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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

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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**

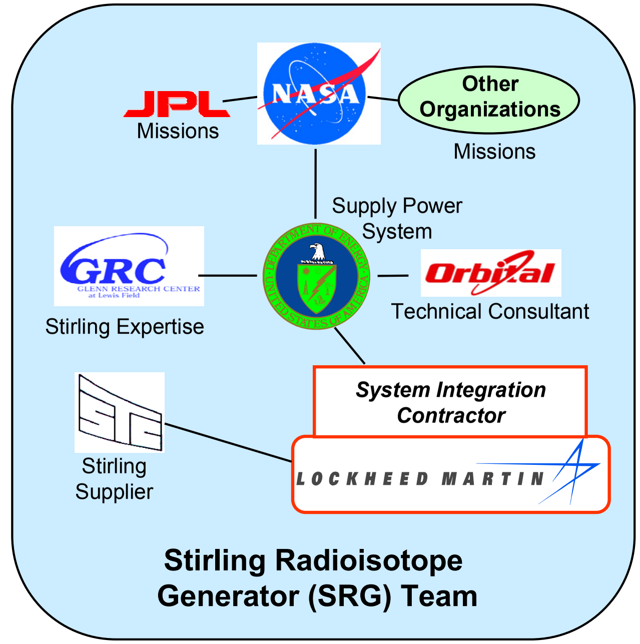
Stirling Radioisotope Generator (SRG110)

- **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



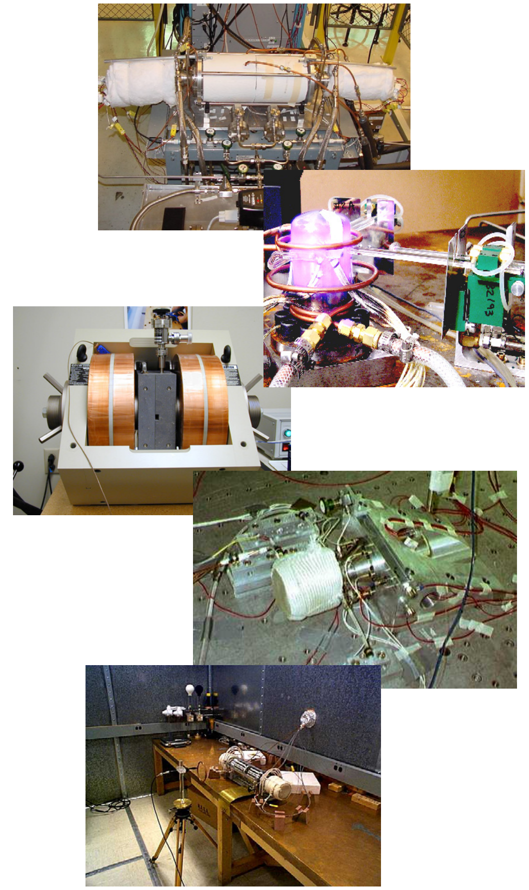
GRC Supporting Technology Development for SRG110

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

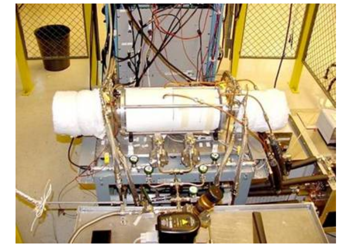
See Geng – C-30

- **Convertor structural dynamics**
- **EMI/EMC reduction and characterization**
- **Evaluation of convertor organics**
- **Reliability evaluation**
- **Electrical interface**
- **Thermodynamic and system dynamic analyses**



Stirling Convertor Operation at GRC

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



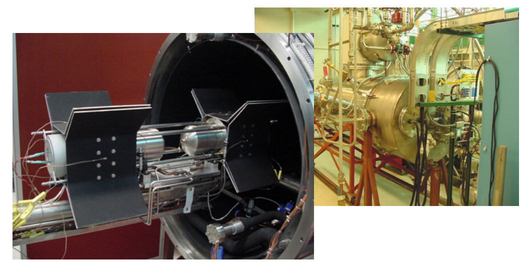
TDC's #13 & #14 on extended operation

- 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

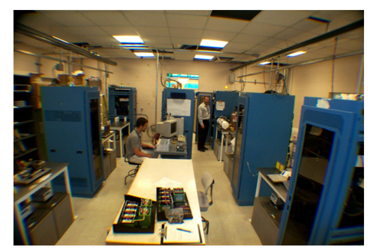


Thermal vacuum testing

- 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



Stirling Research Lab

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)

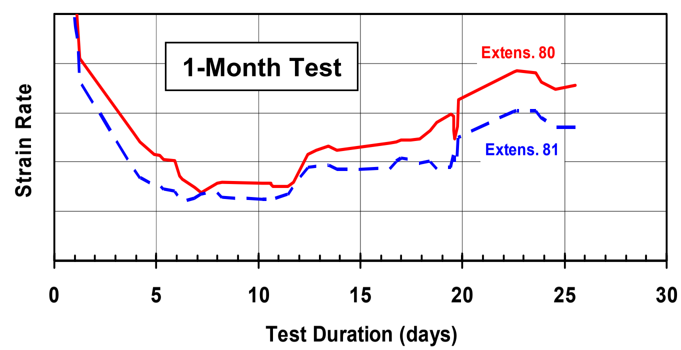
- **5 creep samples still under test from 1st heat of IN718 – longest test to date is 3.8 years**

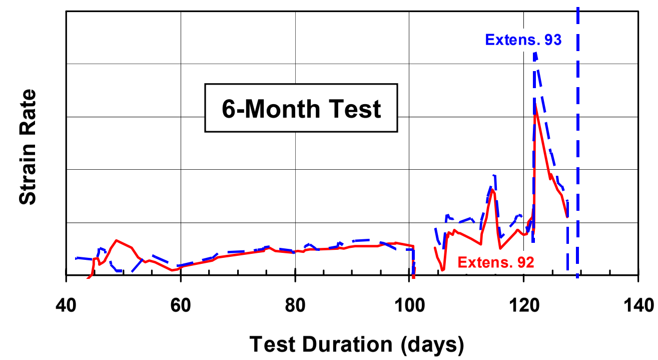
  2nd heat has been purchased by LM/STC and samples are now under test at GRC – several highly-stressed samples have reached rupture lives and show properties to be equivalent to original heat

IN718 creep testing at GRC

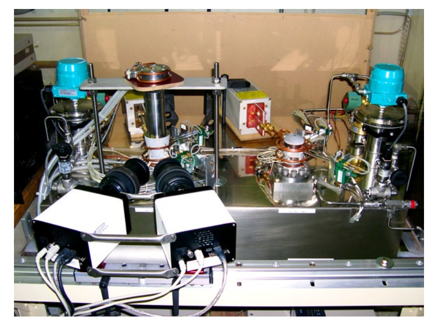
Heater Head Structural Benchmark Testing

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





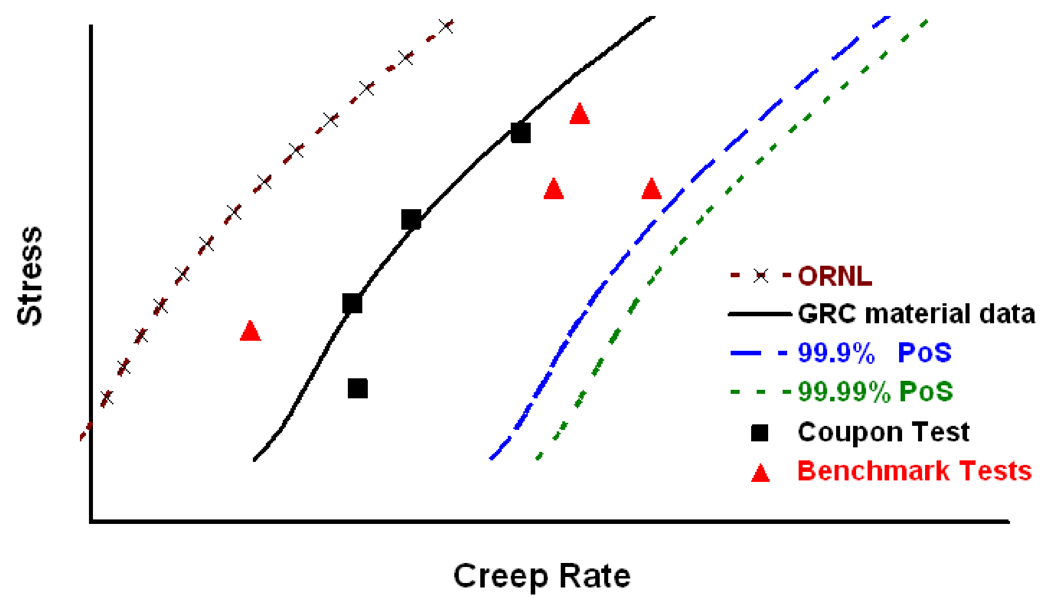
- **Two 12-month benchmark tests about to begin**
  – At design pressure and temperature
  – Extremely small creep strains will be measured both optically and with extensometers
  – One test will include heat collector and axial preload



Heater head structural benchmark testing

Heater Head Structural Benchmark Testing

GRC Predicted and Tested Creep Rates

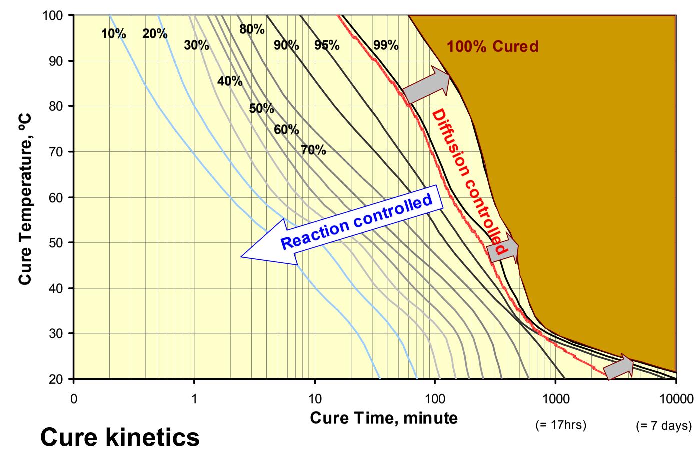


Benchmark test data for initial secondary creep rate all fall within 99.9% PoS (~3 std. deviations)

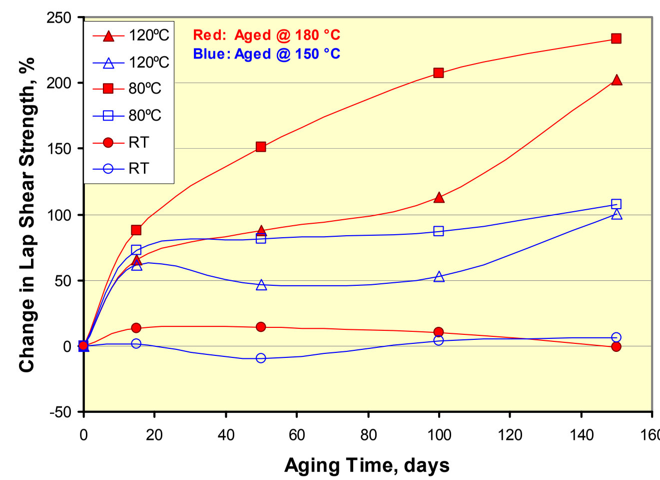
Magnet – Stator Bond Evaluation

- **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**



Cure kinetics



Lap shear strength

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
    Alternator reliability modeling
    Fastener reliability analysis

    Planned

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

    See Shah – C-26

  - Extended operation of TDC’s and cryocooler database

- End-to-End System Dynamic Model

  See Regan – C-26

  Interfacing with Sage Stirling code for improved thermodynamics

  Validation underway

  Being used for controller development by both GRC and LM

Advanced Technology for Stirling Convertors – Goals

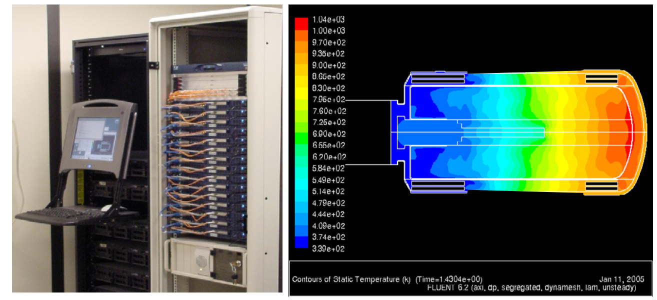
Near Term	Mid Term	Far Term
Stirling Radioisotope Generator (SRG)		
1st Generation	2nd Generation	3rd Generation
BOM 3.3-4.0 W_e/kg 22-25% system efficiency	BOM 6-10 W_e/kg 28-31% system efficiency	BOM 8-10+ W_e/kg 33-36% system efficiency
	Lightweight convertor Advanced superalloy materials Advanced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

- **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 cluster and 2D results

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**

See Tew – C-26

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

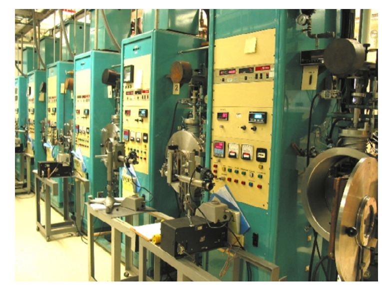
- **Five superalloys chosen for testing based on creep, hermetic sealing, & long-term stability**
  - Alloys 720, 738, and 939; MarM-247; MA754

  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**

  See Leonhardt – C-19

  - 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



High-vacuum creep facility

- **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 W_e/kg** – teamed with Boeing-Rocketdyne
  - NASA Research Announcement (NRA) award for Radioisotope Power Conversion Technology

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

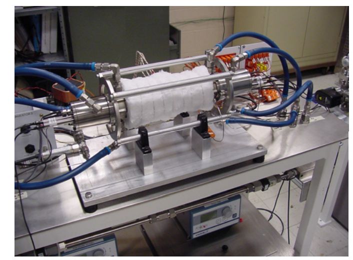
  Design of baseline ASC completed

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

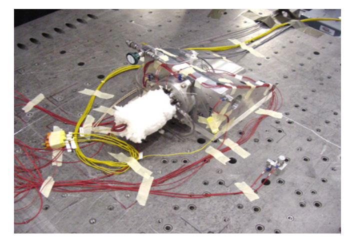
  See Wood – C-30

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



EE-35 test setup at GRC



Random vibration test of EE-35 convertor

STC Lightweight Convertor Design

- **Designed for same temperatures, heat input, and life as TDC**

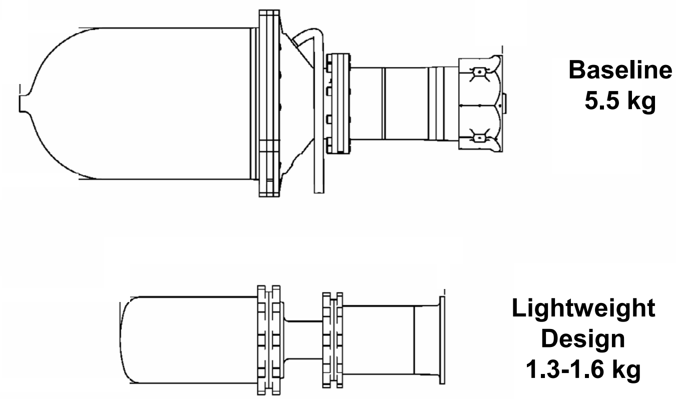
- **Flat heater head**

  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

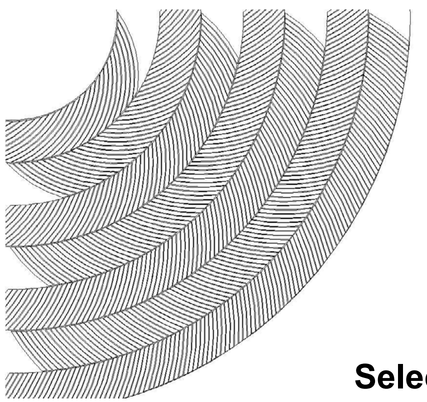
Other Tasks – Advanced Stirling

- **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



Involute foil

- **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

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