Technology Development for a Stirling Radioisotope Power System for Deep Space Missions

Lanny G. Thieme
Glenn Research Center, Cleveland, Ohio

Songgang Qiu and Maurice A. White
Stirling Technology Company, Kennewick, Washington

March 2000
The NASA STI Program Office... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized data bases, organizing and publishing research results... even providing videos.

For more information about the NASA STI Program Office, see the following:


- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at (301) 621-0134

- Telephone the NASA Access Help Desk at (301) 621-0390

- Write to: NASA Access Help Desk NASA Center for AeroSpace Information 7121 Standard Drive Hanover, MD 21076
Technology Development for a Stirling Radioisotope Power System for Deep Space Missions

Lanny G. Thieme
Glenn Research Center, Cleveland, Ohio

Songgang Qiu and Maurice A. White
Stirling Technology Company, Kennewick, Washington

Prepared for the
34th Intersociety Energy Conversion Engineering Conference
sponsored by the Society of Automotive Engineers
Vancouver, British Columbia, Canada, August 1-5, 1999

National Aeronautics and
Space Administration

Glenn Research Center

March 2000
Trade names or manufacturers' names are used in this report for identification only. This usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.
Technology Development for a Stirling Radioisotope Power System for Deep Space Missions

Lanny G. Thieme
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

and

Songgang Qiu and Maurice A. White
Stirling Technology Company
Kennewick, WA 99336

Abstract

NASA Glenn Research Center and the Department of Energy (DOE) are developing a Stirling convertor for an advanced radioisotope power system to provide spacecraft on-board electric power for NASA deep space missions. NASA Glenn is addressing key technology issues through the use of two NASA Phase II SBIRs with Stirling Technology Company (STC) of Kennewick, WA. Under the first SBIR, STC demonstrated a 40 to 50 fold reduction in vibrations, compared to an unbalanced convertor, with a synchronous connection of two thermodynamically independent free-piston Stirling convertors. The second SBIR is for the development of an Adaptive Vibration Reduction System (AVRS) that will essentially eliminate vibrations over a mission lifetime, even in the unlikely event of a failed convertor. This paper discusses the status and results for these two SBIR projects and also presents results for characterizing the friction factor of high-porosity random fiber regenerators that are being used for this application.

Introduction

NASA Glenn Research Center and the Department of Energy (DOE) are developing a Stirling convertor for an advanced radioisotope power system to provide spacecraft on-board electric power for NASA deep space missions. Stirling is being evaluated as an alternative to replace Radioisotope Thermoelectric Generators (RTGs) with a high-efficiency power source. The efficiency of the Stirling system, in excess of 20 percent, will reduce the necessary isotope inventory by a factor of 3 or more compared to RTGs. Stirling is the most developed convertor option of the advanced power concepts under consideration [1,2].

DOE is developing the radioisotope Stirling convertor under contract with Stirling Technology Company (STC) of Kennewick, WA [3,4]. Two 55-We convertors are now being tested in a dynamically-balanced opposed arrangement. A single convertor is shown in figure 1 while figure 2 shows a pair of convertors on test. NASA Glenn is providing technical consulting for this effort under an Interagency Agreement with DOE.

The design of the 55-We Stirling convertor is based on previous successful STC development efforts, particularly those for the 10-We RG-10 radioisotope terrestrial convertor and the 350-We RG-350 aimed at commercial cogeneration and remote power [5]. STC has developed product lines for both power sources and cryocoolers. A remote power generator set with the RG-350 is shown in figure 3. One RG-10 has now been on life test for over 50,000 hours (5.7 years) with no convertor maintenance and no degradation in performance. Two RG-10 convertors are awaiting isotope fueling and subsequent field testing. Multiple units of the RG-350 and their companion BE-COOL cryocoolers have accumulated over 60,000 total hours of operation, much of this at independent third-party test sites. Finally, STC has also completed extensive component life testing and, in particular, has over 1000 years of total test time (230 flexures) on the critical flexural bearings. These numerous test hours on various systems and on key components provide a high confidence that the 55-We convertor will meet its life and reliability goals.

The 55-We convertor uses the following proven STC long life design approaches: non-contacting moving parts with flexural bearings and non-contacting clearance seals, no lubrication, an integral alternator inside the pressure vessel, hermetic sealing, and Inconel 718 for the hot-end material. The use of Inconel 718 allows the necessary long lifetimes at a hot-end temperature of 650 °C. Increased efficiency and/or decreased radiator size can be achieved by using advanced hot-end materials operating at a higher temperature.

As part of the overall radioisotope Stirling development, NASA Glenn is addressing key technology issues through the use of two NASA Phase II Small
Business Innovation Research (SBIR) contracts with STC. Under the first SBIR, STC demonstrated a synchronous connection of two thermodynamically independent Stirling convertors and a 40 to 50 fold reduction in vibrations compared to an unbalanced convertor. This connection method is now being used to connect the DOE/STC 55-We convertors. The second SBIR contract is for the development of an Adaptive Vibration Reduction System that will essentially eliminate vibrations over a mission lifetime and will have the ability to adjust to any changing convertor conditions over the course of the mission.

NASA Glenn has been investigating Stirling isotope power systems for deep space missions since about 1990. This work grew out of earlier Stirling efforts conducted for DOE for a Stirling automotive engine and for the NASA Civil Space Technology Initiative (CSTI) to develop Stirling for a nuclear power system to provide electrical power for a lunar or Mars base. NASA Glenn also provided technical management for DOE for the Advanced Stirling Conversion System (ASCS) terrestrial dish Stirling project. Overall, NASA Glenn has been developing Stirling technologies since the mid-1970's.

In support of DOE, Orbital Sciences Corporation (OSC) has completed system studies for a Stirling radioisotope power system for deep space missions [6,7]. The system was based on a STC Stirling convertor design. OSC has analyzed power system layouts using either two or four convertors and conceptualized the GPHS and radiator interfaces. The choice of two or four convertors per power system is dependent, in part, on system redundancy requirements. One possible OSC system configuration is shown in figure 4. Lockheed Martin is also now evaluating Stirling radioisotope power system designs for DOE.

Systems using Stirling convertors are also being analyzed by NASA Glenn for other space applications including solar dynamic power systems for space-based radar [8] and as a deep space alternative to the radioisotope system, a combined electrical power and cooling system for a Venus lander, and lunar/Mars bases and rovers.

Figure 1.—DOE/STC 55-We convertor.

Figure 2.—Two opposed 55-We convertors on test.

Figure 3.—350-We RG-350 remote power generator set.

Figure 4.—Orbital Sciences Corp. system concept [7].
Synchronous Operation of Opposed Stirling Convertors

STC, as part of a NASA Phase II SBIR contract, has successfully demonstrated synchronous operation of two thermodynamically independent free-piston Stirling convertors with linear alternators connected electrically in parallel. Previous Stirling development had focused on single convertors and had not addressed how to connect multiple convertors in a system. However, in most potential space applications, multiple convertors are important for redundancy and modularity. Thermodynamically independent convertors may allow one convertor to fail without affecting the performance of the other. Finally, the use of multiple convertors is important to controlling vibrations, a critical issue for a dynamic space power system. Synchronization of convertor pairs operating in an opposed configuration provides balanced operation with minimal vibration.

Two RG-350 convertors were used for this development. Initial efforts included computer simulations of multiple-convertor connection methods and single-convertor baseline testing of each of the RG-350 convertors. Each convertor was tested separately over a range of hot-end and cold-end temperatures and charge pressures. Approximately 5 g's vibration was measured at the nominal conditions for a single convertor.

During multiple-convertor testing, synchronization was achieved with the two convertors (see figure 5) operating over a wide range of conditions. The frequency of each convertor was identical, and the pistons operated nominally 180 degrees out-of-phase mechanically. The convertors were connected electrically in parallel and mechanically through external attachments on the cold-end pressure vessels. A mechanical coupler was developed that aligns the two convertors and can compensate for any inherent misalignments. Synchronization produced a 40 to 50 fold reduction in vibrations compared to an unbalanced convertor, a value that appears to be well below pixel smear limits for deep space sensing. Equal power generation between the two convertors was also demonstrated under nominal conditions. This connection method is now being used to connect the DOE/STC 55-We convertors.

The synchronization was shown to be very robust by testing at conditions of simulated degradation and by transient testing. For one set of runs, the average hot-end temperature of one convertor was varied widely while holding the other convertor hot-end temperature nearly constant at about 600 °C. Synchronization was maintained over this range, and figure 6 shows the effects on the phase difference between the power pistons and the maximum vibration measured on the two convertors. Zero-degree phase lag indicates the pistons are operating 180 degrees out-of-phase mechanically. The maximum vibration increased from 0.12 g to just 0.48 g over this wide range of operation; this is compared to about 5 g's vibration for an unbalanced convertor. The convertor power output at the lowest temperature was about 20 percent of the power output for the convertor operating at about 600 °C.

Charge pressure variations of up to 20 percent for one convertor while maintaining constant charge pressure in the other and constant power input to each were also tested. Results for this case are shown in figure 7. Again, synchronization was maintained, and only small increases
Transient data taken during various connections and disconnections of the two convertors showed the ability to achieve synchronization reliably and rapidly. No significant transient overstrokes were seen or any other potentially damaging results. Figure 8 shows transient traces for the piston and displacer motions, voltage, current, and vibrations from one convertor when the other convertor is disconnected and shut down. The convertors are synchronized at nominal conditions at the beginning of the transient. The only noticeable effect is the increase in vibrations of the now electrically uncoupled convertors.

Some transient effects were found when the two convertors were connected while operating at nominal conditions. Typically, an acceleration spike to about 6 to 10 g's was seen and may be due to the two convertors being briefly in-phase mechanically after the coupling. This transient settled out in about 15 cycles (1/4 sec.), after which the vibration level was stable at the very low values achieved with synchronization. If necessary, this transient could be mitigated by adding an extra load briefly on the alternator output while connecting the convertors to dampen the piston motions during the transient.

Successful system operation was demonstrated with the two synchronized convertors feeding a battery charger load, as would most likely be used in a radioisotope power system. Four standard automotive batteries were connected in series and tests run over a range of convertor hot-end temperatures and battery state-of-charge. Operation was found to be essentially the same as when dissipating power to the controller internal load resistors.

Tests were also run with the electrical coupling only and with the mechanical coupling only. With only the electrical coupling, the convertors synchronized as before; however, there was no reduction in vibrations as there was no mechanical connection between the convertors. With only the mechanical coupling, there was at most a weak synchronous connection, and the vibrations were similar to a single unbalanced convertor.

A further innovation during this SBIR project was the demonstration of an artificial neural network (ANN) that could potentially monitor the health of a convertor using only non-invasive instrumentation that does not penetrate the convertor pressure vessel. The ANN successfully predicted piston and displacer amplitudes and phasing for a 10-We RG-10 convertor using voltage, current, and rejection temperature as the only inputs. Simulated pressure degradation for one of the fully coupled RG-350 convertors was also successfully tracked using current, current-voltage phasing, and output power for each convertor as inputs. It is felt that the ANN has a high probability of detecting any convertor degradation that may occur without needing any internal instrumentation that would decrease the convertor reliability. This could then allow the system controller to adjust operation to maximize system performance.

Adaptive Vibration Reduction System

Under a second NASA Phase II SBIR, STC is developing an Adaptive Vibration Reduction System (AVRS) that will further reduce vibration levels by a factor of 10 or more under normal operating conditions. It will achieve this with an active balance system with feedback from a vibration signal and will cancel the fundamental vibration and up to 10 harmonics. Even more importantly, the AVRS will be adaptive and will add the ability to adjust to any changing convertor conditions over the course of a mission. Thus, it should allow successful dynamic balancing over the mission lifetime and will be able to demonstrate its adaptive ability through up-front testing. The AVRS is now being developed on two RG-350 convertors and will also be demonstrated on the DOE/STC 55-We convertors.

The AVRS will use a balance mass driven by a separate linear motor; only one balance mass and motor are needed for two opposed Stirling convertors. A balance mass and motor to be used in the first AVRS testing with the RG-350 convertors is shown in figure 9. The vibration signal will be measured with either a load cell or an accelerometer. A fast Fourier transform of this signal will then be used to construct a compensation signal that will be sent to the balance motor through a power amplifier. Both the amplitude and phase of each harmonic will be adjusted. The motion of the balance mass center-of-gravity will be opposed to and proportional to the motion of the center-of-gravity of the combined system of two pistons and two displacers. The AVRS will adjust to any
change in convertor operating conditions, any convertor
degradation that may occur over a mission, or even in the
unlikely event of a failed convertor.

Stirling cryocoolers are currently used to cool vibration-
sensitive sensors in space applications. STC has demon-
strated a cryocooler vibration level of only 0.007 g's using
similar technology to the AVRS. This technique has been
shown to be effective with reasonable power and mass
budgets. One key difference for balancing power conver-
tors is that the frequency is not fixed as it is in coolers.
Thus, the frequency must be measured on a continual
basis and factored into the control algorithm.

A further task of this contract will demonstrate a pas-
vasive heat rejection system for the 55-We convertor. A
copper/water heat pipe was used in the OSC system con-
cept shown in figure 4 to transport the convertor's rejected
heat to the radiator.

Friction Factor Characterization for
High-Porosity Random Fiber
Regenerators

As part of the Interagency Agreement with DOE, NASA
Glenn performed a review of the DOE/STC 55-We con-
vertor design. This review included modeling the conver-
tor performance with the HFAST Stirling code and
comparing the results to the predictions from the GLIMPS
code used by STC to design the convertor. The two codes
predicted similar convertor performance when the regen-
erator friction factors were adjusted to be similar for each
code. Without this adjustment, the regenerator friction
factor correlations and consequent pressure drop losses
showed significant differences at the high regenerator
porosities (90 to 96 percent) being considered for this
low-power convertor design.

Both GLIMPS and HFAST include a porosity depend-
ence in their friction factor correlations. However, HFAST
has a much higher sensitivity to this than does GLIMPS,
The measured flow data were provided to STC. STC and NASA Glenn first independently reduced this data to friction factor and Reynolds number and then resolved any significant differences. Friction factor versus Reynolds number (based on NASA Glenn's data reduction) is shown for each of the samples in figure 11. It can be seen that the curves for the 80 and 88 percent porosity samples are very similar while the friction factor is significantly higher for the 96 percent porosity sample.

The friction factor curves for the 80 and 96 percent porosity samples are compared with three correlations in figures 12 and 13. The three correlations are the GLIMPS and HFAST random fiber correlations and the latest correlation based on test data taken at Ohio University [9]. All three correlations agree well with the test data for the 80 percent porosity sample. For the 96 percent porosity sample, HFAST compares the best with the test data (data shown is for 100-psia inlet pressure only) at the lower Reynolds numbers, 0 to 300, which was the expected range for the Stirling radioisotope convertor design. However, for the 88 percent porosity sample, the GLIMPS and Ohio University correlations compared the best with the test data while the HFAST correlation yielded a higher friction factor (results not shown).

Following analyses of these results, STC decided to use the GLIMPS correlation for all regenerator porosities up to 88 percent. They then derived a relationship based on the GLIMPS friction factor for 88 percent porosity and the 96 percent porosity test data (average of the curves for 55- and 100-psia inlet pressures) that interpolates between these for porosities from 88 to 96 percent. Figure 14 shows the GLIMPS friction factor curve for 88 percent porosity and the two test data curves for the 96 percent porosity sample over the Reynolds number range of 0 to 350.

STC GLIMPS results with the new friction factor input for 88 to 96 percent porosities showed that the final optimized regenerator design porosity was reduced from the previous 96 percent to 90 percent. This 90 percent porosity was then used for the actual 55-We convertor. It should be kept in mind that no adjustments were made to the heat transfer correlation used in GLIMPS for the higher porosities. NASA Glenn is now setting up a regenerator test rig for another project that could potentially
perform heat transfer testing on high-porosity random fiber regenerator samples.

**NASA Glenn Supporting Technology Development Plans for the Stirling Radioisotope Converter**

Plans have been proposed for further Stirling technology development at NASA Glenn in support of developing the Stirling radioisotope power system for deep space missions. Identified tasks include controls development and performance verification through in-house testing of RG-350 and 55-We Stirling convertors, structural life assessment of the Stirling heater head, materials and joining evaluations, finite element analysis (FEA) of a lightweight linear alternator concept, thermal aging tests of the linear alternator permanent magnets, demonstrating convertor operation under launch and orbit transfer load conditions, and a radiator conceptual design. The vibration test facility of the Structural Dynamics Laboratory at NASA Glenn is shown in figure 15. This facility will be used for any testing under launch and orbit transfer loads. These proposed tasks build on NASA Glenn expertise developed as part of previous Stirling research, especially for the Stirling space power development during the NASA CSTI project [13-15]. These tasks were identified in the appropriate areas where value-added development is provided as part of the overall Stirling radioisotope effort.

**Summary and Concluding Remarks**

NASA Glenn Research Center and the Department of Energy are developing a Stirling convertor for an advanced radioisotope power system to provide spacecraft on-board electric power for NASA deep space missions. Stirling is being evaluated as an alternative to replace RTGs with a high-efficiency power source. STC, under contract to DOE, is making rapid progress in developing and demonstrating the 55-We convertor. Two 55-We convertors are now operating in a dynamically-balanced opposed arrangement, and full electrical power output is expected to be achieved by early summer 1999. Preliminary efficiency indications are also very encouraging. In addition, STC's numerous test hours on various related systems and key components provide a high confidence that the 55-We convertor will meet its life and reliability goals.

NASA Glenn is addressing key technology issues through the use of two NASA Phase II SBIRs with STC. Under the first SBIR, STC demonstrated a synchronous connection of two 350-We thermodynamically independent Stirling convertors. STC achieved synchronization of the two convertors over a wide operating range, showed a 40 to 50 fold reduction in vibrations compared to an unbalanced convertor, and proved the connection to be robust and reliable through numerous transient tests. This connection method is now being used to connect the DOE/STC 55-We convertors. The second SBIR is for the development of an Adaptive Vibration Reduction System (AVRS) that will essentially eliminate vibrations over a mission lifetime, even in the unlikely event of a failed convertor. The AVRS will further reduce vibrations by a factor of 10 or more under normal operating conditions and, even more importantly, will add the ability to adjust to any changing convertor conditions over the course of a mission. Balance motors have been fabricated and baseline tests completed; initial testing of the AVRS is expected to begin shortly.

In support of the design effort for the 55-We convertor, NASA Glenn and STC determined the friction factor characteristics of high-porosity random fiber regenerators. Results for a 96 percent porosity regenerator sample were found to vary significantly from those for 80 and 88 percent porosity samples. The results at 80 and 88 percent porosity agreed well with the correlation used in the GLIMPS computer code. STC derived a revised correlation for random fiber regenerators with porosities between 88 and 96 percent based on these results. New
optimizations with this correlation led to changing their regenerator design porosity from 96 to 90 percent.

Plans have been proposed by NASA Glenn to provide further support for the Stirling radioisotope power system development in the areas of convertor, component, and materials testing. Specific areas identified include convertor performance verification, controls development for multiple convertors and multiple system loads, heater head structural life assessment, materials and joining evaluations, magnet thermal aging tests, and demonstration of convertor operation under launch and orbit transfer load conditions.

References


# Technology Development for a Stirling Radioisotope Power System for Deep Space Missions

**Authors:** Lanny G. Thieme, Songgang Qiu, and Maurice A. White

**Performing Organization:**
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

**Sponsoring/Monitoring Agency:**
National Aeronautics and Space Administration
Washington, DC 20546-0001

**Summary:**
NASA Glenn Research Center and the Department of Energy (DOE) are developing a Stirling convertor for an advanced radioisotope power system to provide spacecraft on-board electric power for NASA deep space missions. NASA Glenn is addressing key technology issues through the use of two NASA Phase I SBIRs with Stirling Technology Company (STC) of Kennewick, WA. Under the first SBIR, STC demonstrated a 40 to 50 fold reduction in vibrations, compared to an unbalanced convertor, with a synchronous connection of two thermodynamically independent free-piston Stirling convertors. The second SBIR is for the development of an Adaptive Vibration Reduction System (AVRS) that will essentially eliminate vibrations over a mission lifetime, even in the unlikely event of a failed convertor. This paper discusses the status and results for these two SBIR projects and also presents results for characterizing the friction factor of high-porosity random fiber regenerators that are being used for this application.

**Subject Terms:**
- Stirling engines
- Synchronization
- Vibration damping
- Regenerators
- Friction factor
- Nuclear electric power generation

**Abstract:**
This is a modified version of a paper prepared for the 34th Intersociety Energy Conversion Engineering Conference sponsored by the Society of Automotive Engineers, Vancouver, British Columbia, Canada, August 1–5, 1999. Lanny G. Thieme, NASA Glenn Research Center; Songgang Qiu, and Maurice A. White, Stirling Technology Company, 4208 West Clearwater Avenue, Kennewick, Washington, 99336 (work funded by NASA Contracts NAS3–98016 and NAS3–27817). Responsible person, Lanny G. Thieme, organization code 5490, (216) 433–6119.