Proceedings of the Space Nuclear Conference 2005
San Diego, California, June 5-9, 2005
Paper 1167

Heat Pipe Reactor Dynamic Response Tests: SAFE-100a Reactor Core Prototype

Shannon M. Bragg-Sitton
NASA Marshall Space Flight Center, ER-11
MSFC, AL 35812
Tel: (256)544-6272, Fax: (256)544-3662, Email: Shannon.M.Bragg-Sitton@nasa.gov

Abstract – *The SAFE-100a test article at the NASA Marshall Space Flight Center was used to simulate a variety of potential reactor transients; the SAFE100a is a resistively heated, stainless-steel heat-pipe (HP)-reactor core segment, coupled to a gas-flow heat exchanger (HX). For these transients the core power was controlled by a point kinetics model with reactivity feedback based on core average temperature; 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 non-nuclear test facility in assessing system integration issues and in characterizing integrated system response times and response characteristics.*

I. INTRODUCTION

The SAFE-100a test article at the NASA Marshall Space Flight Center was used to simulate a variety of potential reactor transients; the SAFE100a is a resistively heated, stainless-steel heat-pipe (HP)-reactor core segment, coupled to a gas-flow heat exchanger (HX). For these transients the core power was controlled by a point kinetics model with reactivity feedback based on core average temperature; the neutron generation time and the temperature feedback coefficient are provided as model inputs. This type of non-nuclear test is expected to provide reasonable approximation of reactor transient behavior because reactivity feedback is very simple in a compact fast reactor (simple, negative, and relatively monotonic temperature feedback, caused mostly by thermal expansion) and calculations show there are no significant reactivity effects associated with fluid in the HP (the worth of the entire inventory of Na in the core is <<\$1, so fluid movement and temperature changes will cause very minor effects). In previous SAFE-100 tests, the point kinetics model was based on core thermal expansion via deflection measurements (Bragg-Sitton and Forsbacka, 2004). It was found that core deflection was a strong function of how the SAFE-100 modules were fabricated and assembled (in terms of straightness, gaps, and other tolerances). To remove the added variable of how this particular core expands as compared to a different concept, it was decided to use a temperature based feedback model (based on several thermocouples placed throughout the core). The bulk core temperature feedback coefficient for most reactors of this class is on the order of -0.1 to -0.2 cents per degree K.

The test matrix included changes in coolant flow rate and step reactivity insertions and decreases. The system responded as "expected" for all induced transients: increased / decreased coolant flow rate with reactivity feedback, increased / decreased coolant flow rate without reactivity feedback (done for comparison), and positive / negative reactivity insertion. "Expected" implies that the transient response was typical of any simple reactor, whether it be cooled by a pumped fluid or by HPs. During the transients, the HPs appear to act as a very good conductor with relatively little thermal inertia, such that system response would be almost the same if the gas was somehow removing the power directly from the core. The time scale of the transient is dictated mostly by the thermal inertia of the core, and to a smaller extent by the HPs and HX. In each transient, the peaks and/or valleys of the power and temperature occurred within 3 to 5 minutes after transient initiation, followed by modest oscillations until the system stabilized at a new steady state condition in about 20-30 minutes. The magnitude of power and temperature overshoots were also modest – there was ~15 degree K overshoot for a \$0.10 reactivity insertion, although the magnitude of overshoot is not of great meaning because this is a low power density core with non-prototypic thermal inertia.

These tests were not intended to predict the actual transient response of a specific HP reactor design; the actual materials and geometry of the core are not prototypic to any design (most importantly the properties of the heaters as opposed to the fuel), and these factors will change transient times and magnitudes by altering the conduction paths and thermal inertia. However, these tests are valid with regard to the role the HPs play in a transient, because the HPs are in the middle of the transient (between the core and flowing gas). Also, the HP/gas HX design is essentially the same as those being proposed for all HP/Brayton systems (although the thermal coupling is via a He gap as opposed to a braze). Therefore, the primary value of these tests was to demonstrate how HPs might perform in reactor transients and to determine if there were any unexpected or unusual effects (because a HP cooled-reactor had never been operated before). In this respect, nothing unexpected or unexplained occurred. The other value of these tests was to begin to investigate the time-scale and magnitude of potential transients (albeit with a non-prototypic core) and the impact of neutron generation time and feedback coefficients. A lot of useful information was obtained, but a wide variety of additional tests can be envisioned to investigate various effects and to broaden the envelope of confidence in HP reactor transient operation. Also, improved reactor test articles could greatly increase the fidelity of actual response magnitudes and times. If needed, the same basic techniques could be used to measure the response of gas-cooled and pumped-liquid-metal cooled systems. The biggest potential improvement would be the addition of a working Brayton engine to the loop, as this would determine system response more that any other factor.

II. SYSTEM MODEL: POINT REACTOR KINETICS

Reactor dynamics can be modeled using the point kinetics equations (PKE), which can be derived from transport and diffusion theory (Hetrick 1971). The PKE representation provides only an approximate model of the reactor; it does not provide a mechanism to describe neutron energy effects or structural details in a heterogeneous reactor. Because fast reactors are relatively small in size and do not contain any moderator to slow the neutrons to a lower energy, the PKE are a good approximation for the dynamics in a fast reactor. Solved in the absence of an external source and written in terms of reactor thermal power, the PKE are given by:

$$\frac{dP}{dt} = \frac{(\rho - \beta)}{\Lambda} P + \lambda_i C_i , \qquad (1a)$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda} P - \lambda_i C_i , \qquad (1b)$$

where the reactivity, ρ, is given by:

$$\rho = \frac{k-1}{k} . \qquad (1c)$$

Reactivity is often expressed in units of dollars. The reactivity scale between zero and β is divided into 100 cents, where 100 cents of reactivity is equal to one dollar. Hence, the reactivity expressed in units of dollars is given by ρ/β. Studies of reactor dynamics generally recognize six distinct groups of delayed neutrons. Approximate solutions to the PKE can be found using a smaller number of groups to represent the delayed neutron population. The dynamic model applied in the present application includes one group of delayed neutrons in the analytical solution to the PKE, applying a weighted average decay constant and the total delayed neutron fraction. The one group decay constant (λ) is calculated as a weighted average of the six individual decay constants. For fast fission of ^{235}U, the total decay constant (λ) is 0.0767 sec^{-1} and the total delayed neutron fraction (β) is 0.00642 (Hetrick 1971).

A simple model of a point reactor with feedback is applied in approximating the temperature reactivity feedback in a heat pipe reactor core. The total reactivity is given by Eq. (2):

$$\rho = \rho_o + \alpha_T(\Delta T) , \qquad (2)$$

where α_T is the temperature coefficient of reactivity,

$$\alpha_T = \frac{d\rho}{dT} , \qquad (3)$$

and ρ_o is the initial steady-state reactivity before a step change in a reactor power. In this analysis α_T will incorporate all reactivity feedback effects due to fuel and structural temperature changes (to include Doppler broadened cross sections and thermal expansion effects).

III. TEST ENVIRONMENT AND EXPERIMENTAL SYSTEM

All dynamic tests were performed on the electrically heated SAFE-100a heat pipe core and integrated heat exchanger. All reactor designs in the SAFE (Safe Affordable Fission Engine) series incorporate liquid metal heat pipes to remove heat from the reactor core. The SAFE-100 is a 100 kWt reactor designed by Los Alamos National Laboratory that includes 61 modules, where each module includes a central heat pipe surrounded by three fuel tubes, spaced at 120° intervals. The SAFE-100a design, used in the electrically heated tests conducted at the NASA Marshall Space Flight Center (MSFC), is a partial array of the SAFE-100, including the central 19 modules from the SAFE-100 core geometry. All components of the SAFE-100a are constructed from stainless steel. Each module incorporates a sodium filled heat pipe surrounded by three fuel tubes; graphite heaters are inserted into each fuel tube to simulate the heat from fission. The heat pipes are approximately twice as long as the fueled region of the core, such that the condenser ends of the heat pipes can be coupled to a prototypic monolithic heat exchanger. The SAFE-100a core, heat exchanger, and test stand are shown in Figure 1, prior to power hook up and attachment of gas supply lines. All testing were performed inside the 9' diameter by 20' length vacuum chamber at the Early Flight Fission Test Facility (EFF-TF) at NASA MSFC. All support hardware and control systems are located adjacent to the chamber; experiments are run real time using multiple computer control consoles.

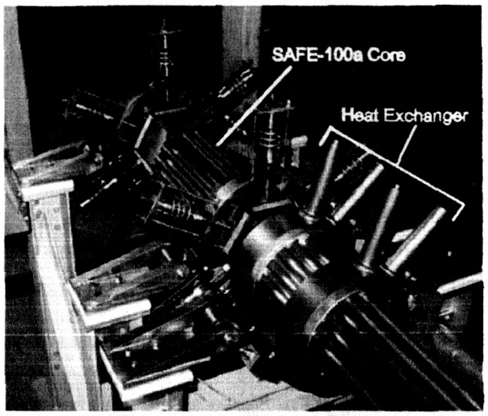

FIGURE 1. SAFE-100a Core and Heat Exchanger Assembly, Uninsulated and Before Hook-up of Gas Lines.

An end view of the SAFE-100a after installation of heaters and internal core thermocouples is shown in Figure 2. Thermocouples are inserted along the interstices between each of the core modules. Because no material is provided to fill the small gaps between modules, coupling of the SAFE-100a core design is not as strong as would be expected in a monolithic core geometry. In addition, there is a significant amount of space around the graphite heater elements and the interior fuel tube walls, such that coupling of the heaters to the fuel tubes is very poor. One of the heater elements used to simulate nuclear fuel in the SAFE-100a core is shown in Figure 3.

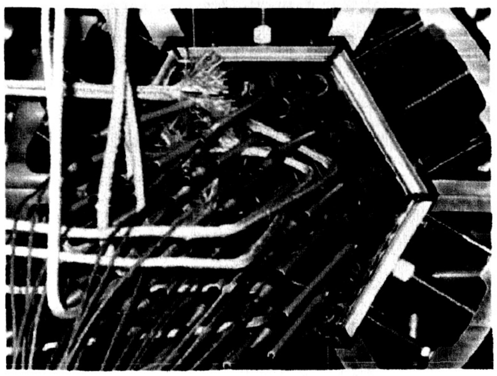

FIGURE 2. End View of the SAFE-100a Core After Installation of the Thermal Simulators and Internal Thermocouples (Inside Alumina Sleeves).

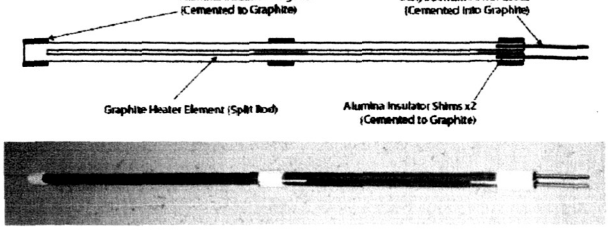

FIGURE 3. Graphite Rod Thermal Simulator.

The thermal simulators are shaped axially to approximate the cosine axial power distribution that would be present in a nuclear core. For the present test, the same power was applied to each heater element (e.g. each simulated fuel pin) to produce a flat radial power distribution. To improve conduction between the thermal simulators and fuel tubes, the vacuum chamber is back-filled with ultra high purity helium at approximately 50 torr. This environment better approximates the coupling between an actual nuclear fuel element and its surrounding clad and sheath materials. To minimize radiation loss from the core, heat pipes and heat exchanger, extensive insulation was wrapped around all components.

Although it is designed to accommodate two heat exchangers, the SAFE-100a is fitted with a single 19 channel heat exchanger (Kapernick and Guffee 2003) for the current tests. The SAFE-100 and 100a designs utilize an annular flow heat exchanger (HX) that fits over the condenser ends the heat pipes that extend from the core. Coolant gas flows through annular flow paths along the outside of the heat pipes to accomplish the necessary heat extraction. The HX flow channel is characterized by an inner wall roughened by square ribs having a rib pitch-to-height ratio of ten. This square-ribbed design prevents a boundary layer from developing and enhances the turbulent heat transfer in the flow annulus relative to a smooth channel design. The as-designed system would then utilize a closed Brayton cycle for power conversion. In the integrated experimental system, the gas-flow heat exchanger is capable of flowing any gas mixture that might be applied in a Brayton cycle. Waste heat rejection is currently provided by a water cooled heat exchanger that is coupled to the hot side of the gas flow lines. This is shown schematically in Figure 4.

The SAFE-100a prototype is fully instrumented with type K thermocouples (TCs) along the core length and at various radial positions. Internal thermocouples are positioned along the interstices between modules, as shown in Fig. 2. A complete set of internal thermocouples (36) is located at the axial center of the heated portion of the prototype, a second set (19) is located on the upstream side of the heat exchanger (adjacent to the inlet plenum) and a third set (19) is located on the downstream side of the heat exchanger (adjacent to the outlet plenum). These locations are identified in Figure 5.

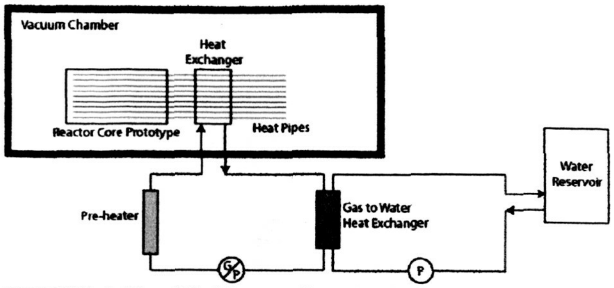

FIGURE 4. Simplified System Overview Identifying Primary (Gas) and Secondary (Water) Heat Exchanger Systems.

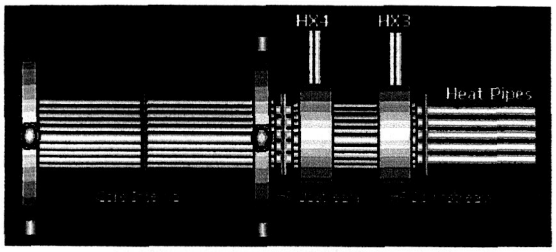

FIGURE 5. Identification of the Internal Thermocouple Locations on the SAFE-100a Core and Heat Pipes.

An additional 58 thermocouples were positioned on the external surfaces of the core and heat pipe condenser sections. Thermocouples were also located on the SAFE-100a support structure, embedded within the layers of insulation wrapped around the core, heat pipes, and heat exchanger, and at several locations on the vacuum chamber walls. Additional instrumentation is included to measure the mass flow rate, temperature, and pressure at various positions along the recirculating gas flow path. The IOtech temperature acquisition system (www.iotech.com) cycles through all thermocouples at a rate of 5.8 Hz.

Power is supplied to the SAFE-100a reactor simulator using five independent power supplies, each capable of providing up to 15 kW (150 V at 100 A); available hardware at the EFF-TF is capable of providing up to 32 independent control zones. The SAFE-100a core is wired to allow for individual control of the power to each concentric ring of heaters. Although the current test applies a flat power profile, independent controls allow for a radial power distribution to mimic the power profile of an operating nuclear reactor. The current power distribution and control assumes nominal operation, such that power is radially symmetric across the core.

The complete test configuration is shown in Figure 6. Note that gas supply lines are wrapped in a layer of insulation to minimize heat loss from the gas as it travels from the preheater to the heat exchanger; under the insulation, additional tape heaters are wrapped around the supply lines. Gas is heated to approximately 400 °C prior to entering the heat exchanger. The gas supply system was operated at a nominal pressure of 100 – 120 psi (~0.7 MPa).

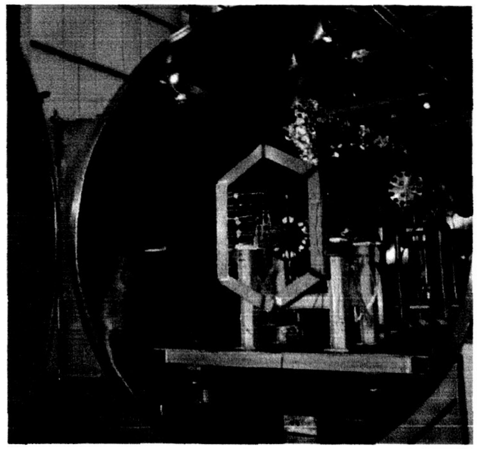

FIGURE 6. Complete Test Set-Up of the SAFE-100a Heat Pipe Reactor Core and Heat Exchanger.

III.A. Test Matrix

Discussions with LANL led to a series of proposed transients that could be tested on the SAFE-100a core. Before any transients were initiated, the core was initialized at a steady state condition of approximately 14-16 kW. All tests were conducted with pure helium gas flowing through the primary heat exchanger and with a 50 torr helium environment in the test chamber. Prior to initializing any transient, the heat exchanger mass flow rate was adjusted to establish a steady state temperature of approximately 950 K (675 °C) along the heat pipes (~700 °C in the reactor core). The test matrix included the test conditions summarized in Table 1.

TABLE 1. Test Matrix.

Case	Reactor Power	He Mass Flow	He Inlet Temperature
1	Constant	Increase ~25%	Constant, ~400°C
2	PKE	Increase ~25%	Constant, ~400°C
3	Constant	Decrease ~25%	Constant, ~400°C
4	PKE	Decrease ~25%	Constant, ~400°C
5	+ $0.10	Constant	Constant
6	– $0.10	Constant	Constant

LabView was used to implement all aspects of system operation. One visual interface was written to provide control to the power supplies and a second was written to monitor core temperatures and to control the gas supply to the heat exchanger. For the cases that simulate the neutronic response of an operating reactor (Cases 2, 4, 5, 6), the LabView control program implements a solution to the point kinetics equations (Eqs. 1) assuming one-group of delayed neutrons, as discussed above.

In the test cases that employ virtual reactivity feedback, feedback was based on the average internal core temperature (average of all TC locations shown in Fig. 2). The control loop is initialized at the initial steady state core power prior to the transient (e.g., 14 kW), and the initial delayed neutron precursor concentration (C_o) was determined from the steady state solution to the PKE at P_o.

III.B. Experiment Control System

To minimize the computation time required by the LabView data acquisition program, the eigenvalues and eigenvectors of the system of ordinary differential equations that compose the point kinetics equations (Eqs. 1) were pre-calculated and programmed in algebraic form in LabView. The PKE applied in the feedback loop were solved in the absence of an external source and for one group of delayed neutrons.

The general solution for this linear, homogeneous system of equations can be constructed from its eigenvalues and eigenvectors. The eigenvalues, r_+ and r_-, are easily found from the homogeneous equations and are given by:

$$r_{\pm}=\frac{1}{2}\left[-\left(\lambda+\frac{\beta-\rho}{\Lambda}\right)\pm\sqrt{\left(\lambda+\frac{\beta-\rho}{\Lambda}\right)^{2}+4\left(\frac{\lambda\rho}{\Lambda}\right)}\right], \quad (4)$$

which have the corresponding eigenvectors, ξ_+ and ξ_-:

$$\xi_{\pm}=\begin{pmatrix}1\\ \dfrac{r_{\pm}-\dfrac{\rho-\beta}{\Lambda}}{\lambda}\end{pmatrix}=\begin{pmatrix}1\\ e_{\pm}\end{pmatrix}. \quad (5)$$

The general solution of Eqs. (1) can then be constructed:

$$\begin{bmatrix}P(t)\\ C(t)\end{bmatrix}=a_+e^{r_+t}\xi_+ + a_-e^{r_-t}\xi_- . \quad (6)$$

Given the initial conditions for the system, the specific solution to the system of differential equations can be found. At time t_o, the power and precursor concentrations are given by $P(t_o) = P_o$ and $C(t_o) = C_o$. Substituting these values at time t_o, the coefficients a_+ and a_- are found from Eq. (7):

$$\begin{pmatrix}a_+\\ a_-\end{pmatrix}=\frac{1}{e_+-e_-}\begin{pmatrix}-e_- & 1\\ e_+ & -1\end{pmatrix}\begin{pmatrix}P_o\\ C_o\end{pmatrix}. \quad (7)$$

Equations (4-7) were programmed into the LabView data acquisition and control program, such that $P(t)$ and $C(t)$ are solved in real time given variations in the core reactivity, ρ_{total}. The solution for $P(t)$ is used to determine the rate of change of input power to the five control zones at each iteration of the control loop. Although the precursors cannot be simulated in the electrically heated core, the solution for $C(t)$ is used to find new initial conditions at each iteration of the control loop. All test cases employing the virtual reactivity feedback control loop implemented a control frequency of 2 Hz (e.g., the control loop was iterated at intervals of 500 ms). As noted previously, the thermocouples are scanned at a rate of 5.8 Hz (approximately once every 100 ms). An additional delay of 150 ms can occur in the communication between the control computer and the power supply controllers. As a result, the total communications delay can be up to 250 ms. Setting the control time at 500 ms prevents the control algorithm from becoming out of synch with the data acquisition or from overloading the power controllers.

As discussed above, a simple model was applied to approximate the temperature reactivity feedback in a heat pipe reactor core (see Eq. (2)). For all cases that require reactivity feedback in the control loop, a temperature coefficient of reactivity (α_T) of -0.2 cents per degree per K is assumed. This estimate includes all contributions to the reactivity feedback (e.g., those resulting from fuel and structural temperature changes as well as thermal expansion). All parameters applied in the point kinetics solution to the reactor dynamic response are provided in Table 2.

TABLE 2. Parameters Applied in the Solution of the PKE.

Parameter	Value
α_T	0.2 cents / K
β	0.00642
λ	0.0767
Λ	1×10^{-7} sec

IV. RESULTS

The results below demonstrate the operation of the integrated test system with and without simulated reactivity feedback, as prescribed in the test matrix.

IV.A. Cases 1, 3: Mass Flow Rate Transients with Reactivity Feedback

During initial testing, small transients were applied to the system by adjusting the mass flow rate of helium gas by approximately 20%. Fig. 7 shows two transients in which virtual reactivity feedback was applied: the first represents a mass flow decrease from approximately 0.011 kg/s to 0.008 kg/s followed by an increase to the original flow rate of approximately 0.011 kg/s. In each of these transients, the average core temperature deviated by less than 10 °C. The corresponding average heat exchanger temperatures and total core power are shown in Fig. 8. The total power delivered to the core and the corresponding (calculated) reactivity are shown in Fig. 9. In each case, the system required approximately 30 minutes to return to steady state after implementing the transient.

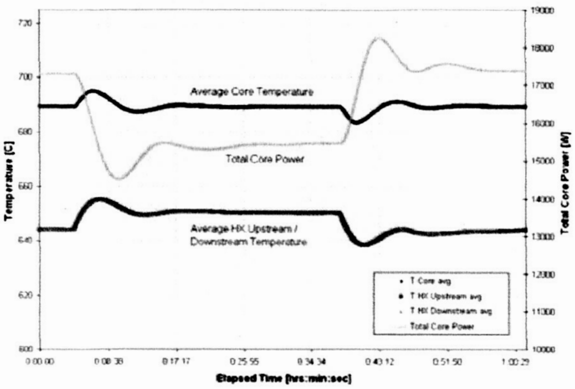

FIGURE 7. Cases 1 and 3: Mass Flow Rate Transients and Corresponding Average Core Temperature.

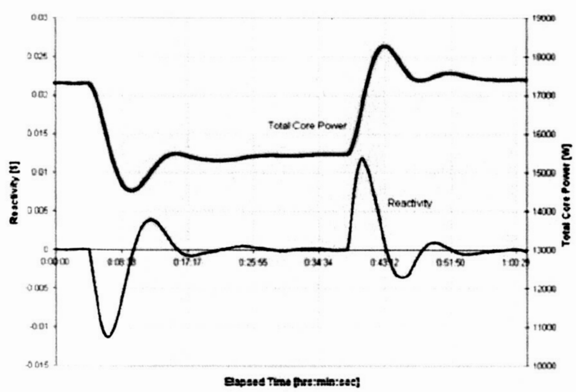

FIGURE 8. Cases 1 and 3: Average Core and Heat Exchanger (Heat Pipe Condenser) Temperature and Core Power.

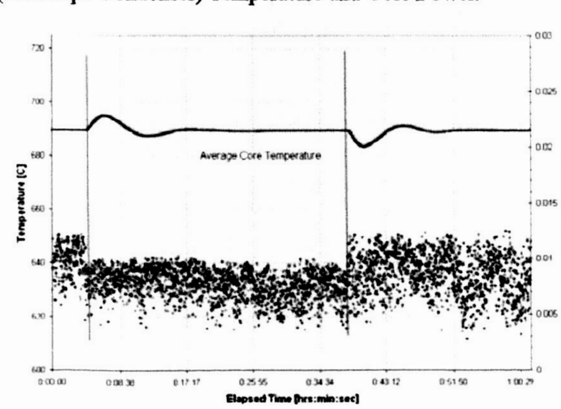

FIGURE 9. Cases 1 and 3: Core Power and (Calculated) Reactivity.

The core temperatures are approximately 45 °C higher than the heat pipe temperatures upstream and downstream of the heat exchanger due to the thermocouple configurations. In the core, the thermocouples are inserted between modules and may be touching surrounding fuel tubes, which would be at a higher temperature than the heat pipes. Thermocouples on the heat pipe condenser are spot welded to the heat pipe surface, such that they correspond more closely to the actual heat pipe temperature. Insulation wrapped around all sections of the core and heat exchanger configuration minimizes the ability of these thermocouples to act as fins. An operating heat pipe is essentially isothermal, such that the heat pipe evaporator temperatures would be equivalent to that of the condenser section. As the operating power increases, the discrepancy between the core internal temperatures and the heat pipe condenser temperatures increases as a result of the higher heater temperatures required to achieve these powers.

Detailed analysis of the data indicates that the heat pipe condenser temperatures responded almost immediately (within 500 ms) of the mass flow rate change; the internal core thermocouples reflected the transient within approximately ten seconds. Because these test cases applied reactivity feedback, the increase / decrease in temperature that resulted from the decrease / increase in helium mass flow rate caused the system to respond by decreasing / increasing reactor power to accommodate the new load. Both cases demonstrate a classical system response in which the steady state operating temperature returned to the pre-transient temperature as the oscillations in the core power dampened and settled at a new steady state condition. The overshoot or undershoot in the power could be reduced by slowly implementing the desired transients over a period of time rather than introducing them as a step change in the system condition.

IV.B. Cases 2, 4: Mass Flow Rate Transients Without Reactivity Feedback (Constant Power)

To decouple the thermal and (simulated) neutronic effects in the reactor core simulator and heat exchanger that result from transients on the secondary side of the system, mass flow rate changes were also implemented without reactivity feedback (e.g., $\alpha_T = 0$, resulting in constant power). To study the system response, the flow rate was first decreased by approximately 25% from ~0.008 kg/s to 0.006 kg/s, followed by an increase back to 0.008 kg/s. With reactivity feedback, steady state operation returned after approximately 30 minutes; without reactivity feedback, steady state was still not achieved after an hour of operation at the new flow rate. At the point at which the transient was interrupted, the core temperature had increased by almost 100 °C. These cases demonstrate similar system time response to changes on the secondary as observed with reactivity feedback; the average core temperature began to demonstrate a response to the change in flow rate within approximately 10 seconds of implementing the transient. As in the previous test case, the heat pipe condenser temperatures began to reflect the change in the helium mass flow rate almost immediately. (See Fig. 10.)

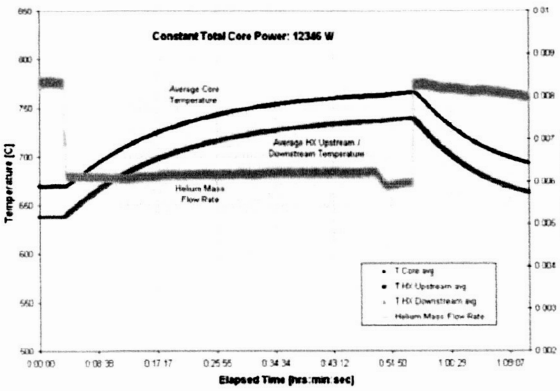

FIGURE 10. Cases 2 and 4: Average Core and Heat Pipe Temperatures (Upstream and Downstream of the HX) Resulting from to Mass Flow Rate Transients (No Reactivity Feedback).

IV.C. Case 5: Reactivity Insertion: Positive $ 0.10

After establishing a steady state condition at 13.5 kW and an average core temperature of 670 °C, a 10 cent positive reactivity insertion was simulated. Reactivity insertion was simulated as a step change in the core reactivity. Helium mass flow rate was maintained constant at approximately 0.008 kg/s. The average core temperature began to reflect the reactivity insertion within approximately 8 seconds of the insertion; the average heat pipe condenser temperatures began to increase approximately 10 seconds after the core temperature rise. The new steady state power level was approximately 14.5 kW (net increase by 1.0 kW) at an average core temperature of 720 °C (a net increase of 50 °C). Power and temperature overshoot reached as high as 25 kW and 740 °C, respectively. As in the case of transients implemented on the secondary side, simulating a load change to the reactor, the overshoot in the power response can be dampened by slowly introducing the transient system rather than implementing it as a step change. (See Fig. 11, 12.)

IV.D. Case 6: Reactivity Insertion: Negative $ 0.10

After establishing a steady state condition at 14.5 kW (following the previous reactivity insertion) and an average core temperature of 720 °C, a 10 cent negative reactivity insertion was simulated. Helium mass flow rate was maintained constant at approximately 0.008 kg/s. The temperature lag to the reactivity insertion was somewhat more delayed than in the positive insertion test case. The average core temperature began to reflect the reactivity insertion within approximately 15 seconds of the insertion; the average heat pipe condenser temperatures began to increase approximately another 15 seconds after the core temperature rise. The new steady state power level was approximately 12.3 kW (net reduction in power by 1.8 kW) at an average core temperature of 670 °C (an decrease of 30 °C). Power and temperature undershoot reached as low as 6.7 kW and 740 °C, respectively. Note that the negative reactivity insertion did not directly mirror the positive insertion, introducing a less drastic power swing but resulting in a larger change in the power levels in the pre- and post-transient steady state conditions. This result suggests that some historesis exists in the system, causing cool-down to be more protracted than heat-up of the the core and heat exchanger. (See Fig. 13, 14.)

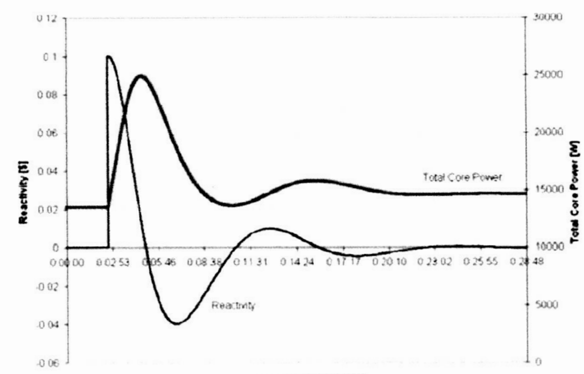

FIGURE 11. Case 5: Total Core Power Due to a (Simulated) 10 Cent Reactivity Insertion.

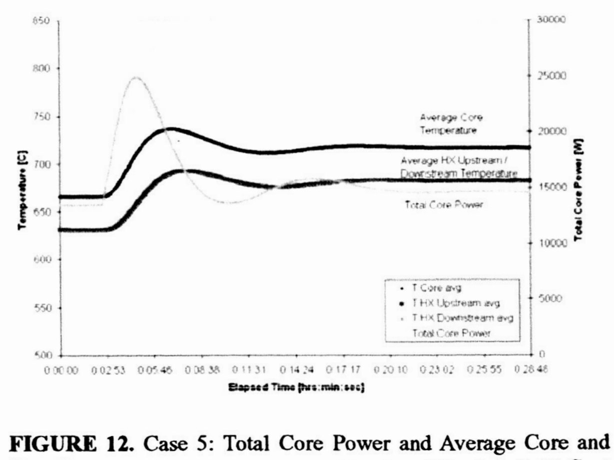

FIGURE 12. Case 5: Total Core Power and Average Core and Heat Pipe Condenser Temperatures Due to a (Simulated) 10 Cent Reactivity Insertion.

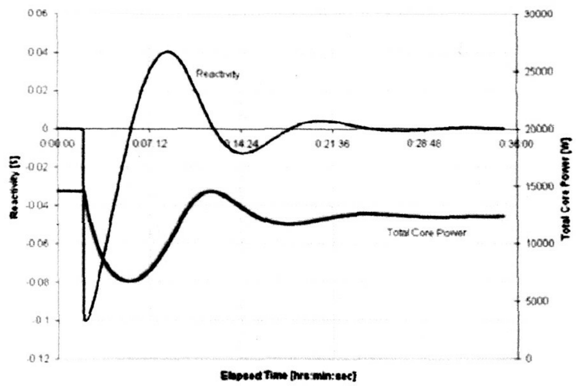

FIGURE 13. Case 6: Total Core Power Due to a (Simulated) Negative 10 Cent Reactivity Insertion.

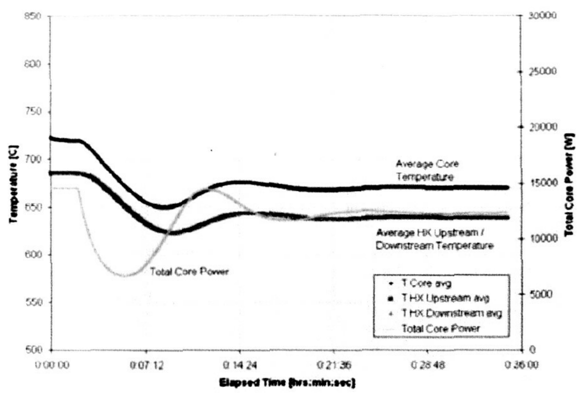

FIGURE 14. Case 6: Total Core Power and Average Core and Heat Pipe Condenser Temperatures Due to a (Simulated) Negative 10 Cent Reactivity Insertion.

V. CONCLUSIONS

These dynamic system response tests demonstrate the overall capability of a non-nuclear test facility in assessing system integration issues and in characterizing integrated system response times and response characteristics. The dynamic reactor model applied in this test series to simulate reactivity feedback in a reactor system could be enhanced by modeling all six groups of delayed neutrons and by breaking up the various components of reactivity feedback. Computational modeling can be used to characterize the various feedback coefficients, and additional instrumentation and/or data acquisition systems could be introduced to provide experimental data to supply to the enhanced system model. For instance, enhanced instrumentation within the thermal simulators and advanced thermal simulators that better replicate the various thermal properties of nuclear fuel elements could provide more accurate temperatures to apply to the fuel temperature reactivity coefficient. Previous work at the EFF-TF considered high resolution imagery to assess the overall core deformation at elevated temperatures, which also feeds into the reactivity response (Bragg-Sitton and Forsbacka, 2004). Although this solution required visual access to the core to assess core deformation over time, additional methods might employ a devise such as a Micro Gauging DVRT (differential variable reluctance transducer), which only requires physical contact with the component whose growth is being measured.

In additional to improving the fidelity of the reactor dynamic model, this approach can also be applied in testing autonomous control systems developed for in-space operation of a reactor system. For instance, one might select a model based predictive controller to control the reactor during start-up and steady state operation (Bragg-Sitton and Holloway, 2004). In this case, a simplified computer model could be applied to predict system response over the future time based on a prescribed operational plan, while the actual system state would be received from the experimental system. Dynamics in the experimental system could then be modeled using a higher fidelity representation of the reactor dynamics (e.g., 6-group representation of the delayed neutrons in the PKE) to assess the applicability of predictive controllers in an autonomous reactor control system.

The EFF-TF is uniquely positioned to implement the tests discussed in this report and to continue system testing at a higher fidelity. The facility was constructed with complete system testing in mind, and the necessary support architecture is available. The tests discussed here were conducted on a heat pipe cooled reactor design. However, the testing method can be ported to other non-nuclear testing of other reactor designs (e.g. gas or liquid metal cooled) by modification of the system parameters in the reactor model in the LabView control code. Although non-nuclear system testing does not replace full power nuclear testing, it does allow one to develop a more complete understanding of system integration and dynamics in a relatively benign environment and at a relatively small fiscal investment.

ACKNOWLEDGMENTS

The author wishes to thank Kenny Webster of the EFF-TF team at MSFC for his significant assistance in building and implementing the LabView control programs. The author also wishes to acknowledge the substantial contributions to the system test design from David Poston (LANL) and Rick Kapernick (LANL) and Mike Houts (MSFC). NASA's Project Prometheus supported the work described within this paper, in whole or part, as part of the program's technology development and evaluation activities. Any opinions expressed are those of the

author(s) and do not necessarily reflect the views of Project Prometheus.

NOMENCLATURE

P = reactor thermal power [W],
t = time [sec],
ρ = reactivity,
K = effective neutron multiplication factor,
$\beta = \sum_i \beta_i$ = total delayed-neutron fraction,
β_i = delayed-neutron fraction, i^{th} precursor group,
C_i = delayed-neutron concentration, i^{th} precursor group,
λ_i = decay constant for the i^{th} precursor group [sec^{-1}], and
Λ = prompt generation time [sec].

REFERENCES

1. S. M. BRAGG-SITTON and M. FORSBACKA, "Application of a Virtual Reactivity Feedback Control Loop in Non-Nuclear Testing of a Fast Spectrum Reactor," *International Congress on Advanced Nuclear Power Plants (ICAPP-2004)*, p. 2259-2268, Pittsburgh, PA (2004).

2. S. M. BRAGG-SITTON and J. P. HOLLOWAY, "Reactor Start-up and Control Methodologies: Consideration of the Space Radiation Environment," *Space Technology and Applications International Forum (STAIF-2004)*, p. 614-622, Albuquerque, NM (2004).

3. D. L. HETRICK, *Dynamics of Nuclear Reactors*, The University of Chicago Press, Chicago, IL (1971).

4. R. J. KAPERNICK and R. M. GUFFEE, "Thermal Stress Calculations for Heatpipe-Cooled Reactor Power Systems," *Space Technology and Applications International Forum (STAIF-2003)*, p. 457-465, Albuquerque, NM (2004).