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# Summary of Test Results From a 1 kWe-Class Free-Piston Stirling Power Convertor Integrated With a Pumped NaK Loop

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## Abstract

As a step towards development of Stirling power conversion for potential use in Fission Surface Power (FSP) systems, a pair of commercially available 1 kW class free-piston Stirling convertors was modified to operate with a NaK liquid metal pumped loop for thermal energy input. This was the first-ever attempt at powering a free-piston Stirling engine with a pumped liquid metal heat source and is a major FSP project milestone towards demonstrating technical feasibility. The tests included performance mapping the convertors over various hot and cold-end temperatures, piston amplitudes and NaK flow rates; and transient test conditions to simulate various start-up and fault scenarios. Performance maps of the convertors generated using the pumped NaK loop for thermal input show increases in power output over those measured during baseline testing using electric heating. Transient testing showed that the Stirling convertors can be successfully started in a variety of different scenarios and that the convertors can recover from a variety of fault scenarios.

## Introduction

Free-piston Stirling power conversion has been identified as a viable option for potential Fission Surface Power (FSP) systems (Refs. 1 to 4). Recent studies have examined the use of Stirling convertors coupled to a low temperature (< 900 K), uranium-dioxide fueled, liquid-metal-cooled reactor for a potential lunar application in year 2020. In order to reduce development risk and address design questions related to the free-piston Stirling FSP system, NASA has begun long lead technology development on multi-kilowatt Stirling power conversion under the Fission Surface Power Technology Project. A key step in the development of Stirling technology relative to FSP systems is to demonstrate that a Stirling convertor can be successfully integrated with a pumped liquid metal loop.

In support of this goal, two 1 kW free-piston Stirling power convertors were procured from Sunpower Inc., of Athens, Ohio. These convertors are designed to produce 1.1 kWe at their design operating conditions of 550 °C hot-end temperature, a 50 °C cold-end temperature, a mean working space pressure of 3.0 MPa, and a piston amplitude of 10 mm. The convertors delivered to the Glenn Research Center (GRC) were configured with electrically heated heads which were used to establish the baseline convertor performance.

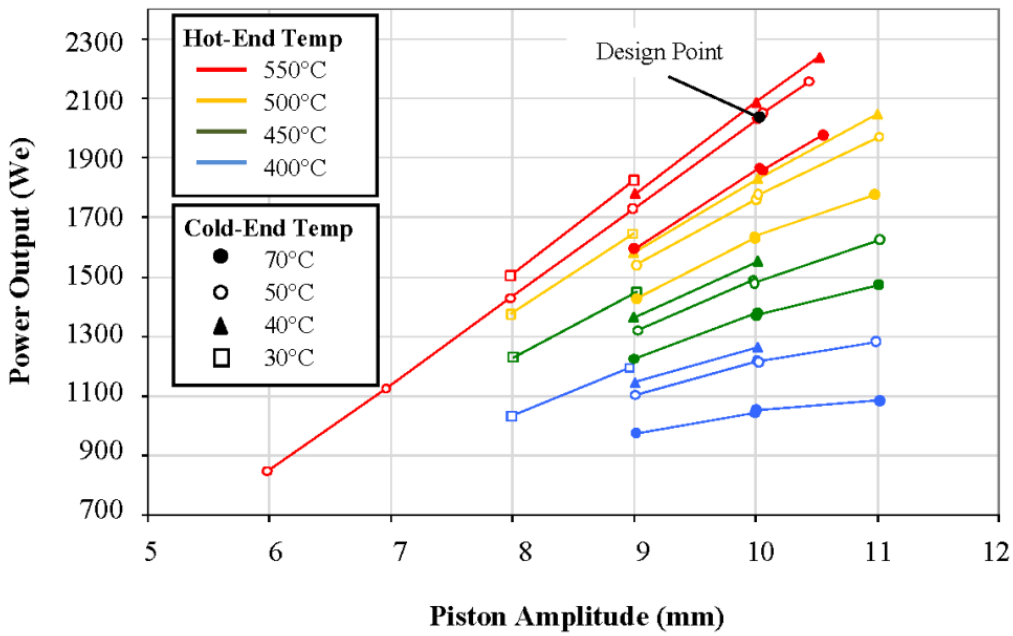


Figure 1.—Baseline performance map with P2A convertors configured with electrically heated heads. Power shown in plot is the total electric power output for both convertors.

Figure 1 shows the electric power output of the convertors during baseline testing with electrically heated heads. At the design operating conditions, the convertors produced 2030 W of electric power at a gross thermal efficiency of 28.1 percent, where gross thermal efficiency is the electrical power output of the alternator divided by the electrical power input into the cartridge heaters. The maximum total power output of 2240 $W_e$ was measured at a 550 °C hot-end and 40 °C cold- end temperature with a piston amplitude of 10.5 mm. This power level was achieved at a gross thermal efficiency of 28.6 percent. The maximum gross thermal efficiency achieved by these convertors was 30.0 percent, which occurred at a hot-end temperature of 550 °C, cold-end temperature of 30 °C, and a piston amplitude of 9 mm. After baseline testing was completed, the convertors were retrofitted with new heater heads to allow the convertors to be interfaced with a pumped NaK loop. The convertors were then delivered to the Marshall Space Flight Center (MSFC) for integration and testing in the Fission Surface Power Primary Test Circuit (FSP-PTC). The integrated liquid metal heat exchanger/Stirling convertor configuration for a single convertor is shown in Figure 2. The dual-opposed convertor configuration employed two independent convertor/heat exchanger assemblies in opposite orientations so as to minimize vibration-induced loads on the test setup. A mechanical support structure connected the alternator pressure vessel portions of the two convertors and acted as the mounting structure for the entire assembly within the vacuum chamber portion of the FSP-PTC. A common supply line from the test facility provided the liquid metal to each convertor. The convertors mounted in the MSFC test facility are shown in Figure 3.

This report describes the testing done at the FSP-PTC and briefly discusses the results of those tests. Prior publications describe the test facility and setup more completely (Refs. 5 and 6). In addition the most comprehensive discussion of the test data can be found the official test report (Ref. 7).

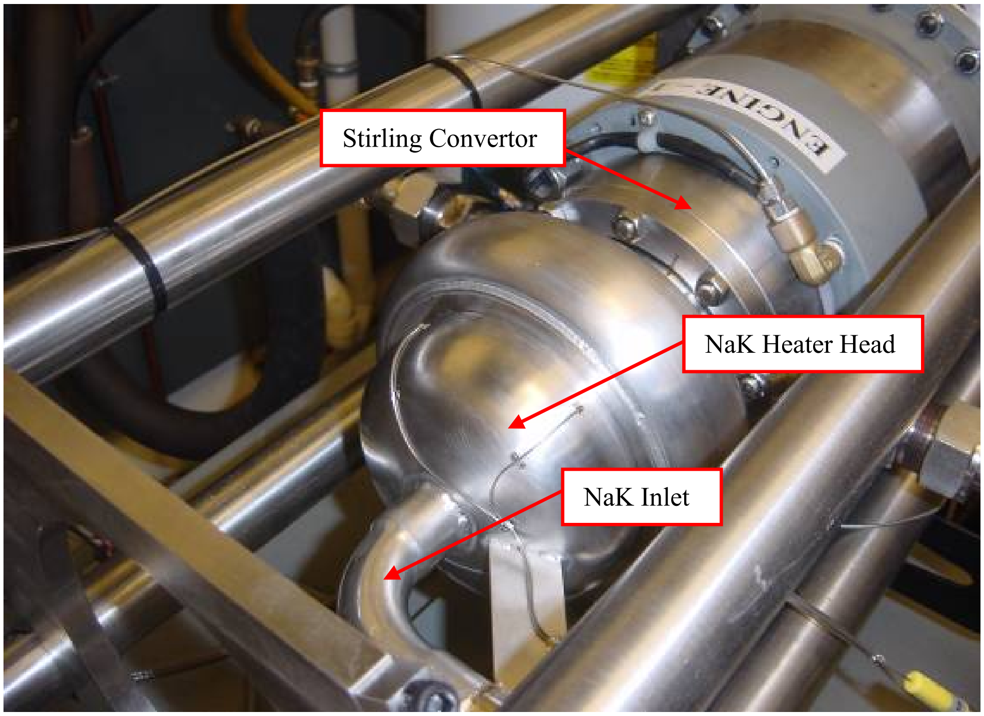


Figure 2.—Single free-piston Stirling power convertor with NaK heat exchanger prior to installation of multi-layer insulation.

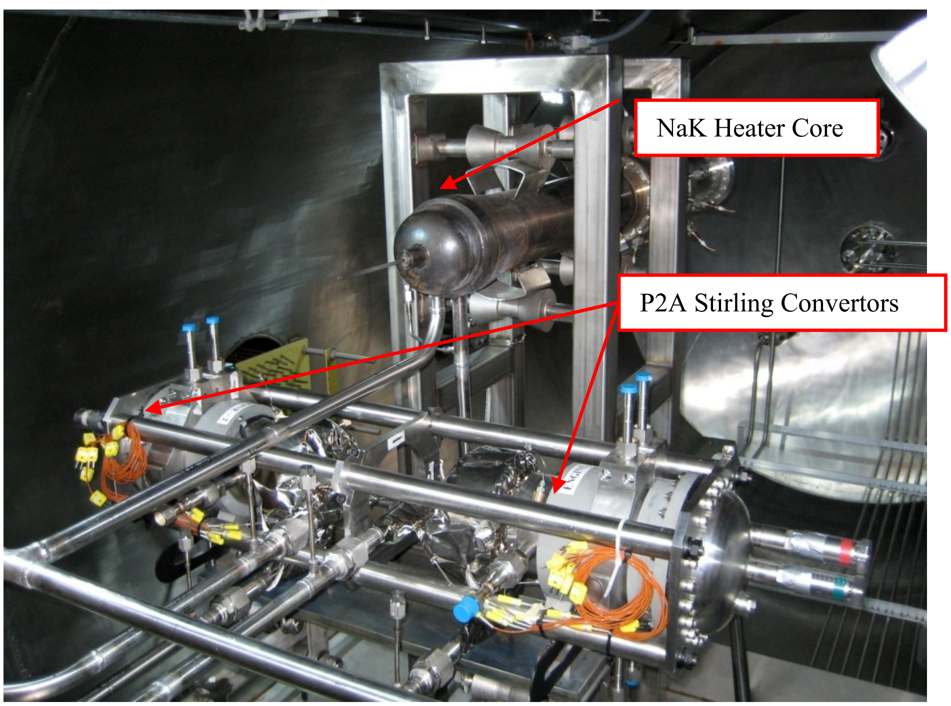


Figure 3.—Dual P2A Stirling power convertors mounted in the MSFC test facility.

# Methodology

To begin all steady-state testing, the cooling water temperature set-point was changed to the desired cold-end temperature for the data points to be acquired. The convertors were then briefly motored to verify the piston motions were centered properly and that their mean position did not drift. The NaK pump was then powered-up at a low to moderate flow setting while the NaK temperatures and flow rates were monitored to ensure normal operation of the NaK system. Next, the NaK pump was adjusted to provide the maximum flow rate, and the NaK heaters were switched on. The Stirling convertor pistons were locked in place using the convertor control system until the convertor hot-end temperatures reached 250 °C. At this point, the convertors were set to a piston amplitude of 6 mm (this is the minimum piston amplitude that engages the gas bearings). The convertors were started this way to avoid piston/displacer contact and minimize run-time prior to gas bearing operation. As the hot-end temperature increased, the piston amplitude was increased until both the hot-end temperature and piston amplitude reached their desired set-points for the performance map point to be acquired.

Transient test procedures differed depending on the nature of the test (high flow start-up, low flow start-up, convertor stall, etc.). These procedures will be discussed individually below.

## Steady—State Testing

During steady-state testing, the power output of the convertors was measured at most of the same operating conditions (temperatures and piston amplitudes) at which data was acquired during baseline testing using electric heater heads. During these tests, the convertors were operated at hot-end temperatures ranging from 400 to 550 °C, cold-end temperatures from 30 to 70 °C, and piston amplitudes ranging from 6 to 11 mm. The performance map testing was conducted with the NaK pump operating at full power. The NaK flow tended to decrease as the test proceeded as the pump temperature increased. The typical drop in mass flow at full pump power during steady-state testing was 200 g/s (900g/s at start of test to 700 g/s at end of test). During mass flow performance mapping, the NaK mass flow started at maximum flow and was decreased incrementally until the maximum temperature difference across the head was reached (40 °C). For each point the system was allowed to dwell until steady-state was reached then data was averaged for 5 min in order to produce the performance map data points.

## Transient Testing

Transient testing was conducted to study fault tolerance scenarios and possible start-up scenarios. Three fault tolerance scenarios were examined: 1) NaK pump loss, 2) heat source loss (i.e., loss of reactor), and 3) shutdown/restart of Stirling convertors. These scenarios were examined to determine the effects on the system, and to determine possible methods of recovery. To begin each of the fault scenarios, the system was brought to the design operating condition, according the steady-state procedure, a steady-state data point was recorded, and then a fault was initiated.

Start-up testing was focused on varying the mass flow rate as well as the temperature at which piston motion was initiated. These tests started by locking the Stirling convertor pistons in place using the controller and setting the NaK flow rate to the desired setpoint. The NaK temperature was then increased at a rate of 10 °C per minute, until the desired piston initiation temperature was reached. At that point the Stirling convertor piston amplitude was controlled to 6 mm. From the NaK temperature continued to increase at 10 °C per minute and the piston amplitude was increased as well, until the design point operating conditions were reached.

## Results

### Steady—State Performance Mapping

Figure 4 shows the combined power output of both convertors plotted as a function of piston amplitude. The power output of the convertors using NaK for thermal input is very similar to the baseline data acquired for the convertors equipped with the electric heater heads. The power output at the design condition was 2026 W for the convertor pair. The maximum power output was 2375 W at a hot-end temperature of 550 °C, cold-end temperature of 50 °C and piston amplitude of 11 mm. It should be noted that convertor efficiency was calculated at all of performance map test points; however, due to large uncertainties in both NaK mass flow as well as temperature difference across the NaK head, the heat input to the convertors and therefore the convertor efficiency measurement has substantial uncertainty. Therefore, the following efficiency values do not definitively quantify convertor efficiency. The calculated convertor efficiency was 32.2 percent at the design point, and ranged from 29.5 to 33.4 percent over the entire range of operating conditions tested.

Figures 5 and 6 compare the power output of the convertors configured with the NaK heater heads with that of the convertors configured with the electric heater heads (baseline data). The convertors configured with the NaK heater heads either equaled or outperformed the convertors configured with electric heater heads at most operating points. The comparisons shown in Figures 5 and 6 are representative of comparisons made at other temperature ratios as well. These comparisons verify that Stirling convertors can be interfaced with a pumped NaK loop successfully, without negatively affecting convertor performance.

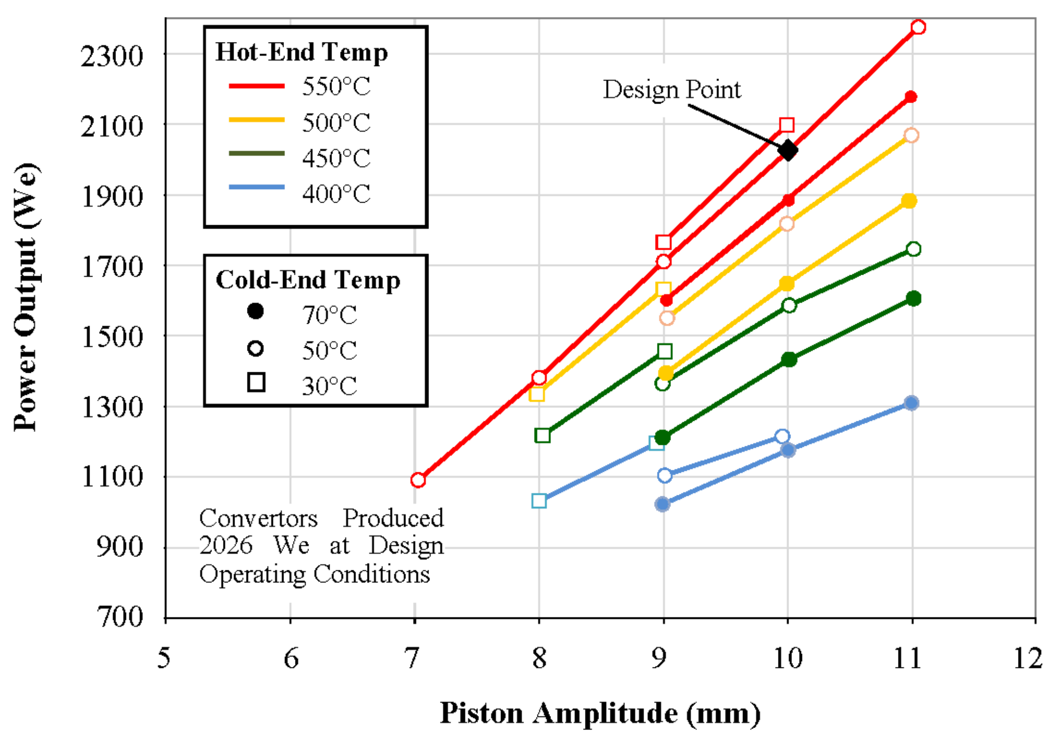


Figure 4.—Combined power output of dual P2A Stirling power convertors configured with NaK heater heads versus piston amplitude.

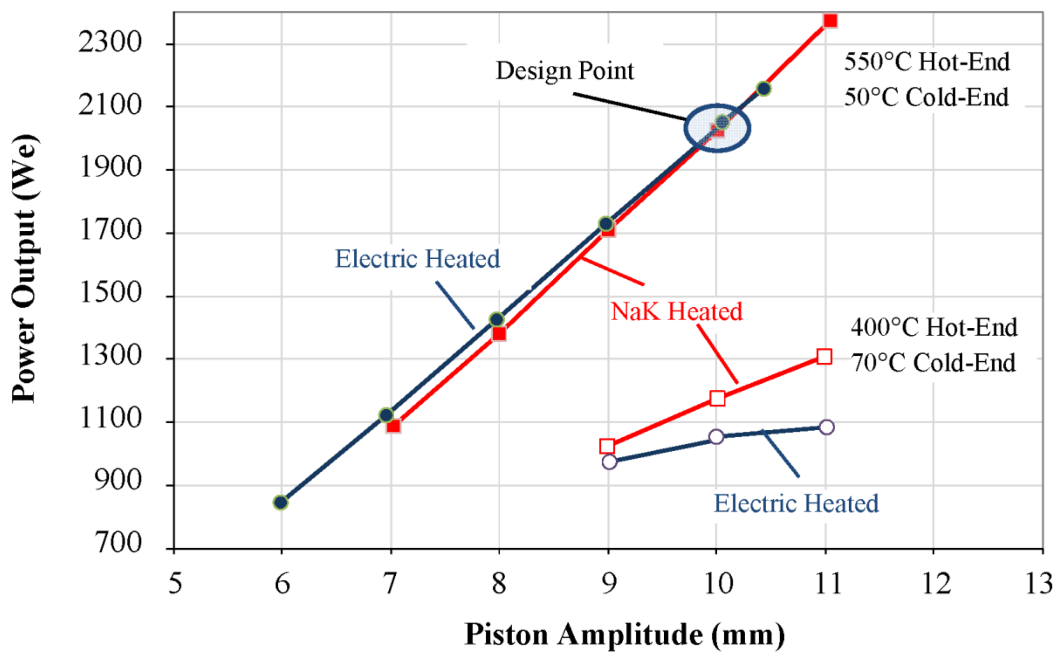


Figure 5.—Combined power output of dual P2A Stirling power convertors configured with NaK heater heads versus piston amplitude compared with baseline data.

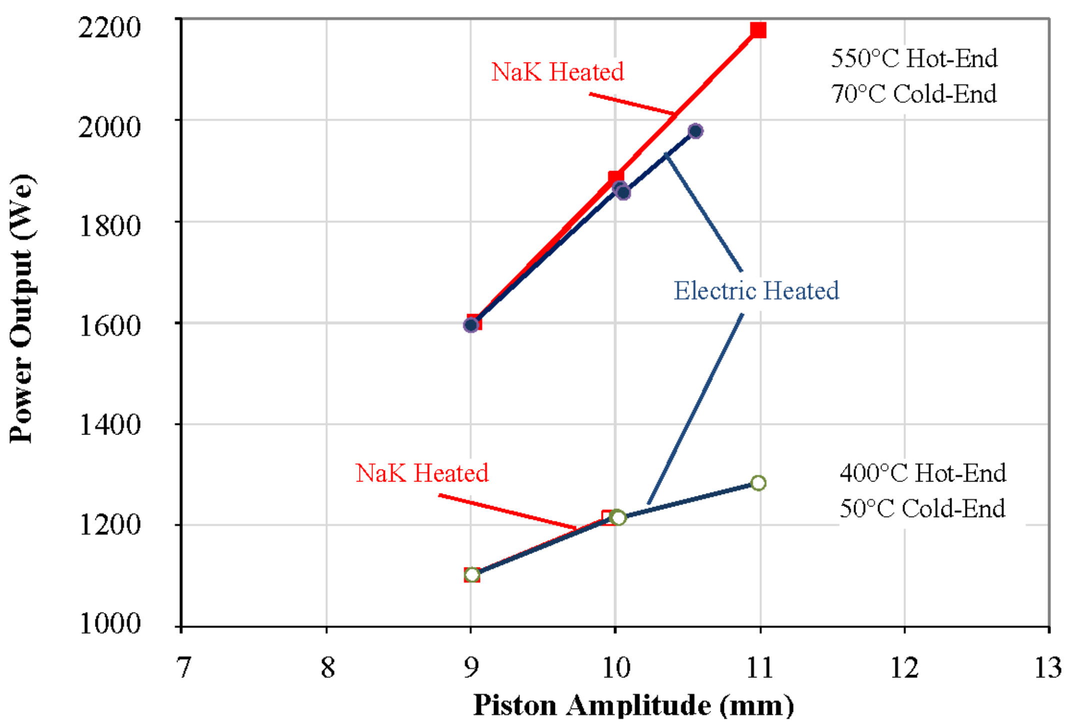


Figure 6.—Combined power output of dual P2A Stirling power convertors configured with NaK heater heads versus piston amplitude compared with baseline data.

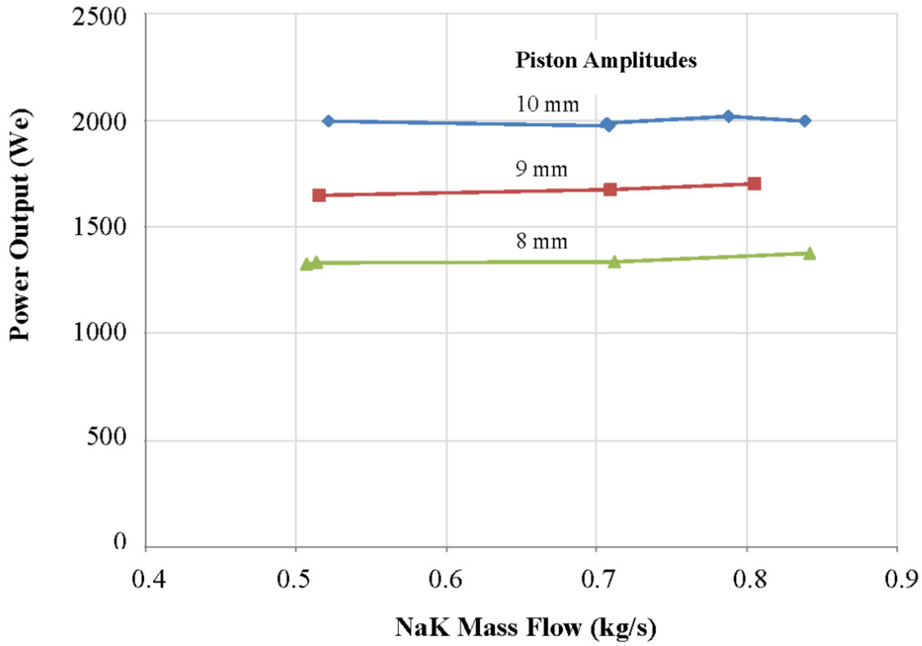


Figure 7.—Sensitivity of P2A Stirling power output for various NaK mass flow rates.

## Steady—State NaK Mass Flow Mapping

During the second phase of steady-state testing, the sensitivity of the Stirling convertor electrical output power to changes in NaK mass flow was measured. Figure 7 shows the total power output at design hot-end (550 °C) and cold-end (50 °C) temperatures at piston amplitudes of 8, 9, and 10 mm. Over the range of flow rates tested, convertor electrical output was insensitive to reductions in NaK mass flow. The maximum NaK mass flow in each case was limited by the NaK pump output capacity and the lower limit was conservatively chosen to constrain the temperature difference across the heater head and thereby limit thermal stresses. In addition, the power requirement of the NaK pump decreased from roughly 4 kW to roughly 2 kW for a reduction in mass flow from 900 to 600 g/s, suggesting that reductions in mass flow during start-up could result in substantial energy savings. This statement must be qualified, however, because the pump used in this test is operating far from its design point, and is therefore very inefficient, so the benefit of reducing mass flow using a more prototypic NaK pump would be less significant.

## Transient Fault Scenarios

Figure 8 shows the system response to the loss of the NaK pump with the convertors still running. Within 30 sec the average hot-end temperature had dropped more than 50 °C, which greatly exceeded the predetermined limit of 10 °C per minute and the temperature gradients across the heater heads had exceeded their upper limit of 40 °C so the test was stopped by stalling the convertors. At the conclusion of this test there was a slug of relatively cold NaK (490 °C) in the region of the heater heads. The remainder of the loop, with the exception of the NaK heater remained at 550 °C. During this time, the NaK heater remained on causing the stationary NaK within the heater to reach 620 °C. In order to avoid thermally shocking the convertor heater heads, the pump was not restarted and the entire system was allowed to cool to ambient temperature. This scenario is regarded as a dangerous one since it causes NaK temperatures to change quickly and creates hot and cold slugs of fluid throughout the system which prevent restart. *This study suggests that both the NaK heater and the convertors should be shut down immediately in the event of NaK pump loss.* Since immediate stall of the convertors results in an immediate stoppage of heat transfer to the cold-end, considerations will also have to be made in order to prevent freezing of the water loop.

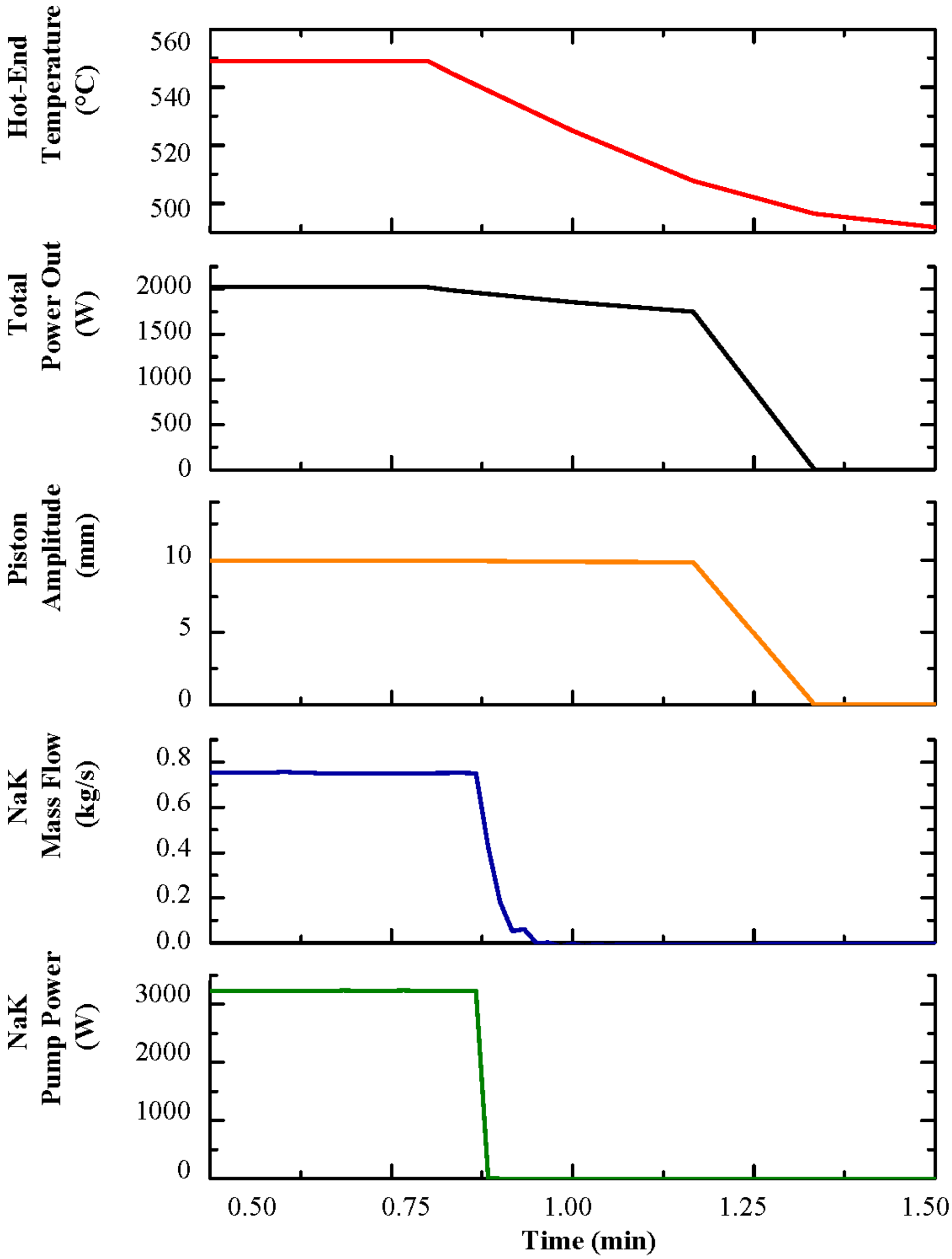


Figure 8.—Transient operating conditions—simulate loss of the ALIP pump/intermediate NaK loop at full NaK flow.

Figure 9 shows the response of the system to a loss of heater power. In this scenario, the hot-end temperature gradually decreases, reducing the heat input to the convertors, resulting in decreased electric power output. As the heat input to the convertors approaches the heat input to the NaK due to the inefficiency of the NaK pump, an equilibrium temperature is reached. As stated previously, the pump used in this test operates very inefficiently which causes this equilibrium temperature to be somewhat higher than it would be in a more prototypic system. This fault scenario is thought to be more benign because changes in heat input to the convertors occurs slowly, resulting in slow temperature changes on both the hot end and cold end. However, it should also be noted that the cooling rate of the NaK seen during this test is specific to this system. If other systems were to cool the NaK at a faster rate it could violate a system constraint on transient heating/cooling time. If this were the case, some type of piston amplitude modification would be required to reduce the amount of heat removed from the NaK by the convertors.

Figure 10 shows the transient data taken when the convertor pistons were stalled. The hot-end temperature was maintained at a constant value by the heater controller so the heater power was reduced, accordingly. In this test the convertors were then restarted at a piston amplitude of 6 mm, then brought to full amplitude of 10 mm. The convertors recovered to full power almost immediately after the piston recovered to the desing amplitude.

## Transient Start-Up Scenarios

There is currently no established start-up scenario for the proposed fission surface power system, so it is important to understand that these scenarios may not be representative of actual start-up scenarios. The start-up scenario tests are simply an examination of the trade between optimizing conditions within the reactor and minimizing the required start-up energy. It is important to note that the relative importance of each of these is not currently well-defined. Nevertheless, several start-up scenarios were run, each following a similar form: 1) the NaK pump was initiated to deliver flow at the desired mass flow rate, 2) the heater was then used to elevate the NaK temperature to an initial setpoint, 3) the convertors were started and operated at an initial piston amplitude of 6 mm, 4) the system was then allowed to reach steady-state, and 5) the NaK temperature was then ramped up to the Stirling convertor design hot-end temperature of 550 °C while the piston amplitude was ramped to 10 mm (design amplitude). The parameters varied during start-up testing were the NaK mass flow and the initial temperature setpoint. The initial Stirling hot-end temperature setpoint ranged from 200 to 500 °C and the NaK mass flow ranged from 600 to 900 g/s (total for both convertors). The results of the start-up testing are shown in Figures 11 to 16. The Stirling convertors were successfully brought to the design operating condition in each scenario, without any issues. This suggests that limitations on the selection of the start-up scenario will not come from the convertors, but from other system components. However, further system level testing of more prototypic convertors will be necessary to validate that assertion.

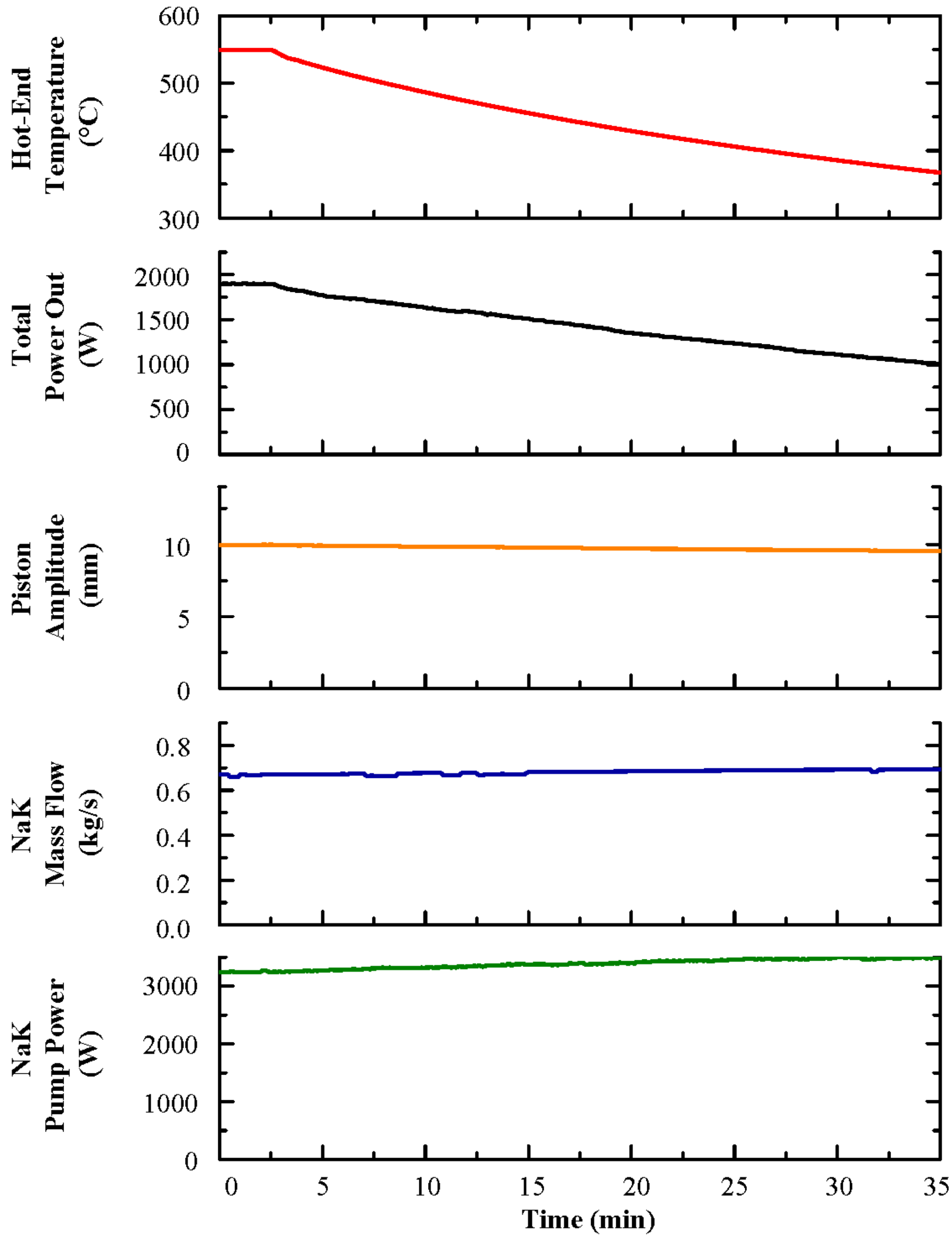


Figure 9.—Transient operating conditions—simulate loss of reactor power/primary NaK loop at full NaK flow.

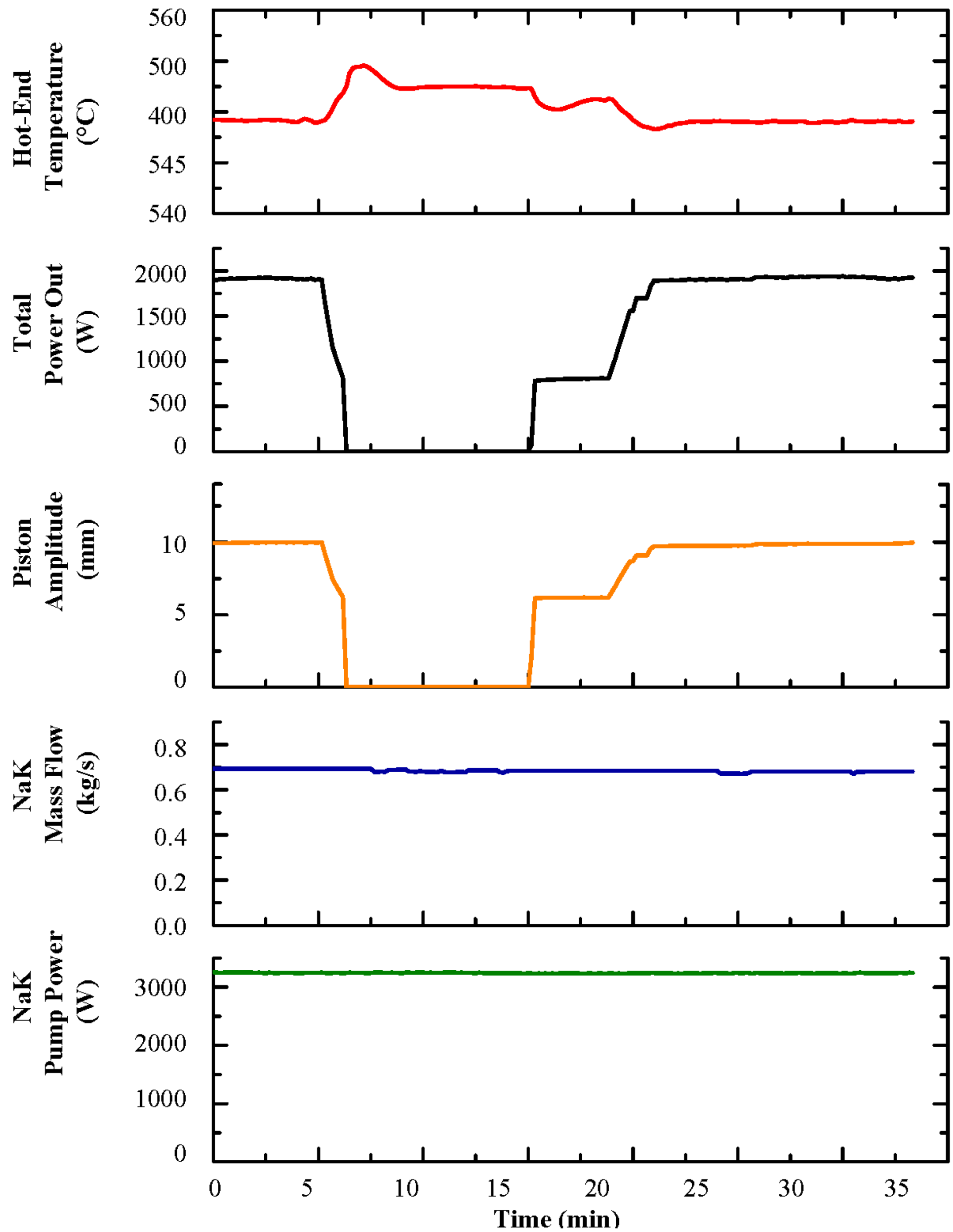

Figure 10.—Transient operating conditions—simulate shutdown/restart of Stirling convertors.

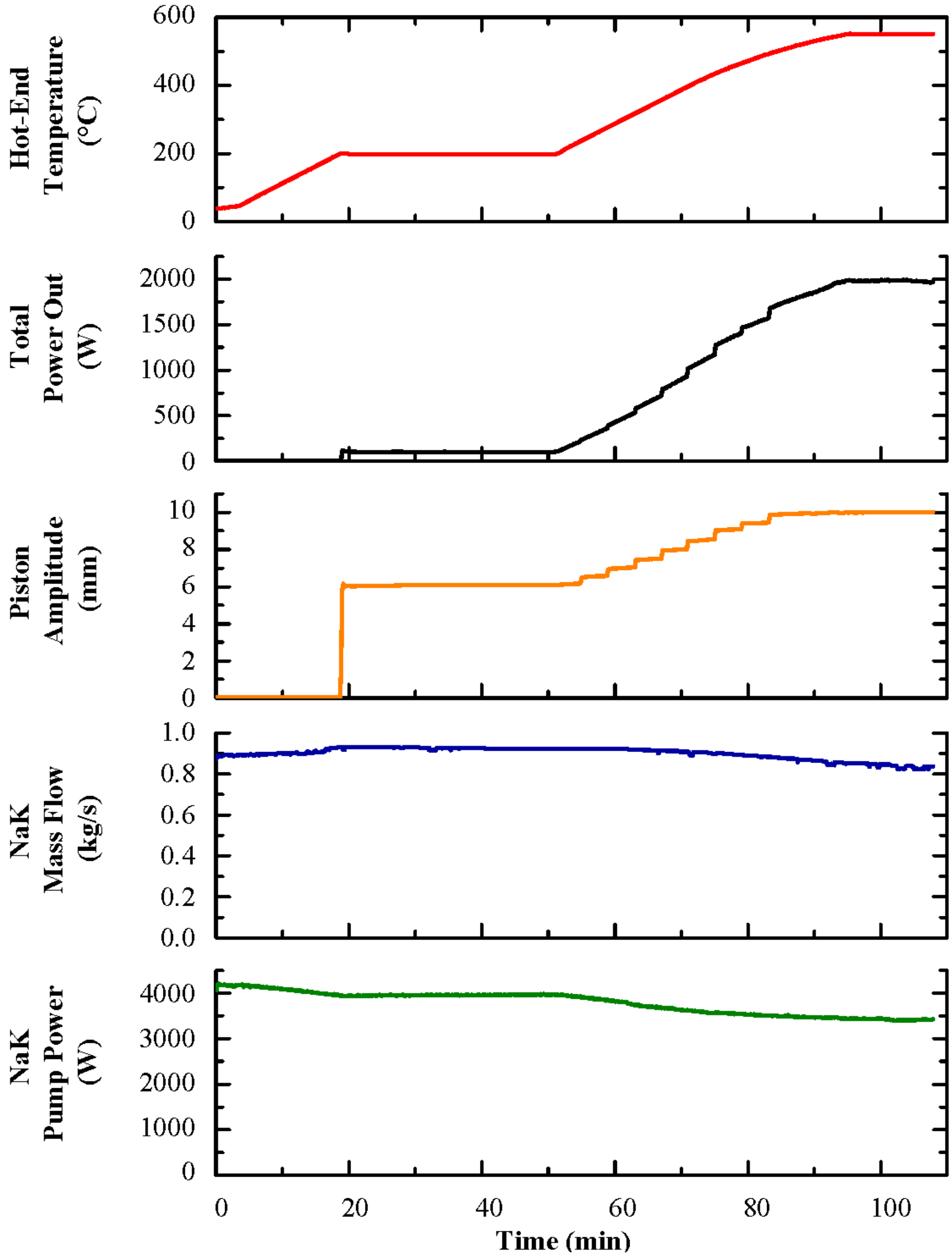


Figure 11.—Transient operating conditions—minimum temperature start-up at full NaK flow.

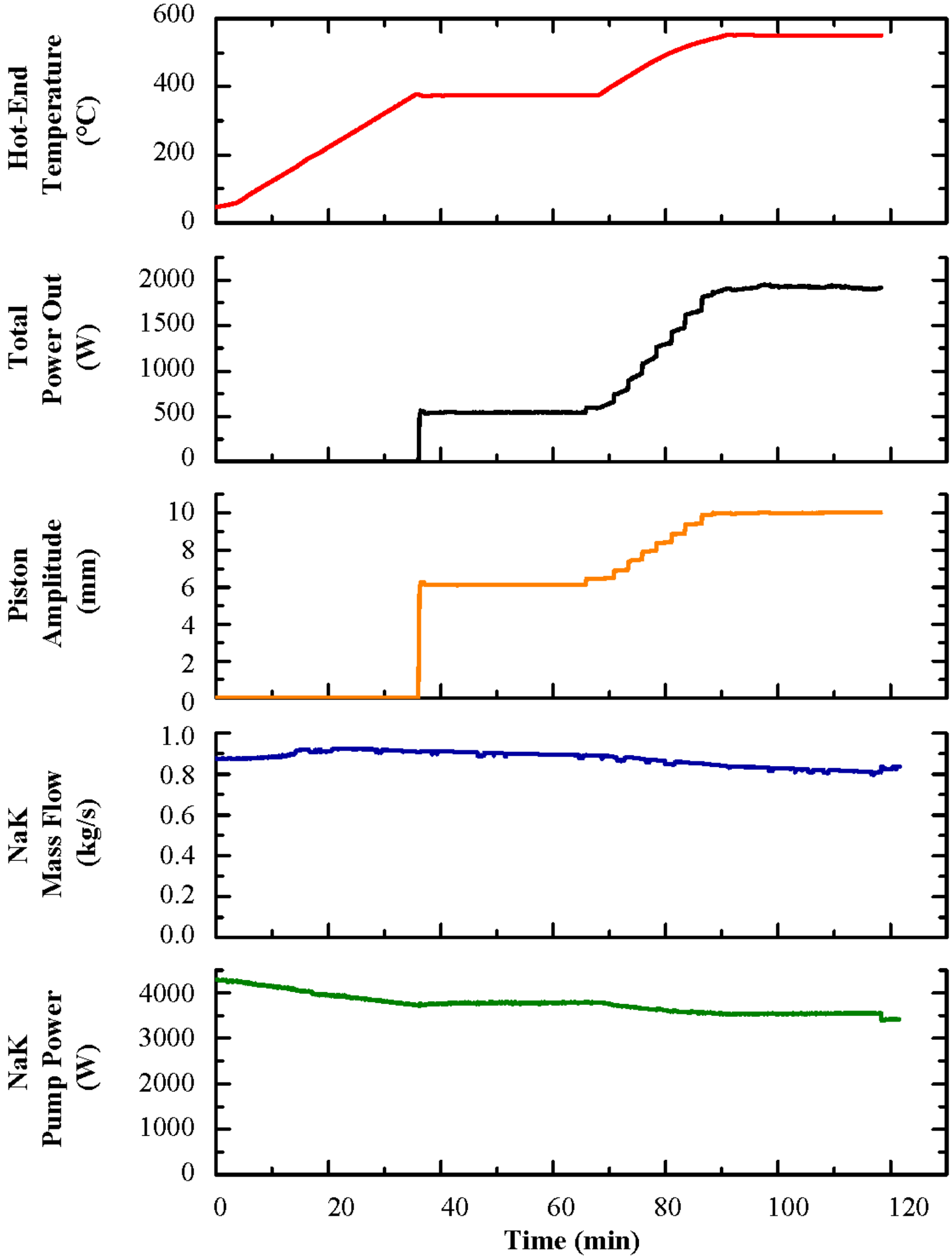


Figure 12.—Transient operating conditions—medium temperature start-up at full NaK flow.

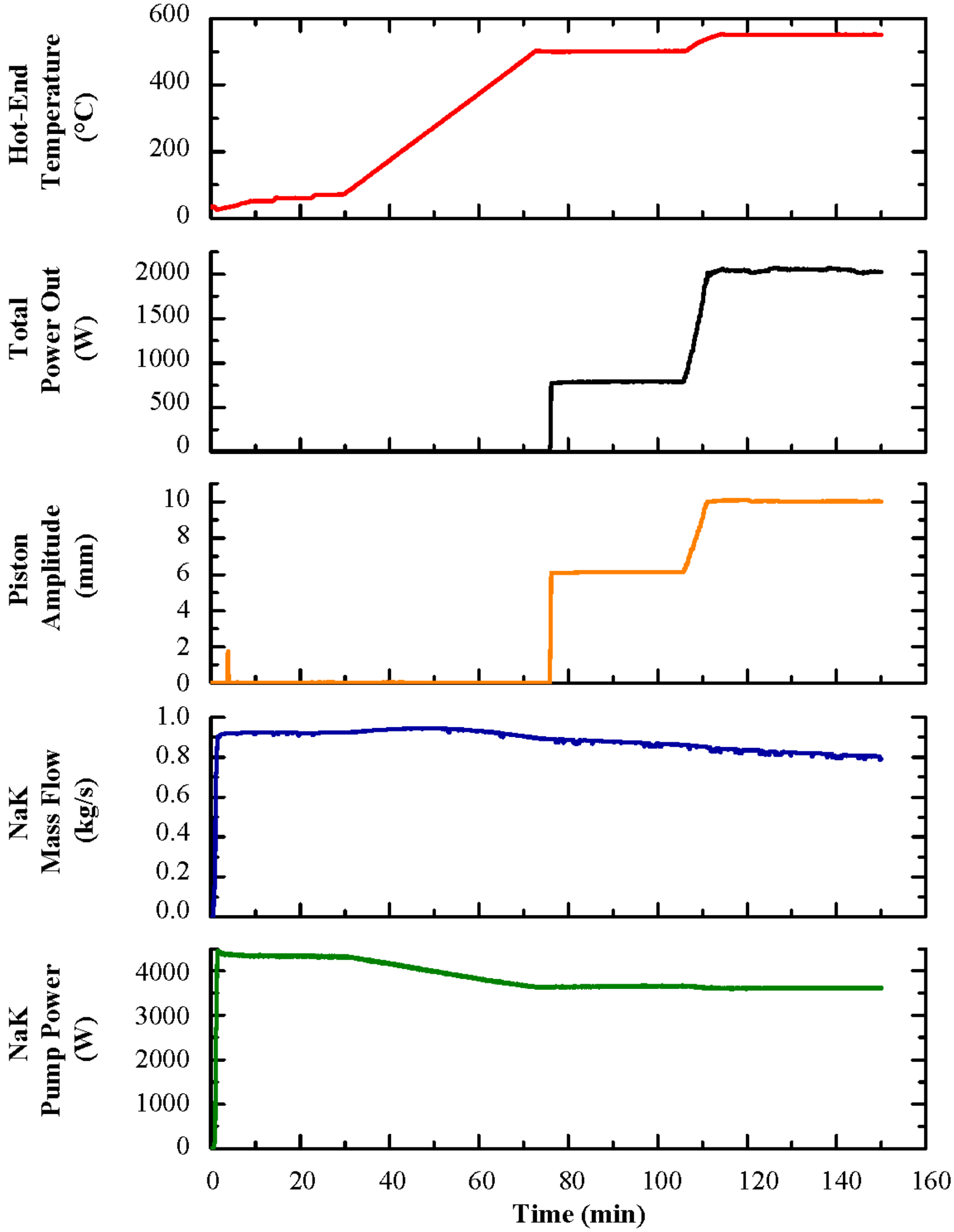


Figure 13.—Transient operating conditions—full (high) temperature start-up at full NaK flow.

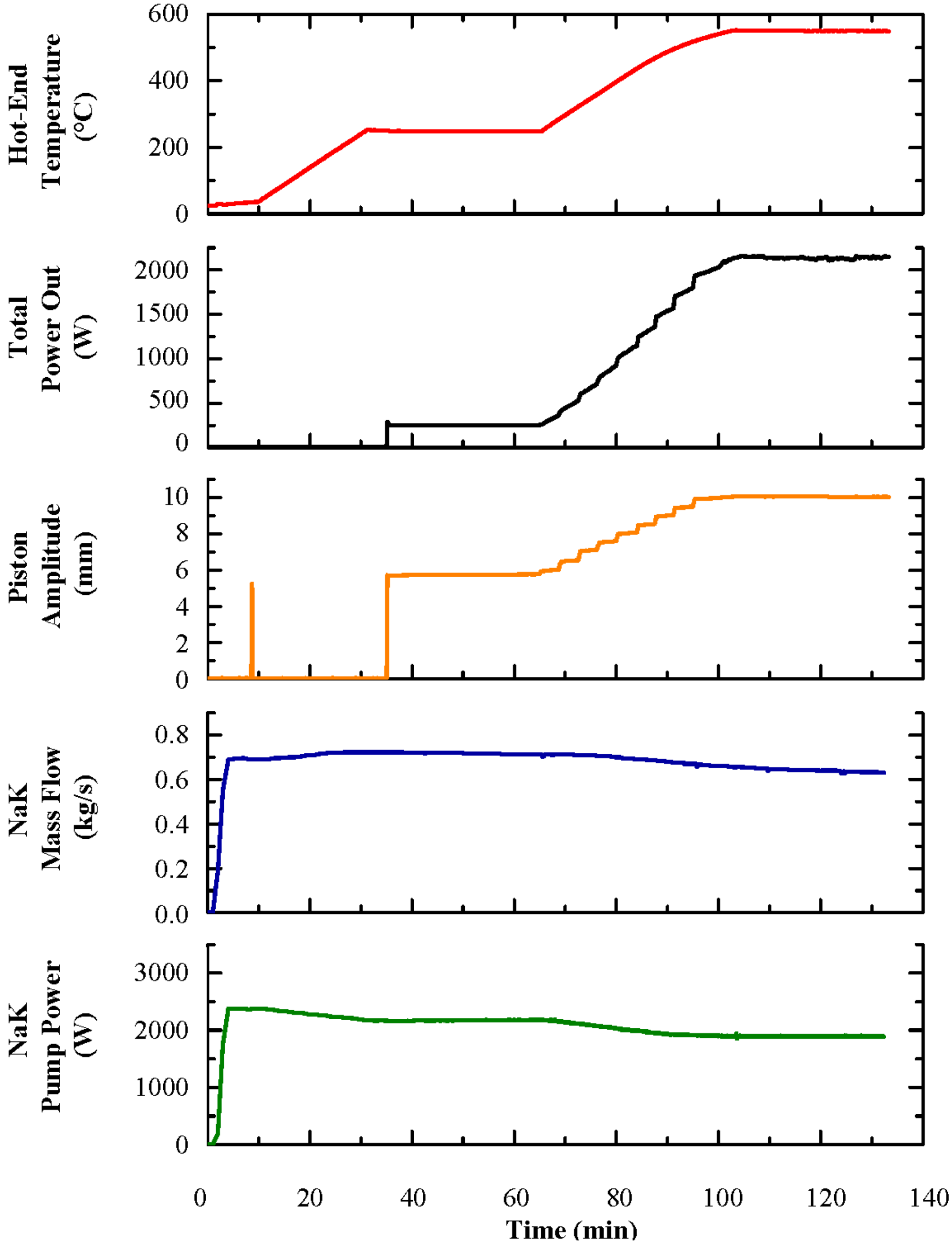


Figure 14.—Transient operating conditions—minimum temperature start-up at 75 percent NaK flow.

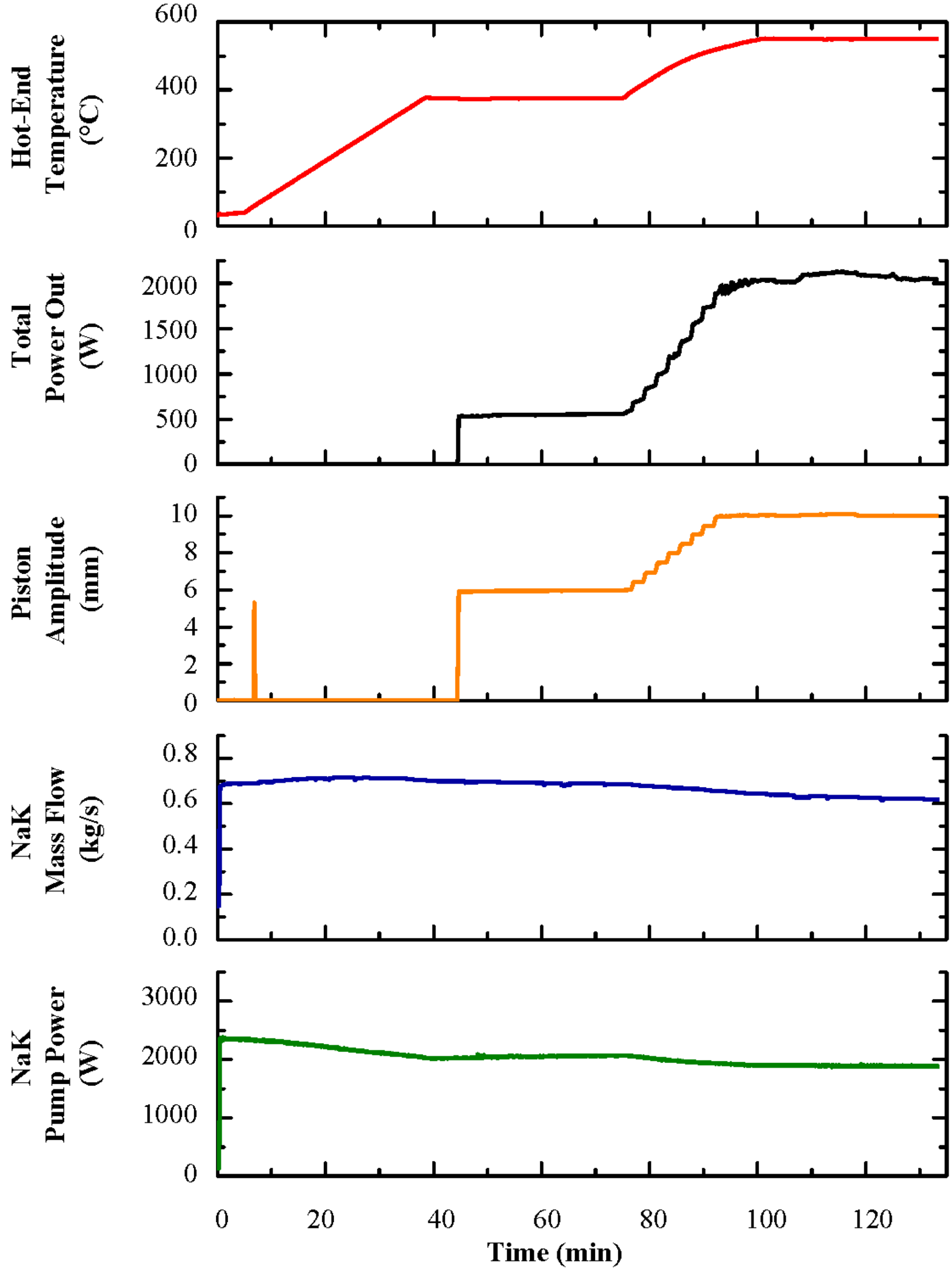


Figure 15.—Transient operating conditions—medium temperature start-up at 75 percent NaK flow.

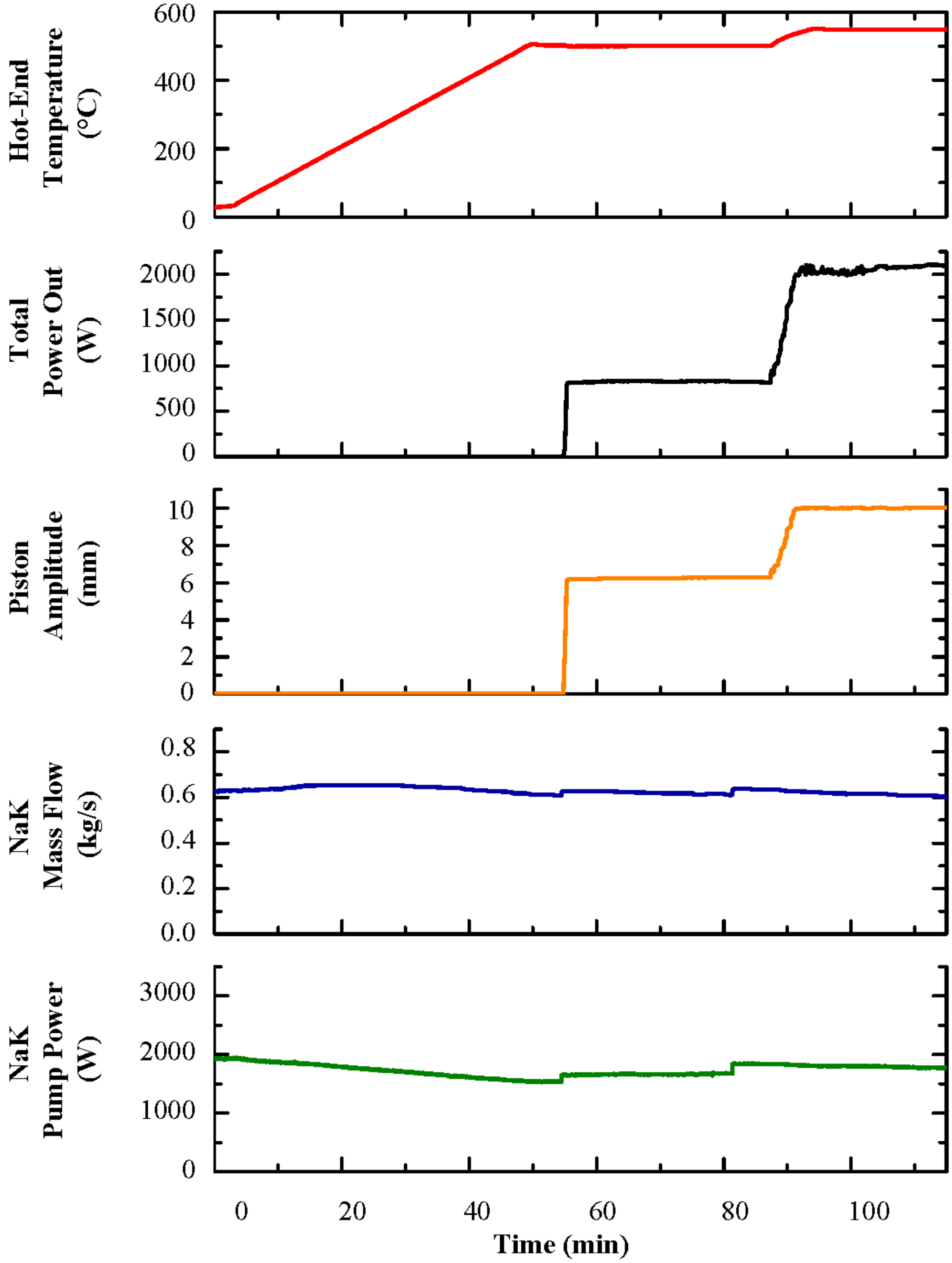


Figure 16.—Transient operating conditions—full (high) temperature start-up at 75 percent NaK flow.

# Conclusions

Performance maps generated using the pumped NaK loop for thermal input consistently show the convertors performing as well or slightly better than they had during operation with electric heater heads. A potential explanation for the slightly better performance is that the convertor-body heat losses due to natural convection were reduced due to operation in vacuum during testing with the NaK heater heads. Uncertainty in the measurement of thermal input to the Stirling convertors made it difficult to calculate converter efficiency precisely; however, consistent improvements in power output when operating in the pumped NaK configuration at similar operating conditions suggest improvements in the efficiency over those measured during electrical baseline testing.

Full-power operation at nominal operating conditions was further demonstrated over a range of NaK mass flows (530 to 850 g/s total for convertor pair). Over the range of mass flows tested, convertor performance was insensitive to NaK mass flow at both nominal and off-nominal piston amplitude. Although system level performance was not considered in this study, the mass flow sensitivity testing illustrates a system level trade between convertor performance, convertor reliability, and pumping power, and shows that during this testing the convertors were operating beyond the point of diminishing returns of convertor performance, with respect to NaK mass flow.

Several possible start-up tests were conducted to generate data relevant to future TDU and FSP system start-ups. The Stirling convertors were started at several different hot-end temperatures ranging from 200 to 500 °C. This data shows that the Stirling convertors are sufficiently robust to handle a wide range of start-up scenarios. This flexibility will be useful to future system designers who will likely find restrictions on reactor start-up and required pump power to be more constraining than any limitations imposed by the Stirling convertors. In addition, start-up scenarios were run at different NaK mass flow rates. This data shows that a reduction of mass flow from 850 to 600 g/s (total for convertor pair) resulted in a reduction in required pump power from about 4000 W to bout 2000 W. Furthermore, reductions in mass flow were shown to have little effect on total time to reach nominal operation. This data suggests that start-up scenarios should occur at low mass flows in order to minimize the total energy required for pumping. However, this statement must again be qualified by noting that the NaK pump used in this test is operating far from its nominal operating condition and therefore exaggerates the benefits of reducing NaK flow rate. Further analysis of a more representative system would be necessary in order to draw more specific conclusions.

Fault recovery tests were also conducted in order to assess the effect of component failures and to identify possible recovery procedures. The loss of the heat source was shown to be a somewhat benign failure for this system resulting in slow reductions in hot-end temperature and power output. The convertor stall test revealed that the system could return quickly to full power operation if control of the convertors is regained. However, precautions must be taken to ensure that a sudden reduction in heat flow to the Stirling convertor cold-end is handled appropriately. Finally, simulation of a NaK pump failure while maintaining convertor operation revealed that the NaK contained in the Stirling convertor heater heads and heater head metal temperatures will drop rapidly. During this fault scenario, temperature ramp-rate restrictions are likely to be violated as well as maximum temperature gradient restrictions within the hot-end. In addition, if the convertors are permitted to run without NaK flow, the NaK contained in the heater head volume could over-cool and cause a thermal shock in the convertor heater head once NaK pump operation is restored. The only method of recovery is to wait for the system to reach thermal equilibrium, which could take many hours. Therefore, the convertors should be stopped immediately in the event of a NaK pump failure and precautions must then be taken to accommodate the loss of heat input to the coolant.

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| **13. SUPPLEMENTARY NOTES** | | | | | |
| **14. ABSTRACT**<br>As a step towards development of Stirling power conversion for potential use in Fission Surface Power (FSP) systems, a pair of commercially available 1 kW class free-piston Stirling convertors was modified to operate with a NaK liquid metal pumped loop for thermal energy input. This was the first-ever attempt at powering a free-piston Stirling engine with a pumped liquid metal heat source and is a major FSP project milestone towards demonstrating technical feasibility. The tests included performance mapping the convertors over various hot and cold-end temperatures, piston amplitudes and NaK flow rates; and transient test conditions to simulate various start-up and fault scenarios. Performance maps of the convertors generated using the pumped NaK loop for thermal input show increases in power output over those measured during baseline testing using electric heating. Transient testing showed that the Stirling convertors can be successfully started in a variety of different scenarios and that the convertors can recover from a variety of fault scenarios. | | | | | |
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