

Advanced Technology Development for Stirling Convertors

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Abstract. The Department of Energy, Lockheed Martin (LM), Stirling Technology Company, and NASA Glenn Research Center (GRC) are developing a high-efficiency Stirling Radioisotope Generator (SRG) for potential NASA Space Science missions. The SRG is being developed for multimission use, including providing spacecraft onboard electric power for NASA deep space missions and power for unmanned Mars rovers. NASA GRC is conducting an in-house supporting technology project to assist in developing the Stirling convertor for space qualification and mission implementation.

GRC is also developing advanced technology for Stirling convertors, aimed at substantially improving the specific power and efficiency of the convertor and the overall power system. Performance and mass improvement goals have been established for second- and third-generation Stirling radioisotope power systems. Multiple efforts are underway to achieve these goals, and the status and results to date for these efforts will be discussed in this paper.

Cleveland State University (CSU) is developing a multi-dimensional Stirling computational fluid dynamics code, capable of modeling complete convertors. A 2-D version of the code is now operational. Validation efforts at both CSU and the University of Minnesota are complementing the code development. A screening of advanced superalloy materials has been completed, and materials have been selected for creep and joining characterization as part of developing a high-temperature heater head. In addition, refractory alloy characterizations will soon be underway, and ceramic alternatives will also be studied. A design has been completed for an advanced controller using power electronics for active power factor control with a goal of eliminating the heavy tuning capacitors that are traditionally needed to achieve near unity power factors. A breadboard characterization of this controller is now underway. An end-to-end system dynamics model is also being developed, and one use will be to help guide the advanced controller work. Key Stirling developments to be done under recent NRA (NASA Research Announcement) awards for radioisotope power system technology will also be discussed. These include a lightweight convertor to be developed by Sunpower Inc. and an advanced regenerator to be done by CSU. GRC is planning a launch environment test of a lightweight convertor in FY04 and also expects to fabricate a higher-temperature superalloy heater head for this convertor.

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Abstract. A high-efficiency Stirling Radioisotope Generator (SRG) for use on potential NASA Space Science missions is being developed by the Department of Energy, Lockheed Martin, Stirling Technology Company, and NASA Glenn Research Center (GRC). These missions may include providing spacecraft onboard electric power for deep space missions or power for unmanned Mars rovers. GRC is also developing advanced technology for Stirling convertors, aimed at substantially improving the specific power and efficiency of the convertor and the overall power system. Performance and mass improvement goals have been established for second- and third-generation Stirling radioisotope power systems. Multiple efforts are underway to achieve these goals, both in-house at GRC and under various grants and contracts. The status and results to date for these efforts will be discussed in this paper. Cleveland State University (CSU) is developing a multi-dimensional Stirling computational fluid dynamics code, capable of modeling complete convertors. A 2-D version of the code is now operational, and validation efforts at both CSU and the University of Minnesota are complementing the code development. A screening of advanced superalloy, refractory metal alloy, and ceramic materials has been completed, and materials have been selected for creep and joining characterization as part of developing a high-temperature heater head. A breadboard characterization is underway for an advanced controller using power electronics for active power factor control with a goal of eliminating the heavy tuning capacitors that are typically needed to achieve near unity power factors. Key Stirling developments just initiated under recent NRA (NASA Research Announcement) awards will also be discussed. These include a lightweight convertor to be developed by Sunpower Inc. and an advanced microfabricated regenerator to be done by CSU.

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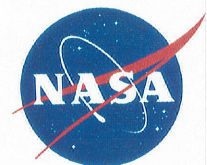
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Outline

- **Background – Stirling Radioisotope Generator (SRG)**

GRC Supporting Technology Development for SRG

- **Advanced Technology Development**

Goals

Multi-Dimensional Stirling CFD Performance Code

High-Temperature Materials

Advanced Controllers

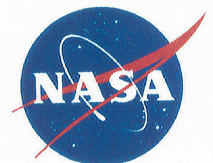
Lightweight Converter Development

Improved Regenerators

- **Summary**

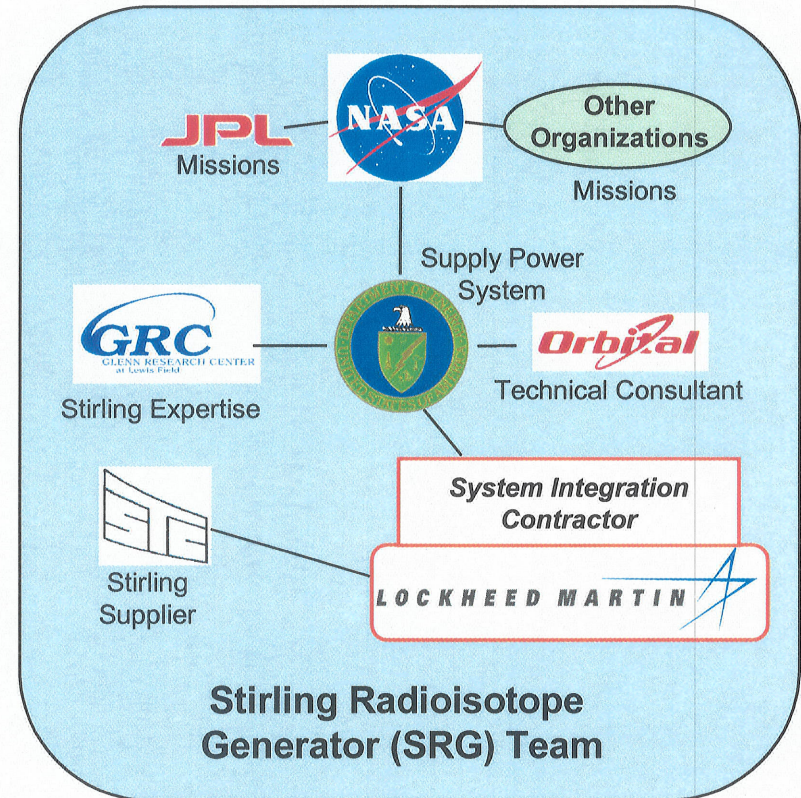
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Stirling Radioisotope Generator (SRG)

- **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
- **> 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 SRG under contract to DOE**
 - Two opposed Stirling convertors with two GPHS modules
 - 4 W/kg and 22% system efficiency at BOM
 - 16 convertors have been built by STC
- **NASA GRC provides:**
 - Technical consulting for DOE
 - In-house supporting technology development project
 - Advanced Stirling technology



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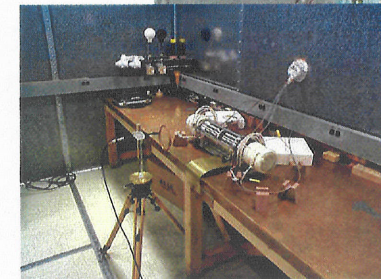
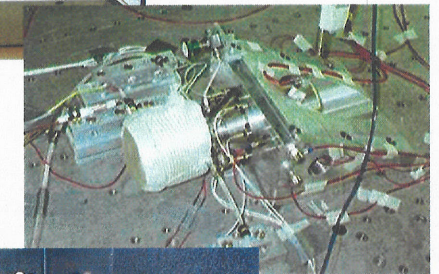
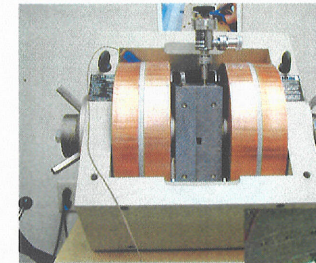
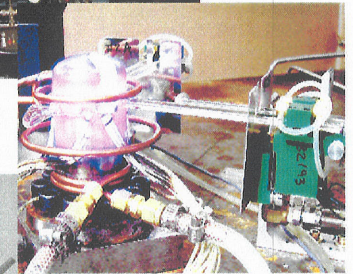
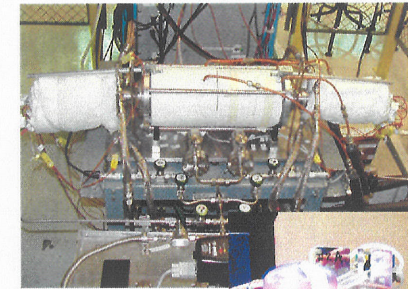
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GRC Supporting Technology Development for SRG

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



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GRC Supporting Technology Development for SRG – Highlights

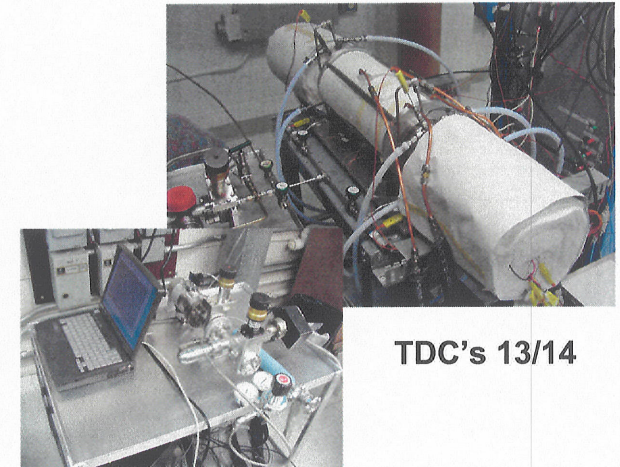
- **Over 4000 hours of extended testing have been completed on TDC's 13/14**
 - Charging cart developed for clean fill and gas analyses
- **Controls tests completed to support LM SRG controller development**
- **Preparations continuing for 3-year thermal vacuum test**
- **Probabilistic life prediction completed for heater head**
 - 116,000 hours at 650°C and 99.99% Probability of Survival

See Ashwin Shah talk in Session C32

Heater head structural benchmark tests underway

- 1, 3, and 6-month cal tests on heater head shells
 - 12-month tests on shell and more complete head
- **18,000 hours of long-term magnet aging completed on two NdFeB magnet grades**
 - **Reliability analyses initiated**

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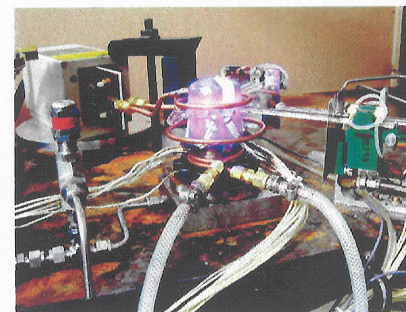


TDC's 13/14

Charging cart



Thermal vacuum testing



Heater head structural benchmark testing



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Advanced Technology for Stirling Convertors – Goals

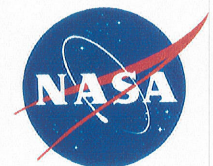
Near Term

Mid Term

Far Term

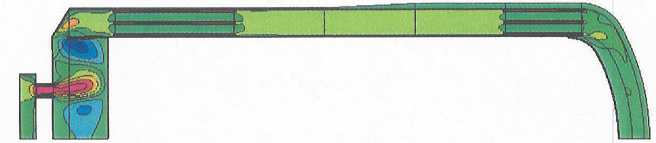
<p>Stirling Radioisotope Generator (SRG)</p> <div style="border: 1px solid black; border-radius: 50%; width: 80%; margin: 10px auto; background-color: #add8e6; padding: 5px; text-align: center;"> <p>1st Generation</p> </div> <p>4 W_e/kg 22% system efficiency</p>	<div style="border: 1px solid black; border-radius: 50%; width: 80%; margin: 10px auto; background-color: #add8e6; padding: 5px; text-align: center;"> <p>2nd Generation</p> </div> <p>6-10 W_e/kg 25% system efficiency</p> <p>Lightweight convertor Advanced superalloy materials Advanced controller</p>	<div style="border: 1px solid black; border-radius: 50%; width: 80%; margin: 10px auto; background-color: #add8e6; padding: 5px; text-align: center;"> <p>3rd Generation</p> </div> <p>8-10+ W_e/kg 35% system efficiency</p> <p>CFD code/loss understanding High-temperature heater head Improved regenerators</p>

- **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
 - Solar deep space power out to Jupiter and possibly Saturn



Multi-Dimensional Stirling CFD Performance Code

- **Grant with Cleveland State University (CSU) to develop multi-dimensional Stirling CFD code**
 - Partnered with University of Minnesota (UMN) and Gedeon Associates – also involves Stirling manufacturers



Sample velocity contours from 2-D code

- **Based on CFD-ACE commercial code**

- **Objectives:**

Significantly improve understanding of Stirling losses and help identify areas for performance improvement

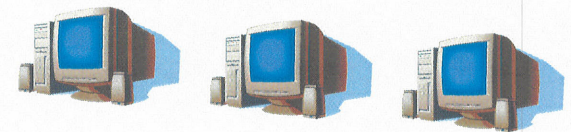
Reduce Stirling performance prediction inaccuracies to less than 5%, from current 10-20%

Utilize multi-D CFD code and supporting validation efforts to improve 1-D design codes

Make multi-D CFD code available to Stirling industry

- **2-D model is operational**

GRC has converted to TDC model and this is now running

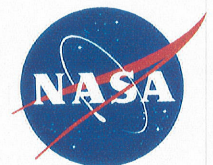


GRC is now setting up initial parallel computer cluster to speed up processing

- Purchased 8 computers so far – eventually expecting 64 computers in cluster

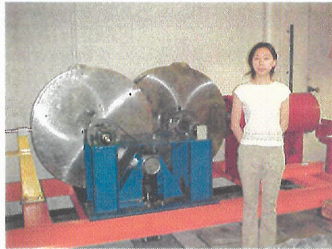
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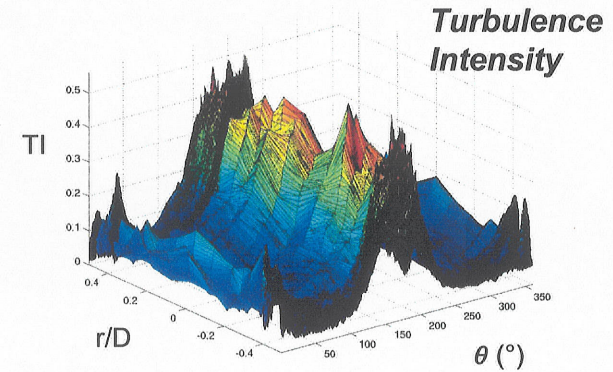
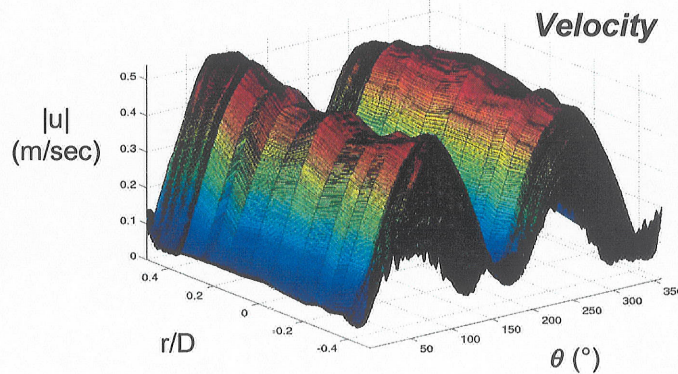


Multi-Dimensional Stirling CFD Performance Code

- **UMN completed validation testing on 90° turn test fixture**
 - Both oscillating and unidirectional flow testing – visualization and hot-wire velocity measurements

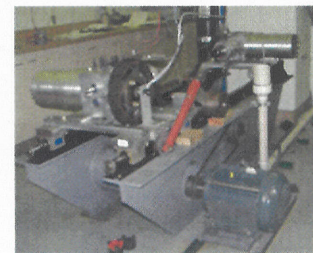


UMN test rig

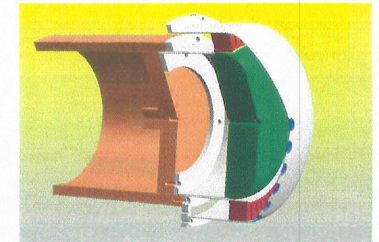


- **CSU code comparisons show reasonable agreement assuming correct choice of laminar vs. turbulent flow**
- **More engine-like 180° turn fixture designed for next testing at UMN**
 - Will include heat transfer testing
- **CSU took initial measurements with SLRE test rig**

See Roy Tew talk in Session C32



CSU SLRE test rig



180° turn test fixture

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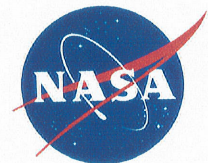
High-Temperature Materials

Objective: Significantly increase Stirling convertor hot-end temperature to increase system efficiency and/or allow possible increase in cold-end temperature to reduce radiator and system mass

- **Advanced superalloys offer 100-200°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**
 - Limit to about 1050°C to maintain GPHS within temperature limits
 - 1125-1200°C may be possible using a cover gas on the GPHS – could also enable extended-duration Venus lander
- **Status – Advanced Superalloys:**
 - **Screening completed based on creep, joining, and stability**
 - **Five candidates selected and creep testing is underway**
 - Mar-M247 High-strength cast alloy with large database of properties
 - MA754 Oxide dispersion strengthened wrought alloy – very stable
 - alloy 939 Weldable high-strength cast alloy
 - alloy 738 Cast alloy designed for long-term stability
 - alloy 720 Wrought alloy with good stability
 - **Primary candidate hermetic sealing technique for use with all 5 alloys has been chosen**
 - Electro-spark deposition
 - Experimental trials will start soon at Edison Welding Institute

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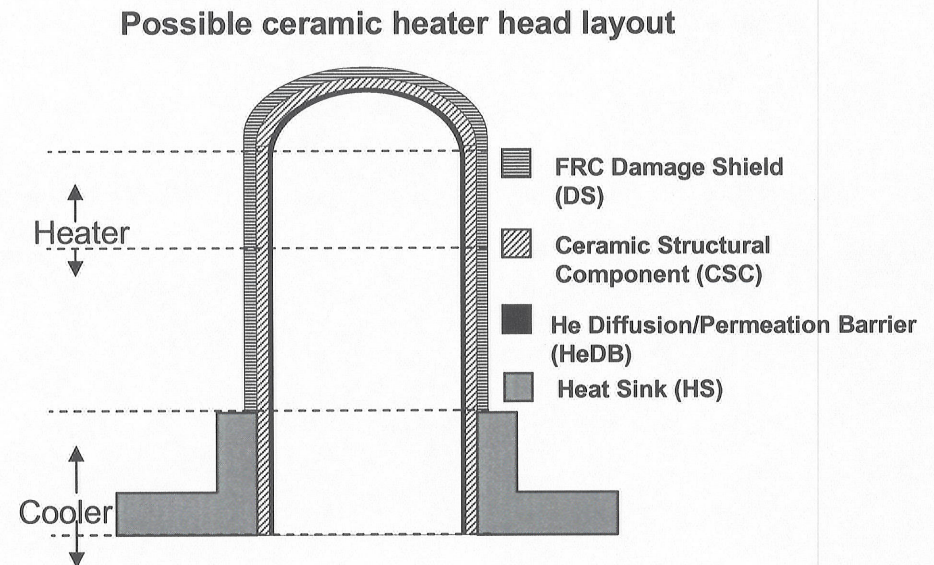
High-Temperature Materials

➤ Status – Refractory Metal Alloys:

- Screened molybdenum, niobium, tantalum, tungsten, and rhenium alloys
 - Typically have smaller databases than superalloys and must be tested in inert environment
- Selected ASTAR-811C (tantalum) and rhenium as primary alloys for further study
 - Both have high strength, good weldability & fabricability, and ductility at low temperatures
- Re-furbishing ultra-high vacuum creep frames

➤ Status – Ceramics:

- Possibly tailor conductivity
Don't require testing in inert environment
- Completed basic heater head layout
 - Damage shield
 - Ceramic structural component
 - Helium diffusion/permeation barrier
 - Heat sink
- Identified helium permeability as only issue that could prevent possible use
 - Initial permeability tests encouraging
 - Must also focus on joining and damage tolerance



See Randy Bowman talk in Session C16

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Advanced Controllers

Description

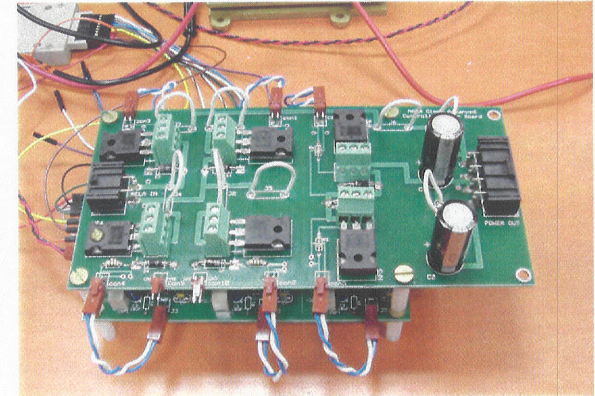
- Power electronics provide active power factor correction (APFC) and stroke control
- PWM load resistor dissipating excess power
- >2 increase in specific power compared to SRG

Status

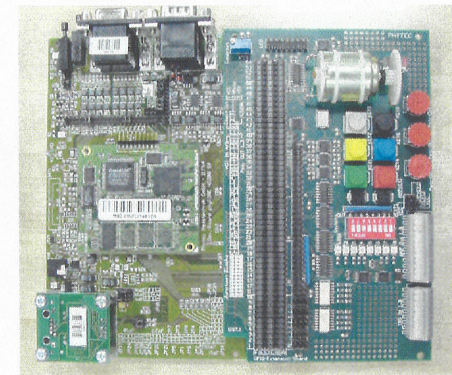
- Several power factor correction circuits conceived and modeled – using Simplorer system dynamics model
- Selected three level full-bridge design
- Hardware fabrication and software integration completed
- Bench tests completed with variac/inductance test circuit

Planned Activities

- Testing with TDC Stirling convertor
- Integrate with active vibration control



Power stage for APFC controller



ARM microcontroller development board

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Lightweight Convertor Development

- Sunpower is developing a lightweight Stirling convertor that could double the specific power of the SRG to about $8 W_e/kg$

Teamed with Boeing-Rocketdyne

Convertor projected to have specific power of nearly $100 W_e/kg$ and efficiency of 30% or greater

- NASA Research Announcement award for Radioisotope Power Conversion Technology
- Sized for two convertors in opposed configuration using heat from 2 GPHS modules
- CSU and UMN providing CFD modeling and testing/analyses to study specific convertor losses

- Sunpower is also developing a lower-power lightweight convertor under a NASA Phase II SBIR

- Sized for two convertors in opposed configuration using heat from 1 GPHS module
- Now under test – has produced full power of over 40 W

- GRC is planning 1) a launch environment test of the Sunpower SBIR convertor and 2) building higher-temperature superalloy heater heads for this convertor

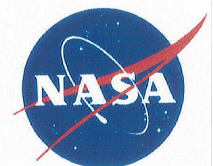
- A new effort is now being initiated with STC to complete a preliminary design of a lightweight version of the convertor used in the 1st generation SRG



Mockup of Phase II SBIR lightweight convertor (courtesy of Sunpower, Inc.)

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Improved Regenerators

- **Grant has been awarded to CSU for follow-on effort on regenerators – CSU team has done previous grant for DOE-Golden to improve solar terrestrial Stirling convertors**
 - Previous work included studying plenum size effects on jetting into the regenerator, flow recirculation near the regenerator wall, and heat transfer rates between the regenerator wire and fluid
 - NASA grant will focus on improving currently-used random fiber regenerators and possibly foil regenerators and obtaining a better understanding of detailed flow fields and heat transfer in oscillating flow
 - Team includes CSU, UMN, Gedeon Associates, and Sunpower
- **CSU is also conducting research effort for microfabricated regenerator**
 - NASA Research Announcement 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
 - Several designs, manufacturing processes, and potential manufacturers have been identified



Oscillating flow test rig
at Sunpower

See Roy Tew talk in Session C32

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Summary

- **Advanced Stirling systems could provide:**
 - **Significant performance and mass benefits for Mars rovers and deep space missions**
 - **Allow use of Stirling radioisotope power for radioisotope electric propulsion and Venus surface missions**
- **Good progress has been made on technologies for achieving goals for 2nd and 3rd generation SRG's**
 - 2D Stirling CFD performance model for TDC is operational and initial parallel computer cluster is under construction
 - High-temperature materials have been selected and tests are underway
 - Advanced controller with active power factor correction has been fabricated and bench tested
- **Key work under NASA NRA has begun on development of lightweight Stirling convertor that is expected to double system specific power to about 8 W_e/kg**
- **GRC's close integration with team developing 1st generation SRG should provide good path for eventual use of advanced technology developments**

