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Test Results From a Pair of 1-kWe Dual-Opposed Free-Piston Stirling Power Convertors 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 were modified to operate with a NaK (sodium (Na) and potassium (K)) 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 convertors were successfully tested at the Marshall Space Flight Center (MSFC) from June 6 through July 14, 2009. The convertors were operated for a total test time of 66 hr and 16 min. The tests included (a) performance mapping the convertors over various hot- and cold-end temperatures, piston amplitudes, and NaK flow rates and (b) transient test conditions to simulate various startup (i.e., low-, medium-, and high-temperature startups) and fault scenarios (i.e., loss of heat source, loss of NaK pump, convertor stall, etc.). This report documents the results of this testing.

Background

In 2007, two P2A (formerly known as EG–1000) 1-kW free-piston Stirling power convertors were procured from Sunpower Inc., of Athens, OH. The P2As 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 P2As are typically configured with gas burners for thermal energy input; however, the P2As delivered to the Glenn Research Center were configured with electrically heated heads to simplify testing. In early 2008, the P2As were tested at Glenn to establish the baseline convertor performance.

Figure 1 shows the convertor power performance map generated during baseline testing for the convertors configured with electrically heated heads. As expected, the total power output increases with both increasing temperature ratio and increasing piston amplitude. At the design operating conditions, the convertors produced 2030 W of electric power at a gross thermal efficiency of 28.1 percent. The maximum total power output of 2240 W_e was measured at a 550 °C hot-end and a 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 efficiency achieved by these convertors was 30 percent, which occurred at a hot-end temperature of 550 °C, a 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 featuring NaK (sodium (Na) and potassium (K)) heat exchangers designed by Glenn to allow the convertors to be interfaced with a pumped NaK loop.

In October of 2008, the convertors were delivered to Marshall Space Flight Center (MSFC) for integration and testing in the Fission Surface Power (FSP) Primary Test Circuit (PTC). A safety review meeting (February 2009) and a test readiness review (April 2009) were held at MSFC in preparation for this test. Permission to proceed with testing was granted by the test readiness review board in May 2009.

Summary

A comparison of the performance map recorded for the convertors configured with the NaK heater heads with the baseline data (for electric heater heads) indicated that the NaK Stirling convertors performed similar to the baseline configuration in terms of both power and efficiency. In addition, the convertor performance was relatively insensitive to NaK mass flow over the range tested. A total of 43 steady-state, 9 transient, and 8 reactivity feedback data points were acquired during this test. 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 total NaK mass flow to both convertors ranged from 500 to 900 g/s. This test met all objectives and the test unit operated as expected.

1.0 Introduction

Free-piston Stirling power conversion has been identified as a viable option for potential FSP systems on the Moon and Mars (Refs. 4 and 5). Recent studies have examined the use of Stirling convertors coupled to a low-temperature (<900 K), uranium-dioxide fueled, and liquid-metal-cooled reactor for potential lunar application in the year 2020. The concept resulted from a 12-month NASA and Department of Energy (DOE) study that examined design options and development strategies based on affordability and development risk. The system is considered a low development risk based on the use of terrestrial-derived reactor technology and conventional materials. The low development risk approach was selected over other options that could offer higher performance and/or lower mass.

To further reduce development risk and address design questions related to the free-piston Stirling FSP system, NASA has begun long lead technology development on multikilowatt 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.

Liquid metal loop integration involved two separate subtasks. First, a pair of 1-kW commercial free-piston Stirling convertors were procured and assembled into a test rig. In parallel, a liquid metal heat exchanger was designed and fabricated for use on the 1-kW convertors to permit integrated testing with an existing pumped NaK heat loop (Ref. 3) at MSFC. This activity was aimed at providing data to support the design of a full-scale FSP power conversion unit (PCU) prototype for use in an end-to-end system Technology Demonstration Unit (TDU) test. The TDU test would be conducted with a pair of 6-kW opposed piston heat engines coupled to a liquid metal reactor simulator and a full-scale radiator in thermal vacuum.

NASA Glenn of Cleveland, OH; SEST Inc., Middleburg Heights, OH; and Sunpower Inc., Athens, OH, teamed to develop a NaK heat exchanger and heater head design for the P2A convertors. While earlier NASA Glenn efforts (Ref. 2) have clearly demonstrated the application of liquid metals as the heat transport medium for a Stirling cycle convertor, it is important to note that these heat exchangers utilized heat pipes in the energy transfer process. The resulting condensing liquid metal vapor heat transfer characteristics are totally different from the conditions expected in the hot-end heat exchanger in the current pumped liquid metal loop heat transport system. During the design phase of the heat exchanger, careful consideration was given to the unique manufacturing and assembly constraints imposed by the P2A hardware. For example, the NaK heat exchanger was to be fabricated by welding a jacket to the outside of a P2A heater head. The P2A heater head consists of a stainless steel dome with a finned copper heat exchanger brazed to the inside surface. It was extremely important that the melt temperature of the braze material was not exceeded during the weld operation. The relative performance and hardware integration risk of each potential approach was evaluated. Throughout the design process, an effort was made, whenever possible, to employ currently understood liquid metal system "best practices" so as to ensure that the resulting heat exchanger is as representative as possible to those needed in future FSP systems. Particular emphasis was placed on the use of materials with proven track records (316 stainless steel), proven joining techniques (emphasis on welding), and maintaining low liquid metal flow velocities.

Computation Fluid Dynamic (CFD) analyses techniques were used to guide the design of the NaK heat exchanger design using FLUENT™ (ANSYS, Inc.). Several numerical approaches that directly solved the Navier-Stokes equations with a specified temperature or heat flux profile along the heater head were employed. The effects of gravity, inlet flow distortion, and exiting pressure drop were included in this analysis. A sampling of the results of the CFD analysis for the selected NaK heat exchanger design is shown in Figure 2.

The resulting integrated liquid metal heat exchanger, P2A heater head, and convertor configuration for a single convertor is shown in Figure 3. Detailed drawings of the P2A heater head design are shown in Appendix C. The dual-opposed convertor configuration employed two independent heat engines and heat exchanger assemblies mounted "head to head" 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 4.

2.0 Purpose of Test

There were four major goals planned for this test: (1) To gain the experience of integrating a Stirling power convertor with a pumped NaK loop. Lessons learned in this process will be useful in making design decisions for future systems including the TDU and future flight or flight-like systems. (2) To evaluate the performance of the custom-made NaK heater head. The most significant difference between baseline testing (electrically heated) and NaK testing is the method of thermal input, so differences in performance from the baseline data could be used to evaluate the design of the heater head and heat exchangers. (3) To better understand the effects of a pumped fluid heat source on Stirling operation. During baseline testing, hot-end temperature was affected by a single parameter, the input electrical power from the heater. During testing at MSFC, the P2A hot-end temperature is affected both by NaK temperature and NaK flow rate. Running at the same hot-end temperature, using different values of flow rate and NaK inlet temperature, could be used to improve Stirling cycle analysis and system optimization. (4) To evaluate the system response transient scenarios such as loss of heater power, stall and restart, and loss of NaK flow.

3.0 Test Facility

The FSP–PTC mounted in a 9-ft-diameter vacuum chamber is shown in Figures 4 and 5. The usable internal length is 18 ft and a rail structure and support table provides a surface for mounting of hardware systems. The chamber can reach an ultimate vacuum level in the low 10^{-7} torr range or better and can be pumped by a combination of four diffusion pumps (32 000 l/s each) backed by three roughing pumps (34 000 l/min each). However, only the roughing pumps were used for the FSP–PTC for the Stirling convertor testing. Primary test article power is provided by a 1.5-MW switchboard unit (480 VAC 3–P (three-phase)) and is distributed to four racks of alternating current (ac) to direct current (dc) power supplies. Each of these racks is equipped with four 15-kW (150-VDC) supplies for a total of 32 supplies capable of delivering up to 480 kW of power. Four power supplies were used to power the FSP–PTC core simulator (heat source). A master power system program (LabVIEW based) controls the power supplies, regulating the power per supply and providing any special ramping or profiling that is required. This system has been used very successfully to provide high-speed power supply response. Data is captured and recorded on a Citadel database system using a number of LabVIEW-based virtual instrument programs. A local instrumentation network has been established to route the flow of information in the test facility. Control and feedback signals (valves, pressure transducers, etc.) are processed with National Instruments Field Point modules while thermocouple data is processed using an IO-Tech DAQ Scan system currently configured for 168 channels (capacity up to 896 channels). Four cameras are mounted inside the vacuum chamber for increased view coverage of the experiment and chamber prior to entry by personnel.

A Chromalox water circulating temperature controller (model CMX–250–9) was used to provide cooling water to the Stirling power convertor. The Chromalox controller was used to control both the cooling water temperature and flow rate to the Stirling convertor.

Figure 6 shows a rendering of the FSP–PTC major component configuration. The system was designed to be gravity drained, consistent with previous circuit designs. Due to the size of the Stirling engines and other components, care was given to placement of all the components. Taking advantage of the rebuild, many design upgrades and improvements were incorporated. The layout shown was selected to provide the greatest access to the system components by technicians and engineers as well as provide complete test functionality. All connection and disconnection points were relocated to the front of the chamber to facilitate safe and rapid disconnection of experiment in the event of a NaK spill. Cameras and LED (light-emitting diode) lights were added to the chamber to provide better illumination and more comprehensive visual inspection of system after test.

The core, heat exchanger, ALIP (Annular Linear Induction Pump), valve, flow meter, and remote-operated valve were reused from previous NaK testing. To accommodate the increase in NaK volume, new lower and upper reservoirs were constructed. The tubing wall thickness was reduced from 0.095 to 0.065 in. Pressure and delta pressure devices were used as in systems prior. Overflow tanks were upgraded with overflow indicators and drain valves. Figure 7 shows the FSP–PTC completed and installed into the vacuum chamber prior to insulation weeks before testing.

4.0 Test Article

As previously mentioned, a pair of commercially available 1-kWe P2A free-piston Stirling power convertors were purchased from Sunpower in 2007. The P2As are designed to produce 1.1 kWe of output power at their design operating conditions of 550 °C hot-end temperature, 50 °C cold-end temperature, a mean working space pressure of 3.0 MPa, and a piston amplitude of 10 mm. The working space fluid is helium. The P2A is a beta-type Stirling convertor consisting of two moving parts: a displacer piston and a power piston. A linear alternator connected to the power piston converts mechanical energy into electricity. The P2A was originally designed to operate in a cogeneration system (Ref. 1). Cogeneration is the use of a heat engine to simultaneously generate both electricity and useful heat. A side-by-side comparison of the commercially available P2A and the P2A as modified for the NaK test is shown in Figure 8.

Each NaK heater head was insulated using multilayer insulation (MLI). The MLI consisted of four layers of stainless steel foil (annealed temper type 304, 0.002-in.thick, and maximum temperature of 870 °C), separated by three layers of 0.125-in.-thick fiberglass insulation paper (temperature range of −220 to 650 °C; heat flow rate of 1.68 W by cm/m^2 at 24 °C). The P2A configured with the NaK heater head with the MLI installed is shown in Figure 9.

5.0 Test Procedure

At the beginning of each test day, the Stirling convertor data acquisition system time clock was synchronized with the FSP–PTC facility computer system. The Stirling convertor cooling water pump was turned on to provide a water flow of ten lpm to each convertor at a temperature of 25 °C. The convertors were then pressurized with helium to the manufacturer's recommended charge pressure of 363 psia with the convertor at 25 °C. The helium working fluid had to be topped off daily to compensate for a helium leak (~1 psi per hour) believed to be located in the piston/displacer position transducers. After pressurization, 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/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 motored briefly (a few seconds) at a piston amplitude of ~3 mm, then motored at a piston amplitude of 6 mm (this is the piston amplitude that engages the gas bearings). The convertors were started this way to avoid piston/displacer contact. 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 data point to be acquired.

Descriptions of transient test procedures differed depending on the nature of the test (high flow startup, low flow startup, convertor stall, etc.). These procedures are detailed in the Test Plan located in Appendix A, as well as in Section 6.0.

6.0 Results and Discussion

6.1 Steady-State Testing

Steady-state testing was conducted in two phases. During the first phase, the performance of the convertors was measured at most of the same operating conditions (temperatures and piston amplitudes) for which data was acquired during baseline testing using electric heater heads, as described in the Background section. 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, as described in the test plan found in Appendix A. The performance map testing was conducted with the NaK pump operating at full power. The total mass flow to both convertors at full pump power ranged from 700 to 900 g/s. The NaK flow tended to decrease as the test proceeded and the pump temperature increased. The steady-state test data can be found in Appendix B. It should be noted that the data contained in the tables of Appendix B were obtained by averaging the measurements over a 5-min time period. The first column in each table is labeled "Test Pt." The test point numbers shown in this column correspond to the operating conditions given in the Performance Map table (Table I) of the test plan of Appendix A. For the test points denoted with the letter "B," these points were not originally planned, but were added by the test director to compensate for planned test points that could not be achieved. Some of the planned test points could not be achieved mostly due to instability in the electronics used to control the engines at the operating conditions of those planned test points.

Figure 10 shows the combined power output of both convertors plotted as a function of piston amplitude that was acquired during the first phase of steady-state testing. 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. Power output increases with both temperature ratio and piston amplitude. 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. A tabular collection of all performance map data can be found in Appendix B. It should be noted that Appendix B includes an estimate of convertor efficiency; 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 have large associated errors. Consequently, efficiency data is considered unreliable and is not reported in this section.

Figures 11 and 12 compare the power output of the dual P2As configured with the NaK heater heads with that of the P2As 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. The comparisons shown in Figures 11 and 12 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 any sacrifice to engine performance.

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 13 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 startup 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.

6.2 Transient Testing

Transient testing was conducted to study fault tolerance scenarios, possible startup scenarios, and reactivity feedback response of the reactor simulator.

Three fault tolerance scenarios were examined: (1) NaK pump loss, (2) heat source loss (i.e., loss of reator), 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.

Figure 14 shows the system response to the loss of the NaK pump with the convertors still running. Within 30 s the average hot-end temperature had dropped more than 50 °C, which greatly exceeded the predetermined limit of 10 °C per min 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. 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 prevents 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 to prevent freezing of the water loop.

Figure 15 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 inefficiently, which causes this equilibrium temperature to be somewhat higher than it would be in a more prototypic system. This failure mode 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 and 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.

There is currently no established startup scenario for the proposed FSP system or the TDU, so it is important to note that these scenarios may not be representative of actual startup scenarios. The startup scenario tests are simply an examination of the trade between optimizing conditions within the reactor and minimizing the required startup energy. It is important to note that the relative importance of each of these is not currently well defined. Nevertheless, several startup 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 set point, (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 startup testing were the NaK mass flow and the initial temperature set point. A full test plan and procedural description can be found in appendix A. The initial Stirling hot-end temperature set point ranged from 200 to 500 °C and the NaK mass flow ranged from 600 to 900 g/s (for both convertors). The results of the startup (transient) testing are shown in Figures 16 through 21. The data shows that the Stirling convertors are quite robust in their ability to handle these starting conditions.

Figure 22 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.

Data acquired during the reactivity portion of the testing are shown in Figures 23 through 30. Figure 23 shows the system response to a convertor stall with the heater in reactivity feedback control, which simulates the response of a fission reactor. At first glance, this fault scenario appears somewhat benign because it is feasible to recover to full power if the convertors can be restarted and if the temperature fluctuations of the reactor are not large enough to cause serious problems on the hot end. However, in this test, the cold-end temperature was being controlled using a proportional-integral-derivative (PID) controller on the water loop, so cold-end temperature remained constant despite a dramatic reduction of the heat input to the water loop. In a flight system, this decrease in heat input could cause a decrease in the cold-side temperature that might potentially freeze the water coolant.

The other class of transient tests that were run examined the system response to various perturbations when the NaK heater controller is simulating the response of a nuclear reactor using a point kinetics algorithm. These tests were performed to aid modeling efforts and estimate time constants for system response, when the NaK heater behavior is more characteristic of a reactor. Figures 24 through 27 show the system response to a 1 mm increase, 1 mm decrease, 2 mm increase, and 2 mm decrease in piston amplitude, respectively.

Figures 28 and 29 show the system response to step changes in NaK mass flow.

Figure 30 shows the system response to an insertion of reactivity.

7.0 Summary of Results

The 1-kW Stirling convertors were shown to produce the same power at nominal operating conditions whether heated by electrical resistance heaters or a pumped NaK loop. 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. Performance maps generated using the pumped NaK loop for thermal input consistently show the convertors performing as well or better than they had during operation with electric heater heads. A potential explanation for the slightly better performance is that the convertor-body radiation losses were reduced due to operation in vacuum. Uncertainty in the measurement of thermal input to the Stirling convertors made it difficult to obtain reliable efficiency data; 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.

Several possible startup tests were conducted to generate data relevant to future TDU and FSP system startups. 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 startup scenarios. This flexibility will be useful to future system designers who will likely find restrictions on reactor startup and required pump power to be more constraining. In addition, startup 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 ~4000 to ~2000 W. Furthermore, reductions in mass flow were shown to have little effect on total time to reach nominal operation. This data suggests that startup scenarios should occur at low mass flows to minimize the total energy required for pumping. However, we must again qualify this statement 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 and that the choice of startup scenario will have to take into account reactor requirements in addition to pump power restrictions. Further analysis of a more representative system would be necessary to draw more specific conclusions.

Fault recovery tests were also conducted 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 time transient, 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 overcool 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. Precautions must then be taken to accommodate the loss of heat input to the coolant.

The NaK heater controller was used to simulate reactivity feedback of a fission reactor. The transient response of the system to changes in mass flow, piston amplitude, and reactivity insertion were evaluated. These were considered follow-on tests done to assist the efforts of future controller designers and system modelers. The data taken during these tests are presented for completeness, but the usefulness of the results and the conclusions drawn are outside the scope of the paper.

8.0 Conclusions

The operation of a pair of kilowatt-class Stirling power convertors using a pumped NaK loop for thermal input was demonstrated. The convertors generated full power at nominal operating conditions and performed as well or better than they did when heated electrically.

Startup scenarios showed that Stirling convertors may be initiated through a wide range of hot-end temperatures and NaK flow rates suggesting that limitations on startup will likely come from either reactor or pump power requirements.

Fault tolerance tests were run to recognize the risks associated with several fault scenarios, which may be encountered in future system-level testing.

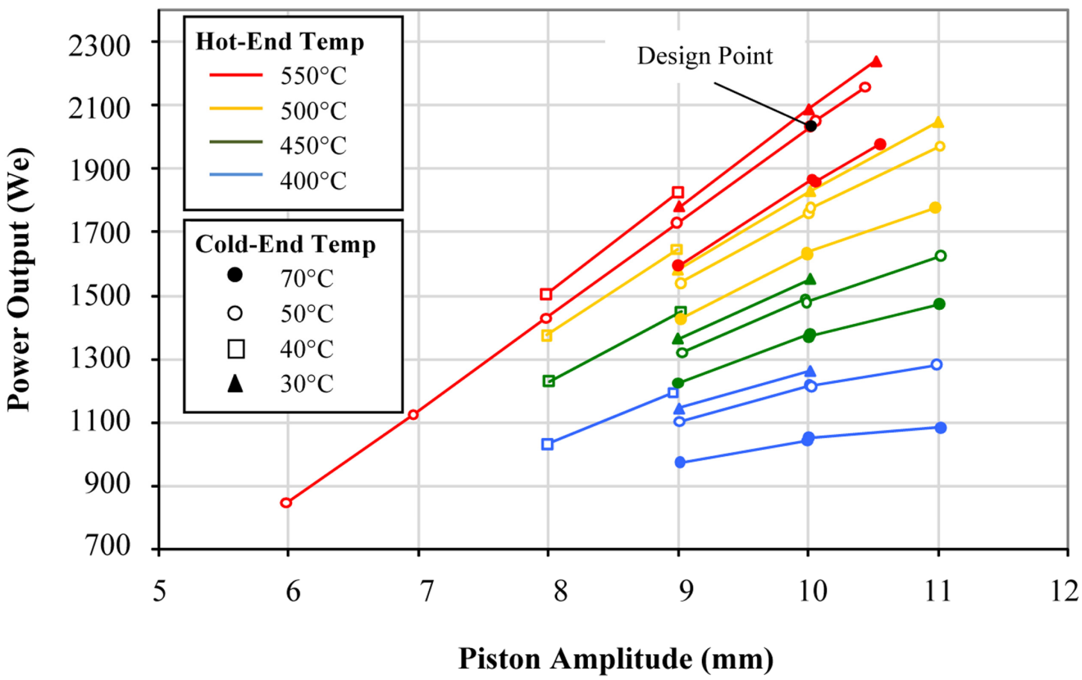


Figure 1.—Baseline performance map with P2A convertors configured with electrically heated heads. Power shown in plot is the total power for two convertors.

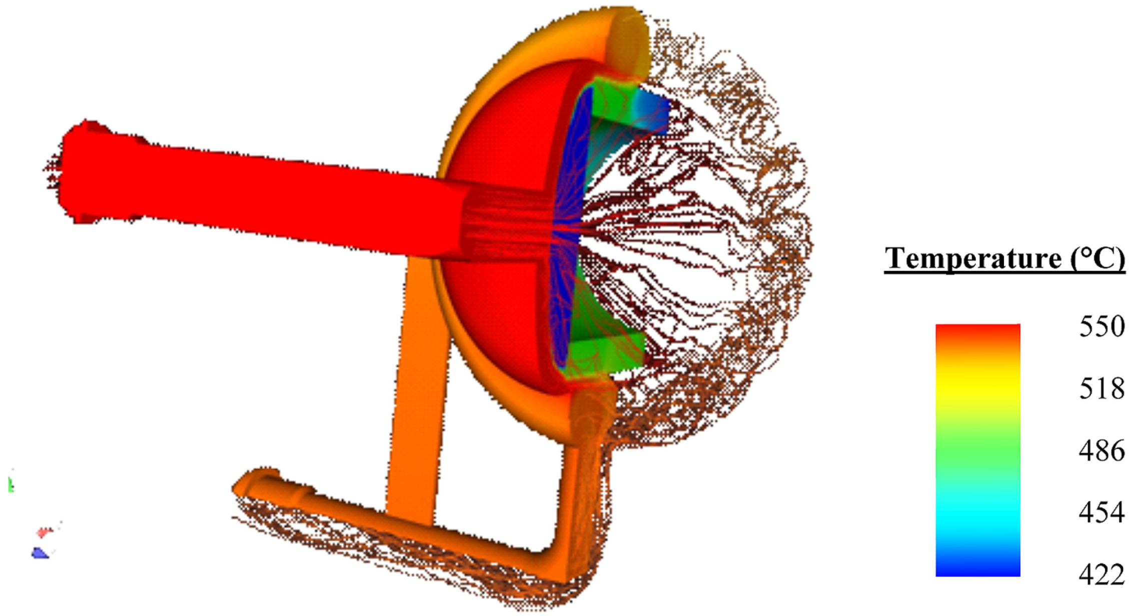


Figure 2.—NaK flow particle trace and heater head temperature profile assuming a NaK mass flow rate of 0.36 kg/s and 4000 W of thermal energy transfer into the Stirling convertor.

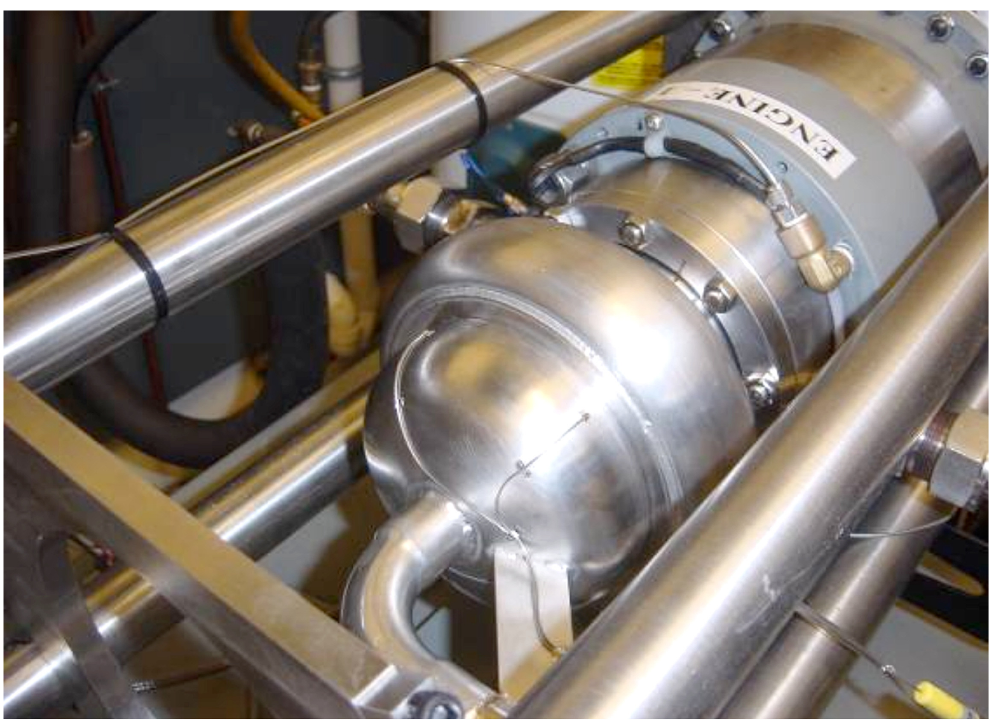


Figure 3.—Single P2A free-piston Stirling power convertor with NaK heat exchanger prior to installation of multilayer insulation (MLI).

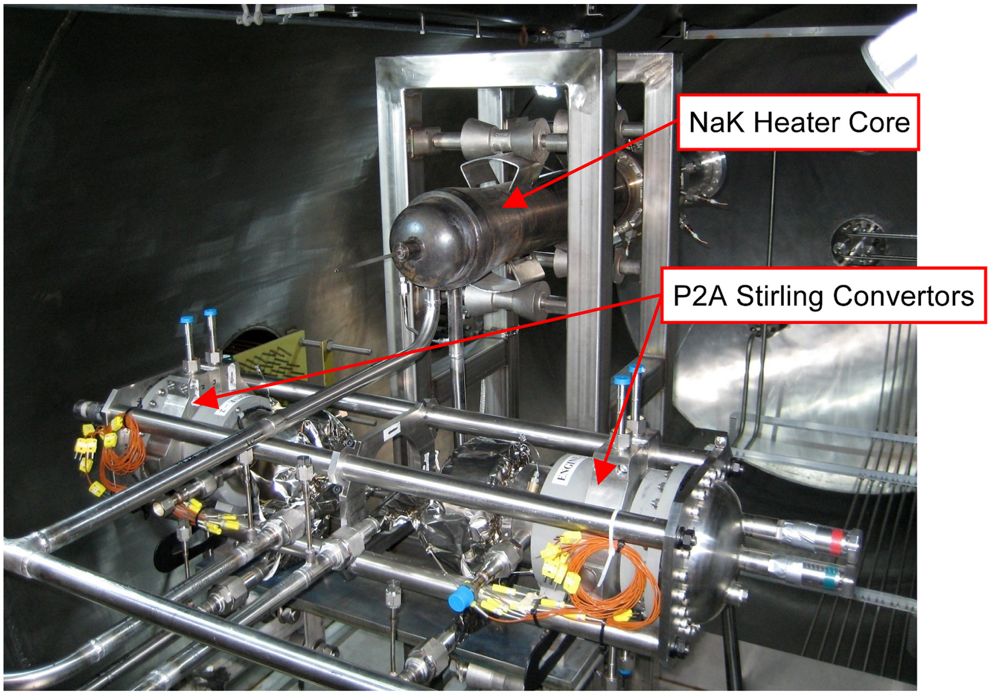


Figure 4.—Dual P2A Stirling power convertors mounted in the MSFC test facility.

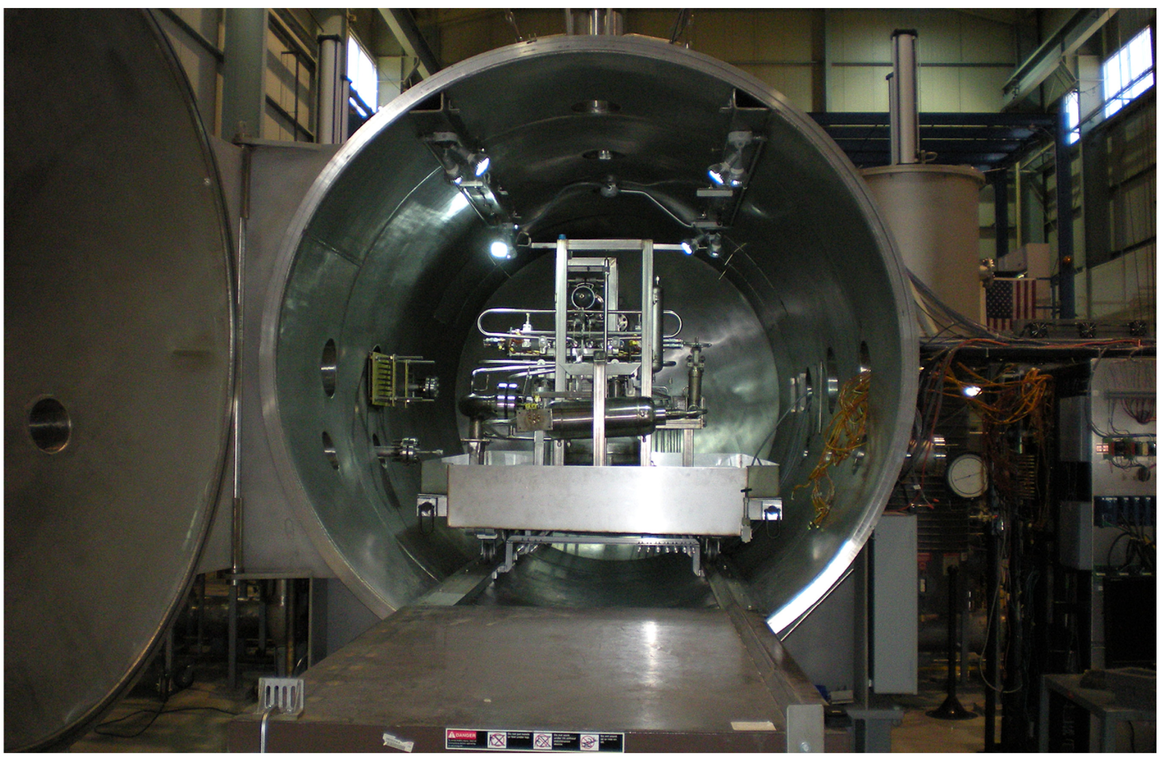


Figure 5.—Dual P2A Stirling power convertors installed in FSP–PTC test facility.

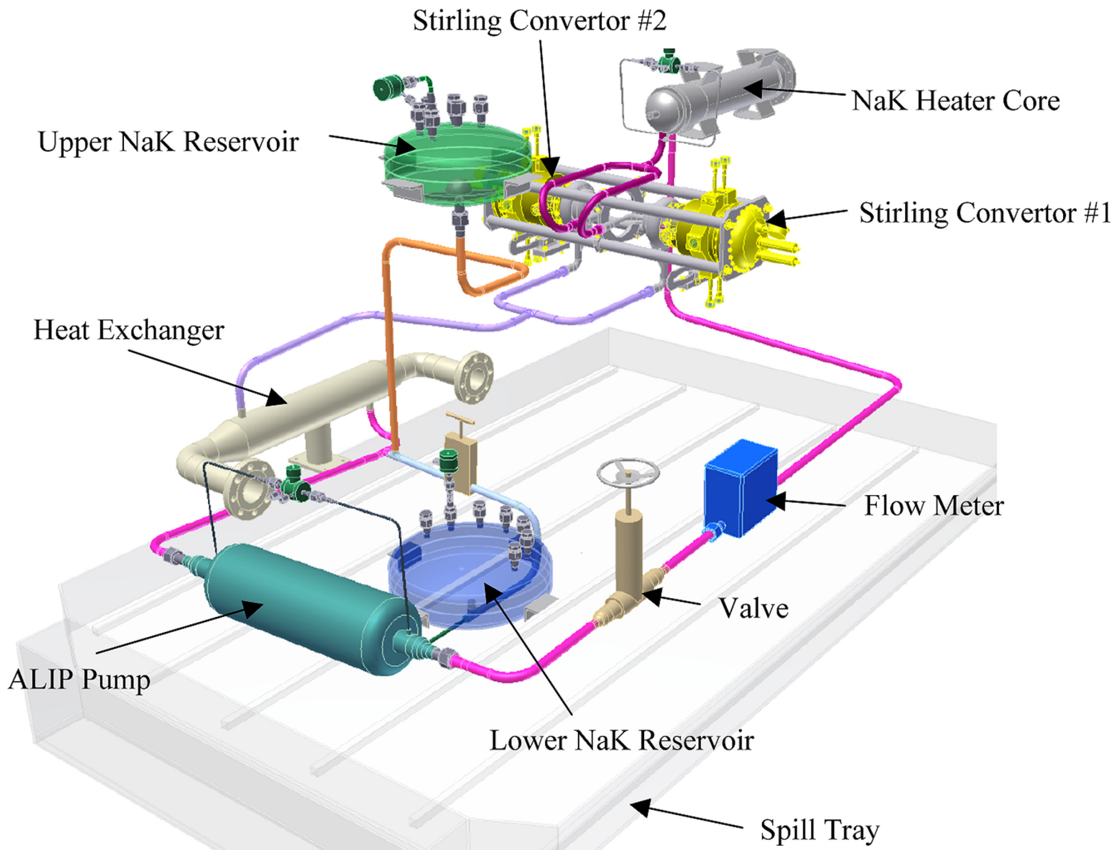


Figure 6.—Rendering of dual P2A Stirling power convertors installed in FSP–PTC test facility.

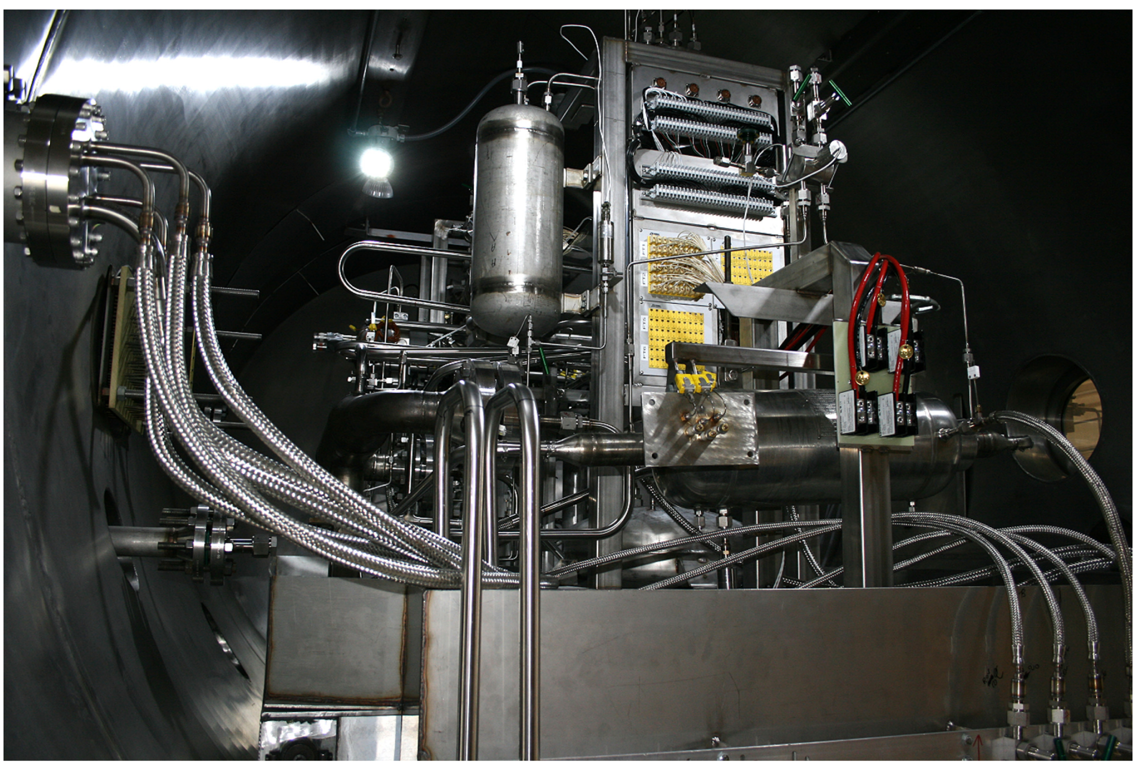
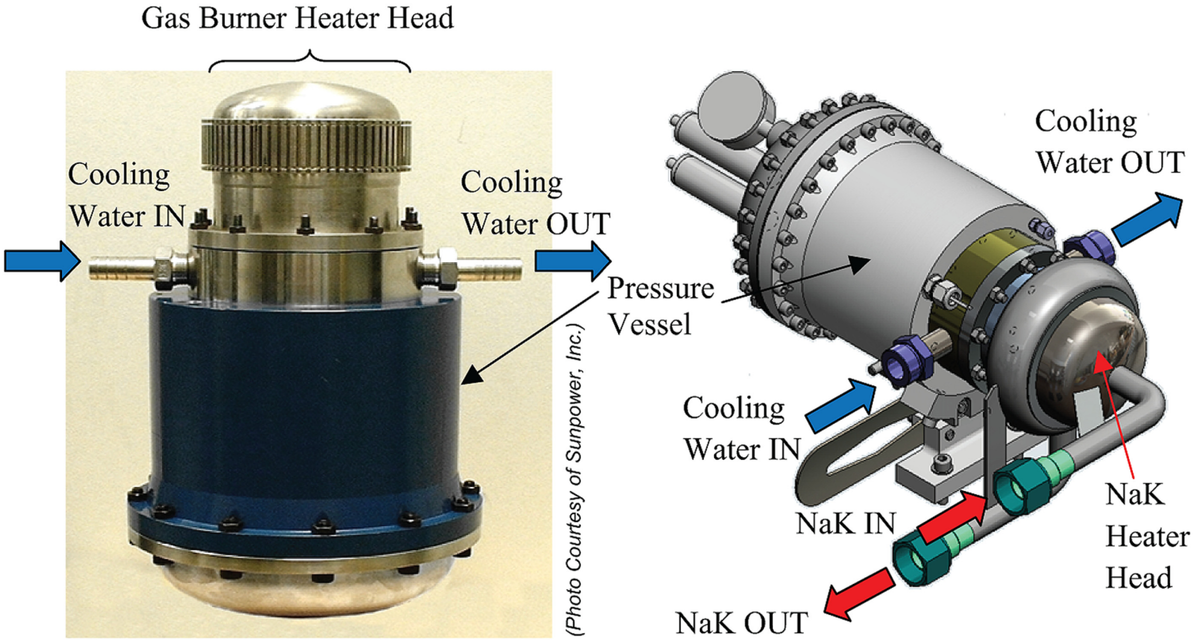


Figure 7.—FSP–PTC completed and installed into the vacuum chamber prior to insulation.



(a) Commercially available P2A. (b) P2A configured with NaK heater head.

Figure 8.—Comparison of commercially available P2A configuration with modified configuration.

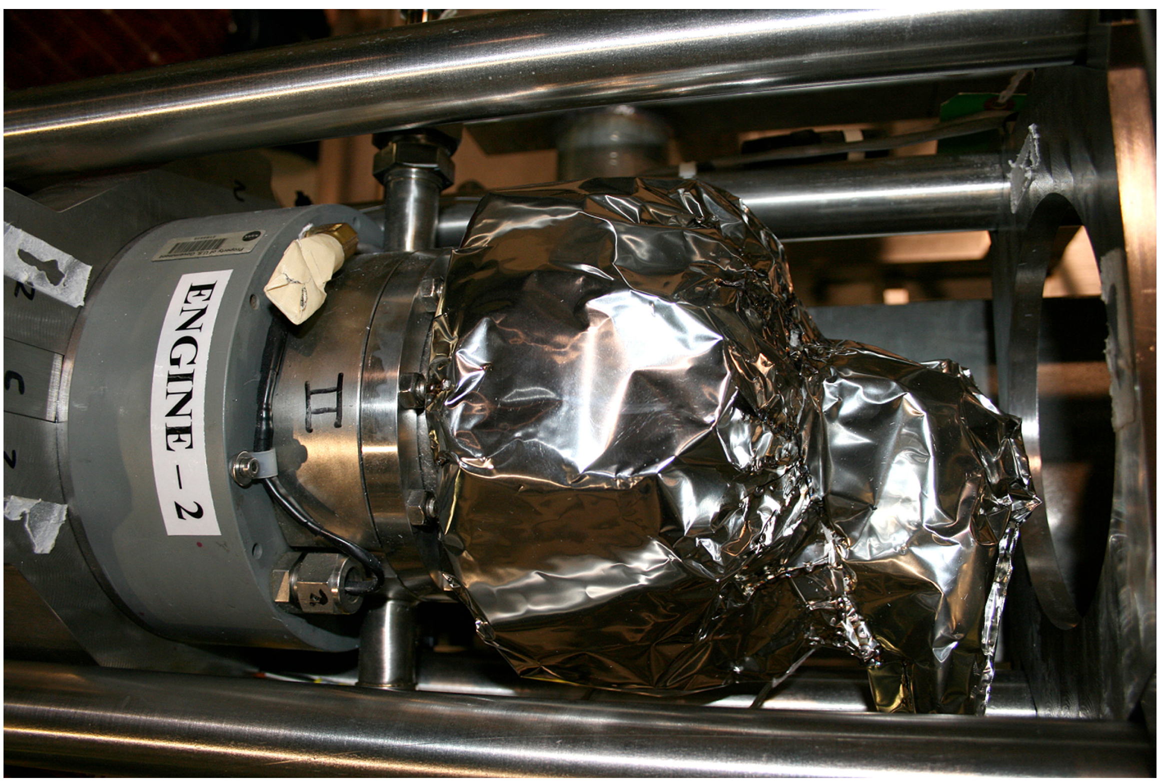


Figure 9.—MLI installed on NaK heater head of P2A Stirling power convertor.

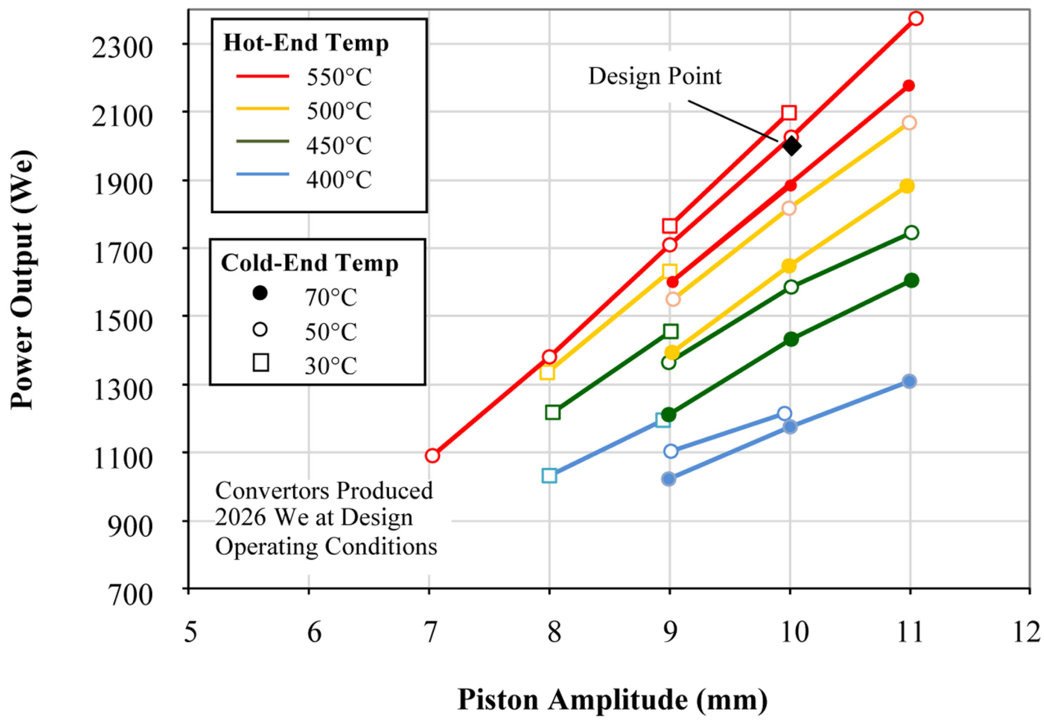


Figure 10.—Combined power output of dual P2A Stirling power convertors configured with NaK heater heads vs. piston amplitude.

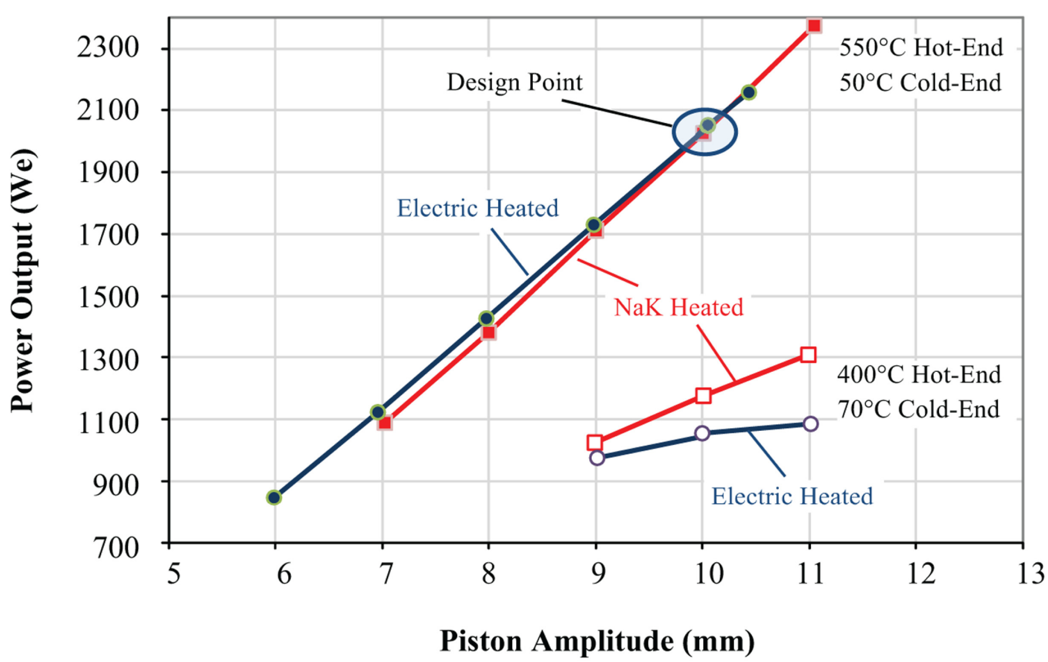


Figure 11.—Combined power output of dual P2A Stirling power convertors configured with NaK heater heads vs. piston amplitude compared with baseline data.

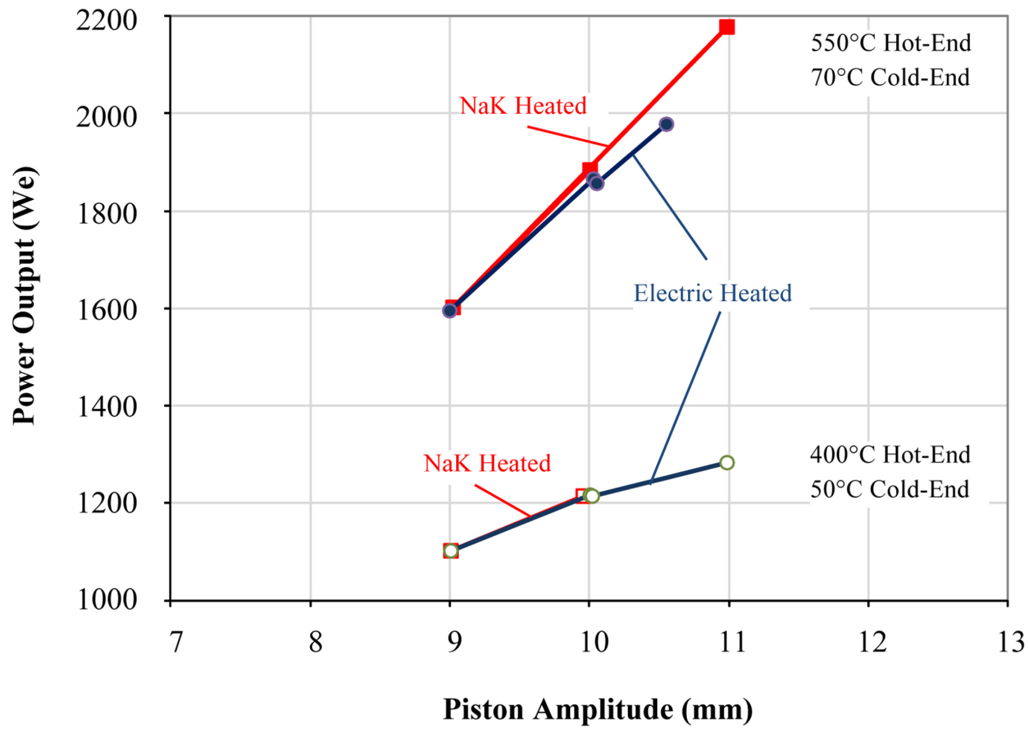


Figure 12.—Combined power output of dual P2A Stirling power convertors configured with NaK heater heads vs. piston amplitude compared with baseline data.

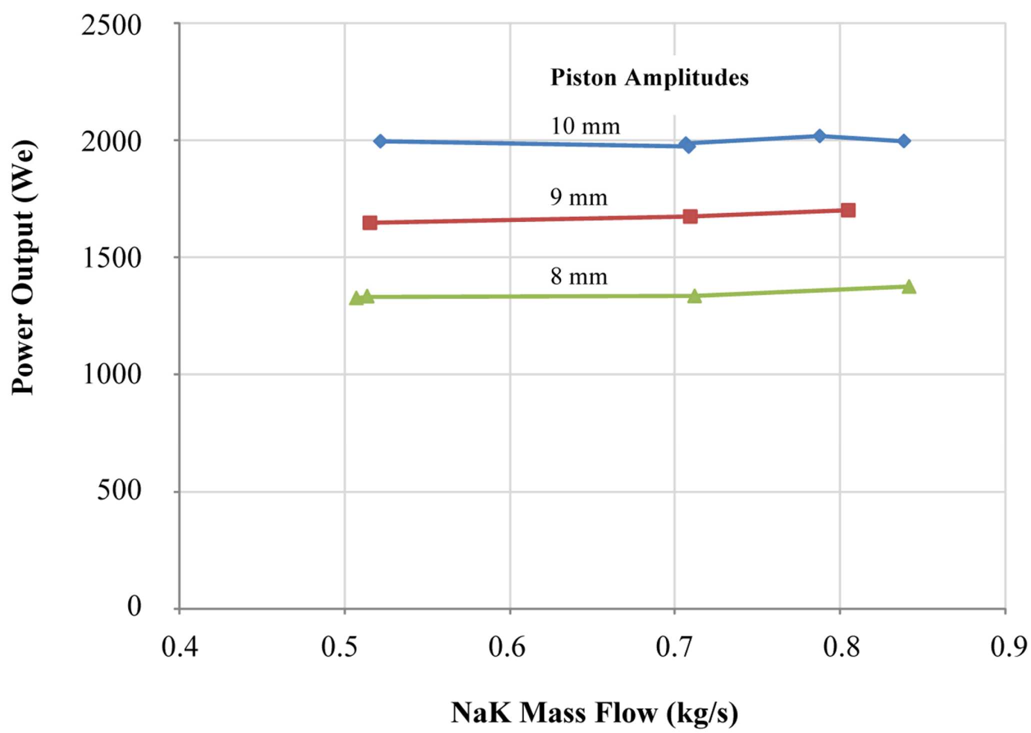


Figure 13.—Sensitivity of P2A Stirling power output for various NaK mass flow rates.

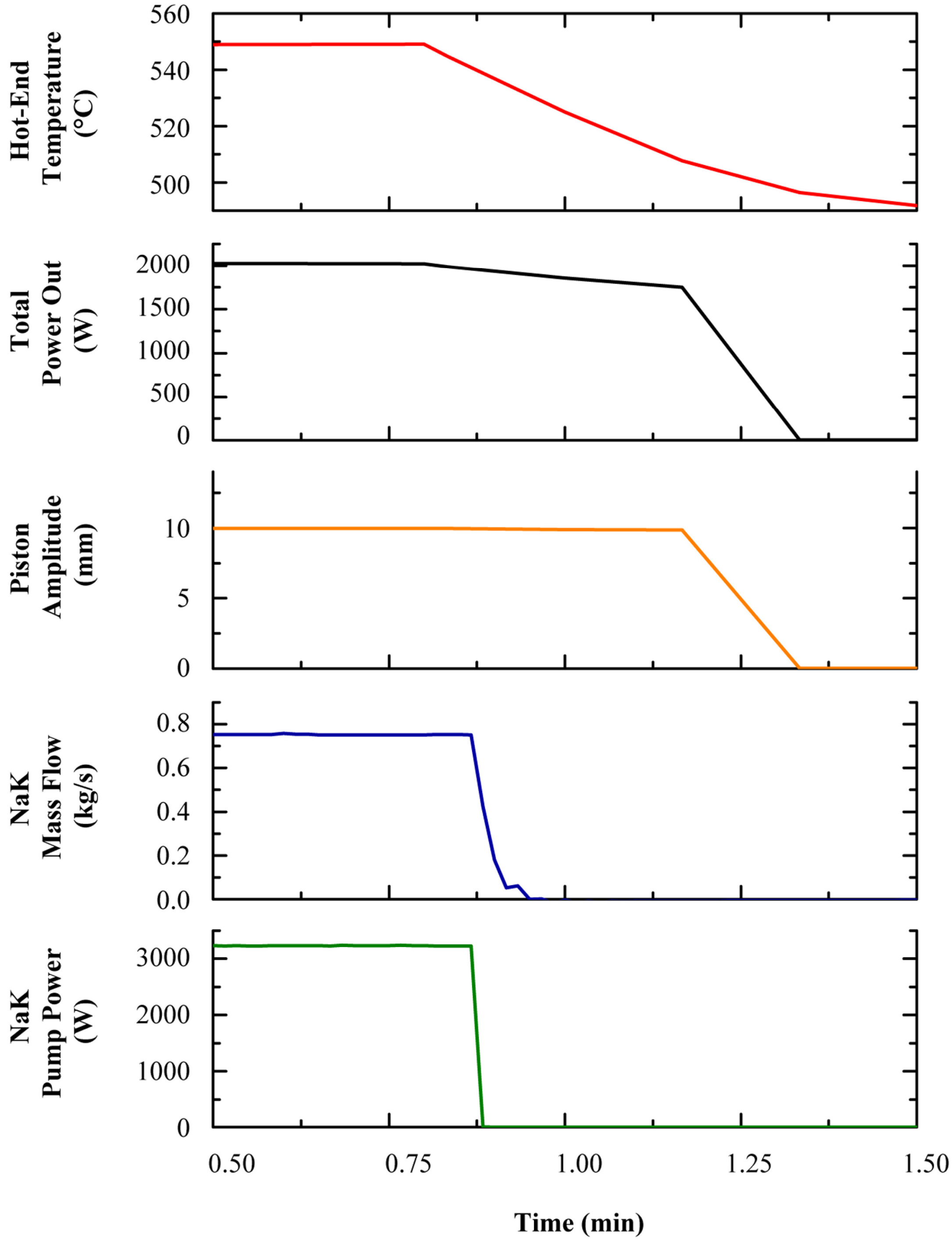


Figure 14.—Transient operating conditions—simulate loss of the ALIP pump and intermediate NaK loop at full NaK flow—transient condition 1.

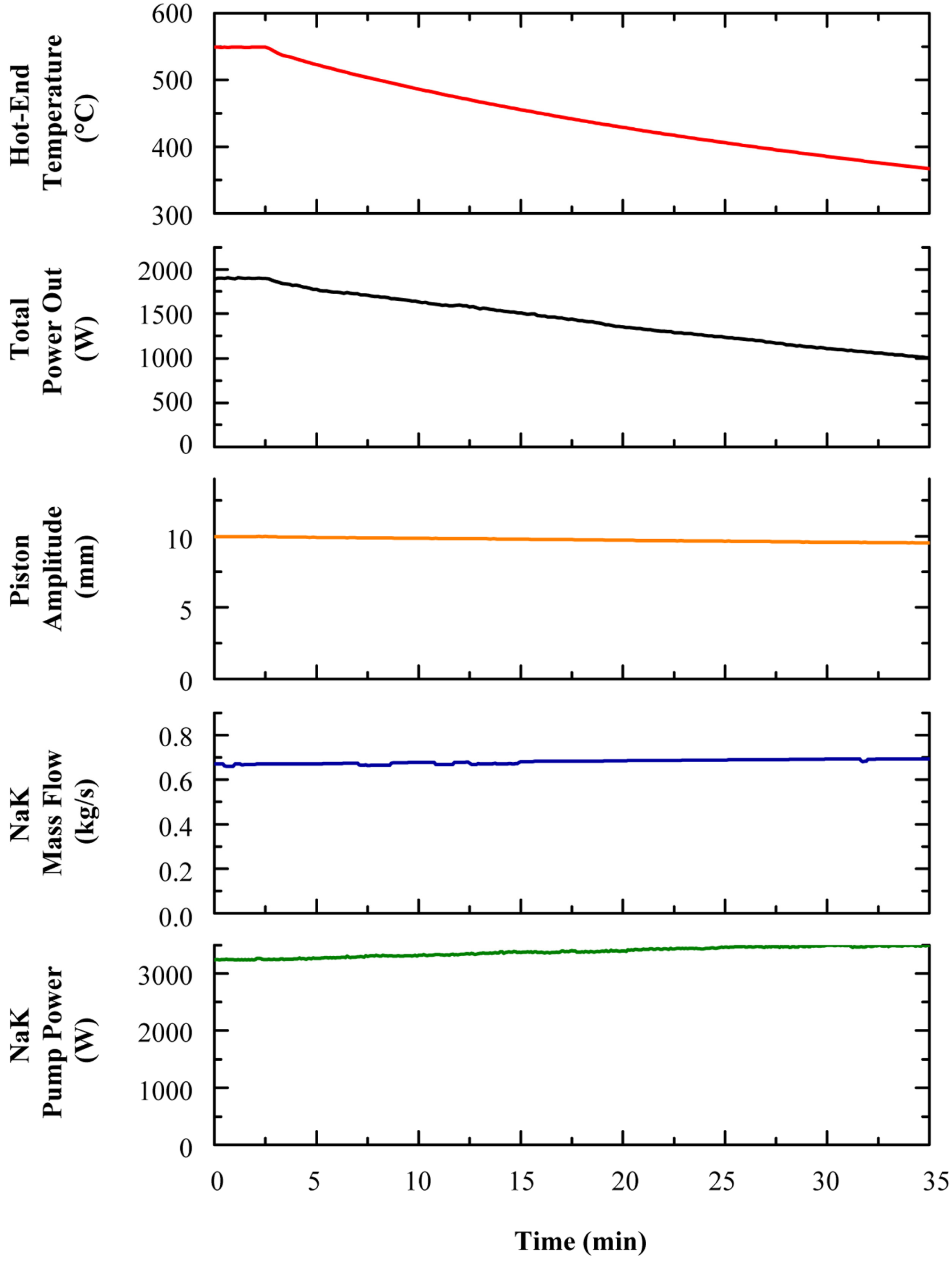


Figure 15.—Transient operating conditions—simulate loss of reactor power and primary NaK loop at full NaK flow—transient condition 2.

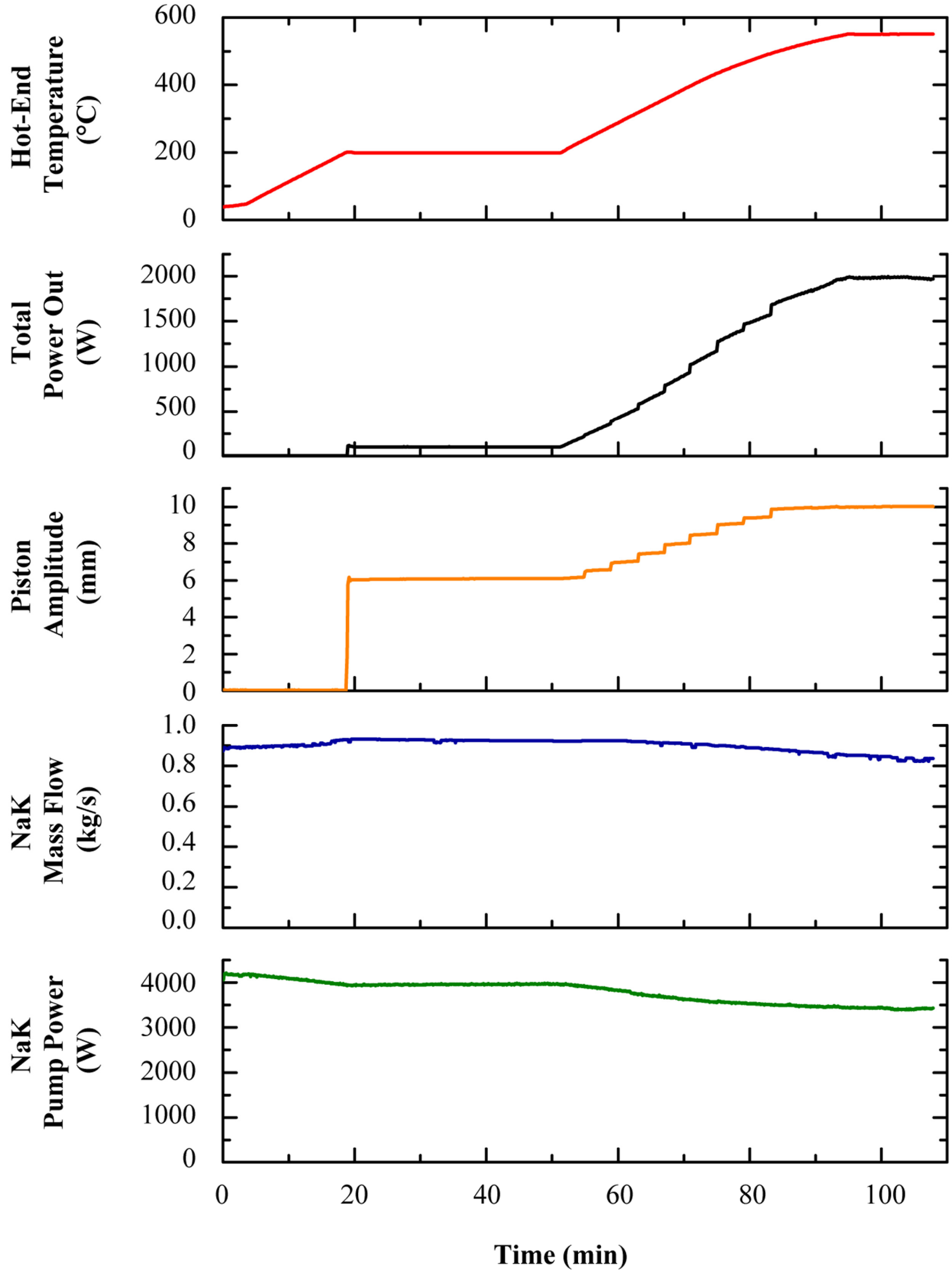


Figure 16.—Transient operating conditions—minimum temperature startup at full NaK flow—transient condition 3.

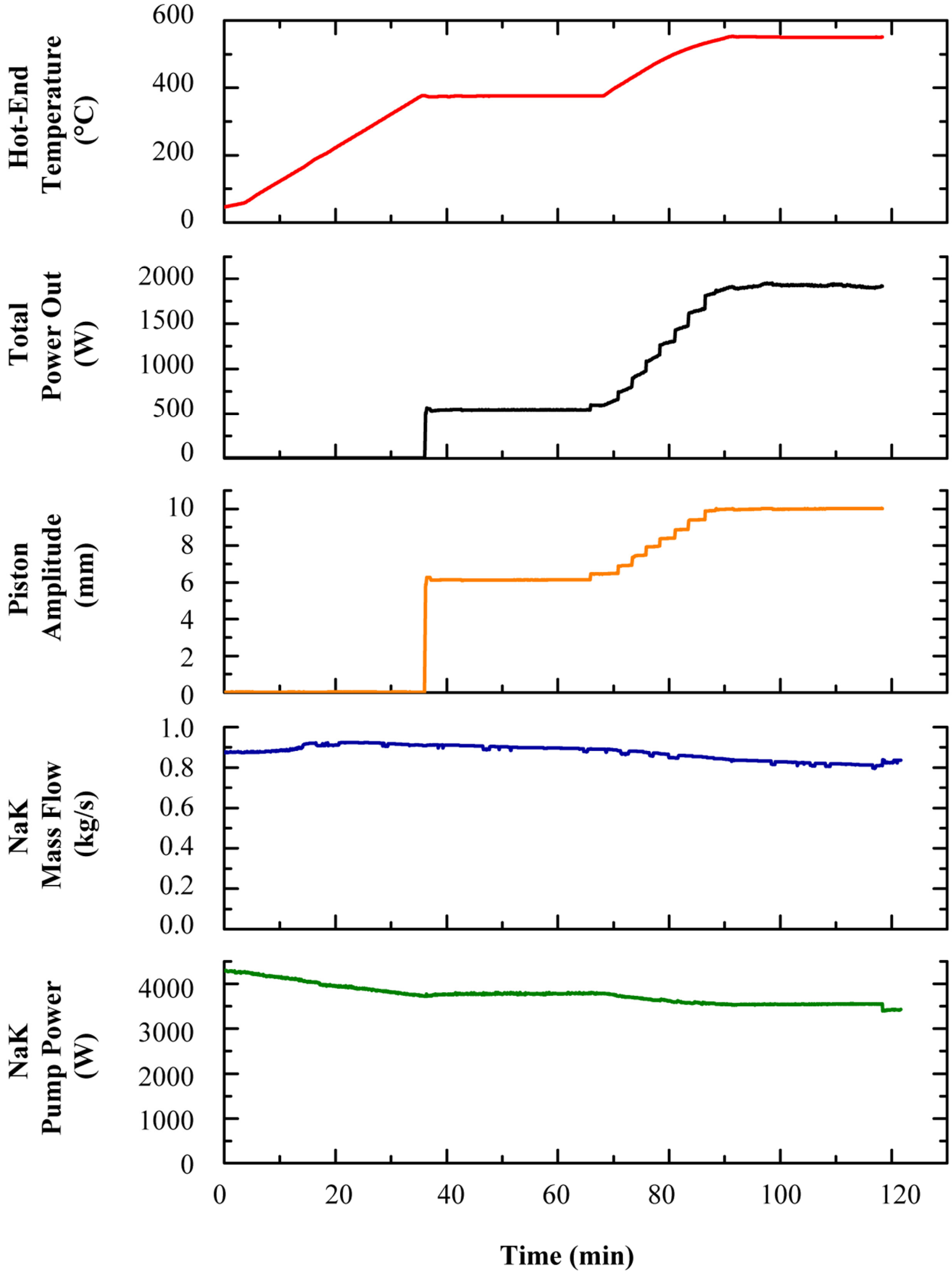


Figure 17.—Transient operating conditions—medium temperature startup at full NaK flow—transient condition 4.

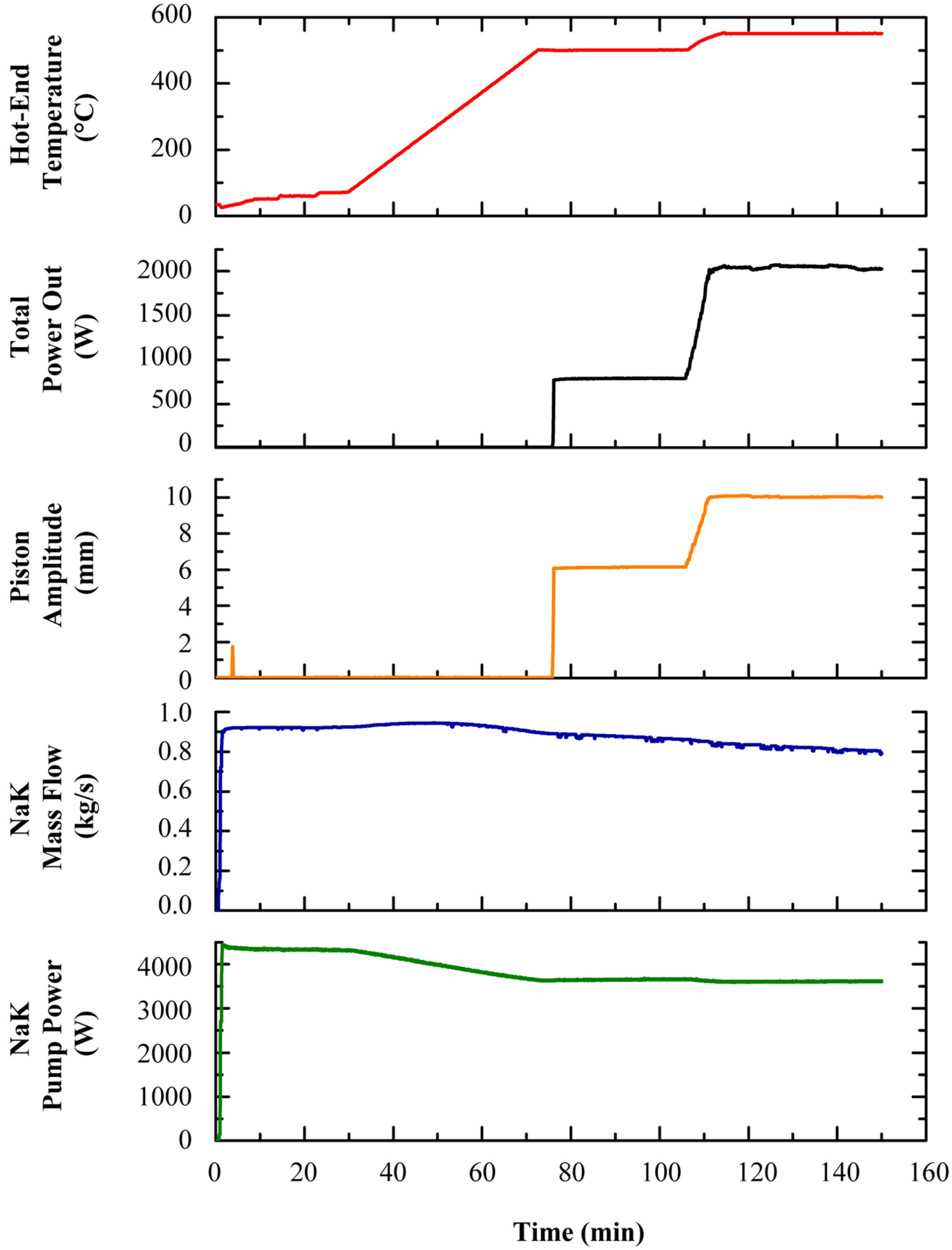


Figure 18.—Transient operating conditions—full (high) temperature startup at full NaK flow—transient condition 5.

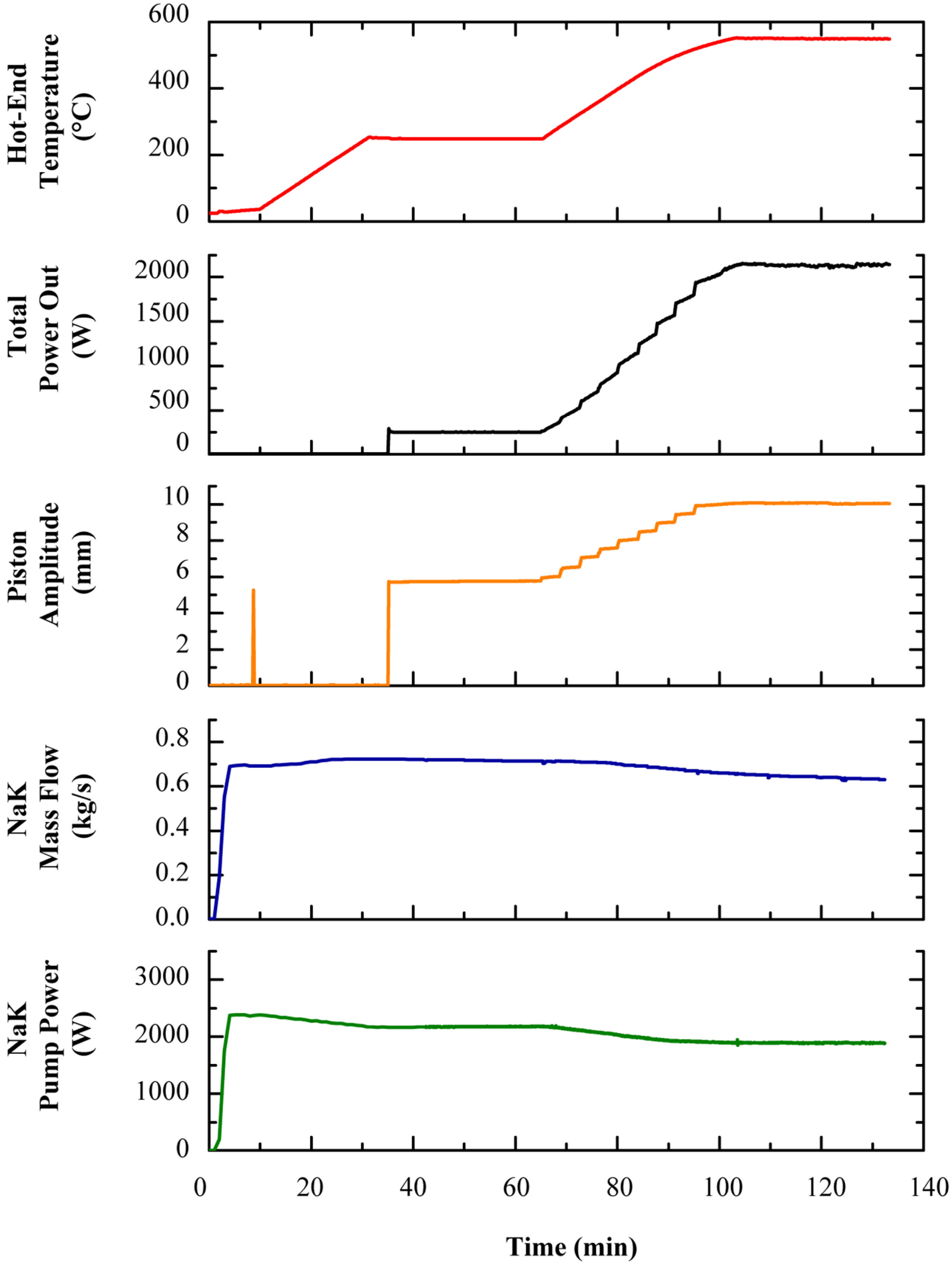


Figure 19.—Transient operating conditions—minimum temperature startup at 75 percent NaK flow—transient condition 6.

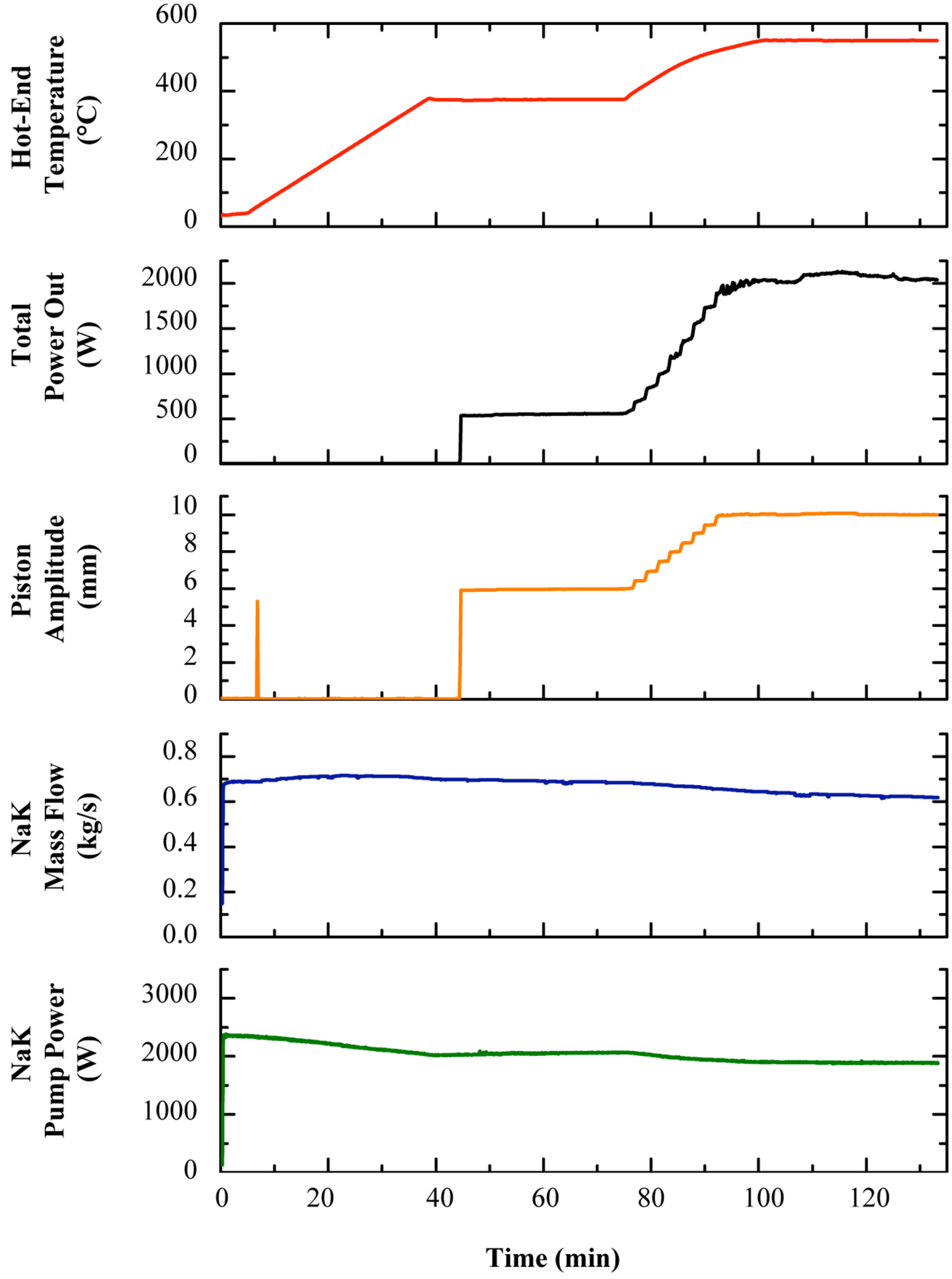


Figure 20.—Transient operating conditions—medium temperature startup at 75 percent NaK flow—transient condition 7.

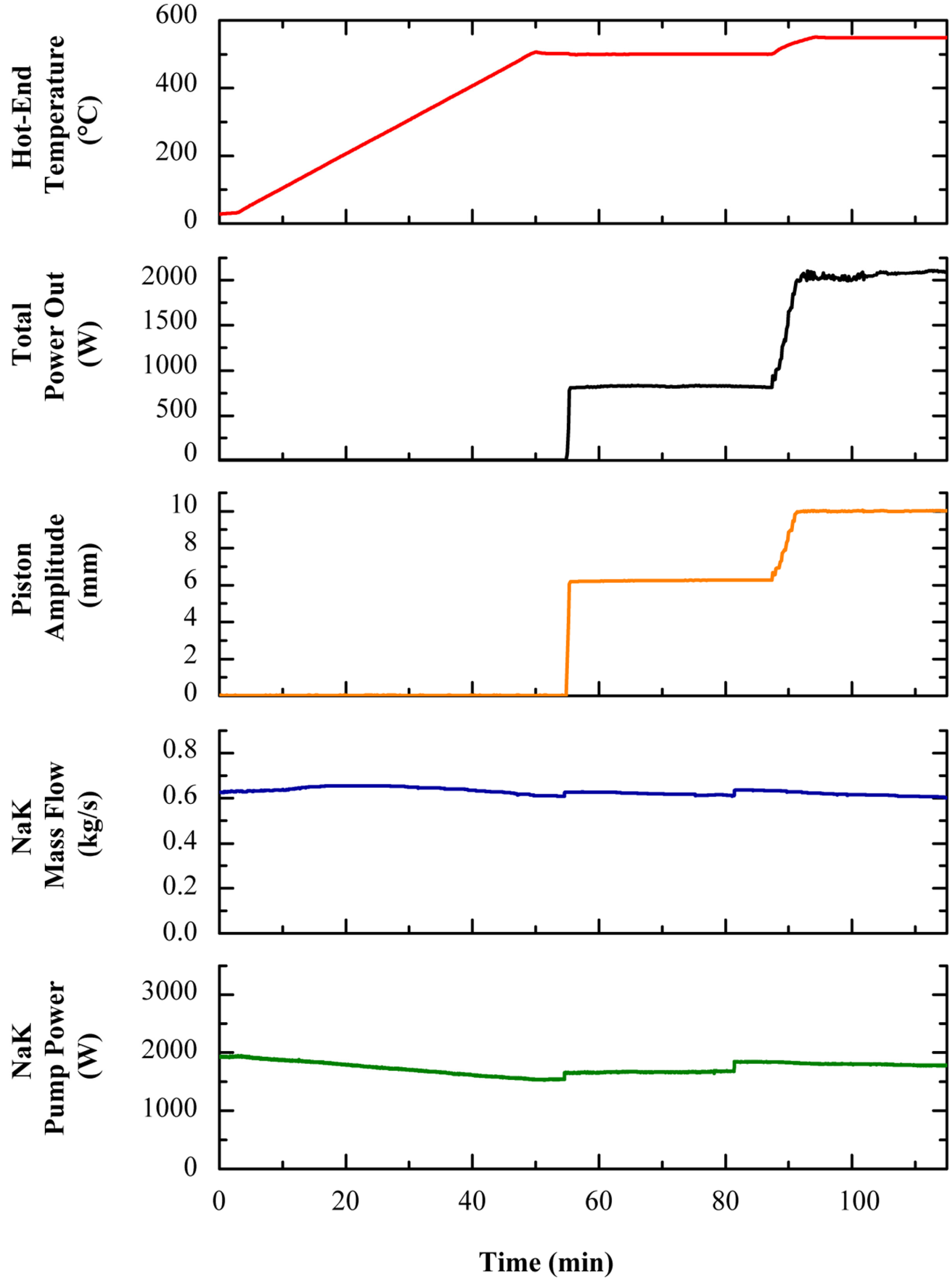


Figure 21.—Transient operating conditions—full (high) temperature startup at 75 percent NaK flow—transient condition 8.

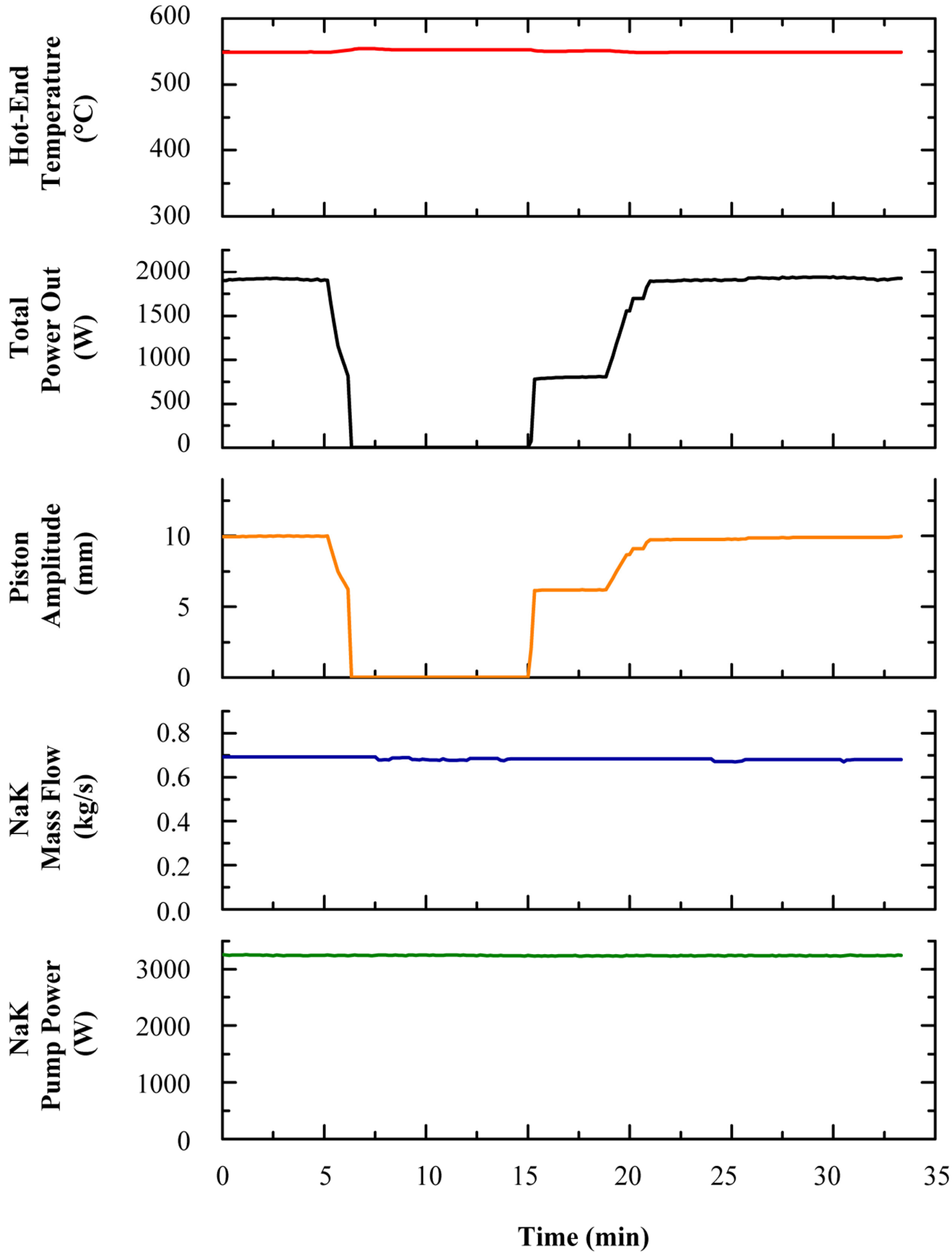


Figure 22.—Transient operating conditions—simulate shutdown/restart of Stirling convertors—transient condition 9.

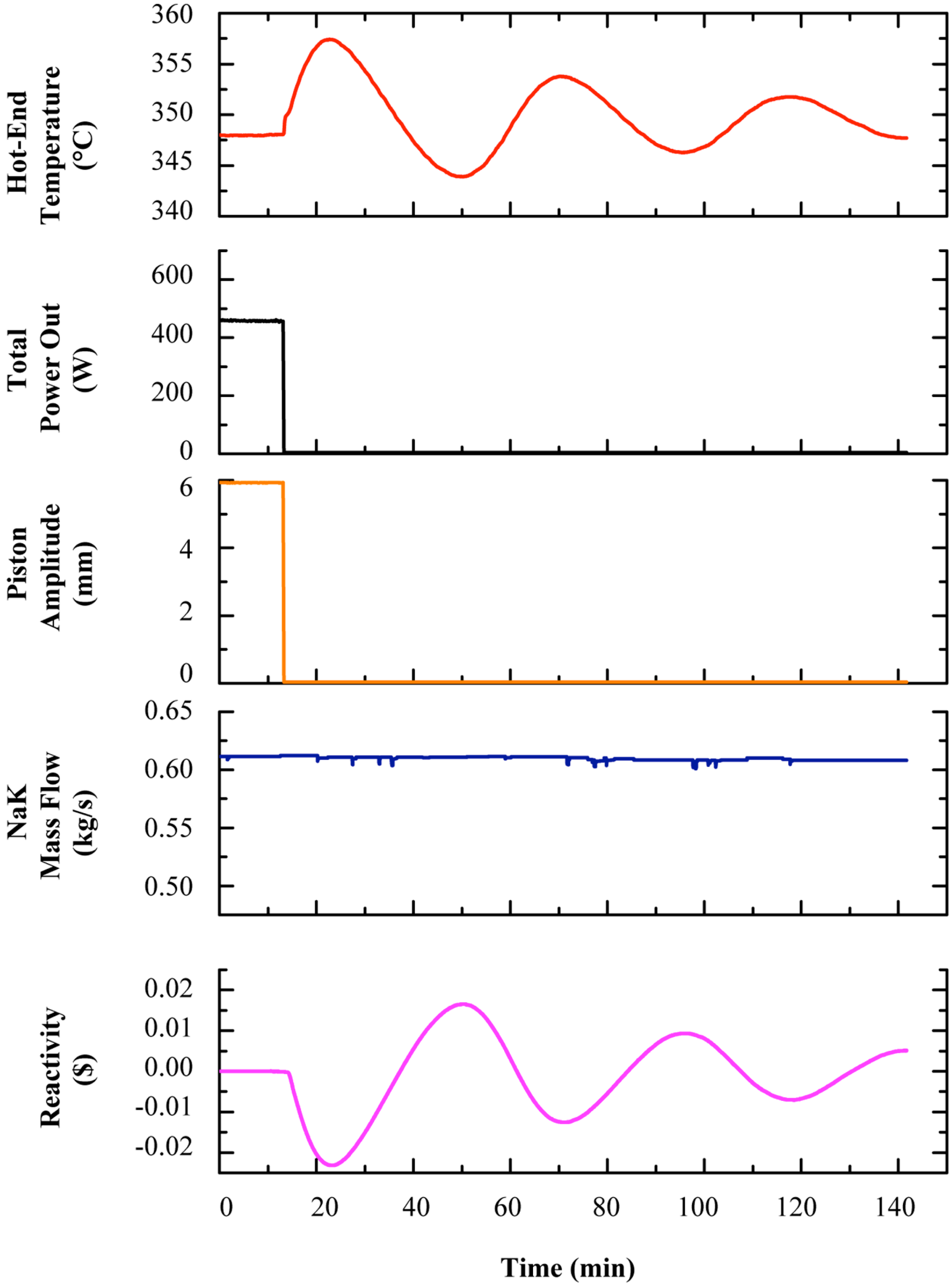


Figure 23.—System response to Stirling convertor stall with reactivity feedback control.

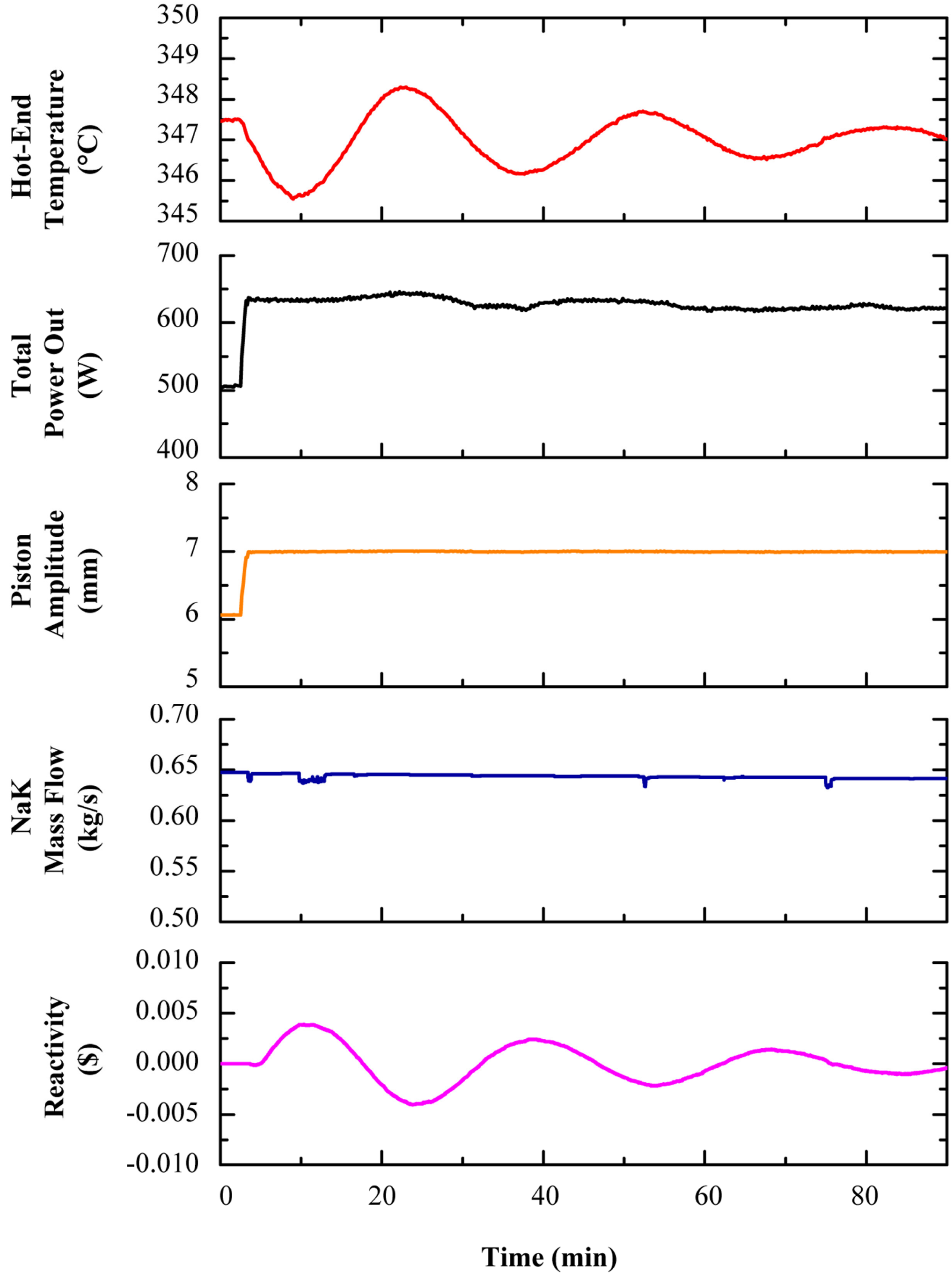


Figure 24.—System response to 1-mm Stirling convertor piston amplitude increase with reactivity feedback control.

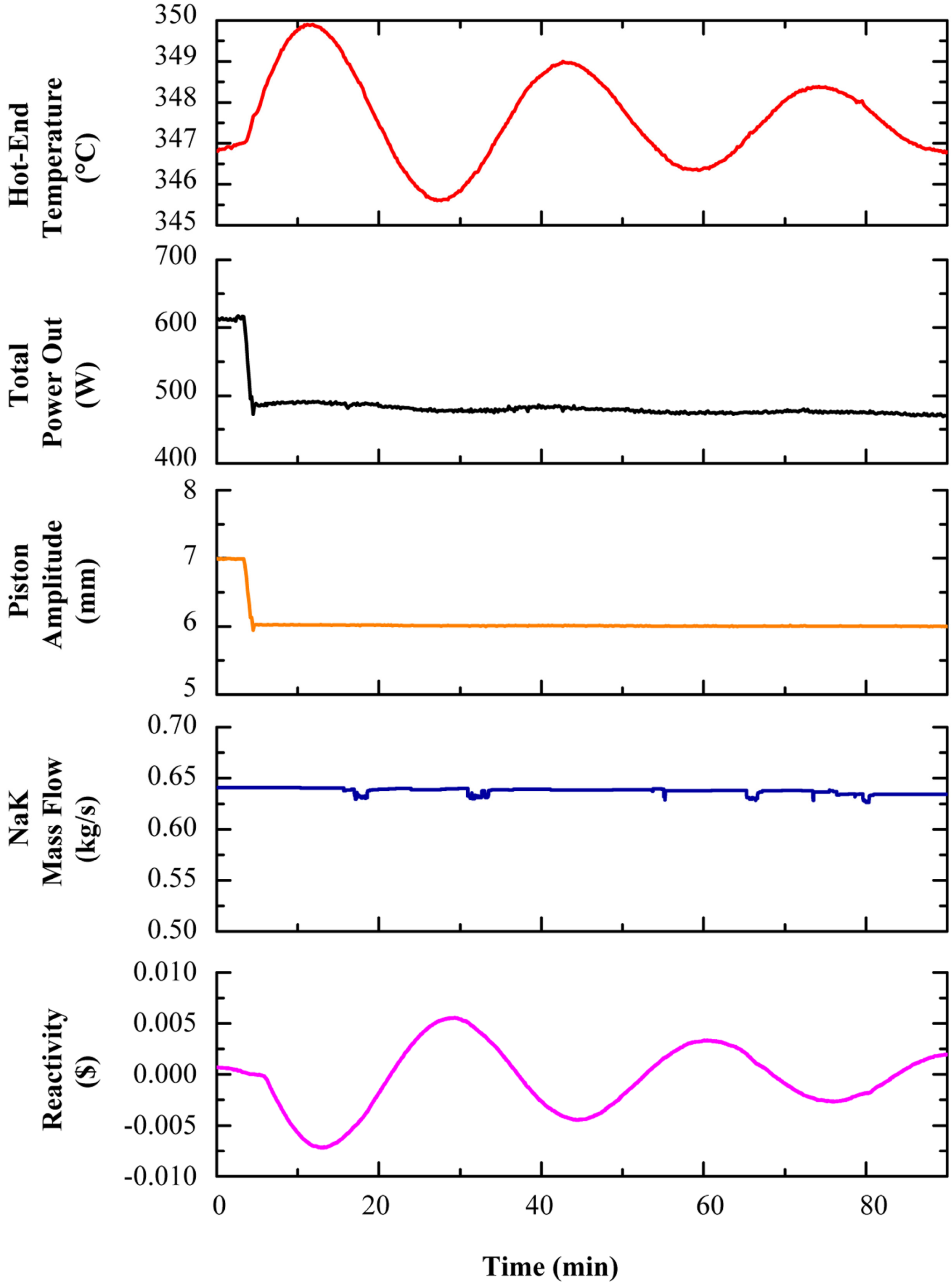


Figure 25.—System response to 1-mm Stirling convertor piston amplitude decrease with reactivity feedback control.

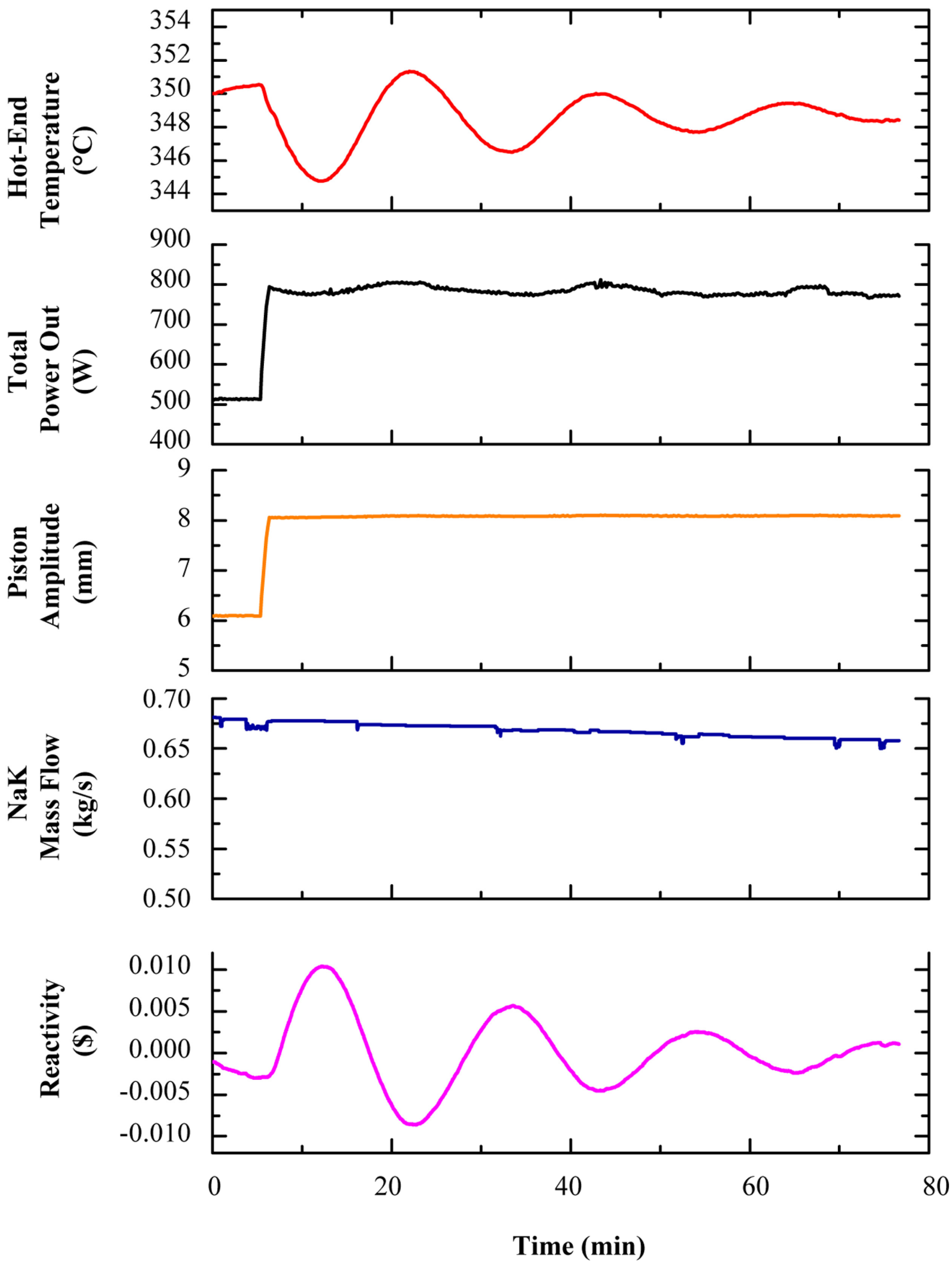


Figure 26.—System response to 2-mm Stirling convertor piston amplitude increase with reactivity feedback control.

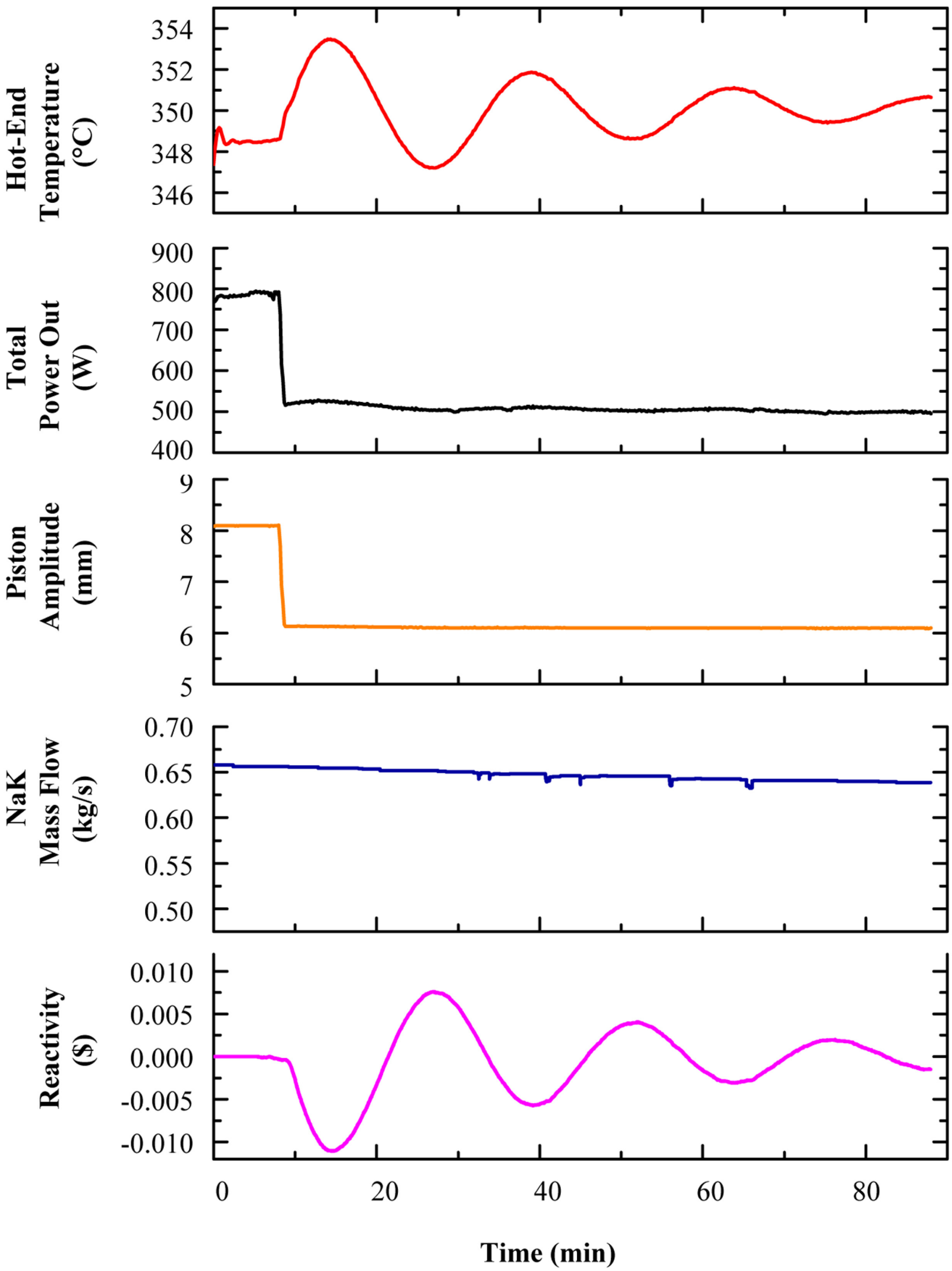


Figure 27.—System response to 2-mm Stirling convertor piston amplitude decrease with reactivity feedback control.

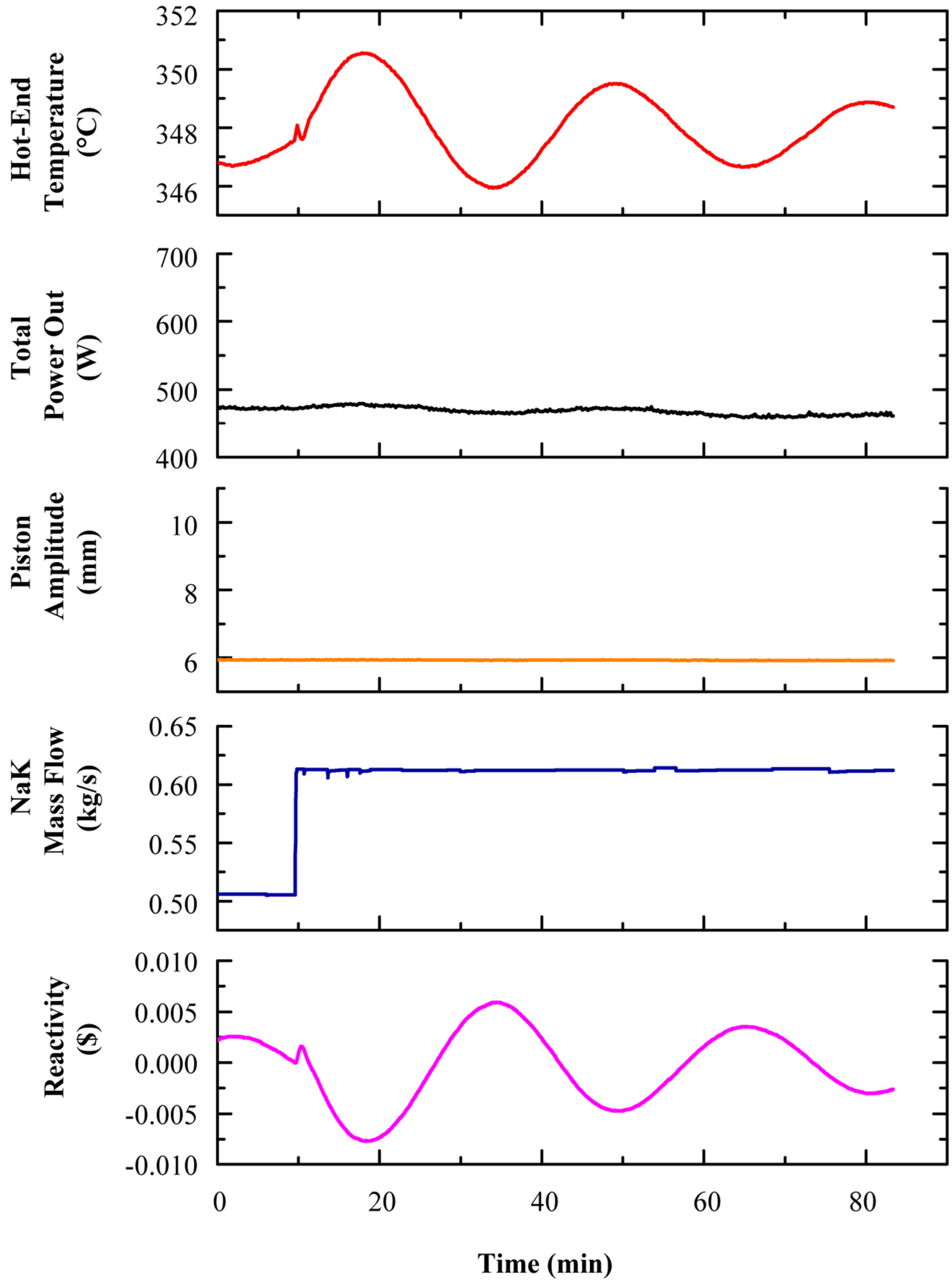


Figure 28.—System response to increase in NaK mass flow with reactivity feedback control.

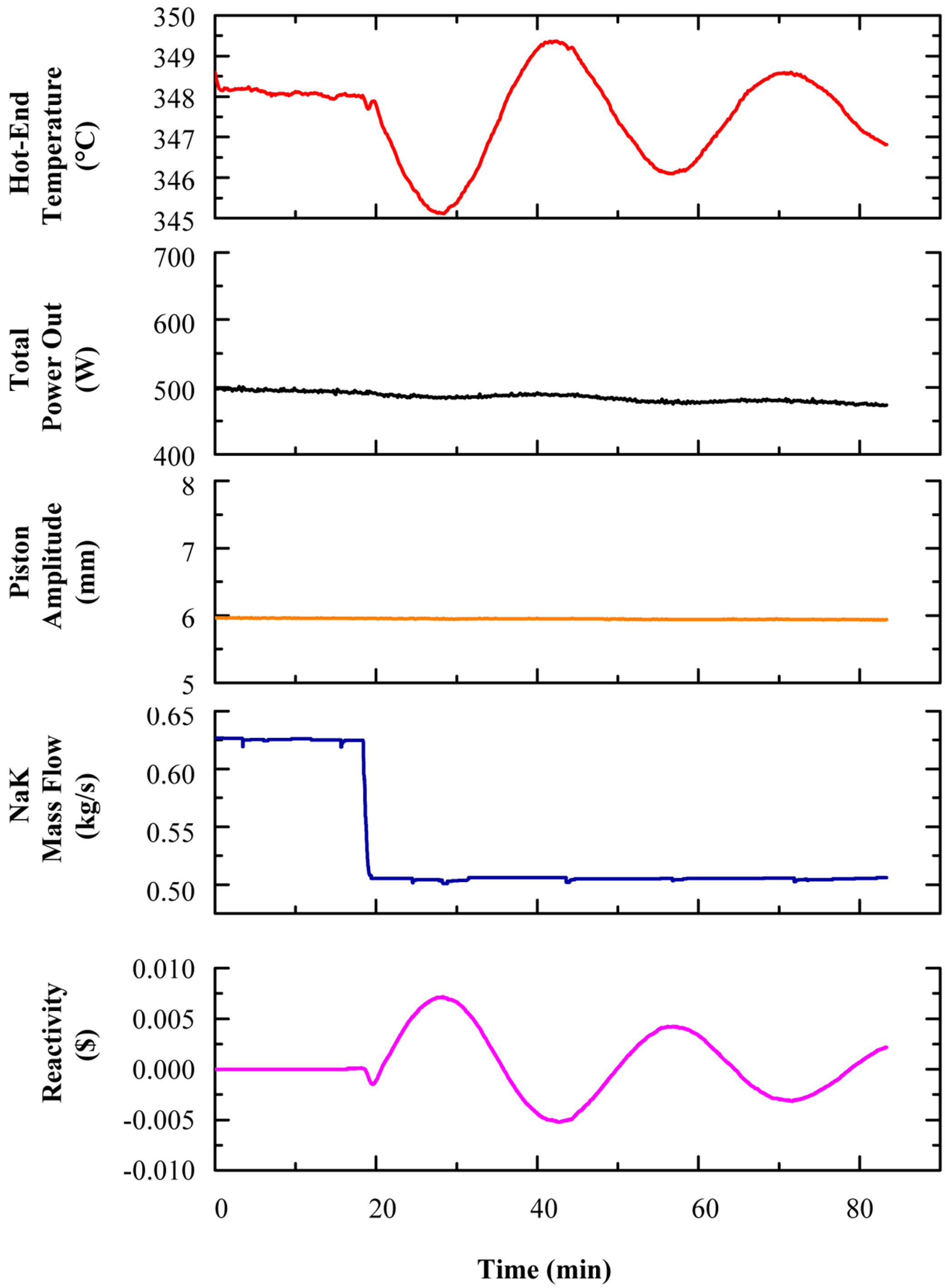


Figure 29.—System response to decrease in NaK mass flow with reactivity feedback control.

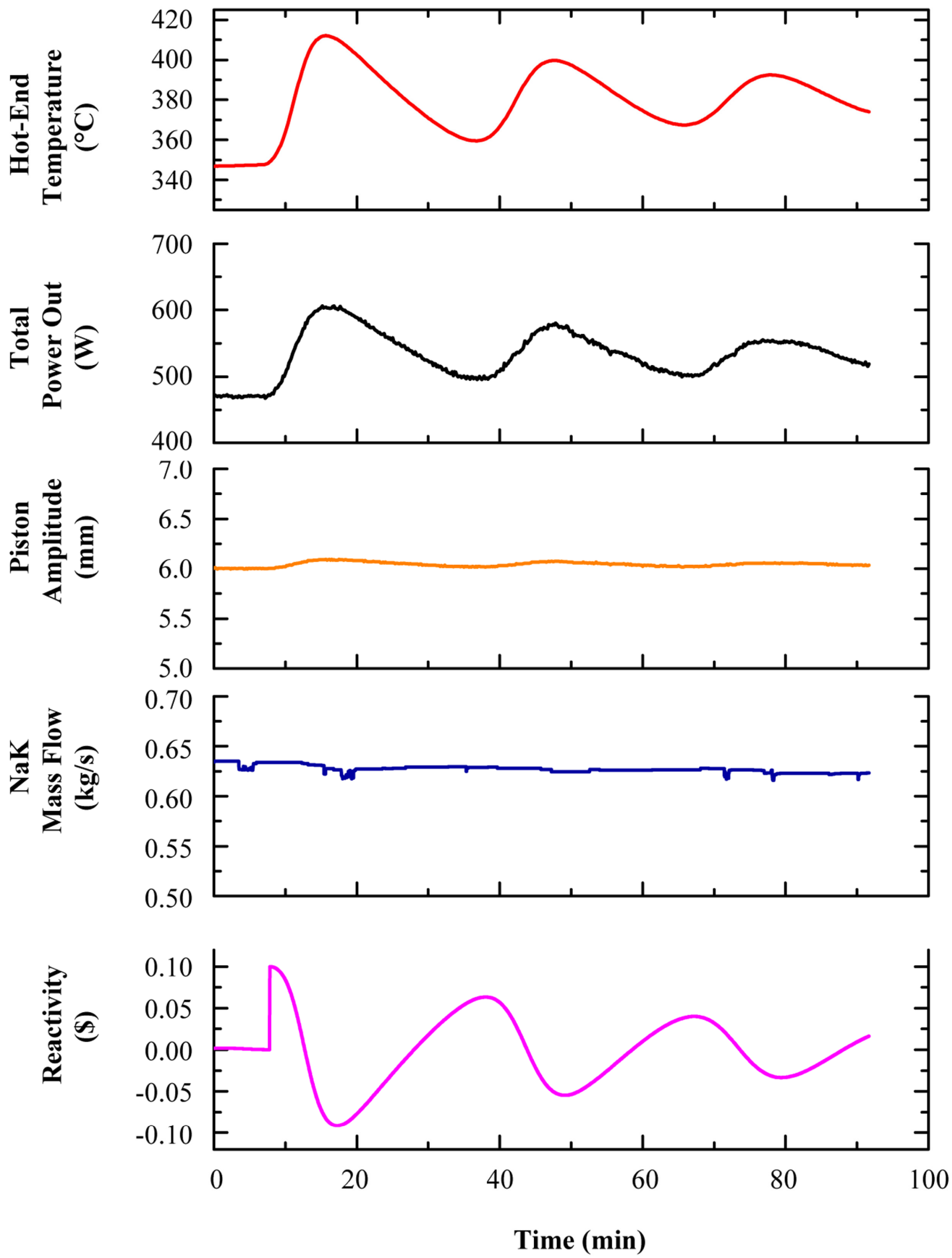


Figure 30.—System response to positive reactivity insertion.

Appendix A.—Test Plan

TP–P2A–001A
Revision 0

Test Plan for Performance Mapping Dual-Opposed P2A Stirling Convertors Using a Pumped NaK Loop for Thermal Input

April 8, 2009

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Revision History

Revision	Description	Date
0	Original issue	April 2009

Configuration Management

The latest version of this document is maintained on the RPT eRoom as a controlled document. Prior to printing, it is the user's responsibility to verify this document is the current revision. Printed copies of this document will be considered uncontrolled. The test plans are located at https://collaboration.grc.nasa.gov/eRoom/NASAm1f1/RPTThermalEnergyConversionBranch/0_92eb0

Background

In 2007, two P2A (formerly known as EG–1000) 1-kW free-piston Stirling power convertors were procured from Sunpower Inc., of Athens, OH. The P2As are designed to produce 1.1 kWe at their design operating conditions of 550 °C hot-end temperature, 50 °C cold-end temperature, and a mean working space pressure of 3.0 MPa. The P2As are typically configured with a gas burner for thermal energy input; however, the P2As delivered to Glenn for performance map testing replaced the gas burners with electric cartridge heaters to simplify testing. Testing performed at Glenn with electric heating established baseline convertor performance. After baseline testing was completed, the convertors were retrofitted with new heater heads to allow the P2A convertors to interface with a pumped NaK loop at MSFC. This test will demonstrate Stirling convertor electrical power generation using a pumped liquid metal heat source.

Purpose of the Test

There are four major goals of testing at MSFC: (1) To gain the experience of integrating a Stirling power convertor with a pumped NaK loop. Lessons learned in this process will be useful in making design decisions for future systems including the Technology Demonstration Unit (TDU) and future flight or flight-like systems. (2) To evaluate the performance of the custom-made NaK heater head. The most significant difference between baseline testing and NaK testing is the method of thermal input, so differences in performance from the baseline could be used to evaluate the design of the heater head and heat exchangers. (3) During baseline testing, hot-end temperature was affected by a single parameter, the input electrical power from the heater. During testing at MSFC, the P2A hot-end temperature is affected both by NaK temperature and NaK flow rate. Running at the same hot-end temperature, using different values of flow rate and NaK inlet temperature could be used to improve Stirling cycle analysis and system optimization. (4) To evaluate the system response transient scenarios such as loss of heater power, stall and restart, and loss of NaK flow.

Safety Precautions and Notes

- If any step does not proceed as planned, bring the system to a safe state, cease action, and notify cognizant engineer.
- For the first few days of testing, a minimum of two people shall participate in operating the P2A Stirling convertors for executing this test plan.
- The Stirling convertor cooling water must be flowing at ten lpm per convertor prior to flowing hot NaK.
- The temperature drop (NaK inlet–NaK outlet temperature) across the Stirling NaK heat exchanger (heater head) must be kept below 40 °C. The circumferential temperature gradient for each Stirling heater head (as measured by thermocouples TCExHOT5 through TCExHOT8) must be kept below 30 °C.

- The ac bus current must be maintained between 2 and 7 Arms.
- The alternator power factors must be monitored to ensure that when the voltage leads the current, the power factor remains above 0.94, and when the voltage lags the current, the power factor remains above 0.83.
- The Stirling convertor heater heads should not be allowed to exceed 570 °C at any time.
- Transient effects should be limited by taking small incremental steps in piston amplitude (0.5 mm).
- Limit Stirling convertor output to 2.8 kWe (total for both convertors).

Applicable Documents

P2A–001A	Instrumentation Rack Checkout Procedure for the P2A
P2A–002A	Data System Shutdown Check-Out Procedure
P2A–003A	Evacuation, Backfill, & Top-Off Procedure for the P2A Convertor
P2A–004A	Centering Procedure for the P2A Convertor
P2A–005A	Startup Procedure for Operating P2A Stirling Convertor with Pumped NaK Loop
P2A–007A	Manual Shutdown Procedure for the P2A with Pumped NaK Loop

Fission Surface Power Primary Test Circuit (FSP–PTC)

MSFC facility operators are responsible for operating the FSP–PTC facility during this test. Glenn personnel are responsible for operating the Stirling engines. Glenn test operators will notify the MSFC facilities operators when adjustments to the NaK parameters are needed. The parameters to be controlled are NaK inlet (to the Stirling convertors) temperature and NaK flow rate.

Test Plan

1. Verify that P2A–001A (Instrumentation Rack Checkout Procedure for the P2A), P2A–002A (Data System Shutdown Check-Out Procedure), and P2A–003A (Evacuation, Backfill, & Top-Off Procedure for the P2A Convertor), have been performed and that the piston limits have been set for the Failsafe Protection Circuit.
2. Verify that the LabVIEW system is properly configured for the test. See Table III for the settings.
3. Synchronize TIME between Glenn data acquisition system computer and the MSFC facility data acquisition system computer.
4. Turn on the cooling fans for the engine loads and the data system rack.
5. Charge the P2As with helium to the design charge pressure of 363 psig at 25 °C according to procedure P2A–003A.
6. Bring the P2As to the startup operating point according to procedure P2A–005A. The initial hot-end temperature set point should be 400 °C while the cold-end temperature and NaK flow rate should be the nominal value selected for the current test. Hot-end temperature is based on the average of the eight thermocouples placed on the heater head on either side of the acceptor. The cold-end temperature is defined as the average of the coolant inlet and coolant outlet temperatures.
7. Once the startup set point has been reached, notify the MSFC facility operator to gradually increase NaK temperature to achieve the desired Stirling convertor hot-end temperature. Do not let any individual heater head temperature reading exceed 570 °C. To minimize the NaK temperature difference across the heater head, it is desirable to run at minimum piston amplitude. The minimum safe P2A piston amplitude is 6 mm. Also, the minimum ac bus power output is 2A. Both of these constraints must be monitored during heatup.
8. Once the desired steady-state temperature has been reached, gradually increase the piston amplitude to the desired value. Increases in piston amplitude will result in larger temperature gradients across

the NaK head. The largest allowable gradient (NaK inlet–NaK outlet temperature) is 40 °C. If this limit is exceeded, the piston amplitude must be reduced. If the piston amplitude is reduced to 6 mm and the temperature gradient is still above 40 °C, the following steps must be performed:

   a. Shut down engines by setting the ac bus output voltages to 0.
   b. Notify MSFC NaK facility operator to turn off NaK heater and turn on NaK cooler while maintaining NaK flow.

9. Obtain steady-state operation at the chosen set point (see Phase I—Steady-State Operating Conditions and Phase II—Transient Operating Conditions sections below) with the heater head average temperatures and average coolant temperatures within ±3 °C of the set point and changing at a rate of less than 2 °C per 10 min, and the alternator gas temperatures changing at a rate of less than 1 °C per 10 min.
10. Return to the reference set point of 400 °C hot end at the end of each test day (set points within ±3 °C, and heater head average temperatures, average coolant temperatures, and alternator gas temperatures changing at a rate of less than 2 °C over a 10 min period) and record the data so that it can be compared with the initial data point recorded at the beginning of the test day. Any discrepancies in convertor performance should be evaluated prior to the continuation of this test.
11. Shut down convertors per the P2A–007A procedure.

Phase I—Steady-State Operating Conditions

Table I lists the convertor operating conditions (i.e., test points) that were either achieved or attempted at Glenn. Not all of these operating conditions could be reached due to either voltage limitations of the electric heater head (will not be an issue for the test at MSFC), or the ac bus power factor limitations. In Table I, an asterisk (*) denotes the subset of test points proposed as the minimum set for this test. Additional test points may be obtained if time permits.

Table II lists the operating conditions used to examine the sensitivity of the Stirling engines to changes in NaK mass flow. The off-nominal mass flow rates appearing in Table II may result in an unacceptable circumferential temperature gradient (TCExHOT5 through TCExHOT8 must be kept below 30 °C) across each NaK head. As a result, these values are subject to change or removal from the test matrix entirely. In Table II, an asterisk (*) denotes the subset of test points proposed as the minimum set for this test. Additional test points may be obtained if time permits.

TABLE I.—PERFORMANCE MAP

Test Pt.	Thot (°C)	Tcold (°C)	Tratio	Pist Ampl. (mm)	NaK Mass Flow (kg/s-conv)
	400	50	2.55	10	.55
1*	550	50	2.55	10	.55
2*	550	50	2.55	11	.55
3*	550	50	2.55	9	.55
4*	550	50	2.55	8	.55
5*	550	50	2.55	7	.55
6*	550	50	2.55	6	.55
	400	50	2.55	10	.55
	400	30	2.72	10	.55
7	550	30	2.72	10	.55
8*	550	30	2.72	9	.55
9	550	30	2.72	11	.55
	400	30	2.72	10	.55
	400	70	2.40	10	.55

TABLE I.—Concluded.

Test Pt.	Thot (°C)	Tcold (°C)	Tratio	Pist Ampl. (mm)	NaK Mass Flow (kg/s-conv)
10*	550	70	2.40	10	.55
11	550	70	2.40	9	.55
12	550	70	2.40	11	.55
	400	70	2.40	10	.55
	400	50	2.39	10	.55
13	500	50	2.39	10	.55
14	500	50	2.39	9	.55
15	500	50	2.39	11	.55
	400	50	2.39	10	.55
	400	30	2.55	10	.55
16	500	30	2.55	10	.55
17	500	30	2.55	9	.55
18	500	30	2.55	11	.55
	400	30	2.55	10	.55
	400	70	2.25	10	.55
19	500	70	2.25	10	.55
20	500	70	2.25	9	.55
21	500	70	2.25	11	.55
	400	70	2.25	10	.55
	400	50	2.24	10	.55
22	450	50	2.24	10	.55
23	450	50	2.24	9	.55
24	450	50	2.24	11	.55
	400	50	2.24	10	.55
	400	30	2.39	10	.55
25	450	30	2.39	10	.55
26	450	30	2.39	9	.55
27	450	30	2.39	11	.55
	400	30	2.39	10	.55
	400	70	2.11	10	.55
28	450	70	2.11	10	.55
29	450	70	2.11	9	.55
30	450	70	2.11	11	.55
	400	70	2.11	10	.55
31	400	50	2.08	10	.55
32	400	50	2.08	9	.55
33	400	50	2.08	11	.55
	400	50	2.08	10	.55
34	400	30	2.22	10	.55
35*	400	30	2.22	9	.55
36	400	30	2.22	11	.55
	400	30	2.22	10	.55
37*	400	70	1.96	10	.55
38	400	70	1.96	9	.55
39	400	70	1.96	11	.55
	400	70	1.96	10	.55

TABLE II.—MASS FLOW SENSITIVITY

Test Pt.	Thot (°C)	Tcold (°C)	Pist Ampl. (mm)	NaK Mass Flow (kg/s-conv)
40*	550	50	10	.41
41	550	50	9	.41
42	550	50	8	.41
43*	550	50	10	.27
44	550	50	9	.27
45	550	50	8	.27
	400	50	MIN	.55

Phase II—Transient Operating Conditions

1. Simulate loss of the ALIP pump/intermediate NaK loop at full NaK flow:
   - 1.1. Bring convertors to steady state at nominal operating condition (Thot = 550 °C, Tcold = 50 °C, and Piston Amplitude = 10 mm) with NaK flow rate of 0.55 kg/s.
   - 1.2. Notify the MSFC facility operator to turn off the NaK pump.
   - 1.3. Allow the system to run down with thermal energy stored in NaK and heater head structure until the power output of the Stirling convertors reaches 0 W.
   - 1.4. Set the voltage on the ac bus to 0 V, then press “enter” on both power supplies SIMULTANEOUSLY to stop convertors**.**
   - 1.5. Monitor minimum temperature limits on NaK loop to avoid freeze. NaK-78 freezes at about −11 °C. DO NOT RESTART THE NaK PUMPS UNTIL THE NaK TEMPERATURES THROUGHOUT THE LOOP HAVE STABILIZED.

2. Simulate loss of reactor power/primary NaK loop at full NaK flow:
   - 2.1. Bring convertors to steady state at nominal operating conditions (Thot = 550 °C, Tcold = 50 °C, and Piston Amplitude = 10 mm) with NaK flow rate of 0.55 kg/s.
   - 2.2. Notify the MSFC facility operator to turn off the NaK heater, but continue NaK flow.
   - 2.3. Allow the convertors to run down until their output power either stabilizes or reaches 0 W.
   - 2.4. Set the voltage on the ac bus to 0 V, then press “enter” on both power supplies SIMULTANEOUSLY to stop convertors**.**

3. Minimum temperature system startup at full NaK flow:
   - 3.1. Motor convertors (Thot = 250 °C, Tcold = 50 °C, Piston Amplitude = 6 mm) with a NaK flow rate of 0.55 kg/s (per convertor) for 30 min.
   - 3.2. Notify the MSFC facility operator to ramp up the NaK temperature (at a rate not to exceed 10 °C per min) to 550 °C.
   - 3.3. As the Stirling convertor hot-end temperatures rise, increase the piston amplitude (at a rate not to exceed 1 mm per 10 min) to 10 mm.

4. Medium temperature system startup at full NaK flow:
   - 4.1. Motor convertors (Thot = 375 °C, Tcold = 50 °C, and Piston Amplitude = 6 mm) with a NaK flow rate of 0.55 kg/s (per convertor) for 30 min.
   - 4.2. Notify the MSFC facility operator to ramp up the NaK temperature (at a rate not to exceed 10 °C per min) to 550 °C.
   - 4.3. As the Stirling convertor hot-end temperatures rise, increase the piston amplitude (at a rate not to exceed 1 mm per 5 min) to 10 mm.

5. Full temperature system startup at full NaK flow:
    5.1. Motor convertors (Thot = 500 °C, Tcold = 50 °C, and Piston Amplitude = 6 mm) with a NaK flow rate of 0.55 kg/s (per convertor) for 30 min.
    5.2. Notify the MSFC facility operator to ramp up the NaK temperature (at a rate not to exceed 10 °C per min) to 550 °C.
    5.3. Increase the piston amplitude (at a rate not to exceed 1 mm per min) to 10 mm.

6. Minimum temperature system startup at 75 percent NaK flow:
    6.1. Motor convertors (Thot = 250 °C, Tcold = 50 °C, and Piston Amplitude = 6 mm) with a NaK flow rate of 0.41 kg/s (per convertor) for 30 min.
    6.2. Notify the MSFC facility operator to ramp up the NaK temperature (at a rate not to exceed 10 °C per min) to 550 °C.
    6.3. As the Stirling convertor hot-end temperatures rise, increase the piston amplitude (at a rate not to exceed 1 mm per 5 min) to 10 mm.

7. Medium temperature system startup at 75 percent NaK flow:
    7.1. Motor convertors (Thot = 375 °C, Tcold = 50 °C, and Piston Amplitude = 6 mm) with a NaK flow rate of 0.41 kg/s (per convertor) for 30 min.
    7.2. Notify the MSFC facility operator to ramp up the NaK temperature (at a rate not to exceed 10 °C per min) to 550 °C.
    7.3. As the Stirling convertor hot-end temperatures rise, increase the piston amplitude (at a rate not to exceed 1 mm per 5 min) to 10 mm.

8. Full temperature system startup at 75 percent NaK flow:
    8.1. Motor convertors (Thot = 500 °C, Tcold = 50 °C, and Piston Amplitude = 6 mm) with a NaK flow rate of 0.41 kg/s (per convertor) for 30 min.
    8.2. Notify the MSFC facility operator to ramp up the NaK temperature (at a rate not to exceed 10 °C per min) to 550 °C.
    8.3. Increase the piston amplitude (at a rate not to exceed 1 mm per min) to 10 mm.

9. Simulates shutdown/restart of Stirling convertors:
    9.1. Bring convertors to steady-state operation at moderate power level (Thot = 550 °C, Tcold = 50 °C, and Piston Amplitude = 8 mm).
    9.2. Stall the convertors while NaK flow continues.
    9.3. Restart convertors as follows:
        9.3.1. Set the voltage on the ac bus to 50 V, then press enter on both power supplies SIMULTANEOUSLY.
        9.3.2. Set the voltage on the ac bus to 150 V, then press enter on both power supplies SIMULTANEOUSLY. Verify ~6 mm of piston amplitude.
        9.3.3. Gradually increase the ac bus voltage until the piston amplitude is 8 mm.

TABLE III.—LABVIEW WARNING AND SHUTDOWN SETTINGS

Parameter	High alarm	High warning	Low warning	Low alarm	Action
TCE1HOT1-8	570 °C	560 °C	10 °C	0 °C	Alarm and Auto Shutdown
TCE2HOT1-8	570 °C	560 °C	10 °C	0 °C	Alarm and Auto Shutdown
TCE1H2OIN	75 °C	73 °C	22 °C	20 °C	Alarm and Auto Shutdown
TCE2H2OIN	75 °C	73 °C	22 °C	20 °C	Alarm and Auto Shutdown
TCE1LAGAS	100	95	-------	-------	Alarm and Auto Shutdown
TCE2LAGAS	100	95	-------	-------	Alarm and Auto Shutdown
XPE1POS	12 mm	11.5 mm	-------	-------	Alarm and Auto Shutdown
XPE2POS	12 mm	11.5 mm	-------	-------	Alarm and Auto Shutdown
XDE1POS	12 mm	11.5 mm	-------	-------	Alarm and Auto Shutdown
XDE2POS	12 mm	11.5 mm	-------	-------	Alarm and Auto Shutdown
PRE1CHRG	486 psig	478 psig	348 psig	333 psig	Alarm and Auto Shutdown
PRE2CHRG	486 psig	478 psig	348 psig	333 psig	Alarm and Auto Shutdown
FME1COOL	16 lpm	15 lpm	8 lpm	7 lpm	Alarm and Auto Shutdown
FME2COOL	16 lpm	15 lpm	8 lpm	7 lpm	Alarm and Auto Shutdown

Appendix B.—Performance Map Data

STEADY STATE (PHASE I—STIRLING CONVERTOR DATA)

Test Pt.	TCE1 HOT1 (°C)	TCE1 HOT2 (°C)	TCE1 HOT3 (°C)	TCE1 HOT4 (°C)	TCE1 HOT5 (°C)	TCE1 HOT6 (°C)	TCE1 HOT7 (°C)	TCE1 HOT8 (°C)	TCE1 PRVSL1 (°C)	TCE1 PRVSL2 (°C)	TCE1 PRVSL3 (°C)	TCE1 H2OIN (°C)	TCE1 H2OUT (°C)	TCE1 LAGAS (°C)	TCE1 PVH2OUT (°C)
1*	555.2	553.7	557.0	557.2	543.2	546.4	544.4	544.2	68.2	68.7	67.0	50.7	53.4	71.5	50.8
2*	555.6	554.5	557.7	557.7	541.6	545.6	543.4	543.0	71.1	72.2	69.9	50.6	54.0	75.1	50.8
3*	554.7	553.0	556.1	556.3	543.9	546.7	545.0	544.8	65.4	66.2	64.4	50.5	52.7	68.7	50.6
4*	554.0	552.0	555.6	555.4	544.9	547.5	545.9	545.9	62.4	63.1	62.0	50.6	52.7	65.5	50.6
5*	553.8	551.8	555.4	555.2	546.2	548.3	546.9	546.8	60.0	60.7	59.6	50.6	52.4	62.7	50.8
7*	556.0	554.8	557.9	558.1	543.6	547.2	545.4	545.1	48.5	49.4	47.5	30.5	32.8	51.9	30.9
8*	555.3	553.6	557.0	556.9	544.1	547.2	545.7	545.6	45.4	46.5	44.8	30.3	32.3	48.4	30.6
10*	555.2	553.9	556.8	557.1	543.1	546.4	544.6	544.4	86.7	87.4	86.2	70.0	72.9	90.2	70.2
11*	554.8	553.4	556.4	556.6	544.4	547.2	545.5	545.3	83.3	84.3	82.7	69.5	71.9	86.4	69.7
12*	556.3	554.7	558.0	557.8	542.3	546.1	543.9	543.6	89.6	90.4	88.6	70.3	73.6	93.6	70.4
13	504.6	503.4	506.1	506.2	493.1	496.0	494.5	494.2	66.8	67.2	65.7	50.6	53.3	70.1	50.8
14	504.7	503.0	505.9	506.2	494.8	497.3	495.7	495.6	63.6	64.2	63.1	50.4	52.7	66.8	50.5
15	504.5	503.4	506.3	506.0	491.4	494.8	493.1	492.7	69.5	70.3	68.4	50.7	53.7	73.3	51.0
17	504.9	503.2	506.2	506.5	495.0	497.4	496.0	495.8	44.8	45.2	43.8	30.3	32.5	47.9	30.2
17B	504.7	502.8	505.8	506.1	496.1	498.3	496.9	496.7	42.5	43.1	42.0	30.2	32.0	45.5	30.2
19*	504.6	503.3	506.3	506.5	493.3	496.6	494.6	494.5	85.6	86.4	85.0	70.5	73.5	88.8	71.2
20*	504.4	503.2	506.1	506.1	494.8	497.2	495.5	495.6	84.6	85.5	84.2	70.7	73.3	87.7	71.3
21*	504.5	503.4	506.4	506.4	491.7	495.0	493.3	493.0	89.2	89.7	87.9	70.9	74.3	92.5	71.8
22	453.6	452.4	455.2	454.9	442.8	445.7	444.2	443.9	66.0	66.4	64.7	50.8	53.6	69.2	51.1
23	453.8	452.3	455.1	454.8	444.6	446.8	445.3	445.1	63.6	63.9	62.9	50.7	52.9	66.6	51.0
24	454.5	453.5	456.2	456.1	442.5	445.6	444.2	443.7	68.5	68.9	67.0	50.8	54.1	72.0	51.3
26	454.0	452.4	455.2	455.0	444.4	446.7	445.4	445.4	43.6	44.1	43.0	30.2	32.4	46.7	30.2
26B	453.8	452.2	454.9	454.9	445.5	447.6	446.3	446.5	41.6	42.2	40.8	30.3	32.1	44.2	30.3
28	454.8	453.6	455.9	455.8	444.1	446.7	445.4	444.9	84.9	85.1	83.9	70.6	73.4	88.3	71.0
29	454.7	453.4	455.8	455.7	445.4	447.9	446.5	446.4	81.9	82.3	81.5	70.3	72.7	85.0	70.8
30	454.7	453.8	456.0	455.8	442.4	445.5	444.0	443.5	87.3	87.6	86.2	70.4	73.9	90.9	71.0
31	405.0	404.0	406.0	405.9	394.4	397.2	395.8	395.5	67.4	68.3	66.1	50.4	52.9	70.6	50.9
32	405.0	404.0	406.0	405.7	395.7	398.0	396.9	396.8	65.0	65.5	64.0	50.4	52.2	67.9	50.7
32B	404.8	403.6	405.6	405.7	397.0	398.8	397.6	397.7	62.4	63.2	61.6	50.3	52.0	64.9	50.8

STEADY STATE (PHASE I—STIRLING CONVERTOR DATA).—Concluded.

Test Pt.	TCE1 HOT1 (°C)	TCE1 HOT2 (°C)	TCE1 HOT3 (°C)	TCE1 HOT4 (°C)	TCE1 HOT5 (°C)	TCE1 HOT6 (°C)	TCE1 HOT7 (°C)	TCE1 HOT8 (°C)	TCE1 PRVSL1 (°C)	TCE1 PRVSL2 (°C)	TCE1 PRVSL3 (°C)	TCE1 H2OIN (°C)	TCE1 H2OUT (°C)	TCE1 LAGAS (°C)	TCE1 PVH2OUT (°C)
35	404.5	403.5	405.5	405.3	395.2	397.5	396.3	396.3	45.8	46.7	44.7	29.8	31.3	48.8	30.0
35B	404.4	402.9	405.1	405.0	396.3	398.2	396.9	397.1	43.5	44.6	42.9	29.9	31.2	46.3	30.0
37	404.6	403.8	405.9	405.8	394.5	397.0	395.5	395.2	85.2	85.7	84.0	70.6	73.4	88.4	71.3
38	404.6	403.6	405.6	405.8	395.9	398.0	396.7	396.6	83.3	84.1	82.8	70.7	73.3	86.4	71.2
39	404.7	404.1	406.2	406.1	392.9	396.0	394.4	394.0	87.9	88.4	86.5	70.5	74.1	91.2	71.4

STEADY STATE (PHASE I—STIRLING CONVERTOR DATA)

Test Pt.	TCE2 HOT1 (°C)	TCE2 HOT2 (°C)	TCE2 HOT3 (°C)	TCE2 HOT4 (°C)	TCE2 HOT5 (°C)	TCE2 HOT6 (°C)	TCE2 HOT7 (°C)	TCE2 HOT8 (°C)	TCE2 PRVSL1 (°C)	TCE2 PRVSL2 (°C)	TCE2 PRVSL3 (°C)	TCE2 H2OIN (°C)	TCE2 H2OUT (°C)	TCE2 LAGAS (°C)	TCE2 PVH2OUT (°C)
1*	556.9	556.2	556.8	556.3	543.4	540.9	547.1	542.5	66.6	67.3	66.7	50.8	53.2	69.9	51.4
2*	557.4	556.6	557.1	556.7	541.4	539.6	546.1	541.4	69.3	70.4	69.6	50.7	53.8	72.9	51.5
3*	556.1	555.2	555.8	555.5	544.0	541.1	547.3	543.0	64.3	65.1	64.3	50.7	52.9	67.3	51.3
4*	555.3	554.6	555.6	555.0	545.3	542.1	547.9	543.6	61.8	62.2	61.7	50.7	52.2	64.2	51.2
5*	555.0	554.3	555.5	554.8	546.8	543.1	548.7	544.5	59.5	59.9	59.5	50.6	51.8	61.6	51.1
7*	557.9	557.1	557.7	557.1	544.2	542.1	548.1	543.4	46.3	47.3	46.5	30.3	32.9	49.5	30.9
8*	556.6	555.8	556.7	556.2	545.2	542.6	548.5	543.9	43.6	44.6	43.9	30.1	32.3	46.6	30.6
10*	556.8	556.0	556.6	556.1	543.8	541.2	547.0	543.1	85.3	86.1	85.5	69.9	72.7	88.4	70.8
11*	556.4	555.7	556.2	555.7	545.0	542.0	547.8	543.9	82.5	82.8	82.5	69.2	71.4	84.9	69.9
12*	557.4	556.9	557.4	557.2	542.6	540.4	546.5	542.4	88.0	89.0	88.2	69.8	73.2	91.3	70.9
13	506.4	505.5	506.1	505.6	493.1	490.8	496.6	492.7	65.3	66.1	65.7	50.6	53.0	68.6	51.2
14	506.3	505.3	506.2	505.7	494.9	492.1	497.8	494.0	62.6	63.3	62.9	50.7	52.7	65.6	51.2
15	506.3	505.4	506.0	505.7	491.3	489.2	495.2	491.3	67.5	68.6	67.8	50.5	53.8	71.2	51.1
17	506.6	505.5	506.5	505.9	494.7	492.0	497.9	493.8	43.4	44.5	43.8	30.6	32.6	46.6	30.5
17B	506.2	505.0	506.3	505.8	496.5	493.2	498.8	495.0	41.6	42.1	41.6	30.6	32.0	44.1	30.5
19*	506.3	505.4	505.9	505.6	494.1	492.2	497.2	493.6	83.9	85.0	84.2	70.4	73.1	87.1	71.4
20*	506.0	505.2	505.9	505.4	495.7	493.3	498.0	494.6	83.2	84.0	83.3	70.6	72.8	86.1	71.6
21*	505.9	505.3	505.9	505.6	492.1	490.4	495.6	491.9	87.1	88.1	87.5	70.7	74.0	90.7	72.0
22	455.3	454.3	454.8	454.5	442.8	440.6	445.4	442.5	64.6	65.5	64.9	50.9	53.4	67.8	51.5
23	455.2	454.2	454.8	454.5	444.3	442.1	446.7	443.7	62.4	63.2	62.7	50.8	52.9	65.3	51.3
24	456.3	455.3	456.0	455.5	442.4	440.4	445.4	442.4	66.2	67.2	66.7	51.0	53.8	70.1	51.6
26	455.2	454.2	455.1	454.9	444.7	442.1	447.3	443.7	42.2	43.1	42.5	30.5	32.4	45.2	30.5
26B	455.0	453.9	455.0	454.7	445.9	443.1	448.1	444.6	40.5	41.2	40.8	30.3	31.8	43.0	30.6
28	456.0	455.0	455.9	455.8	444.3	441.9	446.9	443.6	83.5	84.0	83.8	70.3	72.9	86.6	71.0
29	456.0	454.9	455.9	455.7	445.8	443.6	448.1	445.2	80.8	81.5	81.0	70.2	72.3	83.6	70.8
30	456.1	455.1	455.9	455.8	442.7	440.7	445.8	442.6	85.3	86.3	85.7	70.2	73.5	89.0	71.0
31	406.0	405.0	405.7	405.6	394.5	392.6	396.9	394.2	65.7	66.3	65.8	50.0	52.7	69.0	51.1
32	406.0	405.0	405.6	405.4	395.8	393.7	397.9	395.1	63.7	64.5	63.9	50.0	52.4	66.6	50.8
32B	405.9	404.8	405.6	405.3	397.1	394.8	398.7	396.1	61.6	62.3	61.7	50.1	51.9	64.0	50.8

STEADY STATE (PHASE I—STIRLING CONVERTOR DATA).—Concluded.

Test Pt.	TCE2 HOT1 (°C)	TCE2 HOT2 (°C)	TCE2 HOT3 (°C)	TCE2H OT4 (°C)	TCE2 HOT5 (°C)	TCE2 HOT6 (°C)	TCE2 HOT7 (°C)	TCE2 HOT8 (°C)	TCE2 PRVSL1 (°C)	TCE2 PRVSL2 (°C)	TCE2 PRVSL3 (°C)	TCE2 H2OIN (°C)	TCE2 H2OUT (°C)	TCE2 LAGAS (°C)	TCE2 PVH2OUT (°C)
35	405.6	404.5	405.1	404.9	395.3	393.0	397.4	394.5	44.5	45.3	44.6	29.8	31.8	47.4	30.3
35B	405.4	404.2	404.9	404.6	396.4	393.9	397.9	395.2	43.0	43.1	42.6	30.0	31.7	45.1	30.5
37	405.9	404.9	405.6	405.3	394.7	392.7	396.8	394.2	83.8	84.7	84.0	70.2	72.7	87.1	71.3
38	405.9	404.9	405.7	405.4	396.2	394.3	397.9	395.5	82.5	83.0	82.5	70.3	72.7	85.3	71.3
39	406.1	405.2	405.9	405.6	393.0	391.4	395.4	392.9	86.3	87.1	86.6	70.4	73.6	89.8	71.4

STEADY STATE (PHASE I—STIRLING CONVERTOR DATA)

Test Pt.	TCPV H2OIN (°C)	TC CABLE TRAY (°C)	XPE1 POS (mm)	XDE1 POS (mm)	LAE1 VOLT (V)	LAE1 CUR (A)	LAE1 POW (W)	XPE2 POS (mm)	XDE2 POS (mm)	LAE2 VOLT (V)	LAE2 CUR (A)	LAE2 POW (W)	TCPV H2OIN (°C)	OVR STRK (V)	FME1 COOL (l/min)	FME2 COOL (l/min)
1*	50.9	68.1	10.1	10.0	240.7	4.5	1026.8	9.9	9.7	241.2	4.3	991.2	50.9	0.0	10.7	10.8
2*	50.9	74.2	11.2	10.8	263.9	4.8	1193.2	10.9	10.6	264.4	4.6	1172.6	50.9	0.0	10.7	10.8
3*	50.8	61.4	9.1	9.2	217.7	4.1	859.9	8.9	9.0	218.1	4.1	843.4	50.8	0.0	10.7	10.8
4*	50.8	51.8	8.1	8.3	194.5	3.7	694.1	7.9	8.2	195.0	3.7	680.5	50.8	0.0	10.7	10.8
5*	50.7	42.1	7.1	7.4	171.3	3.4	551.4	6.9	7.4	171.7	3.4	535.0	50.7	0.0	10.7	10.8
7*	30.4	50.5	10.2	9.9	246.9	4.8	1066.8	9.8	9.5	247.3	4.5	1020.7	30.4	0.0	10.4	10.4
8*	30.5	43.2	9.1	9.1	223.7	4.4	907.7	8.9	8.7	224.2	4.1	848.5	30.5	0.0	10.4	10.4
10*	70.2	84.8	10.1	10.1	236.2	4.2	966.7	9.9	9.6	236.7	3.9	910.8	70.2	0.0	10.6	10.8
11*	69.7	81.5	9.1	9.2	213.6	3.9	814.7	8.9	9.0	214.1	3.8	780.7	69.7	0.0	10.6	10.8
12*	70.4	87.6	11.1	10.8	258.3	4.4	1106.1	10.9	10.4	258.8	4.2	1063.3	70.4	0.0	10.7	10.8
13	50.8	57.7	10.1	9.9	243.7	4.1	905.8	9.9	9.7	244.2	3.9	904.4	50.8	0.0	10.7	10.8
14	50.7	54.2	9.1	9.1	221.6	3.7	774.2	8.9	9.0	222.1	3.7	769.7	50.7	0.0	10.7	10.8
15	51.1	60.6	11.2	10.6	265.8	4.5	1025.1	10.8	10.4	266.3	4.1	1036.8	51.1	0.0	10.7	10.8
17	30.7	46.1	9.1	8.9	225.6	3.9	804.4	8.9	8.9	226.1	3.9	822.5	30.7	0.0	10.7	10.8
17B	30.7	41.1	8.1	8.2	200.6	3.6	673.4	7.9	8.0	201.0	3.6	656.7	30.7	0.0	10.7	10.8
19*	70.6	68.4	10.1	9.9	239.7	3.7	840.0	9.9	9.5	240.2	3.5	801.2	70.6	0.0	10.4	10.4
20*	70.8	71.4	9.1	9.2	216.1	3.4	715.5	8.9	8.7	216.6	3.2	674.2	70.8	0.0	10.4	10.4
21*	71.0	74.9	11.1	10.7	262.3	3.8	948.9	10.9	10.3	262.9	3.7	927.3	71.0	0.0	10.4	10.4
22	50.9	53.7	10.1	9.8	247.7	3.5	780.3	9.9	9.7	248.1	3.5	800.2	50.9	0.0	10.7	10.8
23	50.8	51.7	9.1	9.0	223.6	3.2	674.2	8.9	9.0	224.1	3.3	687.0	50.8	0.0	10.7	10.8
24	51.0	55.6	11.1	10.4	266.9	4.0	856.0	10.7	10.3	267.3	3.6	882.8	51.0	0.0	10.7	10.8
26	30.5	36.8	9.1	8.9	228.5	3.5	724.1	8.9	8.7	229.0	3.5	725.5	30.5	0.0	10.7	10.8
26B	30.3	33.1	8.1	8.2	204.0	3.2	611.1	8.0	8.0	204.4	3.3	603.7	30.3	0.0	10.7	10.8
28	70.6	60.9	10.1	9.8	243.8	3.1	713.6	9.9	9.6	244.1	3.1	716.3	70.6	0.0	10.7	10.8
29	70.3	59.5	9.1	9.0	219.6	2.9	614.4	8.9	8.7	220.0	2.8	594.8	70.3	0.0	10.7	10.8
30	70.4	62.1	11.1	10.5	267.9	3.2	802.1	10.9	10.2	268.3	3.1	800.8	70.4	0.0	10.7	10.8
31	50.5	73.3	10.1	9.7	247.6	3.3	640.4	9.8	9.6	248.0	3.0	684.2	50.5	0.0	10.6	10.7
32	50.3	74.6	9.1	9.0	225.6	2.9	573.9	8.9	9.0	226.0	2.9	602.1	50.3	0.0	10.6	10.7
32B	50.2	75.8	8.1	8.2	201.0	2.6	486.2	8.0	8.2	201.4	2.7	502.7	50.2	0.0	10.6	10.7

STEADY STATE (PHASE I—STIRLING CONVERTOR DATA).—Concluded.

Test Pt.	TCPV H2OIN (°C)	TC CABLE TRAY (°C)	XPE1 POS (mm)	XDE1 POS (mm)	LAE1 VOLT (V)	LAE1 CUR (A)	LAE1 POW (W)	XPE2 POS (mm)	XDE2 POS (mm)	LAE2 VOLT (V)	LAE2 CUR (A)	LAE2 POW (W)	TCPV H2OIN (°C)	OVR STRK (V)	FME1 COOL (l/min)	FME2 COOL (l/min)
35	30.3	77.6	9.0	8.8	228.1	3.2	604.2	8.9	8.8	228.5	3.1	648.9	30.3	0.0	10.6	10.6
35B	30.4	78.0	8.1	8.0	204.6	2.8	518.7	7.9	8.1	205.0	3.0	545.9	30.4	0.0	10.6	10.7
37	70.4	58.0	10.1	9.8	246.5	2.6	587.3	9.9	9.6	246.9	2.5	586.6	70.4	0.0	10.6	10.6
38	70.5	62.6	9.1	9.0	221.5	2.4	514.0	8.9	8.8	221.9	2.4	507.2	70.5	0.0	10.6	10.6
39	70.5	67.8	11.1	10.5	270.7	2.6	642.3	10.9	10.4	271.1	2.6	664.7	70.5	0.0	10.6	10.7

STEADY STATE (PHASE I—STIRLING CONVERTOR DATA)

Test Pt.	ACCELX (V)	ACCELY (V)	ACCELZ (V)	FME1PV COOL (L/min)	FME2PV COOL (L/min)	PRE1 CHRG (psig)	PRE2 CHRG (psig)	FreqE1 (Hz)	FreqE2 (Hz)	Phase XpXdE1 (deg)	Phase XpXdE2 (deg)	QWE1 OUT (W)	QWE2 OUT (W)	PlossE1I 2R (W)	PlossE2I 2R (W)	VdropE1 IR (V)	VdropE2 IR (V)
1*	0.02	0.01	0.04	3.9	3.8	440.3	440.3	50.0	50.0	51.6	47.9	1975.4	1824.1	4.2	3.9	0.9	0.9
2*	0.02	0.01	0.05	3.9	3.8	443.2	443.2	50.0	50.0	53.0	49.9	2513.1	2238.7	4.8	4.5	1.0	1.0
3*	0.01	0.01	0.02	3.9	3.8	437.7	437.7	50.0	50.0	50.1	46.8	1615.5	1619.8	3.5	3.5	0.9	0.9
4*	0.01	0.01	0.02	3.9	3.8	434.3	434.3	50.0	50.0	48.5	44.8	1485.3	1095.4	2.9	3.0	0.8	0.8
5*	0.01	0.01	0.02	3.9	3.8	431.1	431.1	50.0	50.0	47.4	43.5	1343.3	960.1	2.4	2.5	0.7	0.7
7*	0.0	0.0	0.0	2.1	2.1	416.8	416.8	50.0	50.0	52.9	49.0	1684.5	1847.5	4.7	4.3	1.0	1.0
8*	0.0	0.0	0.0	2.1	2.1	414.0	414.0	50.0	50.0	52.0	47.3	1420.6	1626.3	4.0	3.6	0.9	0.9
10*	0.02	0.01	0.03	3.8	3.7	460.0	460.0	50.0	50.0	50.0	46.1	2109.5	2068.8	3.6	3.3	0.9	0.8
11*	0.01	0.01	0.02	3.8	3.7	456.7	456.7	50.0	50.0	48.4	44.7	1716.8	1661.4	3.1	3.0	0.8	0.8
12*	0.02	0.01	0.03	3.8	3.7	462.7	462.7	50.0	50.0	51.2	47.7	2455.8	2514.4	3.9	3.7	0.9	0.9
13	0.01	0.01	0.04	3.9	3.8	433.3	433.3	50.0	50.0	52.4	49.8	2054.8	1818.8	3.5	3.2	0.8	0.8
14	0.01	0.01	0.03	3.9	3.8	430.7	430.7	50.0	50.0	51.3	48.4	1692.3	1486.6	2.9	2.9	0.8	0.8
15	0.02	0.01	0.05	3.9	3.8	435.7	435.7	50.0	50.0	53.7	51.7	2165.3	2472.3	4.1	3.6	0.9	0.9
17	0.01	0.01	0.03	3.9	3.8	411.7	411.7	50.0	50.0	52.9	49.7	1625.2	1481.0	3.1	3.3	0.8	0.8
17B	0.01	0.01	0.02	3.9	3.8	410.1	410.1	50.0	50.0	52.0	47.7	1341.7	1091.8	2.7	2.8	0.7	0.8
19*	0.0	0.0	0.0	1.9	2.0	452.8	452.8	50.0	50.0	51.1	47.6	2073.7	1928.2	2.8	2.5	0.8	0.7
20*	0.0	0.0	0.0	1.9	2.0	452.7	452.7	50.0	50.0	49.3	45.9	1768.0	1616.9	2.4	2.2	0.7	0.7
21*	0.0	0.0	0.0	1.9	2.0	456.2	456.2	50.0	50.0	52.4	49.4	2449.5	2370.4	2.9	2.8	0.8	0.8
22	0.01	0.01	0.03	3.9	3.8	430.0	430.0	50.0	50.0	53.8	50.7	2108.8	1840.8	2.5	2.5	0.7	0.7
23	0.01	0.01	0.03	3.8	3.8	428.1	428.1	50.0	50.0	52.9	49.2	1626.9	1626.6	2.1	2.3	0.7	0.7
24	0.02	0.01	0.05	3.9	3.8	432.1	432.1	50.0	50.0	54.7	51.8	2396.7	2115.8	3.3	2.7	0.8	0.8
26	0.01	0.01	0.03	3.9	3.8	409.0	409.0	50.0	50.0	54.5	50.8	1660.8	1430.1	2.5	2.6	0.7	0.7
26B	0.01	0.01	0.03	3.9	3.8	407.3	407.3	50.0	50.0	53.6	49.4	1373.6	1157.0	2.2	2.3	0.7	0.7
28	0.01	0.02	0.03	3.8	3.7	448.6	448.6	50.0	50.0	52.3	49.2	2055.2	1949.3	1.9	2.0	0.6	0.6
29	0.01	0.02	0.03	3.8	3.7	446.1	446.1	50.0	50.0	51.0	47.0	1783.2	1618.6	1.7	1.7	0.6	0.6
30	0.02	0.02	0.03	3.8	3.7	450.5	450.5	50.0	50.0	53.5	50.4	2595.8	2438.6	2.1	2.1	0.7	0.7
31	0.01	0.01	0.03	1.9	2.0	432.1	432.1	50.0	50.0	54.8	52.1	1836.4	2003.0	2.2	1.9	0.7	0.6
32	0.01	0.01	0.02	1.9	2.1	429.8	429.8	50.0	50.0	53.8	50.7	1335.1	1737.8	1.7	1.7	0.6	0.6
32B	0.01	0.01	0.02	1.9	2.0	427.4	427.4	50.0	50.0	52.6	49.1	1192.5	1256.1	1.4	1.5	0.5	0.6

STEADY STATE (PHASE I—STIRLING CONVERTOR DATA).—Concluded.

Test Pt.	ACCELX (V)	ACCELY (V)	ACCELZ (V)	FME1PV COOL (L/min)	FME2PV COOL (L/min)	PRE1 CHRG (psig)	PRE2 CHRG (psig)	FreqE1 (Hz)	FreqE2 (Hz)	Phase XpXdE1 (deg)	Phase XpXdE2 (deg)	QWE1 OUT (W)	QWE2 OUT (W)	PlossE1I 2R (W)	PlossE2I 2R (W)	VdropE1 IR (V)	VdropE2 IR (V)
35	0.01	0.01	0.03	2.0	2.1	409.4	409.4	50.0	50.0	55.0	51.9	1063.5	1472.8	2.2	2.1	0.7	0.7
35B	0.01	0.01	0.02	2.0	2.1	407.2	407.2	50.0	50.0	54.2	50.6	914.2	1193.8	1.7	1.9	0.6	0.6
37	0.01	0.01	0.03	1.8	2.0	449.2	449.2	50.0	50.0	53.6	49.7	2066.5	1869.0	1.3	1.3	0.5	0.5
38	0.01	0.01	0.03	1.8	2.0	448.4	448.4	50.0	50.0	52.2	48.0	1896.7	1728.5	1.2	1.2	0.5	0.5
39	0.01	0.01	0.03	1.8	2.0	451.7	451.7	50.0	50.0	54.6	51.7	2621.4	2320.2	1.4	1.4	0.5	0.6

STEADY STATE (PHASE I—FACILITY AND STIRLING CONVERTOR DATA)

Test Pt.	E1 NaK Inlet Temp (°C)	E1 NaK Outlet Temp (°C)	E2 NaK Inlet Temp (°C)	E2 NaK Outlet Temp (°C)	E1 & E2 NaK Flow (kg/s)	E1 Q in (W)	E2 Q in (W)	E1 Eff (%)	E2 Eff (%)	E1 Piston Amp (mm)	E2 Piston Amp (mm)	AVG E1 NaK Head T (°C)	AVG E2 NaK Head T (°C)	AVG E1 PV T (°C)	AVG E2 PV T (°C)	Avg E1 Cool H2O T (°C)	Avg E2 Cool H2O T (°C)	E1 Qout (W)	E2 Qout (W)	Total Elec Power (We)	Combined Efficiency (%)
1*	555.0	545.9	554.6	545.8	0.7877	3188.0	3,078.9	32.3	32.3	10.1	9.9	549.2	550.0	68.0	66.9	52.0	52.0	1975.4	1824.1	2026.1	32.3
2*	555.9	545.0	555.4	544.8	0.7690	3710.7	3,637.1	32.3	32.4	11.2	10.9	548.8	549.5	71.1	69.8	52.3	52.2	2513.1	2238.7	2375.2	32.3
3*	553.8	546.2	553.4	545.9	0.8048	2705.5	2,678.6	31.9	31.6	9.1	8.9	549.2	549.8	65.4	64.5	51.6	51.8	1615.5	1619.8	1710.3	31.8
4*	552.7	546.6	552.4	546.4	0.8419	2271.0	2,262.3	30.7	30.2	8.1	7.9	549.4	549.9	62.5	61.9	51.7	51.5	1485.3	1095.4	1380.4	30.5
5*	552.1	547.4	552.0	547.2	0.8704	1816.2	1,843.0	30.5	29.2	7.1	6.9	549.9	550.4	60.1	59.6	51.5	51.2	1343.3	960.1	1091.2	29.8
7*	555.3	546.0	555.6	546.6	0.8284	3395.3	3,294.9	31.6	31.1	10.2	9.8	550.0	551.0	48.5	46.7	31.6	31.6	1684.5	1847.5	2096.5	31.3
8*	553.4	546.3	554.4	547.2	0.8518	2692.4	2,735.8	33.9	31.1	9.1	8.9	549.8	550.7	45.6	44.1	31.3	31.2	1420.6	1626.3	1763.9	32.5
10*	555.2	545.9	554.6	546.1	0.7172	2952.0	2,697.4	32.9	33.9	10.1	9.9	549.2	550.1	86.8	85.6	71.4	71.3	2109.5	2068.8	1884.4	33.4
11*	554.4	546.7	553.9	546.6	0.7312	2494.4	2,339.9	32.8	33.5	9.1	8.9	549.6	550.3	83.5	82.6	70.7	70.3	1716.8	1661.4	1601.6	33.1
12*	556.4	545.6	555.8	545.6	0.7009	3351.8	3,176.5	33.1	33.6	11.1	10.9	549.3	550.1	89.6	88.4	71.9	71.5	2455.8	2514.4	2177.1	33.3
13	504.1	495.8	504.0	495.4	0.7839	2822.6	2,953.7	32.2	30.7	10.1	9.9	498.8	499.6	66.6	65.7	52.0	51.8	2054.8	1818.8	1816.9	31.5
14	503.8	496.9	503.7	496.5	0.7992	2377.6	2,514.0	32.7	30.7	9.1	8.9	499.6	500.3	63.6	62.9	51.6	51.7	1692.3	1486.6	1549.6	31.7
15	504.4	494.6	504.4	494.1	0.7737	3315.8	3,440.1	31.0	30.2	11.2	10.8	498.0	498.8	69.4	68.0	52.2	52.2	2165.3	2472.3	2069.7	30.6
17	503.9	497.1	503.8	496.5	0.8319	2458.3	2,651.1	32.8	31.2	9.1	8.9	499.8	500.4	44.6	43.9	31.4	31.6	1625.2	1481.0	1633.3	32.0
17B	503.2	497.6	503.3	497.6	0.8556	2081.6	2,143.6	32.5	30.8	8.1	7.9	500.2	500.8	42.5	41.8	31.1	31.3	1341.7	1091.8	1335.5	31.6
19*	503.9	495.9	504.2	495.8	0.7813	2725.4	2,831.8	30.9	28.4	10.1	9.9	499.0	500.0	85.7	84.4	72.0	71.7	2073.7	1928.2	1646.5	29.6
20*	503.5	497.1	503.7	496.9	0.7709	2157.6	2,286.3	33.3	29.6	9.1	8.9	499.6	500.5	84.8	83.5	72.0	71.7	1768.0	1616.9	1394.3	31.4
21*	504.1	494.8	504.3	494.5	0.7574	3079.3	3,224.7	30.9	28.8	11.1	10.9	498.2	499.1	88.9	87.6	72.6	72.3	2449.5	2370.4	1881.9	29.9
22	453.1	445.7	452.6	445.0	0.8041	2532.5	2,626.5	30.9	30.6	10.1	9.9	448.3	448.8	65.7	65.0	52.2	52.1	2108.8	1840.8	1585.5	30.7
23	452.8	446.8	452.2	446.0	0.8167	2104.8	2,190.6	32.1	31.5	9.1	8.9	449.0	449.4	63.5	62.8	51.8	51.8	1626.9	1626.6	1365.7	31.8
24	454.3	445.8	453.9	445.1	0.7978	2907.5	3,015.1	29.6	29.4	11.1	10.7	448.6	449.2	68.1	66.7	52.5	52.4	2396.7	2115.8	1744.8	29.5
26	452.9	446.7	452.9	446.2	0.8854	2340.9	2,564.0	31.0	28.4	9.1	8.9	449.1	449.6	43.6	42.6	31.3	31.4	1660.8	1430.1	1454.7	29.7
26B	452.3	447.4	452.5	447.1	0.9028	1909.9	2,096.7	32.1	28.9	8.1	8.0	449.5	450.1	41.6	40.8	31.2	31.0	1373.6	1157.0	1219.2	30.4
28	454.2	447.0	453.9	446.3	0.7769	2412.6	2,537.7	29.7	28.3	10.1	9.9	449.3	449.9	84.6	83.8	72.0	71.6	2055.2	1949.3	1433.8	29.0
29	453.8	447.9	453.5	447.5	0.7815	1978.7	2,021.1	31.1	29.5	9.1	8.9	450.0	450.7	81.9	81.1	71.5	71.2	1783.2	1618.6	1212.7	30.3
30	454.5	445.9	454.2	445.4	0.7777	2863.9	2,949.2	28.1	27.2	11.1	10.9	448.6	449.3	87.0	85.7	72.2	71.9	2595.8	2438.6	1607.1	27.6
31	404.4	396.6	404.2	397.1	0.7842	2568.8	2,365.6	25.0	29.0	10.1	9.8	399.7	400.1	67.3	65.9	51.7	51.4	1836.4	2003.0	1328.7	26.9
32	404.0	397.6	403.9	398.1	0.7801	2124.9	1,935.1	27.1	31.2	9.1	8.9	400.3	400.6	64.8	64.0	51.3	51.2	1335.1	1737.8	1179.4	29.0
32B	403.7	398.4	403.6	399.0	0.7716	1729.4	1,492.7	28.2	33.8	8.1	8.0	400.7	401.0	62.4	61.8	51.1	51.0	1192.5	1256.1	991.9	30.8

STEADY STATE (PHASE I—FACILITY AND STIRLING CONVERTOR DATA).—Concluded.

Test Pt.	E1 NaK Inlet Temp (°C)	E1 NaK Outlet Temp (°C)	E2 NaK Inlet Temp (°C)	E2 NaK Outlet Temp (°C)	E1 & E2 NaK Flow (kg/s)	E1 Q in (W)	E2 Q in (W)	E1 Eff (%)	E2 Eff (%)	E1 Piston Amp (mm)	E2 Piston Amp (mm)	AVG E1 NaK Head T (°C)	AVG E2 NaK Head T (°C)	AVG E1 PV T (°C)	AVG E2 PV T (°C)	Avg E1 Cool H2O T (°C)	Avg E2 Cool H2O T (°C)	E1 Qout (W)	E2 Qout (W)	Total Elec Power (We)	Combined Efficiency (%)
35	403.6	397.2	403.4	397.7	0.7537	2030.5	1,849.9	29.9	35.2	9.0	8.9	399.8	400.0	45.8	44.8	30.5	30.8	1063.5	1472.8	1257.4	32.4
35B	403.1	397.9	402.9	398.4	0.7577	1672.8	1,468.5	31.1	37.3	8.1	7.9	400.1	400.3	43.7	42.9	30.5	30.9	914.2	1193.8	1068.2	34.0
37	403.5	396.1	403.9	397.1	0.8333	2607.3	2,413.1	22.6	24.4	10.1	9.9	399.5	400.0	85.0	84.2	72.0	71.4	2066.5	1869.0	1176.5	23.4
38	403.5	397.3	403.7	398.2	0.8223	2149.6	1,906.1	24.0	26.7	9.1	8.9	400.1	400.7	83.4	82.7	72.0	71.5	1896.7	1728.5	1023.7	25.2
39	404.3	395.4	404.5	396.1	0.8080	3052.3	2,885.9	21.1	23.1	11.1	10.9	398.9	399.4	87.6	86.7	72.3	72.0	2621.4	2320.2	1309.9	22.1

STEADY STATE (PHASE I—FACILITY DATA)

Test Pt.	DP-02 (psid)	DP-03 (psid)	VG-02 (torr)	T-018 (°C)	T-019 (°C)	T-020 (°C)	T-021 (°C)	D-FM-01-C (kg/s)	D-Qse1 (W)	D-Qse2 (W)
1*	0.564	0.407	0.0040	555.0	554.6	545.8	545.9	0.7877	3,188.0	3,078.9
2*	0.566	0.417	0.0040	555.9	555.4	544.8	545.0	0.7690	3,710.7	3,637.1
3*	0.553	0.393	0.0041	553.8	553.4	545.9	546.2	0.8048	2,705.5	2,678.6
4*	0.550	0.395	0.0044	552.7	552.4	546.4	546.6	0.8419	2,271.0	2,262.3
5*	0.534	0.398	0.0049	552.1	552.0	547.2	547.4	0.8704	1,816.2	1,843.0
7*	0.510	0.419	0.0031	555.3	555.6	546.6	546.0	0.8284	3,395.3	3,294.9
8*	0.501	0.425	0.0033	553.4	554.4	547.2	546.3	0.8518	2,692.4	2,735.8
10*	0.550	0.425	0.0042	555.2	554.6	546.1	545.9	0.7172	2,952.0	2,697.4
11*	0.550	0.414	0.0041	554.4	553.9	546.6	546.7	0.7312	2,494.4	2,339.9
12*	0.550	0.432	0.0042	556.4	555.8	545.6	545.6	0.7009	3,351.8	3,176.5
13	0.553	0.427	0.0043	504.1	504.0	495.4	495.8	0.7839	2,822.6	2,953.7
14	0.553	0.423	0.0044	503.8	503.7	496.5	496.9	0.7992	2,377.6	2,514.0
15	0.552	0.431	0.0042	504.4	504.4	494.1	494.6	0.7737	3,315.8	3,440.1
17	0.539	0.414	0.0048	503.9	503.8	496.5	497.1	0.8319	2,458.3	2,651.1
17B	0.535	0.419	0.0049	503.2	503.3	497.6	497.6	0.8556	2,081.6	2,143.6
19*	0.551	0.443	0.0024	503.9	504.2	495.8	495.9	0.7813	2,725.4	2,831.8
20*	0.554	0.445	0.0024	503.5	503.7	496.9	497.1	0.7709	2,157.6	2,286.3
21*	0.553	0.453	0.0025	504.1	504.3	494.5	494.8	0.7574	3,079.3	3,224.7
22	0.557	0.440	0.0042	453.1	452.6	445.0	445.7	0.8041	2,532.5	2,626.5
23	0.562	0.442	0.0042	452.8	452.2	446.0	446.8	0.8167	2,104.8	2,190.6
24	0.559	0.443	0.0041	454.3	453.9	445.1	445.8	0.7978	2,907.5	3,015.1
26	0.542	0.437	0.0049	452.9	452.9	446.2	446.7	0.8854	2,340.9	2,564.0
26B	0.536	0.442	0.0051	452.3	452.5	447.1	447.4	0.9028	1,909.9	2,096.7
28	0.556	0.453	0.0040	454.2	453.9	446.3	447.0	0.7769	2,412.6	2,537.7
29	0.555	0.449	0.0040	453.8	453.5	447.5	447.9	0.7815	1,978.7	2,021.1
30	0.558	0.459	0.0040	454.5	454.2	445.4	445.9	0.7777	2,863.9	2,949.2
31	0.537	0.421	0.0064	404.4	404.2	397.1	396.6	0.7842	2,568.8	2,365.6
32	0.538	0.426	0.0065	404.0	403.9	398.1	397.6	0.7801	2,124.9	1,935.1
32B	0.533	0.426	0.0063	403.7	403.6	399.0	398.4	0.7716	1,729.4	1,492.7

STEADY STATE (PHASE I—FACILITY DATA).—Concluded.

Test Pt.	DP-02 (psid)	DP-03 (psid)	VG-02 (torr)	T-018 (°C)	T-019 (°C)	T-020 (°C)	T-021 (°C)	D-FM-01-C (kg/s)	D-Qse1 (W)	D-Qse2 (W)
35	0.525	0.422	0.0061	403.6	403.4	397.7	397.2	0.7537	2,030.5	1,849.9
35B	0.531	0.430	0.0061	403.1	402.9	398.4	397.9	0.7577	1,672.8	1,468.5
37	0.542	0.418	0.0065	403.5	403.9	397.1	396.1	0.8333	2,607.3	2,413.1
38	0.545	0.418	0.0066	403.5	403.7	398.2	397.3	0.8223	2,149.6	1,906.1
39	0.545	0.419	0.0066	404.3	404.5	396.1	395.4	0.8080	3,052.3	2,885.9

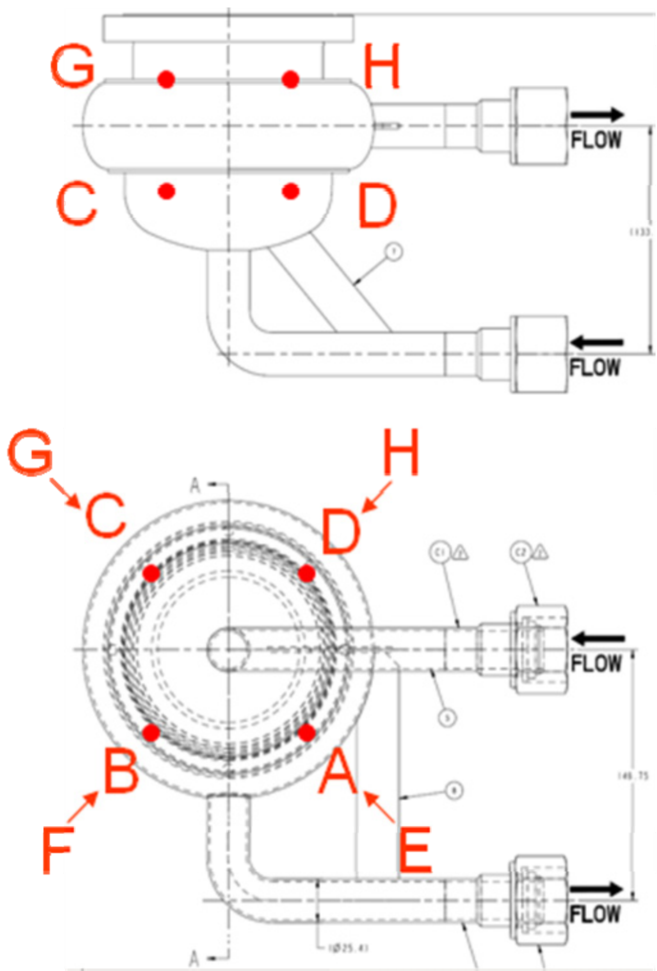
STEADY STATE (PHASE I—NAK MASS FLOW SENSITIVITY)

Test Pt.	Piston Amplitude (mm)	Engine Pressure (psig)	Avg Hot-End Temp (°C)	Stirling Power Out (W)	NaK Flow Rate (kg/s)	NaK Pump Power (W)
40	10.0	433.2	550.5	1988.2	0.8386	3412.7
40B	10.0	434.8	550.0	1976.8	0.7066	2361.5
40B	10.0	440.4	550.0	1966.7	0.7083	3514.7
43B	10.0	439.4	275.4	1989.9	0.5215	1837.2
41B	9.0	434.1	550.5	1668.2	0.7094	2591.7
44	9.0	434.0	549.5	1642.8	0.5150	1362.6
42B	8.0	432.3	550.4	1329.3	0.7120	3187.6
45	8.0	432.0	550.2	1328.2	0.5137	1546.4
45	8.0	431.8	549.1	1320.4	0.5071	1552.2

Parameter Definitions—Engine 1

TCE1HOT1	NaK Jacket Inlet—A (°C) (Eng 1)
TCE1HOT2	NaK Jacket Inlet—B (°C) (Eng 1)
TCE1HOT3	NaK Jacket Inlet—C (°C) (Eng 1)
TCE1HOT4	NaK Jacket Inlet—D (°C) (Eng 1)
TCE1HOT5	NaK Jacket Torus—E (°C) (Eng 1)
TCE1HOT6	NaK Jacket Torus—F (°C) (Eng 1)
TCE1HOT7	NaK Jacket Torus—G (°C) (Eng 1)
TCE1HOT8	NaK Jacket Torus—H (°C) (Eng 1)
TCE1PRVSL1	Press Vessel Temp (°C) (Eng 1)
TCE1PRVSL2	Press Vessel Temp 2 (°C) (Eng 1)
TCE1PRVSL3	Press Vessel Temp 3 (°C) (Eng 1)
TCE1H2OIN	Cooler Water Inlet Temp (°C) (Eng 1)
TCE1H2OUT	Cooler Water Exit Temp (°C) (Eng 1)
TCE1LAGAS	Linear Alternator Gas Temp (°C) (Eng 1)
TCE1PVH2OUT	PV Coolant Water Exit Temp (°C) (Eng 1)
XPE1POS	Piston Position (mm) (Eng 1)
XDE1POS	Displacer Position (mm) (Eng 1)
LAE1VOLT	Linear Alternator Voltage (V) (Eng 1)
LAE1CUR	Linear Alternator Current (A) (Eng 1)
LAE1POW	Linear Alternator Power (We) (Eng 1)
PRE1CHRG	Engine Mean Charge Pressure (psig) (Eng 1)
FME1COOL	Coolant Flow Rate (L/min) (Eng 1)
FME1PVCOOL	PV Coolant Flow Rate (L/min) (Eng 1)

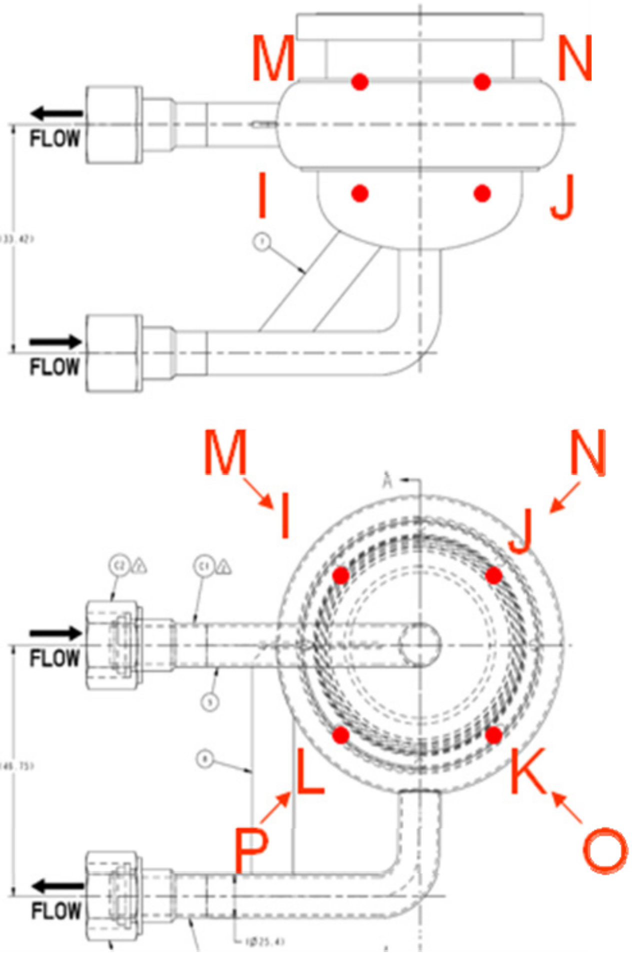
NaK Heater Head Thermocouple Locations—Engine 1



Parameter Definitions—Engine 2

TCE2HOT1	NaK Jacket Inlet—I (°C) (Eng 2)
TCE2HOT2	NaK Jacket Inlet—J (°C) (Eng 2)
TCE2HOT3	NaK Jacket Inlet—K (°C) (Eng 2)
TCE2HOT4	NaK Jacket Inlet—L (°C) (Eng 2)
TCE2HOT5	NaK Jacket Torus—M (°C) (Eng 2)
TCE2HOT6	NaK Jacket Torus—N (°C) (Eng 2)
TCE2HOT7	NaK Jacket Torus—O (°C) (Eng 2)
TCE2HOT8	NaK Jacket Torus—P (°C) (Eng 2)
TCE2PRVSL1	Press Vessel Temp (°C) (Eng 2)
TCE2PRVSL2	Press Vessel Temp 2 (°C) (Eng 2)
TCE2PRVSL3	Press Vessel Temp 3 (°C) (Eng 2)
TCE2H2OIN	Cooler Water Inlet Temp (°C) (Eng 2)
TCE2H2OUT	Cooler Water Exit Temp (°C) (Eng 2)
TCE2LAGAS	Linear Alternator Gas Temp (°C) (Eng 2)
TCE2PVH2OUT	PV Coolant Water Exit Temp (°C) (Eng 2)
XPE2POS	Piston Position (mm) (Eng 2)
XDE2POS	Displacer Position (mm) (Eng 2)
LAE2VOLT	Linear Alternator Voltage (V) (Eng 2)
LAE2CUR	Linear Alternator Current (A) (Eng 2)
LAE2POW	Linear Alternator Power (We) (Eng 2)
PRE2CHRG	Engine Mean Charge Pressure (psig) (Eng 2)
FME2COOL	Coolant Flow Rate (L/min) (Eng 2)
FME2PVCOOL	PV Coolant Flow Rate (L/min) (Eng 2)

NaK Heater Head Thermocouple Locations—Engine 2



Parameter Definitions—Convertor Pair

TCPVH2OIN	PV Coolant Water Inlet Temp (°C) (Eng 1and 2)
TCCABLETRAY	Cable Tray Temperature (°C)
OVRSTRK	Overstroke Protection Circuit (V)
ACCELX	Vibration in the Vertical Direction (g)
ACCELY	Vibration in the Axial Direction (g)
ACCELZ	Vibration in the Radial Direction (g)

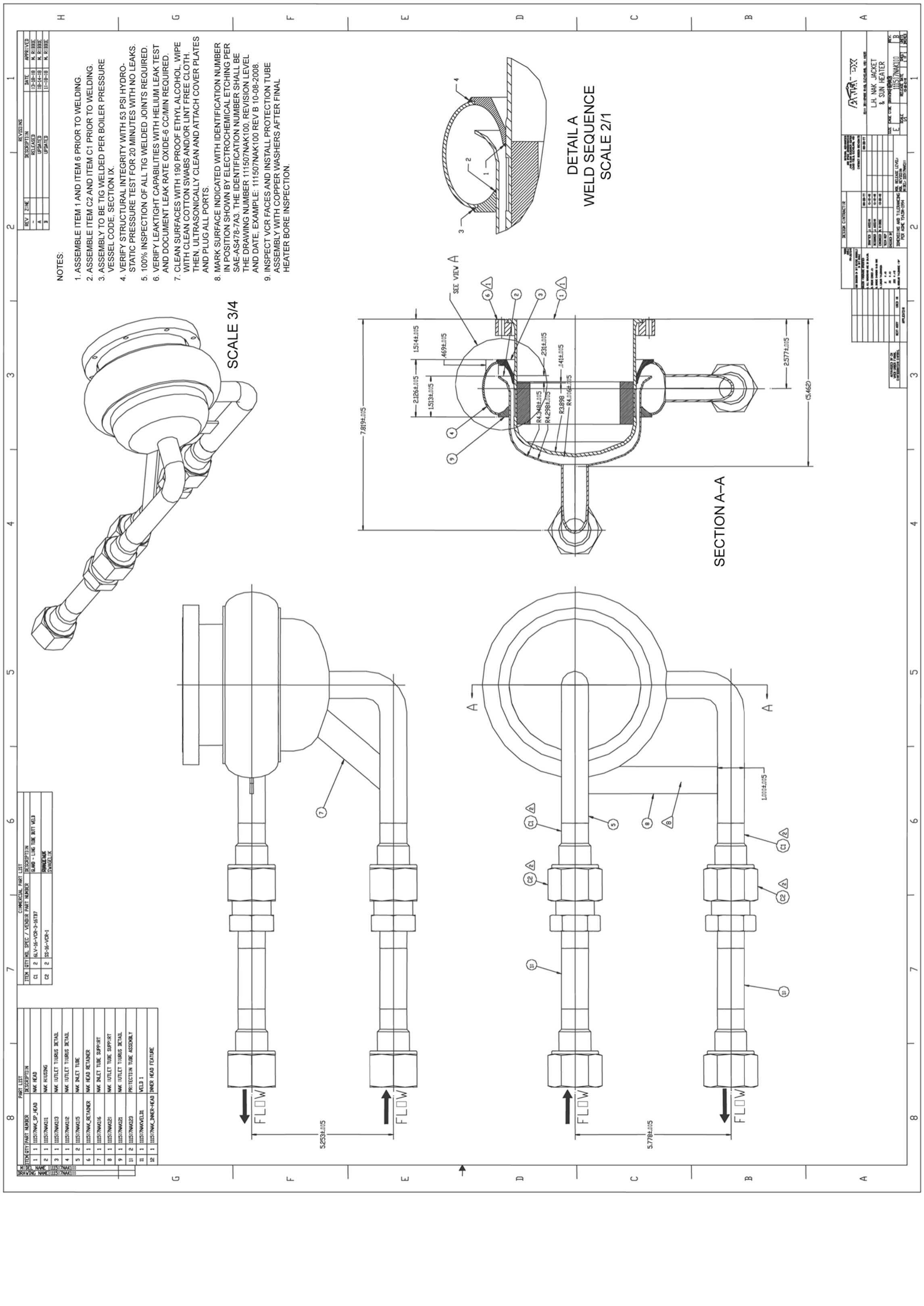
Parameter Definitions—Calculations

FreqE1	Frequency (Hz) (Eng 1)
FreqE2	Frequency (Hz) (Eng 2)
PhaseXpXdE1	Piston/Displacer Phase (°) (Eng 1)
PhaseXpXdE2	Piston/Displacer Phase (°) (Eng 2)
QWE1OUT	Heat Transfer to Cooling Water (W) (Eng 1)
QWE2OUT	Heat Transfer to Cooling Water (W) (Eng 2)
PlossE1I2R	I^2R Power Loss in Alternator Cables (W) (Eng 1)
PlossE2I2R	I^2R Power Loss in Alternator Cables (W) (Eng 2)
VdropE1IR	Voltage Drop in Alternator Cables (V) (Eng 1)
VdropE2IR	Voltage Drop in Alternator Cables (V) (Eng 2)

Parameter Definitions—Facility

DP-02	Stirling Engine 1 Diff Press (psid)
DP-03	Stirling Engine 2 Diff Press (psid)
VG-02	Chamber Press 1 (Torr)
T-018	Stirling Engine 1 Inlet Temperature (°C)
T-019	Stirling Engine 2 Inlet Temperature (°C)
T-020	Stirling Engine 1 Outlet Temperature (°C)
T-021	Stirling Engine 2 Outlet Temperature (°C)
D-FM-01-C	NaK Flow Meter (filtered) (kg/s)
D-Qse1	Heat extracted from NaK by Stirling Engine 1 (W)
D-Qse2	Heat extracted from NaK by Stirling Engine 2 (W)

Appendix C.—NaK Heat Exchanger Drawing



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14. 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 were modified to operate with a NaK (sodium (Na) and potassium (K)) 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 convertors were successfully tested at the Marshall Space Flight Center (MSFC) from June 6 through July 14, 2009. The convertors were operated for a total test time of 66 hr and 16 min. The tests included (a) performance mapping the convertors over various hot- and cold-end temperatures, piston amplitudes, and NaK flow rates and (b) transient test conditions to simulate various startup (i.e., low-, medium-, and high-temperature startups) and fault scenarios (i.e., loss of heat source, loss of NaK pump, convertor stall, etc.). This report documents the results of this testing.					
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