

Oral Presentation/Viewgraphs Summary:

A Direct Drive Gas-Cooled (DDG) reactor core simulator has been coupled to a Brayton Power Conversion Unit (BPCU) for integrated system testing at NASA Glenn Research Center (GRC) in Cleveland, OH. This is a closed-cycle system that incorporates an electrically heated reactor core module, turboalternator, recuperator, and gas cooler. Nuclear fuel elements in the gas-cooled reactor design are replaced with electric resistance heaters to simulate the heat from nuclear fuel in the corresponding fast spectrum nuclear reactor. The thermodynamic transient behavior of the integrated system was the focus of this test series. In order to better mimic the integrated response of the nuclear-fueled system, a simulated reactivity feedback control loop was implemented. Core power was controlled by a point kinetics model in which the reactivity feedback was based on core temperature measurements; the neutron generation time and the temperature feedback coefficient are provided as model inputs. These dynamic system response tests demonstrate the overall capability of a nonnuclear test facility in assessing system integration issues and characterizing integrated system response times and response characteristics.



National Aeronautics and
Space Administration



TEXAS A&M
UNIVERSITY

Testing of an Integrated Reactor Core Simulator and Power Conversion System with Simulated Reactivity Feedback

Authors:

Shannon M. Bragg-Sitton

Texas A&M University, Dept. of Nuclear Engineering, sitton@tamu.edu

David S. Hervol

NASA Glenn Research Center

Thomas J. Godfroy

NASA Marshall Space Flight Center

Outline



- Overview of nonnuclear test approach
- Test objectives
- Modeling reactor dynamics
- Previous hardware tests
- Brief overview of current test hardware:
 - Direct Drive Gas-Cooled reactor core simulator (DDG)
 - Brayton Power Conversion Unit (BPCU)
 - Instrumentation
 - See companion paper (Hervol, et al) for more info
- Test matrix and hardware limitations
- Results of simulated feedback testing
- Conclusions and future work



Overview of Nonnuclear Testing



TEXAS A&M
UNIVERSITY

- Allows evaluation of integrated system performance without use of nuclear materials
 - Validation of thermal hydraulic codes
 - Assess thermal hydraulic behavior in various regimes
 - Characterize stress/strain during operation
 - Verify integration processes
- So, what's the catch?
 - NO NEUTRONS!
 - System feedback is not characteristic of a fully fueled system without introduction of models to mimic the dynamic, neutronic response



Realistic Nonnuclear Testing: Objectives

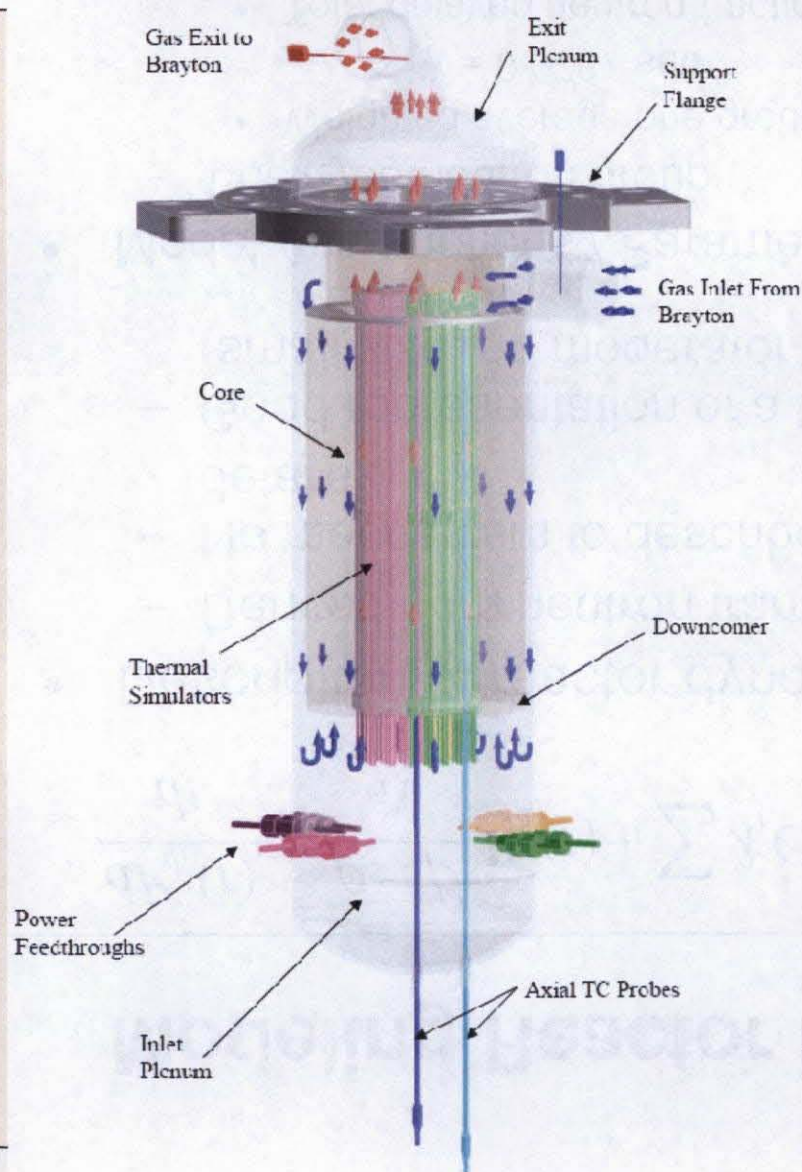


TEXAS A&M
UNIVERSITY

- Integration of thermal hydraulic hardware tests with simulated neutronic response to bridge electrically heated testing and full nuclear testing
- Demonstration of representative neutronic response of the fission system via computational models
- Demonstration of fission system response to changes in the state of the integrated power conversion system
- Dynamic system response tests can be used to:
 - Assess system integration issues
 - Characterize integrated system response times
 - Characterize integrated system response characteristics
 - Assess / enable potential design improvements at a relatively small fiscal investment



Realistic Nonnuclear Testing



- Goal: Implementation of advanced test methodology with realistic feedback components.
- Analysis of key nuclear feedback components in a specific reactor design and development of corresponding hardware control algorithms.
- Application of computational models to hardware in-the-loop tests.

Modeling Reactor Dynamics



$$\frac{dP_{th}(t)}{dt} = \frac{\rho - \beta}{\Lambda} P_{th}(t) + \sum_i \lambda_i C_i(t)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} P_{th}(t) - \lambda_i C_i(t)$$

- Description of reactor dynamics using the point kinetics model
 - Derived from neutron transport and diffusion theory
 - No mechanism to describe neutron energy effects or structural details
 - Good representation of a fast spectrum reactor (small size, no moderator to slow neutrons to lower energy)

- Model Assumptions / Parameters:

- 1 delayed neutron group:

- Weighted average one group decay constant (λ)

$$\lambda = 0.0767 \text{ sec}^{-1}$$

- Total delayed neutron fraction (β)

$$\beta = 0.00642$$

- Prompt neutron lifetime (Λ):

- Fast Reactor, $\Lambda = 10^{-7}$ sec

$$\lambda = \left(\frac{1}{\beta} \sum_i \frac{\beta_i}{\lambda_i} \right)^{-1}$$

$$\beta = \sum_i \beta_i$$



Reactivity Feedback



- Reactivity feedback in a fast spectrum reactor is relatively simple and negative
 - Mostly due to thermal expansion (which is a function of temperature)
- Use of a temperature based feedback model removes the variable of how this core expands relative to a different core concept (tested core is non-prototypic of any particular design)
- Reactivity feedback can be represented by a single temperature feedback coefficient (α_T):

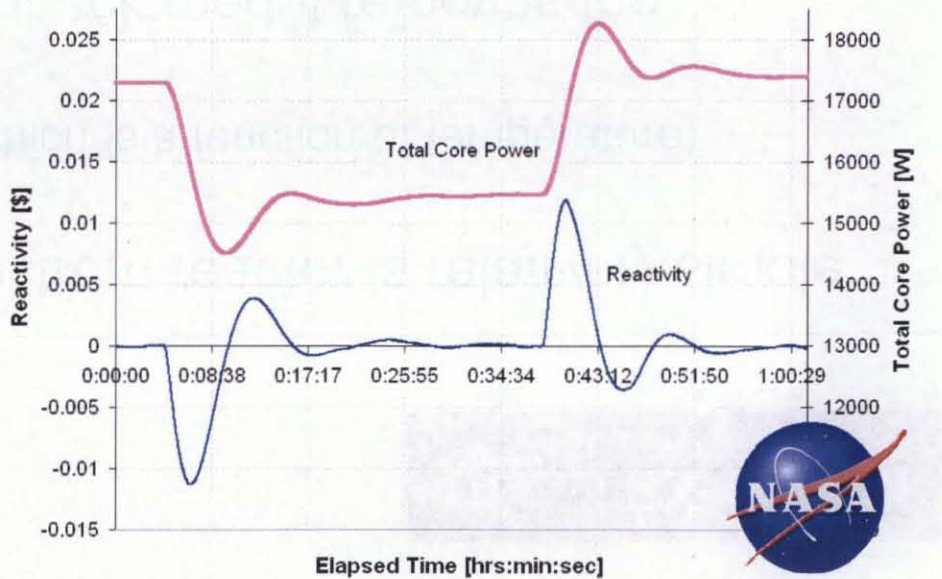
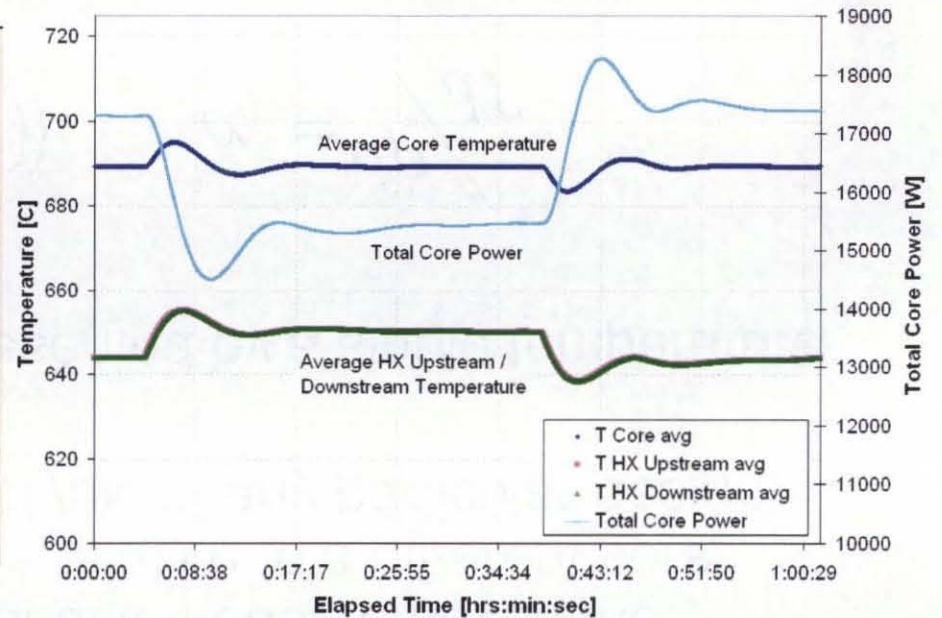
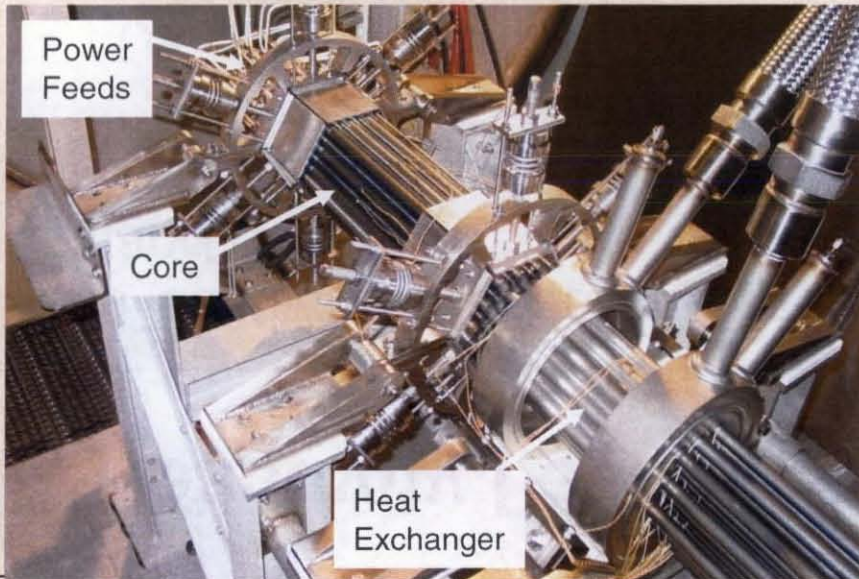
$$\rho = \rho_o + \alpha_T (T(t) - T(t_o)), \quad \alpha_T = \frac{d\rho}{dT}$$

- Bulk core temperature feedback coefficient for most reactors of this class ~ -0.1 to -0.3 cents / degree K \rightarrow -0.2 cents / °K is assumed



Previous Hardware Tests

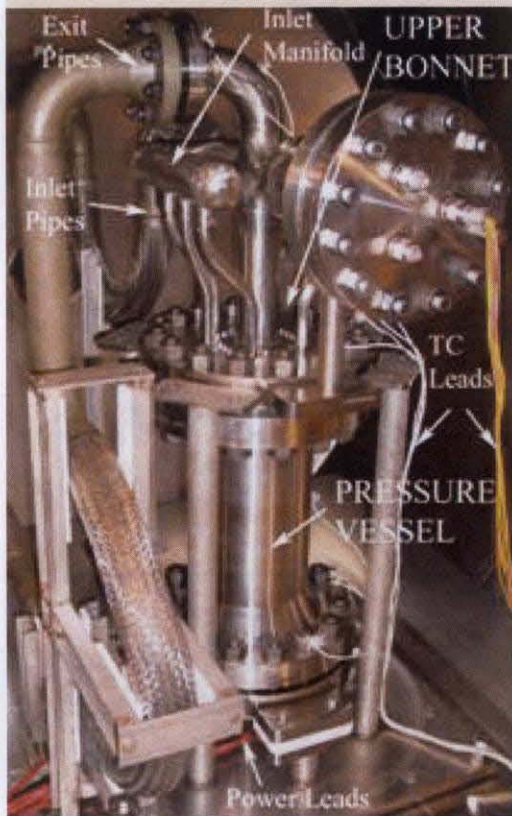
- **Heat pipe cooled core simulator**
 - SAFE-100 and 100a test articles
 - Tested at NASA MSFC with reactivity feedback (2004, 2005)
 - Thermal expansion
 - Average core temperature
 - Transients stabilized to new steady state after ~20-30 min



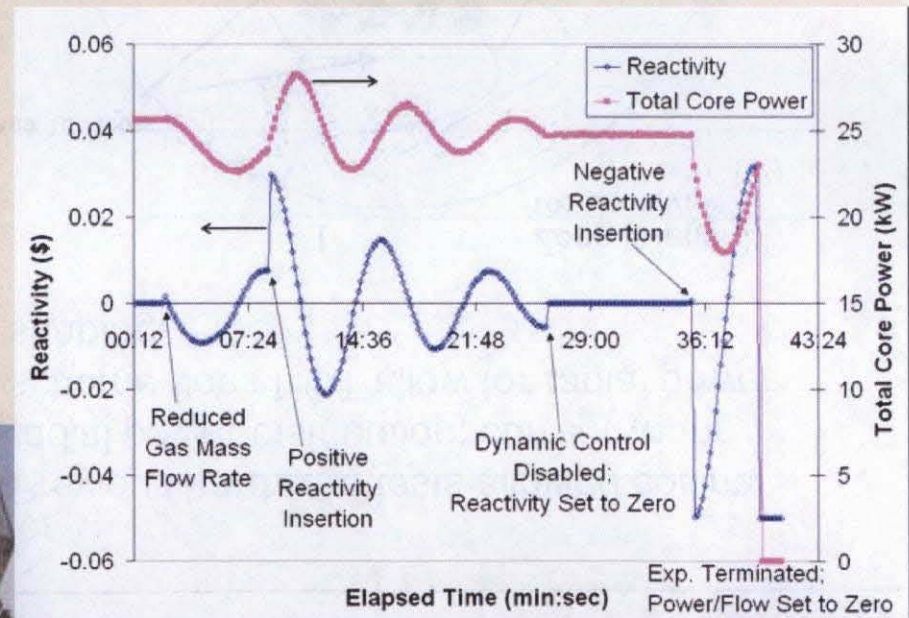
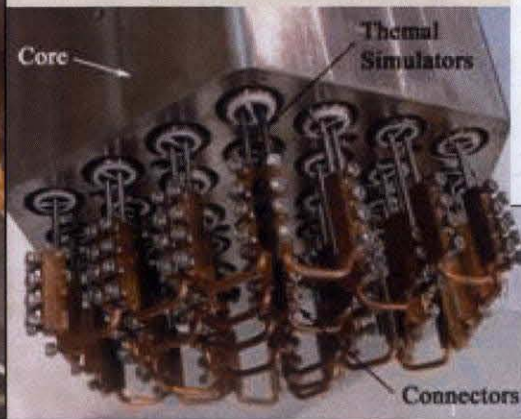
Previous Hardware Tests



- Direct drive **gas-cooled reactor core simulator**
 - DDG testing at MSFC without power conversion system
 - Initial demonstration of feedback testing prior to disassembly and refurbishment for testing at NASA GRC



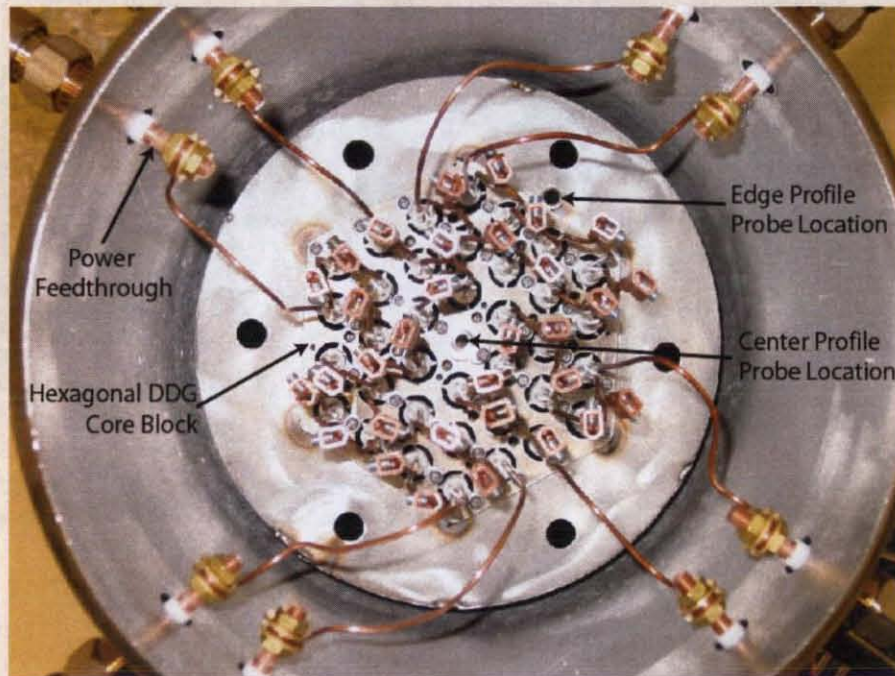
Reference:
S.M. Bragg-Sitton and T.J. Morton, Dynamic Response Testing in an Electrically Heated Reactor Test Facility, STAIF 2006.



Current Test Hardware: DDG Core



TEXAS A&M
UNIVERSITY



Previous hardware tests allowed cosine radial power distribution; current wiring scheme does NOT allow for radial power shaping.

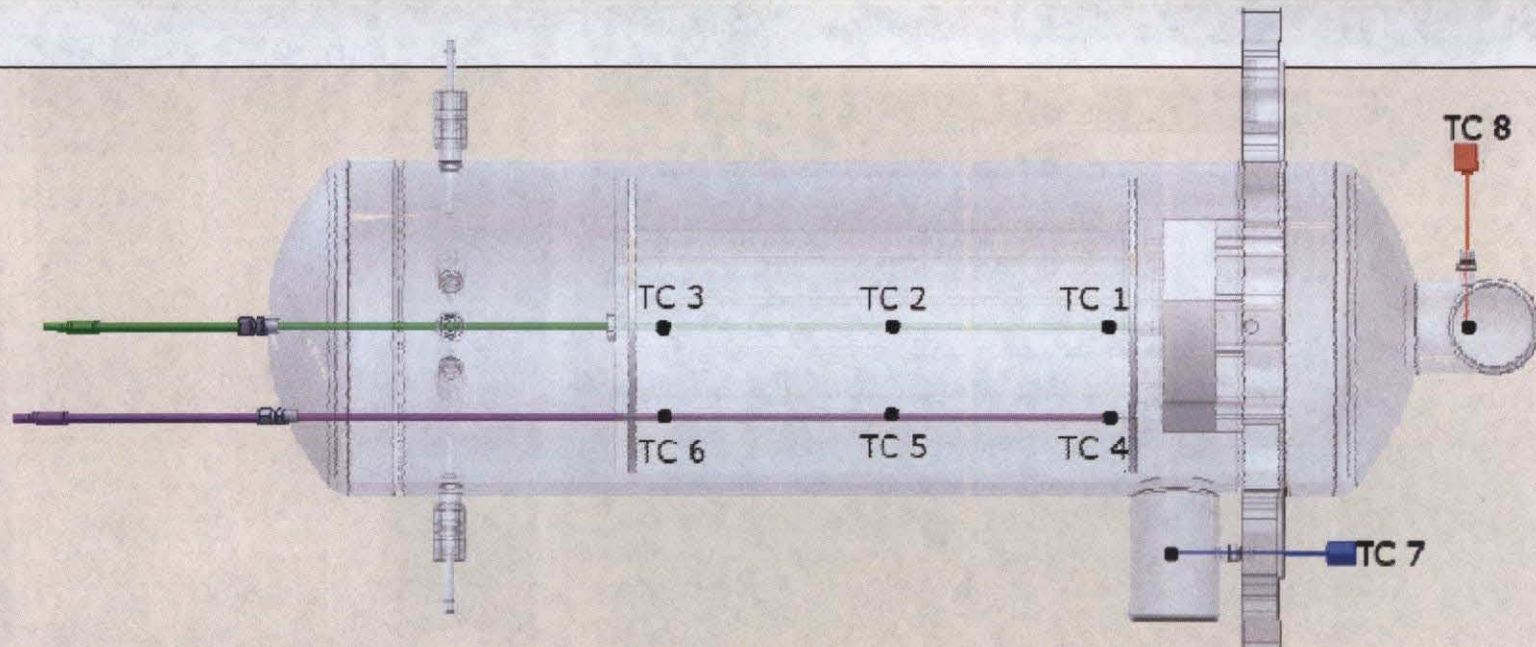


Minimal Instrumentation
Heater elements NOT instrumented.

TCs allow measurement of gas temperature and a rough "block" temperature.



DDG Instrumentation



- State estimator for reactivity feedback control: TC-1
 - Time constant associated with “block” temperature too long
 - Poor estimator of “fuel” temperature
 - Applies to all profile probe TCs
- State estimator: TC-8
 - Outlet gas temperature
 - More tightly coupled to changes in heater element temperature
- Require instrumented heater elements for future applications

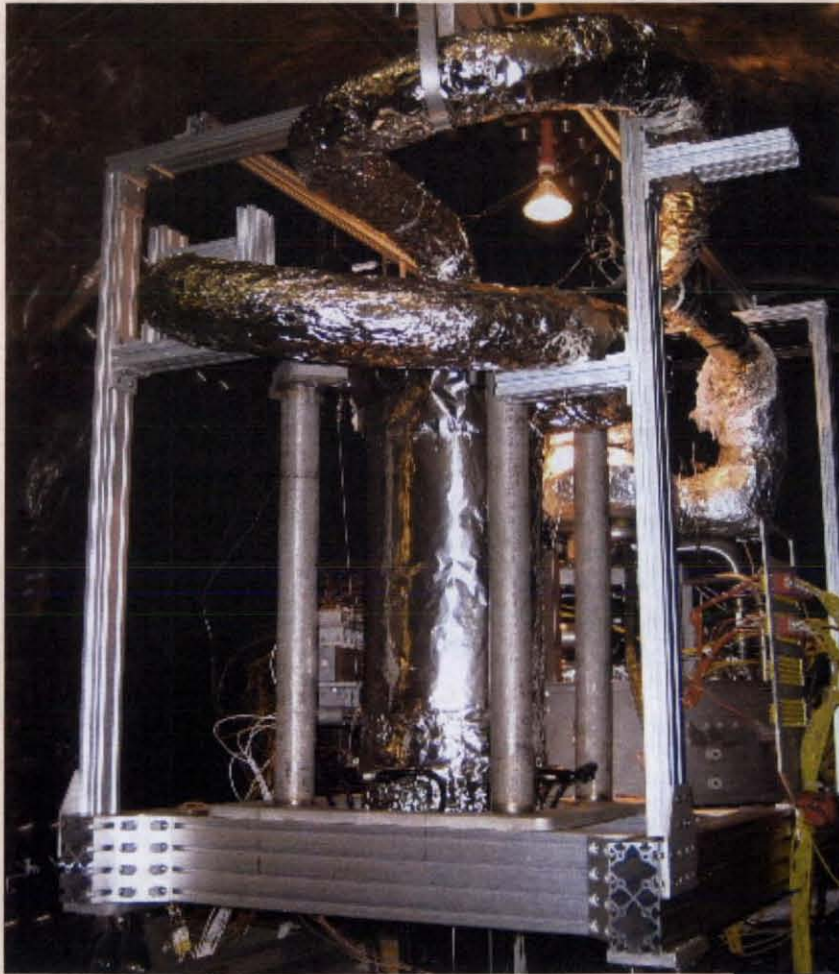


Integrated DDG – BPCU

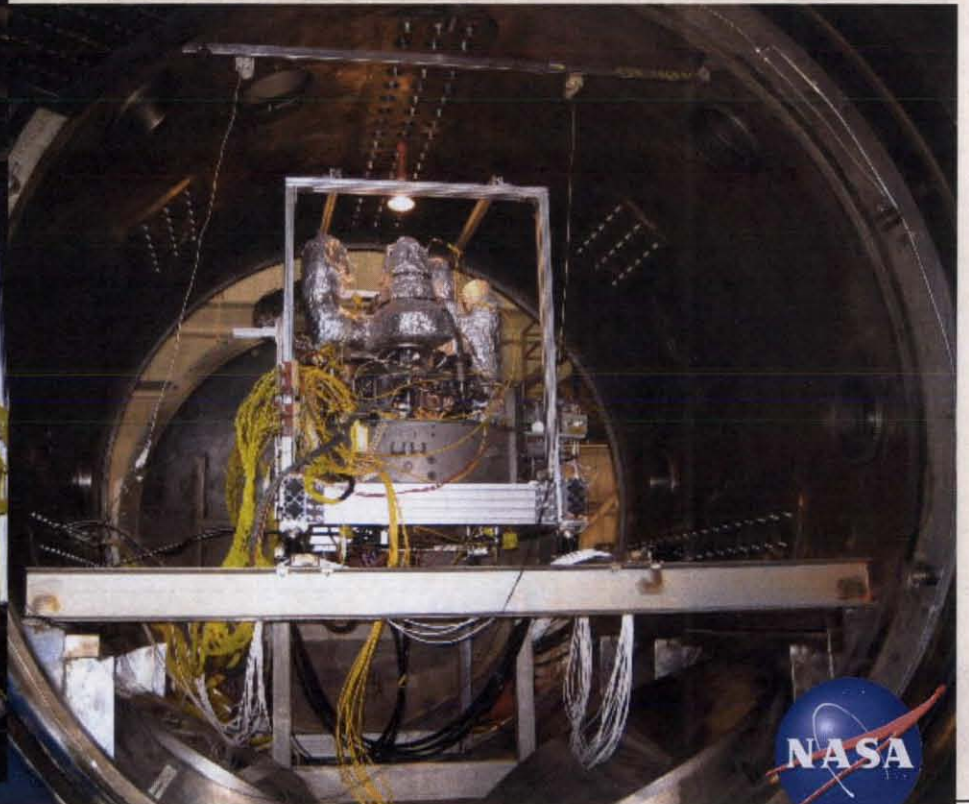


TEXAS A&M
UNIVERSITY

Front View – DDG



Rear View from Tank 6 – BPCU



Test Matrix with Feedback



TEXAS A&M
UNIVERSITY

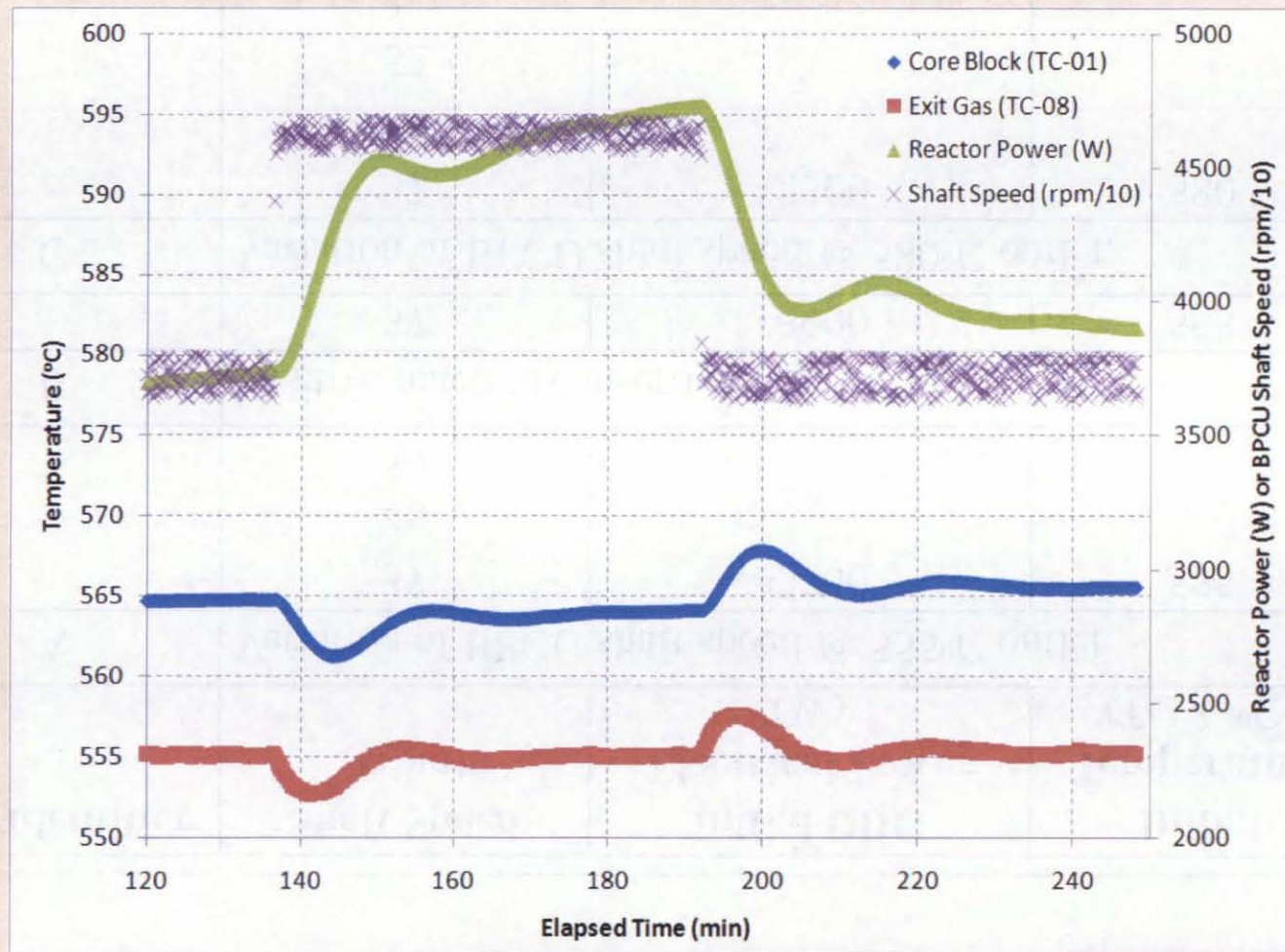
Test Identifier	Shaft Speed (krpm)	Initial DDG Electrical Power (W)	Initial Temperature (TC 8, °C)
A	Variation of BPCU shaft speed @ 555°C outlet.		
	37	~3700	555
	46		
	37		
B	Positive reactivity insertion.		
	37	~3900	555
C	Variation of BPCU shaft speed @ 580°C outlet.		
	37	~4300	580
	46		
	52		
	46		
	37		
D	Negative reactivity insertion.		
	37	~4230	580



Transient Operation (555 °C out)



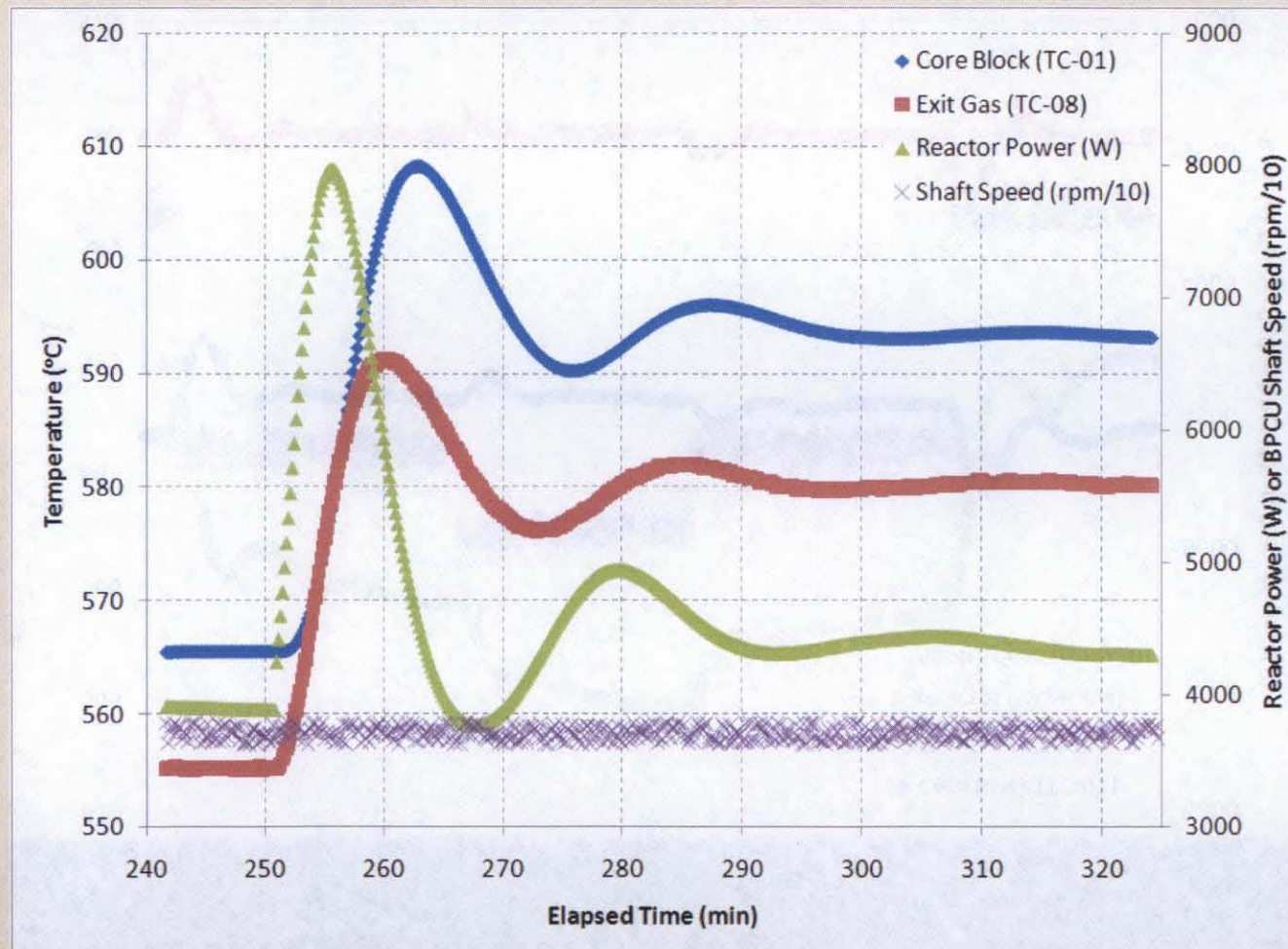
TEXAS A&M
UNIVERSITY



Approximate time constant: ~ 1 hour to reach steady state



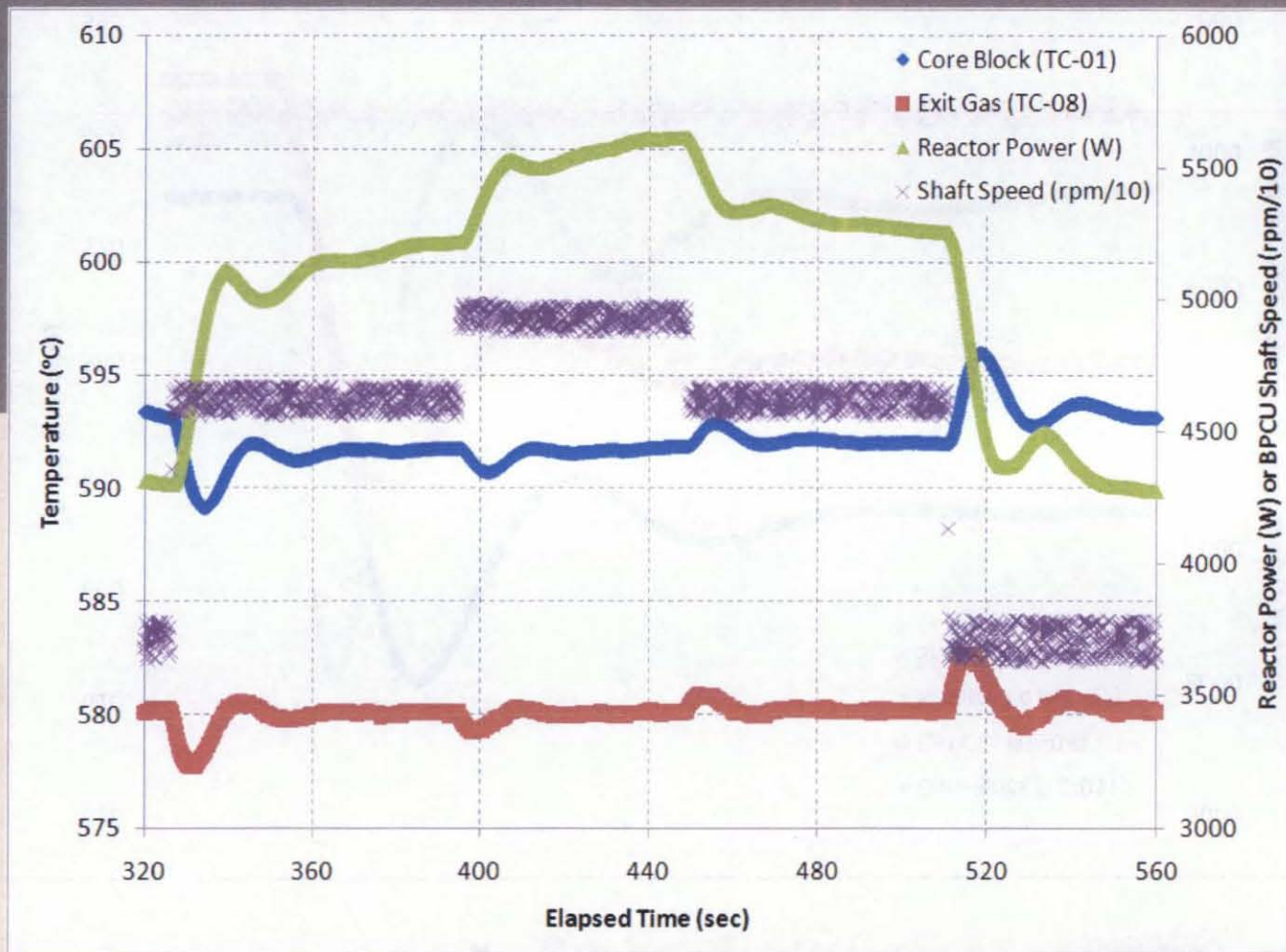
Positive Reactivity Insertion



Approximate time constant: ~ 1 hour to reach steady state



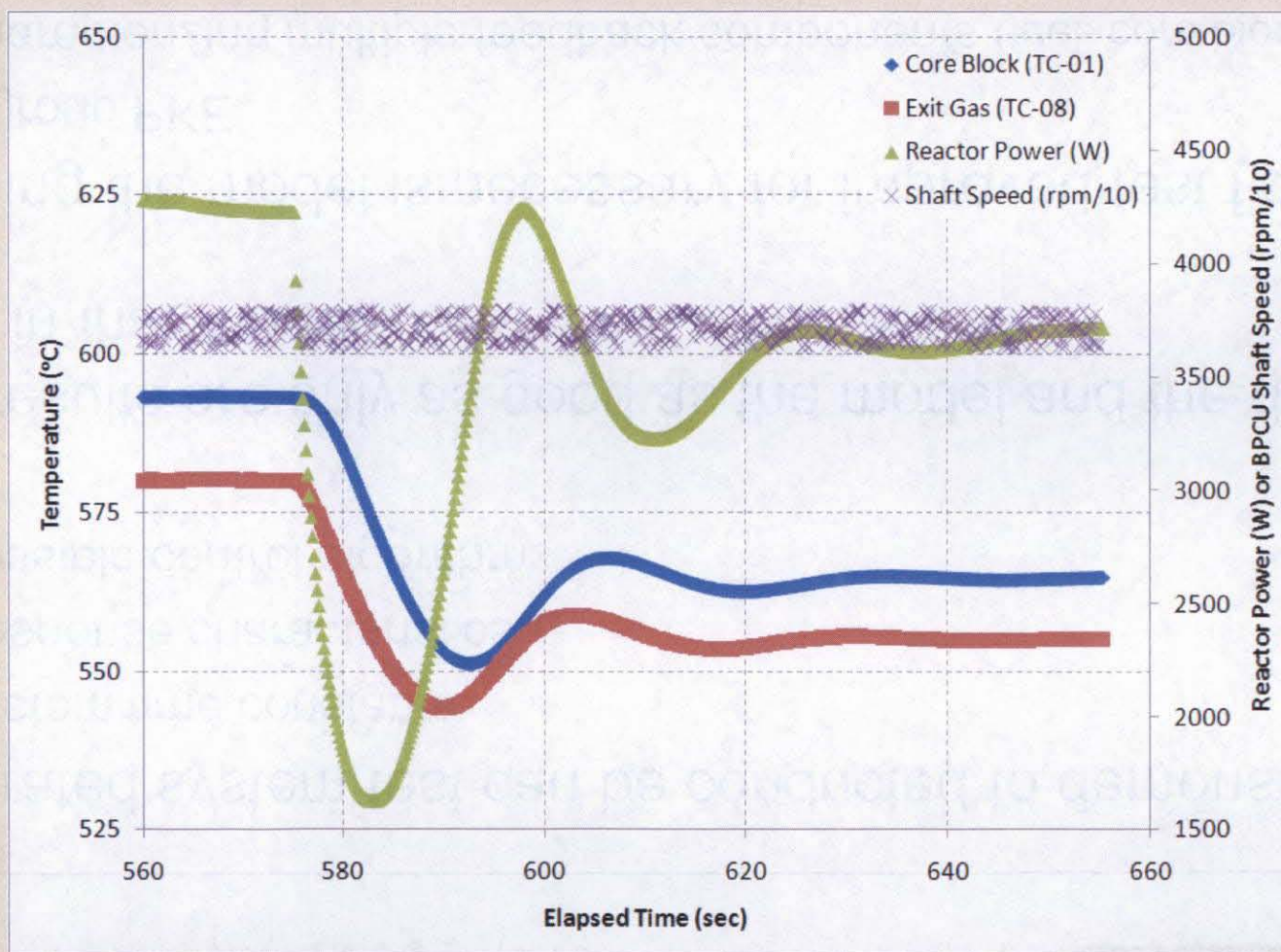
Transient Operation (580 °C out)



Approximate time constant: ~ 1 hour to reach steady state



Negative Reactivity Insertion



Approximate time constant: ~ 1 hour to reach steady state



What did we learn?



- Integrated system test can be conducted to demonstrate
 - System time constants
 - Response characteristics
 - Possible control algorithms

BUT:

The results are only as good as the model and the data used in that model!

- Refining the model is necessary for improved test fidelity
 - 6-group PKE
 - Characterizing multiple feedback components (fuel, core block reflector)
- Instrumentation is the key to success
 - Type, Location
 - Noise reduction



Instrumentation Needs



- Need to adopt a highly realistic approach to system control (with neutronic feedback) early in the design phase to allow appropriate selection of core instrumentation
- Good estimation of “fuel” temperature
 - Heater elements with embedded instrumentation
 - Thermal simulator design that mimics the dynamic response of a nuclear fuel pin
- Highly distributed instrumentation
 - Require multiple temperature (or deflection) measurements to introduce multiple feedback components in the dynamic model



Improved Data Acquisition



- Noise reduction techniques in the data acquisition system:
 - Selection of a feedback control signal from all available TC data or an average of those data points
 - Application of a moving time average to the measured temperature (or deflection) data (i.e. measured temperature input into the control could be the average of the previous 5 or 10 data points, as applied in SAFE-100 testing)
 - Application of a computational filter, such as a Kalman filter, in the control system



Enhanced Control System



- Tested control system simulated inherent transient response of an integrated reactor core and power conversion system, but...
 - NO constraints were applied to the magnitude of the prescribed adjustments in the core power level
 - Step insertions of reactivity resulted in large oscillations in the core power level
- Additional controller can be modeled and introduced to the control system to:
 - Limit the maximum power level or maximum change rate in the power level following a control maneuver to reduce the potential for system damage
 - Provide a test bed for candidate autonomous reactor control systems



Acknowledgements



TEXAS A&M
UNIVERSITY

The work in this paper was supported by and 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. The opinions expressed in this paper are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration.

