SAND2016-6214B

15.2 SNL Recompression Loop

15.2.1 System Description

The recompression configuration has long been recognized to complement closed cycle heat sources, such as nuclear reactors and solar thermal energy fields, because of the extensive heat recovery from the turbine exhaust prior to heat rejection that the cycle achieves. Depending on operating conditions and heat exchanger performance, 60 – 70% of working fluid heating comes from cycle internal heat recuperation, with the remaining 30 – 40% of heat addition provided by an external source. An important consequence of extensive recuperation is that the sCO2 enters the heat source heat exchanger at a high temperature, and thus extracts a relatively small portion of the external heating fluid thermal energy which results in a gross inefficiency in fuel usage for open heat source applications that exhaust the effluent. However, for closed heat source cycles, particularly nuclear reactors, this consequence is highly beneficial. The benefits of this significant degree of recuperation, and other benefits discussed elsewhere (such as reduced compression work), lead to predicted thermal conversion efficiencies on the order of 50% for turbine inlet temperatures around 700 °C and reasonable assumptions of various component performances.

To capitalize on this impressively high theoretical performance, the DOE Office of Nuclear Energy, Advanced Reactors Program established a supercritical carbon-dioxide (S-CO2) recompression closed Brayton cycle (RCBC) to investigate the key technical issues for this power cycle and to confirm model estimates of system performance. For this purpose, the derivative objectives of the Brayton Turbomachinery program are to demonstrate cycle performance and controllability, develop various control algorithms, demonstrate understanding of the relevant physics, baseline computer models, and to serve as a reliable development platform for future technology development programs. Component and system design studies for this effort were performed by both Sandia and Barber-Nichols Incorporated (BNI) to develop the specifications and component designs for the S-CO2 compression and Brayton cycle test loops. From these studies, and with consideration of available resources, an operational design point was established, which included rotor shaft speed of 75,000 rpm, turbine inlet temperature of 538 °C, a pressure ratio of 1.8, and maximum alternator power output of 125 kWe per TAC. All turbomachinery are radial designs. Main compressor design inlet conditions are 7.69 MPa and 32.2 °C, with an isentropic efficiency of 66.5%, mass flow rate of 3.67 kg/s and discharge pressure of 13.8 MPa. The recompressor design inlet conditions are 7.79 MPa and 59.4 °C, with an isentropic efficiency of 70.1%, mass flow rate of 2.27 kg/s, and a discharge pressure of 13.7 MPa. The slightly higher main compressor discharge pressure is necessary to accommodate pressure loss through the low temperature recuperator prior to combining with the recompressor discharge. Both turbines are very similar in design, with the recompressor turbine flow area slightly enlarged to process 53.5% of the flow to partially offset the greater work demanded of the recompressor. Both turbines are designed to operate at approximately 85% isentropic efficiency.

The nuclear reactor heat source is simulated with a bank of electrical immersion heaters which supply up to 780 kW of heat into the power conversion cycle. This heating system has very good response to changes in commanded heat input. The high and low temperature recuperators are both printed circuit heat exchangers (PCHE), with design point duties of 2.2 and 0.6 MW (the low temperature recuperator is designed for 1.6 MW duty for simple cycle testing, but is only required to provide 0.6 MW duty in recompression configuration). Heat rejection is accomplished with a water cooled PCHE with a design duty of 0.5 MW. Because of the small size of the turbomachinery and the high rotational speed, it was determined that labyrinth seals were needed, the flow through which would serve as the lubricant for gas foil thrust and journal bearings. All piping is 3 inch schedule 160 except those portions between the low temperature recuperator low pressure discharge flow to both compressor inlets, andthe discharge of both compressors to their next major components, which are 2 inch schedule 160.

An engineering scale version of the cycle and TACs, with performance conditions described above, was designed and built in collaboration with Barber-Nichols, Inc., during the same period that BMPC was working with BNI to develop their CBC for marine propulsion applications. Extensive collaboration between SNL and BMPC during this time period reduced the risk for both programs, and the resulting high degree of commonality between the two testing platforms afforded continued collaborations throughout the duration of their respective programs. The resulting cycle layout, TAC cross section, and testing facility at SNL are presented in the following three figures.

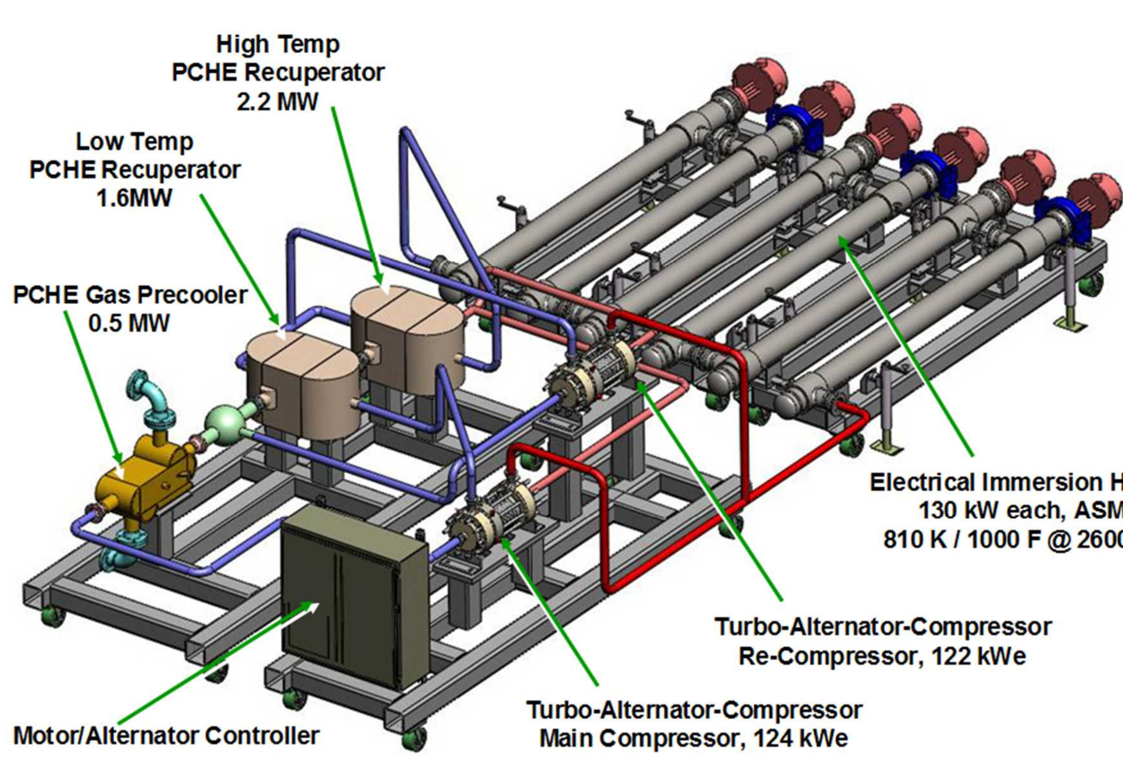


Figure 1: Sandia National Laboratories recompression closed Brayton cycle configuration.

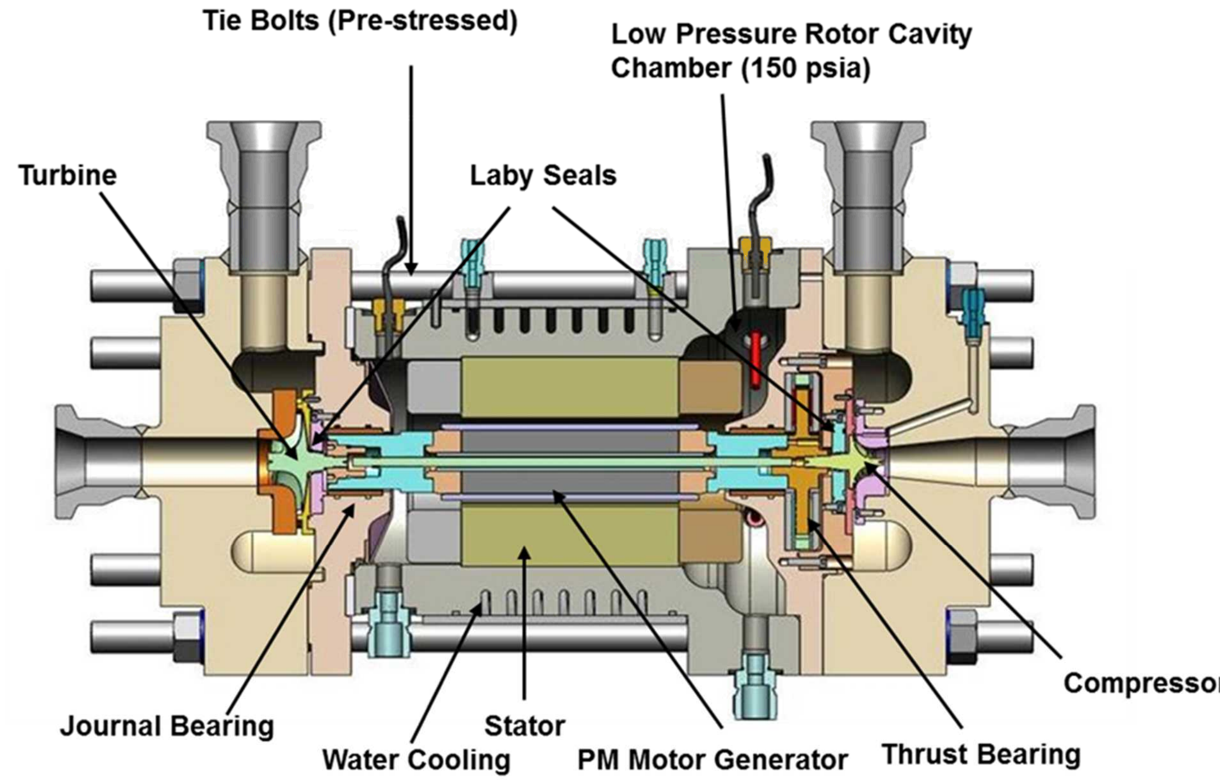
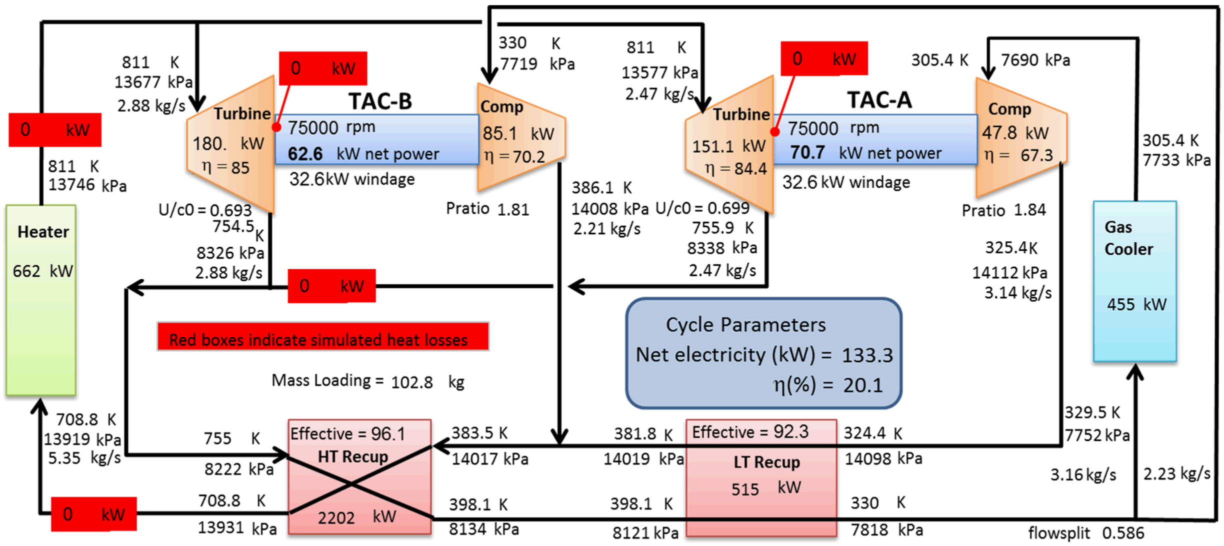


Figure 2: Sandia National Laboratories turbo-alternator-compressor cross section.

Figure 3: Sandia National Laboratories recompression closed Brayton cycle testing platform.

Extensive testing has generated data that have allowed for thorough component performance characterizations and subsequent model baselining since the original system design and performance predictions. The understanding of the two key operational effects of momentum loss throughout piping and components and windage (frictional) losses between the leaked CO2 and the rotor has improved significantly. Actual performance of the recuperators has also been used to baseline predictions of these major components. Turbomachinery has been found to perform close to predictions (as will be discussed shortly). The flow sheet for the SNL RCBC operating at the design point is presented in the figure below. In this, it is seen that some state points and component performances are slightly different than in the original design. These differences are primarily the result of differences in original predictions and actual pressure loss.



15.2.2 Key Test Results and Conclusions

Fluid velocity at the turbine must be greater than turbine blade velocity at the inlet for the device to act as a turbine and generate power. The velocity triangle can be applied to predictthe combination of fluid conditions and turbine speed necessary to establish positive turbine power. Only when the ratio of turbine tangential blade speed to fluid tangential speed is less than unity can the turbine generate power. Experience with TAC operation revealed that conditions with the ratio greater than unity will cause the fluid to churn at the turbine, thus impeding proper fluid flow around the closed circuit. During startup operations from a cold condition, this effect was found to complicate system ramp-up operations by preventing fluid circulation and heat-up. The solution applied a turbine bypass circuit that remained open to allow the fluid to circulate and be heated over a period of minutes. Once the calculated speed ratio was below unity, a valve in the bypass line was closed to direct flow through the turbines. There are certainly alternatives to this solution, such as preheating the fluid prior to startup.

The unique design feature of the recompression cycle has two compressors operating in parallel, with flow streams at different thermodynamic conditions and different flow rates. Experience with the SNL RCBC has demonstrated the difficulty of this operation, particularly with the thermodynamic state of the main compressor flow stream in the vicinity of the critical point. The fundamental requirement of operating in this configuration is the equality of pressures of the two separate flow streams at the point of splitting, and then at the point of combining. Thermodynamic conditions and compressor performance capabilities may preclude a solution that generates equal compressor discharge pressures at the point of combining. Under these conditions, the compressors are susceptible to surge and stall, leading to possible damage. Numerous tests with the main compressor and the recompressor exhibited oscillating flow conditions, as one compressor would overpower the other through. Similar tests with the main compressor replaced with a recompressor, so that both compressors used the recompressor design, have demonstrated significantly improved stability, though caution is still necessary to maintain both compressors simultaneously in safe operating conditions. These test results indicate that design of both compressors should consider stable operating performance over a broad range of thermodynamic and rotordynamic conditions.

A primary benefit of operating a CBC with sCO2 near the critical point is the reduced power of compression relative to gases far removed from their critical points. This benefit could not be realized in the original CBCs that used air as the working fluid since its critical temperature is -141 °C, compared to 31 °C for carbon dioxide. However, this benefit comes at the cost of increased variability in thermodynamic properties with respect to temperature, particularly density. This increased sensitivity to small changes in temperature causes rapid changes in compressor fluid conditions that have been found to complicate operations, particularly with parallel compression. Testing at SNL has revealed the degree to which heat rejection must be controlled to maintain stable conditions at the compressor. Significant effort has been invested in responding to variable environmental conditions, which are exacerbated by changing control actions in summer and winter months. With an evaporative cooler used for heat rejection with the SNL RCBC, even the effects of clouds shading the cooler can be seen in the system operational data.

One of the greatest unknowns going into this research program was the applicability of standard turbomachinery design practices to a working fluid that had very little, if any, relevant history in such cycles. Compression was less of an unknown, with the gas and oil industry commonly performing CO2 compression, albeit not commonly in the immediate vicinity of the critical point. The turbine, however, was recognized as a larger unknown for the even greater dearth of relevant operational information. Thus, demonstrating the applicability of long-established turbomachinery design practices to this new combination of cycle and fluid was a primary objective. Measurements taken during dedicated compressor testing throughout the thermodynamic vicinity of the critical point have consistently shown agreement between predicted and actual performance. Measurements for similar comparisons of turbine performance have also shown excellent agreement. At the time of this writing, the available data are insufficient to establish the technology readiness level of turbomachinery above component validation in a laboratory environment (TRL 4). Thus, more work is necessary to build confidence in the design tools for commercial scale systems, though the risk is deemed relatively low given the successes with the SNL system.

One of the greatest challenges to surface during operation relates to materials. Significant turbine and turbine inlet nozzle erosion has occurred repeatedly throughout the program, even under conditions of relatively light usage. Component degradation has only been observed at this point, where conditions are most extreme. Fluid temperatures and pressures are at the maxima. Due to the inherent design of turbines and inlet nozzles, flow velocity is also at maximum, at roughly half the speed of sound at that point. Efforts to capture or otherwise observe abrasive materials in the fluid have been unsuccessful to date. An aggressive root cause analysis program is underway to resolve the issue. The turbomachinery of the old air CBCs proved to be impressively wear-proof and long-lived, and this degree of operational reliability is necessary for the new age of sCO2 CBCs.

Operating the SNL RCBC has generated data that show the system performs as expected. The RCBC has operated stably over a range of relevant thermodynamic conditions. The main compressor has operated numerous times at inlet conditions that are two-phase and remained stable. Additionally, no detrimental effects to the compressor hardware have occurred due to this two-phase operation. Fluid additives have been added to the CO2 in small quantities to assess the effects on fluid and compressor performance. From these tests, it has been observed that the critical point of the working fluid can be significantly manipulated in this way, thus opening the possibility of chemically tailoring the working fluid to match the local environment. Standard power transients such as ramp-up from cold and hot restarts, and ramp-down are routinely completed without difficulty. More aggressive transients, such as instantaneous large changes in heat input (to simulate solar heating transients) and heat rejection, have also been completed with acceptable, safe, and controllable response from the cycle.

Results from the various tests conducted with the SNL RCBC system and components support the conclusion that the RCBC is a viable power conversion system. Data show that the components with greatest uncertainty in technology maturation do indeed perform as designed, giving credence to the belief that standard turbomachinery design techniques apply to this new combination of cycle and working fluid. The integrated RCBC system has operated stably and reliably under many speed and thermodynamic conditions. While technological challenges remain to be researched and resolved, there is every indication that the remaining issues will indeed be overcome.