

REACTOR SIMULATOR TESTING

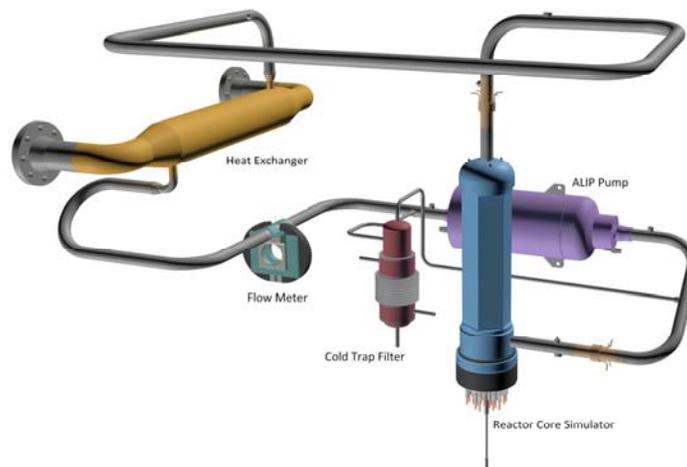
M.P. Schoenfeld, K.L. Webster and B.J. Pearson
NASA MSFC/Propulsion Systems & Technology Branch/Nuclear Systems Team
Huntsville, AL

ABSTRACT

As part of the Nuclear Systems Office Fission Surface Power Technology Demonstration Unit (TDU) project, a reactor simulator test loop (RxSim) was design & built to perform integrated testing of the TDU components. In particular, the objectives of RxSim testing was to verify the operation of the core simulator, the instrumentation and control system, and the ground support gas and vacuum test equipment. In addition, it was decided to include a thermal test of a cold trap purification design and a pump performance test at pump voltages up to 150 V since the targeted mass flow rate of 1.75 kg/s was not obtained in the RxSim at the originally constrained voltage of 120 V. This paper summarizes RxSim testing. The gas and vacuum ground support test equipment performed effectively in NaK fill, loop pressurization, and NaK drain operations. The instrumentation and control system effectively controlled loop temperature and flow rates or pump voltage to targeted settings. The cold trap was able to obtain the targeted cold temperature of 480 K. An outlet temperature of 636 K was obtained which was lower than the predicted 750 K but 156 K higher than the cold temperature indicating the design provided some heat regeneration. The annular linear induction pump (ALIP) tested was able to produce a maximum flow rate of 1.53 kg/s at 800 K when operated at 150 V and 53 Hz.

INTRODUCTION

A 40 kWe fission power system Technology Demonstration Unit (TDU) is being developed under the Fission Power Systems project. The TDU is comprised of a non-nuclear core simulator, sterling engine power conversion system, Annular Linear Induction Pump (ALIP), liquid sodium/potassium (NaK) coolant, and radiator heat rejection. In support of TDU development, the RxSim test loop was developed to perform integrated component testing to verify operability prior to the TDU development. The RxSim was a NaK filled test loop comprising of a 37 pin reactor core simulator, NaK-GN₂ HX (for simulating the thermal load of the sterling power conversion system), an electromagnetic flow meter, and the TDU ALIP. In addition, although not part of the TDU, the RxSim had a secondary bypass loop across the ALIP to test a cold trap purification design. Figure 1 shows the RxSim layout. This report covers testing in the RxSim loop while details of the design and development are in a separate report.



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FIGURE 1. RxSim Test Loop Layout.

REACTOR SIMULATOR OPERATION AND CONTROL

Reactor simulator control systems were developed to provide the following five modes of operation for operations: basic, power, power ramp, temperature and reactor simulator function (RSF). Figure 2 shows the user interface panel for operating the RxSim.

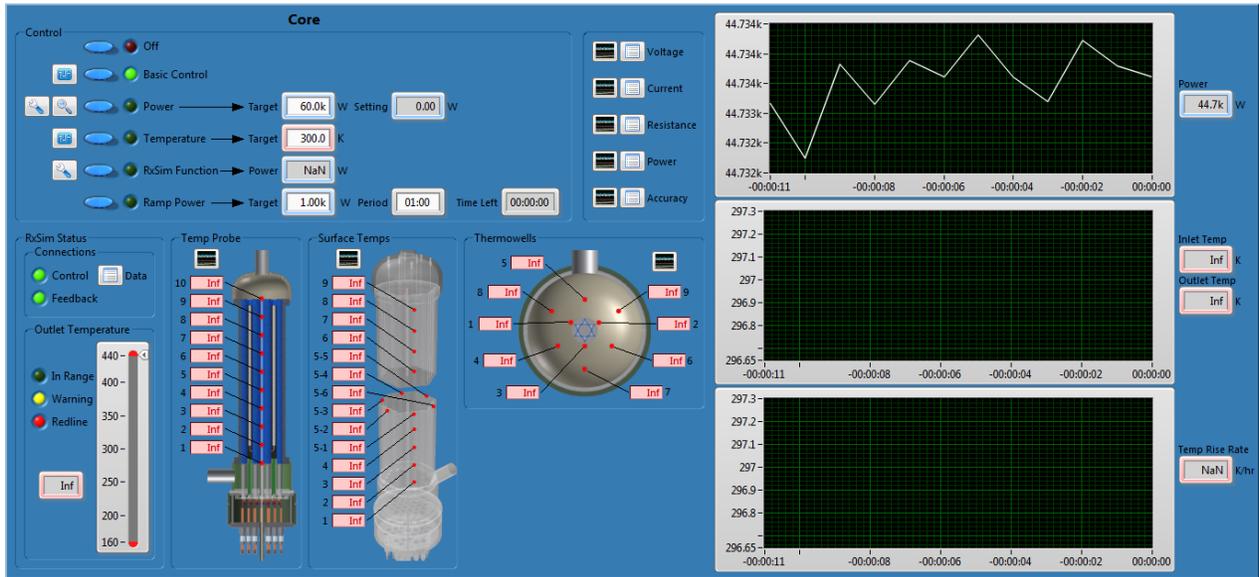


FIGURE 2. User Interface Panel for the RxSim Control.

The basic control mode allows the operator to control the individual voltage and current settings for each of the 12 heater zones of the core simulator. Figure 3 shows the user interface panel for this control mode. This panel also provides a mechanism for calibrating the analog command used to control the current setting of each power supply.

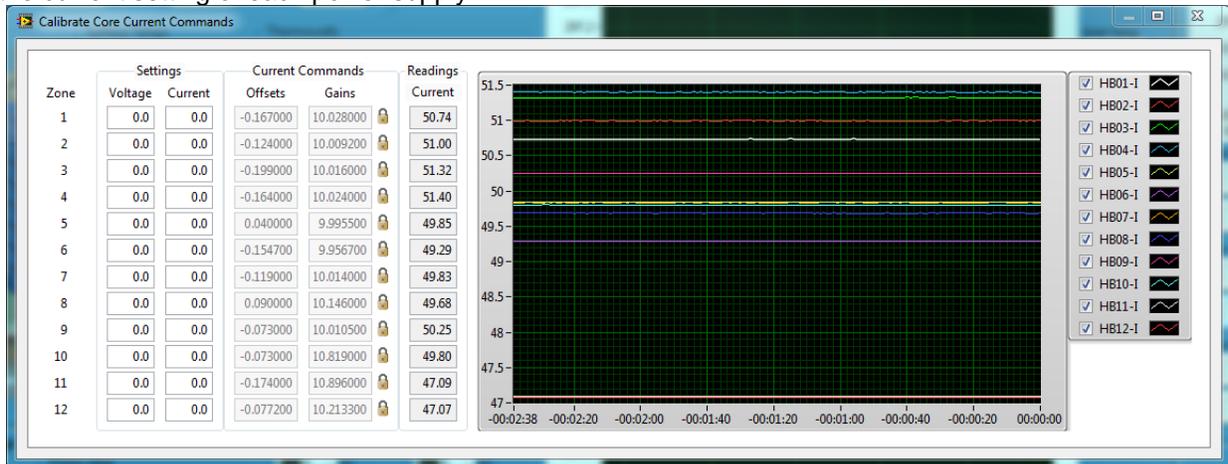


FIGURE 3. User Interface Panel for Basic Control Mode.

Each of the 12 zones can operate in constant current or constant voltage mode depending on the voltage and current settings. When the load attempts to draw more current than the current setting,

constant current mode is enabled. Otherwise, constant voltage mode is enabled. The voltage and current settings for each zone are limited to 150 V and 100 A, respectively.

The power control mode allows the operator to control the total power setting for the core. The power delivered to the core is distributed to each of the 12 heater zones according to weighting factors specified by the operator. For all operations to date, all weighting factors have been set to 1.0 so that the power is distributed evenly among all 12 heater zones. The power to a zone is controlled by operating its power supply in constant current mode. Current and voltage measurements for each zone are used to calculate the load resistance and the target set points required to achieve the desired power setting. As new measurements are taken, the current setting is adjusted to compensate for changes in the load resistance. When starting from a power setting of zero, the current and voltage settings of a zone are gradually increased until useable current and voltage measurements are obtained. The total power setting and power rate of change are limited and constrained by the maximum power and slew rate setting specified by the operator. The following power control configuration dialog is provided for the operator to specify the maximum power, maximum slew rate and weighting factors.

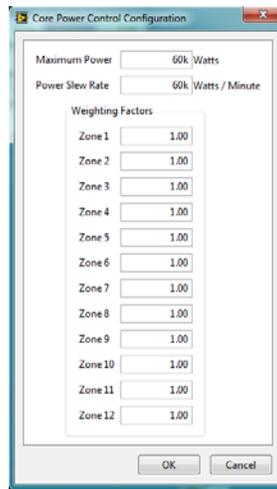


FIGURE 4. User Interface For Configuration Settings of the Core Power Control Mode

The power ramp control mode allows the operator to ramp the total power from a starting set point to a new set point over a specified period of time. Once the desired power is achieved, the control mode switches to the power control mode to maintain the new power setting. The ramp rate is limited by the maximum slew rate specified in the power control configuration dialog.

The temperature control mode allows the operator to control the NaK outlet temperature of the core. This mode uses 2 control loops to achieve temperature control. When the difference between the outlet temperature measurement and the set-point is less than a specified limit, a temperature control loop is used. Otherwise, a temperature rise rate control loop is used. This insures that the temperature does not rise or fall too rapidly when the difference between the measurement and set-point are large. Each of the control loops combines a feedback (closed-loop) PID controller with a feed-forward (open-loop) control. Feed-forward control uses knowledge about the system to estimate the power setting required to achieve the desired set-point, while the PID controller responds to differences between the set-point and the actual measured temperature and adjusts the power setting to eliminate those differences. Although the open-loop estimate is not perfect, it does provide most of the power setting required to achieve the set-point. The combination of feed-forward and PID control greatly improves overall system performance compared with PID control alone. The open-loop power setting estimates for temperature control are given by equation 1 and temperature rise rate given by equation 2.

$$\dot{m}(c_{pt}T_t - c_{pi}T_i) + A\varepsilon\sigma(T_t^4 - T_c^4) \quad [1]$$

$$m_c c_{pc} \dot{T}_o + \dot{m} (c_{po} T_o - c_{pi} T_i) + A \varepsilon \sigma (T_o^4 - T_c^4) \quad [2]$$

In order to insure bump less transfer when the temperature control mode is activated and when switching between temperature and temperature rise rate control loops, both loops continue to perform control calculations even when inactive. Figure 5 shows the user interface for tuning these control loops.

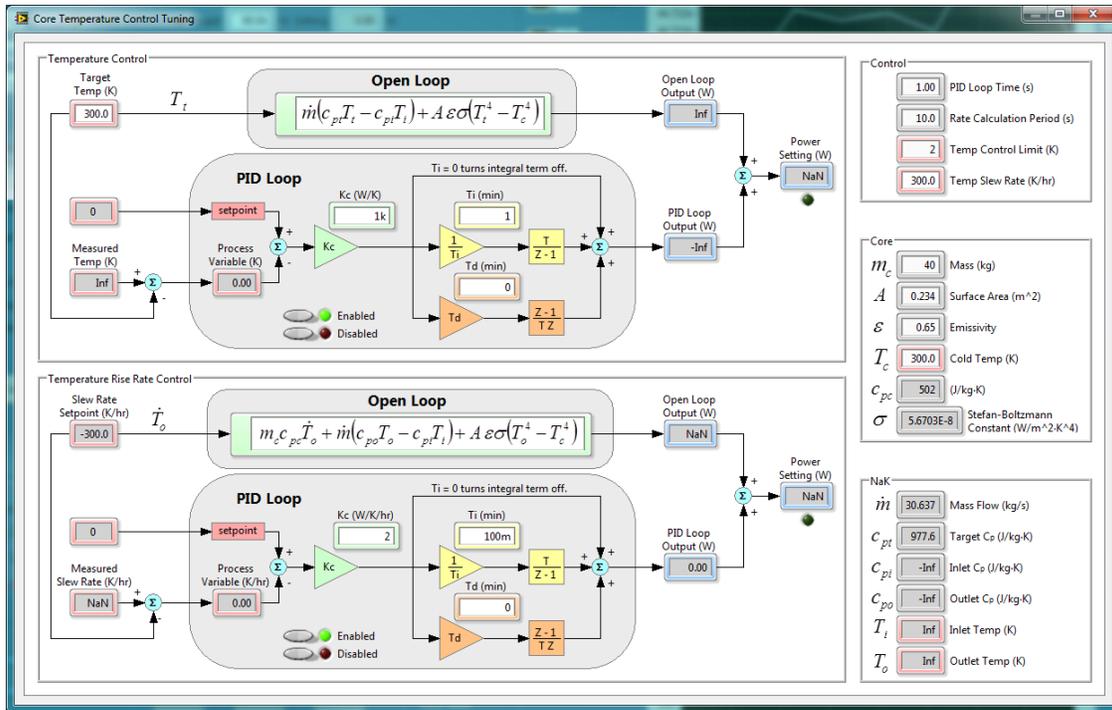


FIGURE 5. User Interface For Tuning Temperature And Temperature Rise Rate Control Loops

The RSF mode enables remote control of the core power by a LabVIEW application running on a National Instruments cRIO-9024 real-time controller. The application runs a Simulink model which simulates the response of a real nuclear reactor. Two TCP network connections are used to communicate with the application. Feedback in the form of the core inlet temperature, NaK pressure and NaK mass flow rate is provided to the application over one connection. The core power setting and various model outputs are returned over the other connection. The RSF mode can only be enabled when both TCP connections are active with no errors and when the core outlet temperature is within an operator specified range. If either connection is lost or the outlet temperature goes out of range, the control mode switches to temperature control mode to take the system back to the operator specified temperature set-point. Figure 6 shows the user interface for specifying the temperature limits and configuring the TCP communication.

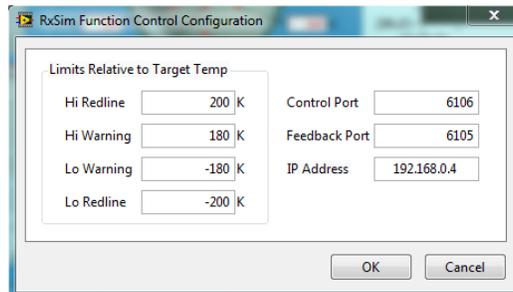


FIGURE 6. User Interface For Specifying Temperature Limits and TCP Communication Regarding the Reactor Simulator Function Control Mode.

CONTROL FOR ALIP OPERATION

Two modes of operation are provided for operating the ALIP: voltage and flow rate. Figure 7 shows the user interface for operating the ALIP.

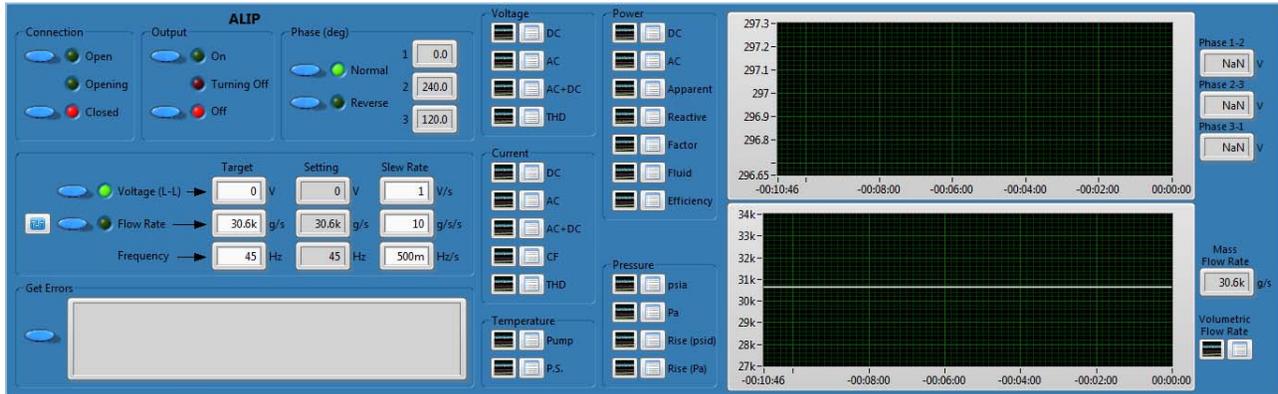


FIGURE 6. User Interface For ALIP Operation.

The voltage control mode allows the operator to control the line-to-line voltage setting of the ALIP power supply. To insure that there are no abrupt changes in voltage while the pump is operating, new settings are limited by an operator specified slew rate. The voltage setting is limited to 150 VAC.

The flow rate control mode allows the operator to control the NaK mass flow rate. This mode is implemented with a control loop that combines a feedback (closed-loop) PID controller with feed-forward (open-loop) control. Feed-forward control uses knowledge about the system to estimate the voltage setting required to achieve the desired set-point, while the PID controller responds to differences between the set-point and the actual measured flow rate and adjusts the voltage setting to eliminate those differences. A linear curve fit of the measured flow rate at various voltage settings was used for the open-loop estimate. The differences due to nonlinearity and changes in temperature dependent fluid characteristics were easily compensated for by the PID controller. The combination of feed-forward and PID control greatly improves overall system performance compared with PID control alone. In order to insure bump less transfer when flow rate control is activated, the control loop continues to perform control calculations even when inactive. Figure 7 shows the user interface for tuning these control loops.

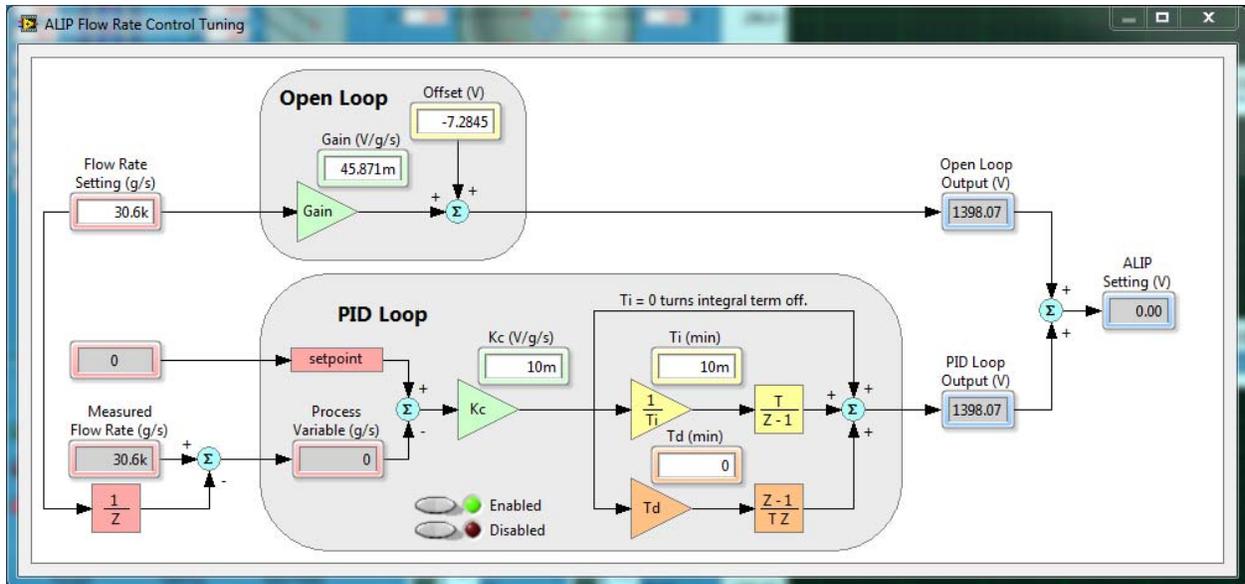


FIGURE 7. User Interface For Tuning ALIP Operation Control Loop.

RESULTS AND DISCUSSION

RxSim testing involved operational checkouts of the loop control and instrumentation system and the gas and vacuum test support equipment. To accomplish this, the RxSim was to be operated at TDU representative temperatures and flow rates (800 K and 1.75 kg/s). Vacuum and gas support equipment were used for NaK transfer operations (evacuating the RxSim loop, lower reservoir or accumulator, applying Ar pressure head, and actuating a remote operating valve). The gas system also supported the TDU ALIP by supplying and regulating (relief valve and regulator in conjunction) He pressure in the electrical areas of the ALIP. In the past, this support equipment was provided by the test facility. These gas and vacuum racks were built to provide dedicated support equipment for the TDU. The vacuum and gas support equipment proved to be sufficient. The system's control and instrumentation program provided control algorithms to operate the loop at targeted core outlet temperatures and either mass flow rates or pump voltage. The control algorithms also controlled the slew rate within constraints. These algorithms proved to be sufficient and effective.

During the first series of test, pump voltages and frequencies were ramped up and varied to achieve the maximum flow rate. It was found that the maximum flow rate obtainable in the RxSim loop with the TDU ALIP pump was about 1.33 kg/s (when the ALIP was provided 120 V at 55 Hz and a NaK temperature of 800 K). Thus it was decided to extend the pump to a maximum of 150 V in which a maximum flow rate of 1.53 kg/s was obtained (Figure 2).

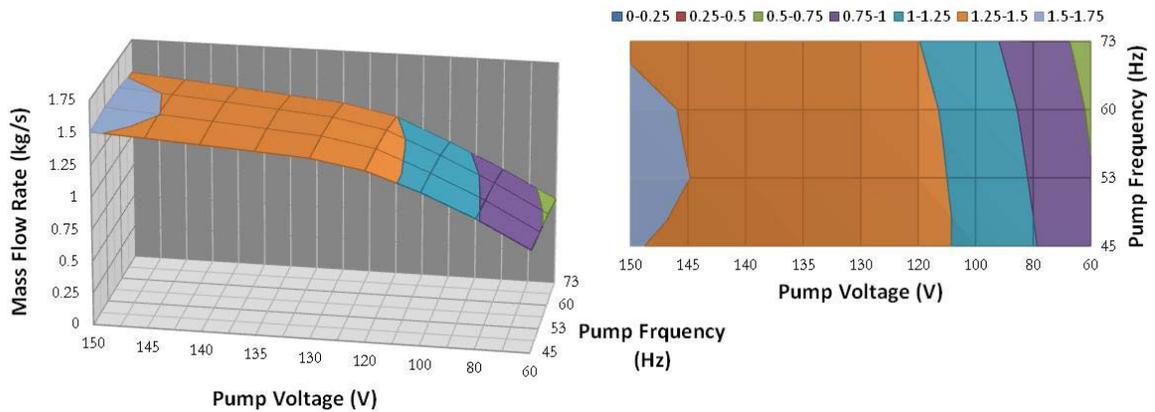


Figure 2. Expanded Pump Testing up to 150 V at $T_{\text{core}}^{\text{out}} = 800$ K. Maximum Mass Flow Rate Observed for the TDU ALIP in the RxSim Test Loop was 1.5 kg/s at 150 V and 73 Hz.

Thermal performance of a cold trap design with heat regeneration was tested. The design consisted of a bellows jacketed GN_2 -NaK HX for cooling and accommodating thermal expansion. The NaK flow path consisted of a downcomer flow through alternating disk and donut baffles to create cross flow and increase NaK residing time within the cold trap. The volume between the baffles was packed with stainless steel wool to provide a reaction surface for oxide precipitation. The return flow path was through a tube running up the centerline of the cold trap and then terminating in a coil that was bathed in hot NaK from the inlet at the top of the cold trap. A cold temperature of 480 K was the targeted goal of the cold trap design as analysis had indicated that purification of the NaK could be obtained within a reasonable period of time with this cold temperature. The analysis also indicated that a return flow through a coil would provide sufficient heat regeneration so cold NaK would not be put back into the system acting a thermal load. However, for this performance, the analysis indicated that a very slow NaK flow rate was required. The design proved to provide a good cooling capacity to reach a sufficiently low cold temperature with slow NaK flow rates as predicted. Heat regeneration was observed to occur more effectively within the cold trap return line than predicted but not as effectively within the coil regenerator than predicted. An outlet temperature of about 750 K was predicted but 636 K was observed (Figure 3).

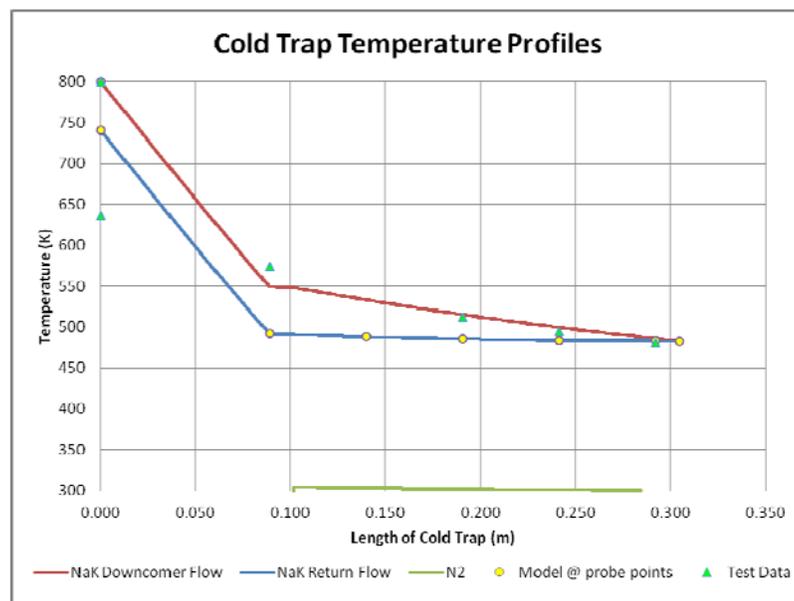
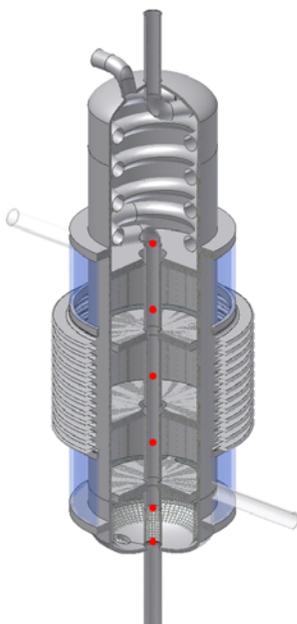


Figure 3. Cold Trap Design and Performance. Left: Cold Trap Design. Dots Correspond to the Locations of the Thermocouple Probe Locations. Right: Comparison of Cold Trap Thermal Model and Measured Temperatures. The Modeled Flow Rates were 0.00635 kg/s (NaK) and 0.078 kg/s (N₂). The Actual NaK Flow Rate Through the Cold Trap was not Measured but in the Primary Loop it was 0.068 kg/s with the Cold Trap Loop Bypass Valve Open ¼ turn. The Actual N₂ Flow Rates Were Not Measured but the Supply Pressure was 6 psi Above Ambient. Modeled Inlet Temperature was Set to Actual Cold Trap Inlet Temperature of 800 K. NaK & GN₂ Mass Flow Rates were Then Tweaked to Get Modeled T_{cold} Approximately Equal to Measured T_{cold}. Yellow Dots are Model Temperature Predictions at Locations Expected to Correspond with Thermocouple Probe Locations Which are the Green Triangles.

SUMMARY AND CONCLUSIONS

Integrated testing of the TDU control and instrumentation, vacuum and gas ground test support equipment, and reactor core simulator components in the RxSim test loop demonstrated them to be operationally ready for TDU integration. The ALIP pump was found to not produce the desired flow rate for the RxSim test loop and thus is being considered as a backup pump for TDU testing. In addition, heat regeneration design feature for cold trap purification was demonstrated with thermal testing of a cold trap integrated into the RxSim test loop.

ACKNOWLEDGMENTS

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