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Supercritical CO_2 Recompression Brayton Cycle: Completed Assembly Description

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Abstract

Through multi-year funding from DOE-NE, Sandia National Labs supercritical carbon dioxide (SCO2) closed Brayton cycle (CBC) research and development team have recently overseen the completion of the SCO2 CBC recompression test assembly (TA), and delivery from the development contractor's facility to Sandia, Albuquerque. The primary components of the completed TA include two turbo-alternator-compressors and associated motor/controllers, three printed circuit heat exchangers, and six shell-and-tube heaters and associated controllers. Principal supporting components include a cooling tower, electricity-dissipating load bank, and leakage flow management equipment. With this milestone completed, significant increase in CBC R&D is anticipated with the objective of advancing the technology readiness level of components seen by industry as immature. This report presents detailed descriptions of all components and operating software necessary to operate the recompression CBC.

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EXECUTIVE SUMMARY

Supercritical CO_2 (S-CO_2) power plants[1] offer the potential for better economics because of their small size, use of standard materials, and improved electrical-power-conversion efficiency at modest temperature (400–750°C). Sandia National Laboratories (SNL or Sandia) and the U.S. Department of Energy Office of Nuclear Energy (DOE-NE) have operated a S-CO_2 Brayton cycle power system that has been located at Sandia contractor Barber-Nichols Inc. in Arvada, Colorado, since the program's inception. This system is one of the first S-CO_2 power-producing Brayton cycles operating in the world. The original design was recently completed and moved from Barber-Nichols' facility to Sandia. This report provides a summary description of the completed design and delivered hardware. The content of this report is intended for unlimited distribution. A subsequent version of this report with extensive details of the test assembly will be published with limited distribution.

[1] Dostal, V. Driscoll, M., and Hejzlar, P. "A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors," MIT-ANP-TR-100, March 2004.

NOMENCLATURE

ASME	American Society of Mechanical Engineers
BNI	Barber-Nichols Inc.
DOE-NE	U.S. Department of Energy Office of Nuclear Energy
FEA	finite-element analysis
GUI	graphical user interface
HT	high-temperature
LDRD	Laboratory Directed Research and Development
LT	low-temperature
MAWP	maximum allowable working pressure
MGC	motor generator controller
OSR	overspeed resistor
PCHE	printed circuit heat exchanger
R&D	research and development
RTD	resistive thermocouple devices
S-CO_2	supercritical CO_2
TA	Test Assembly
TAC	turbo-alternator-compressor

1 INTRODUCTION

The DOE Advanced Reactors Program has developed a megawatt class supercritical carbon-dioxide (S-CO_2) Brayton cycle Test Assembly (TA) to investigate the key technical issues for this power cycle and to confirm model estimates of system performance. The development process has spanned numerous years as a consequence of incremental funding. The final design was recently realized in April 2012 with the installation of the final two of six heaters, the replacement of 1.5-in. diameter piping with 3-in. piping on the hot-flow sections, the replacement of low-temperature limit seals with seals rated for the design temperature of 811 K (1000°F), the installation of overspeed resistors (OSRs), and the installation of additional CO_2 inventory expansion volume tanks. This report provides a description of the final design, as delivered from Sandia National Laboratories' (Sandia or SNL) contractor Barber-Nichols Inc. (BNI) [1] facilities in Arvada, Colorado, to Sandia's Building 6630 in Albuquerque, New Mexico. Where relevant, comparisons of delivered hardware capabilities to the original design objectives are presented.

A schematic of the split-flow heated recuperated Brayton TA, which was used for the final testing at BNI in this report period, is shown in Figure 1-1. The image depicts the loop as it existed during testing in March and April 2012. With the latest upgrades, the TA can achieve the original design heat input of 780 kW with reduced momentum losses in the hot-flow sections.

The focus of the testing in this reporting period was to expand the envelope of operating experience, and, most recently, to verify contractual performance following the final upgrades. Verification at the contractor's facility was limited in scope for several reasons. Most importantly, the speed requirement of 75,000 rpm had not yet been achieved because of a consistently conservative approach to testing that was intentionally used to avoid damaging the hardware. As a result of both this approach and the incremental nature of the TA development, operating experience did not advanced to the point of confidently testing the split-flow TA to the primary design conditions until immediately prior to TA disassembly for transport to Sandia, which limited the available operating conditions. Regardless, the conservative testing philosophy made it highly unlikely that the speed, temperature, and pressure design operating conditions would have been selected as a test objective. Instead, the 811 K (1000°F) requirement was selected for verification, leaving the remaining requirements to be verified using nonoperational data or operational data following delivery.

Although the objective of this report is not to present test results, some results from this reporting period are worthy of mention. Testing in October 2011 expanded the experience envelope for split-flow operating temperatures and speeds, which approached 644 K (700°F) (the maximum limit at that time resulting from low-temperature seals) and 59,000 rpm, respectively. Thermal growth of the recompressor (turbo-alternator-compressor B or TAC-B) rotor shaft caused its turbine wheel to rub into its shroud. Although this necessitated repairs, the data obtained has unprecedented value for comparing with model predictions, evaluating turbomachinery performance maps, assessing recuperator performance, and quantifying certain thermal and efficiency losses.

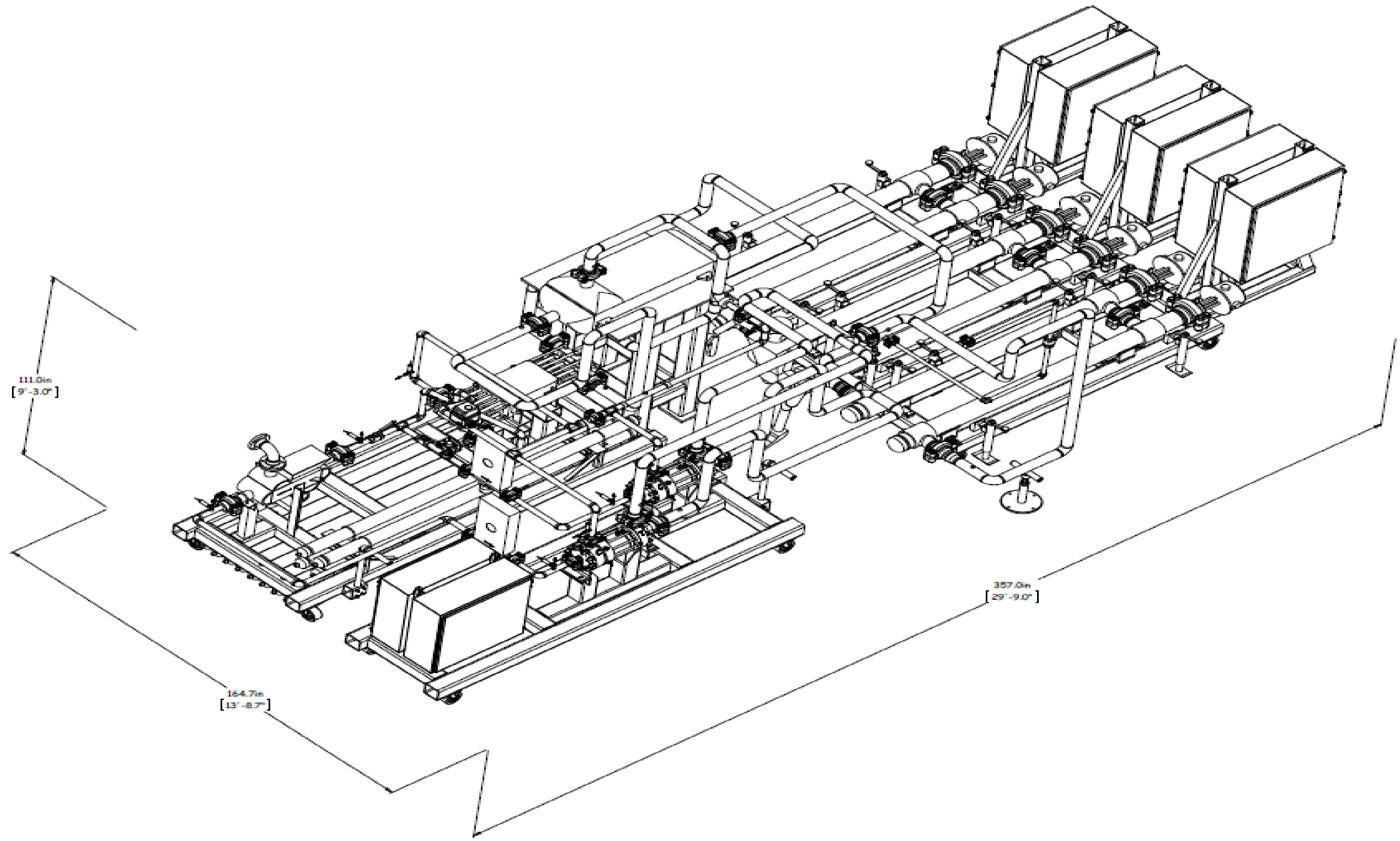

Figure 1-1. Schematic of the delivered S-CO_2 split-flow TA.

Testing in April 2012 resulted in the production of net power by both TACs simultaneously for the first time in this program, and, likely, the first time in the world. At one point during the test, the TAC-B produced 10 kW of power and the main compressor (TAC-A) produced 2 kW. Although cycle efficiency and total power production were far below optimum, this represented a major achievement and contributed to the validation of the basic technical premise of the split-flow design. However, much operational investigation remains to be completed to achieve results that will persuade industry to invest in this technology.

During the April 2012 testing, two tests were completed that extended the high-temperature experience with the TA to approximately 672 K (750°F). A third test was stopped before achieving 811 K (1000°F) as a result of high bearing temperatures. Verifying the safe operation at the design temperature will take place after reassembly at the Sandia location.

The focus of the next phase of testing at Sandia will be to replicate the latest tests performed at BNI and compare the results from the two sets of tests. The goal will be to establish the relocated TA at a performance level at least as high as at BNI, and to understand any observed differences in the results. Subsequent research will focus on continuing to push the operating limits, quantifying the system and subsystem performance, determining various sources of losses, and selectively reducing these losses to achieve the performance necessary to prove the technology to private industry. A constant objective for the remainder of this project will be to achieve the original design performance, as presented in Figure 1-2.

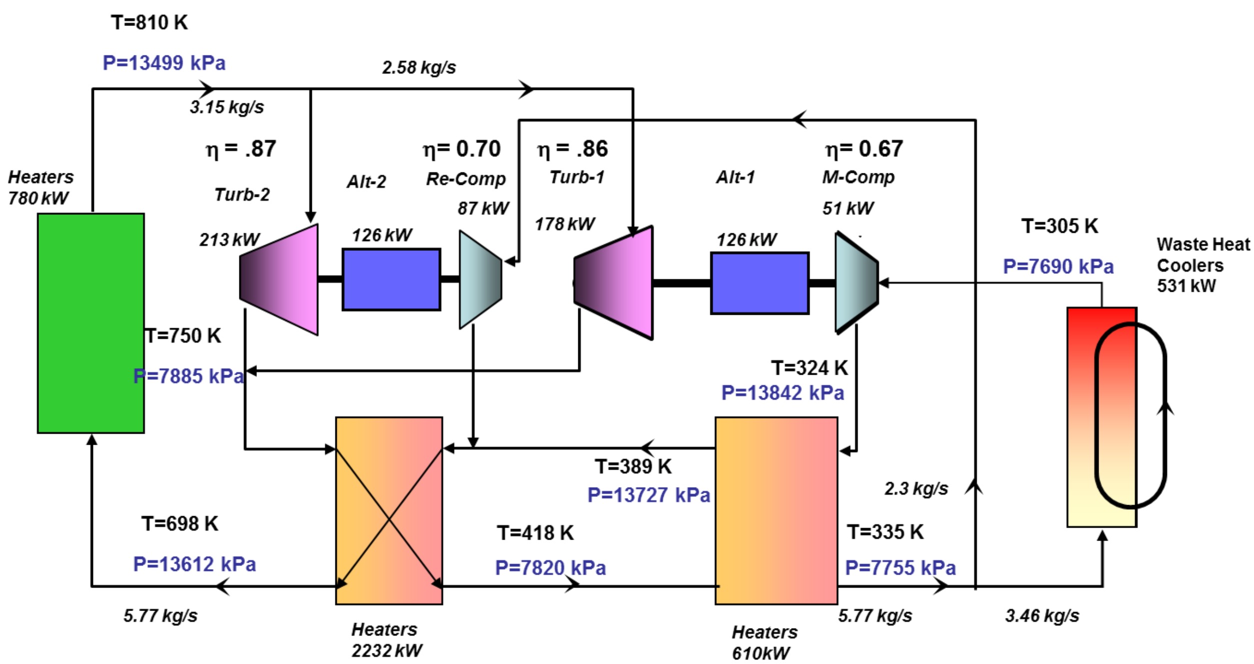

Figure 1-2. State points and component performance of the split-flow TA at design conditions.

2 DESCRIPTION OF DELIVERED TEST ASSEMBLY COMPONENTS

The significant hardware comprising the S-CO_2 split-flow TA includes two TACs and their controlling architecture, two Printed Circuit Heat Exchanger (PCHE) recuperators, one PCHE gas cooler, six shell and tube heaters and their controlling architecture, a Hydro-Pac scavenging pump, CO_2 inventory expansion tanks, heat rejection evaporators, electrical power dissipation load banks, various component cooling circuits, S-CO_2 flow piping, and support skids. The dimensions of this assembly (see Figure 1-1) are 357.0 in. long × 164.7 in. wide × 111.0 in. high. Note that the Hydro-Pac pump, heat rejection evaporators, and electrical power dissipation load banks are omitted from this figure.

A Solidworks depiction of the recompression loop design is presented in Figure 2-1. Each delivered major subassembly is described in this section at a relatively high level. As each subassembly is related to the original design objectives, the methods and results of the performance verification are discussed.

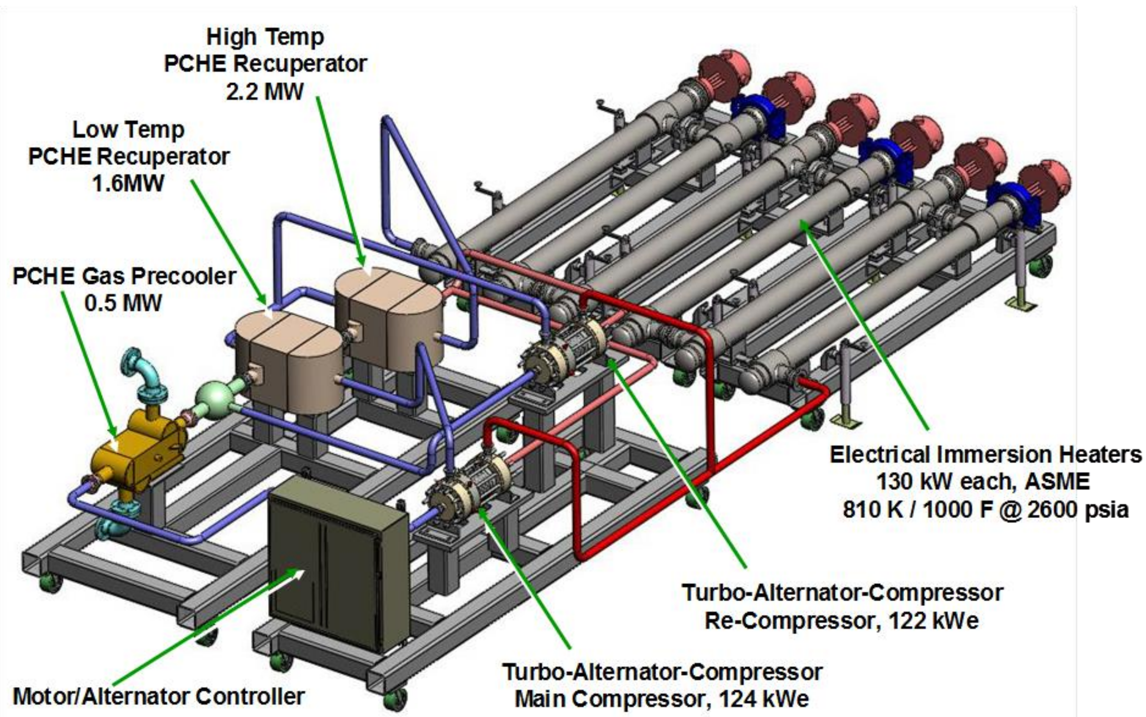

Figure 2-1. SolidWorks schematic of the delivered split-flow recompression loop.

2.1 Turbo-Alternator-Compressors

The split-flow Brayton cycle uses TACs (see Figure 2-2) to compress the low-pressure and low-temperature CO_2 to a high pressure at the compressors, then expand the high-pressure and high-temperature CO_2 in the turbines. At and near design conditions, the turbines generate more power than the compressors and consume inefficiencies, and the remaining power is used to make electricity in the motor alternator. In the power generation mode, the alternator applies an electrical load to the TAC's rotating shaft that is sufficient to maintain the commanded rotational speed. The applied electrical load represents the power that the TAC would produce for consumer use.

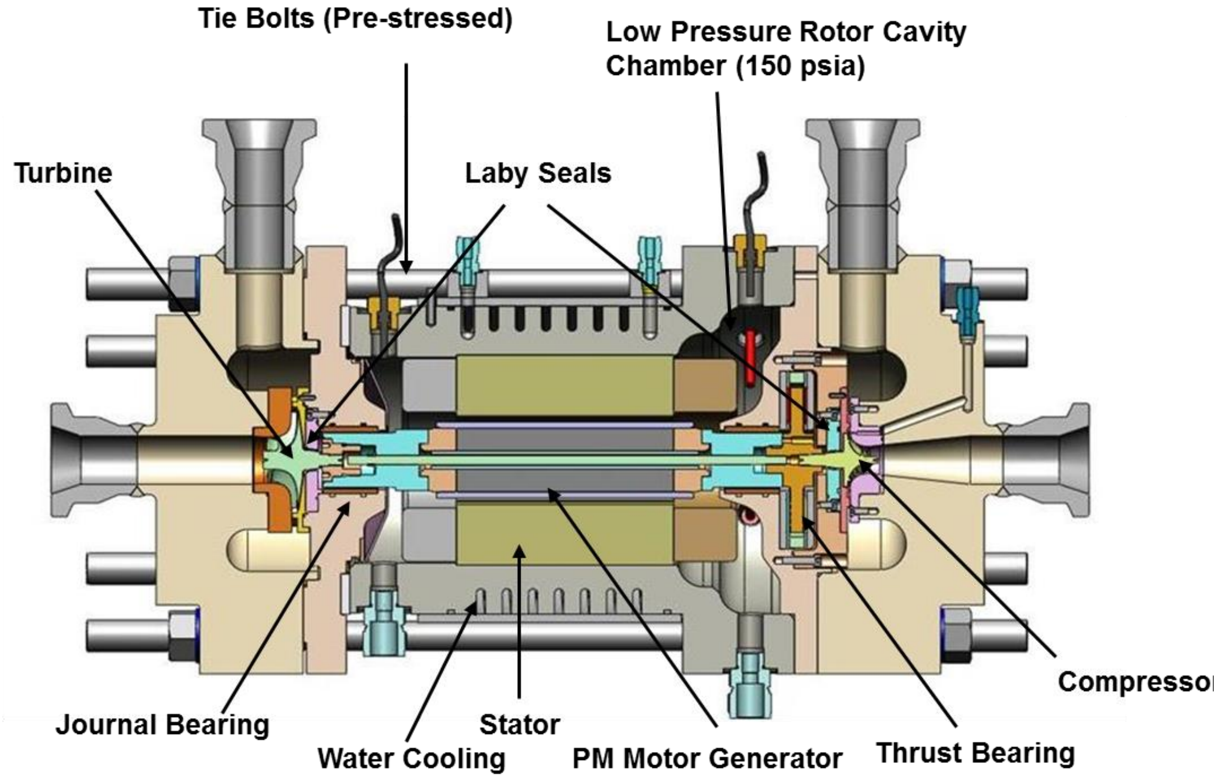

Figure 2-2. Cross section of the TAC.

The recompressor TAC (TAC-B) takes, as input to the compressor, the flow that discharges from the low-pressure side of the low-temperature recuperator. At design conditions, the CO_2 temperature is approximately 332 K, which is somewhat removed from the critical temperature of 304 K. At this elevated temperature, the fluid is more compressible than when in the immediate vicinity of the critical temperature. Therefore, TAC-B consumes more power per unit mass to compress than the main compressor (TAC-A).

TAC-A takes, as input to the compressor, the flow that discharges from the gas chiller, which is the coldest point in the circuit. As such, it is also the least compressible. Therefore, TAC-A consumes less energy per unit mass to compress the fluid than the recompressor.

A single low-pressure flow discharges from the low-temperature recuperator, where it splits into two flow paths, one path to each compressor. The fraction of the total flow going to each compressor is a function of the relative speeds of the two TACs and the thermodynamic state of the fluid at each inlet. These factors combine to determine each compressor's discharge pressure. When the two flows recombine—at the main compressor flow discharge from the low-temperature recuperator—they must be at the same pressure. Pressure mismatch at this point can put a compressor into a potentially damaging state of surge. The primary control to avoid surge is the speed of each TAC, with the magnitude of heat rejection in the gas chiller being of secondary importance. Minimum and maximum rotational speed for each TAC is 25,000 rpm and 75,000 rpm, respectively. The motor generator was designed for performance by analysis using SPEED motor design software and structural finite-element analysis (FEA) on the rotor.

Rotor control was modeled in SPEED, which links the motor design to controlling architecture design, and the results are confirmed in MATLAB®.

2.1.1 Radial Compressor Wheels

The radial compressor wheels are machined from aluminum 6061 blanks. Two sizes were designed and manufactured by BNI: a smaller diameter main compressor wheel and a larger diameter recompressor wheel (see Figure 2-3). The different sizes for these wheels reflect the large density difference that only 27 K of temperature difference makes when operating near the critical point at the inlets to the main compressor and recompressor, which have design inlet conditions of 305.4 K and 332.6 K, respectively. The associated density difference dictates a 35% reduction in the main compressor wheel diameter relative to the recompressor wheel. BNI generated turbine and compressor performance maps in terms of corrected ideal enthalpy change from inlet to discharge versus corrected mass flow. The main compressor performance map is presented in Figure 2-4. The red diamond in the figure indicates the design point. Maximum efficiencies for the main compressor and the recompressor are 67% and 70%, respectively.

Figure 2-3. Main compressor (left) and recompressor (right) wheels.

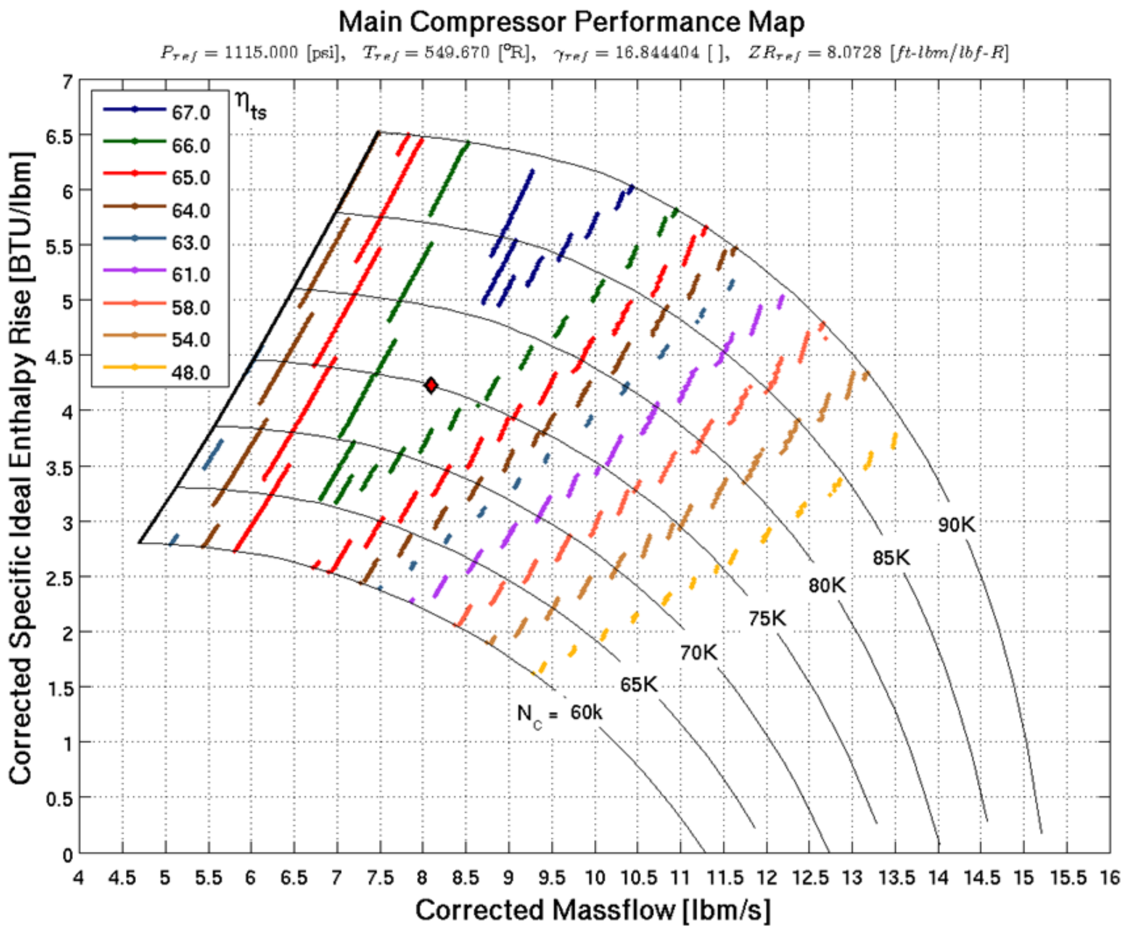

Figure 2-4. Main compressor performance map.
(The design point is indicated by the red diamond.)

2.1.2 Radial Turbine Wheels

Two radial turbine wheel designs were developed by BNI for the split-flow TA (see Figure 2-5). Inconel 718 was used for the turbine wheel material because of its ability to withstand high temperatures and stresses. Both wheels are the same diameter, but have different blade heights. The main compressor turbine performance map is presented in Figure 2-6, again with the design point indicated by a red diamond. Maximum efficiencies for the main compressor and the recompressor turbines are 86% and 87%, respectively.

The hot CO_2 exiting the heater is split into two flows upstream of the turbine inlets; each path flows through its respective turbine, then the separate paths recombine immediately downstream of the turbine exits. The flow split ratio is naturally set primarily as a function of each turbine's speed and slightly different flow area. The maximum turbine inlet temperature is 811 K (1000°F).

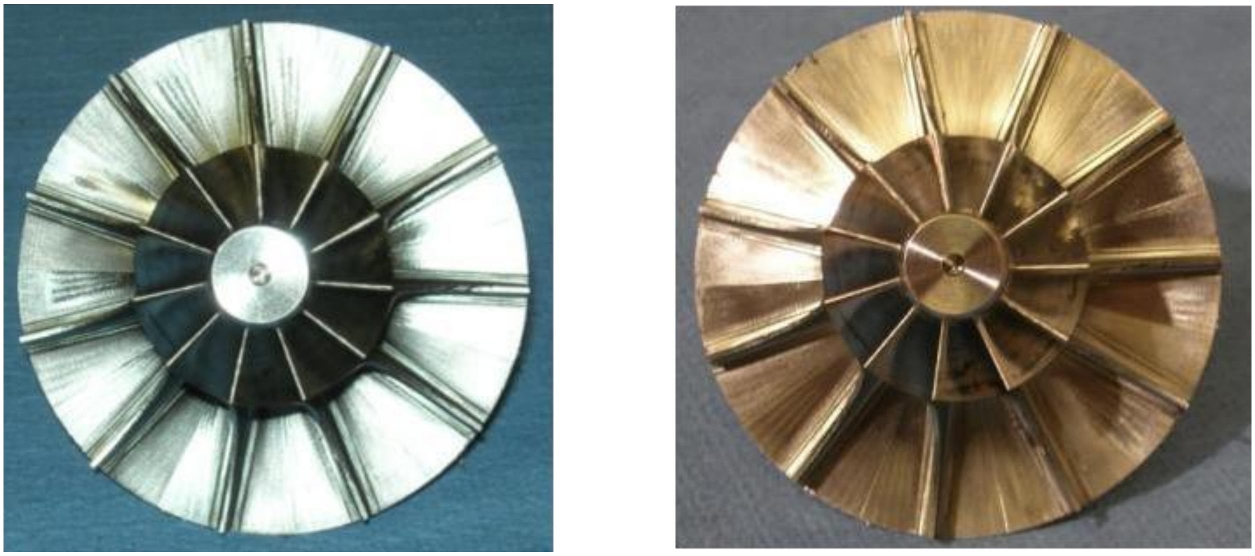

Figure 2-5. Recompressor turbine (left) and main compressor turbine (right).

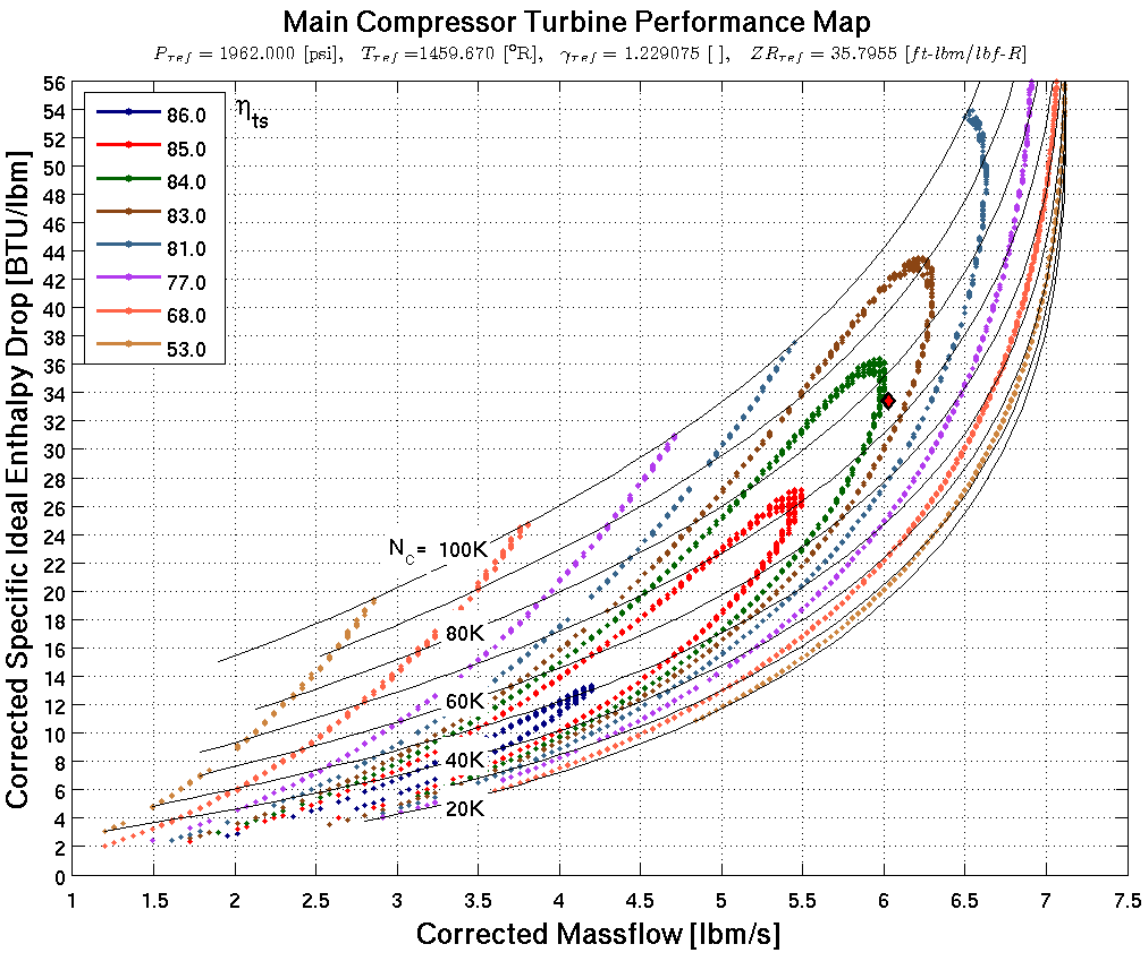

Figure 2-6. Main compressor turbine performance map.
(The design point is indicated by the red diamond.)

2.1.3 Motor Alternator

The motor alternator, assembled by BNI, has two functions. One function is to motor-assist the rotor shaft during the start transient and at any other time when the TAC is producing less power than it is consuming. Maximum motoring input power under any condition is 50 kW. The second function is to apply an electrical load to the rotor shaft at a magnitude necessary to maintain its speed at a user-set value. The generated current is dissipated in the Avtron load banks. The maximum alternator processing power is 120 kW. The maximum operating motor alternator temperature is 450 K (350°F).

2.1.4 Gas Foil Bearings

The journal and thrust bearings (see Figure 2-7) used to maintain the TAC rotor shaft lateral and axial position have been a project in themselves. The thrust bearing generates a reactive axial force in response to axial displacement of the shaft. This bearing in particular has received significant attention from BNI and from within Sandia through an internally funded Laboratory Directed Research and Development (LDRD) program. The design of the thrust disk foil bearings and the thrust disk itself have evolved over time to improve thrust load capacity and simultaneously reduce frictional windage losses. A long-standing thrust disk diameter is being replaced with a slightly smaller diameter disk in an attempt to reduce windage losses. The journal bearings are also gas foil bearings that rely on a thin gas film to generate reactive forces to maintain the rotor shaft in the correct lateral location. These journal bearings are made by Capstone® Turbine Corporation and have performed well.

The maximum operating temperature of both the compressor end journal and thrust bearing is 478 K (400°F). The maximum operating temperature of the turbine end journal bearing is 867 K (1100°F).

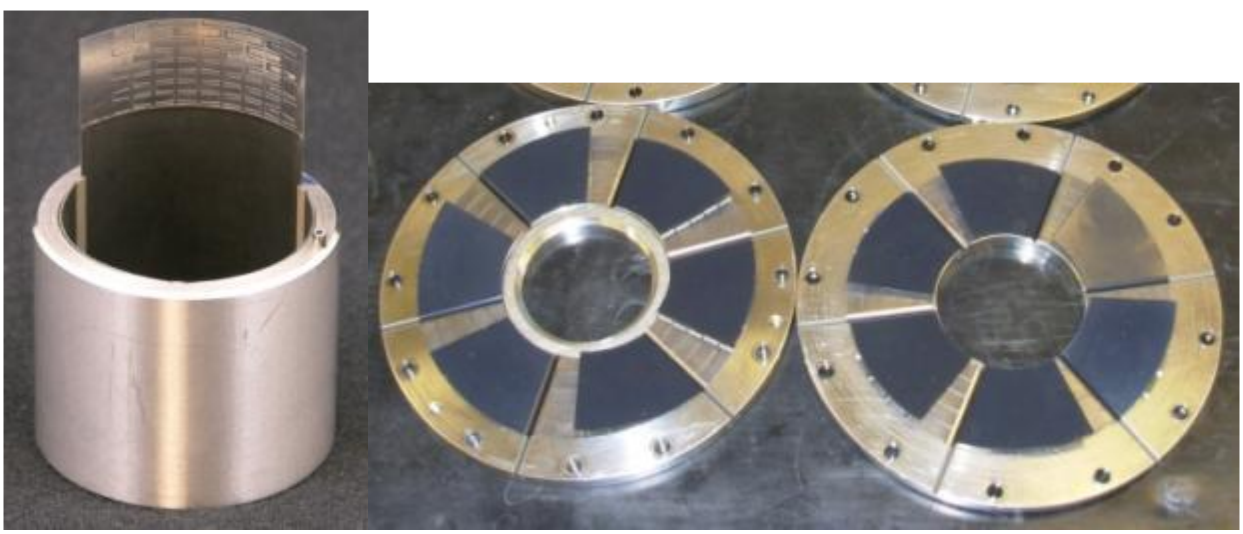

Figure 2-7. Gas foil journal bearing (left) and thrust bearing on thrust disk (right).

2.1.5 Motor Controllers

The motor generator controller (MGC), part number BNMC-14B-000, was designed by BNI for use with the various power converter topologies that support the operation of high-speed turbomachinery [2]. To provide the highest possible flexibility, the system is comprised of a single Top Level Controller, which functions as the master to an arbitrary number of slave controllers. Each of the slaves is, in turn, tasked with the operation of individual power converters. This design is compatible with OSR Cabinets BNPM-13-200 and BNPM-14-200 [3], and the Avtron load bank, part number K874AD45033.

The MGC system operates on 480 VAC and draws 40 Amps. The controller can supply a maximum motoring power of 50 kW, and can process a maximum generator power of 120 kW. A water-cooled circuit is built in to actively remove heat and must therefore have externally supplied water. To accelerate the rotor to a speed that is greater than the minimum sensorless speed, the controller includes an open-loop start-up algorithm that must be tuned to the characteristics of the specific motor. The front panel of the MGC includes a panel display that indicates TAC speed, voltage, current, and various error messages.

2.2 High-Temperature PCHE Recuperator

A high-temperature printed circuit heat exchanger (PCHE) was purchased from Heatric (a division of Meggit [UK] Limited) [4] in November 2009 for use as the high-temperature recuperator (HT Recup) within the Gen-IV split-flow Brayton loop. This component was the third PCHE heat exchanger to be installed in the loop. A photo of the installed high-temperature heat exchanger is shown in Figure 2-8. The heat exchanger was delivered to BNI in October 2010. It is constructed of 316 stainless steel and was designed to transfer 2.3 MW at a flow rate of 5.7 kg/s with a hot-side inlet temperature of 755 K (900°F) and a maximum allowable working pressure (MAWP) of 17.2 MPa. The recuperator and support frame were installed in the split-flow test loop following engineering analysis using the code Caesar II to ensure suitable accommodation during thermal expansion. The approximate dimensions of the HT Recup are provided in **Error! Reference source not found.**.

Figure 2-8. S-CO_2 high-temperature PCHE recuperator.

Table 2-1. Approximate Dimensions of the HT PCHE Recuperator.

Property	Value
HT Recuperator	
Channel Width	1.27 mm (0.05 in.)
Channel Depth	0.77mm (0.0303 in.)
Plate Depth	1.69 mm (0.0665 in.)
Flow Area per Channel	0.768 mm^2 (0.00119 $in.^2$)
Hydraulic Diameter (Dh)	1.0607 mm (0.0418 in.)
Core	
Height	0.296 m (11.65 in.)
Length	0.996 m (39.21 in.)
Width	0.512 m (20.16 in.)
Heat Transfer Area	43 m^2 (462.80 ft^2)
Core Mass	1410 kg (3108 lbm)

2.3 Low-Temperature PCHE Recuperator

The low-temperature recuperator (LT Recup) was installed in the loop in FY2010. A photo of the recuperator is provided in **Error! Reference source not found.** Figure 2-9, and the approximate heat transfer and flow dimensions of the recuperator are provided in

Table 2-2.

Figure 2-9. S-CO_2 LT PCHE recuperator.

Table 2-2. Approximate Dimensions and Flow Area in the LT Recuperator.

Property	Value
LT Recuperator	
Channel Width	0.96 mm (0.0378 in.)
Channel Depth	0.66 mm (0.0260 in.)
Plate Depth	0.97 mm (0.0382 in.)
Flow Area per Channel	0.4976 mm^2 (0.000771 $in.^2$)
Hydraulic Diameter (Dh)	0.8873 mm (0.0349 in.)
Core	
Height	0.3556 m (14 in.)
Length	0.5842 m (23 in.)
Width	0.254 m (10 in.)
Heat Transfer Area	18 m^2 (194 ft^2)
Core Mass	248.5 kg (548 lbm)

In general, the LT Recup has smaller flow passages than the HT Recup, and about half the heat transfer area. As such, its design heat transfer rating is 609 kW in the split-flow configuration. It was also designed to function as the main recuperator in a simple recuperated Brayton cycle and transfers 1712 kW of power in this configuration. At 422 K (300°F), the MAWP is 2800 psi.

2.4 Gas Chiller

Excess cycle heat energy is rejected at the gas chiller, itself a PCHE (see Figure 2-15). The heat removal capacity is approximately 540 kW, which is sufficient to establish the main compressor inlet CO_2 temperature near the critical temperature. Because the cooling mechanism at BNI relied on evaporating water, the gas chiller effectiveness at that location varied depending on the current humidity and ambient temperature. The heat removal capacity is maximized on cold, dry days. If needed, the cooling fluid circuit of the gas cooler can be operated with certain specially designed fluids to enhance heat removal [5].

2.5 Heating system

2.5.1 130-kW S-CO_2 Heaters

Each of the six immersion heaters (see Figure 2-10) provides 130 kW of heat input, providing a total heating capacity of 780 kW. With these heaters, there is sufficient power to reach high temperatures (>650 K), and the Brayton loop should be capable of making electrical power in all configurations, provided sufficient cooling is available. Some configurations should be able to reach the design temperature of 811K (1000°F). The MAWP for the pressure vessels in which the heating elements are wired is 17.8 MPa (2585 psi), and each vessel was hydrotested to a minimum of 23.4 MPa (3400 psi).

The heat system in itself is not the main limiting factor for the operating temperature. Even half of the heating capacity delivered can establish an operating temperature of 811K, the contracted objective temperature. Rather, the combined objectives of 811K, 5.7 kg/s flow rate, and a pressure ratio of 1.8, dictate required heating capacity. Operation at these three conditions simultaneously has been beyond the capabilities of the TA until now.

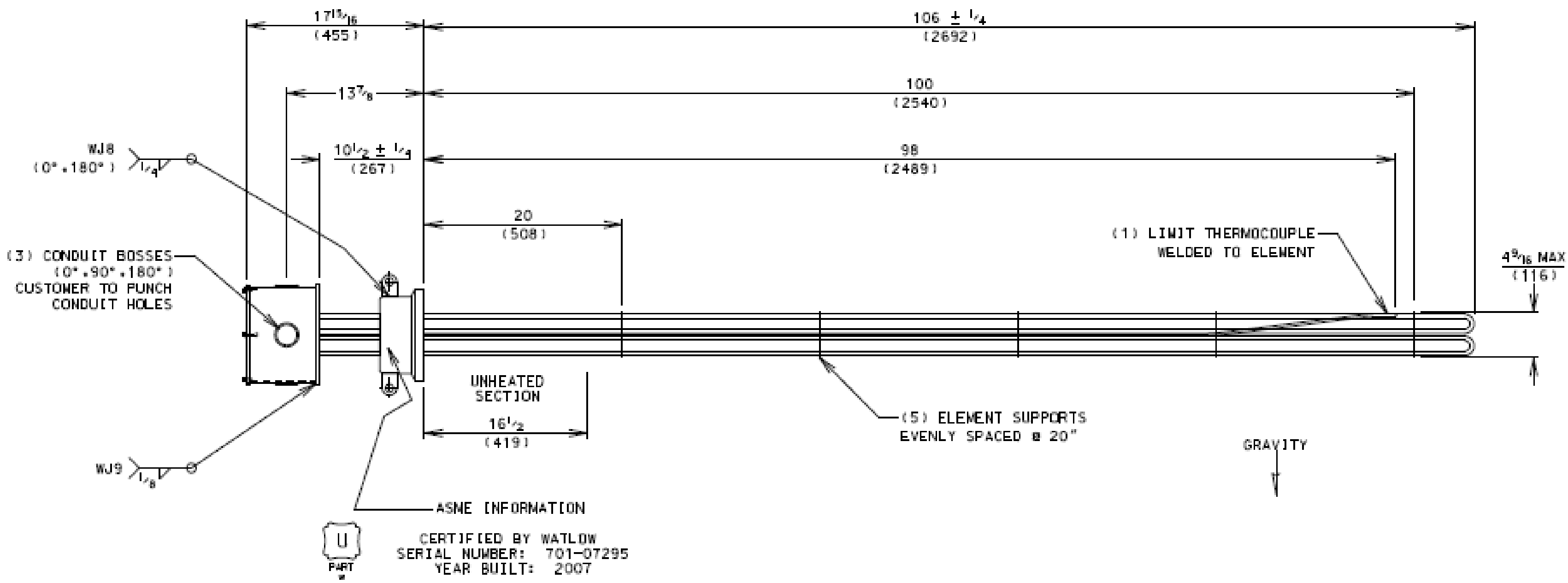

Figure 2-10. Watlow immersion heating element (130-kW heating capacity).

2.5.2 Heater Controllers

Each of the six immersion heating elements has its own controlling architecture in its own box (see Figure 2-10). These control boxes include contact hardware and fuses for 480 VAC power. The control function operates with an input current range of 4 to 20 mA, where 4 mA corresponds to zero power and 20 mA corresponds to 100% power for that heating element. The controls are remotely operated from the human-computer interface and represent one of the primary operating controls of the TA.

2.6 175-kWe Load Banks

The S-CO_2 TA is capable of producing significant power—up to 250 kWe by original design. This power must be disposed of, either by dissipation or by delivering it to the electrical grid. While at BNI, the TA was not connected to the electrical grid; therefore, dissipation was the only option. To accommodate this power dissipation, two 175-kW load banks were ordered from Avtron. These units were delivered to BNI and installed outdoors (see Figure 2-11), adjacent to the Brayton cycle laboratory, where the electrical wiring and connections to the MGC were then completed. When shipped to Sandia, these load banks will be reinstalled in Building 6630. Work is in progress at Building 6630 to deliver generated power to the local electrical grid. This work is being funded by a Sandia group motivated to support high-efficiency power generation.

2.7 Evaporative Cooler (220-kW rated) and Cooling Pumps

Evaporative coolers were purchased and installed at the BNI test site. A photograph of one of the evaporative coolers is shown in Figure 2-12. Sufficient cooling allows the TA to operate at the design temperature, which, in turn, is necessary to achieve design performance. If sufficient cooling is lacking, the maximum allowable heat input declines. The Sandia-purchased coolers provide a cooling capacity at the PCHE gas chiller of 440 kW based on the name plate rating. This total cooling capability was first used with the main compressor Brayton loop tests performed in late November and early December 2010 to produce electrical power in the simple recuperated Brayton cycle configuration, allowing the production of electrical power in this configuration for the first time. These earlier tests revealed that a larger water pump was required; therefore, a low-cost water pump was purchased and installed. Two other small water pumps were purchased to provide upgraded cooling flow for the MGC boxes and turbomachinery housing, and also for cooling the Hydro-Pac hydraulic pump system. These pumps share their closed loop water supply and cooling system with the PCHE gas chiller. The current installation plan for Building 6630 excludes these evaporative coolers because a different, higher capacity cooling system is being installed.

Figure 2-11. Avtron load banks.

Figure 2-12. Evaporative Cooler.
(The cooler has a name plate cooling capability of 220 kW.)

2.8 Hydro-Pac Gas Scavenging Pump

Sandia purchased a hydraulically driven piston pump from Hydro-Pac to more reliably reduce the rotor cavity pressure due to leakage, and to reduce windage and allow higher speed operation without overheating the turbomachinery. This single pump replaces the array of smaller, noisier, and frequently unreliable Haskel pumps that performed the same function in the previous configuration. The Hydro-Pac unit was received, installed, and first tested in April and May of 2011. This upgrade was largely responsible for the high shaft speeds and low windage losses achieved during this period. The Hydro-Pac pump and the Watlow® heater controllers are shown in Figure 2-13.

Figure 2-13. The new Hydro-Pac Scavenging Pump and Watlow® Heater Controllers.

2.9 Overspeed Resistors

The rotors can potentially accelerate to damaging rotational speeds during unexpected anomalous events that can occur during testing and emergency shutdowns. To prevent damage to the turbomachinery, BNI was contracted to build OSRs for the Sandia TA (see Figure 2-14). One OSR is dedicated to each TAC and its associated MGC. The OSR is normally 'on' without an actively generated signal from the TAC controller. If this 'off' control signal fails or is intentionally dropped (as during an emergency power off), the OSR activates and load is transferred away from the normal path to the Avtron load banks and into the OSR. The OSR trips automatically if the sensed speed exceeds a specified limit above the commanded speed.

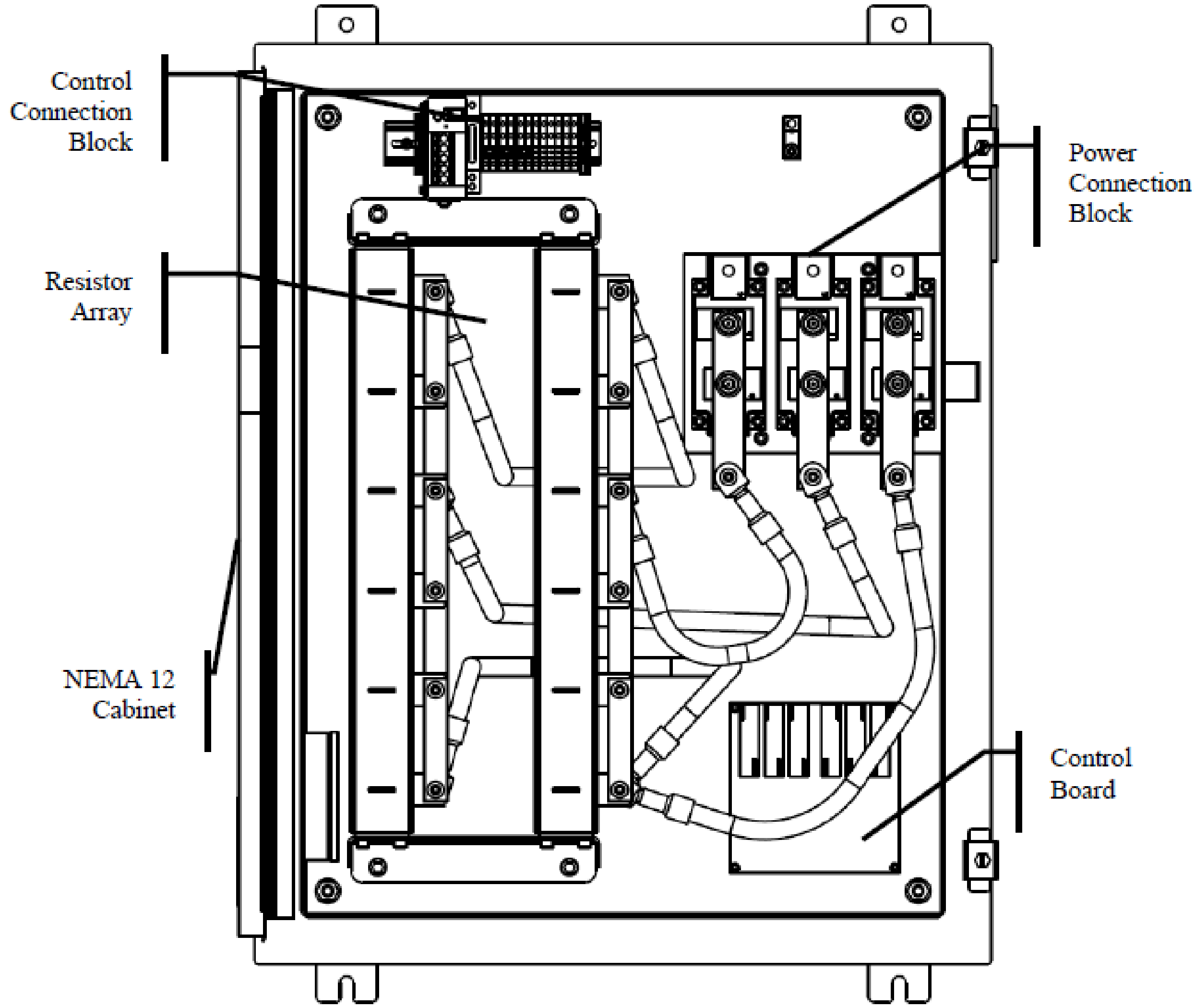

Figure 2-14. Overspeed resistor cabinet.

2.10 Instrumentation

Instrumentation on the TA consists of pressures, temperatures, mass flows, and density measurements. Signals from these measurements are channeled through a National Instruments signal transfer unit that interfaces with a LabVIEW data acquisition program. Pressure transducers are a mix of Honeywell and OMEGA brands with rated accuracies of ± 0.25%, except at the turbine and compressor inlets and discharges, where transducers with accuracies of ± 0.1% have been installed. Temperature measurements are made with resistive thermocouple devices (RTDs) and thermistors. Temperature accuracies are ± 1.1 K. Micro Motion® Coriolis flow and density meters are installed upstream of both compressors. Flow and density measurement accuracies are ± 0.15% and ± 2.0 kg/m^3, respectively. Instrumentation output interface and data processing is accomplished using LabVIEW with a data recording rate of 5 Hz on all instruments.

2.11 Piping

The CO_2 flow piping system is made of 304 and 316 stainless steel, and was designed to American Society of Mechanical Engineers (ASME) Power Piping standard B31.1. The piping is made predominately of two diameters: 3.8 cm (1.5 in.) and 5.1 cm (3.0 in.). Wall thickness corresponds to schedule 160 pipe. The system maximum operating pressure is 15.2 MPa (2200 psia).

All welds on the TA are x-ray inspected. Following completion of welds and inspections, all piping has been hydro proof pressure tested to 23.4 MPa (3400 psi). Note that some piping must perform to this safety standard while heated, corresponding to a higher proof pressure for ambient temperature proof testing. A standard procedure is used to relate the ambient temperature proof pressure that is equivalent to a proof pressure at elevated temperatures. This procedure was followed in proofing some hot end piping. Burst disks are set to open at 18.6 MPa (2700 psi).

2.12 Support structures

All components and piping are supported by steel frames, or skids, that are mounted on wheels. These skids serve three functions: 1) to serve as structural support for the hardware, 2) to allow the assembly to move during thermal expansion and contraction without breaking, and 3) to facilitate transportation of the assembly to various test sites.

2.13 Inventory Expansion Tanks

When the TA is between tests and at room temperature, the thermodynamic state of the fill CO_2 is the same throughout the system. At test conditions, a large disparity in density exists between the low-density hot side and the high-density cold side. The high-temperature side effectively forces CO_2 over to the cold side, and can place the components on the cold side in nonoptimal operating conditions without an inventory management mechanism. The inventory expansion tanks provide volume into which excess CO_2 can flow as the hot side forces the fluid to the cold side. This allows the assembly to continue to operate at desired conditions throughout a test that includes temperatures that range from ambient at test startup to 811 K (1000°F) during the test. These expansion cylinders are designed and manufactured by BNI, and are proof pressure tested to the same standards as the piping.

2.14 Ancillary Components

Flow control in several locations is managed by 120-V motor-controlled valves. Three of these motors are installed—one to control cooling water flow to the cooling towers, and two to manage TAC-A isolation operations during startup (see Figure 2-15). The piping and the motors designed to isolate TAC-A are new and have not yet been tested. This design modification is intended to prevent TAC-A, when configured with the smaller main compressor wheel, from surging due to elevated TAC-B discharge pressures during the start ramp to operating conditions.

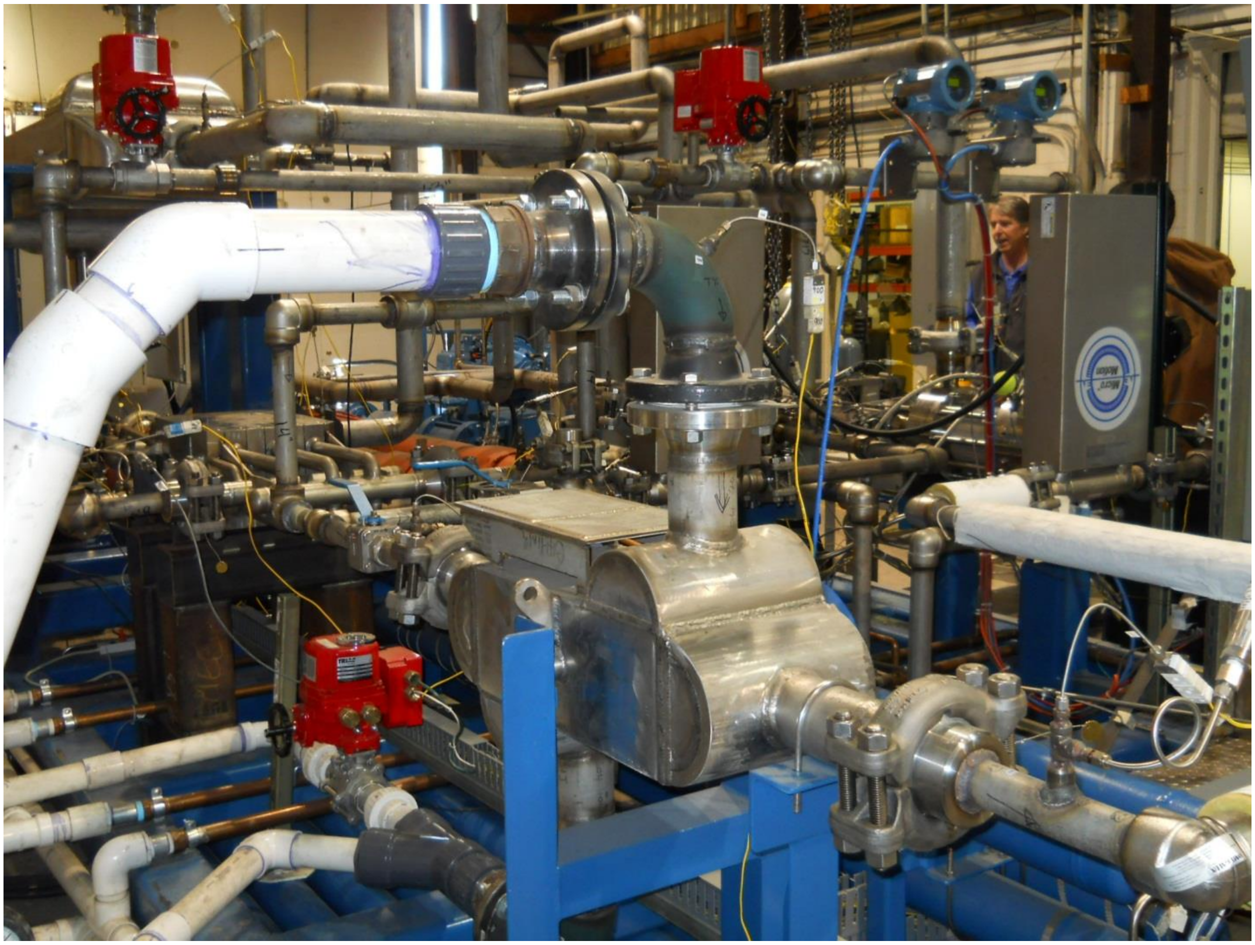

Figure 2-15. Three servo valves (red components) that control the cooling flow path and TAC-A isolation functions.
The gas chiller is in the foreground.

Water plumbing lines supply cooling water to the motor controllers, the TAC motor housings, the Hydro-Pac pump, and the gas chiller. Water pumps are installed to force flow through the different cooling circuits, and back to the heat rejection cooling towers.

2.15 Software

The primary controls available to the user through the human-machine interface to affect the operational state of the TA during testing include the following:

- Cooling water flow rate.
- Heater power.
- Rotational speeds for TAC-A and -B.
- Hydro-Pac vacuum piston stroke.

The graphical user interface (GUI) for these controls is constructed in LabVIEW (see Section 2.10 for more information on instrumentation and LabVIEW data acquisition).

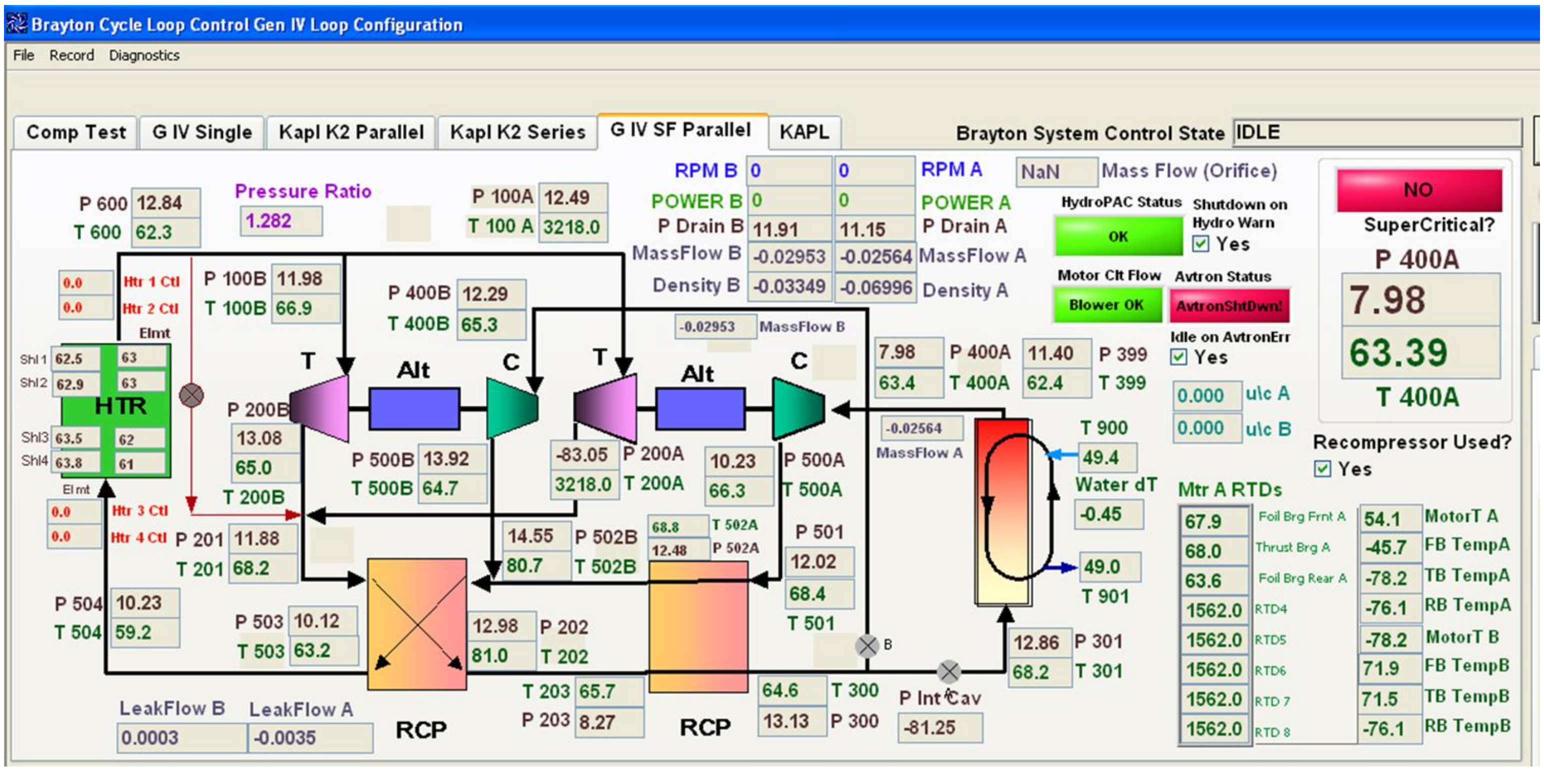

Figure 2-16. GUI that displays the TA operational data.

LabVIEW also provides the programming functionality to read instrumentation cards, process each data stream through the appropriate voltage-to-reading transformation algorithm, and display the data on a GUI. Figure 2-16 presents this GUI for a recent representative test. The human-machine interface includes readouts for all instrumented temperatures, pressures, mass flows, densities, and speeds. Some real-time calculated parameters found to be useful for safe operation are also displayed.

3 CONCLUSIONS

Sandia and contractor BNI have designed and fabricated a highly recuperated, closed Brayton cycle power conversion TA that operates on S-CO_2. The design is intended to be versatile, operating in either simple recuperated or split flow configurations. Expected cycle efficiency is 32% at design conditions of 811 K (1000°F) turbine inlet temperature, 13.8 MPa (2000 psi) compressor discharge pressure, and TAC rotational speeds of 75,000 rpm. The incremental funding spread over numerous years, the conservative approach to testing, and the inherent trial and error nature of new technology research and development (R&D), have all contributed to the delay of testing at design conditions until after delivery of the system from the contractor to the SNL facilities. Therefore, a comprehensive assessment of the TA capabilities relative to the original design objectives has yet to be completed. At the time of delivery, the TA had operated at 672 K, all components had been hydrotested to 22.8 MPa, and rotational speeds of 65,000 rpm in air for an equivalent design had been achieved. Most importantly, operating at these design conditions simultaneously is the true test of the design capability. The most demanding simultaneous operating conditions to date with CO_2 have approached 640 K (700°F), 10.6 MPa (1540 psi), and 59,000 rpm.

BNI has extensive experience in developing turbomachinery, thus mitigating concerns over untested design objectives. BNI remains available for consultation following TA installation at Building 6630. It is anticipated that the BNI program manager will attend the first few commissioning tests of the reassembled TA at SNL to provide expert operational advice.

System functions other than those that contribute directly to operational design conditions will dictate the cycle performance. Issues of particular note are the facility heat rejection capacity, windage losses in the rotor cavity, thermal losses in the vicinity of the turbine and from piping, and thermal environments in the vicinity of the gas foil bearings. Once the TA has been reassembled and commissioned for operation at Sandia Building 6630, a significant acceleration in the R&D of this TA is expected with a corresponding acceleration in learning.

4 REFERENCES

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