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Design and Test of Advanced Thermal Simulators for an Alkali Metal-Cooled Reactor Simulator

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Abstract. The Early Flight Fission Test Facility (EFF-TF) at NASA Marshall Space Flight Center (MSFC) has as one of its primary missions the development and testing of fission reactor simulators for space applications. A key component in these simulated reactors is the thermal simulator, designed to closely mimic the form and function of a nuclear fuel pin using electric heating. Continuing effort has been made to design simple, robust, inexpensive thermal simulators that closely match the steady-state and transient performance of a nuclear fuel pin. A series of these simulators have been designed, developed, fabricated and tested individually and in a number of simulated reactor systems at the EFF-TF. The purpose of the thermal simulators developed under the Fission Surface Power (FSP) task is to ensure that non-nuclear testing can be performed at sufficiently high fidelity to allow a cost-effective qualification and acceptance strategy to be used.

Prototype thermal simulator design is founded on the baseline Fission Surface Power reactor design. Recent efforts have been focused on the design, fabrication and test of a prototype thermal simulator appropriate for use in the Technology Demonstration Unit (TDU). While designing the thermal simulators described in this paper, effort were made to improve the axial power profile matching of the thermal simulators. Simultaneously, a search was conducted for graphite materials with higher resistivities than had been employed in the past. The combination of these two efforts resulted in the creation of thermal simulators with power capacities of 2300-3300 W per unit. Six of these elements were installed in a simulated core and tested in the alkali metal-cooled Fission Surface Power Primary Test Circuit (FSP-PTC) at a variety of liquid metal flow rates and temperatures. This paper documents the design of the thermal simulators, test program, and test results.

Design and Test of Advanced Thermal Simulators for an Alkali Metal-Cooled Reactor Simulator

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Abstract. The Early Flight Fission Test Facility (EFF-TF) at NASA Marshall Space Flight Center (MSFC) has as one of its primary missions the development and testing of non-nuclear fission reactor simulators for space applications. A key component in these simulated reactors is the thermal simulator, designed to closely mimic the form and function of a nuclear fuel pin using electric heating. Continuing effort has been made to design simple, robust, inexpensive thermal simulators that closely match the steady-state and transient performance of a nuclear fuel pin. A series of these simulators have been designed, developed, fabricated and tested in a number of simulated reactor systems at the EFF-TF. The development of such thermal simulators ensures that non-nuclear testing can be performed at sufficiently high fidelity to allow a cost-effective qualification and acceptance strategy to be used. Recent efforts have culminated in the fabrication of simulators with power capacities of 2300-3000 W per unit. Six of these simulators were installed in a representative core element (the 7-pin bundle) and tested in the alkali metal-cooled Fission Surface Power Primary Test Circuit (FSP-PTC) over a range of liquid metal flow rates and temperatures.

INTRODUCTION

Under the NASA Exploration Technology Development program, NASA and the Department of Energy have begun long-lead technology development for potentially supporting future integrated Fission Surface Power (FSP) systems. Work within the FSP technology project has been primarily focused on a reference mission and concept, in which 40 kWe are provided to a lunar habitat with a design life of 8 years. Although many options exist, NASA's current reference FSP system uses a fast spectrum, pumped liquid sodium-potassium- (NaK-) cooled reactor coupled to a Stirling power conversion subsystem. (Detailed development of the FSP concept and the reference mission are documented in various other reports.)¹⁻⁴ In order to simultaneously pursue hardware advancement and address the concept's major technical challenge, the Technology Demonstration Unit (TDU) is currently under development. The TDU will contain a reactor simulator, power conversion unit, power management and distribution (PMAD), and a liquid metal pump.

The Early Flight Fission Test Facility (EFF-TF) at MSFC provides the capability to perform highly realistic, non-nuclear, hardware-based testing of reactor concepts and components. As such, the facility is an important tool in the development of the TDU. Certain critical technologies for the TDU have already been operated in various test articles at the EFF-TF, including two Stirling engines⁵ and an Annular Linear Induction Pump (ALIP)⁶. The TDU's simulated core is another such critical component. Its geometry must be accurate in order to correctly replicate fluid flow conditions in a functional nuclear reactor core. It must also contain a heat source that closely mimics the form and function of a nuclear fuel pin. The development and testing of the simulated core described in this paper (hereafter referred to as the '7-pin bundle') served two important purposes. The 7-pin bundle is a partial section of the TDU core; constructing it served to identify and overcome issues associated with the manufacture and assembly of the full TDU core. Additionally, the TDU's power requirements were high enough to necessitate the creation of a new thermal simulator which could deliver at least 2300 W per unit. This paper documents the construction of the 7-pin bundle, the design of the thermal simulators, the installation of the simulators in the bundle and the testing of the assembly in a pumped alkali metal circuit.

THERMAL SIMULATORS

Simulation of the heat of fission is the cornerstone of a successful non-nuclear testing program. To this end, continuing effort has been made at MSFC's EFF-TF to design simple, robust, inexpensive thermal simulators that closely match the steady state and transient performance of a nuclear fuel pin. As illustrated in Figure 1, a complete thermal simulator consists of a sheath, heater element, power leads, and electrical insulators to separate the heater element from the sheath.

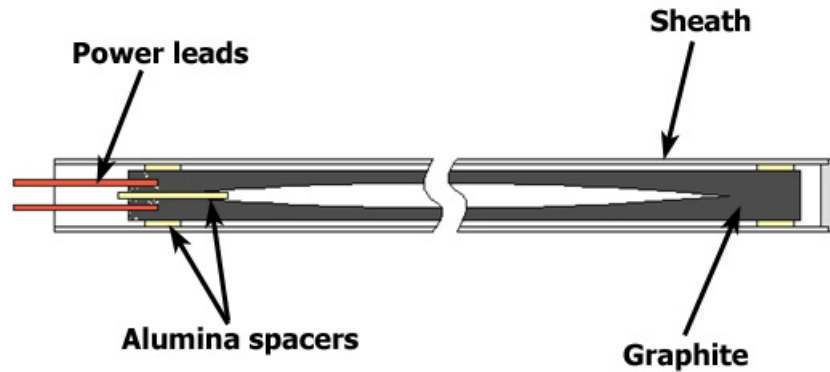


FIGURE 1. Thermal Simulator with Varying Cross Section.

Over the past several years, gas-cooled, heat pipe-cooled, and liquid metal-cooled simulated reactor concepts have all been tested at the EFF-TF.⁷⁻⁹ Heat was provided by a series of thermal simulators which could deliver approximately 1250 W per simulator. However, with the advent of the TDU, higher power levels of 2300 - 2600 W per simulator were required. In order to increase the power that may be delivered by a thermal simulator, the resistance of its heater element must be increased. There are three ways to accomplish this: lengthen the heater element, decrease its cross-sectional area, or fashion it from a material with a higher resistivity. The length of the thermal simulator was set by TDU design requirements, leaving the cross-sectional area and resistivity of the graphite heater element available for adjustment.

While the requirements for the TDU were still in development, thermal simulator redesign work was already underway at the EFF-TF. The first step taken was to alter the design of the heater elements' cross-sections. New heater elements were constructed from two pieces of graphite with the inside face of each piece hollowed out in a 'canoe' shape (Figure 2). When the two halves were placed together, the outer diameters (ODs) of the heater elements formed a circular cross-section. Material was removed from the inner diameters (IDs) of the graphite (as opposed to the ODs) to avoid changing the thermal coupling between the graphite and the steel sheath. Initial power profiling tests of the new simulator confirmed an increase in the simulator's overall resistance. The tests also confirmed the presence of a thermal profile in the simulator, with the greatest concentration in the center. (In addition to increasing the resistance of the simulators, the team also wished to develop units that could better match the axial power profile of a nuclear fuel pin. The original 1250 W simulators featured a non-varying cross-sectional design and, therefore, a non-varying axial power profile.)



FIGURE 2. Internal Shaping of Heater Elements.

Hollowing out the center of the heater element proved effective, increasing the power that could be applied to each simulator - but not quite enough to meet the TDU requirements. With the length of the simulator constrained by the TDU design, changing the heater element material was the logical next step. The original thermal simulators were fashioned from AXZ-5Q graphite, which has a resistivity of 157-315 $\mu\Omega/\text{cm}$ (400-800 $\mu\Omega/\text{in}$). A search for graphite with higher resistivity revealed a new possibility: ACF-10Q, which has a resistivity of 293-467 $\mu\Omega/\text{cm}$ (745-1,185 $\mu\Omega/\text{in}$). As these ranges show, it is quite possible for different batches of the same type of graphite to exhibit different resistivity characteristics; therefore, it is important to have the raw materials tested and certified to verify that heater elements made from the graphite will meet requirements. A new simulator was fabricated from ACF-10Q and tested in a vacuum chamber. The test results indicated that these simulators would indeed meet the power requirements of the TDU.

The thermal simulators are encased in 0.124-cm-thick, SS316 steel sheaths which are then welded into the 7-pin bundle (discussed later in this paper). When sheathed, the simulators have an OD of 1.9 cm and a length of 45.72 cm. The two pieces of graphite are electrically isolated from each other by a thin, flat piece of alumina. Rings of alumina encircle the graphite to isolate it from the steel sheath. The leads are 4-gauge copper - a significantly larger size than was employed in previous designs, necessitated by the high levels of current required to reach the desired power level. To reduce obstruction of liquid metal flow, the diameter of the sheath around the power leads is made as small as possible. During testing, the spaces between the graphite and the steel sheaths are backfilled with low pressure He gas (on the order of 13 kPa) to improve heat transfer from the graphite to the sheaths and into the NaK.

The amount of power that can be applied to each simulator is not limited by the graphite - it is limited by the power leads, with current draw being the limiting factor. The higher the resistance of the simulator is, the lesser is the current it will draw at a given power level. The simulators that will be used in the TDU are made from ACF-10Q graphite of a resistivity near the upper range possible for this type. These simulators will require a lower current draw than those that were tested in the 7-pin bundle, which were made from ACF-10Q graphite with a resistivity near the lower end of the range. The simulators described in this report have a resistance of 0.9 Ω at room temperature and approximately 0.5 Ω at 875 K (graphite temperature). Based on the resistivity of the graphite and the size of the power leads, the recommended maximum power level per simulator was 2800 W (16.8 kW total to the bundle).

7-PIN BUNDLE

The 7-pin bundle (Figure 3, inset) was constructed to facilitate testing of the thermal simulators in a pumped alkali metal test article. As a partial section of the TDU's simulated core, constructing it also served to identify issues that would be encountered during the manufacturing of the full core, which includes an open lattice structure. The 7-pin bundle consists of several components that form the boundaries of the liquid metal flow path inside the bundle. As shown in Figure 3, NaK enters the bundle and flows through the gap between the outer body and the inner body. The flow then turns sharply and passes through the gaps between the sheathed thermal simulators. It is in this region that heat transfer to the liquid metal takes place. After flowing through these channels, the fluid enters the downcomer region and exits the bundle.

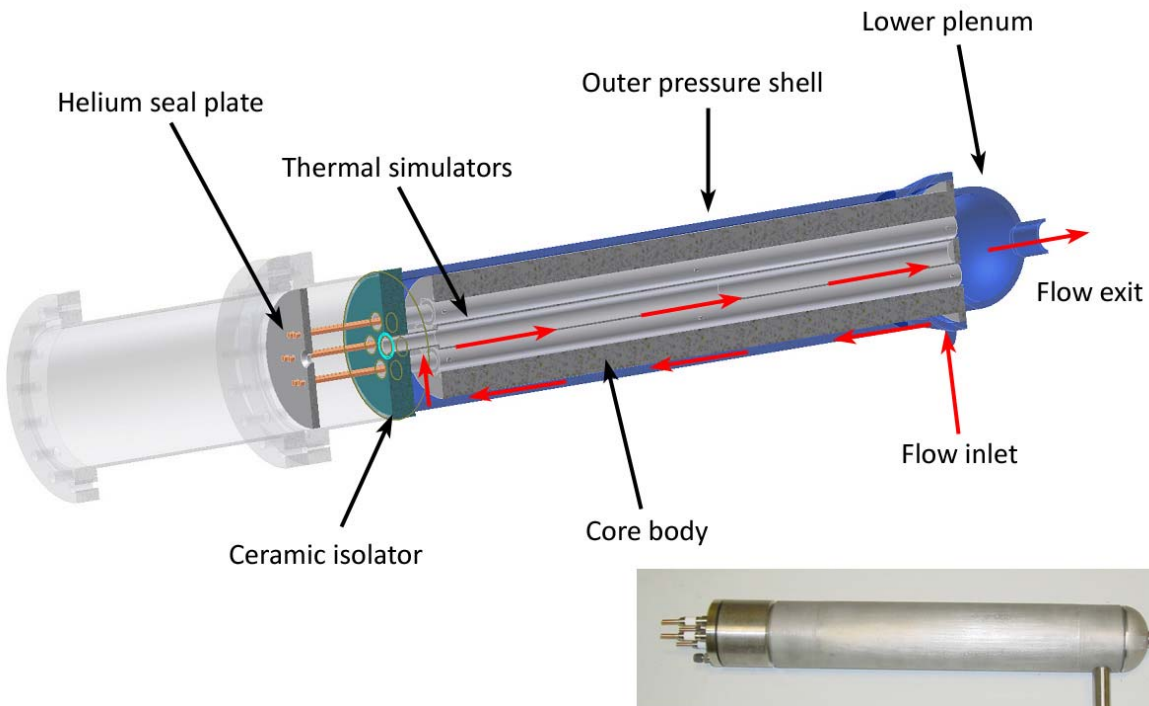


FIGURE 3. 7-Pin Bundle and Liquid Metal Flow Path.

The core body was constructed using a combination of electrical discharge machining (EDM) and electron beam welding. Two 22.86-cm-long sections with identical internal features were fabricated and then seam welded to produce a 45.72-cm-long body. The features at either end of the body keep the component centered within the outer pressure shell, forming a flow path for NaK. Steel-sheathed thermal simulators are placed within the hexagonal region of the core body. Each sheath features a ring of small standoffs at three locations along its length. The standoffs are machined on a snap ring, which is manufactured using EDM to achieve very small dimensions. This ring is then laser welded to the sheath, which is machined to receive the snap ring. During bundle assembly, the sheaths are meticulously positioned to align with each other as shown in Figure 4. Proper positioning results in a minimum distance of 0.097 cm from simulator-to-simulator and simulator-to-wall. Each standoff is approximately 0.318-cm long and 0.159-cm wide, presenting a minimal obstruction to fluid flow. A retaining plate is welded to the sheaths at one end to prevent the sheaths from shifting during assembly or testing. The simulators themselves are sealed into their sheaths by welding a cap on the end of each sheath.

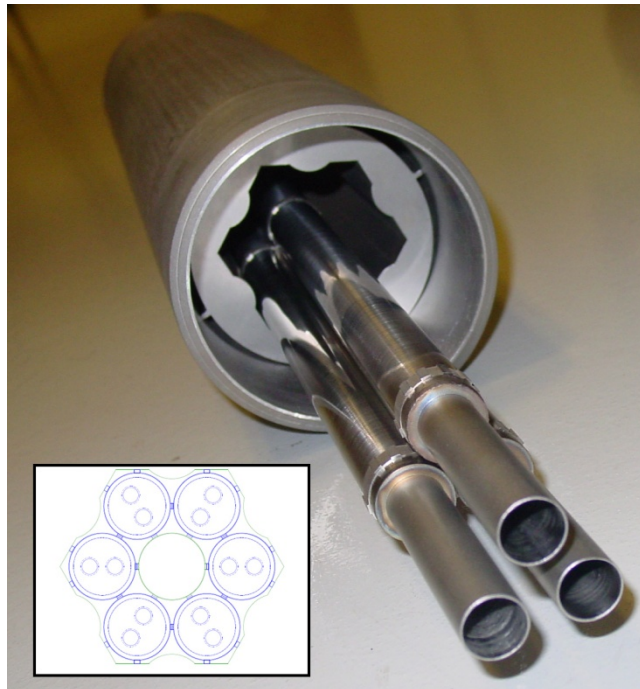


FIGURE 4. Outer Shell, Core Body, Thermal Simulator Sheaths with Snap Rings, and End View of Sheath Orientation.

The TDU simulated core can contain 37 thermal simulators; the 7-pin bundle can contain seven. Six simulators were installed in the bundle and wired in two zones of three simulators each. The seventh and central slot was filled with a thermocouple probe, which measures temperatures at ten locations along the bundle's length.

FISSION SURFACE POWER PRIMARY TEST CIRCUIT (FSP-PTC)

The FSP-PTC, shown schematically in Figure 5 and photographically in Figure 6, was designed to test components of a liquid metal-cooled reactor. The apparatus has been in use at the EFF-TF since 2006, with various components being added or removed as test series were completed and new ones began. At present the FSP-PTC contains the 7-pin bundle, an ALIP, electromagnetic (EM) flowmeter, simulated core, liquid metal-to-gaseous nitrogen (GN_2) heat exchanger (HX), fill and drain (lower) reservoir, expansion (upper) reservoir, throttling valve, remotely operated valve (ROV), instrumentation, and spill tray. All components are constructed of stainless steel (SS). The entire assembly is approximately 3.05 m long, 2.29 m wide, and 1.83 m high. The FSP-PTC interfaces with a variety of other systems, including GN_2 , argon, vacuum, and water systems, all of which are described in other reports.^{7, 10} The instrumentation used during testing included 64 type-K thermocouples, 15 pressure transducers, two flowmeters (for liquid metal and gas), multiple level sensors, and vacuum gauges. Voltages, currents, and power levels for the thermal simulators and the ALIP were also recorded.

It is important to note that the "simulated core" and the "7-pin bundle" are not the same component. The thermal simulators in the 7-pin bundle served as the heat source for the test series described in this paper. The "simulated core" still contains 37 thermal simulators of the older design. Though it remains in the flow path, it was not powered for these tests. The 7-pin bundle *is* a simulated core, but it is not called as such in this paper to avoid confusing it with the older, unpowered core.

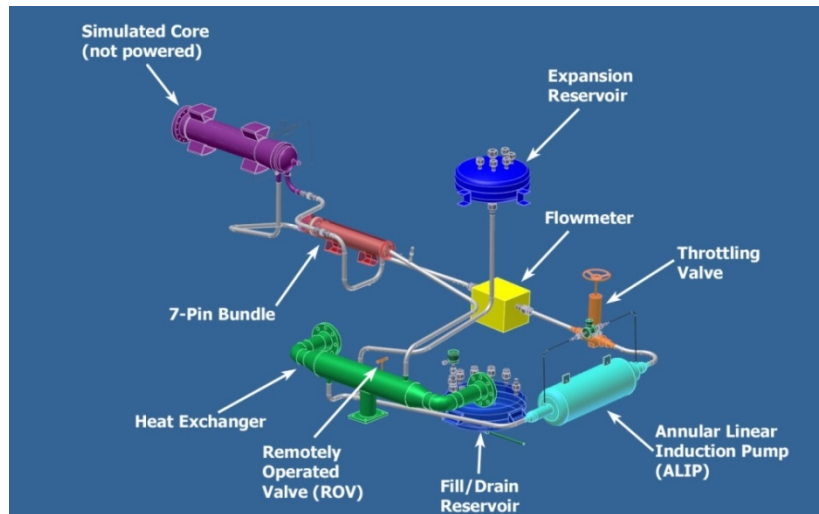


FIGURE 5. CAD Representation of the FSP-PTC.



FIGURE 6. Photograph of the FSP-PTC.

TEST PROGRAM AND DATA

The purpose of this series of tests was to verify thermal simulator robustness in a NaK-cooled environment while ensuring that the simulators and heat exchanger could be used together to bring the liquid metal up to a maximum temperature of 875 K (602 °C). The test program consisted of two phases: steady state testing (phase 1) and transient testing (phase 2). Only phase 1 results are discussed at length in this paper. In phase 1, steady state data was taken over a matrix of constant thermal simulator power, NaK flow rate, and 7-pin bundle outlet temperature. Bundle outlet temperature is brought to steady state by setting the thermal simulators to a desired power level, setting the NaK flow rate, and then adjusting power removal through the HX by controlling GN₂ inlet temperature and flow rate. For the purposes of these tests, steady state is defined as the condition at which the 7-pin bundle outlet temperature is changing by less than 4 °C over one hour. Table 1 shows the steady state test matrix. The power levels in the steady-state matrix were derived from the power levels that will be applied in the upcoming TDU tests. The TDU simulated core will have a nominal power level of 55 kW_e and a maximum power of 90 kW_e for a transient case. The 7-pin bundle contains one-sixth the thermal simulators of the full TDU core; therefore, the

power levels and flow rates to be tested were scaled back accordingly. The first three power levels in the matrix are one-sixth of 55 kW_e (9.17 kW_e), plus and minus 25% (6.88 and 11.46 kW_e). The final power level, 15 kW_e, is one-sixth the TDU transient power level of 90 kW_e. Similarly, the first three flow rates are one-sixth the nominal TDU flow rate of 1.1 kg/s, as well as plus and minus 25%. The fourth flow rate (0.29 kg/s) is one-sixth of 1.75 kg/s, which is the nominal flow rate in the TDU should Brayton engines be incorporated (instead of Stirling engines). As one-sixth of the TDU flow rate and core power, 0.18 kg/s and 9.17 kW_e were considered to be the “nominal” flow rate and power level for the 7-pin bundle testing.

TABLE 1. Steady State Test Matrix.

		6.88 kW _e	9.17 kW _e	11.46 kW _e	15.0 kW _e
650 K (377°C)	0.14 kg/s				
	0.18 kg/s		X	X	
	0.23 kg/s	X	X		
	0.29 kg/s		X	XX	
750 K (477°C)	0.14 kg/s				
	0.18 kg/s		X	XX	
	0.23 kg/s		XX	X	X
	0.29 kg/s				X
875 K (602°C)	0.14 kg/s				
	0.18 kg/s			X	XX
	0.23 kg/s				X
	0.29 kg/s				

The marks in the table indicate which data points have been taken to date. Cells with more than one mark indicate tests that were repeated on separate days. It was not crucial to take data at every possible combination, but rather to take data over a range of power levels and flow rates at each of the three NaK temperatures. At 875 K, it was not possible to take data in some of the cells. For example, the NaK in the FSP-PTC cannot be raised to 875K at 6.88 kW_e or 9.17 kW_e. At these power levels, heat losses due to thermal radiation and the flow of cooling gas through the ALIP (required to keep the pump’s internal components within their operational limits) prevent the NaK from reaching 875 K.

During the execution of the test series, it became apparent that the new thermal simulators could easily be used to raise the temperature of the NaK in the FSP-PTC to 875 K by setting the power level applied to the simulators and regulating heat removal through the heat exchanger. In order to raise the NaK temperature to this level, the GN₂ flow rate through the heat exchanger was kept as low as possible; in three of the four cases, there was no GN₂ flow through the heat exchanger at all. At 875 K, radiative heat transfer to the chamber walls was a dominant factor, and no further active heat removal was required. It was not possible to raise the FSP-PTC to 875 K at the “nominal” power level of 9.17 kW_e, but this should not raise concerns that the TDU will be unable to achieve this temperature at its nominal power level. First, the thermal mass of the FSP-PTC is much greater than one-sixth that of the TDU, and second, the TDU will be far better insulated than the FSP-PTC is. (Prior to the start of testing, all components in the liquid metal flow path were wrapped in several layers of aluminum foil which served as a very basic form of multi-layer insulation.) Figure 7 displays NaK temperatures around the FSP-PTC and total power applied to the 7-pin bundle over the course of an 875 K test. On this particular day, liquid metal temperatures settled out at 855 K, slightly below the desired level, but the operator did not attempt to raise them further due to time constraints. The sudden change in NaK temperature at roughly 7000 seconds occurred when the voltage applied to the ALIP was adjusted, resulting in a change to the liquid metal flow rate.

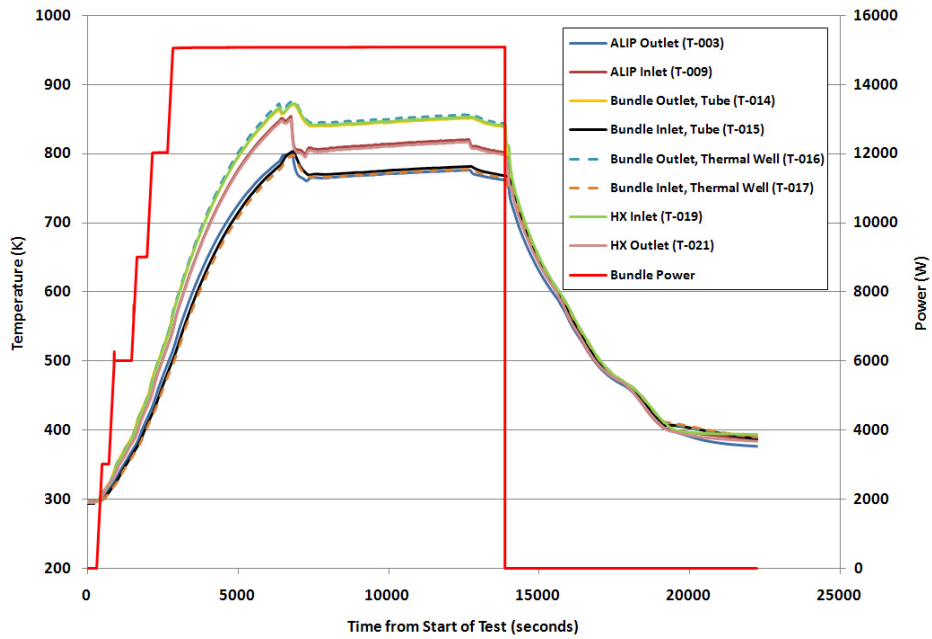


FIGURE 7. Liquid Metal Temperatures and Bundle Power during an 875 K Test.

Figure 8 displays the differential pressures across the ALIP and the 7-pin bundle and the NaK flow rate from the same 875 K test. At its maximum applied voltage, the ALIP can develop between 0.7 and 0.8 kg/s of flow (depending on the NaK temperature), so the flow rates tested in this series are well below the highest achievable. As Figure 8 shows, the 7-pin bundle represents approximately 25% of the total pressure drop in the circuit. (The data spike at 14000 seconds occurred when the ALIP was briefly powered off, bringing the flow rate to zero.) The NaK flow rate as measured by the electromagnetic flowmeter in the FSP-PTC has been observed to drift over time. This effect is attributed to the gradual warming of the magnet in the flowmeter due to radiation heat transfer. The TDU's electromagnetic flowmeter will contain an actively cooled magnet to eliminate this problem.

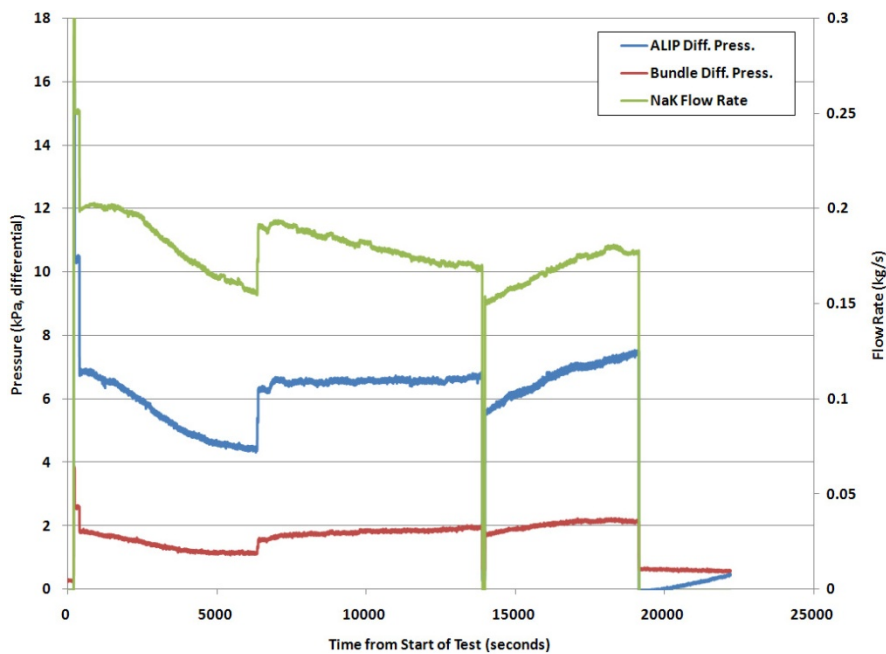


FIGURE 8. Differential Pressures and NaK Flow Rate during an 875 K Test.

More data from the 875 K test are shown in Figure 9, which contains the power applied to each thermal simulator zone and the resistance in each zone. The plot displays trend lines for each of the two thermal simulator zones, each of which operates on its own power supply. (There are two power curves, which lie nearly on top of each other on this graph.) Since there are three simulators in each zone, the average resistance per simulator in a given zone is obtained by dividing the value of the appropriate trend line by three. The same is true for the power applied to each simulator. The simulator behavior shown in this graph is typical of all tests run in this series. Simulator resistance changes smoothly as power is applied. The highest power level applied to the entire bundle during any phase of testing was 18.0 kW (3000 W per simulator), applied for five minutes during a transient test. The resistance of each simulator during this time was approximately 0.41 Ω . The highest power applied to the bundle for a sustained period of time was 16.6 kW (2767 W per simulator), applied for 40 minutes during a transient test. Again, the resistance of each simulator during this time was approximately 0.41 Ω . At these power levels the simulators' resistances change very little with an increase in power. More power could probably have been delivered to the simulators from the power supplies, but the test program had already shown that the simulators could handle more than the required amount of power, and driving the simulators to failure in a pumped NaK loop was not desirable.

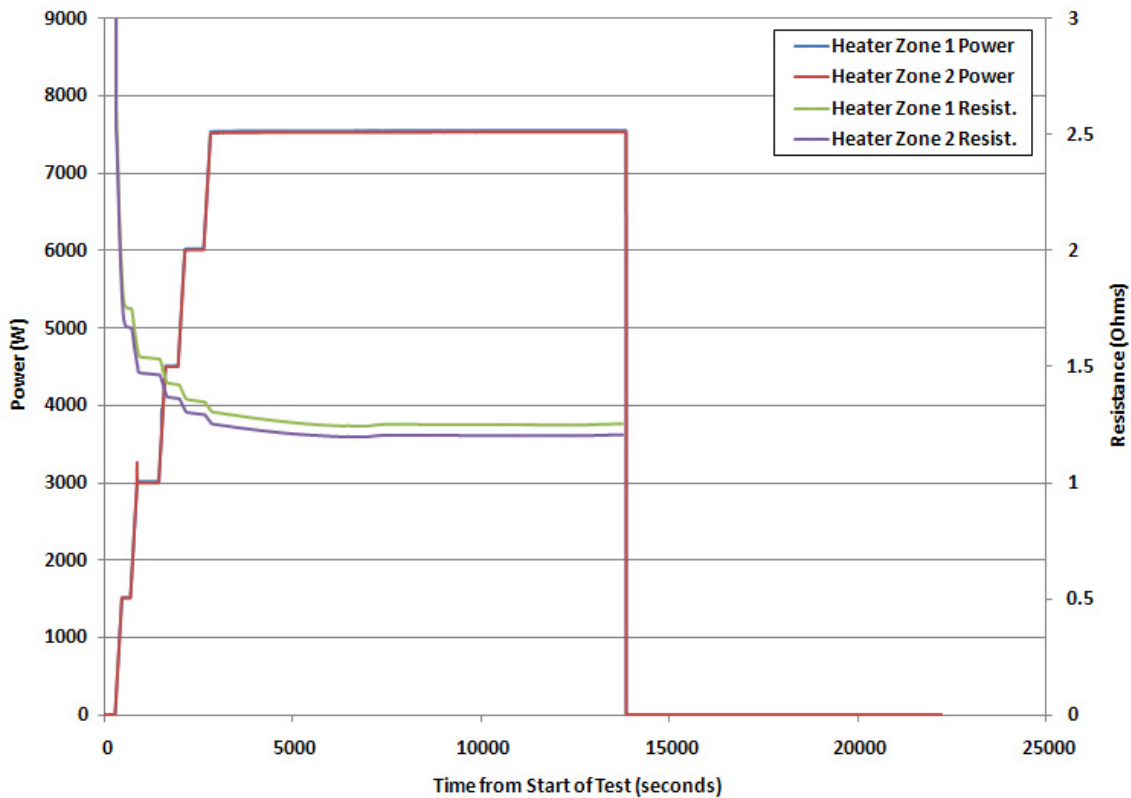


FIGURE 9. Thermal Simulator Power and Resistance during an 875 K Test.

CONCLUSION

A new series of thermal simulators has been developed at MSFC to facilitate non-nuclear testing of reactor concepts. These simulators can deliver a greater amount of power than simulators that have been used in previous test articles. The robustness of these simulators was confirmed by testing them in the FSP-PTC, an actively pumped liquid metal test article. The liquid metal in the FSP-PTC was raised to the desired maximum temperature of 875 K by controlling the addition of heat via the 7-pin bundle (which contained six thermal simulators) and the removal of heat via the heat exchanger. A maximum of 2500 W was applied to each of the simulators - or 15 kW total - during steady state testing. A maximum of 3000 W was applied to each of the simulators for five minutes during a transient test. The simulators have proved to be quite capable of delivering the power levels and temperatures

needed for the upcoming TDU. Because the TDU will be better insulated than the FSP-PTC, it should be possible to reach higher temperatures at lower power levels than were achievable with the FSP-PTC.

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