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Impact of Closed Brayton Cycle Test Results on Gas Cooled Reactor Operation and Safety

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Abstract –*This report summarizes the measurements and model predictions for a series of tests supported by the U.S. Department of Energy that were performed using the recently constructed Sandia Brayton Loop (SBL-30). From the test results we have developed steady-state power operating curves, controls methodologies, and transient data for normal and off-normal behavior, such as loss of load events, and for decay heat removal conditions after shutdown. These tests and models show that because the turbomachinery operates off of the temperature difference (between the heat source and the heat sink), that the turbomachinery can continue to operate (off of sensible heat) for long periods of time without auxiliary power. For our test hardware, operations up to one hour have been observed. This effect can provide significant operations and safety benefits for nuclear reactors that are coupled to a Brayton cycles because the operating turbomachinery continues to provide cooling to the reactor. These capabilities mean that the decay-heat removal can be accommodated by properly managing the electrical power produced by the generator/alternator. In some conditions, it may even be possible to produce sufficient power to continue operating auxiliary systems including the waste heat circulatory system. In addition, the Brayton plant impacts the consequences of off-normal and accident events including loss of load and loss of on-site power. We have observed that for a loss of load or a loss of on-site power event, with a reactor scram, the transient consists initially of a turbomachinery speed increase to a new stable operating point. Because the turbomachinery is still spinning, the reactor is still being cooled provided the ultimate heat sink remains available. These highly desirable operational characteristics were observed in the Sandia Brayton loop. This type of behavior is also predicted by our models. Ultimately, these results provide the designers the opportunity to design gas cooled reactor Brayton plants such that the system is inherently capable of dealing with a variety of off-normal and accident conditions.*

I. INTRODUCTION

Gas Cooled Reactors (GCR) that drive Closed Brayton Cycle (CBC) power conversion systems are being evaluated by the U.S. Department of Energy for high-efficiency electricity generation (1). The reactor design community's understanding of these systems is limited because only a few closed Brayton cycles have ever been developed (2), and the experience with reactor driven Brayton cycles is even more limited (3). This paper describes recent results of an experimental research program at Sandia National Laboratories that is based on operating a recently constructed closed cycle Brayton loop. The test loop is called the Sandia Brayton Loop (SBL-30). It can currently produce 10 kWe and operates at 96,000 rpm with a turbine inlet temperature of 900 K (4 & 5). In addition to having the hardware we have also developed an integrated dynamic system model of reactor-driven closed Brayton cycle systems (6,7 & 8). Our current efforts are focused on operating the loop, and validating and improving the models, by performing a variety of transient tests and by using various coolants, inventory fill pressures, and other control mechanisms.

Based on our operating experience, we have observed that Brayton cycle power plants have a number of highly desirable operating characteristics that can provide inherent cooling and safety capabilities not typically observed in steam power plants. This report describes the general operating characteristics of these Brayton cycle plants through a series of measured (and modeled) steady-state curves that predict the generated electrical power as a function of rpm (shaft speed) for various turbine inlet temperatures. We call these curves the operating power curves (9). The operating curves are very useful and can be used to predict the behavior of the plant at fixed or at variable speed, and during normal and off-normal conditions. This report also describes the transient behavior of the Brayton loop by way of two experiments that illustrate the inherent cooling and safety capabilities of Brayton cycles.

The first transient experiment to be described illustrates the self-sustained cooling capabilities of the Brayton cycle in a “Decay Heat Removal” test (11). In this test the reactor simulator (electrical heater) power was turned off and the shaft speed of the turbo-alternator-compressor was initially reduced but kept at a value that allowed 500 W of electrical power to be produced by the alternator. During this test, positive power (500 W) was generated from the sensible heat that remained in the heaters and other structure for over one hour. This test illustrates that, provided certain thermal conditions are met, the Brayton cycle can continue to operate off of the temperature difference between the heat source and the heat sink. The thermal conditions that must be met require a sufficiently high turbine inlet temperature and availability of the heat sink. Under these conditions the turbine can produce sufficient power to operate both the compressor and the alternator/generator. No external power is required to keep the turbomachinery spinning. In fact electrical power can be produced and used provided proper power conditioning is available. Furthermore reactor cooling continues and can be maintained for very long times.

The second transient experiment describes an off normal event that actually occurred in our loop. During this test, the turbomachinery controller stopped functioning (due to over current fault) and the electrical load was lost. When this transient occurred the turbomachinery increased its shaft speed to a new but stable rpm and then slowly dropped in speed while the turbomachine kept spinning and kept removing heat from the heater. The heater temperature slowly decreased because the supervisory controller (which was still operating) turned off the heater power (equivalent to scram). The free wheeling coast down of the turbomachine consisted of a slow speed reduction that lasted for over 11 minutes even though we had no ability to control the load or shaft speed. This test illustrates the inherent ability of the turbomachinery to operate in a stable and predictable manner while continuing to cool the reactor even during very adverse off-normal conditions including loss of load and loss of feedback control of the loop.

The authors believe that CBC power systems can offer some inherent cooling and safety advantages over steam power plants provided the design of the power plant takes advantage of these capabilities. These advantages exist because the Brayton systems continues to operate and remove heat from the reactor during a number of off-normal conditions, including loss of on-site power, loss of load events. These features also make it relatively easy to deal with decay heat by properly managing the sensible heat within the system. Furthermore, it is even possible to generate sufficient power (for many tens of minutes to hours, depending on design) to keep the main or auxiliary pumps/circulators (such as the waste heat rejection pumps) operating. We believe that with proper design, this inherent cooling capability of the gas turbine engine can provide enhanced safety for reactors cooled with CBC systems.

II. REPORT OUTLINE

The body of this report first describes the Sandia Brayton loop. This is followed by a very brief summary description of the Brayton cycle dynamic model that is used to analyze the behavior of the loop. A description of the predicted and measured operational power curves is then presented. These curves are can be used to predict the consequences of various normal and off-normal events. The last section of the report describes two transients that illustrate the utility of the operating power curves and the inherent ability of the Brayton cycle to provide cooling and enhanced safety measures for these systems.

III. SANDIA BRAYTON LOOP (SBL-30)

After performing a feasibility study on how best to fabricate an inexpensive closed Brayton cycle test loop, Sandia contracted Barber-Nichols Corporation (11) to design, fabricate, and assemble an electrically heated CBC system. The system design is based on modifying commercially available micro-turbine power plants (4, 5). This approach was taken because it was the most cost effective, as all the rotating components, the recuperator, the gas bearings, and the control components could be reused. In addition, it only required modifying the housing to permit the attachment of an electric heater and a water cooled chiller. The recuperated test loop uses a 30 kWe Capstone C-30 gas-micro-turbine that normally operates at 1144 K turbine inlet temperature (TIT) with a shaft speed of 96,000 rpm (12). Figure 1 shows the test loop as assembled and operating at Sandia. A more detailed description of the loop is provided by Wright (4, 5). Currently the loop is heated by a 63 kWe heater and is limited to a 900 K turbine inlet temperature. Working fluids of air, nitrogen, carbon dioxide, and mixtures of argon-nitrogen and argon-helium have been used in the loop. We have been operating the loop for over one year and are currently modifying it to add bypass flow control capabilities.

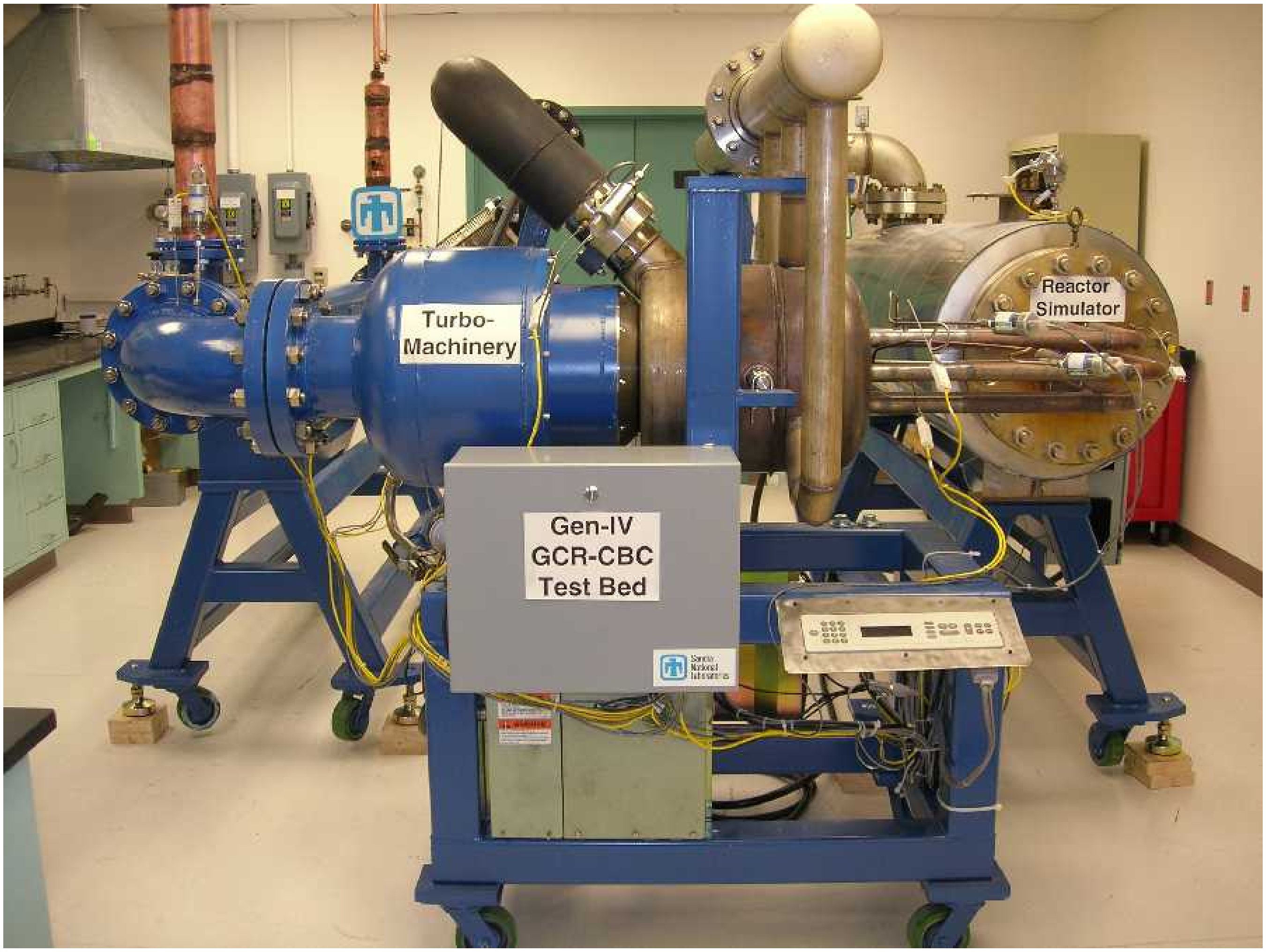

Figure 1: Photo of the Sandia Brayton Loop (SBL-30) installed at Sandia The water cooled gas chiller is on the left and the electrical heater is on the right. The alternator is inside the blue turbomachinery housing while the compressor, turbine and recuperator are hidden within the stainless steel cylindrical housing and the controllers are mounted to the center frame.

IV. DYNAMIC SYSTEMS MODEL

The CBC dynamic model equations were first described in the proceedings of the "1st International Energy Conversion Engineering Conference" (6). A more detailed version of these equations is solved in the Sandia Reactor Power and Control System Simulator (RPCSIM) model which is implemented in Simulink^{TM} (7, 8). Simulink^{TM} is a development environment packaged with MatLab^{TM} (13, 14) that allows the creation of dynamic state flow models.

The RPCSIM dynamic model requires detailed compressible flow models for the radial turbine and compressor. These flow models are obtained from mean line compressible flow analysis methods and codes (15, 16). The major assumption made by RPCSIM is that the mass flow rate is constant everywhere around the loop. With this assumption every component must simply determine the outlet temperature and pressure of the coolant or fluid given the initial inlet temperature, pressure and mass flow rate. RPCSIM has building blocks that solve the momentum and energy equations for ducts, heat exchangers, recuperators, and radiators. It also has a point kinetics reactor model, as well as models for quasi-static compressible flow in the turbine and compressor A nonlinear stiff differential equation solver is used to iteratively solve for a consistent set of temperatures, pressures, and mass flow for all components in the CBC loop with the constraint that the total gas inventory remains constant (or varies in a known way) throughout the loop.

Other models are also required for the alternator, turbo-compressor-shaft speed and control systems.

The current set of equations used by RPCSIM ignores the inertia of the coolant mass and also assumes that the temperature of the coolant reaches its equilibrium temperature in a single time step. These assumptions limit the applicability of the flow rate to time scales that are greater than about 0.1-0.3 seconds.. Also because the reactor and CBC components are relatively massive, the thermal behavior of the combined system changes very slowly (1000's of seconds for the Sandia Brayton loop). Therefore, the thermal transients are not greatly affected by neglecting the inertial momentum of the fluids within the model. The great benefit of these assumptions is that the transient behavior of a complete CBC system can be rapidly solved. Typical problems can run 100 to 1000 times faster than real time.

In addition a simple steady-state version of the reactor driven closed Brayton cycle equation set was developed (4). This equation set was solved to determine the power versus shaft speed curve (from 20,000-90,000 rpm) for the Sandia Brayton loop. The average turbine inlet temperature was treated parametrically and varied from 500 K to 880 K. Figure 2 shows the shape of these "operating" power curves as predicted by the simple lumped-parameter model.

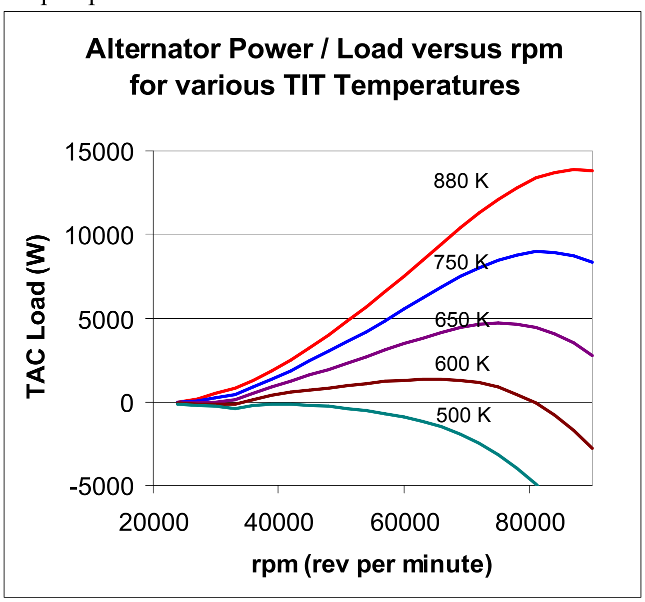

Figure 2: SBL-30 lumped-parameter model predictions for the generated electrical power as a function of shaft speed for fixed turbine inlet temperatures for nitrogen at 1 atmosphere fill pressure.

The non-linear nature of these curves is illustrated by the fact that for a specified load (generated electrical power) the solution has two shaft speeds. The higher speed solution with negative slope is dynamically stable, but the positive sloped solution at lower speeds is preferable, even though it is dynamically unstable, because it has higher efficiency. A dynamic feedback load-control system (which is part of the Capstone inverter/controller) is required to operate on the positive sloped portion of the curve.

Also observe in Figure 2 that if the turbine inlet temperature is too low (approximately <500 K based on this simple model) that the alternator must be motored to spin the turbo-alternator-compressor (TAC). Above this "break-even" temperature the CBC loop can produce positive power provided the shaft speed does not get too high. Thus overall, there is a minimum temperature below which the TAC is not self-sustaining. The predicted self-sustaining TIT is 500 K, but as shown in the next section the measured value is closer to 650 K.

V. MEASURED OPERATING POWER CURVE

One of our first series of experiments was aimed at measuring the shape of the operating power curve that was predicted by the simple models. Figure 3 shows a summary plot of the results of this series of tests. The turbine inlet temperature was parametrically varied from 600 K to 880 K in this plot. The measured operating curves (Figure 3) show the same trends as predicted and shown in Figure 2. Specifically they show that there is a self-sustaining turbine inlet temperature (TIT), and it also verifies the non-linear behavior by validating that there are two steady-state shaft speeds for each load.

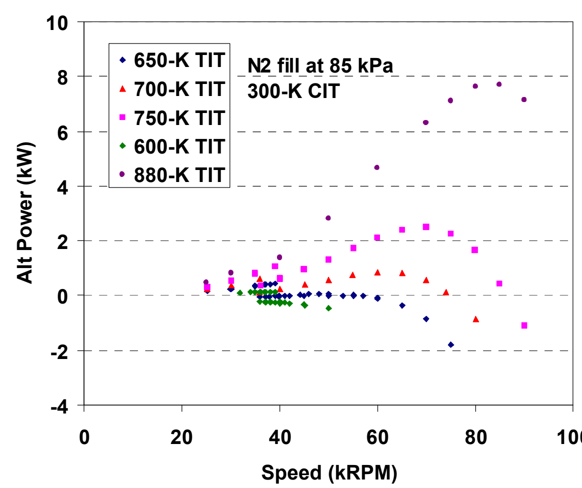

Figure 3: Measured operating power curve for the Sandia Brayton Loop. The curve shows the measured generated alternator power as a function of shaft speed for fixed turbine inlet temperatures that were varied parametrically from 600 K to 880 K

For the nitrogen working fluid at one atmosphere of fill pressure, the threshold TIT for self-sustaining operation is about 650 K, as shown by the dark blue points in Figure 3. At low temperatures and low shaft speeds we expect differences between the model predictions and the measured data because the flow curves for the compressor and turbine are inaccurate. The flow curves were developed for high speed and high temperature operations, but they are being extrapolated to low flow. At high temperature (880 K TIT) and flow the measured peak power (8 kWe) is less than predicted by the simple lump-parameter model (13 kWe) because the simple model does not take into account thermal losses, pressure drop losses, windage, and electrical losses. However, the dynamic model does account for these effects and the predictions are much closer to the observations (9). Over all, the models correctly predict the major trends and magnitude of the cooperating curves.

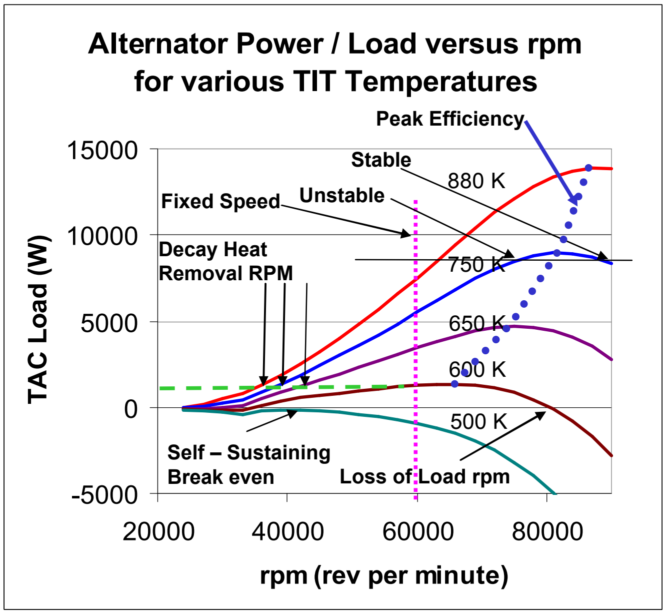

Figure 4: Operating curve significance showing operations at peak efficiency, fixed speed, dynamically stable and unstable speeds, loss of load rpm and speed increase observed in the Decay Heat removal test.

The utility of the operating curve is shown in Figure 4. In this figure a variety of operating scenarios are predicted and indicated on the plot. The peak efficiency occurs at the maximum of the power curve (blue dotted line). If the system were operated at fixed frequency, as would be required if a synchronous generator were used, the pink dotted line shows that the only way to change power is by changing the turbine inlet temperature. This is of course very undesirable, so the traditional way to change the power is to change the fill gas inventory (pressure). The operating curve is valid for a single fill pressure (inventory), thus it does not show this effect, but it does reveal the need to provide a method for inventory control. The non-linear nature of the operating curve and the dynamically stable and unstable points are also illustrated in the curve for fixed load and fixed TIT (e.g. 8 kWe at 750 K).

The operational curves also predict the behavior observed in the two transient tests that are presented next in this report. In the decay heat transient it was observed that to maintain a fixed power generation of 500 W, it was necessary to increase the TAC shaft speed as the heater cooled. This effect is illustrated by the green dashed line in Figure 4. Similarly for the loss of load and free wheeling coast down transient, the shapes of the curves (at fixed TIT) predict that the shaft speed will increase to a new but higher rpm indicated by the zero load line. Then as the TIT cools the shaft speed will slowly decrease until self-sustaining operations are no longer possible. Again this is just what was observed. Of course to deal with this type of transient the turbomachinery must be designed to withstand the higher zero load rpm.

VI. DECAY HEAT REMOVAL TEST

The Sandia Brayton loop was used to provide an illustrative example of self-sustained flow in a CBC system shortly after reactor shut down when it is important to remove decay heat. The decay heat removal test was performed in August 2005 (10). A summary of the recorded data for this test is shown in Figure 5. The top portion of the plot shows the gas coolant temperatures and the water cooling temperatures. The central region shows the pressures, and the bottom shows both the alternator power and the shaft speed. The test had multiple objectives. The first objective was to measure the operating power curve at 880 K. During this phase of the test the turbine inlet temperature was brought to 880 K and kept at that temperature while the shaft speed was reduced from 90,000 rpm to 25,000 rpm. The alternator power levels (blue line) were recorded for each shaft speed during this portion of the test which lasted for about 20,700 seconds.

At 20,700 seconds the decay portion of the test began when the electrical heater power was turned off. At this time the shaft speed was manually adjusted to keep the alternator power at 500 W. Because the shaft speed was already low at this time (approximately 25,000 rpm) the TIT could be kept at high levels for long times because the low flow would remove heat at a lower rate.

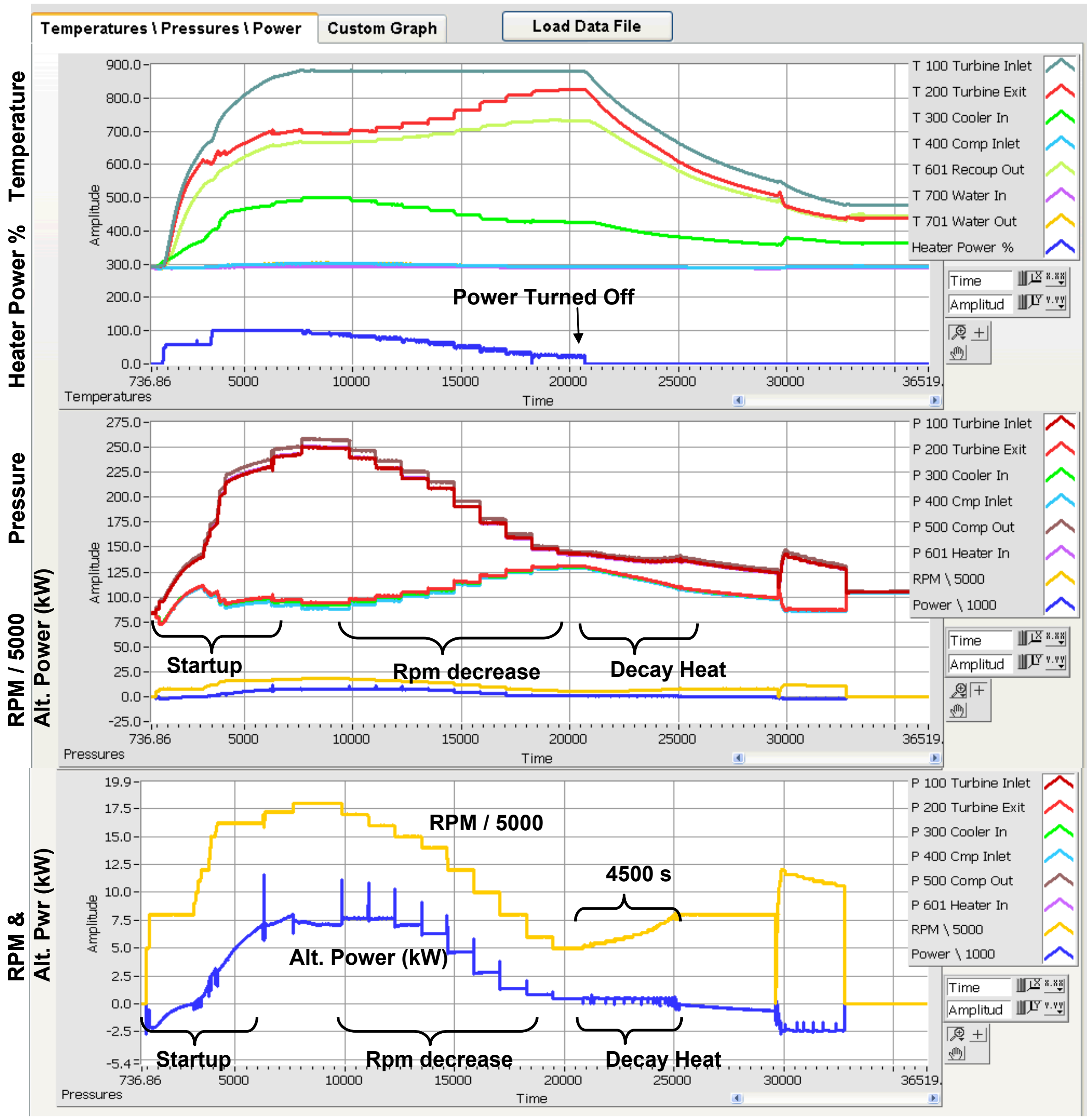

Figure 5: Summary plot of decay heat removal test. The top curves show gas and water cooling temperatures, the central curves show the gas pressure and the bottom curves show the alternator power and shaft speed. The heater power was turned off at 20,700 s. The rpm was adjusted to keep the reported alternator electrical power at 500 We. State point temperatures, flow, and shaft speed are shown.

The bottom set of curves in Figure 5 shows that from 20,700 s to 25,200 seconds (a duration of 4500 s) the alternator power was kept at approximately 500 W, but the shaft speed had to increase from 25,000 rpm to 40,000 rpm while the TIT declined from 880 to 650 K (see the top set of curves). Note that once the TIT fell below the self sustaining operating temperature (650 K, at 25,200 s) the generated alternator power fell to negative levels indicating that we had to motor the TAC set.

The key to prolonging the duration of self-sustained flow is to keep the shaft speed as low as possible so that the heat transported from the reactor/heater is minimized. This also allows time for the decay heat levels to fall to negligible levels. Once the power was turned off in the test, it was necessary to slowly increase the shaft speed from 25,000 to 40,000 rpm over a period of time lasting 4500 seconds (see gold line in the bottom plot of Figure 5). Note that during this time the flow rate gradually increased because the rpm levels were increasing even though the

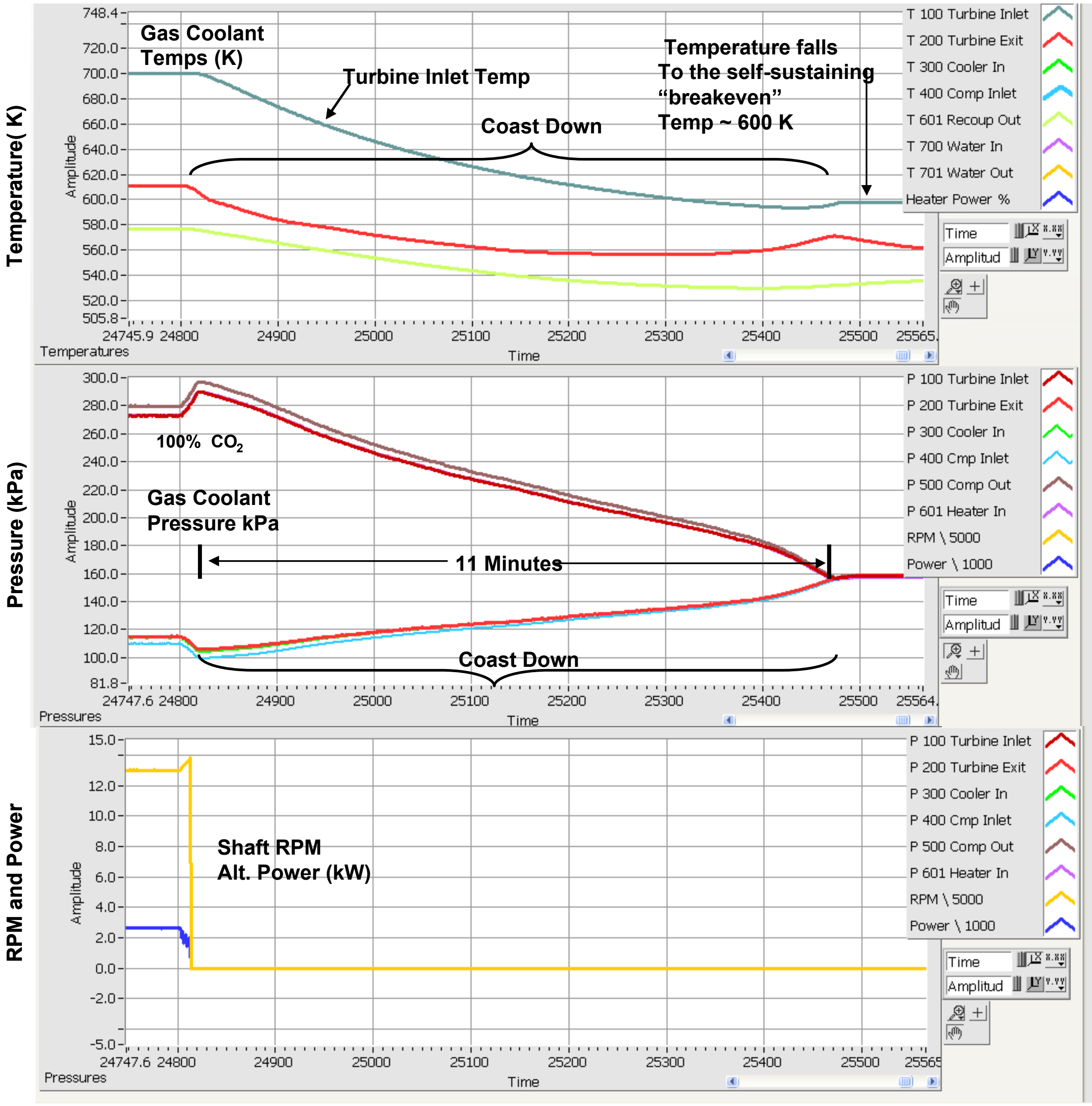

Figure 6; Summary plot of loss of load and free wheeling coast down transient. The top curves show gas and water cooling temperatures (K), the central curves show the gas pressure and the bottom curves show the alternator power and recorded shaft speed. The actual shaft speed decreased from 70,000 rpm to 0 over a period of 11 minutes.

power generated in the alternator was kept constant. This type of behavior was predicted by the operating power curves (see green dashed line Figure 4) and by the dynamic models (SS Reno).

VII. FREE WHEELING COAST DOWN

The "free wheeling" coast down transient experiment describes an off normal event that actually occurred in our loop. The test was performed in May 2006 for the DOE Generation IV program. In this test the working fluid was CO_2 not nitrogen. When the off-normal transient occurred we were attempting to map out the operating curve at 700 K by increasing the rpm from 65,000 rpm to 70,000 rpm.

This caused the high pressure leg of the loop to increase in pressure (see 24,800 s). The peak pressure reached 290 kPa, which was near our operational limit, so the master real time controller requested a reduction in shaft speed. This caused a momentary increase in electrical power that exceeded the capability of the power inverters. The Capstone controller protective circuits dropped the power generation capability and stopped responding to the master controller. At this time the electrical power generation was near zero.

The over all effect was that the turbomachinery increased its shaft speed to a new but stable rpm indicated by the zero power load line at the 700 K TIT. The reduction in alternator power can be seen in the blue line shown in the bottom curve of Figure 6. Then the shaft speed slowly dropped in speed while the turbomachine kept spinning and kept removing heat from the heater. The Capstone controller was no longer reporting the rpm to the master controller hence the recorded data shows the rpm at zero. In fact the TAC kept spinning as indicated by the pressure data (middle curves in figure 6.) The heater temperature slowly decreased because the master controller turned off the heater power (equivalent to a scram). The free wheeling coast down of the turbomachine consisted of a slow speed reduction that lasted for over 11 minutes even though we had no ability to control the load or shaft speed. This test illustrates the inherent ability of the turbomachinery to operate in a stable and predictable manner while continuing to cool the reactor even during very adverse off-normal conditions including loss of load and loss of feedback control of the loop.

VIII CONCLUSIONS

This report describes results from our operations of a recently constructed closed Brayton cycle and shows that Brayton cycle power plants have a number of highly desirable operating characteristics that can provide inherent cooling and safety capabilities not typically observed in steam power plants. The general operating characteristics of these Brayton cycle plants was shown in both measured and modeled steady-state curves that predict the generated electrical power as a function of shaft speed for various turbine inlet temperatures. These curves are called the "operating" power curves. The operating curves are very useful and can be used to predict the behavior of the plant at fixed or at variable speed, and during normal and off-normal conditions. This report also describes the transient behavior of the Brayton loop by way of two experiments that illustrate the inherent cooling and safety capabilities of Brayton cycles.

The first transient illustrates the self-sustained cooling capabilities of the Brayton cycle in a "Decay Heat Removal" test. This test illustrates that provided the self sustaining turbine inlet temperature is exceeded; the Brayton cycle can continue to operate off of the temperature difference between the heat source and the heat sink. No external power is required to keep the turbomachinery spinning;, and in fact electrical power can be produced.. Furthermore reactor cooling continues and can be maintained for very long times (hours).

The second transient describes an off normal event that actually occurred in the Sandia loop. During this test, the turbomachinery controller stopped functioning and the electrical load was lost. When this transient occurred the turbomachinery increased its shaft speed to a new but stable rpm and then slowly dropped in speed while the turbomachine kept spinning and kept removing heat from the heater. The free wheeling coast down of the turbomachine consisted of a slow speed reduction that lasted for over 11 minutes even though we had no ability to control the load or shaft speed. This test illustrates the inherent ability of the turbomachinery to operate in a stable and predictable manner while continuing to cool the reactor even during very adverse off-normal conditions including loss of load and loss of feedback control of the loop.

The authors believe that CBC power systems offer some inherent cooling and safety advantages over steam power plants provided the design of the power plant takes advantage of these capabilities. These advantages exist because the Brayton system continues to operate and remove heat from the reactor during a number of off-normal conditions, including loss of on-site power, loss of load events. These features also make it relatively easy to deal with decay heat by properly managing the sensible heat within the system. We believe that with proper design, this inherent cooling capability of the gas turbine engine can provide enhanced safety for reactors cooled with CBC systems.

ACKNOWLEDGMENTS

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NOMENCLATURE

TIT Turbine Inlet Temperature
TOT Turbine Outlet Temperature
HIT Heater Inlet Temperature
GCR Gas Cooled Reactor
CBC Closed Brayton Cycle
TAC Turbo-Alternator-Compressor
rpm shaft speed in revolutions per minute
RPCSIM Reactor Power and Control SIMulator
SBL Sandia Brayton Loop

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