NASA/TM—2010-215843 NETS–2009–204416

Test Results From a Direct Drive Gas Reactor Simulator Coupled to a Brayton Power Conversion Unit

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February 2010

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Prepared for the
Nuclear and Emerging Technologies for Space (NETS–2009)
sponsored by the American Nuclear Society and the American Institute of Aeronautics and Astronautics
Atlanta, Georgia, June 14–18, 2009

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

February 2010

Acknowledgments

The work in this paper was performed for the NASA Exploration Technology Development Program and the Fission Surface Power Project. The authors would like to thank David Riquelmy (BAE Systems), Kenny Webster (NASA MSFC), Maxwell Briggs (NASA GRC) and A. Karl Owen (NASA GRC) for their assistance with software development and system testing.

Level of Review: This material has been technically reviewed by technical management.

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Abstract

Component level testing of power conversion units proposed for use in fission surface power systems has typically been done using relatively simple electric heaters for thermal input. These heaters do not adequately represent the geometry or response of proposed reactors. As testing of fission surface power systems transitions from the component level to the system level it becomes necessary to more accurately replicate these reactors using reactor simulators. The Direct Drive Gas-Brayton Power Conversion Unit test activity at the NASA Glenn Research Center integrates a reactor simulator with an existing Brayton test rig. The response of the reactor simulator to a change in Brayton shaft speed is shown as well as the response of the Brayton to an insertion of reactivity, corresponding to a drum reconfiguration. The lessons learned from these tests can be used to improve the design of future reactor simulators which can be used in system level fission surface power tests.

I. Introduction

Component level tests of fission surface power systems typically do not require a nuclear heat source to obtain valuable data. Consequently, these tests have utilized relatively simple electric heaters, which do not accurately replicate proposed reactors (Ref. 1). However, as testing transitions from the component level to the system level, the interaction between the reactor and the rest of the system becomes important and a more accurate representation of the reactor is required.

The Direct Drive Gas (DDG) heater is an electric heater which mimics the geometry of a fast neutron gas-cooled reactor concept. The thermal output of the DDG is controlled by a simulated reactivity feedback controller. DDG geometry allows for assessment of the hydraulic and heat transfer performance of the proposed design, while the controller allows for assessment of the reactor's transient response.

The Brayton Power Conversion Unit (BPCU) is a closed Brayton cycle power conversion unit which has previously been used in both solar dynamic and ion thruster testing at GRC (Refs. 2 and 3) The DDG-BPCU test described below integrated the DDG into the BPCU test loop. Various characterization tests were run to determine important test parameters, such as thermal time constants. After characterization was complete, the reactor's response to a change in Brayton shaft speed was observed, followed by the Brayton response to a change in simulated reactivity insertion.

II. Test Rig Description

The testing was performed in Vacuum Facility 6 (VF6) of Building 301 at the NASA Glenn Research Center in Cleveland, Ohio. The BPCU/DDG test rig as installed in the endbell of VF6 is shown in Figure 1. All electrical, instrumentation, and fluid connections are provided to the unit via tank wall feedthroughs. Three instrumentation racks house the BPCU Power Management And Distribution (PMAD), data acquisition, and BPCU test support equipment control electronics. Additional equipment supporting the testbed operation includes the gas loop charging system, DDG gas heater power supply, a waste heat water chiller, and the DDG controller and data acquisition.

The DDG requires that cooling gas flow be available before power can be applied. The BPCU provides this gas flow by operating the alternator as a motor to spin the rotor shaft. The gas temperature at the turbine inlet continues to rise until a self sustaining condition occurs. This condition is reached at a turbine inlet temperature of approximately 700 K. At this point, the BPCU automatically switches to an alternator function, generating AC power.

A. Brayton Power Conversion Unit (BPCU)

The BPCU is a fully integrated power conversion system including a common shaft turbine-alternator-compressor, recuperator, and gas cooler connected by gas ducts. The rotating assembly is supported by gas foil bearings and consists of a turbine, compressor, thrust rotor, and alternator on a single shaft. The gas loop is designed to use a working fluid of 62.7 mole % Helium and 37.3 mole % Xenon gas mixture with an average molecular weight of 83.8 g/mol. It can also use 100 percent Krypton but performance is reduced by the lower heat transfer coefficients. It is designed to produce an AC electrical power output of up to 2 kWe on He-Xe at an operating point of 1100 K heater exit temperature, 283 K compressor inlet temperature, and 52,000 rpm shaft speed.

Waste heat is removed from the gas loop via a commercial gas-to-liquid cooler using ethylene glycol on the liquid side. Multi-Foil Insulation (MFI) is used to cover all the high temperature components (Ref. 1) to minimize radiative heat loss in the vacuum environment, The Brayton cycle gas loop was modified by removing the existing gas loop heater (Fig. 2) and replacing it with the DDG. A portion of the connecting gas tubing was removed and replaced by flexible high temperature hoses to account for thermal expansion. All connections between the DDG and BPCU were welded. To accommodate the added weight of the DDG, the original test support cart was replaced by one with a higher load capacity and the structural rails within the VF6 endbell were strengthened.

The BPCU is operated via a standalone PMAD system contained in a dedicated rack located outside of the vacuum chamber. The rack houses a DC load bank to regulate shaft rotational speed using parasitic loading. The BPCU shaft speed is held constant when the rotor torque is equal to the induced torque from the applied load. Reducing the applied loading increases shaft speed while increasing the loading decreases shaft speed. The power from the parasitic load is

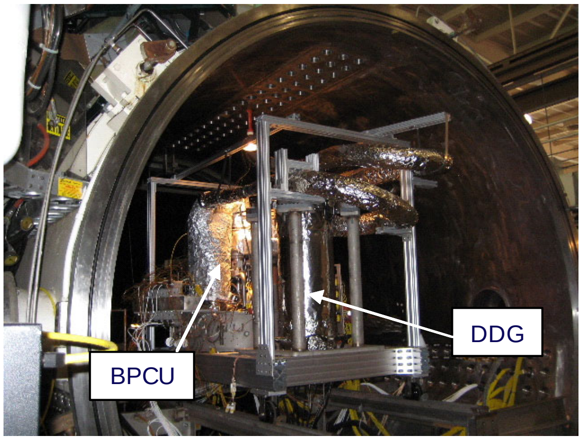

Figure 1.—BPCU/DDG as installed in Vacuum Facility 6.

Figure 2.—Previous BPCU gas heater (shown uninsulated).

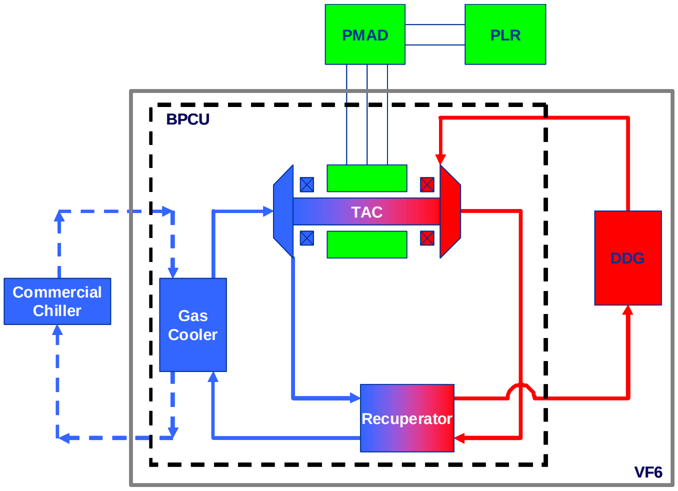

Figure 3.—DDG/BPCU test schematic.

dissipated into the air as waste heat. The PMAD also provides redundant and automatic overspeed shutdown protection for the turboalternator. Finally, this rack houses the electronics that operate the alternator as a motor during start-up.

The BPCU is instrumented with temperature and pressure transducers at pertinent state points relative to the thermodynamic cycle. A commercial AC power meter collects all power data. Shaft speed measurements were provided by a Hall Effect transducer, and the mass flow rates were calculated from the turbine and compressor maps.

A schematic of the overall DDG/BPCU test setup is shown in Figure 3.

B. Direct Drive Gas Heater (DDG)

The DDG heat source is a reactor simulator that uses electric resistance heaters to simulate the heat generated from nuclear fuel in a fast spectrum nuclear reactor. This system, used previously at the MSFC (Ref. 4), was redesigned to provide increased performance and allow straightforward integration with the Brayton system at GRC. This redesign involved replacement of the upper bonnet area with a more stream-lined and compact configuration while preserving fundamental design concepts including the use of a down-comer. It utilizes channels in a solid stainless steel core block for heat removal via a He/Xe mixture or Krypton gas. It has the ability to heat a mixture of He/Xe or other inert gas to deliver up to 15 kWe of power at an operational temperature of 1000 K, operational pressure of 689.5 kPa, and mass flow rates of up to 0.2 kg/s. The earlier DDG design included flanges and gaskets for access to internal components. The redesign, excluding the power and thermocouple feedthroughs, relies on all-welded construction to eliminate potential gas leak paths of the He-Xe mixture. Graphite resistance heaters, custom designed by MSFC, provide the simulated heat from nuclear fuel pins, and are grouped in four control zones. Each zone is comprised of 9 fuel pin simulators wired in series and independently powered by a dedicated power supply. Individual software control of each zone is possible if desired. The four zones are shown in a top-down view in Figure 4. The DDG gas flow path is shown in Figure 5. He-Xe flows along the outside surface of the core, enters a plenum area at the base of the core, flows up through the coolant flow channels around the heaters, reaches a second plenum area at the top of the core where it exits through a common flow channel and travels to the Brayton unit for energy extraction and power generation.

The DDG was instrumented with eight type K thermocouples. They were placed axially along the centerline of the DDG, along the outside of the core, and at the inlet and exit. Their relative locations are shown in Figure 6 and Table I. All temperature measurements were recorded on the DDG data acquisition system. Any one of these measurements can be used as the feedback parameter for the DDG controller.

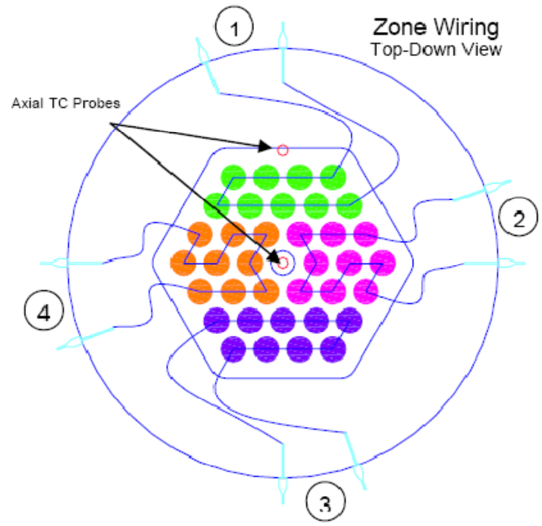

Figure 4.—DDG electrical wiring zones.

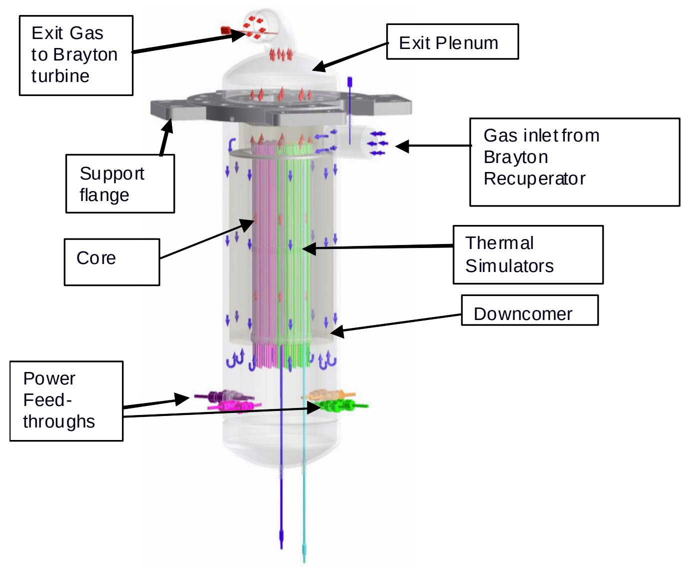

Figure 5.—DDG flow path.

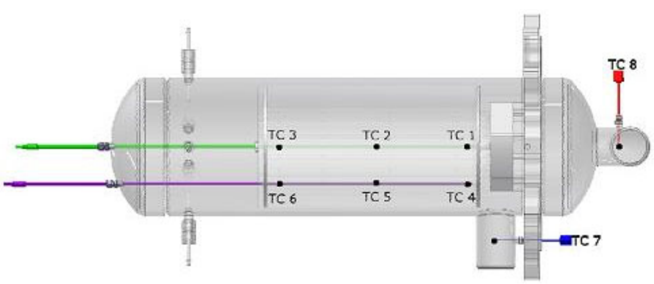

Figure 6.—Schematic of DGG thermocouple placement.

TABLE I.—DDG THERMOCOUPLE LOCATIONS

Number	Location
TC-1	Center Core, Exit End, 5 cm from core exit face
TC-2	Center Core, Center, 26.7 cm from core exit face
TC-3	Center Core, Entrance End, 48.3 cm from core exit face
TC-4	Center Side, Exit End, 5 cm from core exit face
TC-5	Center Side, Center, 26.7 cm from core exit face
TC-6	Center Side, Entrance End, 48.3 cm from core exit face
TC-7	Inlet gas temperature
TC-8	Exit gas temperature

C Test Rig Control and Operation

The BPCU and DDG are controlled independently of each other. The BPCU rotor speed and the DDG heat output are the two input variables affecting operation.

The control software for the DDG was developed in LabVIEW (National Instruments Corporation). Conceptually, it is based on a point kinetics model used in previous simulated reactor tests (Ref. 5), in which a characteristic core temperature is used as the feedback parameter for the control loop. The software consists of two parts: the realtime control software running on the Compact FieldPoint controller and the user interface software running on a Windows computer. The system is operated with its own isolated local area network. The embedded software that runs on the Compact FieldPoint controller is responsible for conducting measurements, setting outputs, monitoring for alarm conditions, and communicating measurements and setpoints with the host software on the Windows (Microsoft Corporation) computer. The host software provides the user interface.

III. Testing Summary

Testing was conducted in three phases consisting of: Heater Output Power Control Testing, Heater Exit Temperature (HET) Control Testing, and Simulated Reactivity Control Testing.

A. Phase I Testing- Heater Output Power Control Tests

This first round of tests examined the thermal response of the system to perturbations of heater output power and shaft speed and to provide initial operational checkout data of the integrated BPCU/DDG test rig. These tests allowed PID constants to be estimated for use in subsequent temperature control testing.

For this set of tests, steady-state conditions were defined as a HET change of less than 2° over a 10 min span. It was found that the test equipment required over 90 min to achieve “steady state” as defined above. Post-processing of the data revealed that although temperatures had reached HET steady-state, electric power output was still trending with time. Therefore, subsequent testing used electrical output power and/or heater input power to determine steady-state, as those were found to have the longest time constants. Since the heater power test was primarily performed to provide time constant estimates for input to the PID controller, the acquisition of true steady-state data was not required.

B. Phase II Testing-HET Control Tests

During Phase II testing a PID controller was used to vary the DDG input power to maintain a constant HET. These values of power and temperature were used as input values to the Phase III simulated reactivity control testing. The response of the system was compared with the simulated reactivity control response for speed perturbations. During temperature perturbations, heater power was controlled manually until HET was within 10 °C of the desired setpoint. At this point the PID controller was engaged. This was done to avoid high power transients commanded by the PID controller far away from the setpoint. When initiating a speed perturbation the PID controller was engaged the entire time, with no manual modifications.

C. Phase III Simulated Reactivity Control Tests

During the third phase of testing, a reactivity feedback control loop was used to control the heater output power to simulate the reactivity of a nuclear reactor. Two types of tests were completed. In the first test, the reactivity feedback control loop simulated the inherent response of the reactor to a step change in shaft speed. In the second series of tests a control drum maneuver was simulated by commanding the reactivity controller to simulate insertion of positive or negative reactivity. After the initial insertion command was given the simulator returned to simulating the inherent passive reactor response. A companion paper (Ref. 6) goes into considerable detail on the simulator methodology and results from the simulated reactivity testing.

IV. Testing Results

A. Comparison of Steady State Test Results with Prior BPCU Test Data

Reliable steady-state conditions were achieved during temperature control testing, allowing data points to be compared with similar BPCU operating conditions from prior testing with the original electric gas heater. The BPCU running with the DDG heater produced at least as much power as it produced using the previous electric heater, when operating at the same hot-end temperatures (Ref. 7). Although this comparison was not the primary focus of this testing, it demonstrates that BPCU performance did not change significantly as a result of integration with the DDG. This comparison is shown in Figure 7.

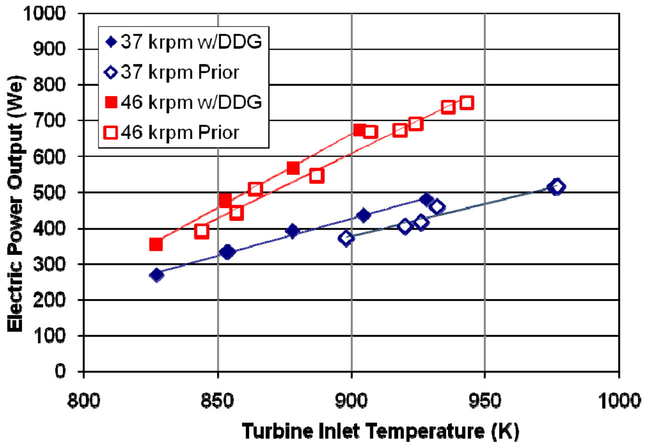

Figure 7.—DDG-BPCU test steady-state power output comparison.

B. System Transient Response Test Results

The following selected test results provide a comparison of the three different DDG control schemes in response to a negative step change in BPCU shaft speed which decreases the gas loop mass flow rate. In the first case, the DDG power is held constant at 5500 We (Fig. 8). The HET, which is not controlled, rises gradually in response to the reduction in mass flow. The alternator power initially drops and then begins to rise as the HET increases. This test point was discontinued when the HET exceeded 900 K.

In the second case, the DDG HET is held constant at 900 K under PID control (Fig. 9). In response to the reduced mass flow, the DDG heater power gradually declines. The alternator power output drops in response to the reduced mass flow and then stabilizes at a lower output power.

In the third case, no parameter is forced to remain constant, instead the DDG simulated reactivity control is used to simulate reactor response (Fig. 10). The BPCU alternator power response is similar to the PID control. The HET varies by a small amount but maintains a fairly constant value. The DDG simulated reactivity and heater input power both exhibit a damped waveform response.

C. Simulated Reactivity Insertion Test Results

Perhaps the most interesting test results are obtained by operating the DDG using reactivity control and introducing a simulated negative reactivity insertion (Fig. 11). It is noteworthy that the level of reactivity insertion is an order of magnitude greater than the DDG reactivity response from the phase III transient tests. The HET shows a damped waveform response and the overall reactivity response is almost a mirror image. The BPCU rotor speed is unaffected. However BPCU alternator output drops in a damped response fashion similar to the HET response.

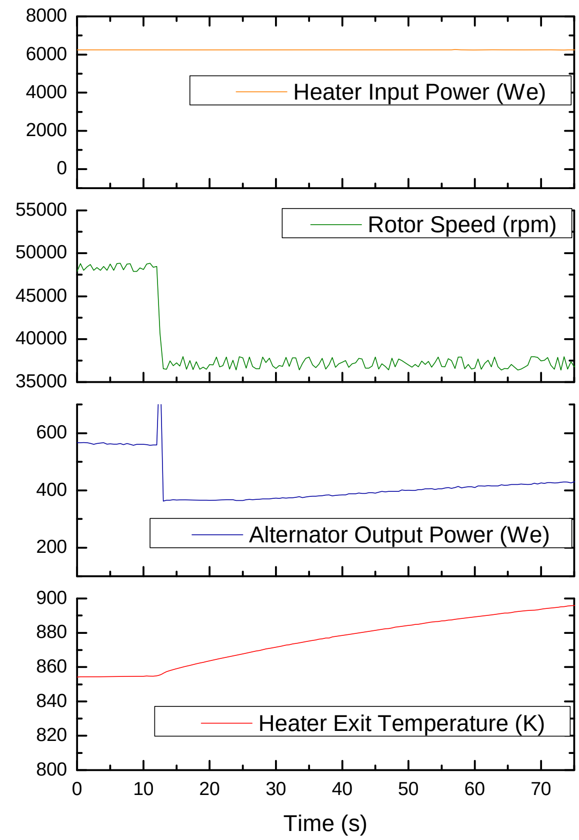

Figure 8.—System response at constant DDG power.

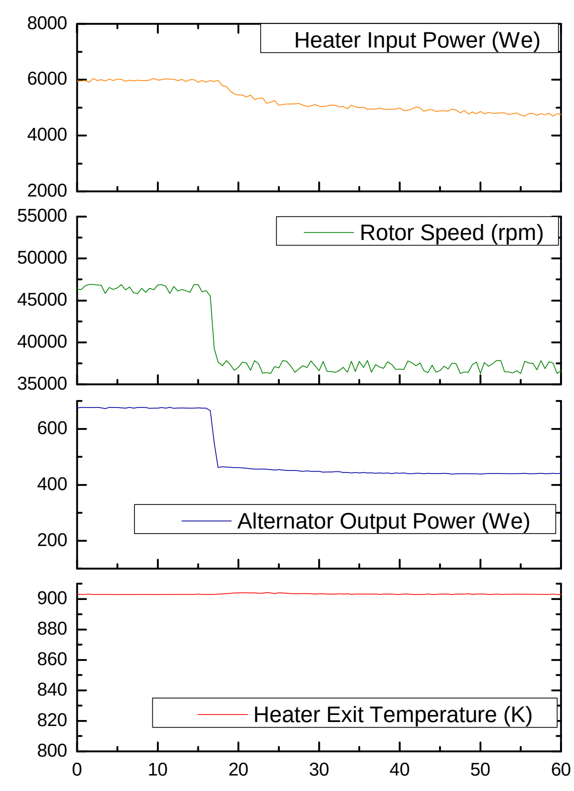

Figure 9.—System response using DDG PID HET control.

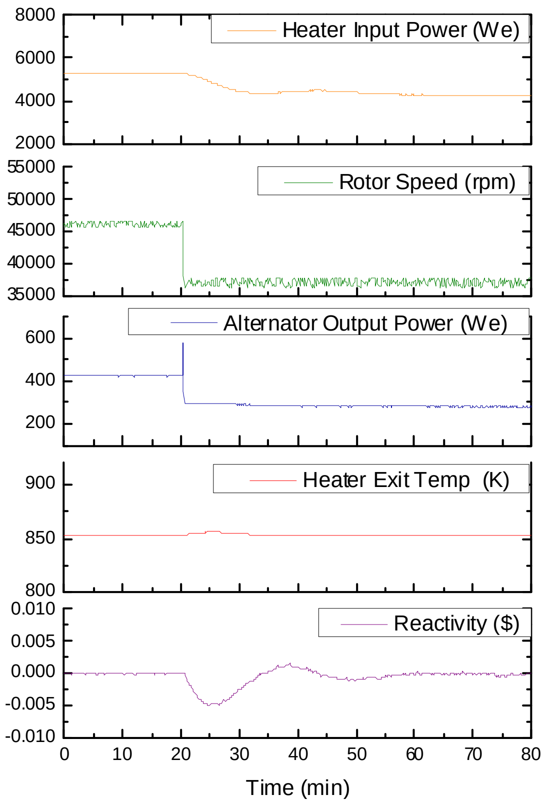

Figure 10.—System response using simulated DDG reactivity control.

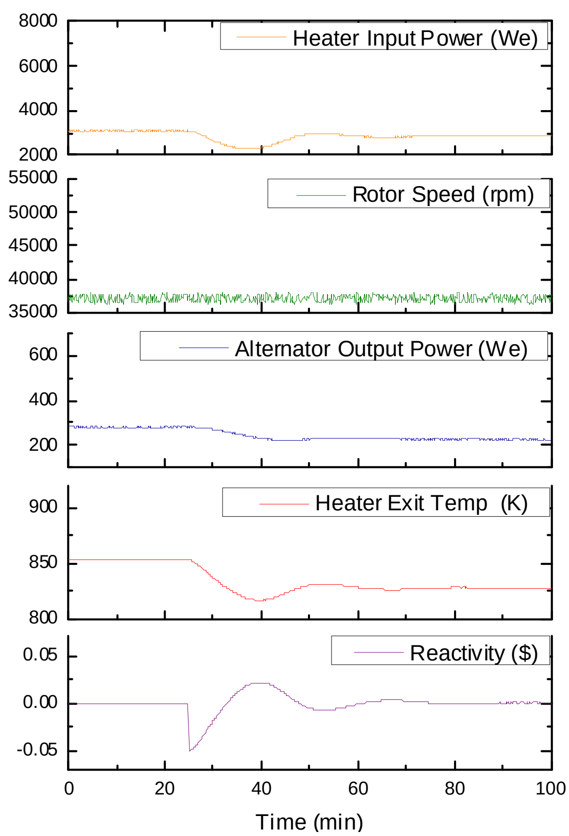

Figure 11.—DDG simulated reactivity response to a step change in shaft speed.

V. Conclusions

These tests demonstrated the viability of replacing a simple electrical resistance heater of an existing closed Brayton cycle power conversion unit with an electrically powered nuclear reactor simulator. Test results showed that the alternator electrical output of the BPCU was in good agreement with prior results within the range of temperatures and speeds tested. Furthermore, it showed that a nuclear reactor simulator integrated with a power conversion system can provide useful system response data. This type of testing can be used in future nuclear power system development efforts to minimize risk and help characterize system response.

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REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01-02-2010

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Test Results From a Direct Drive Gas Reactor Simulator Coupled to a Brayton Power Conversion Unit

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Hervol, David, S.; Briggs, Maxwell, H.; Owen, Albert, K.; Bragg-Sitton, Shannon, M.; Godfroy, Thomas, J.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 463169.04.03.04.02.02

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-17105

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2010-215843

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 44
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Component level testing of power conversion units proposed for use in fission surface power systems has typically been done using relatively simple electric heaters for thermal input. These heaters do not adequately represent the geometry or response of proposed reactors. As testing of fission surface power systems transitions from the component level to the system level it becomes necessary to more accurately replicate these reactors using reactor simulators. The Direct Drive Gas-Brayton Power Conversion Unit test activity at the NASA Glenn Research Center integrates a reactor simulator with an existing Brayton test rig. The response of the reactor simulator to a change in Brayton shaft speed is shown as well as the response of the Brayton to an insertion of reactivity, corresponding to a drum reconfiguration. The lessons learned from these tests can be used to improve the design of future reactor simulators which can be used in system level fission surface power tests.

15. SUBJECT TERMS
Thermodynamic cycles; Space power unit reactors; Gas turbines

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18