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# Modifications to the Fission Surface Power Primary Test Circuit (FSP-PTC)

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Abstract – *An actively pumped alkali metal flow circuit, designed and fabricated at the NASA Marshall Space Flight Center, underwent a range of tests at MSFC in early 2007. During this period, system transient responses and the performance of the liquid metal pump were evaluated. In May of 2007, the circuit was drained and cleaned to prepare for multiple modifications: the addition of larger upper and lower reservoirs, the installation of an annular linear induction pump (ALIP), and the inclusion of a closeable orifice in the test section. Modifications are now complete and testing has resumed. Performance of the ALIP, provided by Idaho National Laboratory (INL), is the subject of the first round of experimentation. This paper provides a summary of the tests conducted on the original circuit, details the physical changes that have since been made to it, and describes the current test program.*

## I. INTRODUCTION

To expand the multi-mission technology base related to the use of alkali metal systems for potential surface power application, an effort was launched within the Early Flight Fission- Test Facilities (EFF-TF) team to design, fabricate and test a pumped alkali metal (NaK) flow circuit. Previously published papers may refer to this test article as the Stainless Steel NaK-Cooled Circuit (SNaKC); however, it has since been renamed the Fission Surface Power Primary Test Circuit (FSP-PTC). The hardware was first filled with NaK in November 2006 and tested until April 2007. The main objective of these tests was to characterize the performance of the circuit's AC-style electromagnetic (EM) pump. A short series of tests to gather information on the circuit's response to transients was also conducted. When testing was complete, the circuit was drained and cleaned of residual NaK in preparation for modification. Some of the changes include the addition of an annular linear induction pump (ALIP), a closeable orifice, the replacement of the circuit's two reservoirs, and instrumentation updates. The primary goal of the upcoming testing is to characterize the performance and capabilities of the ALIP.

This paper begins with a description of the original test article and the results of its testing, followed by system cleanout, a detailed discussion of the changes that have been made, and a description of the current test program.

## II. ORIGINAL CIRCUIT CONFIGURATION

The original configuration of the liquid metal cooled circuit contained the following major components: simulated core, heat exchanger, electromagnetic (EM) pump, fill/drain reservoir, expansion reservoir, tubing, and instrumentation.[1] The circuit also contained a test section, which was attached to the flow path using VCR fittings instead of welds. This removable section was intended as a placeholder for other components, such as a power conversion system or a second, highly instrumented test cell. The test article was mounted on a spill tray which was angled at 5° to improve drainage into the lower reservoir. All wetted components were constructed from stainless steel, primarily 316 and 304. The maximum pressure and temperature that could be obtained in this test article were 20 psi and 525°C, respectively. Testing was conducted in the 9-ft chamber at the Early Flight Fission Test Facility, under rough vacuum conditions if power was applied to the core.

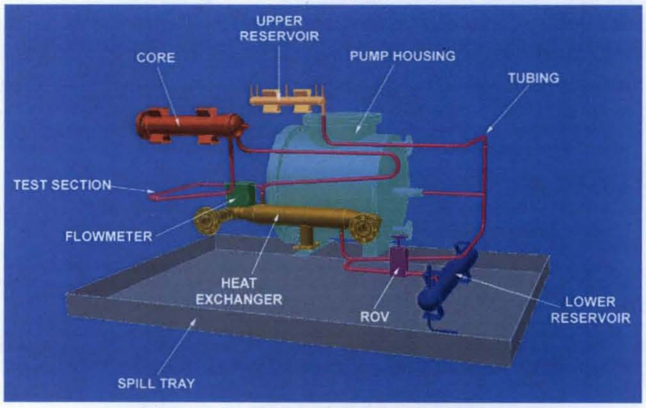


Figure 1. FSP-PTC (Configuration 1).

### *II.A. Core and Heat Exchanger*

The geometry of the simulated core is based on a 100-kWt Los Alamos design study[2]. In order to simplify the fabrication, integration and testing of the hardware, only the central three rings (37 fuel pins, or a 1/3-power assembly) were included, and the reflector drums and shields beyond the outer pressure shell were eliminated. 36 of the pin slots are occupied by graphite resistance heaters[3] that simulate the heat of fission. The central slot is occupied by a temperature probe, which contains thermocouples for measurements at multiple axial locations within the core.

After passing through the simulated core, the NaK enters a liquid metal-to-gas heat exchanger. This component is a 0.6 m long counter-flow design with NaK confined by the outer jacket and the secondary coolant flow ($GN_2$) confined by 107 tubes that pass through the NaK flow pool. The exchanger is equipped with temperature and pressure measurements to monitor material and fluid conditions. Flow rates in excess of 0.4 kg/sec can be achieved with nitrogen inlet temperatures of 490°C. The heated exhaust gas is vented to the atmosphere.

### *II.B. Pump*

The pump used in the first configuration is an AC conduction style EM pump. Originally marketed by Mine Safety Appliances, it was selected for a variety of reasons. Not only did it meet the circuit's flow, temperature and pressure requirements, but it contained no moving parts, could be welded into the flow path (as opposed to mechanically connected), and was readily available. The pump consists of nickel bus bars brazed to either side of a flattened section of 1" 316 stainless steel tubing, and of commercial windings as well. When power is applied, current flows through the NaK in the flattened duct, and the electromagnets simultaneously generate a magnetic field at 90° to this current. The interaction of this flowing current in the magnetic field results in a net force on the fluid, which circulates through the test article. The pump components are encased in a stainless steel housing, which itself is purged with nitrogen gas during heated tests. This enclosure is necessary since the system is tested in a vacuum chamber under pressures of $10^{-3}$ torr or lower, eliminating convective cooling of the pump. The pump provides continuous operation at temperatures up to 816°C, with flow control from 10% to 100% (provided by a three-phase motor driven variable transformer).

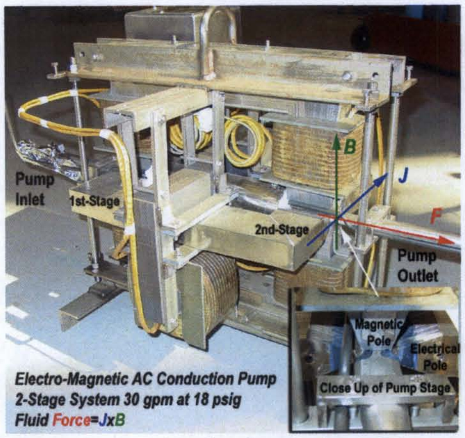

Figure 2. AC Conduction Style EM Pump.

### *II.C. Instrumentation*

The circuit was heavily instrumented with type-K thermocouples (TCs) that were spot-welded directly to the stainless steel. The TC wire, manufactured by Omega (HH-K-24-SLE), is a high temperature, glass-jacketed 24 gauge wire capable of operation at up to 704°C. TCs are located approximately every six inches along the lengths of tubing and are distributed over the surfaces of the core, heat exchanger, and reservoirs.

The FSP-PTC contained ten locations in the NaK flow path for pressure transducers: at the inlet and outlet of the heat exchanger, pump, and core, two on the core's outer pressure shell, and one each on the upper and lower reservoirs. The two locations on the core pressure shell were not used during testing. The units measuring NaK pressure are manufactured by Honeywell Sensotec, model TJE, with a range of 0-75 psia. All wetted parts are stainless steel. The temperature of the sensor electronics must remain at 162°C or below, which did prove to be a problem during the hottest tests that were conducted. (The problem was eventually solved by installing some basic radiation shielding on the circuit.) Multiple transducers were also used on the gas lines that service the heat exchanger and EM pump housing.

The level of NaK in the circuit was monitored using level sensors in the upper and lower reservoirs. Shown in Figure 3, these are 5 kV, 30 A power feedthroughs that terminate in weld lips that are welded to a VCR fitting. These are then mated to VCR fittings on the reservoirs. This is then mated to a VCR fitting on the upper and lower reservoirs. The level sensor works by completing a circuit (resistance measurement) when the level of the NaK comes in contact with the stainless steel pin of the feed-through. The team learned early on that if any NaK splashes into the space between the pin and the weld lip, it can permanently bridge the gap, resulting in a sensor that always indicates contact with NaK (whether or not there is any liquid metal in the reservoir). To prevent this, the pins were sheathed in alumina until just above their tips.

Figure 3. Level sensors with alumina sheaths.

NaK flow was measured using a liquid metal flowmeter, which was designed and built by Creative Engineers, Inc. It consists of a section of stainless steel tubing placed between two permanent magnets. Electrodes are welded to the tube at right angles to the magnetic field and the liquid metal flow. When the NaK flows through the magnetic field, it acts as a moving conductor and induces a current in the electrodes. This current is proportional to the average velocity of flow. The flowmeter must be wetted to assure a uniform current path; once this is done, its output signal can be considered trustworthy. Wetting temperature can vary, but this instrument wetted in the vicinity of 200°C. The flowmeter need only be wetted once before it will operate reliably over a full range of temperatures.

## III. SNAKC TEST RESULTS

### *III.A. Pump Performance Tests*

TABLE 1
Pump Performance Test Matrix

| | | EM Pump Voltage | | | |
|---|---|---|---|---|---|
| | | **100V** | **140V** | **200V** | **235 V** |
| | **350°C** | 4 | 2 | 3 | 1 |
| | **375°C** | 3 | 1 | 4 | 2 |
| | **400°C** | 1 | 3 | 2 | 4 |
| **NaK Flow Temp** | **425°C** | 2 | 4 | 1 | 3 |
| | **450°C** | 4 | 2 | 3 | 1 |
| | **475°C** | 3 | 1 | 4 | 2 |
| | **500°C** | 1 | 3 | 2 | 4 |
| | **525°C** | 2 | 4 | 1 | 3 |
| | **538°C** | 4 | 2 | 3 | 1 |

The pump performance test matrix was designed to characterize the developed NaK pressure and flow rate as a function of pump power over a range of flow temperatures. The variable transformer allows the test engineer to adjust the voltage applied to the pump to up to 235 V maximum. Table 1 shows the test matrix. The yellow boxes indicate which points were obtained. The matrix was intended to be run one row (NaK temperature) at a time. The numbers in each box indicate which pump setting is to be run first, second, etc. at the given temperature. In Table 1, "NaK Flow Temp" is the temperature of the NaK within the liquid metal pump. Due to thermal losses, there is some difference between the NaK temperatures at these locations.

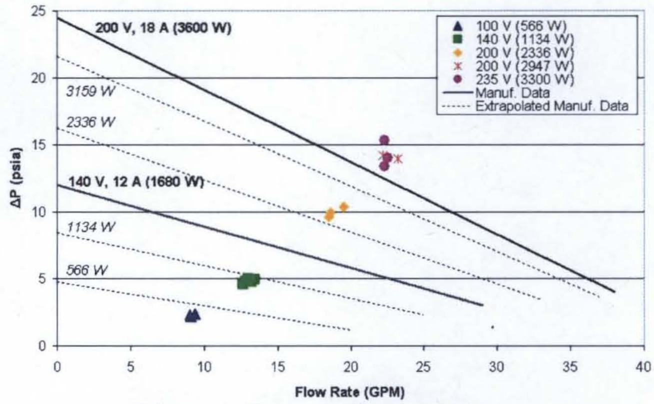


Figure 4. Pump performance data.

Figure 4 shows pump performance data (developed pressure versus flow rate). The bold lines indicate data that was experimentally taken by the pump manufacturer in the 1970s. The MSFC experimental data have been grouped by applied voltage in this figure, with the average pump power for each group of points indicated in the legend. (Note that 3159 W is the average pump power of *all* the data points in the upper right group.) The dashed lines were extrapolated from the bold lines for the purpose of comparison with the power levels seen at MSFC. Each individual data point on this graph represents the average of approximately one hour of thermal steady state data. Steady state was declared whenever the temperatures of the NaK in the flow path were changing by no more than 4°C per hour. Liquid metal pressures and flow rates required much longer to level off, quite possibly because the pump's efficiency is affected by temperature. Due to time constraints on the project, it was not possible to wait until the all these values had come to true steady state before taking a data point. For the purposes of these tests, it was determined that the pressures and flow rate were sufficiently stable to warrant declaring "steady state" when the aforementioned conditions have been met.

The NaK flow rate and developed pressure increase in a roughly parabolic fashion as applied pump power is increased. In general, the experimental data taken at MSFC track well with the manufacturer data; however, two points stand out: the red stars, taken at 200 V, which are not located near the other 200 V points (the orange diamonds). Factoring in the NaK flow temperature at each point may help to explain the separation.

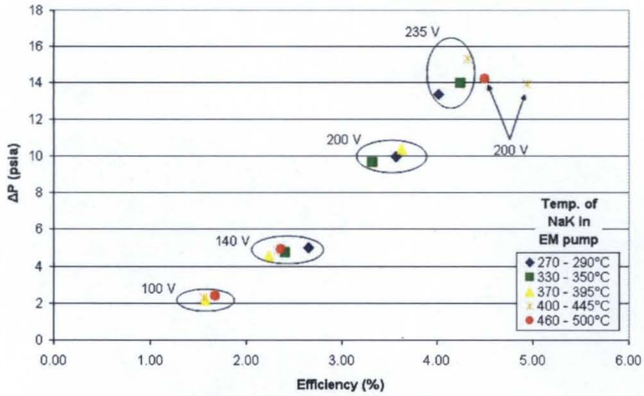

Figure 5. Pump efficiency.

Figure 5 is a plot of developed pressure versus pump efficiency. To illustrate the effect of NaK temperature on pump performance, the data points have been grouped by temperature rather than applied voltage/power. Pump efficiency is calculated per the following equation:

$$Eff(\%) = \frac{VolumetricFlowRate\left(m^3/_s\right) \times \Delta P(Pa)}{PumpPower(W)} \qquad (1)$$

where ΔP is the NaK pressure rise and pump power is the wattage that is applied for pump operations. Figure 5 clearly shows that the pump is more efficient when it is operating near its maximum rating. Note again the two 200 V points that fall outside their main grouping. At these particular points the temperatures of the NaK in the pump were 428°C and 493°C, respectively – hotter than the rest of the points taken at this voltage. No temperature data is taken on the pump mechanics themselves (most temperature measurements within the pump housing have proven to be either noisy or unreliable), but test data shows that the pump was drawing a higher current at these two points than at the other three, resulting in a higher overall applied pump power. According to the vendor, the EM pump operates more efficiently at NaK temperatures greater than 427°C. (At 358°C and below, nickel has a ferromagnetic quality[4] which can negate some of the flux generated by the pump's electromagnetic windings.) The two outstanding 200 V points were taken above 427°C, while the other three were below it. Additionally, the pump drew a higher current at these two points than it did at the other three. This can also be attributed to the temperature increase: the inductance of the nickel bus bars has dropped, enabling the pump to draw more current at the same voltage. It is not known precisely how long it takes for the pump to "warm up"; the nitrogen gas that flows through the pump housing is cold, and vies with the heated NaK to affect the pump's overall thermal state. Thermocouples inside the housing gave very noisy data and have not been useful in determining the actual temperature of the pump mechanics. Still, Figure 5 does appear to indicate a general trend toward higher efficiencies as NaK temperature increases. In the case of the data taken at 235 V, developed pressure rises with increasing NaK temperature, but pump efficiency does not increase a great deal. This seems to suggest that the pump is already operating at near-best efficiency when the maximum possible power is applied, leaving less room for an increase in performance as NaK temperature rises.

### *III.B. Transient Tests*

A brief series of tests were conducted for the purpose of evaluating the core's response to a thermal perturbation. Three different types of transients were simulated: 1) sudden change in core power; 2) sudden change in $GN_2$ flow rate through the heat exchanger; and 3) sudden change in NaK flow rate. In this document, only the results of the core power transient tests are provided.

As in the pump performance tests, steady state was declared when the temperature at the exit of the core was varying by less than 4°C over the course of one hour. During the transient tests, the system was not always allowed to linger at steady state for the full hour; however, by the time these experiments were run, the behavior of the circuit was generally well known.

In order to quantify the thermal response of the core, the time constant at CP-T-1 (the probe thermocouple nearest the core exit) was calculated for each of the various transients. The time constant is defined as the point at which the temperature has come within 36.6% of its final, steady-state value. This value is relevant because the FSP-PTC can be modeled using lumped parameters. In other words, at all locations in the circuit, the NaK temperature is changing on time scales of the same order. All points on the NaK flow path are affected by thermal gradients and respond accordingly. Figure 6, which shows temperatures at several locations around the circuit, illustrates this fact well. The thermocouples clearly "track" together when a system parameter is changed. This figure also illustrates that the transient curves can be described by an exponential function, which is required when calculating a time constant.

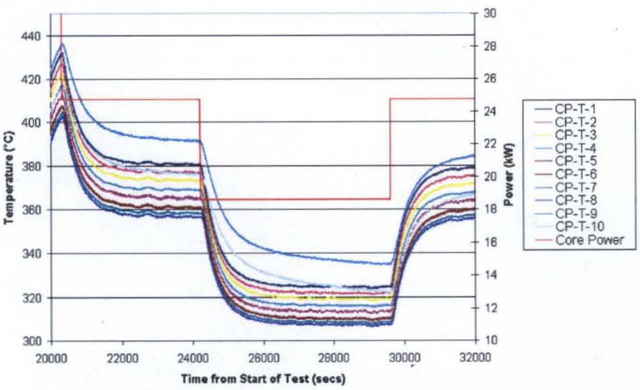


Figure 6. Core temperature transients.

Six transients were induced in which core power was suddenly changed. (Two of these events are shown in Figure 6.) In four of these cases, core power was either increased or decreased by 25%. This perturbation in core power, whether up or down, resulted in an average temperature change through the transient of 55.2°C, with a standard deviation of 0.65°C. The average time constant for these four tests was 465.5 seconds, with a standard deviation of 15.6 seconds. In the fifth core transient, the power was reduced from 25.6 kW to 15 kW – a drop of approximately 40%. The resulting temperature change in temperature at CP-T-1 was 93.6°C, and the time constant was calculated to be 630 seconds. It should be noted that this change in power was not instantaneous; it took place over 300 seconds, or at 35.3 W/sec.

## IV. SYSTEM CLEANOUT

Before any major components of the FSP-PTC could be changed out, draining and "cleaning" of the circuit was required. NaK adheres to the surface of its container when it has been heated to temperatures well in excess of ambient. The high temperatures seen in the pump performance tests ensured that some NaK would remain on the interior walls of the circuit, even after it had been fully drained. To prepare the circuit for modification, a device called the Alkali Metal Steam Cleaning System (hereafter referred to as the cleaning system) was procured from Creative Engineers, Inc. The system generates a superheated mixture of steam and nitrogen which is passed through the NaK-wetted test article. The steam reacts with the NaK, resulting in the production of sodium hydroxide, potassium hydroxide and hydrogen gas. The hydroxides are collected in a large scrubber upon exiting the circuit, and the hydrogen gas is vented outside the building. NaK reaction rate is monitored using gas sensors, sight glasses and thermocouples. The steam concentration is increased as the reaction rate decreases. When it is determined that all residual NaK in the system has been reacted, the test article is flooded with water as a final step.

The bulk of the liquid metal was drained from the system before cleaning began. Based on the weight of the NaK that was removed, it was determined that 0.68 kg remained to be reacted. The steam cleaning of the FSP-PTC progressed very smoothly and required only a few hours to complete. The NaK-water reaction itself was completed in less than one hour, though the system was flushed with steam (and subsequently water) for a considerably longer period of time.

## IV. CIRCUIT MODIFICATIONS

A variety of changes have been made to the FSP-PTC, including the addition of an Annular Linear Induction Pump (ALIP) and a throttling valve, the replacement of the two reservoirs, and updating instrumentation. All of the new units have been inserted into the circuit using VCR fittings. In the original configuration, nearly all components were welded into the flow path (with the exception of the test section, which did employ VCR fittings). The mechanical junctions were monitored closely throughout the test program, and no signs of leakage were found. Using VCRs as connection points lends an aspect of modularity to the system. It is far more difficult to change out components when they must be cut out of the circuit.

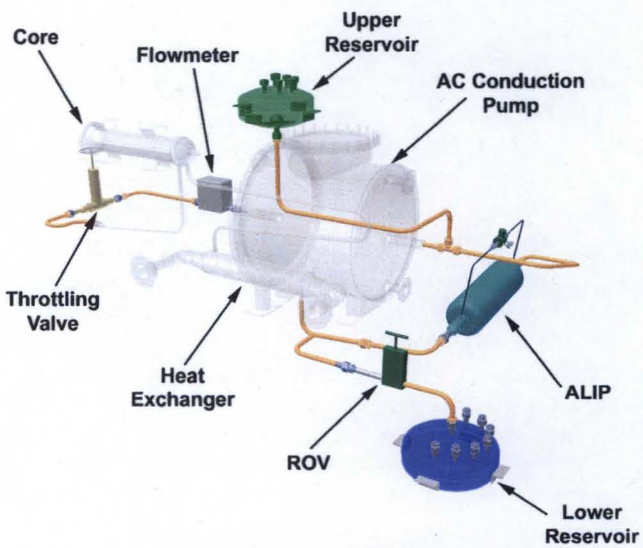


Figure 7. Modified FSP-PTC.

The inclusion of the ALIP is the most significant modification and drove many of the other changes. ALIPs are attractive for surface power systems because they contain no moving parts and are capable of developing higher flow rates and operating at higher temperatures than conduction-style pumps. This particular unit, shown in Figure 8, was built in 1989 by MHD Systems and was originally used to circulate sodium. It is on loan to MSFC from Idaho National Laboratory (INL). The pump consists of a central, two-inch duct with a torpedo inserted inside to create a thin annulus for liquid metal flow. The duct is surrounded by a series of stators. The application of three-phase AC power results in a traveling magnetic wave that moves down the length of the duct. The traveling wave itself induces currents in the liquid metal, and the interaction of these currents with the magnetic field results in a net force on the fluid. All wetted components are stainless steel. The pump is nominally capable of developing 30 psi at 60 GPM and a maximum temperature of 650°C. As with the AC conduction pump, power is provided through a variable transformer, allowing a maximum of 200 V to be applied to the pump.

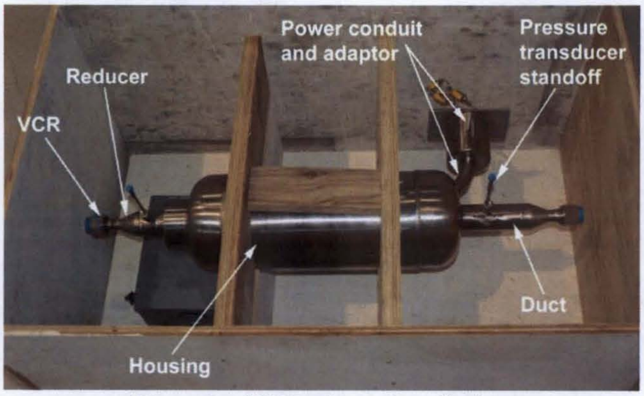

Figure 8. ALIP prior to installation.

The removable test section from the original circuit configuration has been filled with a throttling valve. Previously, the test article had a set hydraulic diameter, and the flow rate could only be altered by changing the applied pump power (or, to a lesser degree, the flow temperature). With the inclusion of this valve, the test engineers plan to generate multiple data points at a single power setting. Manufactured by Bonetti, this valve has a body, bonnet, and seat of 316 stainless steel and bellows of 321 stainless steel with graphite packing. Its maximum rating is 135 psi at 800°C. Gate valves are not typically used for throttling flow; however, discussions with Bonetti representatives have alleviated any concerns on the subject. The pressures and flow rates that will be generated should be low enough that vibration will not be an issue. The valve will be monitored to verify that everything is in good order. The unit is not equipped with an actuator and must be operated by hand. Since the circuit cannot be approached when hot, the valve position will be set prior to the start of a test. It cannot be changed until the test has been shut down and the circuit has cooled.

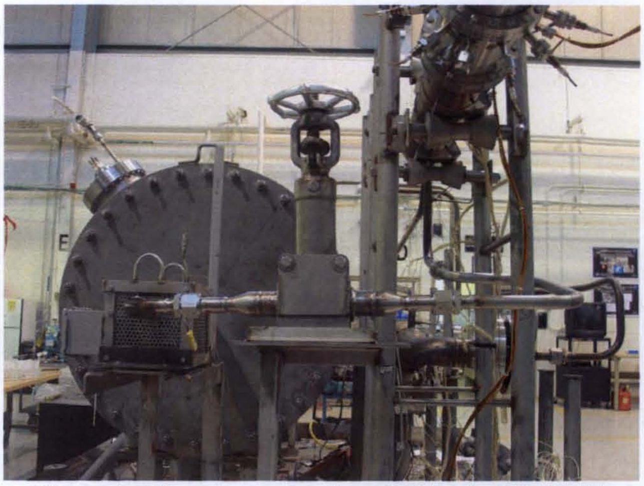
Figure 9. Throttling valve, installed in the FSP-PTC.

The inclusion of the ALIP and throttling valve has increased the volume of the NaK flow path from what it was originally – enough that the lower reservoir was replaced with a redesigned, larger version. What is more, it was sized not only to accommodate the new valve, ALIP, and tubing, but also other components that may be added in the future. The new lower reservoir has a volume of 26530 $cm^3$, compared to the 16928 $cm^3$ of the original. The upper reservoir was replaced for similar reasons. Its function is to contain the expansion of NaK at high temperature, and more liquid metal in the flow path results in a larger expanded volume. A lesson learned on the day after the first heated test (in 2006) also influenced the upper reservoir redesign. At the time of the event the liquid metal flow path was full and argon gas was present in the upper reservoir, providing head pressure for the pump. When the argon pressure in the upper reservoir was reduced, its level sensors began to indicate contact with liquid metal at increasing heights. When the pressure reduction stopped, so too did the rising NaK levels. It was determined that a gas bubble in the core had expanded when the pressure was reduced, which pushed the surrounding fluid out of its way and into the upper reservoir. The back end of the core is the highest point on the circuit with the exception of the upper reservoir (due to the 5° angle of the spill tray), and is a natural location for the collection of gas should any be present in the flow path. The only way to remove it is to drain the liquid metal into the lower reservoir and evacuate the flow path. A logical safeguard, beyond procedurally checking for these bubbles, was to increase the volume of the upper reservoir such that it could not be fully filled with liquid metal should another such event occur. The new component has a volume of 19157 $cm^3$, compared to 3583 $cm^3$ in the first configuration.


Figure 10. Lower reservoir and ALIP.

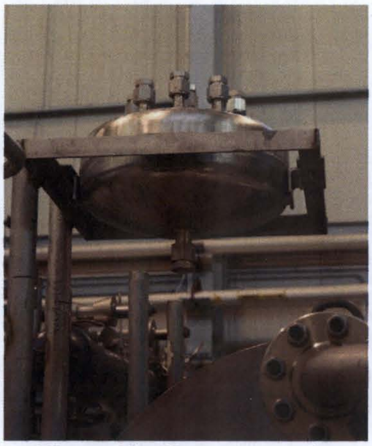
Figure 11. Upper reservoir.

Changes have been made to the instrumentation used in the modified circuit. First, the flow path now contains three differential pressure transducers: one across the ALIP, core, and AC conduction pump, respectively. Absolute pressure measurements are taken on the upper and lower reservoirs and at the inlet of the core and outlet of the ALIP. These units were specially made by Delta Metrics for the Early Flight Fission Test Facility. The diaphragm regions are larger than those on the transducers that were previously used, and they contain ports on the sides to allow steam to flow through the wetted space during the cleaning process. The absolute transducers represented dead ends in the steam flow path during the first system cleanout, and not all the residues in these instruments were reacted. (The pressure transducers were removed prior to flooding the test article with water.) In the end, the instruments had to be destroyed in order to fully clean them. The new, specially designed transducers should pose no such problem for the steam cleaning system, and should be reusable afterwards.


Figure 12. Differential pressure transducer.

In the original test article, type-K thermocouples were tack-welded directly to the surfaces of the tubing and components. While these units provided very reasonable data, the uncertainty in the measurements was higher than was desirable. This became apparent when calculating a power balance across the heat exchanger: small changes in NaK temperature resulted in large changes in the calculated wattages. To decrease this uncertainty, sheathed thermocouples are now being used. Tack-welding bare wire to the test article results in grounded thermocouples with significant noise in their signals. The sheathed units are not grounded and show significantly less noise in their output. Furthermore, these new instruments have been clamped to the test article rather than welded in place. The units at the inlet and exit of every major component in the flow path (pumps, core, flowmeter and heat exchanger) are in the process of being calibrated. Due to time constraints, it is not possible to calibrate every thermocouple on the test article.

As in the original test article, static level sensors are being used to monitor the height of the liquid metal in the upper and lower reservoirs. These units have been proven to be effective and reliable. However, the information given by these units is discrete, and it would be desirable to know the precise level of NaK in the reservoirs at any given moment. To this end, a dynamic level sensor has been developed and installed in each reservoir. The dynamic sensors essentially consist of a pair of pins, one of which is a very fine wire. As the probe is submerged in the NaK, the measured resistance of the wire changes. This resistance can then be correlated to a certain liquid metal level.

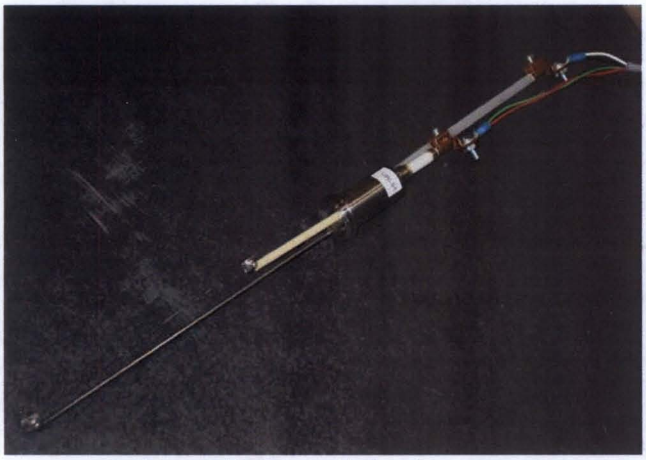

Figure 13. Dynamic level sensor.

## VI. TESTING OF THE MODIFIED CIRCUIT

The FSP-PTC was refilled with NaK in early February 2008, and testing has begun. Preliminary tests will serve as a checkout of the data acquisition system and instrumentation. Following this, a series of cold flow tests will be performed to determine the effect of the throttling valve on flow conditions. At a set ALIP power, the valve will be gradually closed (in discrete steps), with pressure and flow rate data being taken at each step. This process will be repeated for a variety of pump power settings. Achieving thermal equilibrium during these throttling valve tests is not necessary. Next, a series of heated flow tests will be conducted. A desired flow temperature and ALIP power will be set, and data will be taken at thermal equilibrium. The throttling valve will then be reset at a new position and the test will be repeated at the same flow temperature and ALIP power. A variety of temperatures will be tested, with 525°C being the maximum. During these experiments, the frequency of the power applied to the ALIP will be 60 Hz; however, this is not necessarily the frequency at which the pump operates most efficiently. An adjustable frequency AC motor drive has been located which should allow for the execution of a test series to determine the optimal value. Finally, a pair of 1 kW Stirling converters are being readied at the Glenn Research Center (GRC) for incorporation into the FSP-PTC. This unit should be delivered to MSFC in the spring.

## VII. CONCLUSIONS

The FSP-PTC underwent a successful series of tests at MSFC in 2007, resulting in the characterization of the performance of the circuit's original pump. The system was then drained, cleaned of residual NaK, and modified to include several pieces of new hardware. The primary goal of the upcoming series of tests is to quantify the capabilities of the ALIP. The circuit has been refilled with NaK, and testing has resumed, starting with a series of cold flow tests to understand the effect of the throttling valve on liquid metal flow.

## ACKNOWLEDGMENTS

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## NOMENCLATURE

| | |
|---|---|
| A | Amperes |
| AC | Alternating current |
| ALIP | Annular Linear Induction Pump |
| °C | Degrees Celsius |
| cm | Centimeters |
| EM | Electromagnetic |
| FSP-PTC | Fission Surface Power Primary Test Circuit |
| ft | Feet |
| GPM | Gallons per minute |
| Hz | Hertz |
| K | Kelvin |
| kg | Kilograms |
| kW | Kilowatts |
| m | Meters |
| NaK | Sodium-potassium |
| P | Pressure |
| Pa | Pascals |
| psi | Pounds per square inch |
| psia | Pounds per square inch, absolute |
| s | Seconds |
| sec | Seconds |
| SNaKC | Stainless Steel NaK-Cooled Circuit |
| TC | Thermocouple |
| V | Volts |
| W | Watts |

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