Progress in High Power Free-Piston Stirling Convertor Development

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ABSTRACT

The U.S. Space Exploration Policy has established a vision for human exploration of the moon and Mars. One option for power for future outposts on the lunar and Martian surfaces is a nuclear reactor coupled with a free-piston Stirling convertor at a power level of 30-40 kWe. A 25 kW convertor was developed in the 1990s under the SP-100 program. This system consisted of two 12.5 kWe engines connected at their hot ends and mounted in tandem to cancel vibration. Recently, NASA began a new project with Auburn University to develop a 5 kWe, single convertor for use in such a possible lunar power system. Goals of this development program include a specific power in excess of 140 We/kg at the convertor level, lifetime in excess of five years and a control system that will safely manage the convertors in case of an emergency. Foster-Miller, Inc. is developing the 5 kWe Stirling Convertor Assembly. The characteristics of the design along with progress in developing the system will be described.

1. INTRODUCTION

The U.S. Space Exploration Policy proposed an ambitious program to return astronauts to the Moon by the year 2018. The mission plan looks much like the Apollo missions. NASA has announced an initial target for an outpost at the lunar South Pole on the edge of the Shackleton Crater. That location was chosen because of its' abundant sunlight (>60% on a monthly basis) which permits solar arrays to be used in the initial deployment. This abundance of sunlight minimizes the energy storage requirements. The use of photovoltaic power systems also allows incremental development of the outpost. Although power requirements are not clear at this time, it appears that power levels will rise from the level of a few kilowatts to anywhere from 25 to 50 kWe as development of in-situ resources increases. Key products envisioned include water from the crater and oxygen from the regolith.

In the 1990s, NASA developed a 25 kW free piston Stirling Space Power Demonstrator Engine for the SP-100 program shown in Fig. 1 [1,2]. This system

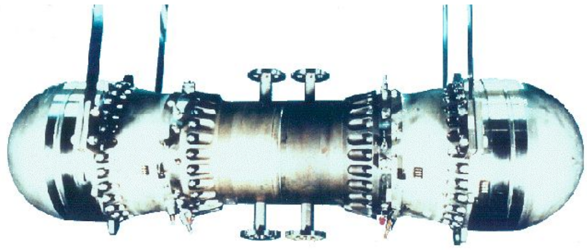

Figure 1 25 kWe Space Power Demonstrator Engine (1992)

consisted of two 12.5 kW engines connected at their hot ends and mounted in a linear arrangement to cancel vibration. Thermal input was introduced in the center through an innovative heater head. After operating for about 1500 hrs as a dual engine system, the unit was separated into two individual "Space Power Research Engines" (SPRE) for further study. An improved version of the SPRE, the Component Test Power Convertor (CTPC) was also designed, fabricated successfully.

The free-piston Stirling conversion system offers significant advantages over other dynamic conversion systems such as Rankine or Brayton. Operating in an opposed-piston configuration, the engines are dynamically balanced. In addition, the FPSE operates with high efficiencies (>30%) at T_H/T_C ratios of 2 to 2.5 (instead of 3+ as the other systems require), this leads to a heat rejection radiator that is smaller than the Brayton or Rankine options. If all systems are operating at the same hot input temperature, the rejection temperature of the Stirling system is higher leading to reduced radiator mass and area which leads to cost reductions.

One common feature to these three conversion systems is that they naturally produce alternating current instead of direct current that has been used in space from the beginning. Conversion to direct current reduces overall system efficiency; therefore some consideration in the lunar architecture should be given to alternating current systems.

Because the future possible NASA power needs on the Moon range from 25 to 50 kWe, specific mass of the Stirling convertor is important. As noted above, in the 25 kWe Space Power Demonstrator Engine, the system goal was a T_H of 1050 K (777 ºC) and T_C of 525 K (252 ºC) and a temperature ratio of 2. In order to save time and costs, the convertor was made from Inconel 718 and operated at a hot-end temperature of 650 K (377 ºC) and a cold-end of 325 K (52 ºC). This program laid a solid foundation for future large free-piston Stirling conversion systems and demonstrated the feasibility of this type of conversion system for space power applications.

The specific mass estimates based on known technology advances at that time projected a convertor mass over 200 We/kg (4.9 kg/kWe) from its 140

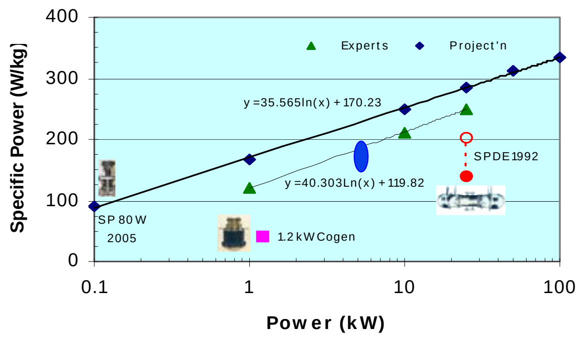

Figure 2 Specific Power Projections for Free-Piston Stirling Convertors.

We/kg (7.1 kg/kWe) value. Thus with the new developments in better understanding these engine-alternator assemblies, the specific mass should be within this range, although 100 We/kg for the 80 We engine hardware represents the current state of art for these small, ~100 We Stirling convertors. Figure 2 shows estimations of the trend in specific power of present day designs as the power level increases. A trend line based on the slope of expert opinions from Sunpower, Inc. and Infinia Corp., and starting with the Sunpower 80 We Stirling is shown with the diamond symbols. These experts have had experience with larger, multi-kilowatt units in addition to their current efforts with smaller sizes. The expert opinions are shown by triangle symbols but to be sure, any extrapolations to larger sizes must be considered speculative at this time. The projections made for the SPDE shows how the technology has improved since 1992. Based on these projections and the demonstrated range of the SPDE, the range of specific power for the 5 kWe developments was established as the ellipse at 5 kWe and spans from 140 to 200 We/kg. A point of 140 We/kg was selected as a goal value. Thus a new free-piston Stirling convertor development at larger sizes is needed to provide a sound basis for potential fission-based lunar surface power. The development of this new convertor will help firm up these projections.

2. NEW 5 kW FREE-PISTON STIRLING CONVERTOR DESIGN

In order to provide the technological infrastructure for Stirling power conversion subsystems for fission surface power systems on the Moon and to take advantage of the most recent developments in low-mass free-piston Stirling convertors, a new project aimed at a nominal 5 kWe convertor system has been initiated. The 5 kWe size was selected based on previous studies outlined above. No current free-piston Stirling manufacturer in the U.S. has such a unit and detailed requirements for the lunar system have not been defined.

As noted above, the Stirling Converter Assembly (SCA) is based on the Space Power Demonstrator Engine (SPDE) and Component Test Power Converter (CTPC) demonstrated under NASA contract[1,2] but with certain differences due to cost and time constraints. Foster-Miller is responsible for the design and fabrication of an SCA demonstrator, as well as prototype test to characterize dynamics and steady-state operation and determine power output and system efficiency. The Space Research Institute of Auburn University is responsible for performance tests to determine start-up and shutdown characteristics and assess transient response to temperature and load variations.

In order to have a consistent starting point for the 5 kWe designs, a common set of "assumed" reference requirements has been created because NASA has not yet defined the requirements for a lunar fission power system. Furthermore, multiple options exist for the conversion subsystem. Therefore, the requirements

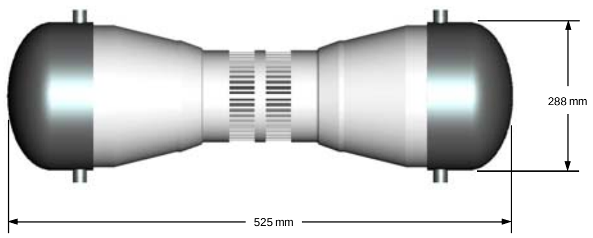

Figure 3 10 kWe Conceptual Reference Convertor

provided in this section are not sanctioned by NASA, but serve as a possible set for a Stirling power conversion system. A panel of industry, university and NASA experts created the list collaboratively.

First, because most of the studies of a lunar fission power system ranged from 25 to 50 kWe, a level of 30-40 kWe was selected. The minimum-sized building block was the 5 kWe Stirling Convertor Assembly (SCA). Two 5 kWe SCAs connected together are dynamically-balanced and will deliver 10 kWe. Three such pairings deliver 30 kWe etc. Because of the mass of the reactor system, efficiency was considered more important than mass, however a goal near the 140 We/kg is still desired.

A hot-end temperature of 830 K (557 ºC) was chosen for the "reference design" and assumed Inconel 718 would be used. This eliminates the need for a new materials data base. A schematic diagram of the reference convertor at 10 kWe is shown in figure 3. This condition led to choosing a cold-end temperature of 415 K (142 ºC) in order to achieve a T_H/T_C ratio of 2. The lower temperature is at least 100 K above the average lunar temperature of 315 K (42 ºC). A lifetime of 5 years at full power was chosen with a 2 MRad total dose. The controller must be able to protect the Stirling convertor against sudden open circuit and a sudden short circuit and control a range from 50 to 120% power output. The control system will also monitor all temperatures and protect against any over-temperature condition and control the stroke and other internal conditions to ensure successful operation.

Design parameters for the SCA are operation at a hot-end temperature of 830 K and a cold-end temperature of 415 K, with a nominal power output of 5 kWe, a peak power output of 6 kWe with over stroke, and a design life of 5 years (44,000 hr) of continuous operation at 100% power level. The working gas is high-pressure (15 MPa) helium, and the convertor operates at a resonant frequency of 85 Hz. The output voltage of the SCA will be 400 Vrms at 85 Hz based on early NASA studies of the power distribution system of the lunar outpost.

The final design goal is to achieve a minimum of 25% overall efficiency (electrical power out over heat in) and a specific mass of 6 kg/kWe. Substitution of materials such as alloy steel for beryllium, use of a commercially available linear alternator, and inclusion of bolted joints for convenience will preclude achievement of the efficiency and specific mass goals at this time. Facilities limitations will also constrain testing of the hot end to 617 K at Foster-Miller and 650 K at Auburn University.

3. DEMONSTRATOR DESIGN PARAMETERS

As noted above, the demonstrator convertor will have a T_H of 650 K (377 ºC) and a T_C of 325 K (52 ºC). The nominal power output is 5 kWe with a peak output of 6 kWe. The efficiency goal is 25% and the specific mass is 6 kg/kWe for the reference design. The life goal is 5 years of continuous operation (44,000 hours) at 100% power. Foster-Miller's design of the convertor has been guided by their existing HFAST codes with NASA Glenn Research Center (GRC) making backup calculations using the Sage code. GRC is also supporting the design via three-dimensional computational fluid dynamics (CFD) modeling of the gas bearings and the rest of the engine working space. The output voltage of the SCA is 400 VAC at 85 Hz based on early NASA studies of the power distribution system of the lunar outpost. A cut-away diagram of the convertor is shown in Fig. 4.

3.1 Hot End Assembly

The hot-end assembly consists of the three heat exchangers: the heater head, regenerator, and cooler. The heater head and cooler are both shell and tube heat exchangers, each with 1800 small diameter tubes (0.89 mm ID, 1.65 mm OD). The ends of each tube are electron-beam welded to the tube sheets. Figure 2 shows a photograph of the heater head and cooler prior to electron-beam welding of the tubes. The heater shell, cooler shell, and tubes are constructed of Inconel 718. The regenerator is constructed of a porous metal matrix with 80% porosity (20% density) brazed to an inner and outer metal liner. The matrix is a sintered structure of randomly arranged metal fibers 0.022 mm in

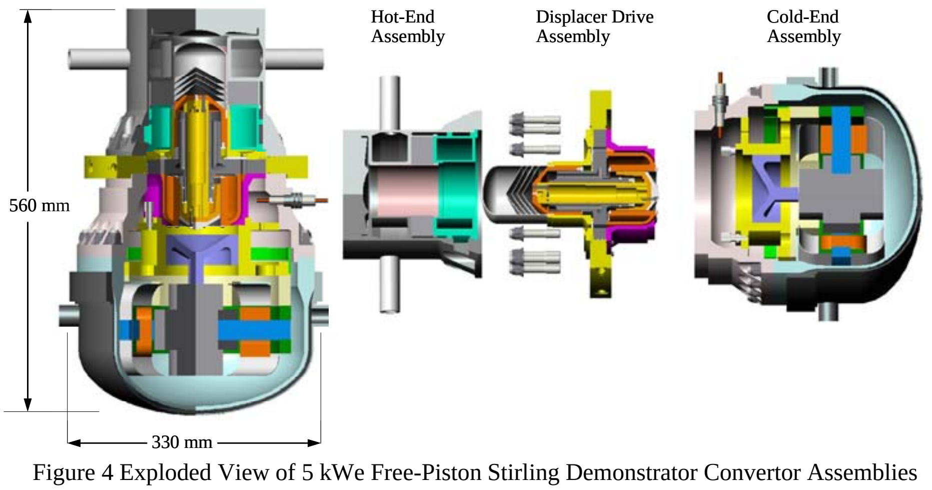

Figure 4 Exploded View of 5 kWe Free-Piston Stirling Demonstrator Convertor Assemblies

diameter. The matrix is type 316 stainless steel; the inner and outer liners are Inconel 718. Fabrication of these components has required multi-step processes due to the intricacy of the design and particular challenges inherent in their manufacture. The hot end pumped loop has been provided by HEAT, Inc. and provides 650 K (377 ºC) temperatures with Therminol VP-1 fluid. The cold end pumped loop is a water-glycol system that supplies temperatures from 275 to 415 K (2 to 142 ºC). Testing at Foster-Miller will be done at a hot end temperature of 617 K (344 ºC).

Figure 5 Heater head and cooler assemblies

3.2 Displacer Drive Assembly

The displacer drive pumps the helium through the heat exchangers (see Fig. 6 for a photograph of several displacer drive components). It consists of the displacer (dynamic component) and the post and flange (stationary component). The displacer consists of a central rod, a displacer dome and its support on the hot end, and the gas spring piston on the cold end. Two gas springs, one on each end, provide the spring stiffness needed to establish resonance. The forward spring is relatively weak (24% of stiffness) versus the aft spring (76% of stiffness). The rod provides the bearing support for the displacer drive. An internally pumped hydrostatic gas bearing is used in the SCA design for long life. All components in the displacer drive are alloy steel, with the exception of the displacer dome, which is Inconel 718 due to exposure of the dome to the hot expansion space. In the CTPC, the equivalent steel parts were fabricated from beryllium for its low density and high stiffness. Because of the additional losses in the gas springs suspending a heavy steel displacer, a penalty of approximately 3.5 points in efficiency is predicted. Since the bearings are not active during initial engine start-up, a compliant wear couple is used on the bearing and seal surfaces to tolerate transitory contact. The inside diameters of the cylinders are plated using Poly-Ond®, and the outside diameters of the rod and pistons are coated with Xylan® 1054.

Figure 6. Displacer drive components: post and flange, gas spring cylinder, gas spring piston (l to r)

3.3 Cold End Assembly

The cold-end assembly consists of the alternator assembly, pressure vessel, and joining ring. The alternator assembly includes the linear alternator, power piston and cylinder, and the suspension system. A flexure support is used instead of a gas bearing to support the piston and plunger. The flexure provides radial and circumferential stiffness which resists the forces between the magnets and stator iron. The entire alternator assembly, including power piston and cylinder, is a single assembled unit supplied by Qdrive, Inc. (Troy, NY) (see Fig. 7). The alternator is designed to deliver 5 kWe at a nominal stroke of 22 mm and 6 kWe at an overstroke of 24 mm, both at 85 Hz. To reduce lead time and expense, an off-the-shelf size was customized to obtain the power output, voltage level, and temperature capability of the design requirements. These modifications included slightly larger magnets, Hiperco laminations in the stator, samarium cobalt magnets, and custom windings. A performance penalty was accepted in lieu of an optimized custom alternator design. The current design is calculated to provide 88% efficiency at 5 kWe, versus approximately 93% efficiency with an optimized design. Similar assemblies have been operated for over 65,000 hours without failure. At the present time, the alternator has been assembled to the cooler assembly.

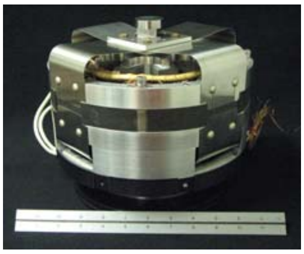

Figure 7 5 kW Star 241 Alternator

3.4 SCA Control System

The control system incorporates several novel ideas such as a pulse start capability and a piston stroke set point control strategy that provides the ability to throttle the engine to match the required output power. It also ensures stable response to various disturbances such as electrical load variations while providing useful data regarding the position of both power piston and displacer.

A key thrust of the control development effort was to establish the dynamic characteristics of a FPSE and to develop an acceptable method of controlling the piston stroke of the engine [3,4]. In order to experiment with various control strategies, without damage to the actual engine, a dynamic model of the engine was developed. We start with a linear model and then extend the analysis to a non-linear model. The non-linear model was then used to analyze different control strategies. Each control strategy was then evaluated using the nonlinear model. The dynamics of a FPSE can be modeled by a 6th order nonlinear model consisting of three pairs of complex conjugate poles. It is possible to maintain stable operation of a FPSE, at a desired stroke amplitude set point, by modulating a control resistance in parallel with a user load. Since the 6th order model is a type 0 dynamic system, integral action is required to maintain an offset error of zero in the steady state.

A master controller will monitor all subordinate controllers including: the stroke controller, the heating loop controller, and the cooling loop. In the event there is a problem with any of these subordinate controllers, the master controller will implement a safe shutdown of the entire system. A touch screen will provide the user interface for the control system. Process data will be displayed and operator functions can be performed via the touch screen.

A pair of capacitance gap sensors monitors both displacer and power piston positions. The sensors are located 180° apart and their signals averaged to eliminate variations due to eccentricities, thermal growth, and so forth. Since the sensors have a small range (~2 mm) compared to the stroke (22 mm), a taper is machined into the target to turn down the displacement.

The controller monitors both displacement signals to safeguard against an over stroke condition. It also uses the power piston stroke as the process variable in the control scheme. A separate control load is used in parallel with the user load, and by pulse width modulation (PWM) switching of the control load, a change in total load resistance is induced to maintain the piston stroke set point

4. SCA OPERATION AND TEST

The output power of the SCA is a function of the hot-end temperature, cold-end temperature, mean pressure, frequency, displacer stroke, piston stroke, and displacer-piston phase angle. In the test facility at Foster-Miller, heat will be provided via an electrically heated pumped loop using Therminol® 72 heat transfer fluid. The heating loop will have a separate controller to maintain a set temperature value up to 617 K. Heat will be rejected through a water/glycol pumped loop connected to an air-cooled radiator. A separate controller on the cooling loop will maintain a set temperature by operating a mixing valve.

Initial testing of the SCA will focus on characterizing the power output in relation to varying heater and cooler temperatures under steady-state conditions. Following this, the transient response of the converter to load and temperature changes will be tested and the controller fine-tuned. Load impedance characterization will also be performed to establish the effects of both inductive and capacitive loads on the system. Further testing will evaluate the optimum pulse start parameters, such as temperature, AC voltage, power, and burst time, that will safely and consistently start the system. Facility preparations are complete and initial testing of the convertor is expected to begin the first or second week of August, 2008.

TABLE 1 Comparison of HFAST and Sage Models for the Stirling Demonstrator Convertor at the 830/415K Design Conditions.

Value	**HFAST**	**Sage**
Total PV Power (Exp. Sp. + Cmp. Sp.) (We)	7,586	8,160
Total Heat In (Wt)	25,404	24,910
Total Heat Rejection (Wt)	17,818	16,750
Cycle Efficiency (Total PV Power/Total Heat In, %)	29.9	32.8
Power from cycle to power piston (We)	6,923	7,355
Efficiency based on power to power piston (%)	27.2	29.5
Power out of the 87.5% efficient alternator (We)	6,058	6,436
Efficiency with the 87.5% efficient alternator (%)	23.8	25.8

5. CODE COMPARISONS

Foster-Miller in cooperation with GRC has done a comparison of performance predictions using the older HFAST and the newer Sage codes as shown in Tab. 1. The HFAST code was used extensively in the SPDE and CTPC developments in the 1990 time frame. Since then, the Sage code has been developed and is the current model of choice for other NASA Stirling contractors. Both codes are based on one-dimensional fluid flow and heat transfer models using correlations derived from experiments on components.

The code comparisons for the 5 kWe convertor yield an efficiency of about 25% and indications are that more than 5 kWe of power can be produced. These tabular results do not include the "mechanical losses" such as gas spring hysteresis losses and seal leakage losses, however.

6. SUMMARY AND CONCLUSIONS

The U.S. Space Exploration Policy envisions a wide range of manned lunar missions over the next two decades. Electric power will be needed for an outpost, for example, on the edge of the Shackleton crater at the lunar South Pole. Later, as in-situ resource utilization could mature, a nuclear reactor power system providing power from 25 to 50 kWe could be implemented. Our present development effort aims at producing a Stirling convertor assembly that could be used with a future nuclear-fission-powered, 30-40 kWe Stirling powered system on the lunar surface.

The project has a specific power goal of about 140 We/kg for the Stirling power convertor assembly. The initial step is design and development of a nominal 5 kWe per cylinder Stirling convertor which could serve as a prototype of one or more SCAs that could make up a final 30-40 kWe power system. Reference requirements have been assumed to help guide development of the convertor assembly. These requirements defined the operating temperatures, lifetime, and trade-off between mass and efficiency.

Testing in summer 2008 will demonstrate performance at the 5-kWe power level. With the potential for high efficiency, low specific mass, and long life, Stirling systems are an attractive power generation technology not only for space but terrestrial applications. The present system technology will be readily extensible for use in "green" power applications that use gases from sewage digesters, landfills, and industrial processes, as well as use in military field support operations for generators powered by diesel or JP-8 fuels.

7. ACKNOWLEDGEMENTS

This work is supported by NASA through the Exploration Systems Mission Directorate, Exploration Technology Development Program, Fission Surface Power Project under NASA contract #NNC06CB81C "Development of High Efficiency, Free-Piston Stirling Convertors." Any opinions expressed are those of the authors and do not reflect the views of NASA.

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