



Initial Test Results of a Dual Closed-Brayton-Cycle Power Conversion System

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Abstract

The dual Brayton power conversion system constructed for NASA Glenn Research Center (GRC) was acceptance tested April 2007 at Barber-Nichols, Inc., Arvada, Colorado. This uniquely configured conversion system is built around two modified commercial Capstone C30 microturbines and employs two closed-Brayton-cycle (CBC) converters sharing a common gas inventory and common heat source. Because both CBCs share the gas inventory, behavior of one CBC has an impact on the performance of the other CBC, especially when one CBC is standby or running at a different shaft speed. Testing performed to date includes the CBCs operating at equal and unequal shaft speeds. A test was also conducted where one CBC was capped off and the other was operated as a single CBC converter. The dual Brayton configuration generated 10.6 kWe at 75 krpm and a turbine inlet temperature of 817 K. Single Brayton operation generated 14.8 kWe at 90 krpm and a turbine inlet temperature of 925 K.

I. Introduction

With recent attention given to gas cooled reactors for potential space power applications,¹⁻⁷ a high power dual CBC test system was built to provide proof of concept. In April of 2007 the NASA GRC participated in the acceptance testing of the dual Brayton system at Barber-Nichols, Inc., Arvada, CO, the company contracted to build the system. A single Brayton test loop very similar in construction to this system, also built by Barber-Nichols, has been tested by Wright at Sandia National Laboratories (SNL).^{6,7} However, the dual Brayton system is unique because it employs two CBC converters sharing a common gas inventory and common heat source. The heat source is not segmented and therefore the working fluid is free to redistribute between the two converters as system operation dictates.

The test hardware is not flight-like, but the system is sufficient for demonstrating a dual loop configuration. The dual Brayton loop is the first of its kind and provides insight into potential operation of future flight-like systems. The approach is to use a gas cooled reactor coupled to two or more CBC converters to provide redundancy within the system. Testing

to date has been limited to turbine inlet temperatures and shaft speeds below the system design point, but operational areas of interest for future tests include running at full design power output, running the CBCs at equal and unequal shaft speeds, running one CBC while the other is standby, and starting the CBCs in both staggered and simultaneous fashion. Test results will also be used to validate a system analytical model.

II. Dual Brayton Test Loop Hardware

The goal was to build a dual closed-Brayton-cycle power conversion system in a relatively short timeframe. The elapsed time from when the request for proposals was sent out until the acceptance test was performed was less than 12 months. In order to accomplish this, most of the hardware had to be off-the-shelf items that required minimal modification. Barber-Nichols was contracted to design and build the system and they chose to center the design around a modified Capstone C30 commercial microturbine.⁸ Other major components that make up the system are the gas cooler, electric resistance heater, and interconnect ducting. The resulting system is not flight-like; therefore, the system is larger and heavier than a system designed for operation in space.

Figure 1 is a schematic of the dual Brayton loop. Solid red lines indicate hot gas flow; solid blue lines indicate cold gas flow; and dotted blue lines indicate water coolant flow. System design point turbine inlet temperature is 1000 K; compressor inlet temperature is 300 K; compressor inlet pressure is 100 kPa; and speed is approximately 90 krpm.

II.A. Brayton Components

Turbomachinery is the heart of a Brayton system and the Capstone microturbine is proven commercial technology that provides the power level desired for this particular test loop. Figure 2 shows a cross-section view of the components and working fluid flow path for the standard Capstone C30. The Capstone C30 is an air-cycle machine that uses a single-stage centrifugal compressor and single-stage radial turbine to produce a maximum of 30 kWe at a shaft rotational speed of 96 krpm. Atmospheric air entering the unit passes over the alternator for alternator cooling, flows to the compressor

where it is compressed to the system peak pressure, and is preheated by the recuperator before entering the combustor. The combustor adds fuel to the air and ignites the mixture, where the air mixture reaches 1144 K. The hot combustion gas enters the turbine where it is expanded and work is produced. The low pressure turbine exhaust is cooled by the recuperator before it is discharged back into the atmosphere.

An open-cycle machine can use a combustor to heat the working fluid because the combustion products are expelled into the atmosphere, but a closed cycle machine requires an external heat source to avoid contamination of the fixed inventory working fluid. To convert the Capstone C30 from an open-cycle to a closed-cycle machine the combustors were removed and ducts were added to route the working fluid from the recuperator high pressure exit to an electric resistance heater and back to the turbine inlet. Because the Capstone C30 has such a compact design, the only practical way to route the gas was through a series of ducts. Figure 3 shows the modified unit. The four ducts extending radially (located where the fuel injector ports used to be) from the housing lead to a plenum that connects the recuperator high pressure exit to the heater inlet. The six ducts extending axially from the housing direct the gas from the heater exit to the turbine inlet. High temperature flexible hoses are used to connect the hardware together.

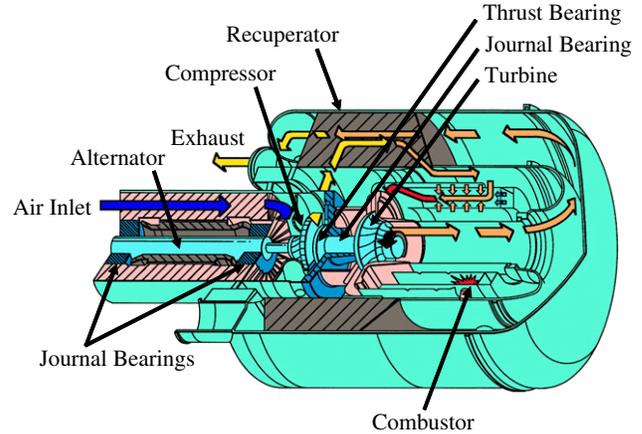
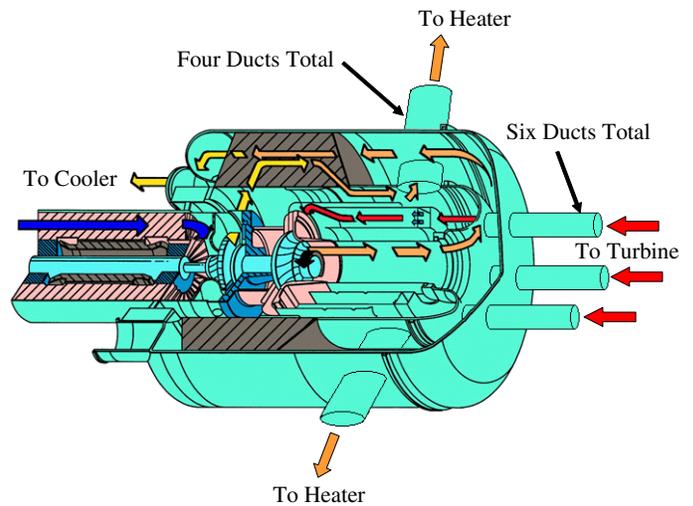
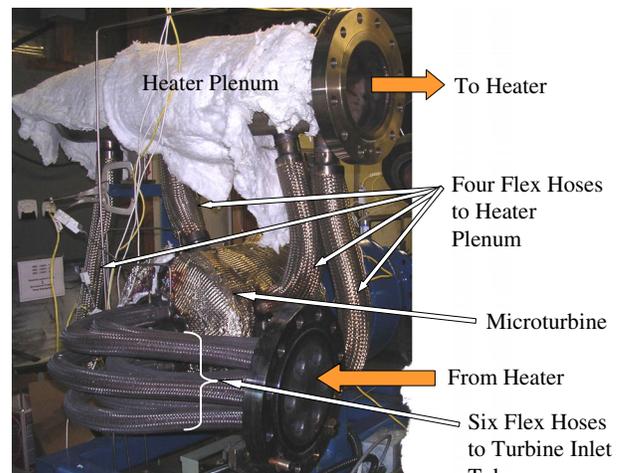


Figure 2.—Cross-section of the standard Capstone C30 commercial generator.



(a) Cross-section of the modified Capstone C30.



(b) Flex hoses connecting Capstone C30 to heater.

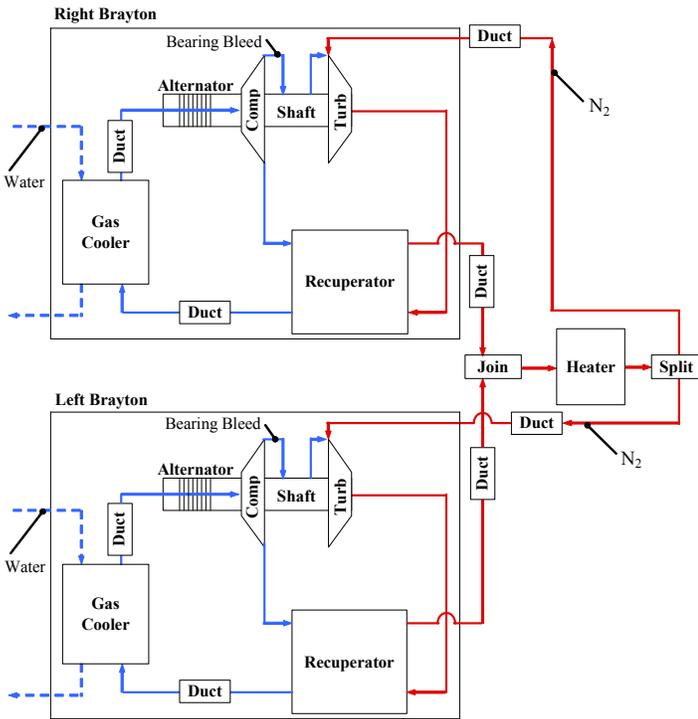


Figure 1.—Dual Brayton loop schematic.

Figure 3.—Capstone C30 unit modified with ducts to and from the heater.

The electric heater provides the substitute for the combustor for the closed cycle. In the dual Brayton system it serves as the only component shared by the two CBC converters, where working fluid from each CBC joins at the heater inlet and splits at the heater exit. A flight system would potentially use a nuclear fission reactor as the heat source, and an electric resistance heater could be used to simulate a reactor for flight-like test systems. However, this test loop uses a customized version of a commercial electric resistance heater that does not represent the temperature profile or control behavior of a nuclear reactor. The heater configuration is very similar to that of a shell and tube heat exchanger. A bundle of 24 “U” shaped heating elements (48 rods) acts as the tube portion that runs axially along the length of the shell, and a series of baffles persuades the gas working fluid to serpentine across the tubes in the shell portion of the heat exchanger. The heating elements are divided into four sections, each with its own power rating. The section at the cold gas inlet has the highest power input (55% of the total heater power) while the last section receives the least power (10% of the total heater power). This is done to keep the heating element material temperature below design limits. All four heater sections combine for a total maximum heating power of about 260 kW. The heater can either be set to deliver a constant power or maintain a user-specified gas exit temperature. Although the turbine was designed for an inlet temperature of 1144 K, the electric heater materials limit the maximum achievable gas temperature to about 1000 K. Figure 4 shows the heater assembly and heating element arrangement.

The other main component required to build the closed cycle system is the gas cooler. In the open cycle machine fresh, cool air is constantly drawn in from the atmosphere, but in a closed cycle machine the recycled working fluid must be cooled to the desired compressor inlet temperature. A flight unit could use a variety of liquids to cool the gas, and waste heat would be rejected to space by radiators.

The test loop uses a commercial counter flow shell and tube heat exchanger for the gas cooler, as shown in figure 5. A flight-like gas cooler would most likely be a compact heat exchanger, but mass and size are not restricted for this system so the commercial heat exchanger chosen provides an inexpensive alternative. Facility water is pumped through the shell side of the heat exchanger while the gas flows through a bundle of 70 tubes, producing compressor inlet temperatures around 300 K. There are two gas coolers in the system, one for each CBC converter, and water coolant flow rate is controlled to achieve a target compressor gas inlet temperature.

II.B. System Setup

The modified Capstone C30 units, gas coolers, and heater were assembled to form the dual Brayton test loop as shown in figure 6. The entire system is 5.8 m long, 3.0 m wide, and 2.4 m high. Each CBC is identical and the heater resides between the two. Arrows indicating the direction of gas flow

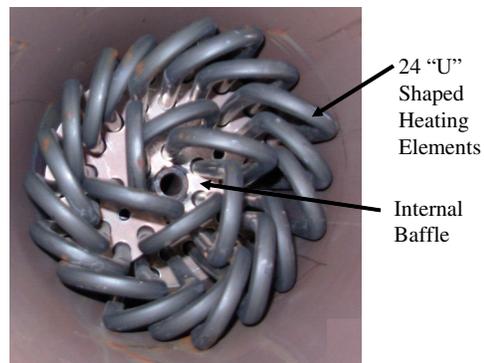
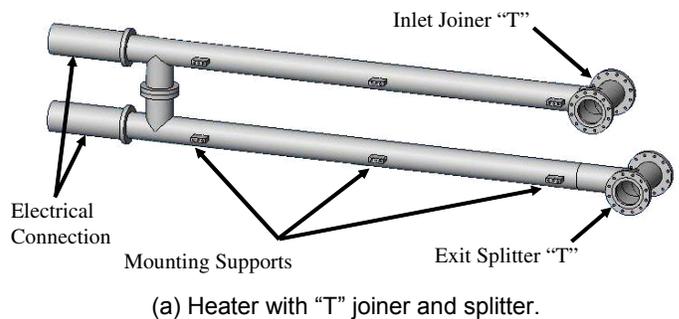


Figure 4.—Electric resistance heater.



are shown in figure 6. Cold, low pressure gas enters the modified Capstone unit, passes over the alternator, enters the compressor, and is then preheated by the recuperator. The warm, high pressure gas is then combined with the recuperators discharge gas from the other CBC before entering the heater. Hot gas exiting the heater splits into two flows and enters the two CBC turbines. After exiting the turbine the gas is precooled by the recuperator before entering the gas cooler. The longest duct in the system connects the recuperator low pressure exhaust to the gas cooler inlet. This length of pipe provides a good location for the flow orifice that is installed to measure gas mass flow rate.

Although the commercial Capstone units were designed to operate with air as the working fluid, the test loop uses

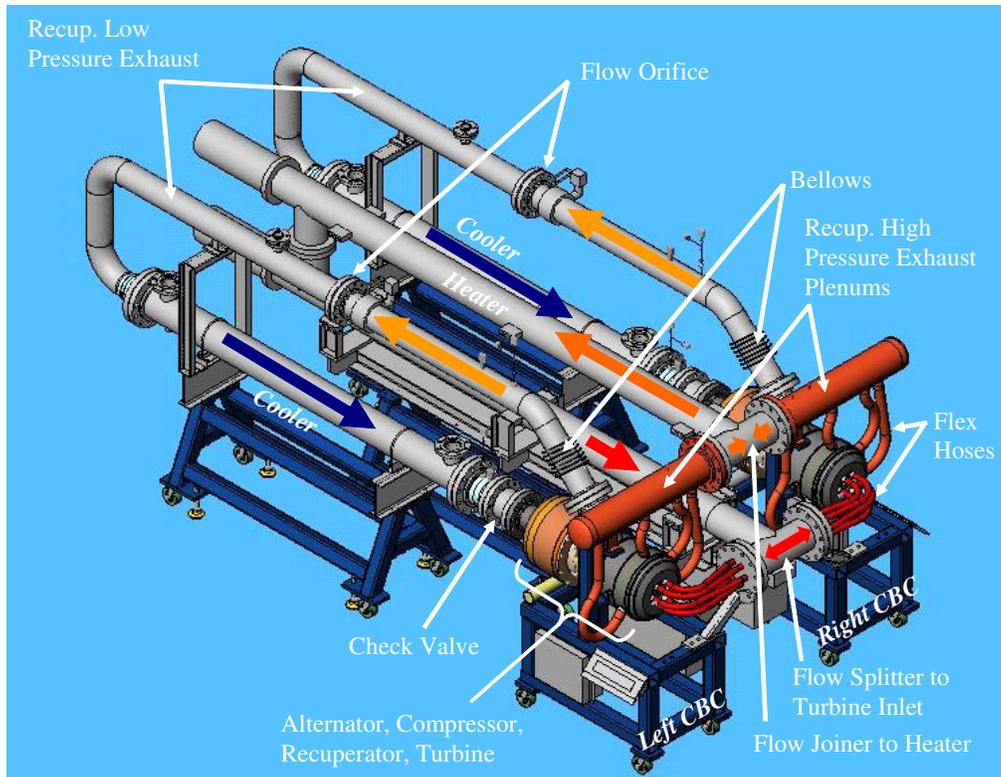


Figure 6.—Assembled dual Brayton test loop.

nitrogen because it is an inexpensive inert working fluid with properties similar to air. A bottle of nitrogen is connected directly to the test loop, allowing gas to be added to the system at any time. Gas can be vented from the system at any time using a manual valve as long as the compressor inlet pressure is above atmospheric. A vacuum pump is used to evacuate the system of gas as needed. The test loop could eventually be operated using a variety of working fluids. A flight-like system would likely be designed to use a mixture of helium and xenon.³

The hardware expands and contracts as it is heated and cooled and measures were taken to make the system compliant. A bellows joint is located on the pipe at the recuperator low pressure exit to allow the hot-end components to move relative to the cold-end components. The four ducts entering the heater and the six ducts entering the turbine are made of flexible hose to allow the hot-end components to move relative to each other. The heater expands the most, so it is supported by a stand that allows the heater to grow and move as it is heated. The two CBC flows join at a simple “T” junction and split at a similar junction. The amount of gas inventory that resides in each CBC at any given time is strictly a function of the gas pressure and temperature in each system component. The inventory distributes naturally based on operating conditions so the pressure of the gas exiting each CBC is identical; the pressure drops around each loop are equal because the two flows are in parallel. Because the heater is a shared component, the turbine inlet temperatures and

pressures are equal as long as both CBCs are running. In the event that one CBC is running while the other is standby (i.e., its shaft is not turning), the standby CBC will act as an accumulator and gas inventory is free to flow in and out of the standby CBC as thermodynamics dictate. In theory, gas would be forced to flow backwards through the standby CBC because it is in parallel with the operational CBC; the pressure at the standby CBC exit (heater inlet) is higher than at the CBC inlet (heater exit), which would compel some gas to flow backwards through the turbomachinery, damage might be incurred by the gas foil bearings that support the shaft. It is for this reason that a check valve is located at the gas cooler exit, as labeled in figure 6. The check valve forces the gas in the recuperator high pressure leg and the compressor to equilibrate with the heater inlet pressure; the gas in the turbine, recuperator low pressure leg, gas cooler, and connecting ductwork equilibrates with the heater exit pressure.

II.C. System Operation

The dual Brayton system is operated using only a few user control inputs. A basic Brayton power conversion system requires heat input, heat rejection, and an electric load. The test loop retains the Capstone commercial controller which uses a parasitic load to maintain a set shaft speed. The heater can be set to a specific power setting, but is more commonly

employed to maintain a set turbine inlet temperature using a programmable PID controller. The test loop is setup with a computer interface that sends command signals to the Capstone and heater controllers. Each CBC can be operated at different shaft speed set points, but only one turbine inlet temperature is allowed as there is only one heater. Waste heat is rejected to the facility cooling water flowing through the gas cooler. The water supply temperature is relatively constant for a given day, and a valve is used to control the flow rate of the water, and in turn, the compressor gas inlet temperature.

When starting the system, the microturbines are spun up before the heater is turned on per the heater manufacturer's recommendation. By default, the Capstone controller startup speed is 25 krpm to ensure gas foil bearing liftoff. This speed is also sufficient for the turbomachinery to circulate the cold working fluid through the system. Because the two CBC converters operate independently, they can be spun up simultaneously or separately in a staggered fashion. The heater can be turned on once gas is flowing. The operator then has the option to set a heater power level or target turbine inlet temperature as well as the freedom to increase shaft speed.

III. Results and Discussion

Testing to date has been limited to only a few operating points, but the data is sufficient to serve as operational proof of the dual Brayton system concept. All of the data presented herein was collected during acceptance testing at Barber-Nichols. As such, the power delivered to the heater was limited to about 57% capacity (about 147 kWe) because of the electrical service limitations at Barber-Nichols. This, combined with the lack of thermal insulation on the heater, resulted in turbine inlet temperatures lower than the design specification of 1000 K. When the system is installed at GRC with sufficient electrical service and is fully insulated, expectations are that the design turbine inlet temperature of 1000 K will be achieved.

Three types of tests were conducted with the system. The first test operated the dual loop with both CBCs at equal speeds over a range of shaft speeds. The second test operated one CBC over a range of shaft speeds while the other CBC speed was held constant. The third test operated the system as a single loop with one CBC completely detached from the system. All the data is preliminary and an uncertainty analysis has not been performed.

III.A. Dual Brayton Loop at Equal Shaft Speeds

The first test was to operate the CBC converters over a range of shaft speeds while always keeping the speeds of the two CBCs equal. To generate the data the system was heated at a constant heater power to near steady-state. Data was collected at a constant heater power as shaft speed was changed in increments of 5 krpm over the course of a few minutes. This method of collecting data provided a turbine

inlet temperature (TIT) that varied no more than ten degrees over the course of each run; TIT values reported are the average for the run. Gas inventory remained fixed throughout the run, and compressor exit pressure for all three runs ranged from 85 to 146 kPa, with the higher pressures occurring at faster shaft speeds and higher turbine inlet temperatures.

Figure 7 is a plot of system power output (right CBC plus left CBC) as a function of shaft speed with TIT as a parameter. At a TIT of 817 K power increases nearly linearly from 2.2 kWe at 45 krpm to 10.6 kWe at 75 krpm. At a TIT of 763 K power increases less than linearly from 1.1 kWe at 45 krpm to 5.2 kWe at 75 krpm; as speed increases it appears as though power is heading towards some maximum located beyond 75 krpm. At a TIT of 710 K power increases from 0.2 kWe at 45 krpm to 1.5 kWe at 65 krpm and appears to reach a maximum somewhere between 65 and 75 krpm. This data indicates that for a given TIT there are two shaft speeds that will yield the same power output. For example, the 710 K case produces about 1.2 kWe at both 60 and 75 krpm.

If shaft speed was increased beyond 75 krpm for the 817 K and 763 K TIT cases, a similar trend as seen for the 710 K case would have been observed; for a given TIT there is a speed that will yield maximum power, and the higher the TIT, the faster the speed is at which this maximum power point occurs. This CBC behavior has also been observed by Wright on the single Brayton loop located at SNL.⁷

Cycle efficiency is a useful metric for assessing Brayton system performance. Efficiency (defined as the ratio of electrical power output to heat input to the gas) for the dual CBC operating at 817 K TIT and 75 krpm was about 14%. However, this operating point was at a lower TIT and speed than the design point of 1000 K and 90 krpm, and efficiency is expected to increase as system operation nears the design point.

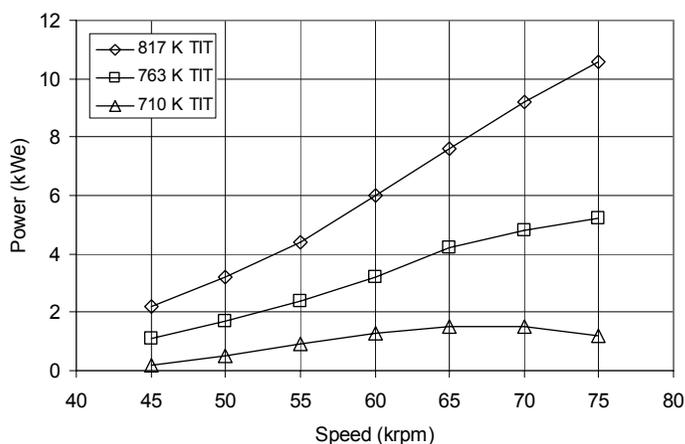


Figure 7.—Total system power output as a function of shaft speed at three turbine inlet temperatures.

III.B. Dual Brayton Loop at Unequal Shaft Speeds

The previous section presented test results of the CBC converters operating at equal speeds, but that type of test does not reveal much about the nature of a dual loop system because both CBCs behave identically. The second set of tests involved operating the two CBC shafts at different speeds. There are countless combinations of speeds, pressures, and temperatures one could potentially test using this system, but a simple strategy was employed where one CBC shaft was held at a constant speed while the other CBC shaft was operated over a range of speeds. Two runs were performed in this fashion, one at a lower system gas pressure and one at a higher system gas pressure.

Figure 8 is a plot of each CBC power output as a function of the left CBC shaft speed while the right CBC shaft speed was held at 45 krpm. The low pressure case (solid lines) had a compressor exit pressure that ranged from 155 kPa to 168 kPa (left and right compressor exit pressures are always equal, but compressor inlet pressures may differ), depending on speed, and an average TIT of 843 K. At 60 krpm the left CBC power starts off much higher than the right CBC power, 2.7 kWe and 1.2 kWe respectively. The left CBC Power increases nearly linearly to 4.6 kWe at 75 krpm. Right CBC power appears to increase slightly as left CBC speed increases, but further testing is required to investigate this phenomenon.

After the first run was completed, gas was added to the system to raise compressor exit pressure by about 32 kPa. Turbine inlet temperature also drifted up to 865 K between runs. Figure 8 presents the data from this higher pressure case (dotted lines). The data for the higher pressure case looks very similar to the lower pressure case, except it has been shifted up by about 1.3 kWe for the left CBC and 0.6 kWe for the right CBC. The increase in power is due to a combination of the higher TIT and higher system pressure.

This test demonstrated that a dual loop system can be operated with the CBC converters at unequal shaft speeds. Although the high and low pressure runs were simple in nature, more testing is needed to further reveal the interaction between the two CBCs.

III.C. Single Brayton Operation

The dual loop test was only able to achieve a TIT of 865 K because of limited electrical service to the heater. In an attempt to maximize TIT, one CBC was unbolted from the system and blanking plates were used to cap off the open heater inlet and exit. This allowed the system to function as a single Brayton converter, which means reduced flow rate through the heater and therefore a higher turbine inlet temperature. A TIT of 925 K was achieved, which is higher than the dual Brayton loop, but still 75 K shy of the 1000 K target. A TIT of 1000 K should be attainable when the system is installed at GRC.

Figure 9 shows a plot of power output as a function of shaft speed for turbine inlet temperatures of 925 K, 868 K, and 811 K.

811 K. All three cases show a nearly linear increase in power from 60 to 70 krpm. The 811 K TIT case yielded a maximum power of 6.4 kWe at 80 krpm. The 868 K TIT case appears to maximize power near 10 kWe somewhere between 85 and 90 krpm. The 925 K TIT case yielded 14.8 kWe at 90 krpm and power appears to be still increasing at 90 krpm. Given that the Capstone C30 is limited to a speed of 96 krpm, maximum power at a TIT of 925 K or higher would occur at 96 krpm.

The Capstone C30 microturbine is designed to generate up to 30 kWe as an open-cycle machine, but there are two main factors that preclude the closed loop from achieving that power level. The first factor is the limitation on turbine inlet temperature; figures 7 and 9 showed how TIT can affect power output. The design TIT for the open cycle is 1144 K, but the electric heater limits TIT to 1000 K.

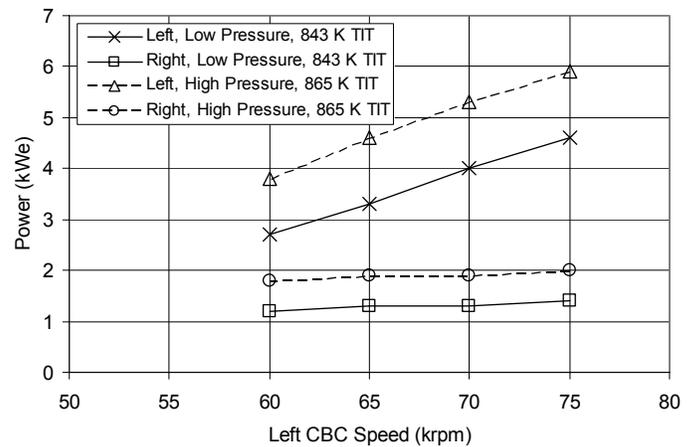


Figure 8.—Left and right CBC power output as a function of left CBC shaft speed with right CBC shaft speed held constant at 45 krpm.

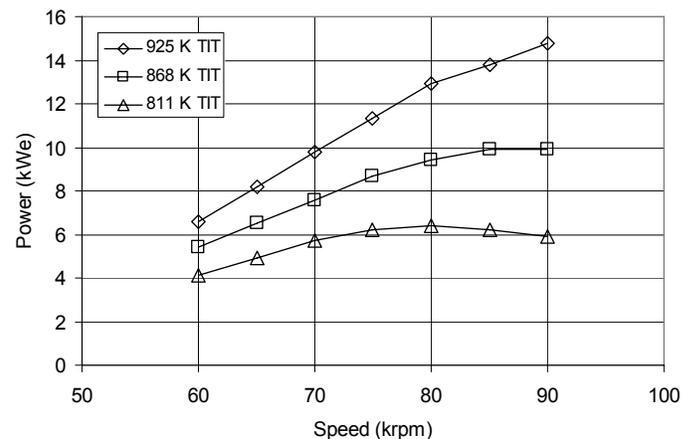


Figure 9.—Single CBC power output as a function of shaft speed at three turbine inlet temperatures.

The second factor is the increased pressure drop that results from adding the closed loop hardware (i.e., ducting, gas cooler, and heater). Brayton performance is very sensitive to the system pressure drop because additional pressure loss deprives the turbine of expansion work, reducing power output. The single loop produced 14.8 kWe at 90 krpm and 925 K TIT with a cycle efficiency of about 22%. A data point was not recorded with the dual loop operating at that exact speed and temperature, but the dual loop would produce less than twice the single loop power because the higher flow rate through the shared heater would result in a greater system pressure loss.

IV. Conclusions

The dual Brayton system was operated with the CBC converters at equal and unequal shaft speeds. When running at equal shaft speeds the system generated a total of 10.6 kWe at 75 krpm and a TIT of 817 K. When the left CBC was operated at 75 krpm and the right was operated at 45 krpm, they produced 5.9 and 2.0 kWe, respectively, at a TIT of 865 K. The system was also tested in a single Brayton loop configuration and produced 14.8 kWe at 90 krpm and a TIT of 925 K.

When the system is installed at GRC a matrix of tests will be conducted in order to characterize the nature of the system. Steady-state tests will include operating the dual CBC at the system design point of 1000 K TIT and 90 krpm to produce maximum power; operating at equal speeds over a range of speeds and TIT values; operating one CBC over a range of speeds while the other CBC is held at a variety of fixed speeds; operating one CBC while the other CBC is standby; and repeating previous test operating points at different system pressures. Other tests will include studying the effects of starting the system in simultaneous and staggered fashion, or shutting down one CBC and restarting it while the other remains operational. System startup and shutdown will also provide data for transient operation. Test results will be used to validate a system analytical model.

Testing to date has shown that a dual Brayton system can operate with a common gas inventory and a common heat source, and further testing is required to better understand the system behavior. The dual Brayton concept could prove to be valuable for making a gas cooled nuclear reactor directly coupled to a dynamic power conversion system a viable candidate for potential space power applications.

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14. ABSTRACT The dual Brayton power conversion system constructed for NASA Glenn Research Center (GRC) was acceptance tested April 2007 at Barber-Nichols, Inc., Arvada, Colorado. This uniquely configured conversion system is built around two modified commercial Capstone C30 microturbines and employs two closed-Brayton-cycle (CBC) converters sharing a common gas inventory and common heat source. Because both CBCs share the gas inventory, behavior of one CBC has an impact on the performance of the other CBC, especially when one CBC is standby or running at a different shaft speed. Testing performed to date includes the CBCs operating at equal and unequal shaft speeds. A test was also conducted where one CBC was capped off and the other was operated as a single CBC converter. The dual Brayton configuration generated 10.6 kWe at 75 krpm and a turbine inlet temperature of 817 K. Single Brayton operation generated 14.8 kWe at 90 krpm and a turbine inlet temperature of 925 K.					
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