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Overview of Multi-Kilowatt Free-Piston Stirling Power Conversion Research at Glenn Research Center

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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 and a pair of commercially available pressure wave generators (which will be plumbed together to create a high power Stirling linear alternator test rig) have been procured for in-house testing at Glenn Research Center (GRC). Delivery of both the Stirling convertors and the linear alternator test rig is expected by October 2007. The 1 kW class free-piston Stirling convertors will be tested at GRC to map and verify performance. The convertors will later be modified to operate with a NaK liquid metal pumped loop for thermal energy input. The high power linear alternator test rig will be used to map and verify high power Stirling linear alternator performance and to develop power management and distribution (PMAD) methods and techniques. This paper provides an overview of the multi-kilowatt free-piston Stirling power conversion work being performed at GRC.

Nomenclature

DOE	Department of Energy
FSP	Fission Surface Power
FSPS	Fission Surface Power System
GRC	Glenn Research Center
HPLATR	High Power Linear Alternator Test Rig
ISS	International Space Station
NaK	Sodium-Potassium
MSFC	Marshall Space Flight Center
PMAD	Power Management and Distribution
PTC	Primary Test Circuit
TDU	Technology Demonstration Unit

Introduction

Free-piston Stirling power conversion has been identified as a viable option for potential Fission Surface Power (FSP) systems on the moon and Mars (Mason 2006a; 2006b). Recent studies have examined the use of Stirling convertors coupled to a low temperature (<900 K), uranium-dioxide fueled, liquid-metal-cooled reactor for potential lunar application in year 2020. The concept resulted from a 12 month NASA/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.

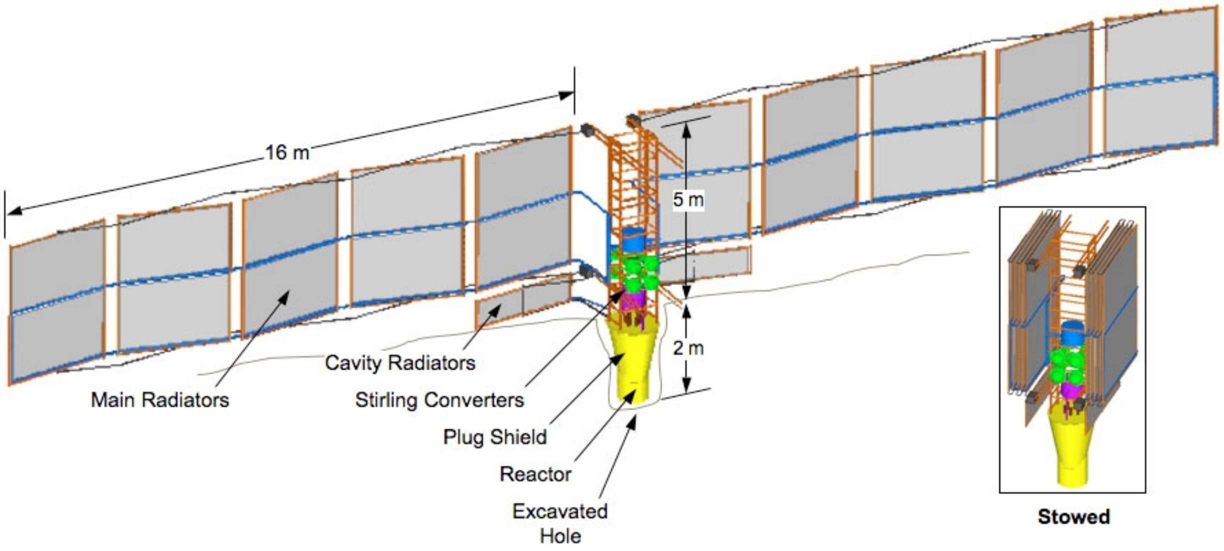


Figure 1.—Deployed and Stowed versions of Emplaced FSPS.

In addition, all materials and components are compatible with the Martian environment. A Mars-based system is expected to be very similar in configuration, set-up, and operations. The slightly colder average thermal environment at Mars could result in greater power output or permit the system to be operated at lower reactor temperature to extend life.

The notional Fission Surface Power System (FSPS) is shown in figure 1 in both the deployed and stowed configurations. The FSPS configuration is based on emplacing the reactor in a 2 m deep by 1.5 m diameter hole to provide shielding. This results in a radiation dose from the FSPS of less than 5 rem/yr to an exposed astronaut at 100 m from the reactor centerline, approximately 10 percent of the natural background dose. The emplaced configuration permits near-outpost siting of the reactor to simplify the installation and power transmission. The stowed envelope is approximately 3 by 3 by 7 m tall. The deployed span is approximately 34 m tip-to-tip and 5 m above grade. The bottom edge of the radiator is approximately 1 m above the surface to reduce the potential for dust on the radiator surfaces.

The FSPS consists of five modules (1) Reactor, (2) Shield, (3) Power Conversion, (4) Heat Rejection, and (5) Power Management and Distribution. The Reactor Module includes the fueled core, pressure vessel, and primary heat transport subsystem that delivers the reactor heat to the power conversion module via the liquid metal coolant (Sodium-Potassium-NaK) at an outlet temperature of 900 K. The Reactor Module also includes a cavity radiator subsystem to dissipate waste heat generated within the excavation. The Shield Module consists of boron-carbide and stainless steel cap or “plug” above the reactor to protect equipment from radiation damage.

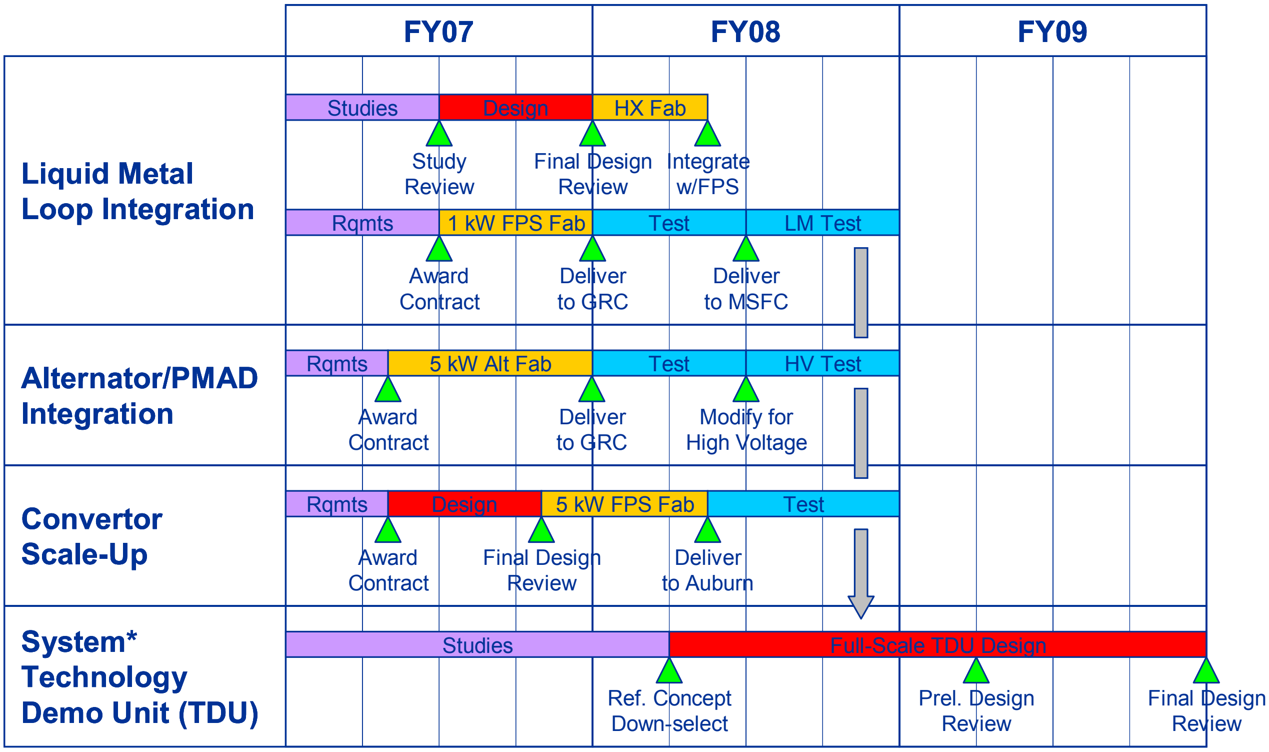
The Power Conversion Module includes four dual-opposed Stirling converters operating at a hot-end temperature of 830 K and cold-end temperature of 415 K. Each converter pair produces 12 kW (total of 48 kWe at full power) via two linear alternators supplying 400 Vac at 100 Hz, and partial system power can be provided with as few as one converter operating (Mason, Poston, and Qualls, 2008). The Stirling converter’s waste heat is dissipated by the Heat Rejection Module, consisting of four, independent pumped water coolant loops coupled to composite radiator panels operating at 400 K. The vertical, two-sided radiator panels are deployed from a central truss via a scissor mechanism, similar to the International Space Station (ISS) radiators.

The PMAD includes the transmission cabling, power controls, and electrical bus interface. The 400 Vac Stirling output is delivered directly to the PMAD power hub, where it is converted to 120 Vdc for distribution to the loads. The gross Stirling power output of 48 kWe is sufficient to account for FSPS auxiliary loads (pumps, motors, etc.) and PMAD losses in providing a net power of 40 kWe available at the PMAD power hub. A parasitic load radiator in the PMAD Module dissipates excess electrical power not consumed by the outpost loads. The system is intended to operate autonomously. A remote operations console located within a hab module would provide health monitoring and a local control interface for the crew.

Multi-Kilowatt Stirling Technology Development

In order to reduce development risk and address design questions related to the notional 40 kW FSPS, NASA has begun long lead technology development on multi-kilowatt Stirling power conversion under the Fission Surface Power Technology Project, as shown in figure 2. There are four main activities related to Stirling (1) Liquid Metal Loop Integration, (2) Alternator/PMAD Integration, (3) Converter Scale-Up, and (4) Technology Demonstration Unit (TDU).

The Liquid Metal Loop Integration task has two separate subtasks. First, a pair of 1 kW commercial Free-Piston Stirling (FPS) converters will be procured and assembled into a test rig. In parallel, a liquid metal heat exchanger will be designed and fabricated for use on the 1 kW converters to permit integrated testing with an existing NaK heat loop (Garber, 2007) at Marshall Space Flight Center (MSFC). The Alternator/PMAD Integration task involves the procurement of two 10 kW linear motor/alternator pressure wave generators that will be plumbed together to simulate the input characteristics of a Stirling heat engine. The Converter Scale-up task is an activity with Auburn University and Foster Miller (Brandhorst, 2007) to design and fabricate a 5 kW FPS converter with design lineage to the 1980’s converters built and tested by Mechanical Technology Inc under the NASA SP-100 Program (Dochat and Dhar, 1989). Each of these activities is aimed at providing data to support the design of a full-scale FSP converter prototype for use in an end-to-end system TDU test. The TDU test would be conducted with a pair of 6 kW opposed piston converters coupled to a liquid metal reactor simulator and a full-scale radiator in thermal vacuum.



* System is full-scale, 1/4th power and includes 48 kWt reactor simulator, 2x6 kWe Stirling convertors, and 36 kWt radiator.

Figure 2.—Near Term Multi-Kilowatt Stirling Development Plan.

1 Kilowatt Stirling Converters

Two P2A (formerly known as EG-1000) 1 kW free-piston Stirling power convertors were procured from Sunpower Inc., of Athens, Ohio, and are scheduled for delivery to GRC by October, 2007. The P2As produce 1.1 kWe at their design operating conditions of a 550 °C hot-end temperature, a 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 to be delivered to GRC will be configured with electric heater heads to simplify initial performance map testing. The P2A is shown in figure 3 (Kim, Huth, and Wood, 2005) and its nominal operating conditions are shown in table 1. Typical P2A performance is shown in figure 4 (Kim, Huth, and Wood, 2005).

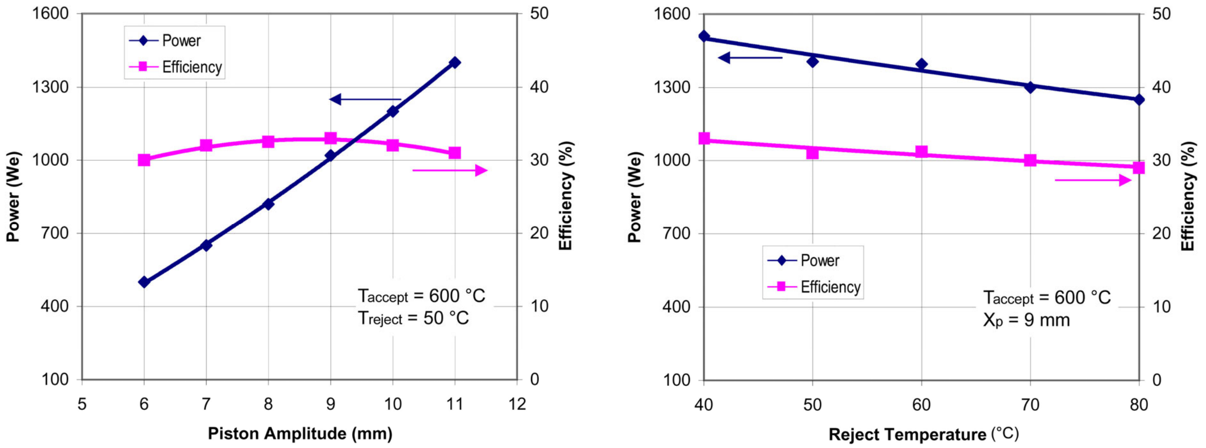
The P2A is a commercially available convertor; Sunpower has sold over 100 units in Europe with over 30 units sold over the past 3 years. There have been no reported failures of any of these units when operated within specifications. The P2A was originally designed to operate in a cogeneration system (Kim, Huth, and Wood, 2005). Cogeneration is the use of a heat engine to simultaneously generate both

TABLE 1.—P2A NOMINAL OPERATING CONDITIONS

Parameter	Value
Nominal Hot-End Temperature (°C)	550
Nominal Cold-End Temperature (°C)	50
Charge Gas	Helium
Charge Pressure (MPa)	3.0
Nominal Operating Frequency (Hz)	50
Nominal Output Voltage (Vac)	240
Nominal Generator Output Power (kW)	1.1
Alternator Efficiency (%)	90
Generator Efficiency (%)	31
Engine/Alternator Mass (w/o Vibration Absorber) (kg)	35

(Photo Courtesy of Sunpower, Inc.)

Figure 3.—P2A 1 kWe Free-Piston Stirling Convertor.



(a) P2A Power and Efficiency vs. Piston Amplitude.

(b) P2A Power and Efficiency vs. Reject Temperature.

Figure 4.—Typical P2A 1 kWe Free-Piston Stirling Convertor Performance *(Courtesy of Sunpower, Inc.)*.

electricity and useful heat. Eleven P2As are currently in field trials in Europe as part of a domestic cogeneration system. Based on the number of units that have been built and operated, the P2A should serve as an ideal test bed convertor.

A test facility is being prepared for testing the P2A convertors at GRC. The convertors will be initially tested in a dual-opposed configuration and will be operated over a range of hot-end temperatures (450 to 550 °C), cold-end temperatures (30 to 70 °C), and piston amplitudes (6 to 11 mm). The convertors may also be tested individually using a balancer. Testing is expected to begin in late 2007. The electric power output, convertor efficiency, alternator voltage and current, and temperatures will be recorded. The purpose of this performance map testing is to establish the baseline convertor performance prior to reconfiguring them for operation with a NaK pumped loop. This data will aid engineers in evaluating the performance of the NaK heat exchanger/P2A heater head discussed in the next section.

NaK Heat Exchanger/P2A Heater Head Design

NASA Glenn Research Center of Cleveland, Ohio, SEST Inc., of Middleburg Hts., Ohio, and Sunpower Inc., of Athens, Ohio, have designed a heat exchanger/heater head for the P2A convertors that should allow operation of the convertors with a NaK pumped loop. While earlier NASA GRC efforts (Dhar 1999) 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.

The initial design trade-space efforts focused on different heat exchanger mechanical configurations. Since GRC and MSFC are planning to test the P2A convertors in the Fission Surface Power Primary Test Circuit (FSP-PTC), located at MSFC, it was also necessary to incorporate the facility operating characteristics/limitations into this study. Performance tradeoffs were made with respect to the liquid metal loop pressure drop through the heat exchanger and the temperature distributions along the heater head wall while maintaining various levels of convertor output power. In addition, the mechanical/thermal integration of the proposed NaK heat exchanger with the convertor had to be fully incorporated since a number of unique manufacturing and assembly constraints are imposed by the current P2A hardware. The relative performance and hardware integration risk of each potential approach was evaluated. Throughout this process, an effort was made, when ever possible, to employ currently understood liquid metal system “best practices” so as to insure that the resulting heat exchanger is as representative as possible to those needed in future higher power 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.

From the start of the liquid metal heat exchanger design process, it was evident that the optimal heating of the Stirling convertor required careful consideration of heat exchanger geometry and fluid flow conditions both within the heat exchanger itself and the entering/exiting flow manifolds. This is due to the fact that the liquid metal heat transfer coefficients are of limited accuracy due to a lack of empirical data and the sensitivity of the desired wall flux distribution to fluid flow maldistributions. To overcome these issues, the basic approach employed in the heat exchanger development was to first carry out an initial evaluation of the overall heat exchanger, integrated with the known P2A heat exchanger requirements, using conventional design tools. This process allowed the key attributes of the various heat exchanger configurations to be evaluated. This was followed by the use of Computation Fluid Dynamic (CFD) analyses techniques for the candidate designs using FLUENT (Fluent, 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. The results of the CFD analysis for the selected preliminary NaK heat exchanger design are shown in figure 5.

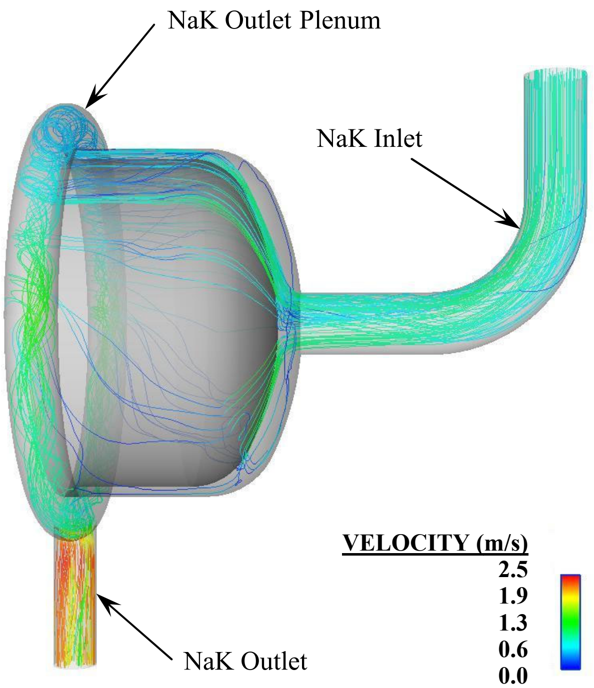


Figure 5.—CFD Analysis of NaK Heat Exchanger for P2A.

The resulting integrated liquid metal heat exchanger/P2A heater head/convertor configuration for a single convertor is shown in figure 6. The dual opposed convertor configuration will employ two independent convertors/heat exchanger assembles mounted “head-to-head” so as to minimize vibration-induced loads on the test setup. A mechanical support structure will connect the alternator pressure vessel portions of the two convertors and will act as the mount for the entire assembly within the vacuum chamber portion of the FSP- PTC. A common supply line from the test facility will provide the liquid metal to each convertor. The entire heat exchanger and regenerator portions of the assembly will be contained within a single high temperature insulation package.

To date all indications are that the primary goal of the NaK heat exchanger/P2A heater head design effort have been met and the convertor performance will be comparable to, or exceed, that of the P2A configured with the electric heater head.

High Power Linear Alternator Test Rig

Two Pressure Wave Generators (PWGs) have been procured from Clever Fellows Innovation Consortium (CFIC), of Troy, New York, and are scheduled for delivery to GRC by October, 2007. Each PWG unit consists of two CFIC STAR linear motors (relevant technology to high power Stirling FPSE designs) that are mounted in a dual-opposed configuration for balanced operation. The PWGs will be plumbed together to create a High Power Linear Alternator Test Rig (HPLATR). One of the PWGs (drive motor unit) will be used to generate the pressure wave that will drive the other PWG (test alternator unit) similar to the way a Stirling convertor creates a pressure wave that drives its power piston. A photograph of the PWG unit (Corey, 2006) along with a photograph of a PWG pair configured as a HPLATR is shown in figure 7. The nominal operating conditions of the PWG are given in table 2.

The PWGs have no wearing parts or lubrication needs, which means long-life and no scheduled maintenance. CFIC has sold a total of ten PWG units of this power level over the past few years. There have been no reported failures of any units when operated within specifications.

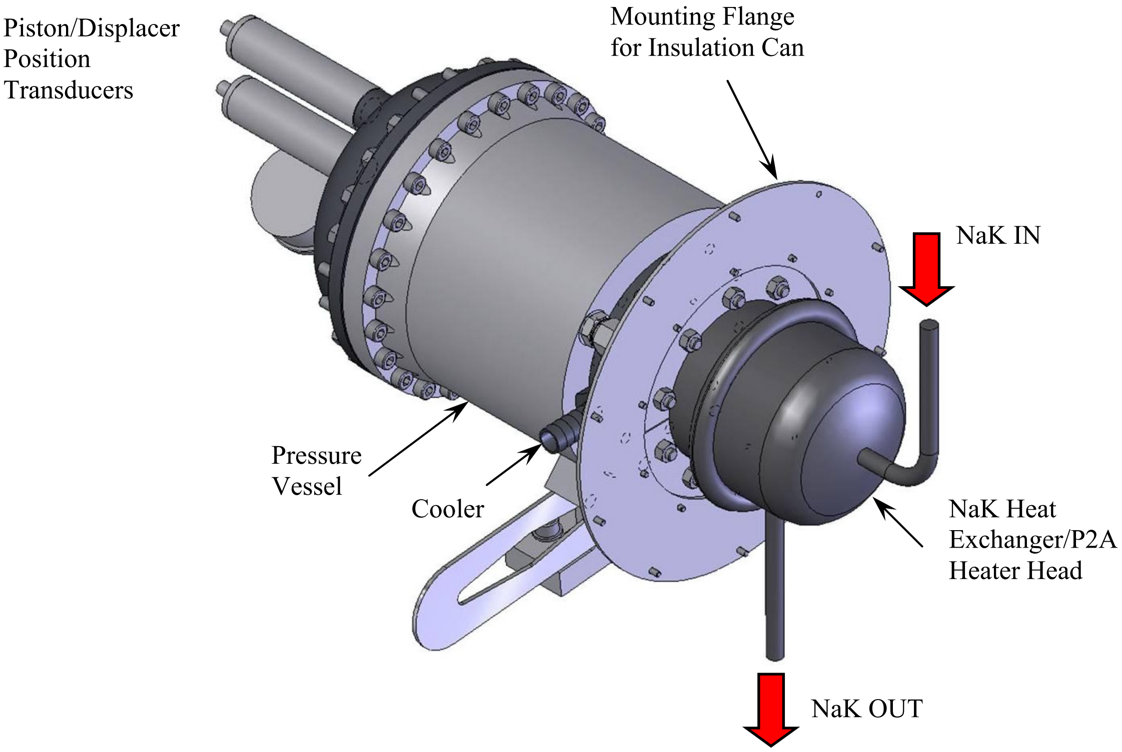
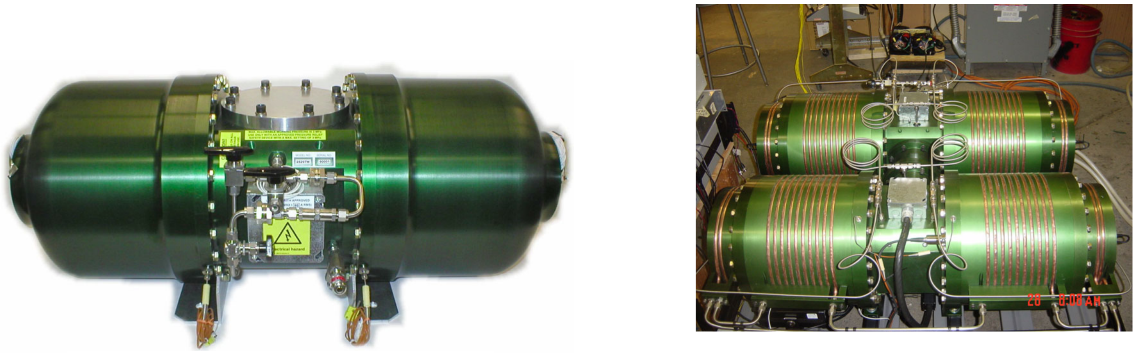


Figure 6.—P2A Convertor Equipped With a Nak Heat Exchanger/Heater Head.



(a) Commercially Available 10 kWe PWG.

(b) Two PWGs Configured as HPLATR.

Figure 7.—CFIC Pressure Wave Generators (PWGs) *(Courtesy of CFIC, Inc.).*

TABLE 2.—PWG NOMINAL OPERATING CONDITIONS

Parameter	Value
Charge Gas	Helium
Charge Pressure (MPa)	4.0
Nominal Operating Frequency (Hz)	90
Nominal Voltage (Vac)	330
Nominal Motor Input Power (kW)	10
Motor Efficiency (%)	90
Mass (kg)	270

The HPLATR will be used to develop a Power Management and Distribution (PMAD) system applicable to a lunar power system. The PMAD consists of the control algorithms and power electronics required for the conversion of the single phase ac output of the Stirling alternator to a regulated dc voltage for use in lunar applications. The task will include simulated power transmission over a few hundred meters, rectification, filtering, and regulation of the ac output, distribution of the power to simulated loads, and control of the Stirling power convertor piston amplitude. Testing will determine the power quality of the dc output voltage, including transient response and determine system efficiencies and mass.

Conclusions

Significant progress has been made toward reducing the development risk associated with the development of Stirling power conversion technology for potential FSP applications. A pair of proven 1 kWe free-piston Stirling power convertors has been procured for the purpose of demonstrating that a Stirling power convertor can be integrated with a NaK pumped loop using modern materials and technology. A NaK heat exchanger/P2A heater head has been designed to facilitate this demonstration. A high power linear alternator test rig has been procured for developing the PMAD system needed for surface power applications. Stirling technology is a viable option for FSP applications.

References

Brandhorst, H.W., "New 5 Kilowatt Free-Piston Stirling Space Convertor Developments," in proceedings of *Space Technology and Applications International Forum (STAIF-2007),* edited by M.S. El-Genk, American Institute of Physics, Melville, New York, 2007, pp. 466–471.

Corey, J.A., Clever Fellows Innovation Consortium, Inc., "Pressure-Wave Generators—2S297W," (2006), http://www.qdrive.com/index.php?id=54, accessed October 10, 2007.

Dhar, M., *Stirling Space Engine Program, Volume1 - Final Report*, NASA CR 1999-209164/VOL1, NASA Glenn Research Center, Cleveland, OH, 1999.

Dochat, G.R., and Dhar, M. "Free-Piston Space Stirling Technology Program," in proceedings of the *Twenty-fourth Intersociety Energy Conversion Engineering Conference*, Volume 2 (A90-38029 16-20), edited by W.D. Jackson and D.A. Hull, Institute of Electrical and Electronics Engineers, New York, NY, 1989, pp. 849–854.

Garber, A.E., "Capabilities and Testing of the Fission Surface Power Primary Test Circuit (FSP-PTC)," in proceedings of *Space Nuclear Conference 2007*, American Nuclear Society, La Grange Park, IL, 2007, paper 2030.

Kim, S.Y., Huth, J., and Wood, J.G., "Performance Characterization of Sunpower Free-Piston Stirling Engines," in proceedings of *3rd International Energy Conversion Engineering Conference*, San Francisco, California, 2005, paper AIAA 2005-5540.

Mason, L.S., "A Comparison of Fission Power System Options for Lunar and Mars Surface Applications," in proceedings of *Space Technology and Applications International Forum (STAIF-2006)*, edited by M.S. El-Genk, American Institute of Physics, Melville, New York, 2006a, pp. 270–280, NASA/TM—2006-214120, NASA Glenn Research Center, Cleveland, OH, 2006a.

Mason, L.S., "A Practical Approach to Starting Fission Surface Power Development," in proceedings of *International Congress on Advances in Nuclear Power Plants (ICAPP'06)*, American Nuclear Society, La Grange Park, IL, 2006b, paper 6297, NASA/TM—2006-214366, NASA Glenn Research Center, Cleveland, OH, 2006b.

Mason, L.S., Poston, D.I., Qualls, A.L., "System Concept for Affordable Fission Surface Power," in proceedings of *Space Technology and Applications International Forum (STAIF-2008)*, edited by M.S. El-Genk, American Institute of Physics, Melville, New York, 2008.

Penswick, L.B., *1050 K Stirling Space Engine Design*, NASA CR 182149, NASA Lewis Research Center, Cleveland, OH, 1988.

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13. SUPPLEMENTARY NOTES

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 and a pair of commercially available pressure wave generators (which will be plumbed together to create a high power Stirling linear alternator test rig) have been procured for in-house testing at Glenn Research Center (GRC). Delivery of both the Stirling convertors and the linear alternator test rig is expected by October 2007. The 1 kW class free-piston Stirling convertors will be tested at GRC to map and verify performance. The convertors will later be modified to operate with a NaK liquid metal pumped loop for thermal energy input. The high power linear alternator test rig will be used to map and verify high power Stirling linear alternator performance and to develop power management and distribution (PMAD) methods and techniques. This paper provides an overview of the multi-kilowatt free-piston Stirling power conversion work being performed at GRC.

15. SUBJECT TERMS

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