Oral Presentation/Viewgraph Summary:

The NASA Glenn Research Center (GRC) has been testing high efficiency free-piston Stirling convertors for potential use in radioisotope power systems since 1999. Stirling convertors are being operated for many years to demonstrate a radioisotope power system capable of providing reliable power for potential multi-year missions. Techniques used to monitor the convertors for change in performance include measurements of temperature, pressure, energy addition, and energy rejection. Micro-porous bulk insulation is used in the Stirling convertor test set up to minimize the loss of thermal energy from the electric heat source to the environment. The insulation is characterized before extended operation, enabling correlation of the net thermal energy addition to the convertor. Aging microporous bulk insulation changes insulation efficiency, introducing errors in the correlation for net thermal energy addition. A thin-mm heat flux sensor was designed and fabricated to directly measure the net thermal energy addition to the Stirling convertor. The fabrication techniques include slip casting and using Physical Vapor Deposition (PVD). One micron thick noble metal thermocouples measure temperature on the surface of an Alumina ceramic disc and heat flux is calculated. Fabrication, integration, and test results of a thinfilm heat flux sensor arc presented.

Fabrication and Testing of a Thin-Film Heat Flux Sensor for a Stirling Convertor

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by

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Outline

- Introduction
  - Stirling convertor testing
  - Heat flux sensor purpose
- Thermal Analysis
  - Assumptions and results
- Fabrication
  - Ceramic substrates
  - Thin-film thermocouple deposition
- Component testing
  - Thermal and load testing
  - Output signal characterization
- System Integration
  - Sensor subassembly signal checkout
  - Wire soldering
  - Cold junction compensation scheme
  - Heat flux calculation
  - Installation and use

Stirling Convertor Testing

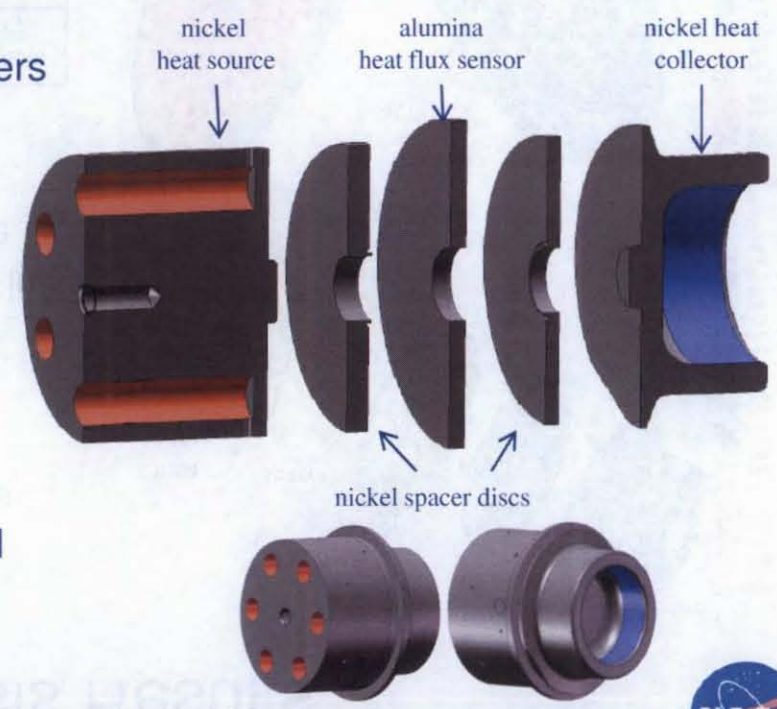
- GRC Stirling Supporting Technology Development Effort
  - Consists of tasks in areas of
    - Reliability
    - **Convertor testing**
    - High-temperature materials
    - Structures
    - Advanced analysis
    - Organics
    - Permanent magnets
  - Convertor testing and performance data
    - Data used to monitor convertors for change in performance include
      - Temperature
      - Pressure
      - Piston position
      - **Energy addition**
      - Energy rejection

Net Heat Input

- Why measure heat flux?
  - Micro-porous bulk insulation is used to minimize thermal energy losses from electric heat source to environment
    - Insulation is characterized before extended operation, enabling correlation of net thermal energy addition to the convertor
    - Aging microporous bulk insulation changes insulation efficiency, introducing errors in the correlation for net thermal energy addition
  - Heat flux sensor proposed to directly measure heat transfer from heat source to Stirling convertor heat collector
    - Thin-film heat flux sensor was designed and fabricated to directly measure the net thermal energy addition to the Stirling convertor

Thermal Analysis Setup

- FEA used to simulate heat transfer in the assembly
  - Estimate temperatures of the assembly
    - Heat source, heat collector, heat flux sensor
    - Determine temperature distribution on the face of the sensor
  - Boundary conditions
    - Red = Heat input from cartridge heaters
    - Blue = Constant temperature
    - Gray = Adiabatic
    - Insulation losses neglected
  - Material properties
    - Nickel 201 (f_n *of Temp*)
    - Alumina (f_n *of Temp*)
  - Mesh
    - Mesh independence study performed

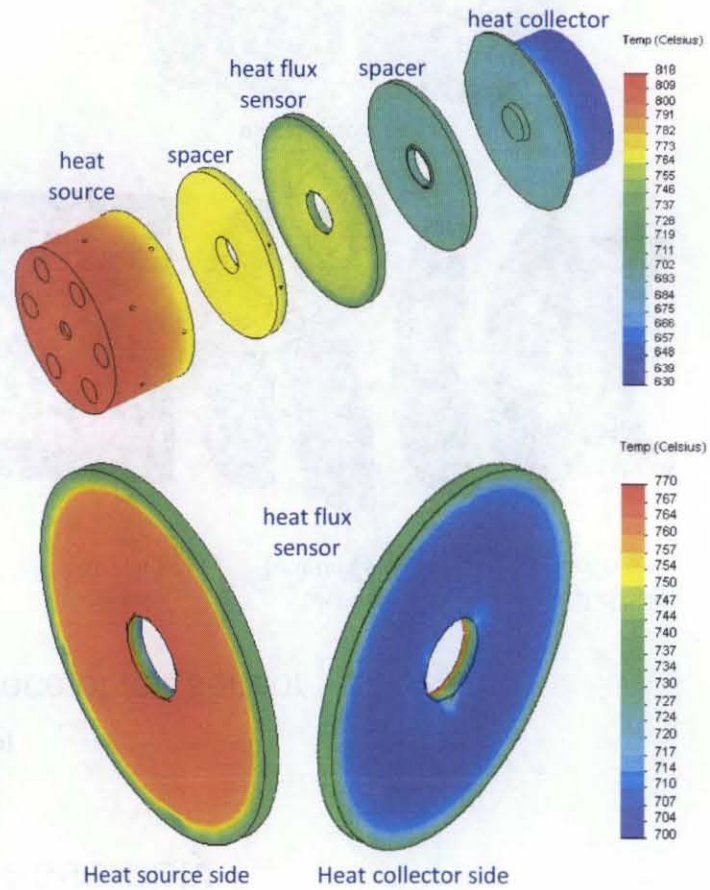


Thermal Analysis Results

- Heat flux sensor assembly
  - Heater max temperatures = 818 °C
  - Heat flux sensor temperatures for conditions expected during Stirling operation
    - Face max temperature spread ≈ 30 °C
    - **Only 3 °C spread** across heat transfer area, remaining temperature spread is in area where wire attachments are made
    - **Sensor faces have good uniform temperature distribution uniformity**

Red surface	Blue surface	HFS face (heater side)			HFS face (Stirling side)			Sensor heat transfer
Gross heat input (W)	Constant temp (°C)	Max temp (°C)	Min temp (°C)	Ave temp (°C)	Max temp (°C)	Min temp (°C)	Ave temp (°C)	Net heat input (W)
300	630	746	715	737	721	689	698	217
315*	630	751	720	**743**	725	692	**702**	227
330	630	758	724	749	730	695	705	237
345	630	764	728	754	735	698	708	248
360	630	770	733	760	739	700	712	258

**anticipated operating point*

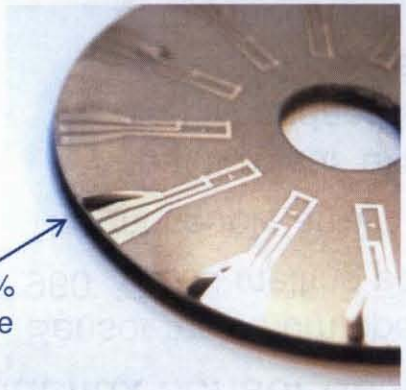


Temperature gradients shown

Fabrication

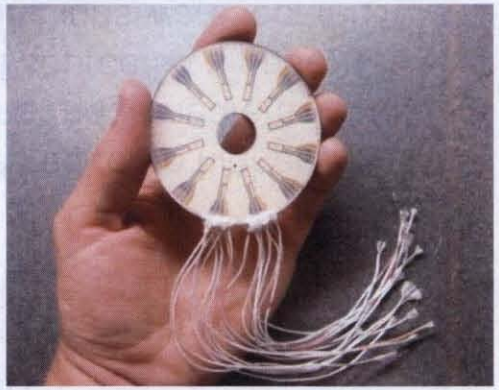
- Fabrication
  - Ceramic fabrication – slipcasting
    - bisque firing, fully sintering, finish machining, and measuring the ceramic thermophysical properties
  - Thin-film fabrication - Physical Vapor Deposition and parallel gap welding
    - One-micron-thick thin-film thermocouples deposited onto ceramic substrate, small diameter noble metal wires welded onto thin-films

alumina ceramic substrates



Pt-Rh13% films were peeling

Pt vs. Pt-Rh13% on mullite substrate
Investigated early in program

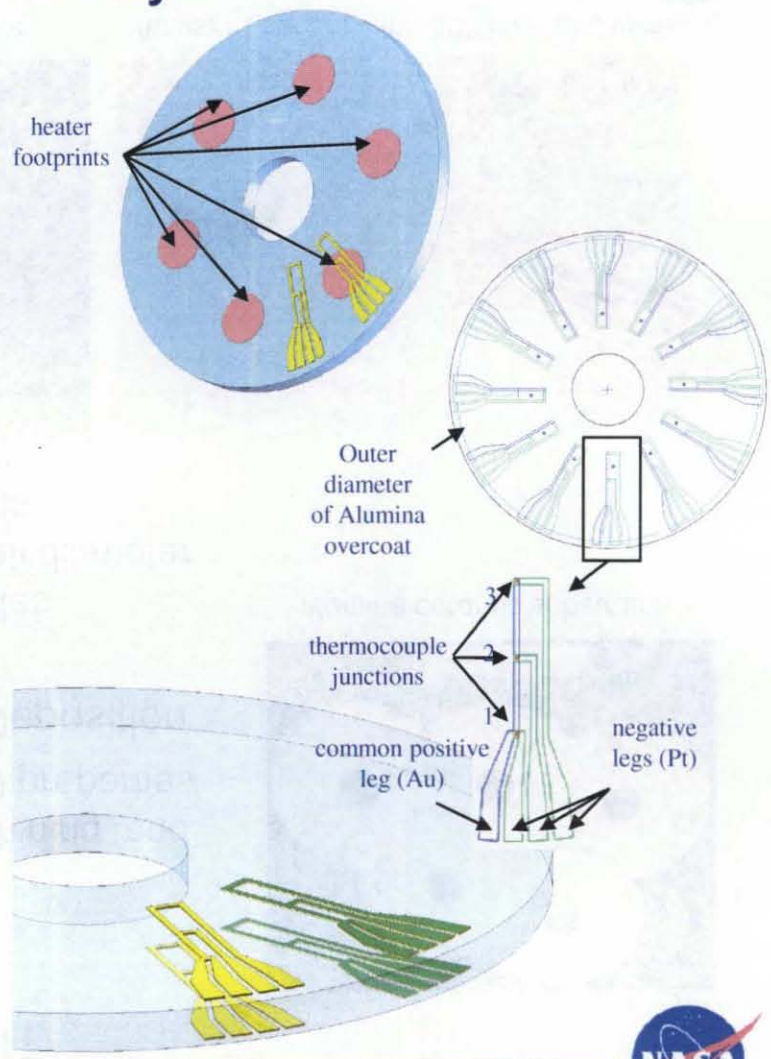


completed Au vs. Pt sensor

Au vs. Pt sensor with .003 inch dia. wires

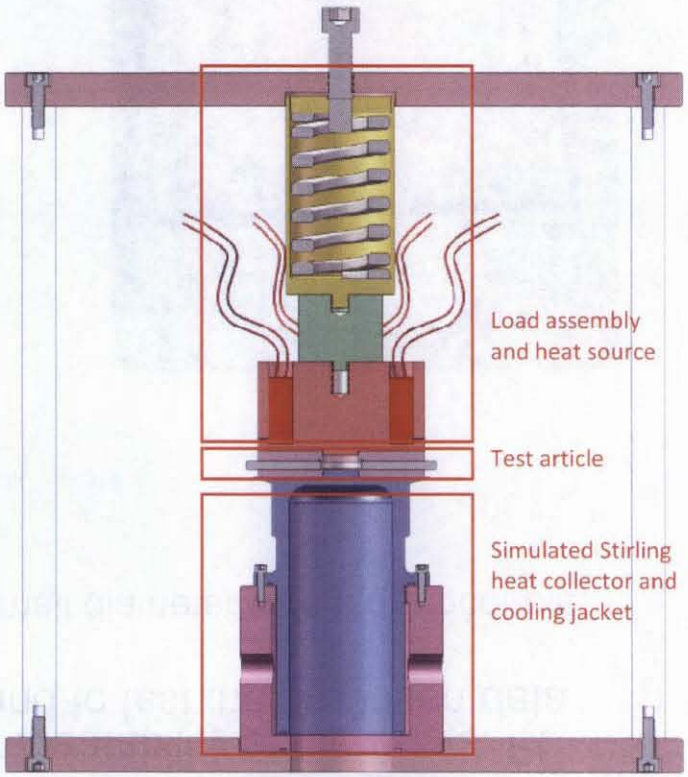
Thermocouple Array

- Heat flux sensor design
  - Sensor maximum operating temperature is 960 °C (Au melting point is 1,064 ° C)
  - Thermocouple array
    - heat flux was expected to be highest directly under the cartridge heaters present in the heat source so a pattern of thermocouple junctions were located under the footprint of each heater
    - same array can be found between each heater to measure heat flux variation in the circumferential direction
    - Each array has three junctions arranged from center to edge on the disk to enable measurement of heat flux variation in the radial direction



Thermal and Load Component Testing

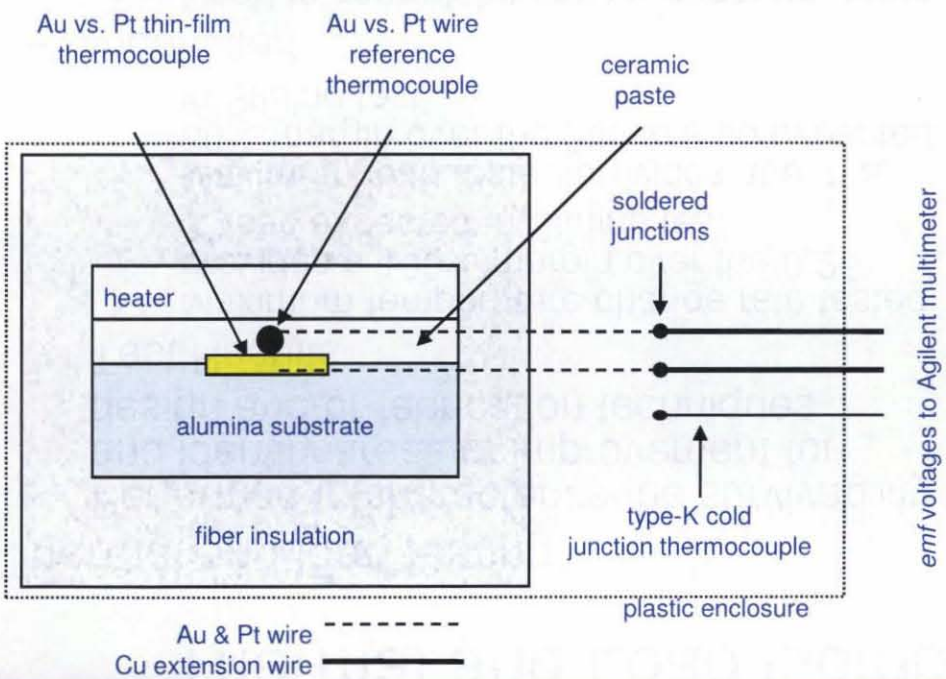
- Thermal and load testing
  - Performed to characterize the survivability and identify areas of improvement for design and/or fabrication techniques
  - Test Results
    - Maximum temperature change rate tested provides a 100% margin over the 0.25 ℃/sec expected in Stirling test
    - Maximum load tested provides about a 60% margin over the 300 lb load expected in Stirling test
  - Indentified
    - Need to control the spacer geometry more closely in order to minimize contact resistance and prevent rough surfaces from damaging the thin films on the sensor
    - Need for additional layer of aluminum oxide deposited on nickel spacers and sensor to electrically insulate the thermocouple array and provide protection against chemical reaction

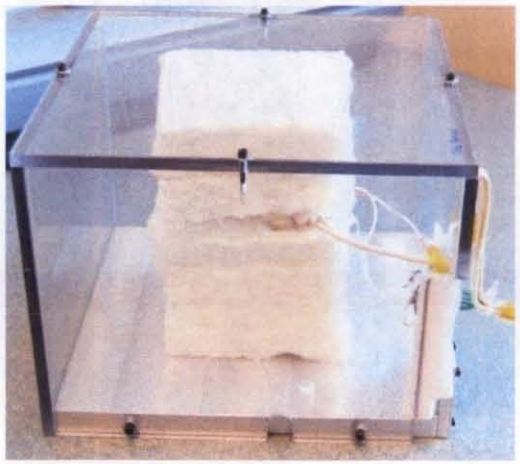


Component Test Rig

Sensor Bench Top Test Setup

- Purpose
  - Performed to characterize the stability and repeatability of the Au vs. Pt thin-film thermocouples fabricated at GRC and to test the proposed data acquisition process
    - Test setup includes Au vs. Pt thin-film and small diameter wire thermocouple, heater, and cold junction thermocouple

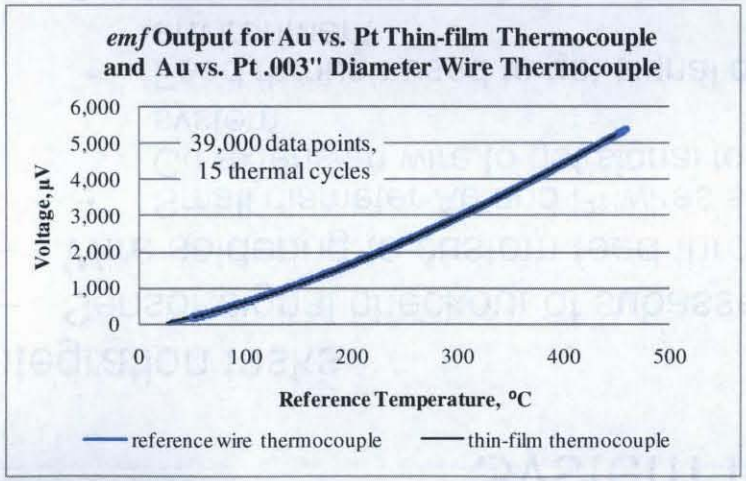


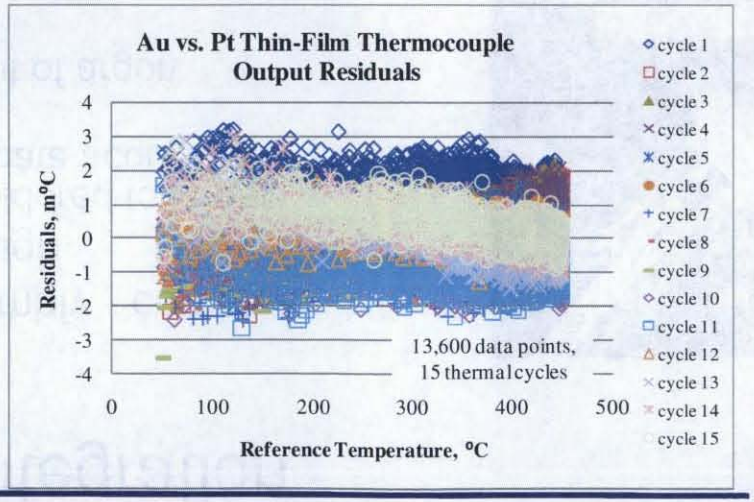


Bench top Test Setup

Bench Top Test Results

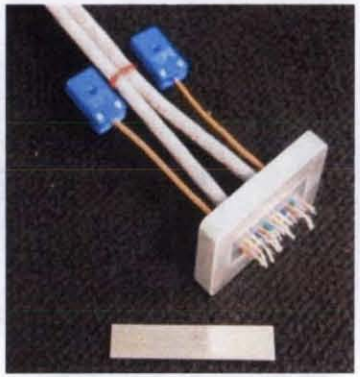
- Results
  - Results
  - 50 to 450 °C, then allowed to cool to 50 °C before another thermal cycle was automatically performed, 15 thermal cycles completed
    - LabVIEW recorded *emf* voltages at scan frequency of 2 seconds
    - 39,000 data points collected
    - Maximum temperature difference of 9 °C between thin-film and wire thermocouples, probably due to thermal resistance of ceramic paste
    - Residuals computed for heat up periods only
    - **Maximum temperature variation did not exceed ±3.5 m°C**



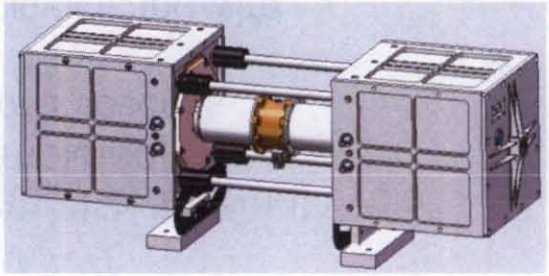


System Integration

- Integration tasks
  - Sensor signal checkout of subassembly - complete
  - Wire soldering to custom feed through
    - Small diameter Au and Pt wires soldered to larger Cu extension wire to get signal to data acquisition system
    - Feed through used to get signal out of argon environment
  - Cold junction compensation for all signals
  - Heat Flux Calculation
    - Currently using simple averaging scheme based on assumption of uniform temperature distribution across heat transfer area of sensor
    - Could apply area weighted scheme (or other) to calculate heat flux through sensor
  - Installation and testing
    - To be installed and tested in ASC-E #1 and #4 test setup in 2009



Custom wire feed through



ASC-E #1 and #4 Test Setup

Summary

- Purpose
  - Heat flux sensor designed and fabricated for use in Stirling convertor testing
- Analysis and component testing performed to characterize parts in heat flux sensor assembly
  - Provided insight into how to fabricate and how the sensor will perform
- Techniques for fabrication of ceramic substrates and thin-film thermocouple
- System Integration outlined
  - Sensor subassembly signal checkout - complete
  - Wire soldering - complete
  - Cold junction compensation scheme- complete
  - Heat flux calculation - complete
  - Installation and use – scheduled for Aug/Sept 2009

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- Ceramics Branch
  - Ali Sayir, Tom Sabo

Questions?

NIST Reference Functions

- NIST Au vs. Pt Reference Functions
  - Investigation quantified the stability and reproducibility of Au vs. Pt thermocouples
  - Wire thermocouple used for characterization
- Reference functions
  - Convert voltage to temperature for Au vs. Pt thermocouples
  - Inverse functions to convert temperature to voltage for cold junction compensation