SunShot and the compressor designed for Apollo have been optimized to perform together in the phase 3 cycle configuration. This pre-planned coordination in the design of these components will allow for re-use of the drawings and manufacturing methods developed in the earlier programs thus saving substantial design cost for the overall test facility.

Component	Design Basis	Phase 1	Phase 2	Phase 3
High Temperature Turbine	SunShot	○	○	●
Main Compressor	Apollo	○	○	●
Bypass Compressor	GE Product Line			●
Re-bladed Bypass Compressor	Apollo/GE Prod Line		●	
Low Temperature Turbine	SunShot		●	
Primary Heater	Vendor	○	○	●
High Temperature Recuperator	Vendor	○	○	●
Low Temperature Recuperator	Vendor	○	○	●
Heat Rejection Cooler	Vendor	○	○	●

● = Optimized ○ = Re-used off design

Table 1 Component Re-use Strategy

6. SUMMARY AND CONCLUSIONS

Closed loop CO_2 power cycles have potential for improved efficiency relative to steam cycles in a variety of applications. The nearest term application is a cascaded CO_2 cycle as a bottoming cycle for aeroderivative gas turbines and this application will provide needed long term experience with CO_2 cycles. The global research community has built and operated several small scale test loops demonstrating the overall feasibility of CO_2 power cycles but none of these existing loops has sufficient scale to demonstrate technologies needed for utility scale applications. Previous studies showing that a 10 MWe facility is sufficient to evaluate utility scale turbomachinery have been confirmed and this size facility selected. Technology gap analysis shows acceptable risks for construction of a 10 MWe test facility at 550C and moderate risks for construction of a 10 MWe facility at 700+C. To meet the multiple objectives of providing data quickly, demonstrating cascaded cycles for WHR to accelerate commercialization, achieving high temperature operation with cycle efficiency above current SOA, and managing cost and risk profiles a test facility with three distinct phases of facility configuration and testing is proposed. This paper provides a master plan connecting the three phases in a way that allows for re-use of major cycle components while maintaining a design optimized to demonstrate peak performance in the high temperature recompression configuration. Through a combination of component reuse and utilizing turbine and compressor designs developed on previous programs the total cost of the multi-phase test program can be kept competitive with a single high temperature test program without the benefit of pre-existing designs.

REFERENCES

[1] G. Angelino, "Perspectives for the Liquid Phase Compression Gas Turbine," *Journal of Engineering for Power*, volume 89, April 1967.

[2] G. Angelino, "Carbon Dioxide condensation cycles for power production," ASME Paper 68-GT-23, *Journal of Engineering for Power*, volume 90, July 1968.

[3] D. H. Brown, J.C. Corman, R.B. Fleming, "Energy Conversion Alternatives Study, ECAS, General Electric Phase 1 Final Report, Volume II Advanced Energy Conversion Systems, Part 2 Closed Turbine Cycles, NASA-CR 134948, February 1976.

[4] O. V. Combs, "An Investigation o fthe Supercritical CO_2 Cycle (Feher Cycle) for Shipboard Application," MS Thesis, MIT, May 1977.

[5] V. Dostal, M. Driscoll, P. Hejzlar, "A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors," MIT-ANP-TR-100, The MIT Center for Advanced Nuclear Energy Systems, March 2004.

[6] Yoonhan Ahn, et al, "Review of Supercritical CO2 Power Cycle Technology and Current Status of Research and Development," Nuclear Engineering Technology, 42, 647-661, 2015.

[7] T. Conboy, S. Wright, J Pasch, D Fleming, G Rochau, R Fuller, "Performance Characteristics of an Operating Supercritical CO2 Brayton Cycle," *J. Eng. for Gas Turbines and Power*, vol. 134, November 2012.

[8] E. M. Clementoni, T. L. Cox and C. P. Sprague, "Startup and Operation of a Supercritical Carbon Dioxide Brayton Cycle," *J. Eng. for Gas Turbines and Power,* vol. 136, p. 071701, 2014.

[9] Motoaki Utamura, et al, " DEMONSTRATION OF SUPERCRITICAL CO2 CLOSED REGENERATIVE BRAYTON CYCLE IN A BENCH SCALE EXPERIMENT," GT2012-68697, 2012.

[10] Timothy J. Held, "Initial Test Results of a MegaWatt-Class Supercritical CO_2 Heat Engine," in *4th International sCO_2 Power Cycles Symposium*, Pittsburgh, PA, 2014.

[11] Jeff Moore, et al, "Development of a 1 MWe Supercritical CO_2 Brayton Cycle Test Loop," in *4th International sCO_2 Power Cycles Symposium*, Pittsburgh, PA, 2014.

[12] C. Kalra, D. Hofer, E. Sevincer, J. Moore and K. Brun, "Development of High Efficiency Hot Gas Turbo-expander for Optimized CSP sCO2 Power Block Operation," in *4th International sCO_2 Power Cycles Symposium*, Pittsburgh, PA, 2014.

[13] P. Huck, S. Freund, M. Lehar, M. Peter, "Performance comparison of supercritical CO2 versus steam bottoming cycles for gas turbine combined cycle applications," in *The 5th International Symposium - Supercritical CO_2 Power Cycles*, San Antonio, TX, 2016.

[14] http://energy.gov/eere/sunshot/concentrating-solar-power

[15] R. A. Bidkar, G. Musgrove, M. Day, C. D. Kulhanek, T. Allison, A. M. Peter, D. Hofer and J. Moore, "Conceptual Designs of 50MWe-450MWe Supercritical CO_2 Turbomachinery Trains for Power Generation from Coal. Part 2: Compressors," in *The 5th International Symposium - Supercritical CO_2 Power Cycles*, San Antonio, TX, 2016.

[16] R. A. Bidkar, G. Musgrove, M. Day, C. D. Kulhanek, T. Allison, A. M. Peter, D. Hofer and J. Moore, "Conceptual Designs of 50MWe-450MWe Supercritical CO_2 Turbomachinery Trains for Power Generation from Coal. Part 2: Compressors," in *The 5th International Symposium - Supercritical CO_2 Power Cycles*, San Antonio, TX, 2016.

[17] J. J. Sienicki, A. Moisseytsev, R. L. Fuller, S. A. Wright and P. S. Pickard, "Scale Dependencies of Supercritical Carbon Dioxide Brayton Cycle Technologies and the Optimal Size for a Next-Step Supercritical CO2 Cycle Demonstration," in *Supercritical CO_2 Power Cycle Symposium*, Boulder, CO, 2011.

AUTHOR BIOGRAPHY

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