Performance of an Advanced Stirling Convertor Based on Heat Flux Sensor Measurements

Abstract:

The U.S. Department of Energy (DOE) and Lockheed Martin Space Systems Company (LMSSC) have been developing the Advanced Stirling Radioisotope Generator (ASRG) for use as a power system for space science missions. This generator would use two high-efficiency Advanced Stirling Convertors (ASCs), developed by Sunpower, Inc., and NASA Glenn Research Center. The ASCs convert thermal energy from a radioisotope heat source into electricity. As part of ground testing of these ASCs, different operating conditions are used to simulate expected mission conditions. These conditions require achieving a particular operating frequency, hot-end and cold-end temperatures, and specified electrical power output for a given heat input. It is difficult to measure heat input to Stirling convertors due to the complex geometries of the hot components, temperature limits of sensor materials, and invasive integration of sensors. A thin-film heat flux sensor was used to directly measure heat input to an ASC. The effort succeeded in designing and fabricating unique sensors, which were integrated into a Stirling convertor ground test and exposed to test temperatures exceeding 700 °C in air for 10,000 hr. Sensor measurements were used to calculate thermal efficiency for ASC–E (Engineering Unit) #1 and #4. The post-disassembly condition of the sensors is also discussed.

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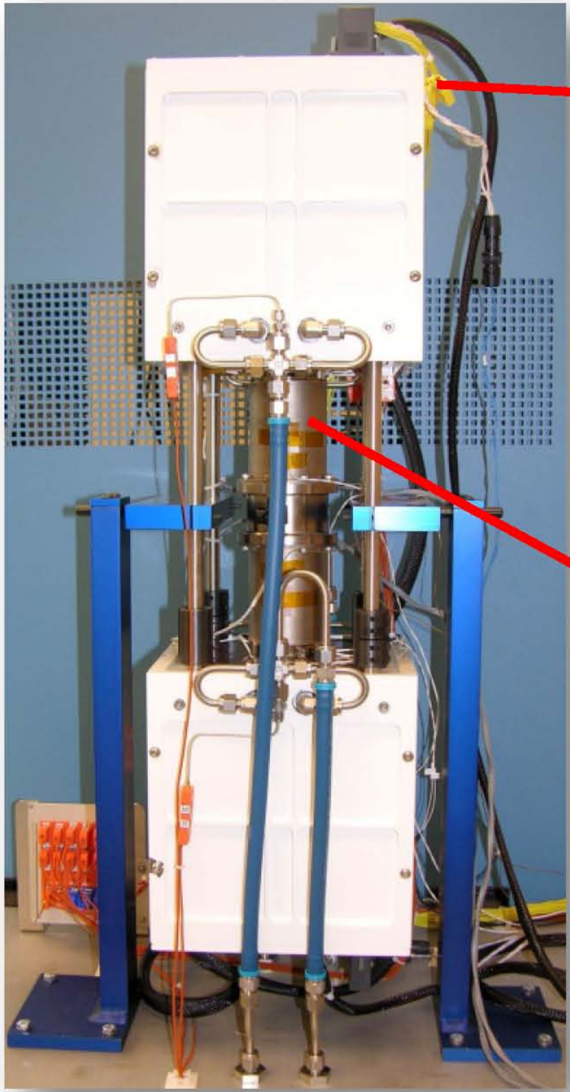
Outline

- Stirling Heat Addition
- Design, Fabrication, & Installation
- Data Processing & Results
- Disassembly & Summary

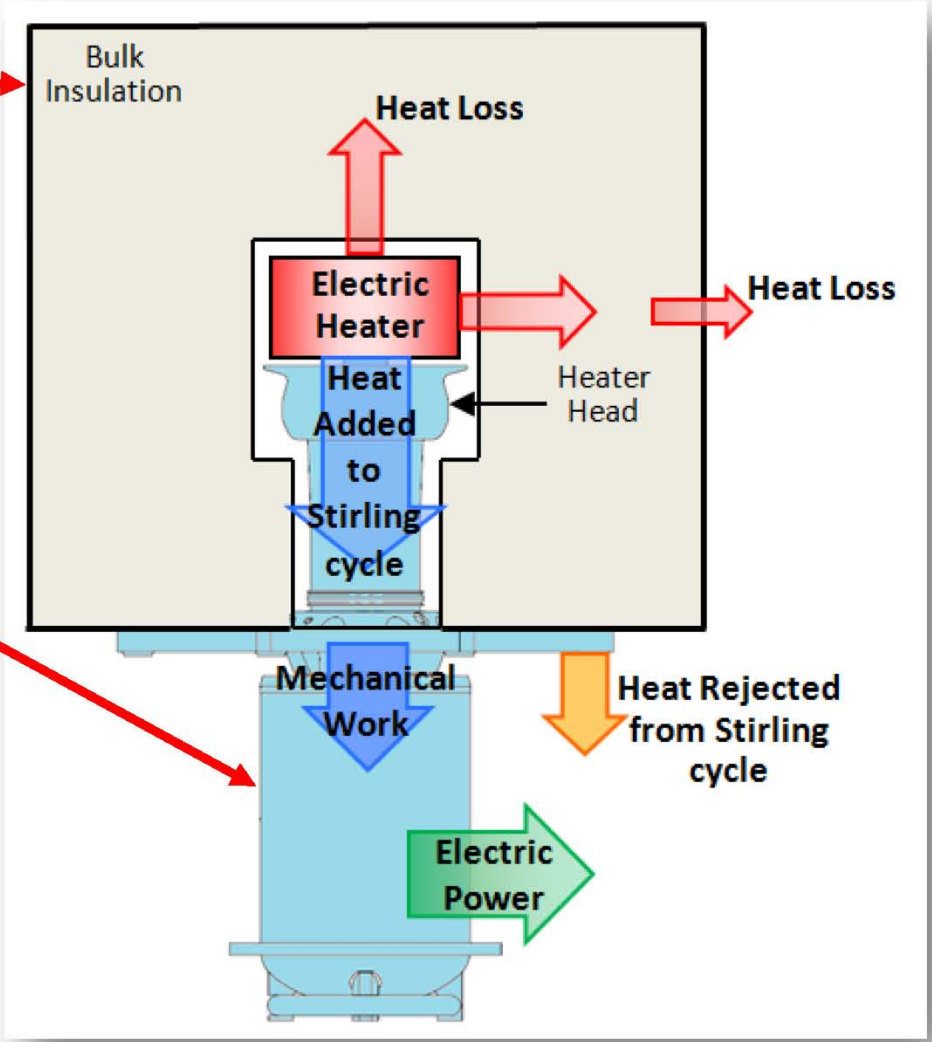
Overview

- Advanced Stirling Radioisotope Generator (ASRG) being developed for use as a power system for space science missions contains two Advanced Stirling Convertors (ASCs)
- Heat input to Stirling convertors is typically modeled
- Thin-film heat flux sensor was conceptualized to directly measure heat input to ASC
- Effort fabricated unique sensors which were integrated into a Stirling convertor ground test
- Exposed to test temperatures exceeding 700 °C in air for 10,000 hours

Stirling Heat Transfer



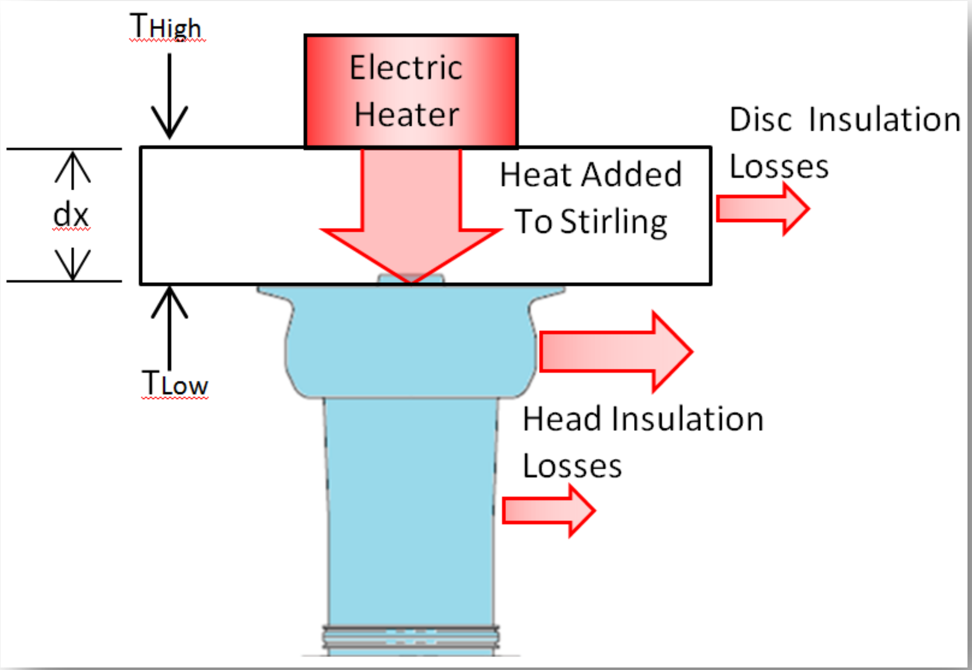
ASC-E #1 & #4 Ground Testing



Energy flow for in-air ground testing

Heat Addition Measurement

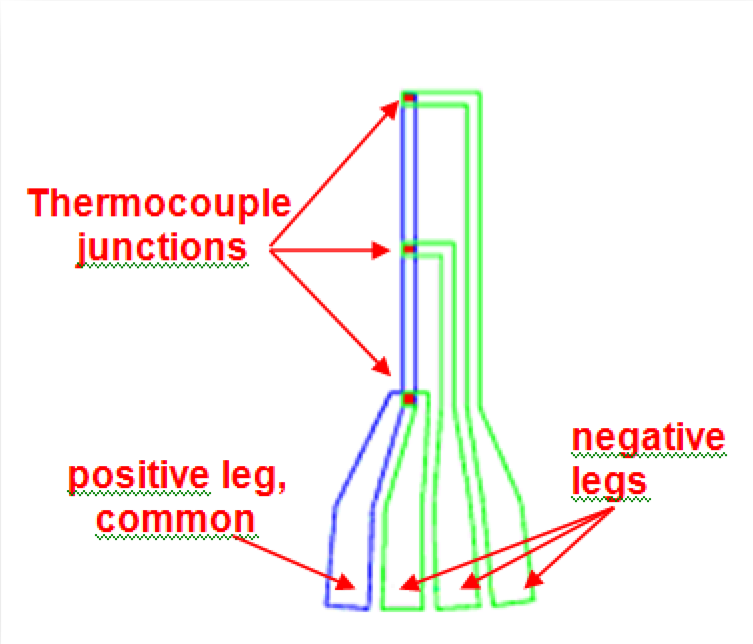
- **Concept:** Calculate heat flow using face temperatures of heat source and heater head (Fourier's Law)
- Temperature measured across a finite thickness
- Measurement does not include an estimated 5 W of heat lost from ceramic disc and heater head to surrounding insulation, accounted for in energy balance



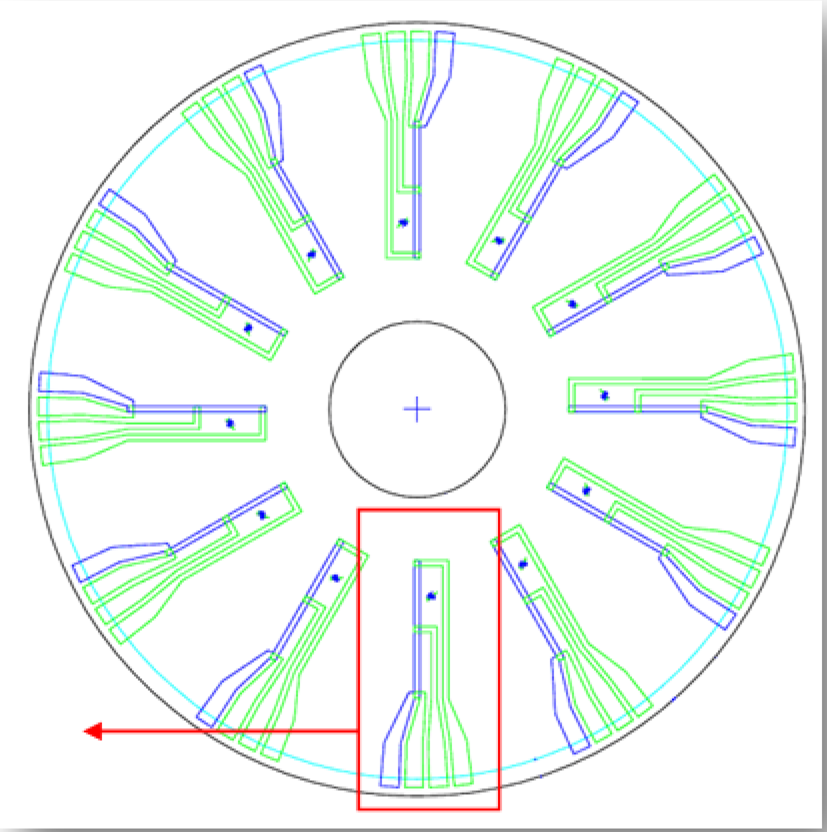
Sensor concept

Design

- Physical Vapor Deposition used to deposit noble metal films
- Films of ultra high purity (99.99+%) sputtered in vacuum
- 12 patterns deposited on each side of disc, only 2 needed for measurement



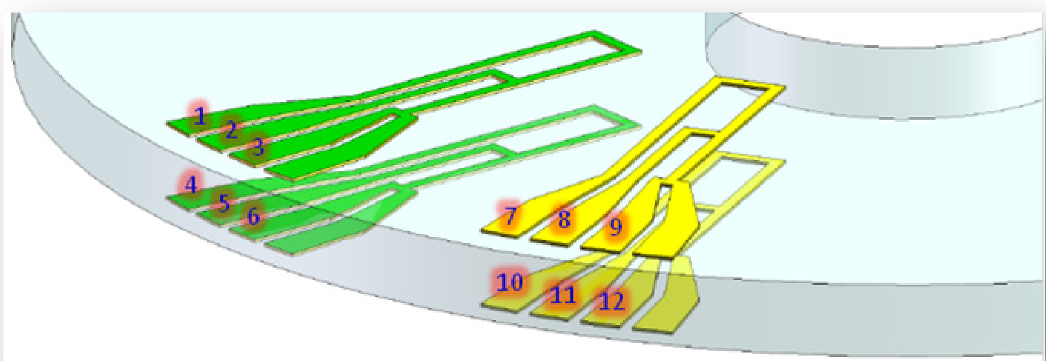
Final pattern thermocouple design



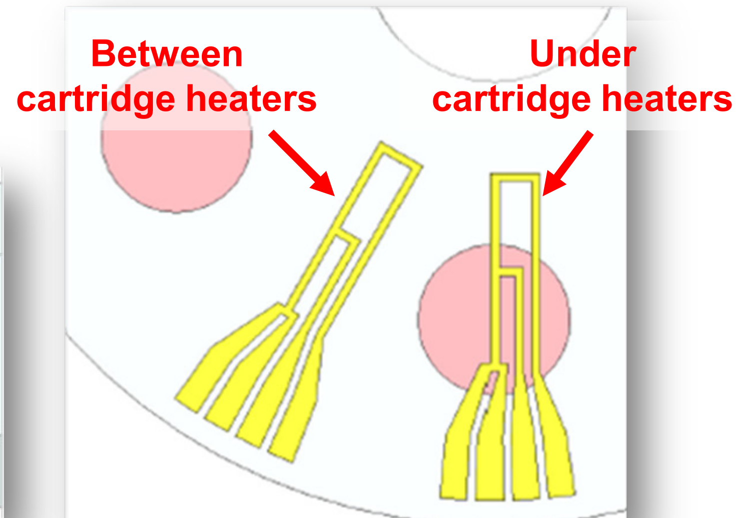
12 patterns printed to each side of disc

Design (cont.)

- 12x wires connected to 4x patterns (2 per side) for a total of 24 wires for each sensor, two sensors used
- Each side had a pattern under a cartridge heater and a pattern between cartridge heaters
- Designed to quantify radial and circumferential gradients



Total of 12 thermocouple junctions

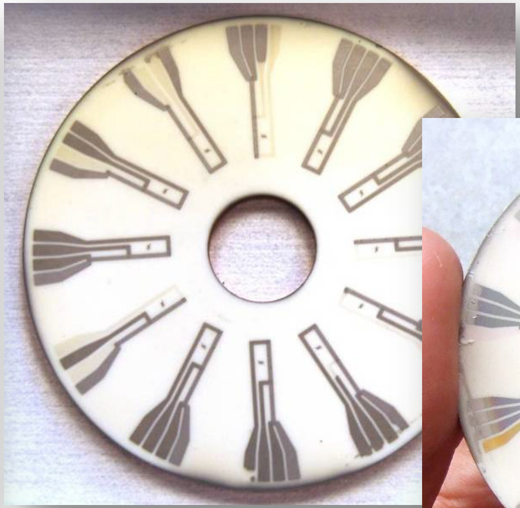


Two patterns per side

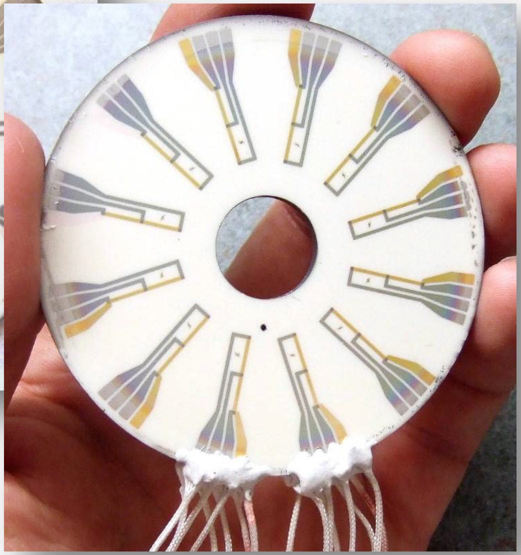
Fabrication

- Full dense Alumina ceramic discs fabricated at GRC
- 1 micron thin-film thermocouples CVD sputtered at GRC
    - Type-R trials had poor film adhesion
    - Au vs. Pt trials passed adhesion tests and were selected for use

Full dense Alumina discs were 3 mm thick



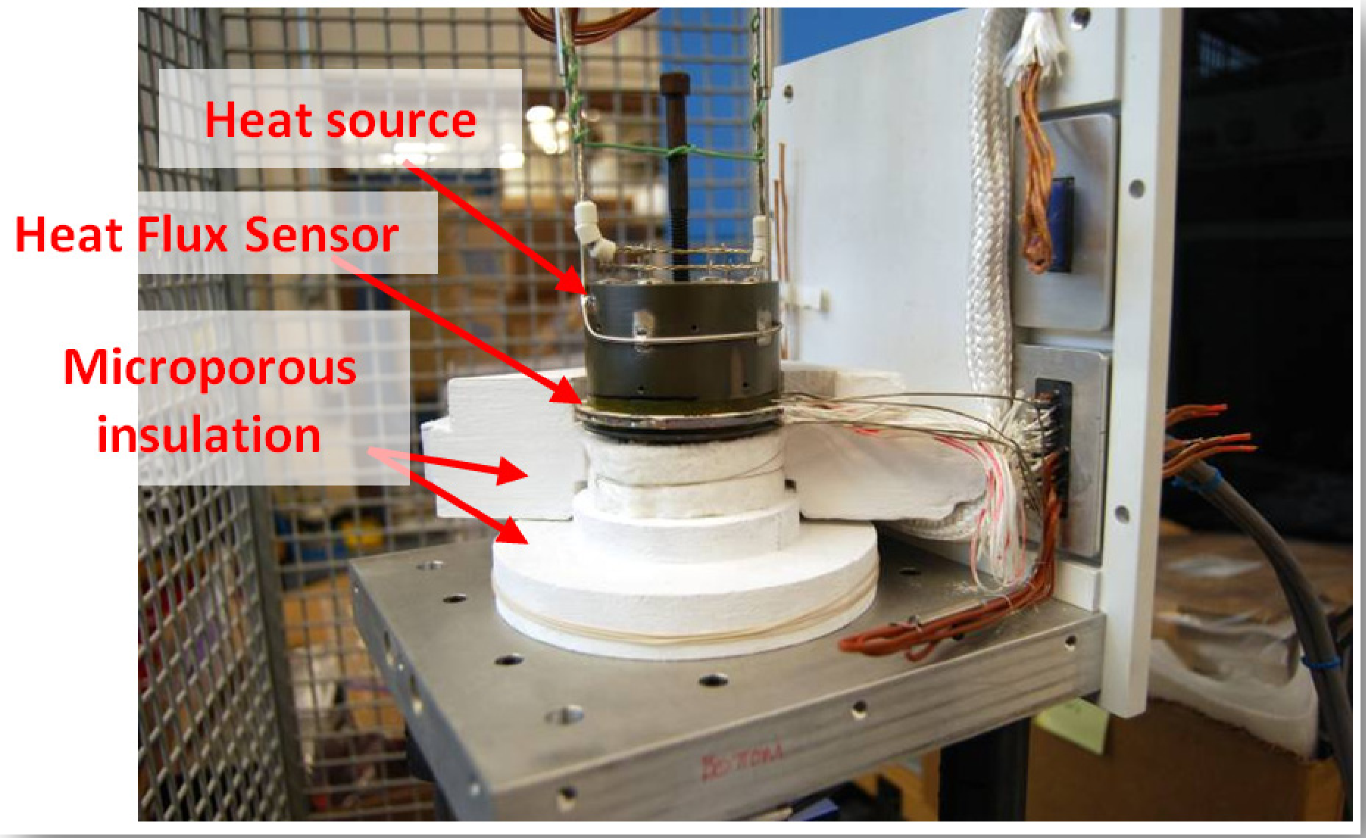
Early trials included Type-R thermocouples



Au vs. Pt TC selected

Installation

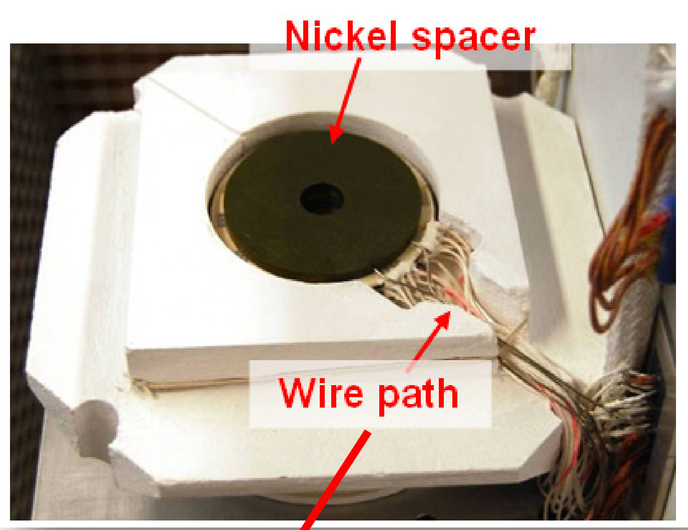
- Sensor installed between Stirling convertor and heat source
- Blanket insulation used to fill in voids
- Heat source mechanical load applied was 160 lb

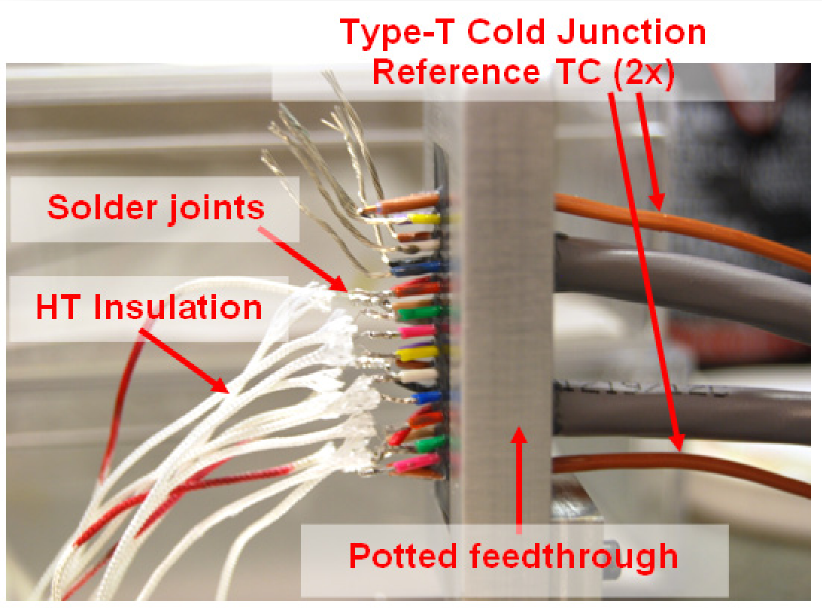


ASC-E #1 test setup assembly

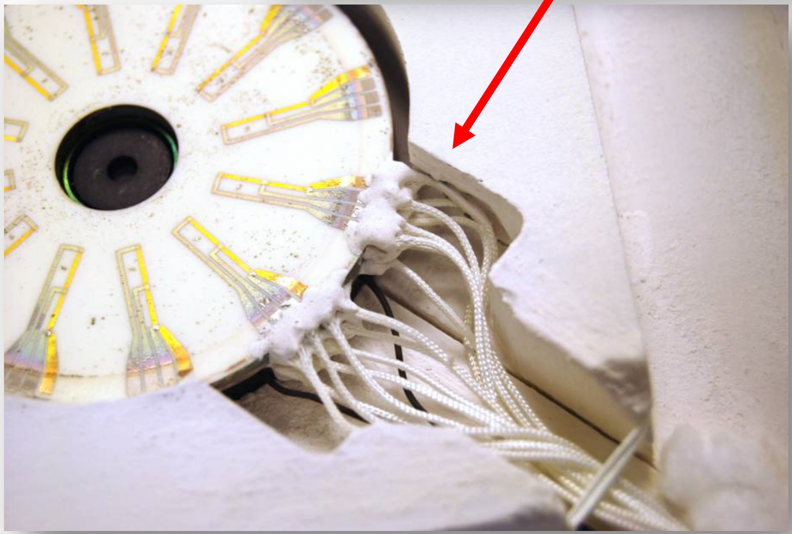
Wire Connections

- Parallel gap welded 76 micron noble metal wires to 1 micron films
- Routed 24 wires through channel designed into bulk insulation
- Soldered wires to copper extension wires in feedthrough





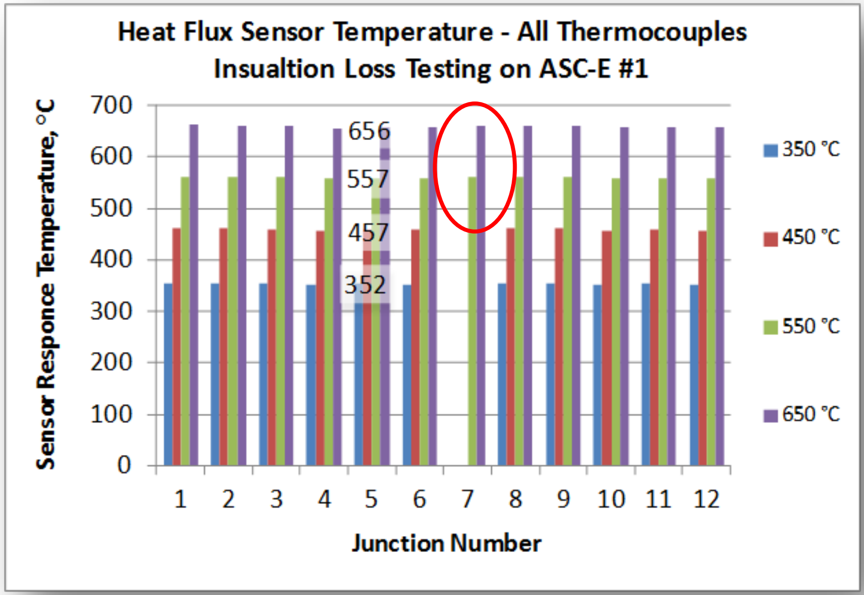
Noble metal wire connection to potted feedthrough



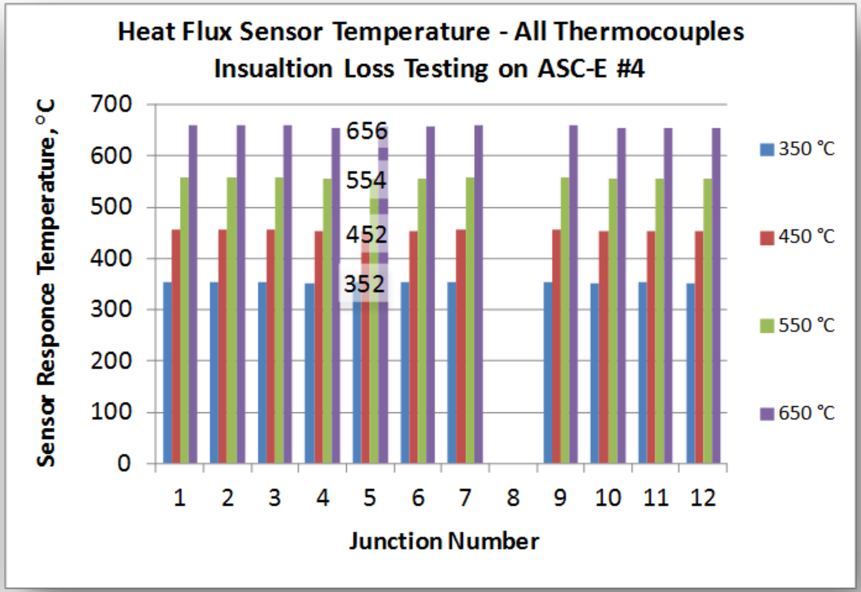
Wire path in bulk microporous insulation

Testing

- Sensor output voltage converted to temperature via NIST non-standard Au vs. Pt calibration tables
- Sensor on ASC-E #1 lost Junction #7, that same junction recovered half way through test but later only produced erroneous data
- Sensor on ASC-E #4 lost Junction #8, it did not recover



Sensor on ASC-E #1

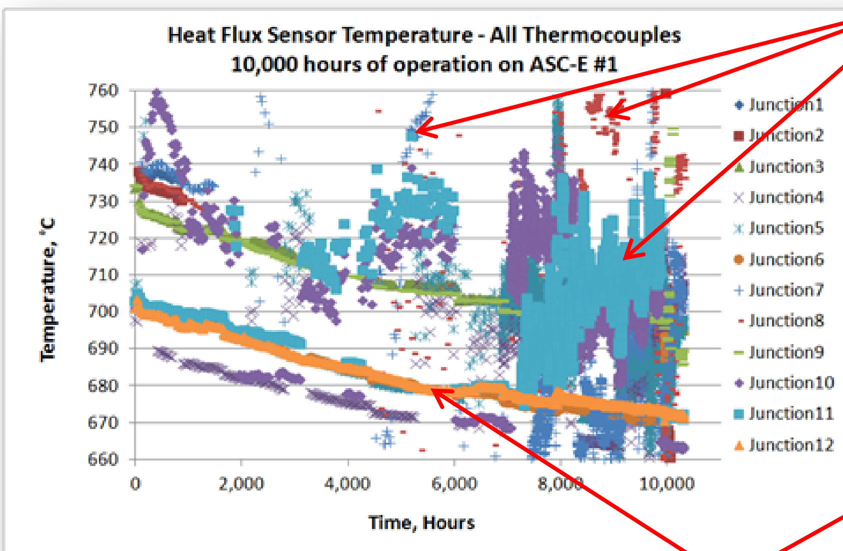


Sensor on ASC-E #4

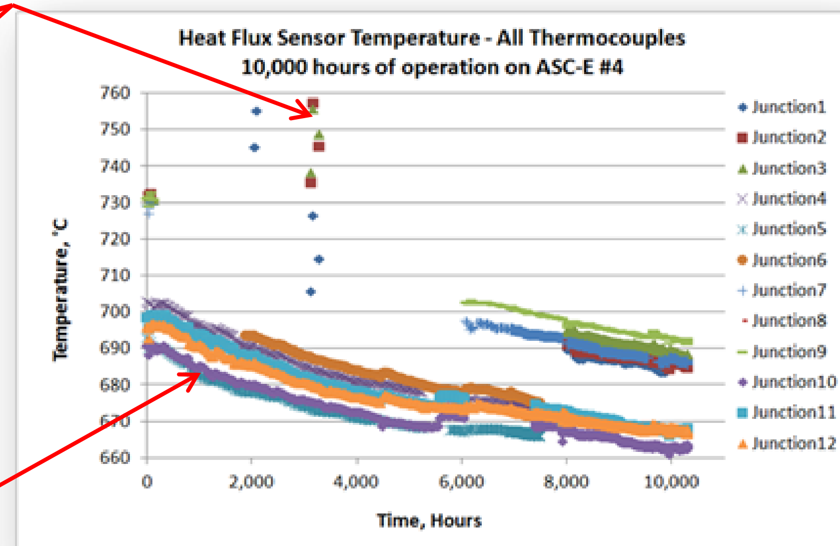
Data Processing

- Many junctions did not survive the entire test
- Filtering needed to utilize good output voltage signals, initial filtering used in LabVIEW data acquisition system, additional filtering needed during post processing
- Surviving junctions were used in the temperature difference calculations

Erroneous output



Sensor on ASC-E #1

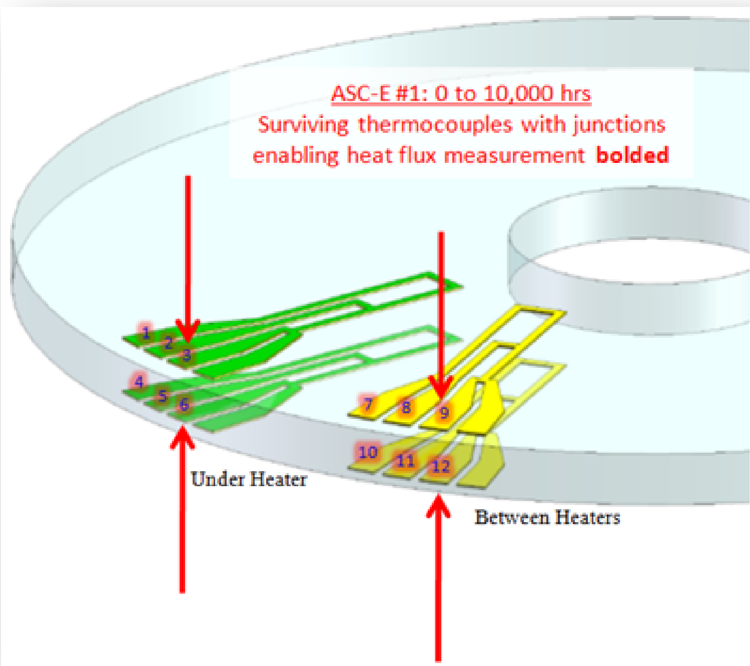


Sensor on ASC-E #4

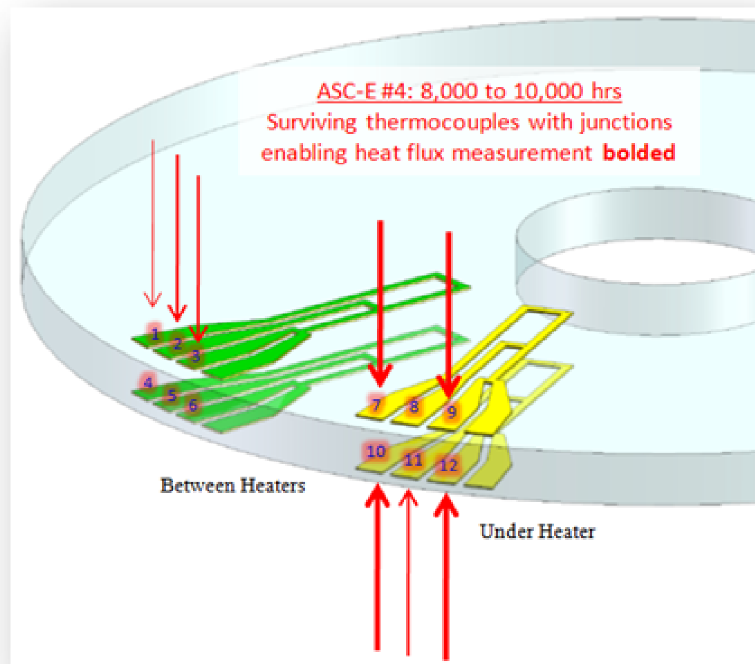
Expected output

Surviving Junctions

- Highlighted junctions were used to measure temperature
- Not all temperature measurements could be used for heat flow calculation
- Needed junctions on each side of the disc so only two heat flux measurements were available per disc



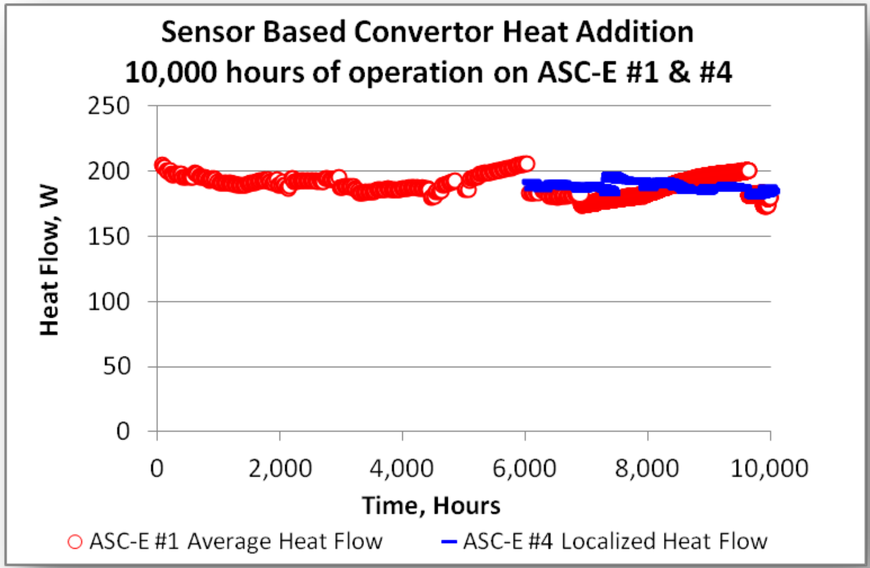
Sensor on ASC-E #1



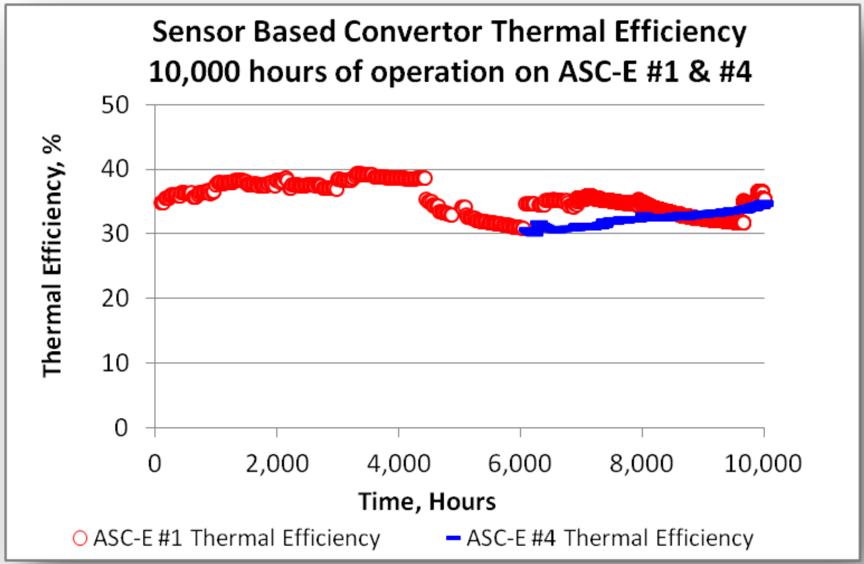
Sensor on ASC-E #4

Results

- Heat flow calculations were available for 10,000 hrs on ASC-E #1 while only available last 4,000 hrs on ASC-E #4
- Heat flows ranged from 180 to 200 Wth as expected
- Thermal efficiencies range from 30 to 35 % as expected
- While sensor output seems logical, the results have not been validated or modeled



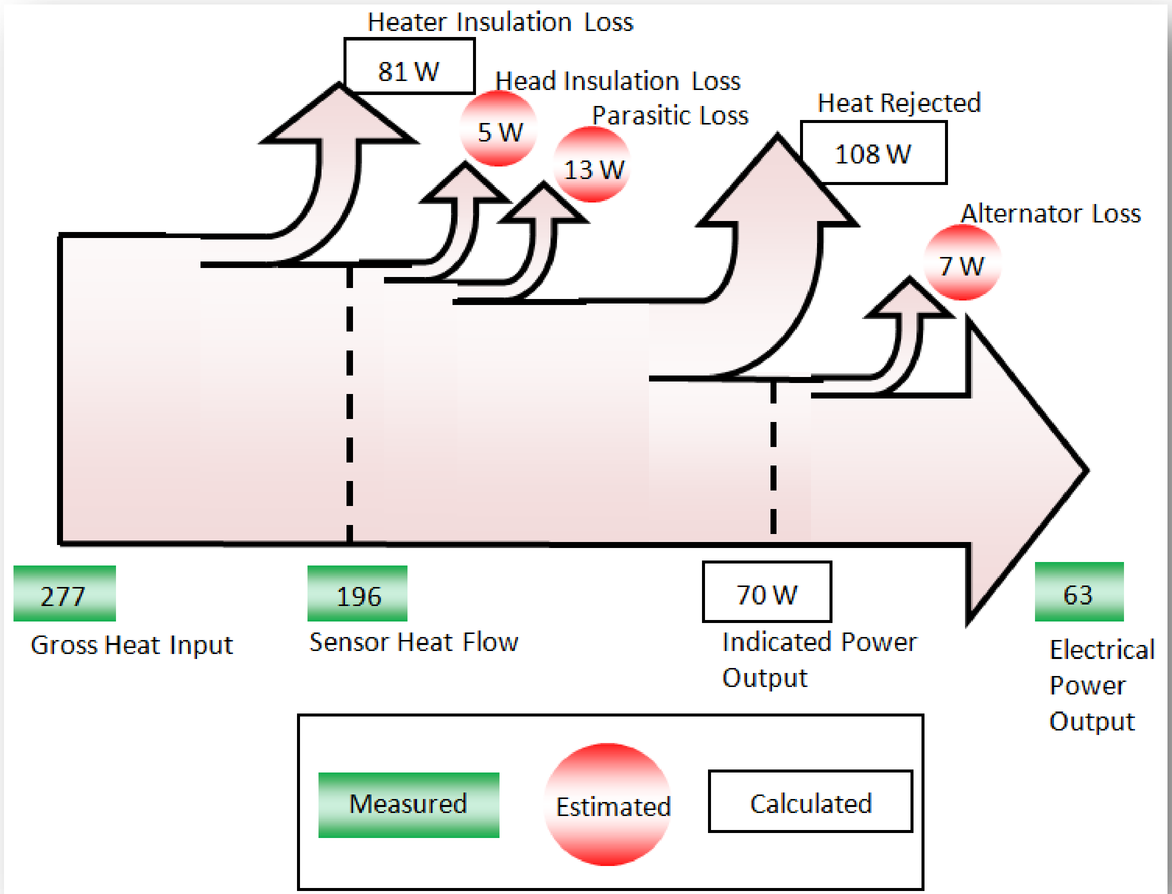
Sensor based Heat Flow



Sensor based Thermal Efficiency

Energy Balance

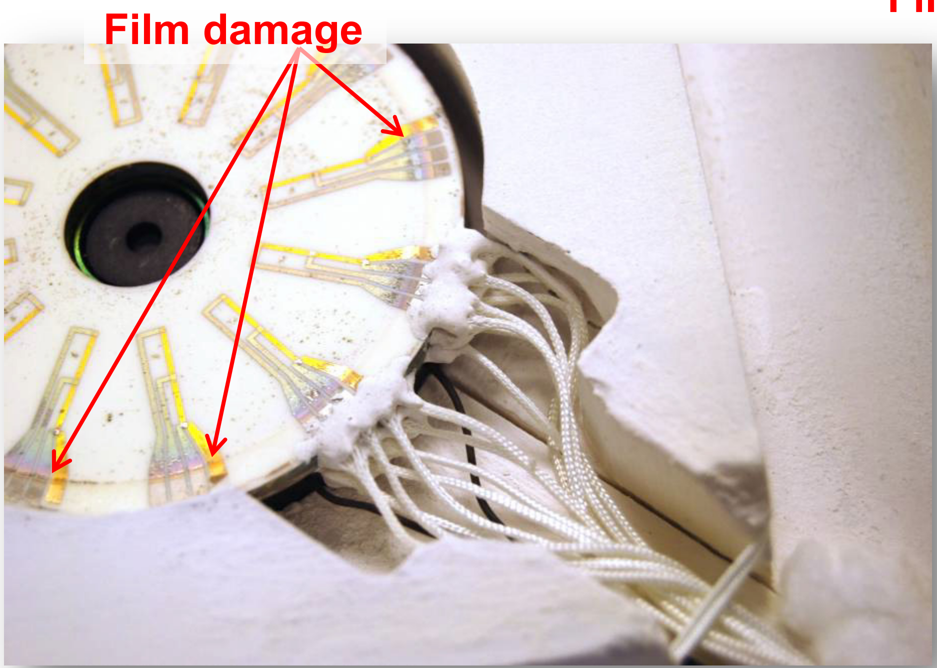
- Energy balance for ASC-E #1 at 9,000 hr of operation
- Measured, estimated, and calculated values shown



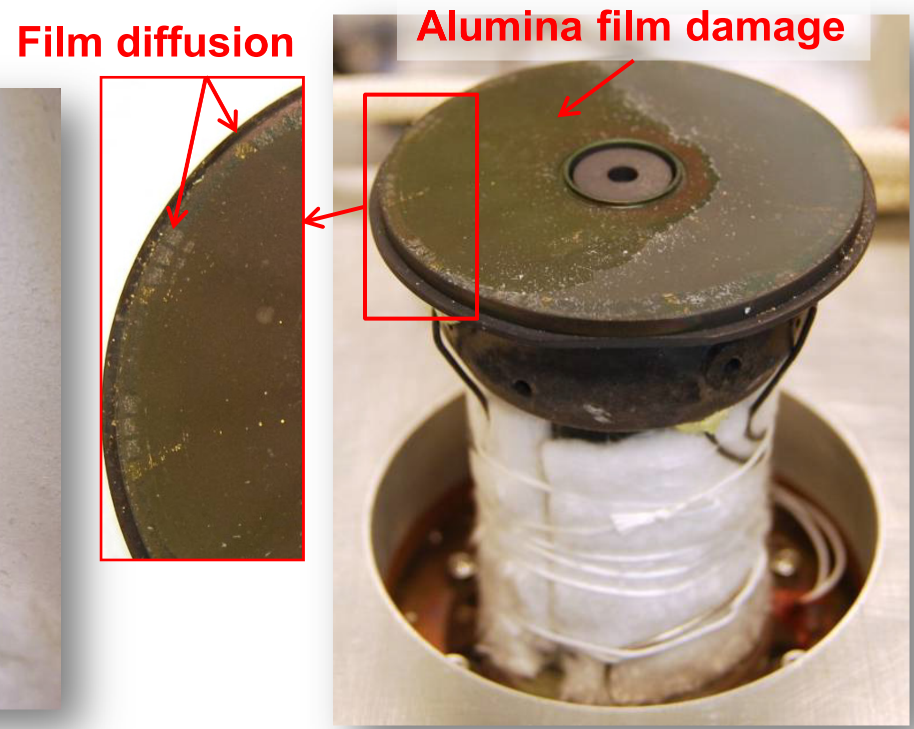
Energy Flow Diagram

Disassembly

- **Overall appearance was better than expected**
- Some damage was observed on outer edges of the films
- Film diffusion was unavoidable in areas where protective Alumina layers were degraded
- Film diffusion could explain intermittent behavior observed during thermal transients



Film damage observed during disassembly



Alumina layers degradation

Summary

- Fabricated unique sensor, integrated it into Stirling convertor ground tests, and exposed to 700 °C in air for 10,000 hr
- Many thermocouple junctions failed during the test, however, surviving junctions were used to calculate heat flow into the Stirling convertor for over 10,000 hr on ASC–E #1 and for the last 4,000 hr of testing on ASC–E #4.
- Thin-film heat flux sensor succeeded in directly measuring heat input to ASC-E (operating at 625 ^{0}C hot-end temperature)
- Recent ASC designs operate at 850 ^{0}C hot-end temperature which precludes the use of the heat flux sensor
- **Effort proved direct measurement concept** but design improvements aimed at improving sensor reliability would be needed for future use

Acknowledgement

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Any opinions, findings, conclusions, or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of NASA.

Thank you.