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NEW 5 KILOWATT FREE-PISTON STIRLING SPACE CONVERTOR DEVELOPMENTS

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ABSTRACT

The NASA Vision for Exploration of the moon may someday require a nuclear reactor coupled with a free-piston Stirling convertor at a power level of 30-40 kW. In the 1990s, Mechanical Technology Inc.'s Stirling Engine Systems Division (some of whose Stirling personnel are now at Foster-Miller, Inc.) developed a 25 kW free piston Stirling Space Power Demonstrator Engine under the SP-100 program. This system consisted of two 12.5 kW engines connected at their hot ends and mounted in tandem to cancel vibration. Recently, NASA and DoE have been developing dual 55 W and 80 W Stirling convertor systems for potential use with radioisotope heat sources. Total test times of all convertors in this effort exceed 120,000 hours. Recently, NASA began a new project with Auburn University to develop a 5 kW, single convertor for potential use in a lunar surface reactor power system. Goals of this development program include a specific power in excess of 140 W/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. Auburn University awarded a subcontract to Foster-Miller, Inc. to undertake development of the 5 kW Stirling Convertor Assembly. The characteristics of the design along with progress in developing the system will be described.

INTRODUCTION

The NASA Vision for Exploration, announced by President Bush in January 2004, proposed an ambitious program to return astronauts to the moon in the 2018 time frame. 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 kW as development of in-situ resources increases. Key products envisioned include water from the crater and oxygen from the regolith. As power levels climb, nuclear power systems may be required to eliminate the need for storage.

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 heavy. A past study gave a mass of 5880 kg for a 20 kW (3.4 W/kg) system [1]. On the other hand, dynamic conversion systems powered from thermal sources have been shown to be potentially lighter at about 100 W/kg [2]. 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 a fission power plant ranges from lander-based to locations remote from the lander. The power plant may be stationary or mobile [3]. A stationary plant has lower mass 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.

A recent study of potential reactor power systems for the lunar environment envisions a 100 kW_t reactor system coupled to six Stirling convertors [4]. Three sets of dual 5 kW free-piston Stirling convertors would take the thermal output and provide 30 kWe. Operating in tandem, each pair would be dynamically balanced. However, the power level and other system requirements are not known at this time but would 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 in 1992 of the 25 kW SPDE [5] 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 operating temperature and materials properties needed 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 potential lunar applications.

LUNAR SURFACE REACTOR STUDIES

Several recent studies of lunar and Mars surface reactor studies have been presented [5-9]. The reactor system proposed by Marcille [5] 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 (607 ^oC). 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 was 6.8 kW for a total power capability of 40 kW. This includes margin for a convertor failure and power processing efficiencies.

Mason [8] made 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. Use of stainless steel limits operating temperature to less than 900 K. Brayton, Stirling and thermoelectric conversion options were included. 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 concept uses four convertors in serial pairs, with two convertors required for full power operation. Average heater head temperature was 850 K (577^{o}C). Water heat pipe radiators provided thermal rejection from the convertors.

A recent NASA study of an "Affordable Fission Surface Power System" suggests a 40 kWe, 900

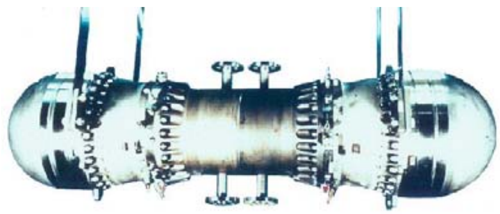

Fig. 1: The 25 kW Space Power Demonstrator Engine (ca 1992)

K, NaK-cooled, with Stirling conversion for a conceivable 2020 launch may be appropriate. An excellent summary of future opportunities for dynamic power systems for NASA missions has been provided by Shaltens [10].

FREE-PISTON STIRLING BACKGROUND

In the 1990s, NASA and MTI developed a 25 kW free-piston Stirling Space Power Demonstrator Engine for the SP-100 program. Figure 1 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 [4]

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 advancing Stirling Radioisotope Generators (SRG) for use with radioisotope heat sources. SRG engineering and qualification units may be developed and some 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, a pair of 55 W Stirling convertors is under test in a thermal vacuum environment at NASA GRC to advance the technology readiness level.

Testing efforts at NASA GRC have provided major 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 that produces 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 is not practical. Hence a new convertor would be 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.

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 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

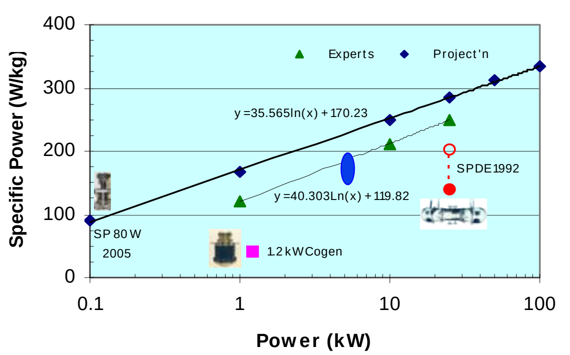

Fig. 2: Specific power projections for free-piston Stirling convertors

Stirling is shown in blue. These experts have had experience with larger, multi-kilowatt units in addition to their current efforts with smaller sizes. The expert opinions are shown in green 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 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. 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.

<u>NEW 5 kW FREE-PISTON STIRLING CONVERTOR</u>

In order to provide the technological infrastructure 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 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.

<u>Assumed Reference Requirements:</u> In order to have a consistent starting point for the 5 kW 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 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 kW, a level of 30-40 kW was selected. The minimum-sized building block was the 5 kW Stirling Convertor Assembly (SCA). Two 5 kW SCAs connected together are dynamically-balanced and will 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 140 W/kg is still desired.

A hot-end temperature of 830 K was chosen for a “reference design” and assumed the use of Inconel 718. This eliminates the need for a new materials data base. A schematic diagram of the reference convertor at 10 kW is shown in figure 3. This condition led to choosing a cold-end

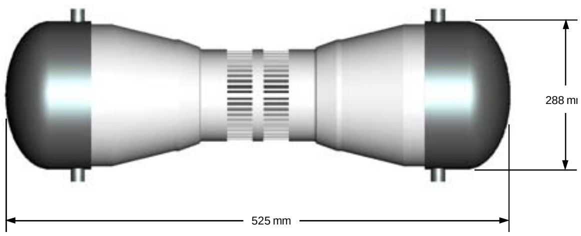

Fig. 3: 10 kW Conceptual Reference Convertor

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.

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 1 and the later and geometrically similar 12.5 kWe Component Test Power Convertor (CTPC) [5]. This 5 kW convertor is a scaled-down version of the CTPC design. As noted above this effort includes a reference design that would operate at 830 K. However, in order to save costs, a demonstrator SCA will be built that has a T_H of 650 K (377 ºC) and a T_C of 325 K (52 ºC). The hot side of the convertor will be heated with a commercial hot oil system. The commercial units that provide this temperature oil are ASME certified and are safe and available. 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.

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 kW with a peak output of 6 kW. The efficiency is 25% and the specific mass is 6 kg/kW for the reference design. The life is 5 years of continuous operation (44,000 hrs) at 100% power. Foster-Miller’s design of the convertor is being guided by their existing H-FAST 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 will be 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 figure 4.

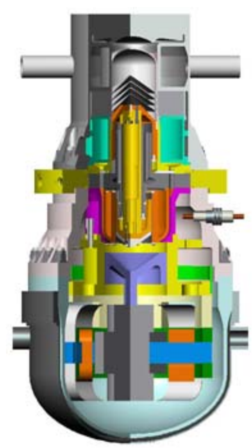

Fig. 4: Cut-away view of the 5 kW demonstrator convertor

The hot end pumped loop will be provided by HEAT, Inc. and will provide 650 K temperatures with Therminol VP-1 fluid. The cold end pumped loop will be a water-glycol system that will supply temperatures from 275 to 415 K. The hot and cold ends will be shell and tube heat exchangers.

An exploded view of the demonstrator SCA is shown in figure 5. The heater head assembly will be a tube-in-shell design made with Inconel 718 with 1800 tubes around which the hot oil

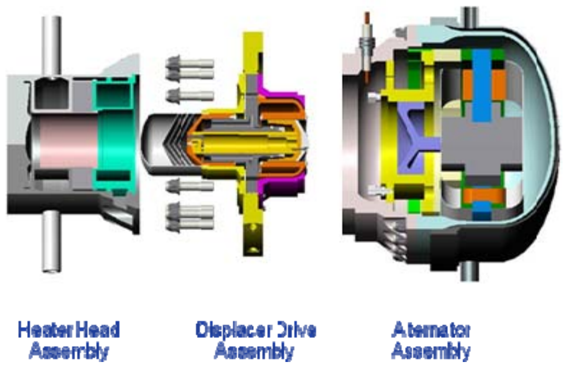

Fig. 5: Exploded view of 5 kW free-piston Stirling demonstrator convertor assemblies

will flow. The regenerator will be made from 316 stainless steel sintered wires and the cooler will be made from Inconel 718 and have 1800 tubes.

The displacer drive assembly will be made from steel rather than beryllium to save cost. The displacer dome and radiation shields will be made from Inconel 718 to withstand the operating temperatures. The displacer bearings will be internally pressurized.

The alternator will be provided by Clever Fellows Innovative Consortium based on the STAR 241 frame. The plunger is supported by flexure bearings and the magnets will be Sm-Co capable of >415 K operation. The stroke will be 22 mm (5 kW) with over stroke capability to 24 mm (6 kW). Laminations will be made from Hiperco 50 material. The flexure bearings will be made from austenitic stainless steel. Similar assemblies have been operated for over 65,000 hrs without failure.

Code comparisons: Foster-Miller in cooperation with GRC have done a comparison of performance predictions using the older HFAST and the newer Sage codes. 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.

Table I shows the comparisons for the 5kW convertor. In both cases, the efficiency comes out at about 25% with more than 5 kW of power being produced. These tabular results do not include the "mechanical losses such as gas spring hysteresis losses, seal leakage losses, etc.

Value	HFAST	Sage
Total PV Power (Exp. Sp. + Cmp. Sp.) [W]	7,586	8,160
Total Heat In [W]	25,404	24,910
Total Heat Rejection [W]	17,818	16,750
Cycle Efficiency (Total PV Power/Total Heat In)	0.299	0.328
Power from cycle to power piston [W]	6,923	7,355
Efficiency based on power to power piston	0.272	0.295
Power out of the 87.5% efficient alternator [W]	6,058	6,436
Efficiency including the 87.5% efficient alternator	0.238	0.258

Table I: Comparison of HFAST and Sage models for the Stirling demonstrator convertor at 830/415 K

SUMARY 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, 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 50kW 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 kW Stirling powered system on the lunar surface. The project has 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 which could serve as a prototype of one or more SCAs that could make up a final 30-40 kW 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.

Foster-Miller, Inc. has been selected as the contractor and is developing a demonstrator SCA that will be capable of operation at a 830K/415K temperature ratio. However, it will only be operated at a T_H of 650 K and a T_C of 325 K due to facility limitations. Furthermore, this approach eliminates the need to use high temperature materials and data base. The convertor will be capable of 5 kW at normal 22 mm stroke and 6 kW at a 24 mm stroke.

ACKNOWLEDGEMENTS

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