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Abstract

An electric power supply, small enough to be man-portable, is being developed for remote, terrestrial applications. This system is designed for an operating lifetime of five years without maintenance or refueling. A small Radioisotope Stirling Generator (RSG) has been developed. The energy source of the generator is a 60 watt plutonium-238 fuel clad used in the General Purpose Heat Sources (GPHS) developed for space applications. A free piston Stirling Engine drives a linear alternator to convert the heat to power. The system weighs about 7.5 kg and produces 11 watts AC power with a conversion efficiency of 18.5%. Two engine models have been designed, fabricated, and tested to date: (a) a developmental model instrumented to confirm and test parameters, and (b) an electrically heated model with an electrical heater equipped power input leads. Critical components have been tested for 10,000 to 20,000 hours. One complete generator has been operating for over 11,000 hours. Radioisotope heated prototypes are expected to be fabricated and tested in late 1995.

INTRODUCTION

Since the first launch of a radioisotope power generator on Nimbus B-1 in 1968, a large number and variety of isotope power generators have been developed. Not only have they found use in producing power for space activities but also in a wide variety of terrestrial applications. These generators have varied in power output from a few tenths of a watt to 500 watts. With few exceptions, past and present generators use thermoelectric conversion. The thermoelectric converters are highly reliable, convert heat to power with no moving parts, and, thus, generate no vibration or noise. A major drawback is that they have a low heat to electricity conversion ratio and, thus, require a larger radioisotope heat source and must reject more heat than would be necessary with more efficient conversion. In this study, we have evaluated the use of higher efficiency heat to electricity conversion systems without compromising reliability, size, weight, noise generation, or detectability of the unit. Although several dynamic conversion systems have potential, a small Stirling heat engine, based on Stirling Technology Company's (STC) experience with the development of a heart assist device, was selected as the most promising for a 10 W_e generator. The Stirling heat pump, under development for about 25 years for the National Institutes of Health, converted heat to mechanical energy to assist the heart in pumping blood through the body. This system was light weight, with a small volume, operated without maintenance for several years, and achieves a relatively high conversion efficiency. Using the experience in developing this small Stirling system, a Stirling generator was designed, fabricated, and tested using a linear alternator for conversion of mechanical energy to electricity. The target overall conversion efficiency of the generator was 20%, about five times that of a thermoelectric generator at the same power level.

This paper describes the design of a 10 W_e RSG that is small enough to be man-portable and be operated for at least five years without maintenance or refueling. The results of fabrication and testing of the following two versions of the generator are described: Demonstration models used to develop the design parameters and to test the performance, and electrically heated generators identical in size, shape, and design to the final RSG except heated with an electrical heater equipped with power input leads.

SELECTION OF RADIOISOTOPE FOR HEAT SOURCE

Of the many sources of energy for production of electric power, the use of heat producing radioisotopes is uniquely suited for small, long-lived, portable power generators. Therefore, an evaluation of the most suitable radioisotope was performed. The evaluation of suitability considered the following:

- Decay half-life,
- Energy released/unit weight,
- Shielding requirements,
- Source volume and weight,
- Stability of compound,
- Compatibility with encapsulating material,
- Heat transfer properties,
- Toxicity and safety,
- Regulatory controls,
- Isotope availability,
- Infrastructure for production,
- Possible heat source delivery schedule, and
- Overall heat source cost.

Although these criteria are clearly interrelated, they provided a structure on which to base a selection. For example, the heat source cost is directly affected by the available infrastructure for production of the isotope as well as production of the heat source. For the initial assessment, only those radioisotopes with a half-life between 100 days and 1000 years were considered. From the 103 isotopes in this category, 31 were considered for more careful evaluation. Eight of the 31 radioisotopes (with half lives less than 2 years) were eliminated because of the large heat rejection required at beginning of life to have sufficient energy at the end of 5 years. Another 10 were eliminated because of the shielding requirements due to the production of gamma rays or bremsstrahlung. An additional five were eliminated from consideration because of the requirement for isotope separation to obtain a suitable density of the radioisotope in the heat source. The remaining eight (^{3}H, ^{63}Ni, ^{147}Pm, ^{171}Tm, ^{227}Ac, ^{238}Pu, ^{241}Am, and ^{244}Cm) were considered to be suitable and were thus evaluated primarily on the basis of availability and cost. Plutonium-238 was desirable based on the ultimate source size and weight. Of even greater importance is availability of the heat sources. The infrastructure is well established for producing the ^{238}Pu and cladding for the General Purpose Heat Sources (GPHS) for space applications. One iridium clad, ^{238}Pu fuel pellet generates the proper amount of heat for a 10 W_e RSG. Thus, sources are taken directly from the fabrication line for the GPHS and further encapsulated as necessary for our application. The design and fabrication of these Isotopic Heat Sources (IHS) are the subject of another paper presented herein.

RADIOISOTOPE STIRLING GENERATOR DESIGN

The conceptual design of the converter unit for the RSG was presented in some detail earlier (Ross et al. 1991). The proposed Stirling generator employs only proven technologies. The engine subsystem technology, using radioisotope energy in the power range of interest, was developed and successfully demonstrated by the STC of Richland, Washington in the 1970s for the National Institutes of Health. The technology has undergone continuous refinement in the intervening years.

A simplified schematic of the converter design is shown in Figure 1. The piston and displacer are arranged in a single cylinder (beta configuration) to minimize dead volume and for simplicity. The

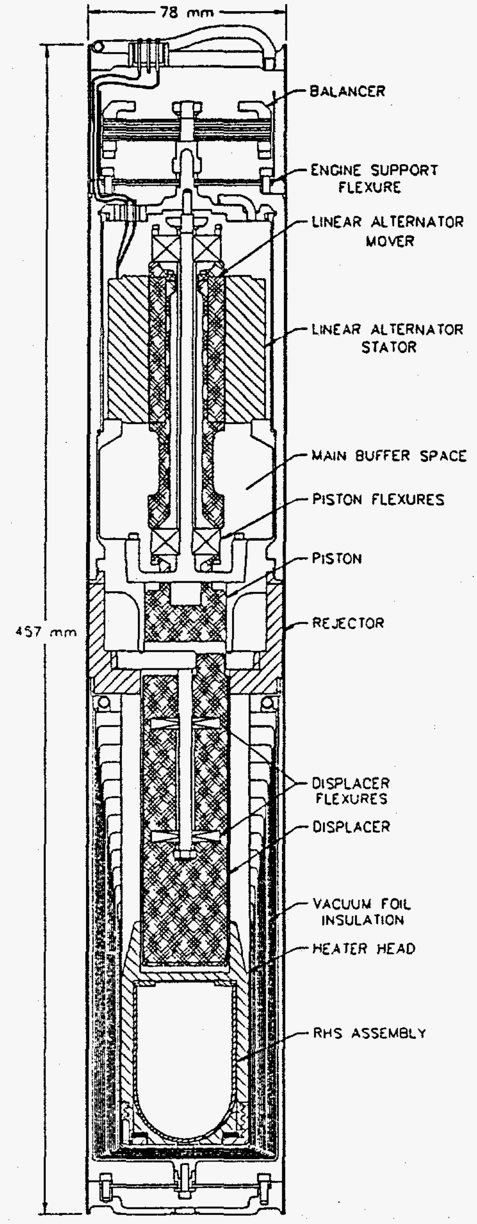

FIGURE 1. Simplified Schematic of Engineering Model (EM)

hollow displacer is located on a stationary post through internal flexures. The post is supported by a spider between the piston and the displacer. In the free piston Stirling engine, the piston is not directly coupled to the displacer but is driven by the pressure changes in the helium working fluid as it is heated and cooled. The moving yoke of the linear alternator is mechanically coupled to the piston with flexures on both ends. The alternator coil and magnet are both stationary. The piston/alternator pressure vessel was made as large as possible approaching the diameter of the insulation package in order to minimize the length. One end of the pressure vessel is attached to the rejecter block. A cap is attached to the other end of the pressure vessel that provides a mounting point for the piston rod on the inside and a mounting point for the support flexures on the outside as well as providing a pressure vessel wall.

Long-life performance of the RSG is based on development of flexural bearing technology. Flexible sheet metal bearings guide the displacer and the piston/alternator yoke with extremely high accuracy, due to the high radial stiffness of the flexure design. As a result, the moving components can operate within their bore with a clearance on the order of 13 μm (one-fifth the thickness of a sheet of paper) completely free of friction, wear, and lubricants. The small clearance minimizes leakage losses of the helium working gas surrounding the piston, thus increasing system efficiency.

Heat is transferred from the isotope heat source (IHS) through a nickel heater head that is brazed directly to a superalloy (Inconel 617) displacer cylinder at the hot end of the engine. A helium cover gas in the system will allow sufficient energy transfer to maintain the IHS at an acceptable temperature.

The insulation package for the RSG will normally operate at a temperature of approximately 920 K. Thus, a high temperature, light weight, multi-foil vacuum insulation package was selected. The RSG multi-foil insulation package consists of an outer stainless steel (304) container; 45 very thin (25 μm) nested nickel cups held apart with small, low conductivity zirconia beads; an Inconel-617 inner can, and a stainless steel base plate to which both inner and outer cans are attached. The resultant multi-foil vacuum package is evacuated to a pressure of about 10^{-8} torr and outgassed for several weeks at 970 K until the outgassing rate at operating temperature is sufficiently low to maintain the pressure less than 10^{-3} torr for at least 6 years.

The inner can of the insulation package contains a thermal fuse designed to allow helium to spoil the vacuum if the temperature exceeds 1070 K. This fuse is made of a sandwich of silver between two thin copper plates. This system forms a eutectic that melts at 1050 K and allows helium to flow into the package when the eutectic melting temperature is reached. With the vacuum spoiled, the heat is readily transported through the insulation and the temperature of the heat source decreases, even if the generator stops operating.

The heat from the thermodynamic cycle and the engine conduction losses are rejected at the cool end of the engine cylinder through a copper heat rejection block. The gap between the rejecter block and the outer canister wall must be about 0.1 mm or less to maintain the temperature drop across the helium gap to less than 3 K.

The entire generator assembly is mounted on support flexures in a 78 mm diameter by 457 mm long copper canister for containment, corrosion control, and to aid heat rejection. A balancer is attached to the top end of the generator assembly. The balancer is tuned by adjusting the mass and the spring rate (through the number of flexures) to keep the generator assembly amplitude to less than 0.13 mm.

GENERATOR PERFORMANCE

The development of the RSG is being conducted in three hardware stages as follows: 1) Developmental models that are highly instrumented to determine optimum parameters and the test design concepts, 2) electrically heated engineering models to permit evaluation of the design and testing without the expense and controls required when using radioactive sources, and 3) prototype models for field testing and delivery to users. The developmental models were fabricated, assembled, and tested in 1992. The engineering models have been fabricated and some testing completed. The performance data reported here are, to the extent possible, based on the engineering models but most of the operating data are from the earlier demonstration model generators. Table 1 lists the characteristics and performance of the RSG as determined to date.

For remote applications, the reliability of the generator is of prime importance. Thus, as soon as critical components could be fabricated, endurance tests were initiated. Table 2 shows the tests currently underway and the extent of the tests to date.

TABLE 1. Physical Characteristics and Performance of RSGs

Parameter	Demonstration Model	Engineering Model
Length (mm)	--	457
Diameter (mm)	--	78.3
Mass (kg)	--	7.5
Input power (W)	68	59.3
AC output (W)	11.7	11.0
Efficiency	17.1	18.5
Output voltage (V AC)	22.5	21.3
Frequency (Hz)	60.1	62.0
Mean pressure (MPa)	0.48	0.45

TABLE 2. RSG Endurance Testing at STC (as of 1 September 1994)

Test Rig	Test / Nominal Amplitude	Test Temperature (K)	Test Rig Operating Hours Without Failure	Total Flexure Hours
Laboratory Engine	1.00	330 to 870	10,817	2,305,122
Displacer Flexures	1.00	290	21,221	
Piston Flexures	1.00	290	18,976	
Displacer Flexures	1.65	330 to 620	10,936	
Piston Flexures	1.65	290	10,089	
Linear Alternators (2 per rig)	1.00	290	17,652	

CONCLUSIONS

Although the program is not yet complete, the original goals of the program are being met. We have successfully developed a generator which will be man-portable, which will produce 10 watts of electrical power. Although we demonstrated only 18.5% conversion efficiency, we expect that, with further improvements in controlling heat loss, we will approach the goal of 20% conversion efficiency. Optimization of the parameters during the design stage with a state-of-the-art thermodynamic model proved to be effective. These parameters were confirmed and further refined using the highly instrumented Developmental Model Generators. These refinements were incorporated in the electrically heated Engineering Models. We anticipate completion of the first ^{238}Pu heated generators late in 1995.

Acknowledgments

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