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Free-Piston Stirling Power Conversion Unit for Fission Power System, Phase II Final Report

J. Gary Wood and John Stanley
Sunpower, Inc., Athens, Ohio

August 2016

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Summary

In Phase II, the manufacture and testing of two 6-kW_e Stirling engines was completed. The engines were delivered in an opposed 12-kW_e arrangement with a common expansion space heater head. As described in the Phase I report, the engines were designed to be sealed both hermetically and with a bolted O-ring seal. The completed Phase II convertor is in the bolted configuration to allow future disassembly. By the end of Phase II, the convertor had passed all of the final testing requirements in preparation for delivery to the NASA Glenn Research Center.

The electronic controller also was fabricated and tested during Phase II. The controller sets both piston amplitudes and maintains the phasing between them. It also sets the operating frequency of the machine. Details of the controller are described in the Phase I final report. Fabrication of the direct-current to direct-current (DC–DC) output stage, which would have stepped down the main controller output voltage from ~700 to 120 V_{DC}, was omitted from this phase of the project for budgetary reasons. However, the main controller was successfully built, tested with the engines, and delivered. We experienced very few development issues with this high-power controller.

The project extended significantly longer than originally planned because of yearly funding delays. The team also experienced several hardware difficulties along the development path. Most of these were related to the different thermal expansions of adjacent parts constructed of different materials. This issue was made worse by the large size of the machine. Thermal expansion problems also caused difficulties in the brazing of the opposed stainless steel sodium-potassium (NaK) heater head. Despite repeated attempts Sunpower was not able to successfully braze the opposed head under this project. Near the end of the project, Glenn fabricated an opposed Inconel NaK head, which was installed prior to delivery for testing at Glenn. Engine development prior to this was performed using both single- and dual-opposed (common expansion space) Inconel heads with clamp-on electric heaters.

Description of Power Conversion Unit

The Power Conversion Unit (PCU) consists of a pair of 6-kW engines arranged in an opposed head-to-head configuration to produce 12 kW. Figure 1 shows a cross section of one engine (half of the opposed unit), and Figure 2 shows the final hardware configuration.

The convertor closely follows the design presented in the Phase I Final Report (Ref. 1). As given in the Phase I report, the hot-end components in contact with NaK are 316L stainless steel, with the rest of the engine vessel made of Inconel alloys. The joint between these materials is near the hot end of the regenerator.

All of the major design decisions from Phase I remained and were incorporated into the Phase II hardware. A few changes to internal components were made as the result of testing. These changes are described in the Lessons Learned section of this report.

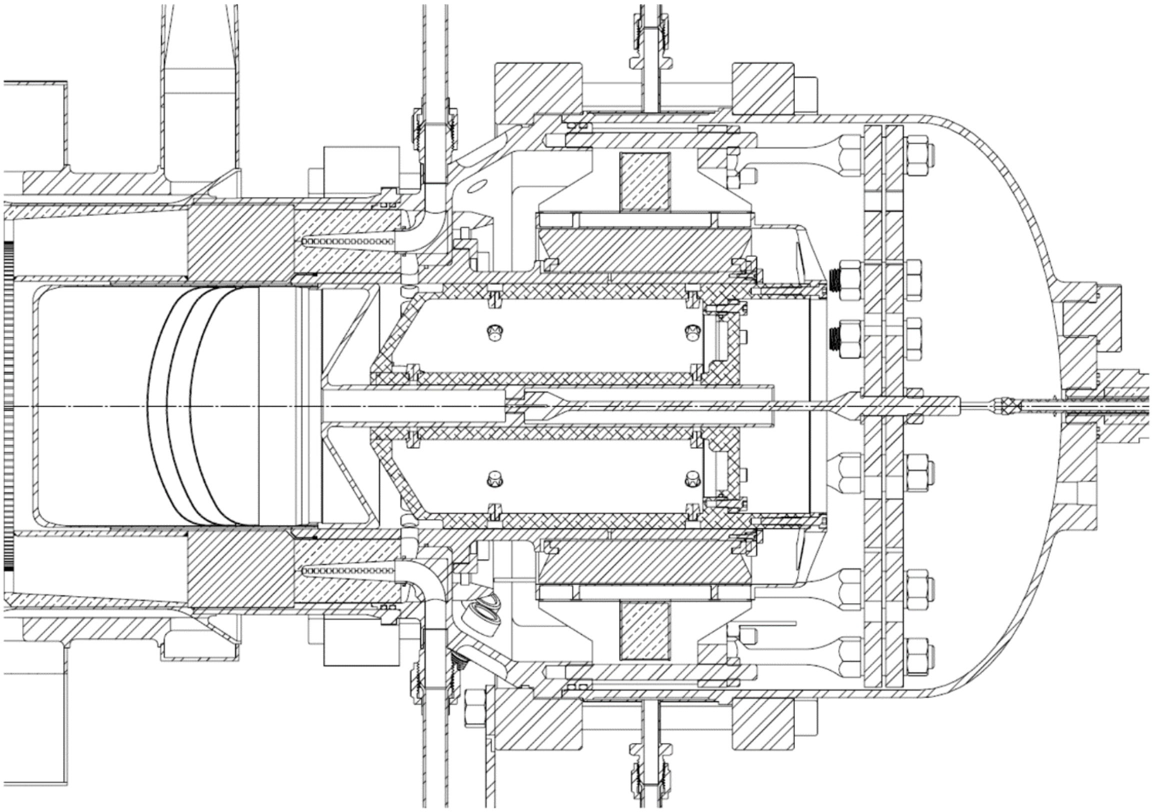

Figure 1.—Cross section of 6-kW engine.

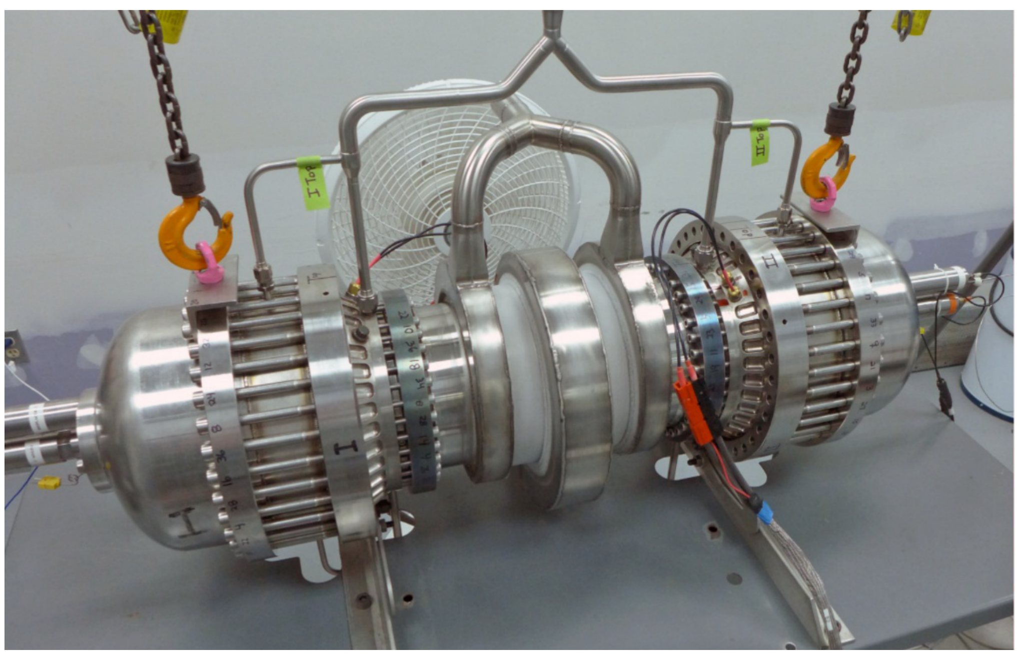

Figure 2.—Final hardware configuration being motored as a cryocooler.

Mass Analysis

The delivered mass of the convertor (Table I) was 269 kg, obtained from the computer-aided design (CAD) model. This includes the masses of flanges and instrumentation for the nonhermetic design. A fully welded assembly would have a mass of 219 kg.

Because the direct-current to direct-current (DC–DC) output stage portion of the controller was not fabricated because of funding, a finalized mass of the controller was not generated. However, during the Phase I effort the mass of the controller was estimated to be 67.7 kg.

TABLE I.—MASS BREAKDOWN

Component	Mass, kg
Hermetic components	
Head	54.7
Rejector copper	13.7
Structure	70.7
Alternator (stator)	48.3
Alternator (magnet can)	8.5
Piston	4.5
Displacer and springs	18.5
Hermetic total	219.0
Nonhermetic components	
Bolts and flanges	50.0
Total (hermetic + nonhermetic)	269.0

Testing Overview

Testing was performed at Sunpower with electrically heated test heads. A number of acceptance tests were performed to ensure safe operation during testing at Glenn. Table II shows an overview of the important test points, and Table III gives the details of the tests. Appendix A has an expanded table that shows additional relevant parameters for each test (Table X).

TABLE II.—ENGINE TESTING OVERVIEW

Milestone	Hardware	Date	Temperature, °C			Amplitude, mm	Power, W		Duration at test point, hr
			Head center		Reject inlet		Engine 1	Engine 2	
			Engine 1	Engine 2					
First run	Engine 1	10/26/2011	----	----	---	---	------	------	-----
6 kW of power	Engine 1	12/13/2011	390	----	30	16	6000	------	0.25
First run	Engine 2	5/30/2012	----	----	49	13	------	4000	-----
6 kW of power	Engine 2	7/2/2012	----	413	50	16	------	6000	-----
High-amplitude test	Engine 2	9/11/2012	----	360	50	18	------	3800	-----
Test with maximum specified coolant inlet temperature	Engine 2	9/19/2012	----	450	127	14	------	3750	-----
Nominal design point test	Engine 2	9/19/2012	----	503	102	16	------	5900	-----
6 kW of power (with controller)	Engine 1	2/5/2013	425	----	50	16	6000	------	-----
First dual-opposed test	Opposed	1/31/2014	----	----	53	14	3250	3250	0.5
40-hr overstroke test	Opposed	7/11/2014	350	430	52	17.6	4200	6100	0.5
		7/14/2014	380	430	52	17.6	4800	6200	3.5
		7/15/2014	380	435	52	17.6	4800	6300	9.0
		7/16/2014	385	435	52	17.6	4900	6300	10.0
		7/17/2014	380	435	52	17.6	4850	6350	2.5
		7/18/2014	375	435	52	17.6	4700	6350	7.0
		7/21/2014	350	435	52	17.6	4200	6350	7.5
8-hr nominal design test (with controller)	Opposed	11/3/2014	530	570	102	16	6000	6000	5.0
		12/2/2014	550	555	102	16	6100	6050	8.0

TABLE III.—DETAILS OF ACCEPTANCE TESTS

Maximum coolant inlet test	
Coolant inlet temperature, °C	127
Maximum amplitude test	
Piston amplitude, mm	18
Overstroke test (10 percent)	
Duration, hr	40
Piston amplitude, mm	17.6
Nominal design point test	
Duration, hr	8

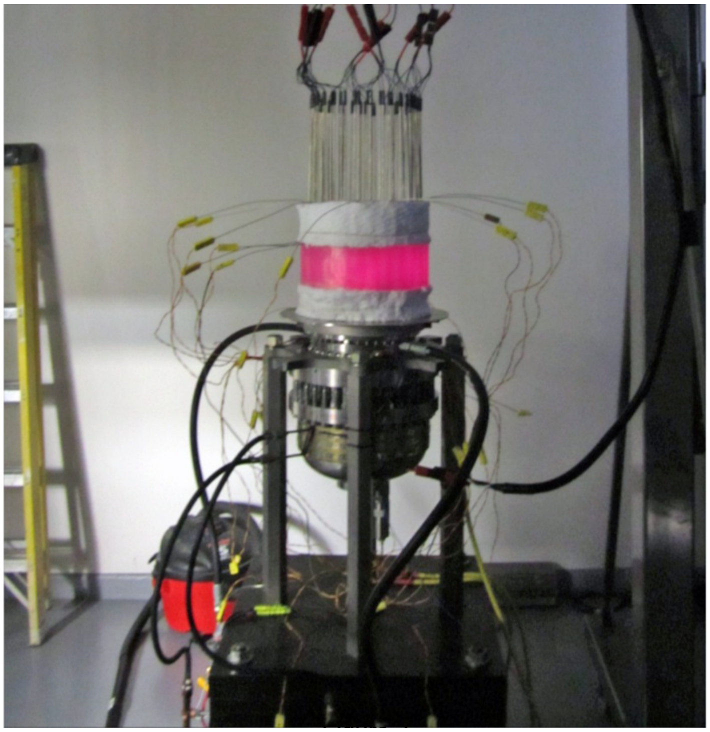

Figure 3.—Engine 2 during operation.

Single Engine Testing

Single-engine testing began with Engine 1 on October 26, 2011, and continued for 7 months. In May 2012 the assembly of Engine 2 was completed and testing began on that engine. Single-engine testing was performed on a vertical test stand with the engine attached to a 4000-lb mass (see Fig. 3). The mass greatly reduced housing vibration, which would have otherwise influenced engine dynamics. In the opposed configuration the individual engine vibrations were balanced.

Dual-Opposed Engine Testing

Dual-opposed engine testing began on January 31, 2014. The first opposed test was run at 6-kW total power (3 kW for each engine). The dual-opposed convertor was run 63 times for a total of 170 hr of testing including startup. A number of the runs were short development tests with most time spent in startup, but more than 70 hr of the testing were at steady state. Engine cooldown occurs much faster than startup because the engine can be operated to quickly remove heat from the massive test heads.

Dual-opposed engine testing was performed in the horizontal configuration with the engines mounted opposed. The initial dual-opposed runs were performed with an electrically heated head with a combined expansion space. This configuration is shown in Figure 4. Unfortunately, the heater blocks on this head experienced poor thermal contact because of an incomplete braze joint, and it was not possible to get full performance with this configuration. The significant result of this testing was proving stable operation of the convertor with a combined expansion space.

An interesting result of the opposed test with combined expansion spaces is that the power produced by the two pistons is always essentially equal. In hindsight this makes sense since the arrangement is essentially one common workspace with two pistons. Thus, even if displacer dynamics do not match or if there is a heating problem with an acceptor (i.e., poor bonding or loose heater blocks), the power output from the two pistons will still be very nearly equal.

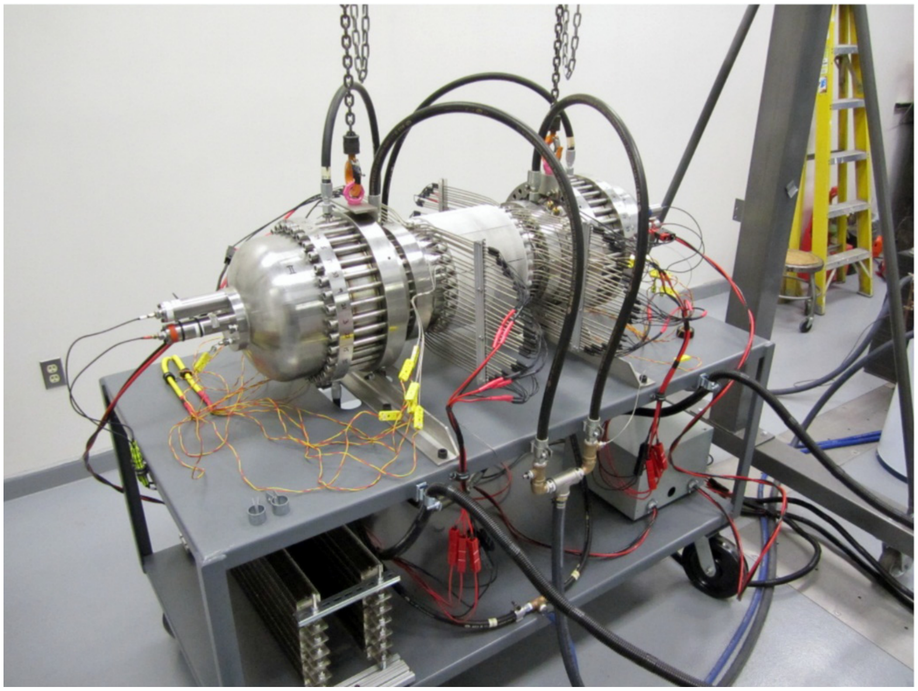

Figure 4.—Dual-opposed test setup.

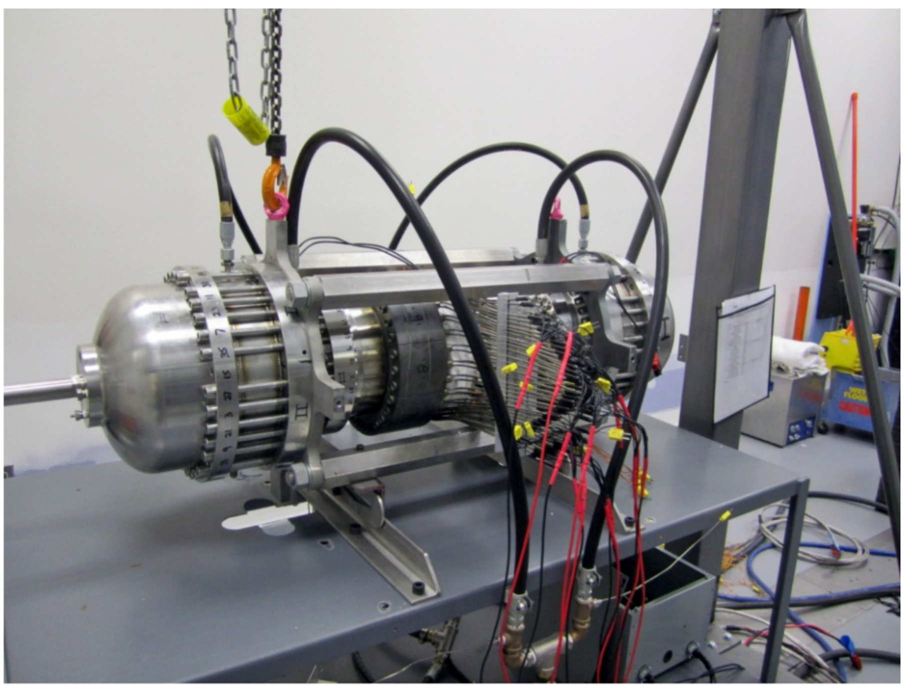

Figure 5.—Dual-opposed test setup with individual heater heads.

Because of the incomplete heater brazes, it was not possible to provide enough heat to the head. Convertor testing was accommodated by continuing with the individual heads from single engine testing. The convertor was operated in an opposed configuration but with separate expansion spaces. A support structure was added, which joined the two engines at their transition flanges, as shown in Figure 5. This configuration was used for the remainder of the dual-opposed engine testing.

Maximum Reject Temperature Testing

The capability of the 127 °C reject inlet was shown in the single configuration with Engine 2. On September 19, 2012, Engine 2 reached 3750 W at a piston amplitude of 14 mm and a reject inlet temperature of 127 °C. Because of the limitations of the external cooling system, the convertor was only able to sustain this point for a short period of time. The controller for the Chromalox water circulator could only control the temperature up to 121 °C. The Chromalox cooling water flow rate was therefore decreased to achieve the higher temperature. (The Chromalox water circuit is separate from the circuit for the engine coolant). This was an effective, but not a stable, test condition. The engine ran at a reject inlet temperature of above 122 °C for 6 min.

The coolant for each convertor was divided between the main rejector and auxiliary separate heat rejector on the back pressure vessel to remove alternator waste heat. The auxiliary flow to the back vessel was needed to control alternator temperatures because even an efficient alternator produces heat that needs to be dissipated. The delivered design uses a cooling jacket integrated into the pressure vessel. This jacket was not completed in time for the high reject temperature test, so a wrapped copper tube cooling jacket was used. The copper tube made limited contact with the vessel so the available heat transfer was much lower than with the integrated cooling jacket. This also limited the amount of time at the high reject temperature because the backend temperature could not be managed properly.

High Piston Amplitude Test

For this test the piston amplitude was taken to 18 mm, whereas the nominal design point is 16 mm. The engine was run at this piston amplitude for 4.5 min.

Overstroke Testing Requirement

An overstroke testing requirement was added to test the durability of the internal components. The acceptance test was 40 hr at 10-percent overstroke (17.6-mm amplitude). The testing was performed at reduced temperature and power as necessitated by the incomplete thermal contact of the heating blocks. This testing was performed to ensure that the internal hardware problems discussed in the Lessons Learned section had all been discovered and corrected. Note that the engine achieves 10^6 cycles (the typical endurance limit for steels) in 4.6 hr. The intent here was to run at higher loads (10 percent over nominal) for a significant time period. Reduced power output is acceptable because stress is mostly a function of piston amplitude. In normal operation, the inertia force of the magnet can assembly is 9.7 times the power-producing load force of the alternator.

The test was performed over seven separate runs from July 11 to 21, 2014. Table II shows the major test parameters of these runs. Engine 2 produced above 6 kW, whereas Engine 1 produced between 4.2 and 4.9 kW. The lower power of Engine 1 was the result of poorly attached heater blocks—not a limitation of the engine. The head temperature for that engine could not be maintained at the higher amplitudes, so output power was limited. Testing for shorter periods with a shut down in between is actually a better test than a continuous long test. In addition to the stresses from normal operation, stresses arise during the heating and cooling of the convertor.

The convertors passed this structural testing requirement with no issues. The 40-hr test was spread out over a week and a half, and the convertors were not disassembled during this time. This test was performed using the alternating-current (AC) power supplies instead of the controller because the primary purpose of the test was to evaluate the engine's structural integrity.

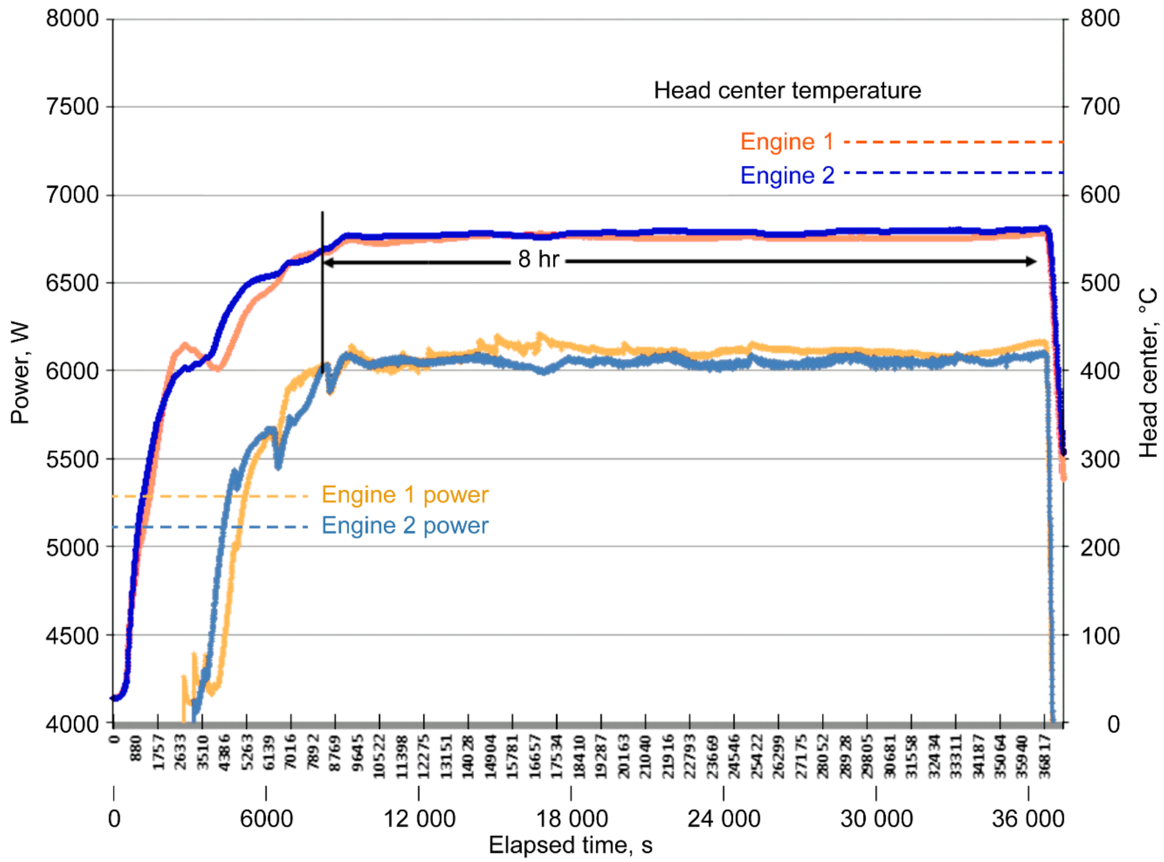

Figure 6.—Nominal design point controller testing. Cooling water inlet temperature, 102 °C; piston amplitude, X_p, 16 mm.

Nominal Design Point Testing Requirement

An 8-hr nominal design point test was also required. This test was run on the controller, the piston amplitude was 16 mm, the coolant inlet temperature was 102 °C, and the power produced was 6 kW for each engine. This test was completed on December 2, 2014. The run lasted a total of 10.5 hr, with 8 hr at the design point. This test point had been reached a number of times previously, including for 5 hr the month before. This was the first time that the engines had run continuously at the design point for 8 hr.

For this run, the amplitude was fixed and the heat input was adjusted to reach a power level of 12 kW. The flat heads for the engines ended up at temperatures of 550 to 560 °C. This is the best indicator of head temperature. Figure 6 is a plot of relevant data from the run.

Controller Testing

The controller was developed in tandem with the convertors. On February 5, 2013, 6 kW was achieved with Engine 2 from a single convertor on the controller. On December 2, 2014, for the 8-hr design-point test, the opposed engines produced more than 12 kW combined while running on the controller. The logic board and the power stage of the controller are shown in Figure 7. After the initial development, the controller performed reliably and met the revised design requirements. Because of budget constraints, the test had been revised to omit the output DC-DC stage, which would have converted the voltage output to 120 V_{DC}.

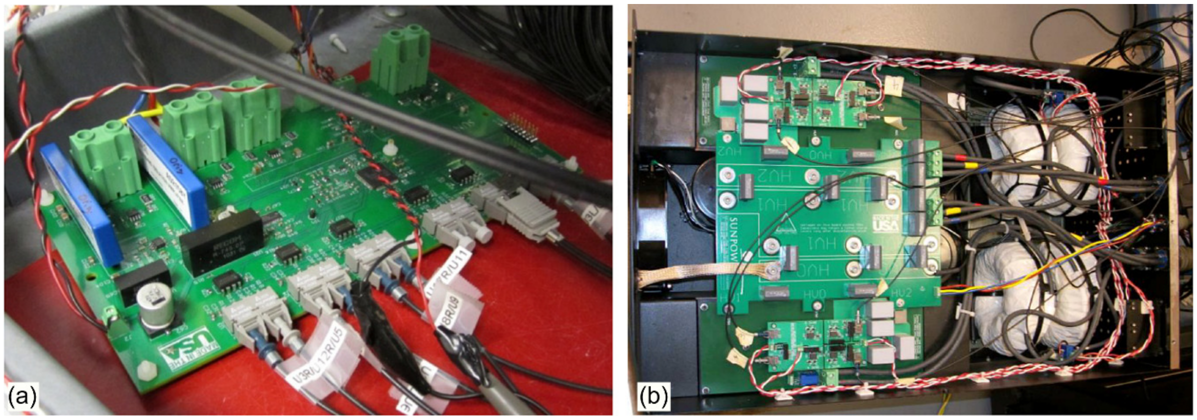

Figure 7.—Controller components. (a) Logic board. (b) Power stage.

Figure 8.—Air-cooled shunt load.

An air-cooled shunt load was fabricated to handle power not demanded by the Glenn's facility loads. This shunt handles any instantaneous drop in demanded load until engine piston amplitudes are decreased by the controller. The shunt load is shown in Figure 8. In controller testing at Sunpower, this shunt load was used as the only load. This was not used during AC bus testing because that required much larger resistors, which were mounted high on the walls of the test cell.

Originally the shunt load was designed to use water coolant. Commercially available water-cooled resistors were obtained, but the water circuit was prone to leak and the design presented a potential shock hazard. As a result, Sunpower decided to implement the physically larger forced-air-cooled shunt load pictured in Figure 8.

TABLE IV.—PERFORMANCE COMPARISONS

Performance metric	Predicted	Actual	
		Engine 1	Engine 2
Piston amplitude, mm	16	16.13	16.23
Displacer amplitude, mm	12	11.38	12.86
Head center temperature, °C	----	551	559
Reject inlet temperature, °C	----	102	102
Maximum metal temperature of hot heat exchanger, °C	570	------	------
Minimum wall temperature of cold heat exchanger, °C	111	------	------
Power, W	6000	6109	6048
Efficiency of electric out/heat in, percent	27.0	26.5	24.4

Performance Analysis

The 8-hr nominal design point test produced steady-state data that could be compared with Phase I Sage simulations. Table IV summarizes the predicted and actual performances.

Because of the difficulties encountered with the electric heater heads, steady-state test data could not be obtained for higher than nominal conditions with regards to piston amplitude and reject temperatures. The 17.6-mm overstroke test revealed the heat transfer limitation of the clamped-on heating arrangement. The temperature limitations of the heater blocks were reached while attempts were being made to obtain sufficient heat transfer into the heater heads of the engines. NaK testing will be able to better show the convertors' capabilities.

Specification Compliance Matrix

A number of requirements for the PCU were laid out in the Phase II contract: some directly related to the PCU and the rest flowed down from the technology demonstration unit (TDU) requirements. These requirements are included in Appendix B (Table XI). Each requirement is listed as met or not met, and a brief description is included where necessary.

Lessons Learned

A number of lessons were learned during the development of the hardware. Effort was spent on a number of areas to change and improve the convertor design. The following sections describe these changes.

Brazed-Flange NaK Head

The major difficulty encountered during this program was with the fabrication of the opposed NaK-heated head. The original design used a central stainless steel 316L NaK heat exchanger cylinder with two Inconel 718 pressure wall flanges along the regenerator and rejector length of each convertor. The two Inconel flanges were designed to be brazed to the central stainless steel heat acceptor region. Because the braze joints are through the pressure containment wall of the convertors, they are strength and leak critical.

To support the heater head design for this project, Glenn evaluated braze alloy compatibility and conducted strength testing (Ref. 2). The tensile test data from this report were used to guide the structural design of the braze joint.

At braze temperature, the thermal expansion of stainless steel 316L is 20.6 $\mu m \cdot m^{-1} \cdot K^{-1}$. The thermal expansion of Inconel 718 is 18 $\mu m \cdot m^{-1} \cdot K^{-1}$. The difference in thermal expansion leads to a difference in diametral growth of about 0.5 mm. The desired braze gap is on the order of 0.025 mm, so the thermal expansion made accurate control of the braze gap very difficult.

Problems also stemmed from the use of a vacuum oven to perform the brazing. Because radiation is the only heat transfer mechanism available, the shape and mass of the part caused large thermal gradients. The flanges are thin and heated much more quickly than the large, centrally located stainless section with internal copper acceptors. The thermal gradient caused permanent deformation of the parts during heating and cooling.

Of the two Inconel flange braze joints, only one could be successfully brazed. The other flange came unseated slightly during brazing and did not fully join. Multiple attempts were made to patch the joint but the gap was too large, and as a result, it could not be completely filled. Successful brazing of one of the flanges demonstrated that the heater head could potentially be produced as designed. As a next step, the flange with the faulty braze could have been removed and replaced with a new flange. However, because of funding limitations and the high risk associated with this approach, Sunpower and Glenn decided not to move forward with this heater head. There was also concern that the large number of heat treatment cycles could have changed the mechanical properties of the base materials.

Owing to the difficulties encountered with the brazed NaK heater head, a single-piece design was developed jointly by Sunpower and Glenn. The single-piece design removes the stainless steel to Inconel braze joint. Instead, the Inconel is a single machined tube that runs the full length of the heater head. The internal acceptors are still brazed to the inside diameter of the Inconel tube. The risk associated with this braze was judged to be low because Sunpower had much experience and success with this type of braze joint in the past. In addition, the internal acceptor to Inconel tube braze joint is only required for heat transfer, not strength.

The single-piece NaK head fabricated by Glenn allows for Inconel 718, Inconel 625, and stainless steel 316L to be in contact with the NaK. Allowing this makes the heater head stronger and easier to fabricate; however, the original requirement specified only that the stainless steel 316L be in contact with the NaK. To satisfy the original requirement, one could use the original brazed design with a number of changes to the fabrication and brazing steps:

Changes that were implemented for the last braze attempt follow:

- Where the braze had to flow around the corner, grooves were added to the corner to prevent choking of the braze flow.
- More thermocouples were added, and their temperature spread was controlled during oven ramping.
- The mass of the support fixtures was minimized to allow heat to penetrate to the inside of the assembly.
- Radiation shielding was added around exposed thin parts to slow their heating rate.

Changes that could be implemented in the future follow:

- Switch from a vacuum oven to a hydrogen oven for more even heating.
- Add a nickel plate or fluoride ion cleaning preparation step to the Inconel flanges.
- Identify a different braze alloy with better flow and wetting characteristics that still meets the strength requirements.

From all the lessons learned in working on the NaK heater head, it should be possible to fabricate a head based on the original brazed design. This head would only have 316L stainless steel for all the NaK contact surfaces. The brazed head is still a higher risk option than the single-piece head.

Internal Component Design Changes

Some design changes were implemented either during initial fabrication or to correct problems discovered during testing. The problems experienced were the result of the high power level and physical size of this convertor, which is much larger than convertors previously built by Sunpower. Problems were discovered that had never been experienced with smaller hardware running at lower rejection temperatures.

Internal Acceptor Design Change: April 2011

The internal acceptor geometry was changed to both improve performance and to ease fabrication (Fig. 9). After the influence of any nonuniform NaK flow between passages was considered, an improvement was devised for the internal acceptor design. The solid copper wall was increased from 1.5 to 2 mm thick and was allowed to taper up to 7 mm near the expansion space where the wall heat flux was highest. This added copper helped to distribute heat more uniformly and allowed the acceptor to remain more round prior to brazing.

Inner Iron Retaining Ring: April 2012

When running at elevated reject temperatures, the engine would become noisy. Sunpower determined this to result from the axial differential thermal expansion between the engine cylinder and the inner alternator laminations. At elevated reject temperatures, the inner laminations were no longer axially clamped. This problem was solved by adding a round wire wave spring washer to ensure that the inner laminations never became loose (Fig. 10).

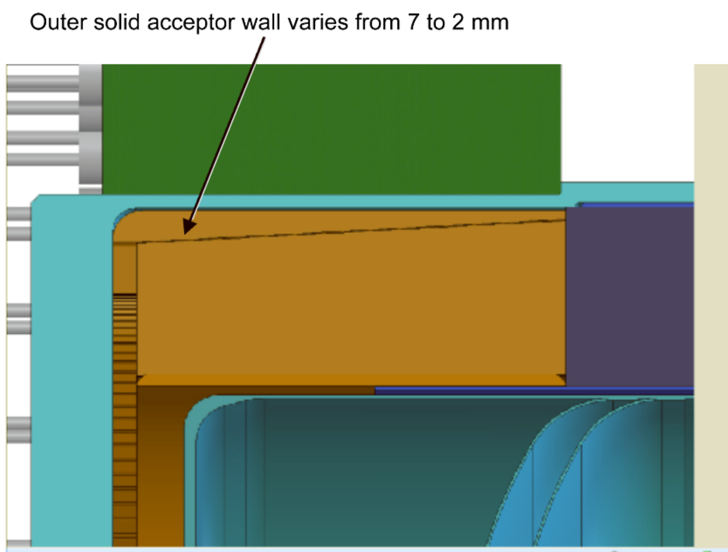

Figure 9.—Improved internal acceptor design.

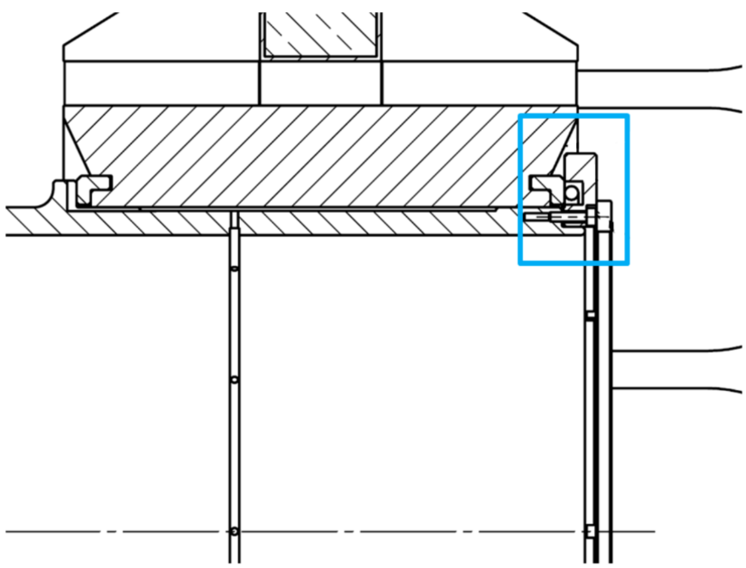

Figure 10.—Inner iron retaining spring.

Magnet Can Bolted Joint: August 2012 to September 2012

After some tens of hours of engine operation, the magnet can attaching bolts that thread into the piston began to fatigue. The problem was corrected by adding a 15-mm-deep counterbore to the threaded holes in the piston and using longer bolts. The revised joint is shown and highlighted in Figure 11. The longer clamp length of the bolts allowed them to be more compliant during operation without being overstressed. In addition, a higher quality bolt was used with a more carefully controlled root radius.

Displacer Spring Mounting: July 2012

The original displacer spring mount used the design shown in Figure 12. Four mounting bolts attached the displacer springs to a single-piece machined spring mount.

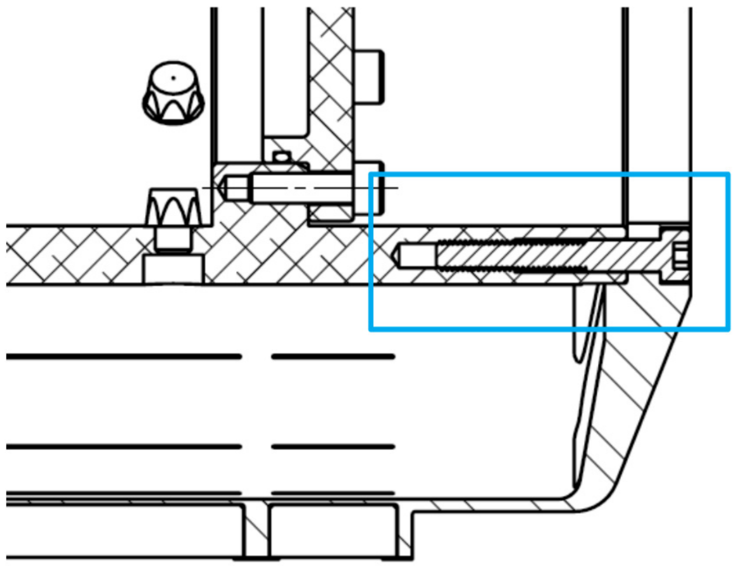

Figure 11.—Magnet can bolted joint.

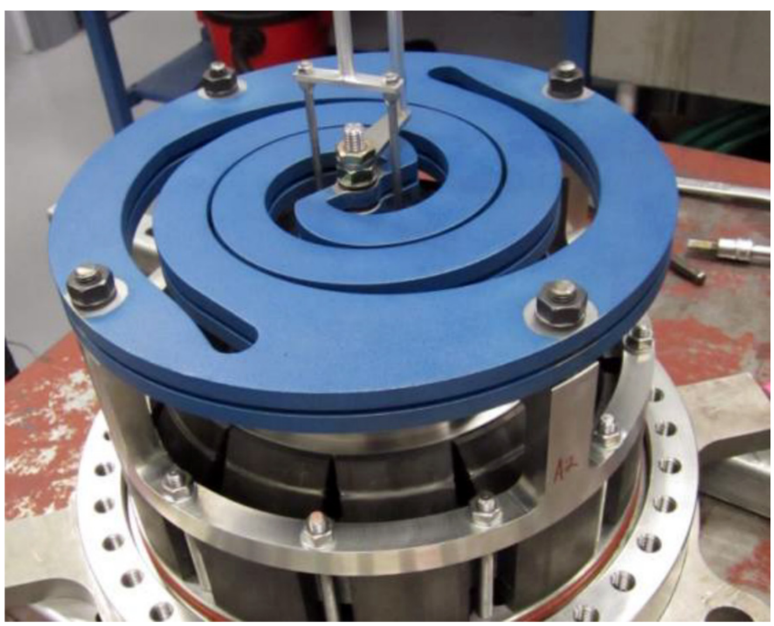

Figure 12.—Original displacer spring mounting.

Early problems were found with the displacer spring mounting bolts, and these were replaced with stronger bolts. After this correction was made, it was found that the loads were large enough to break the heavy original mounting ring. The solution here was to change the mounting arrangement to allow for compliance in this area. The number of mounting bolts was increased to eight, with four additional short bolts clamping the two springs together. The supports were designed to be flexible and were fabricated using a fatigue-resistant 416 stainless steel. Figure 13 shows the finalized design.

Regenerator End Screens Added: March 2013

Sunpower discovered that the sintering of the regenerator by the supplier was not sufficient and fibers would often be found in the running surfaces after early runs. This problem was solved by adding screens to the end faces of the regenerator. The screens were wrapped around the corners and tack-welded to the sides of the regenerator to seal the ends (Fig. 14).

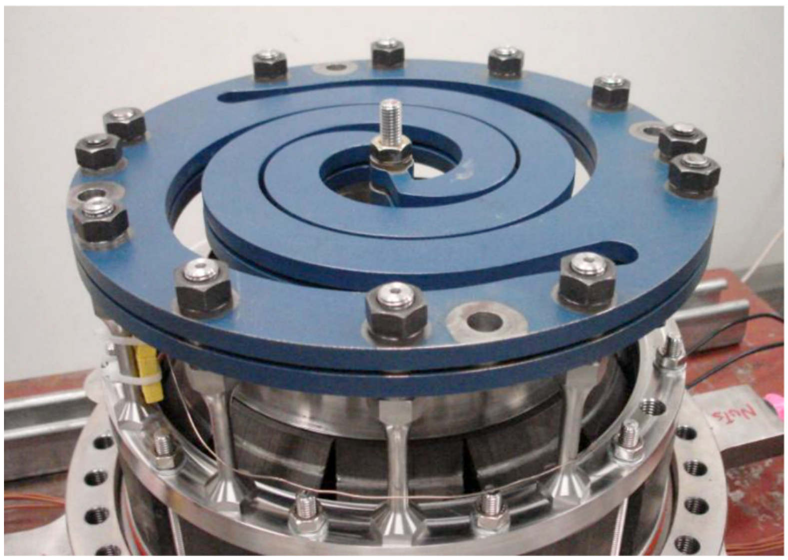

Figure 13.—Finalized displacer spring mounting.

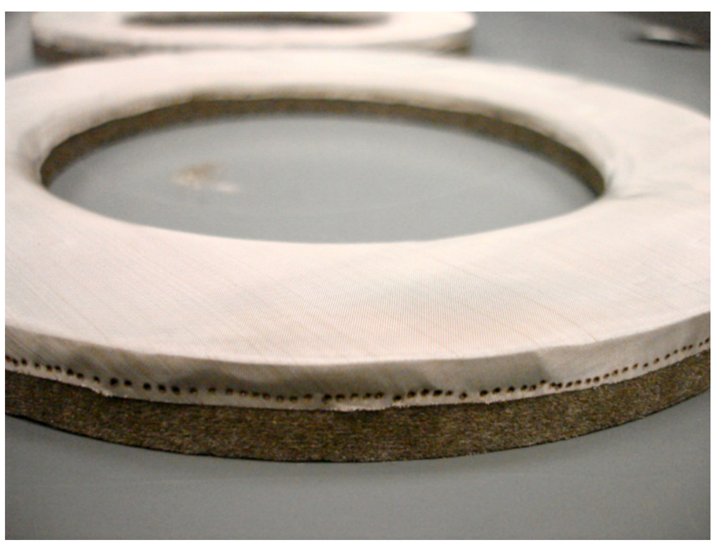

Figure 14.—Regenerator screen.

Displacer Baffle Tacking: August 2013

The displacer baffles were resistance spot welded into the displacer dome in eight places for each baffle. After several hours of operation, cracks in the dome initiated at these welds. Inspection of the welds showed that they were over welded and that many had craters at the weld site. To fix this, Sunpower performed development testing with the spot welder to find the correct parameters for the time and heat setting. On a new set of hardware, complete fusion of the weld area was achieved without melting and cratering the outer surfaces.

Displacer Dome Weld: November 2013

The original design for attaching the displacer dome to the displacer body was a plasma-arc-welded joint. This design worked through most of the single-engine testing, but the weld joint eventually fatigued. Cutting apart the failed joint showed that there was incomplete weld penetration. In addition, the crack initiated where a repair had been made to a small section during the original welding to fix some burn through of material.

The joint was redesigned to use a vacuum brazing process. In order to use the existing hardware, which had been turned apart on a lathe, an adapter piece was welded in between the dome and the body. This weld was in a lower stress region and could be inspected for penetration and then followed by the final brazing. In future hardware, this would be reduced to only the braze joint.

Clamp-On Electric Heater Difficulties

The original design for heating the engines used a clamp-on electric heater ring. A custom band clamp was used to clamp nickel blocks containing cartridge heaters to the outside diameter (OD) of the head. In Figure 15, the configuration is shown clamped around an aluminum plug.

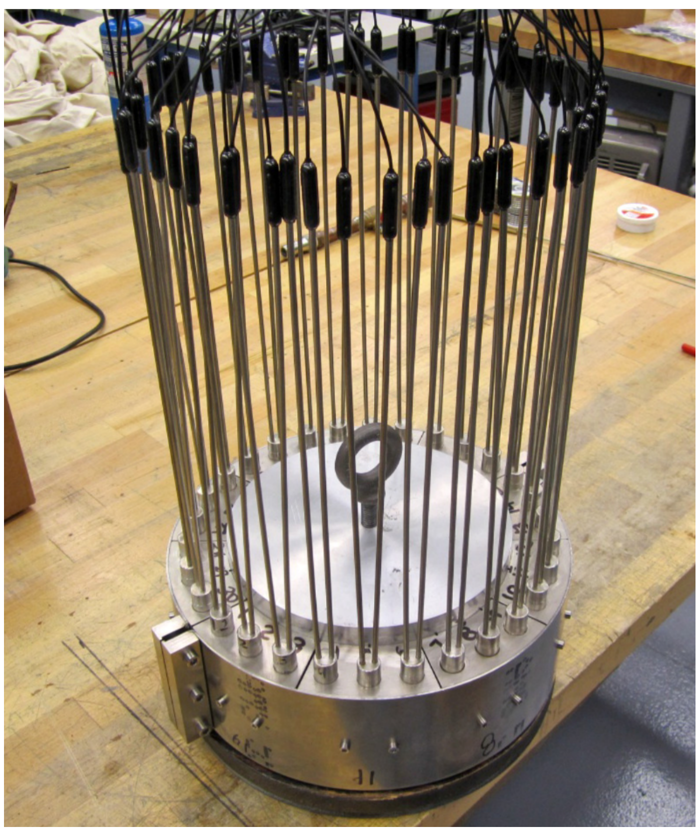

Figure 15.—Clamp-on electric heater ring (assembled around test plug).

Early testing showed limited heat transfer. Because of internal pressure and heat, the outer diameter of the head would not stay cylindrical enough during operation to maintain contact. The flat end of head was the main cause of this problem. Because of internal pressure, the flat end domed out slightly, creating a short taper at the outer diameter. This pushed the end of the blocks out so that they only made line contact at the edge next to the flat head and the edge next to the regenerator.

The loss of contact and heat transfer created a runaway effect. Because the clamp ring was a complete loop, as the temperature difference to the head increased, the ring grew larger and pulled away. Even the smallest of gaps would start this feedback. To improve heat transfer, Sunpower modified the design to use brazed-on nickel blocks. This method was more successful, but issues were encountered with the brazing process. It was difficult to braze the blocks on properly, which limited some of the performance testing.

Stress Analysis

The ASME Pressure Vessel Code (Ref. 3) was used as a guideline for the pressure vessel stress analysis, and allowable stress limits for the materials came from the Phase II specification. Table V summarizes the pressure testing performed and the helium, water, and NaK volumes.

The NaK head and the back pressure vessels were pressure tested at 1.5 times the operating pressure. The NaK head was tested independently. The back pressure vessels had been tested previously using the single-engine test heads.

The NaK plenum was pressure tested and bubble leak checked with helium at 207 kPa at room temperature (Table VI).

Of the three components of the water loop, only the back pressure vessel jacket was pressure tested (Table VII). The internal rejector did not need to be tested because it was under compression from the 6.2-MPa internal helium. Pressurizing the water side actually relieved stress. The water lines were fabricated from seamless 316L tubing. The assembly was welded and has three tubing sizes: 1-in. OD by 0.065-in. wall, 0.75-in. OD by 0.065-in. wall, and 0.375-in. OD by 0.038-in. wall. The minimum allowable working pressure is 2400 psi (16.5 MPa) for the 1-in. tubing.

TABLE V.—INTERNAL HELIUM VOLUME

Fluid	Helium
Design pressure, MPa	6.2
Tested pressure, MPa	9.3

TABLE VI.—SODIUM-POTASSIUM ALLOY (NaK) PLENUM

Fluid	NaK
Design temperature, K	875
Design pressure, kPa	150
Tested pressure, kpa	207

TABLE VII.—WATER–LOOP TESTING

Fluid	Water
Design temperature, K	400
Design pressure, kPa	700
Tested pressure	
Water lines	---
Internal rejector	---
Back pressure vessel jacket, kPa	862

Finite Element Analysis of Single-Piece Head

The pressure vessel was designed using the "Part 4: Design by Rule" requirements of the *Pressure Vessel Code*, but the complicated geometry and the high-temperature gradients of the head required finite element analysis (FEA). "Part 5: Design by Analysis" requirements were used as a guideline.

Allowable stress is calculated as the minimum of one-third ultimate strength (S_u) and two-thirds yield strength (S_y) (see Table VIII). Local stresses higher than allowable stress are acceptable according to the code, up to 1.5 times allowable (Fig. 16).

Primary membrane stresses are all below the allowable stress. A few localized stresses are higher, but they are still below 1.5 times allowable. The high stresses shown at the weld joint are artifacts of the sharp corner in the model and are not realistic. The stress measured a few elements away from the corner is within stress limits.

TABLE VIII.—ULTIMATE STRENGTH S_u, YIELD STRENGTH S_y, AND ALLOWABLE STRENGTH S_{allow} OF INCONEL ALLOYS

Precipitation-hardened Inconel 718	
S_u, MPa	1101
S_y, MPa	893
S_{allow}, MPa	367
Annealed Inconel 625	
S_u, MPa	679
S_y, MPa	279
S_{allow}, MPa	186

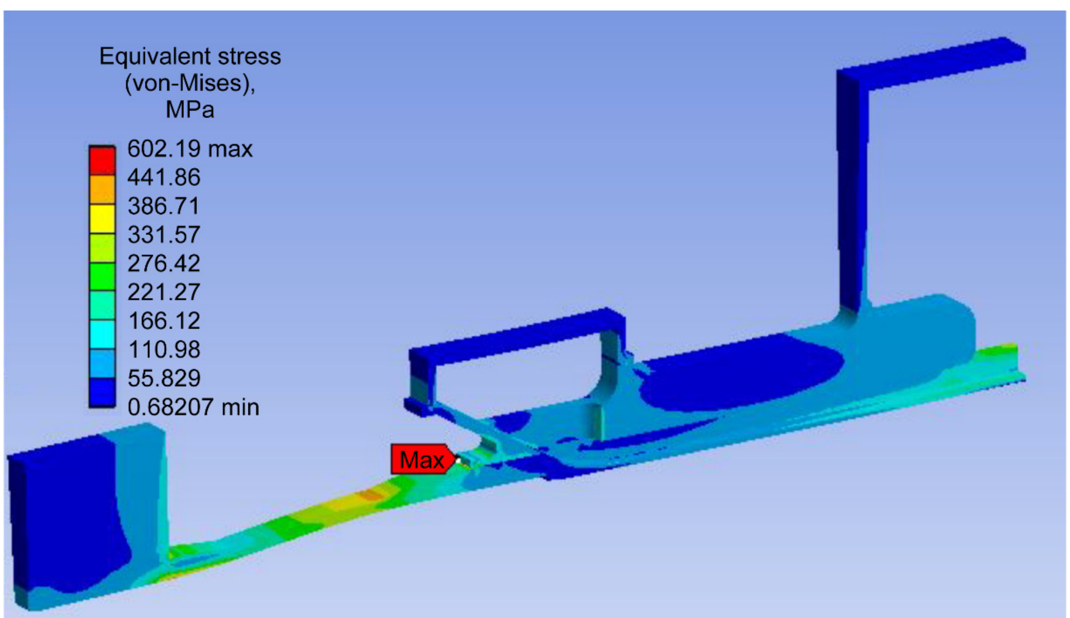

Figure 16.—Stress analysis of single-piece head.

Electrical Analysis

Alternator

The design of the alternator remained the same as for the Phase I design, which is described in detail in the *Phase I Final Report* (Ref. 1). Figure 17 shows the efficiency of the alternator at various temperatures.

Controller

Table IX summarizes the controller efficiency analysis, and Reference 1 describes the detailed design of the controller. Note that the 12-kW specification is for the output of the engines.

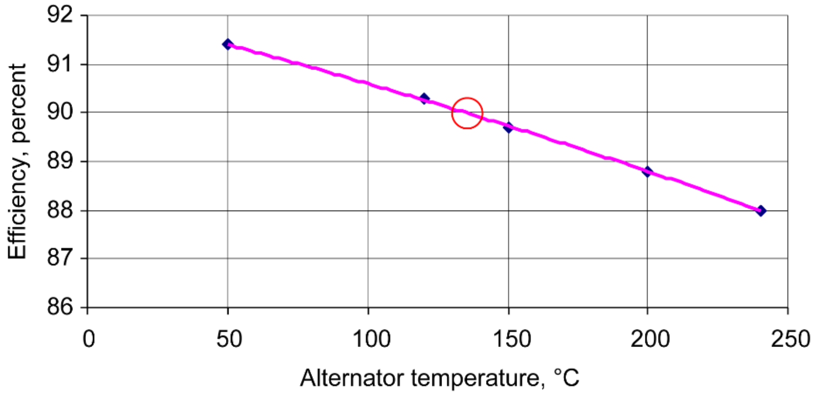

Figure 17.—Alternator efficiency.

TABLE IX.—CALCULATED EFFICIENCY OF CONTROLLER

Component	Quantity	Unit loss, W	Extended loss, W
LC filter[a]	2	58	116
Convertor power stage	2	202	404
DSP board[b]	1	4	4
DC–DC full bridge[c]	1	245	245
DC–DC magnetics[c]	1	103	103
Synchronous rectifier	1	54	54
Shunt controller	1	2	2
Output switch	1	20	20
Interconnect	1	60	60
Bus capacitors	1	30	30
Total loss, W			1038
Efficiency, percent			91.35

[a]LC, inductance/capacitance.
[b]DSP, Digital Signal Processing.
[c]DC, direct current.

Final Hardware Configuration

The final hardware configuration is described in the *Build Book*, which was delivered with the hardware. Final drawings of all the delivered components as well as assembly pictures are included. Figure 18 shows the convertor as delivered.

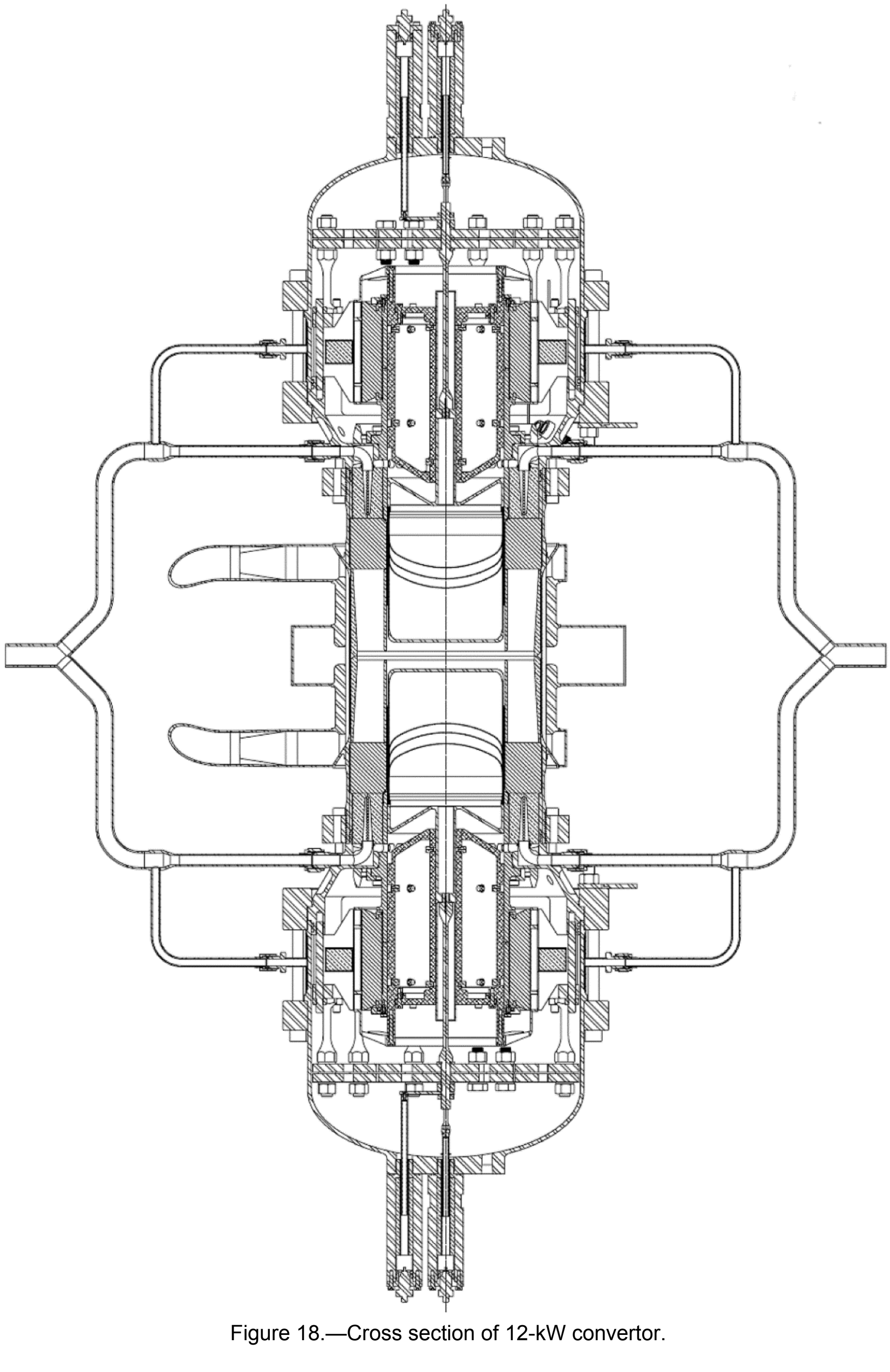

Figure 18.—Cross section of 12-kW convertor.

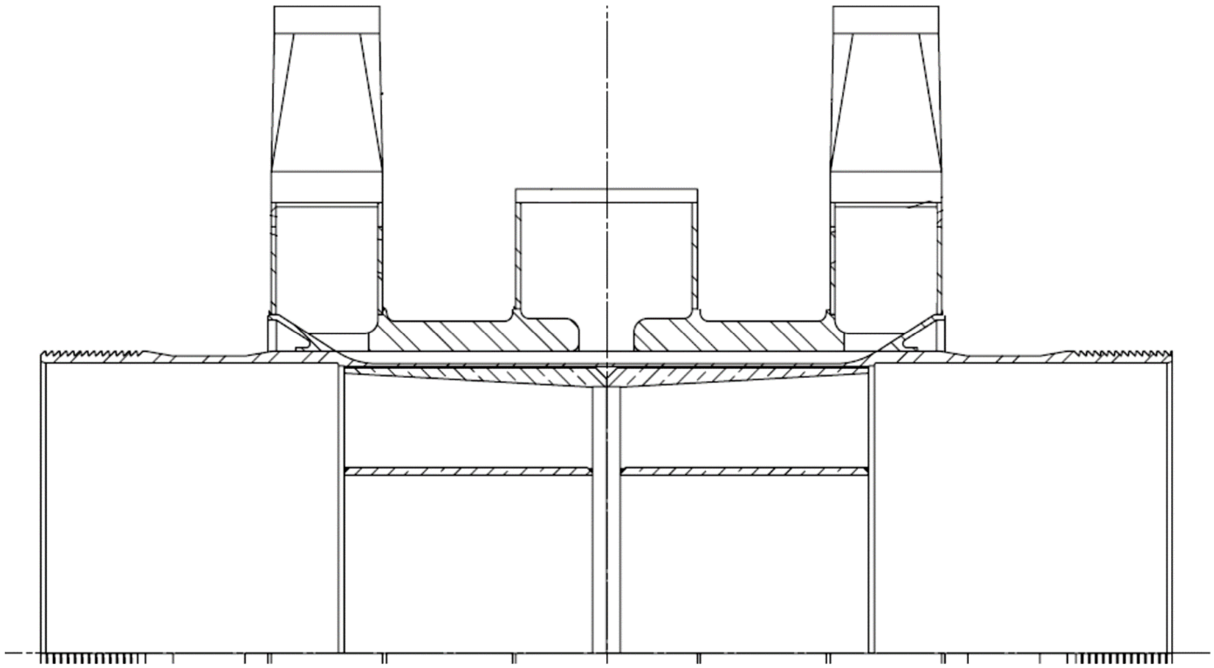

Figure 19.—Single-piece heater head design.

Single-Piece Head

The PCU was delivered with the single-piece heater head design. Figure 19 shows a cross section of this design. “Single piece” refers to the continuous Inconel 718 pressure wall, which extends all the way axially though the head. A threaded-on flange (buttress thread) attaches it to the two engines. Two support tubes are laser welded to the outside of the pressure wall to add strength and form the outer wall for the NaK heat exchanger. The external NaK plenums are tungsten inert gas (TIG) welded in place.

The threaded-on flange design was chosen because of limitations on the outer diameter of the head in this area. The laser-welded support tubes need to slide on over the head for installation, limiting the diameter of the threaded area. A welded-on flange design was considered, but it was not selected because of some concerns. First, the weld would be next to the head O-ring sealing surface, so any distortion could cause sealing problems. Second, a welded design locks the rotational alignment of the two engines. The reject water lines also lock the rotation, leading to an overconstraint. The threaded flange allows rotational adjustment.

Glenn fabricated all the components, brazed the acceptors, and welded the support tubes to the single-piece head tube. Sunpower performed the finish machining on the brazed head assembly and welded the NaK plenums.

Delivery of the Convertor

Before the convertor was delivered to Glenn, it was motored up to 150 V at Sunpower to proof check the assembly of the internal components. This is the extent of the testing that could occur without heating the head, which required the NaK system.

The convertor was delivered with both the piston and displacer Fast Linear Displacement Transducer (FLDT) position sensors for each engine. The original plan was to deliver only piston FLDTs to reduce the number of seals, but Sunpower decided that the additional operational information from the displacer FLDTs was worth the additional risk of helium leakage. For temperature measurement, two thermocouples were installed—one in the back of each engine—to measure bounce space temperature.

Conclusions

The Power Conversion Unit (PCU), including the opposed convertor and the controller, was delivered to the NASA Glenn Research Center in August 2015. The PCU passed all the testing requirements and was ready for installation into the technology demonstration unit test stand. Sunpower was not able to successfully braze the sodium-potassium (NaK) head under the project. However, Glenn fabricated and brazed a modified design, which was installed by Sunpower. Although a number of hardware issues arose during the development project, these were resolved successfully before the PCU was delivered.

Appendix A.—Acceptance Test Points

Table X shows the acceptance test points for the Power Conversion Unit (PCU) testing.

TABLE X.—ACCEPTANCE TEST POINTS

Milestone	Hardware	Date	Temperature, °C			Amplitude, mm				Power, W		Frequency, Hz	Mean pressure gauge, MPa	Duration at test point, hr
			Head center		Reject inlet	X_p, Piston		X_d, Displacer						
			Engine 1	Engine 2		Engine 1	Engine 2	Engine 1	Engine 2	Engine 1	Engine 2			
First run	Engine 1	10/26/2011	----	----	---					------	------	-------	------	-----
6 kW of power	Engine 1	12/13/2011	390	----	30	16		11.5		6000	------	60.00	6.20	0.25
First run	Engine 2	5/30/2012	----	----	49		13		9.2	------	4000	60.06	6.02	-----
6 kW of power produced	Engine 2	7/2/2012	----	413	50		16		11.5	------	6000	60.06	6.16	-----
High-amplitude test	Engine 2	9/11/2012	----	360	50		18		10.3	------	3800	60.06	6.25	-----
Test with maximum specified coolant inlet temperature	Engine 2	9/19/2012	----	450	127		14		10.6	------	3750	60.06	6.23	-----
Nominal design point test	Engine 2	9/19/2012	----	503	102		16		11.6	------	5900	60.06	6.17	-----
6 kW of power (with controller)	Engine 1	2/5/2013	425	----	50	16		11.5		6000	------	58.5	6.28	-----
First dual-opposed test	Opposed	1/31/2014	----	----	53	14	14	9.2	9.1	3250	3250	59.4	5.94	0.5
40-hr overstroke test	Opposed	7/11/2014	350	430	52	17.6	17.6	11.7	12.5	4200	6100	59.4	6.25	0.5
		7/14/2014	380	430	52	17.6	17.6	11.5	12.5	4800	6200	59.35	6.28	3.5
		7/15/2014	380	435	52	17.6	17.6	11.5	12.5	4800	6300	59.2	6.17	9
		7/16/2014	385	435	52	17.6	17.6	11.4	12.4	4900	6300	59.2	6.23	10
		7/17/2014	380	435	52	17.6	17.6	11.5	12.4	4850	6350	59.2	6.28	2.5
		7/18/2014	375	435	52	17.6	17.6	11.6	12.5	4700	6350	59.2	6.21	7
		7/21/2014	350	435	52	17.6	17.6	11.5	12.4	4200	6350	59.2	6.22	7.5
8-hr nominal design test (with controller)	Opposed	11/3/2014	530	570	102	16.3	16.3	11.3	12.8	6000	6000	59.2	6.21	5
		12/2/2014	550	555	102	16.1	16.2	11.4	12.8	6100	6050	59.2	6.15	8

Appendix B.—Specification Compliance Matrix

Tables XI, XII, and XIII show compliance with the requirements for the technology demonstration unit, Power Conversion Unit (PCU), and PCU controller, respectively.

TABLE XI.—TECHNOLOGY DEMONSTRATION UNIT REQUIREMENTS FLOWED DOWN TO POWER CONVERSION UNIT

Requirement	Met?	Comments
The technology demonstration unit (TDU) test system shall have a design life of 1000 hr, with up to 100 thermal cycles from ambient to full operating temperatures.	Y	The head analysis shows thermal cycle stability.
All materials used in fabricating TDU components shall include material certifications.	Y	Material certifications are supplied in the *Build Book*.
The TDU components inside the vacuum chamber shall be designed to start and operate in a thermal-vacuum environment.	Y	
TDU components shall be designed using safety factors based on American Society of Mechanical Engineers (ASME) guidelines: nonaustenitic materials shall be limited to the lesser of two-thirds S_y and one-third S_u at the maximum operating temperature; austenitic materials (including stainless steel 316L) shall be limited to the lesser of 0.9 S_y., 10000-hr creep rupture strength at nominal temperature, and 1000-hr creep rupture strength at maximum temperature	Y	
TDU components inside the vacuum chamber shall be proof-pressure tested to 1.3 times the maximum allowable working pressure, corrected for temperature.	Y	Pressure vessel was tested at 1.5 times nominal charge pressure at room temperature.
TDU components inside the vacuum chamber shall be leak tested to have a helium leak rate less than 10^{-6} cm^3/s at nominal operating pressure.	N	Silicone O-rings were required for low-temperature survivability, but they have high helium permeability.
Components inside the vacuum chamber that contain sodium-potassium (NaK) or water shall be designed to permit gravity drain.	Y	
Components inside the vacuum chamber shall be designed to accommodate a pumpdown from atmosphere to vacuum in 24 hr.	Y	
Components inside the vacuum chamber shall be designed to withstand a thermal cold soak environment of 175 K without core simulator power for up to 4 hr.	N	The Hysol epoxy (Henkel AG and Co.) and the feedthroughs were not rated at 175 K by the manufacturer. Testing would be needed to verify survivability.
Components shall be designed to withstand heatup from 300 K to operating temperatures in 2 hr.	Y	Test data of startup < 2 hr.
Components shall be designed to withstand cooldown from operating temperatures to 300 K in 2 hr.	Y	
The TDU test system and all related documents shall use the International System of Units (SI units).	Y	

TABLE XII.—POWER CONVERSION UNIT REQUIREMENTS

Requirement	Met?	Comments
The Power Conversion Unit (PCU) shall accept heat from the reactor simulator, generate electric power, and transfer waste heat to the Heat Rejection System (HRS).	Y	On the basis of checkout testing with the electric heater head, this requirement should be met.
The PCU shall be capable of operating in a vacuum chamber.	Y	
The PCU nominal electric power shall be 12 kW_e and 400 V_{AC} root mean square.	Y	Test data with the electric heater head confirms performance.
The PCU output operational range shall be 2.4 to 14.4 kW_e (20 to 120 percent).	Y	The PCU could not be tested at 14.4 kW_e because of difficulties with the electrically heated heads, but it should be capable of operating at this level.
The PCU shall include a sodium-potassium (NaK)-to-gas hot-side heat exchanger for heat input with a stainless steel 316L NaK pressure boundary.	N	This requirement was waived because of difficulties encountered in fabricating the original NaK head. The new head design allows NaK to contact Inconel; however, the NaK head will be retired after the test.
The hot-side NaK change in pressure ΔP shall be at most 7 kPa at 1.75 kg/s NaK flow.	Y	Fluent finite element analysis (FEA) indicates <2 kPa ΔP.
The PCU nominal NaK supply temperature shall be 850 K, with a maximum of 925 K (p. 70 of contract).	N	The PCU was designed to handle an NaK supply temperature of up to 875 K.
The PCU shall include gas-to-water cold-side heat exchangers for waste heat removal with titanium fluid loop connections.	N	The titanium requirement was waived; the connections are stainless steel.
The cold-side heat exchanger water ΔP shall be at most 15 kPa at 0.375 kg/s water flow.	Y	Fluent FEA analysis indicates <13 kPa ΔP.
The PCU nominal water supply temperature shall be 375 K, with a maximum of 450 K.	N	The PCU was designed to handle a water supply temperature of up to 400 K.
The PCU shall include at least 30 thermocouples, 4 gas pressure transducers, and provisions to measure two voltage, two current, two frequency, two power, and two displacement signals.	N	Only one pressure transducer was needed; the other requirements were met.
The PCU dry mass shall be at most 300 kg.	Y	The PCU weighs 269 kg.
The PCU outside dimensions shall be at most 1.5 m long by 0.5 m wide by 0.5 m tall.	Y	The PCU dimensions are 1.4 by 0.4 by 0.5 m.

TABLE XIII.—POWER CONVERSION UNIT CONTROLLER REQUIREMENTS

Requirement	Met?	Comments
Collect data, relay command signals, and supply startup electric power for the Power Conversion Unit (PCU)	Y	
Provide power conditioning including alternating-current to direct-current (AC–DC) conversion, parasitic load control, and voltage regulation	Y	
Be located outside of the vacuum chamber with interface wiring to the PCU	Y	
Have the capability to collect at least 100 data signals at a rate of 1 scan/s	Y	
Use National Instruments (NI) data and control modules	Y	
Include the computer interface to display data, save data, enter test limits, and enter commands	Y	
Include the communication bus for sending data to the data acquisition system	Y	It uses Labview shared variables,
Have the capability to set and hold piston stroke	Y	
Convert the alternator output to 120±6 V_{DC}	N	This requirement was deleted because of project funding irregularities and multiple replan efforts.
Regulate the DC output voltage for PCU input power levels from 6 to 13.2 kW_e (50 to 110 percent)	Y	
Shall have a maximum input power rating of 14.4 kW_e	Y	
Shall have an AC–DC conversion efficiency of at least 90 percent at 12-kW_e input power	Y	
Shall use parasitic load control	Y	
Shall include a parasitic load radiator to dissipate total PCU power output	Y	This capability is in the voltage shunt module.
Shall include a means to switch power to the electric load simulator	N	This capability required the direct-current to direct-current (DC–DC) convertor, which was cut from the project because of funding.
Supply electric power to the PCU for startup	Y	
Include provisions to measure at least four voltage, four current, two frequency, four power, and two displacement signals	N	The PCU measures two voltage, two current, two frequency, two power, and four displacement signals.
Shall house controller components in a standard 19-in. rack; the Parasitic Load Resistor (PLR) may be located outside of the rack owing to size and thermal management concerns	Y	

References

1. Wood, J. Gary, et al.: Free-Piston Stirling Power Conversion Unit for Fission Surface Power, Phase I Final Report. NASA/CR—2010-216750, 2010.
2. Locci, Ivan E.; Bowman, Cheryl L.; and Gabb, Timothy P.: Development of High Temperature Dissimilar Joint Technology for Fission Surface Power Systems. Proceedings of the 4th International Brazing and Soldering Conference, 2009.
3. An International Code 2010 ASME Boiler & Pressure Vessel Code. Section VIII, Division 2, American Society of Mechanical Engineers, New York, NY, 2011.