Development of a 5 kW Free-Piston Stirling Space Convertor

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[Abstract] NASA has recently funded development of a 5 kW (or greater) free-piston Stirling conversion system for reactor power systems. A nominal 5 kW convertor allows two of these units to be dynamically balanced. A group of three dual-convertor combinations would yield the desired 30 kW. The status of this program will be presented. Goals include a specific power in excess of 140 W/kg at the convertor level, lifetime in excess of five years and AC output. The initial step is the design and development of a nominal 5 kW per cylinder Stirling convertor assembly (SCA) which will serve as a prototype of one or more SCAs that will make up the final 30 kW Stirling Convertor Power System. Assumed requirements for this new convertor for lunar fission power systems will be presented. The primary objective of this development effort will be to demonstrate a 5 kW SCA that can be tested to validate the viability of Stirling technology for space fission surface power systems.

I. Introduction

The new NASA Vision for Exploration, announced by President Bush in January 2004, proposes an ambitious program that plans to return astronauts to the moon by the 2018 time frame. The mission plan looks much like the Apollo missions. Recently NASA has announced that their initial target is 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 allows solar arrays to be used for the initial deployment. The 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 kW as in-situ resource development increases. Key products that are envisioned are water from within the crater and oxygen from the regolith. As power levels climb, nuclear power systems are envisioned.

The primary energy issue arises when stay times in excess of 14 days are envisioned. For locations other than at the poles, the 14-day long night poses challenges for an energy storage system connected to traditional solar arrays. Past studies have shown that a solar array/regenerative fuel cell system is exceptionally massive – weighing 5880 kg for a 20 kW (3.4 W/kg) system. (Kohout, 1989) On the other hand, dynamic conversion systems powered from thermal sources have been shown to be potentially lighter at about 100 W/kg. (Brandhorst, 2005) Thus there is a significant opportunity to develop new, larger free-piston Stirling convertor systems to meet future NASA needs. The options for lunar surface nuclear (fission) power systems continue to evolve. Placement of the fission power plant ranges from lander-based to locations remote from the lander. One option is shown in figure 1. (Cataldo, 2005) the power plant may be stationary or mobile. A stationary plant has lower mass and risk but requires precision landing and detailed site information. Shielding represents another set of issues. If regolith is used, regolith moving equipment is needed and dust issues become significant.

Figure 1. Lunar Nuclear Surface Power Concept

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A recent study of reactor power systems for the lunar environment envisions a 100 kWt reactor system coupled to six Stirling convertors. (Marcille, 2006) Three sets of dual 5 kW free-piston Stirling convertors would take the thermal output and provide 25 kWe. Operating in tandem, each pair will be dynamically balanced. However, the power level and other system requirements are not known at this time but will evolve with time. Additional issues such as the operating temperature of the thermal source (a materials issue), the frequency and voltage output desired and durability and lifetime of both the reactor and the conversion subsystem have also not been defined.

Reducing the mass of the Stirling convertor will also be a goal. As a data point, projections (Dhar, 1999) in 1992 of the 25 kW SPDE indicated that specific power in the range of 200 W/kg was reasonable for the technology at that time and for Stirling convertors that size. Given the specific mass improvements made in current Stirling convertors, that projection may be pessimistic. Of course hot-end operating temperature and needed materials properties to achieve the life goals will ultimately determine the specific power. This paper will present the results of recent studies and the desired characteristics of the 5 kW free-piston Stirling convertor systems for lunar applications.

II. Lunar Surface Reactor Studies

Several recent studies of lunar and Mars surface reactor studies have been presented (Marcille, 2006, Kang, 2006, Elliott, 2006, Mason, 2006, Houts, 2006)). The reactor system proposed (Marcille, 2006) has 85 UO_2 pins enriched to 93% ^{235}U and clad in SS316. This 101.8 kW_t design uses pumped NaK as the coolant with a mean outlet temperature of 880K (607ºC). Its projected lifetime is 5 years. A boiling potassium intermediate heat exchanger provides thermal input to the Stirling conversion systems. The nominal size of these convertors is 6.8 kW for a total power capability of 40 kW. This includes margin for a convertor failure and power processing efficiencies.

A recent study, (Mason, 2006) has done comparisons of nominal 50 kW class lunar and Mars surface power options with power levels from 25 to 200 kW. One option assumes a low temperature, stainless steel reactor with either liquid metal or gas cooling as a baseline. The stainless steel limits operating temperature to below 900 K. Brayton, Stirling and thermoelectric conversion options were included. The Brayton units are integrated with the gas-cooled option. The dual-opposed free-piston Stirling convertors receive the reactor thermal energy via sodium heat pipes that interface with the pumped liquid-metal coolant. The Stirling heater head would use nickel-based superalloys. The concept uses four convertors in serial pairs, with two convertors required for full power operation. The average heater head temperature would be 850 K (577ºC). A high temperature option is also considered wherein the reactor exit temperature is 1100 K (827ºC) with a liquid lithium coolant. This provides a 1050 K (777ºC) heater head temperature. Water heat pipe radiators provide thermal rejection from the convertors. For the Stirling option, a minimum mass system was obtained at a cold-end temperature of 460 K (187ºC), although the mass differences are small for cold-end temperatures between 400 and 550 K (127 to 277ºC).

III. Free-Piston Stirling Background

In the 1990s, NASA developed a 25 kW free-piston Stirling Space Power Demonstrator Engine for the SP-100 program. Figure 2 shows a photograph of that convertor. This system 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 disassembled into two Space Power Research Engines for further study. Considering the time frame and the state of knowledge of free-piston Stirling engines this was an outstanding accomplishment[5].

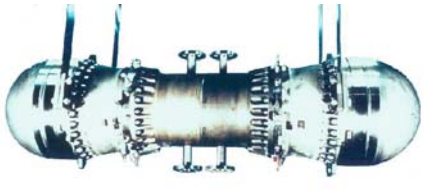

Figure 2. The 25 kW Space Power Demonstrator Engine (ca 1992)

Since that time, NASA has shown continued interest in free-piston Stirling conversion systems. As part of the NASA Radioisotope Power Systems program, DoE has been developing the Stirling Radioisotope Generator (SRG110) – using dual 55 W Stirling convertor systems for use with radioisotope heat sources. Engineering and qualification units are being produced and multiple dual-generator system tests are ongoing. Test times over 20,000 hrs have been accumulated on the one set of Stirling convertors at NASA GRC. In addition, recent testing of a pair of 55 W Stirling convertors are under test in a thermal vacuum environment at NASA GRC to advance the technology readiness level is underway.

The testing efforts at NASA GRC have yielded significant engineering and modeling information that lays a firm foundation for future efforts. In addition, substantial advances in the design of free-piston Stirling convertors has led to specific power values of about 100 W/kg for a single convertor capable of producing about 90 WAC. However, for exploration of the moon power systems ranging from 25 to 50 kW are envisioned. Obviously, trying to reach this goal by assembling multiple small 55 to 90 W engines may not be practical. Hence a new strategy is needed.

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 kW, specific mass of the Stirling convertor is important. As noted above, in the 25 kW Space Power Demonstrator Engine, the system goal was a T_H of 1050 K and T_C of 525 K 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 and a cold-end of 325 K. 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.

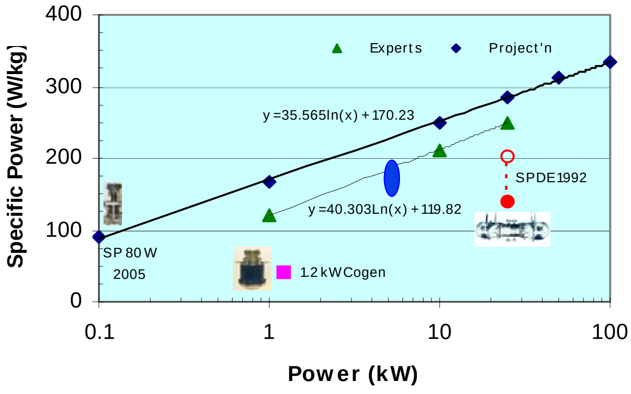

Figure 3. Specific Power Projections for Free-Piston Stirling Convertors

The specific mass estimates based on known technology advances at that time projected a convertor mass over 200 W/kg (4.9 kg/kW) from its 140 W/kg (7.1 kg/kW) value. Thus with the new developments in better understanding these engine/alternator assemblies, the specific mass should be within this range, although 100 W/kg for the 80 W engine hardware represents the current state of art. Figure 3 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. is shown in blue. The expert opinions are shown in green and are a little lower. Extrapolations to larger sizes are 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 kW developments was established as the blue ellipse and spans from 140 to 200 W/kg. A point of 140 W/kg was selected as a goal value. New free-piston Stirling convertor development at the larger sizes is needed to provide a sound basis for fission-based lunar surface power.

IV. 5 kW Free-Piston Stirling Convertor System

In order to provide the basis for Stirling power conversion subsystems for nuclear reactor 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 kW convertor system has been initiated. The 5 kW size has been loosely determined based on the previous studies outlined above. No current developer of free-piston Stirling convertors in the U.S. has such a unit; furthermore, requirements for the lunar system have not been defined. Therefore a multiphase effort is underway.

V. Project Description

Preliminary work will be performed toward development of a nuclear-fission-powered nominal 30 kW Stirling power system for use on the lunar surface with a specific power goal of about 140 W/kg for the Stirling power convertor assembly. The initial step is the design and development of a 5 kW per cylinder Stirling convertor assembly (SCA) which will serve as a prototype of one or more SCAs that will make up the 30 kW power systems. A range of options for the 5 kW/piston unit exists, from the usual single unit beta configuration to a multi-cylinder (alpha) configuration and various hybrid versions.

VI. Requirements Definition

In order to have a consistent plan for development of the new 5 kW convertor system, an overall architecture with definitions must be established as shown in figure 4. The Stirling convertor (SC) is defined as the engine/linear alternator alone. When the essential controller is included, it becomes the SCA. Finally, when the power management and distribution system is added, the ensemble becomes the Stirling Power Conversion System (SPCS).

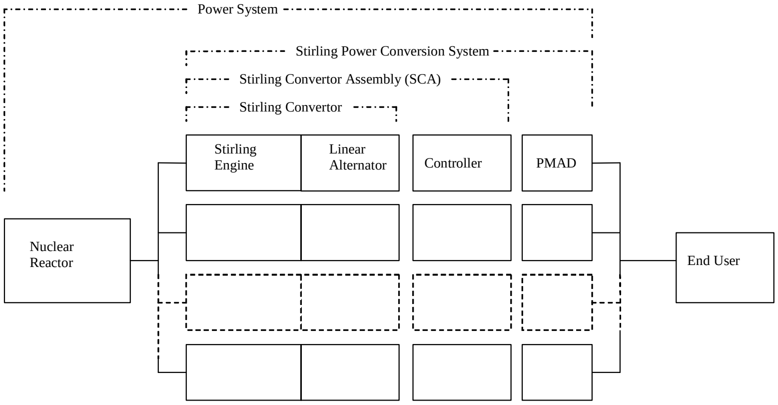

Figure 4. Schematic Architecture of a Reactor-Stirling Power System

In order to provide a firm foundation for this development, an expert panel will be used to provide the expected mission requirements and determine the key issues for development of the fission-based, nominal 30 kW Stirling power conversion system. Specific factors to be studied include the building block size of the Stirling convertor, its voltage output and frequency, type of heat rejection, PMAD, total mass goal of the power conversion system. Other factors include: lifetime, environmental hazards, system dynamic balance requirements, control stability and system integration issues (including load characteristics) will also be included.

Assumed Reference Requirements: In order to have a consistent starting point for the 5 kW designs, a common set of assumed reference requirements has been created. These requirements are “assumed” because NASA has not defined requirements for a lunar fission power system. Furthermore, multiple options exist for the conversion subsystem. Therefore, the requirements provided in this section are not sanctioned by NASA, but serve as a possible set for a Stirling power conversion system. A panel of NASA, industry and university experts worked together to assemble the list.

First, because most of the studies of a lunar fission power system ranged from 25 to 50 kW, a level of 30 kW was selected. Convertor technology meeting this requirement is easily extended to the 60 kW range. The minimum-sized building block was the 5 kW SCA. Two 5 kW SCAs could be connected together; thus the paired and thus dynamically-balanced unit would deliver 10 kW. Three such pairings deliver 30 kW etc. Because of the mass of the reactor system, efficiency was considered more important than mass, however a goal near the 166 W/kg is still desired. A hot-end temperature of 830 K was chosen assuming use of stainless steel in order to ensure that no new materials data base need be developed. 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 should 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. It should also monitor all temperatures and protect against any over-temperature condition and should control the stroke and other internal conditions to ensure successful operation. Modeling should guide the effort.

VII. Stirling Convertor Assembly Technology Development

Based on the requirements developed above, and based on information provided by the free-piston Stirling developer, a "reference design" will be created. The "reference design" will help define trades between mass, convertor efficiency, temperature ratio, etc that will meet NASA needs as they evolve. The reference design shall incorporate the latest available technology for free-piston SCAs that can meet the requirements and lead to a SPCS. In order to initiate this development, Auburn University issued a request for a cost-capped, fixed-price proposal and sent it to five companies: Clever Fellows Innovative Consortium, Foster-Miller, Inc., Infinia Corp., Sunpower, Inc., and TIAX, Inc. The proposals were evaluated by an expert panel consisting of NASA, industry and university personnel.

Foster-Miller, Inc. of Albany, New York was selected to develop the new 5 kW SCA. Key staff at Foster-Miller were involved in developing the 25 kW SPDE shown in figure 2. This 5 kW development will be a scaled-down version of that convertor. The SCA that will be built will have a T_H of 650 K (377 ºC) and a T_C of 325 K (52 ºC) to save costs and eliminate the need for new high temperature materials. The hot end will be heated with hot oil. Commercial units that provide this temperature flowing oil are safe and available. The cold end will be cooled with tempered water to match the requirement. The output voltage of the SCA will be selected based on NASA studies of the power distribution system of the lunar outpost. The operating frequency will be determined by the resonant design of the SCA. At the present time, the preliminary design is being prepared and is not available for publication. NASA will be supporting this effort with their extensive modeling tools such as the SAGE code. This development is targeted for a one-year effort and the delivered SCA will be tested in the nuclear reactor simulator facility at the NASA Marshall Space Flight Center. Because that facility uses a flowing NaK loop, the use of flowing hot oil for the hot end is a good design choice.

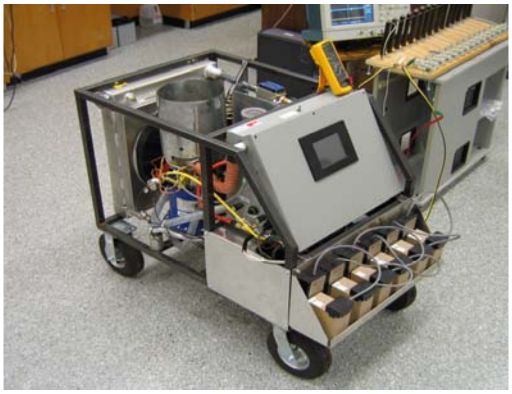

Figure 5. Stand-Alone, 1.2 kW Stirling Convertor Battery Charging Power System.

The reactor output temperature will be a significant issue in developing a reference design. As noted above, the low-temperature design requirement has been selected to obviate the need for superalloys for the Stirling convertor, and enable use of Inconel 718 that has been in common use in these convertors. Because of cost issues, the nominal 5 kW SCA to be developed in this first effort will be operated at temperature consistent with Inconel 718. The most important issue to be resolved in this initial effort is to determine if the specific power advances made to date in small units will also translate into larger units. Another outcome of this work will be to assess whether the trends projected in figure 3 are valid.

VIII. Stirling Convertor Assembly Testing

Although testing of the new 5 kW SCA may not occur in the first phase of this effort, a multi-kilowatt free-piston Stirling test bed will be assembled to begin to assess system integration issues. A stand-alone, propane-fired 1.2 kW free-piston SCPS based on the Sunpower EG 1000 unit has been in operation for several years. It has been used to demonstrate dissipative controls and battery charging for DOD applications and is shown in figure 5 (Brandhorst, 2004).

The new test bed is planned to add a second EG 1000 Stirling convertor that are being produced for commercial co-generation applications. These SCAs are generally designed to integrate with European electric power systems and produce 230V, 50 Hz output. Two of these units will be used in tandem so they are dynamically balanced. They will be electrically heated to simulate the reactor thermal output and the electrical output will be combined to provide power to various loads. A power management and distribution system will also be built to interface between the SCAs to provide a realistic SCPS. In order to make these tests more accurate, a cooling system capable of maintaining temperature ratios representative of the lunar surface will be developed. These tests will be helpful in developing experimental protocols, system integration into the experimental facilities, data acquisition and analysis that will ensure testing of the 5 kW SCAs will proceed smoothly. The test procedures will address issues associated with: system robustness, load disturbance response, environmental behavior, durability, failure analysis and mitigation, maintenance requirements, and life-cycle testing as a minimum.

IX. Summary and Conclusion

The NASA vision for exploration envisions a wide range of manned lunar missions over the next two decades. The first step is to provide electric power for an outpost on the edge of the Shackleton crater at the lunar South Pole. Later, as in-situ resource utilization matures, a nuclear reactor power systems providing power from 25 to 50 kW is envisioned. Because no present Stirling convertor assembly exists in the requisite size for this application, a new effort has begun to develop that technology option. This paper has described the preliminary work being performed toward development of a Stirling convertor assembly to be used with a future nuclear-fission-powered nominal 30 kW Stirling power system on the lunar surface. There is a specific power goal of about 140 W/kg for the Stirling power convertor assembly. The initial step is design and development of a nominal 5 kW per cylinder Stirling convertor assembly (SCA) which will serve as a prototype of one or more SCAs that will make up the final 30 kW power system. Assumed reference requirements have been developed that will guide development of the convertor assembly. These requirements defined the operating temperatures, lifetime, and trade-off between mass and efficiency. Foster-Miller, Inc. has been selected as the contractor and will develop a reference design that has T_H = 830 K and T_C = 415 K. The demonstrator SCA will have a T_H of 650 K and a T_C of 325 to save cost and the need to use high temperature materials and data base. The new SCA should be available in one year.

X. Acknowledgements

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