Supporting Development for the Stirling Radioisotope Generator and Advanced Stirling Technology Development at NASA Glenn Research Center

Lanny G. Thieme and Jeffrey G. Schreiber
Glenn Research Center, Cleveland, Ohio

April 2005
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 databases, organizing and publishing research results . . . even providing videos.

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

- Access the NASA STI Program Home Page at http://www.sti.nasa.gov
- 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
Supporting Development for the Stirling Radioisotope Generator and Advanced Stirling Technology Development at NASA Glenn Research Center

Lanny G. Thieme and Jeffrey G. Schreiber
Glenn Research Center, Cleveland, Ohio

Prepared for the
Space Technology and Applications International Forum (STAIF-2005) sponsored by the University of New Mexico’s Institute for Space and Nuclear Power Studies (UNM-ISNPS)
Albuquerque, New Mexico, February 13–17, 2005

National Aeronautics and Space Administration
Glenn Research Center

April 2005
Acknowledgments

The work described in this presentation was performed for NASA Headquarters, Science Mission Directorate and Exploration Systems Mission Directorate.

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.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov
Supporting Development for the Stirling Radioisotope Generator and Advanced Stirling Technology Development at NASA Glenn Research Center

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

Abstract

A high-efficiency, 110-We (watts electric) Stirling Radioisotope Generator (SRG110) for possible use on future NASA Space Science missions is being developed by the Department of Energy, Lockheed Martin, Stirling Technology Company (STC), and NASA Glenn Research Center (GRC). Potential mission use includes providing spacecraft onboard electric power for deep space missions and power for unmanned Mars rovers. GRC is conducting an in-house supporting technology project to assist in SRG110 development. One-, three-, and six-month heater head structural benchmark tests have been completed in support of a heater head life assessment. Testing is underway to evaluate the key epoxy bond of the permanent magnets to the linear alternator stator lamination stack. GRC has completed over 10,000 hours of extended duration testing of the Stirling convertors for the SRG110, and a three-year test of two Stirling convertors in a thermal vacuum environment will be starting shortly. GRC is also developing advanced technology for Stirling convertors, aimed at substantially improving the specific power and efficiency of the convertor and the overall generator. Sunpower, Inc. has begun the development of a lightweight Stirling convertor, under a NASA Research Announcement (NRA) award, that has the potential to double the system specific power to about 8 We/kg. GRC has performed random vibration testing of a lower-power version of this convertor to evaluate robustness for surviving launch vibrations. STC has also completed the initial design of a lightweight convertor. Status of the development of a multi-dimensional computational fluid dynamics code and high-temperature materials work on advanced superalloys, refractory metal alloys, and ceramics are also discussed.
Supporting Development for the Stirling Radioisotope Generator and Advanced Stirling Technology Development at NASA GRC

Presented at
Space Technology and Applications International Forum (STAIF-2005)

by

Lanny G. Thieme and Jeffrey G. Schreiber

NASA Glenn Research Center at Lewis Field
Outline

• Background – Stirling Radioisotope Generator (SRG110)

• GRC Supporting Technology for SRG110
  Convertor Testing in Stirling Research Lab
  Heater Head Life Assessment
  Magnet-Stator Bond Evaluation
  Other Tasks

• Advanced Stirling Technology Development
  Goals
  Multi-Dimensional Stirling CFD Performance Code
  High-Temperature Materials
  Lightweight Convertor Development
  Other Tasks

• Summary
Stirling Radioisotope Generator (SRG110)

- **100-W class, high-efficiency power source for NASA Space Science missions**
  - Unmanned Mars rovers for long-duration missions
  - Spacecraft onboard electric power for deep space missions
  - Lunar distributed power, communication stations, and rovers

- **> 20% efficiency reduces isotope inventory by factor of 4 or greater compared to RTG’s**
  - Reduces radioisotope/system cost and radiological inventory

- **Lockheed Martin and Stirling Technology Company (STC) are developing SRG110 under contract to DOE**
  - Two opposed Stirling convertors with two GPHS modules
  - Engineering Unit FDR completed – fab to be completed by September, 2005

- **NASA GRC provides:**
  - Technical consulting for DOE/LM
  - In-house supporting technology development project
  - Advanced Stirling technology

<table>
<thead>
<tr>
<th>Missions</th>
<th>Other Organizations</th>
</tr>
</thead>
<tbody>
<tr>
<td>JPL</td>
<td>System Integration Contractor</td>
</tr>
<tr>
<td>NASA</td>
<td>Lockheed Martin</td>
</tr>
<tr>
<td>GRC</td>
<td>Orbital</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technical Consultant</th>
<th>Stirling Expertise</th>
<th>Stirling Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA</td>
<td>GRC</td>
<td>Lockheed Martin</td>
</tr>
</tbody>
</table>
GRC Supporting Technology Development for SRG110

Objective: Support development of Stirling convertor for space qualification and mission implementation

- Independent convertor performance verification
  - Convertor extended operation
  - Controller tests
  - Thermal vacuum test
- Heater head life assessment and materials studies
- Magnet aging characterization
  - Linear alternator analysis and testing
- Convertor structural dynamics
- EMI/EMC reduction and characterization
- Evaluation of convertor organics
- Reliability evaluation
- Electrical interface
- Thermodynamic and system dynamic analyses

See Geng – C-30
Stirling Convertor Operation at GRC

• 13,200 hours of extended operation on TDC’s #13 & #14 as of 2/9/05

• TDC’s #15 & #16 just received at GRC – will do random vibration test and extended operation
  Discussions are underway with Edison Welding Institute to hermetically seal TDC’s #15 & #16 and #13 & #14

• 3-year test of TDC’s #5 & #6 in thermal vacuum environment initiated in November, 2004
  - 838 hours of operation as of 2/8/05

• Stirling Research Lab moved to new facility in August, 2004
  Six test stations surround Power System Test Bed (PSTB)
  PSTB will be capable of simulating variety of spacecraft power systems and can accept power from any combination of convertors on test
Heater Head Life Assessment

- Heater head probabilistic life prediction completed
  - 116,000 hours (13.25 years) at 650 °C and 99.99% probability of survival (PoS)
  - 188,000 hours (21.5 years) for PoS of 99.9%

Based on GRC thin-specimen creep testing and extensive ORNL database (up to 87,000 hours)

- 5 creep samples still under test from 1st heat of IN718 – longest test to date is 3.8 years

2nd heat has been purchased by LM/STC and samples are now under test at GRC – several highly-stressed samples have reached rupture lives and show properties to be equivalent to original heat
Heater Head Structural Benchmark Testing

• 1, 3, and 6-month heater head structural benchmark tests have been completed to factor in biaxial stress state and begin validation of analysis

• Two 12-month benchmark tests about to begin
  – At design pressure and temperature
  – Extremely small creep strains will be measured both optically and with extensometers
  – One test will include heat collector and axial preload
Benchmark test data for initial secondary creep rate all fall within 99.9% PoS (~3 std. deviations)

Heater Head Structural Benchmark Testing

GRC Predicted and Tested Creep Rates

Creep Rate

Stress

- x - ORNL

GRC material data
- 99.9% PoS
- 99.99% PoS

Coupon Test

Benchmark Tests
Magnet – Stator Bond Evaluation

- 3M Scotch-Weld™ 2216 B/A Gray epoxy
- GRC completed cure kinetics for epoxy and recommended cure cycle – worked with STC to incorporate cure cycle into LA processing
  - Increase of 40% in lap shear strength compared to standard room-temperature cure cycle
- Epoxy shown to be stable to 180 °C
  Ran short-term accelerated aging tests for up to 150 days at 150 and 180 °C
  - No performance degradation observed
  - Substantial increases in lap shear strength at 80 and 120 °C
- Also investigating two higher-temperature epoxies
  - Masterbond EP33 and Supreme 10HT
- Remaining: Fatigue testing at GRC and Cincinnati Testing Labs and 1/3, 1, and 3-year lifetime tests
Other Tasks for SRG110

• Probabilistic-based reliability analysis
  – Component and subsystem analysis and test activities – use for reliability analysis of complete convertor

  **Completed or underway**
  - Inconel 718 characterization and creep tests, heater head structural benchmark tests, and heater head life assessment
  - Magnet characterization/aging tests
  - Alternator flexure analysis
  - Organics assessment and tests

  **Planned**
  - Displacer flexure analysis
  - Heat exchanger
  - Misc. (controls, feedthroughs, internal seals, hermetic welds, sensors)

  – Extended operation of TDC’s and cryocooler database

• End-to-End System Dynamic Model
  - Interfacing with Sage Stirling code for improved thermodynamics
  - Validation underway
  - Being used for controller development by both GRC and LM

See Shah – C-26

See Regan – C-26
Advanced Technology for Stirling Convertors – Goals

<table>
<thead>
<tr>
<th>Near Term</th>
<th>Mid Term</th>
<th>Far Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stirling Radioisotope Generator (SRG)</td>
<td>2nd Generation</td>
<td>3rd Generation</td>
</tr>
<tr>
<td>1st Generation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOM</td>
<td>BOM</td>
<td>BOM</td>
</tr>
<tr>
<td>3.3-4.0 W_e/kg</td>
<td>6-10 W_e/kg</td>
<td>8-10+ W_e/kg</td>
</tr>
<tr>
<td>22-25% system efficiency</td>
<td>28-31% system efficiency</td>
<td>33-36% system efficiency</td>
</tr>
<tr>
<td>Lightweight convertor</td>
<td>Advanced superalloy materials</td>
<td>CFD code/loss understanding</td>
</tr>
<tr>
<td>Advanced controller</td>
<td></td>
<td>High-temperature heater head</td>
</tr>
<tr>
<td>Improved regenerators</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• Advanced high efficiency, lightweight Stirling power could enable:
  – Higher power per GPHS module
  – Use of radioisotope electric propulsion
  – Venus surface mission with combined Stirling power convertor/cooler

• Advanced RPS System Assessment Team has started system conceptual design based on Sunpower lightweight convertor

• Advanced technologies also applicable to higher-power Stirling

See Schmitz – C-23
Multi-Dimensional Stirling CFD Performance Code

• GRC and Cleveland State University (CSU) are developing multi-dimensional Stirling CFD code
  – CSU grant partners: University of Minnesota (UMN) and Gedeon Associates – also involves Stirling manufacturers

• 2D Fluent and CFD-ACE models of TDC operational – will soon be transitioned to 3D – will also be modeling lightweight convertors

Microway 32-processor cluster with high-speed communications has been installed at GRC

• UMN is beginning validation testing with engine-like 180° turn fixture – will include heat transfer testing – CSU compares with CFD code predictions

• Several key areas remain to be addressed:
  – Non-equilibrium models for regenerator matrix
  – Accurate modeling of turbulent flow and transition flow
  – Improved methods for faster temperature convergence for solids with large heat capacity exchanging heat with gases of small heat capacity

• Further plans include high-order techniques for faster, more accurate processing and multi-D transient and steady-periodic codes fast enough for design
High-Temperature Materials

• Advanced superalloys offer 200 °C increase compared to current 650 °C hot-end temp. Refractory metals and ceramics could achieve up to 1200 °C for 120,000-hour lifetimes
  – GPHS temperature limits may require ≤ 1050 °C – possibly higher with cover gas and modified system layout

• Five superalloys chosen for testing based on creep, hermetic sealing, & long-term stability
  – Alloys 720, 738, and 939; MarM-247; MA754

  In testing to date, MarM-247 has highest creep strength – 2nd heat processed to test finer grains – optimized grain size has now been selected
  – Will next test under wide range of stresses and temperatures to provide data for life analysis

• Refractory metal alloys under study are Astar-811C (tantalum alloy) and rhenium
  – Near net shape rhenium heater head demo vessel has been fabricated
  – Rhenium specimen will be tested with iridium coating to show ability to test for 1000’s of hours in air environment

• Preparing for permeability tests of 5 SiN ceramics at operating temperatures and pressures and SiN property tests – structural assessment starting and will eventually include probabilistic life analysis
Sunpower Lightweight Convertor

- Sunpower is developing a lightweight Advanced Stirling Convertor (ASC) that could double the specific power of the SRG to about 8 Wₑ/kg – teamed with Boeing-Rocketdyne
  - NASA Research Announcement (NRA) award for Radioisotope Power Conversion Technology

  Power of ~88 Wₑ, specific power of 91 Wₑ/kg, and efficiency approaching 40% are projected – hot-end temperature of 850°C and lifetime of 14 years

Design of baseline ASC completed

Frequency Test Bed convertor has demonstrated 36% efficiency at 105 hz and 3.0 temp. ratio

- Sunpower also developed nominal 35-Wₑ lightweight convertor (EE-35) under a NASA Phase II SBIR
  - Achieved over 40 Wₑ power output and 31% efficiency at 2.6 temp. ratio
  - Convertor specific power estimated to exceed 90 Wₑ/kg in final configuration

- GRC performed random vibration test of two EE-35’s to evaluate robustness to survive launch vibrations
  - Tested one unit to 23.9 grms in axial direction and other to 23.9 grms in lateral
  - Power remained nearly constant and no damage in initial assessments after test
STC Lightweight Convertor Design

- Designed for same temperatures, heat input, and life as TDC
- Flat heater head
  Reduced alternator over-capacity
  Increased frequency
  Titanium piston housing & pressure vessel
  Flux concentration and moving magnet linear alternator configurations
- Flat heater head gives simple interface to GPHS – no heat collector required
- Mass substantially reduced from 5.5 kg (with heat collector) to 1.3-1.6 kg – convertor specific power increased to ~46-57 \( W_e/kg \) based on 72 \( W_e \) power output
- Decreased diameter and length for improved packaging and further system mass reductions

See Qiu – C-21
Other Tasks – Advanced Stirling

- Advanced controller uses power electronics to provide active power factor correction (APFC) and stroke control
  – Eliminate tuning capacitors to reduce controller mass and volume

Initial lower-power testing demonstrated ability to adjust power factor & control stroke
Rack versions completed for both TDC and EE-35 testing
Will next test at full power and then explore integration with active vibration control

- CSU team is developing microfabricated regenerator
  – NRA award for Radioisotope Power Conversion Technology
    Team includes CSU, UMN, Gedeon Associates, Sunpower, and STC

Goals are improved convertor performance, increased regenerator durability, and improved fabrication consistency

Selected involute foil concept by Mezzo Technologies
  – Test large-scale mockup at UMN and samples in oscillating flow rig at Sunpower – then demo in convertor, as possible

See Tew – C-26  See Qiu – C-31
Summary

• Key GRC efforts continue in support of SRG110 development
  – Extended duration test of TDC’s #13 & #14 has achieved over 13,000 hours
  – 3-year test started of TDC’s #5 & #6 in thermal vacuum
  – Structural benchmark testing of heater heads validating life assessment
  – Probabilistic-based reliability analysis underway on components, subsystems, and convertor

• Advanced Stirling systems could provide:
  Significant performance and mass benefits for lunar and Mars rovers, stationary power generators including lunar distributed power and communication stations, and deep space missions
  Allow use of Stirling radioisotope power for radioisotope electric propulsion and extended-duration Venus surface missions

• Good progress has been made on technologies for achieving goals for 2nd and 3rd generation SRG’s
  – Development of CFD codes is accelerating
  – Optimized grain size selected for MarM-247 – testing will next provide data for life analysis
  – Sunpower lightweight Stirling convertors have shown excellent performance and robustness in early testing and have the potential to double system specific power to about 8 W_e/kg
# Supporting Development for the Stirling Radioisotope Generator and Advanced Stirling Technology Development at NASA Glenn Research Center

**Author(s):** Lanny G. Thieme and Jeffrey G. Schreiber

**Performing Organization Name(s) and Address(es):**
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

**Funding Numbers:**
WBS–22–972–20–01

**Performing Organization Report Number:**
E–15111

**Sponsoring/Monitoring Agency Name(s) and Address(es):**
National Aeronautics and Space Administration
Washington, DC 20546–0001

**Sponsoring/Monitoring Agency Report Number:**
NASA TM—2005-213628

**Supplementary Notes:**

**Distribution/Availability Statement:**
Unclassified - Unlimited
Subject Categories: 20 and 44
Available electronically at http://glnrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

**Abstract:**
A high-efficiency, 110-We (watts electric) Stirling Radioisotope Generator (SRG110) for possible use on future NASA Space Science missions is being developed by the Department of Energy, Lockheed Martin, Stirling Technology Company (STC), and NASA Glenn Research Center (GRC). Potential mission use includes providing spacecraft onboard electric power for deep space missions and power for unmanned Mars rovers. GRC is conducting an in-house supporting technology project to assist in SRG110 development. One-, three-, and six-month heater head structural benchmark tests have been completed in support of a heater head life assessment. Testing is underway to evaluate the key epoxy bond of the permanent magnets to the linear alternator stator lamination stack. GRC has completed over 10,000 hours of extended duration testing of the Stirling convertors for the SRG110, and a three-year test of two Stirling convertors in a thermal vacuum environment will be starting shortly. GRC is also developing advanced technology for Stirling convertors, aimed at substantially improving the specific power and efficiency of the convertor and the overall generator. Sunpower, Inc. has begun the development of a lightweight Stirling convertor, under a NASA Research Announcement (NRA) award, that has the potential to double the system specific power to about 8 We/kg. GRC has performed random vibration testing of a lower-power version of this convertor to evaluate robustness for surviving launch vibrations. STC has also completed the initial design of a lightweight convertor. Status of the development of a multi-dimensional computational fluid dynamics code and high-temperature materials work on advanced superalloys, refractory metal alloys, and ceramics are also discussed.

**Subject Terms:**
Stirling engines; Nuclear electric power generation; Deep space; Mars; Roving vehicles; Life (durability); Epoxy resins; Computational fluid dynamics; Heat resistant alloys; Refractory metals; Ceramics; Regenerators; Dynamics; Reliability

**Number of Pages:**
24

**Limitation of Abstract:**
Unclassified