Overview of Heat Addition and Efficiency Predictions for an Advanced Stirling Convertor

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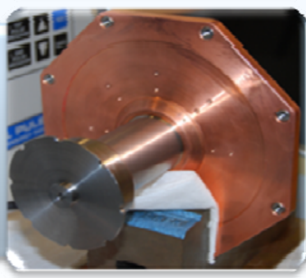
Net Heat Input Session Presentations

Overview of Heat Addition and Efficiency Predictions for an Advanced Stirling Convertor (ASC)

- Effort improved accuracy of net heat input predictions for ASCs tested at GRC
- Author: Scott Wilson

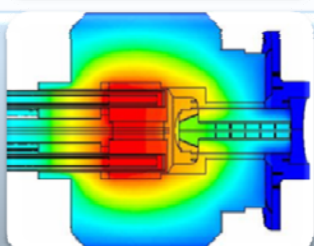
Environmental Loss Characterization of an ASC Insulation Package using a **Mock Heater Head**

- Test hardware used as pathfinder for Thermal Standard test materials and methods
- Author: Nick Schifer



Evaluation of Advanced Stirling Convertor Net Heat Input Correlation Methods using a **Thermal Standard**

- Test hardware used to validate net heat prediction models
- Author: Max Briggs, presented by Nick Schifer



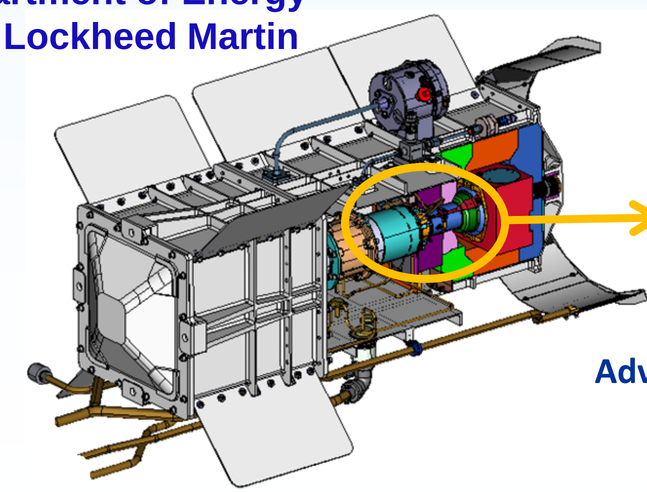
A **Computational Methodology** for Simulating Thermal Loss Testing of the Advanced Stirling Convertor

- Numerical models validated using test data
- Author: Terry Reid

Why is Net Heat Input Needed?

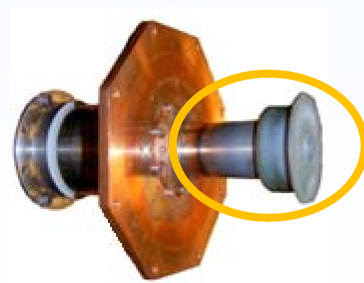
- Problem: Net Heat Input cannot be measured directly during operation
- Net heat input is a key parameter needed in prediction of efficiency for convertor performance
- Efficiency = Electrical Power Output (**Measured**) divided by Net Heat Input (**Calculated**)
- Efficiency is used to compare convertor designs and trade technology advantages for mission planning

ASRG developed by Department of Energy and Lockheed Martin

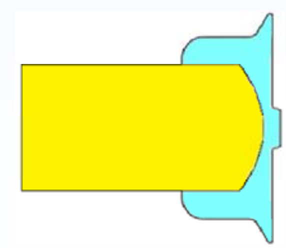


Advanced Stirling Radioisotope Generator (ASRG)

ASC developed by Sunpower, Inc. & NASA Glenn Research Center



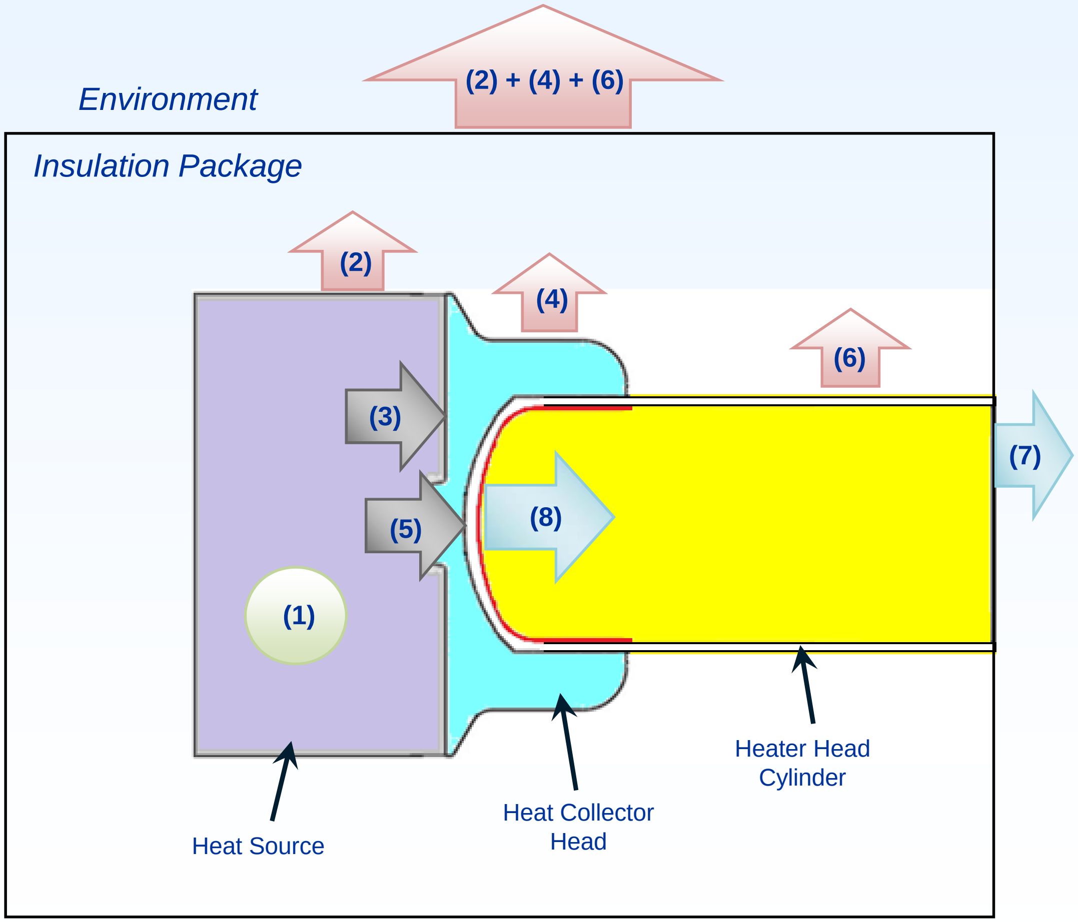
Advanced Stirling Convertor (ASC)



ASC Heater Head Diagram

What is Net Heat Input?

- Net Heat Input is heat energy required for **thermodynamic cycle** heat addition + **parasitic heat transfer losses** inherent to heat engines



(1) Gross heat input to Heat Source
(2) to Insulation Package
(3) to Heat Collector Head
(4) to Insulation Package
(5) to Heater Head Cylinder
(6) to Insulation Package
(7) to Cold End of convertor
(8) to Stirling cycle

Net Heat Input = (8) + (7)

Outline

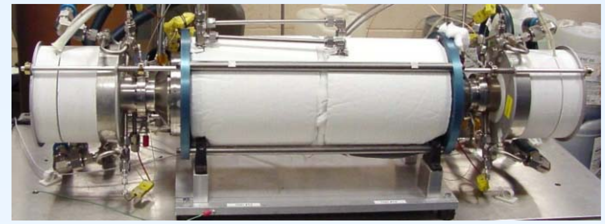
- Previous net heat input predictions
- Net Heat Input Effort Components
  - Improved Model Inputs
  - High Fidelity Models
  - Model Validation
- Conclusions

Previous Net Heat Input Predictions

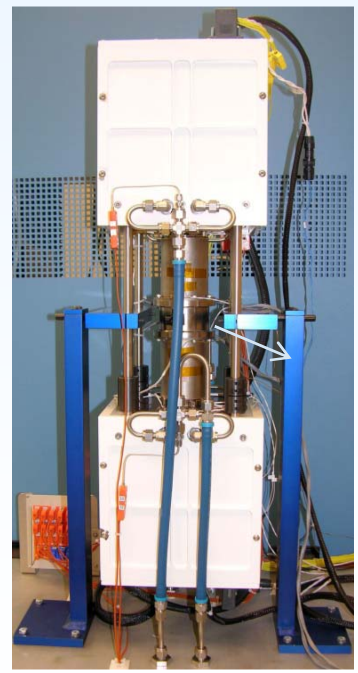
Operating parameters controlled to achieve specified electrical power output for given value of thermal net heat input

- Technology Demonstration Convertor (TDC)
  - Heat Source integrated into Heater Head
  - **Curve fits**: insulation loss vs. heat source temperature
  - Results compared well to expected values
- ASC-E #1 & #4
  - ~750 ºC heat source, 650 ºC hot-end, Heat Source & Heater Head are separate components so a simplified **FEA model** was used (model was constrained by test measurements)
  - Results compared well to expected values
- ASC-E2's
  - ~1,000 ºC heat source, 850 ºC hot-end, Heat Source & Heater Head are separate components so simplified **FEA model** used again
  - Results did not compare well to expected values

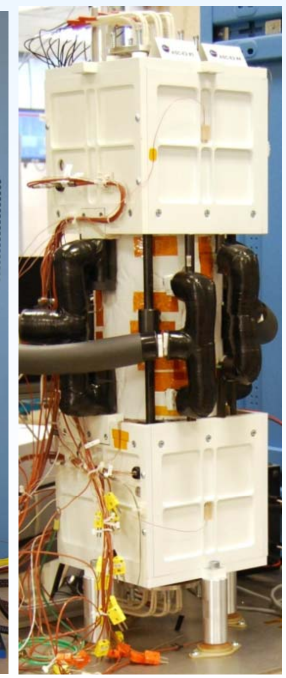
Investigation launched to identify sources of error



TDCs #13 & #14, 2003



ASC-Es #1 & #4, 2009



ASC-E2s, 2010

Previous Net Heat Input Predictions

- Curve fits of environmental losses vs. a reference temperature has worked in the past with test hardware that contains an integrated heat source/heater head design and with lower hot-end temperatures
- Reference temperature has typically been the heat source due to its strong influence on thermal gradients in the test setup
- The accuracy of curve fits can be improved using multi-parameter functions but a bias error still exists for each test setup (Ref: Briggs)
- The limitation of the curve fit method is due to it’s assumption that the temperature profiles of an operating convertor are accurately represented by a non-operating convertor, such as during the Insulation loss test.

More accurate prediction methods were needed

Net Heat Input Effort Components

Steps taken to improve net heat input predictions

- **Improve Model Inputs –** Measured thermal conductivity of test setup materials to provide accurate inputs to prediction models and acquire additional convertor test data to provide numerical models with temperature profiles of the test setup via thermocouple and infrared measurements
- **High Fidelity Models -** Used multidimensional numerical models (computational fluid dynamics code) to predict net heat input of an operating convertor
- **Model Validation -** Used validation test hardware to provide direct comparison of empirical and numerical results

Effort focused on improving accuracy of net heat input predictions

Improved Model Inputs

Material Properties

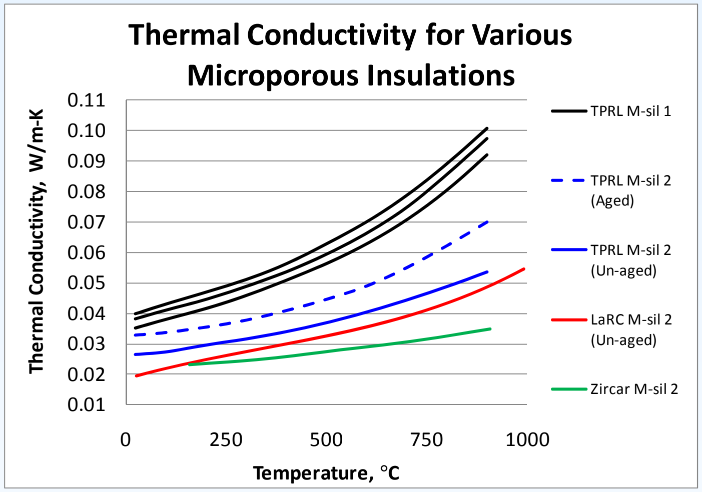
- Tested thermal conductivity of micro-porous insulation
- Ensured all material properties were temperature dependent

Additional Thermocouples Added

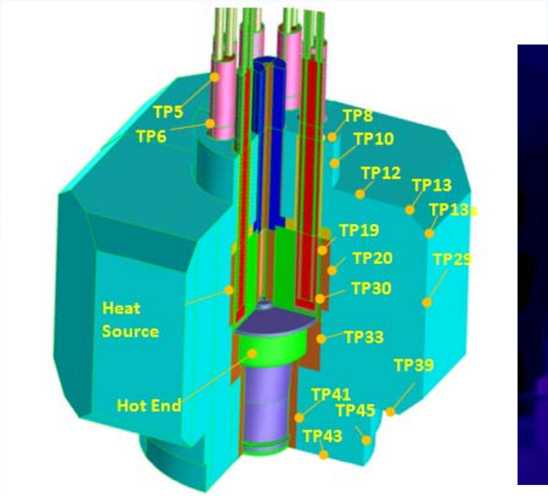
- Measured temperatures at locations throughout setup, especially where bulk thermal conductivity and contact resistance are unknown

Infrared Temperature Data

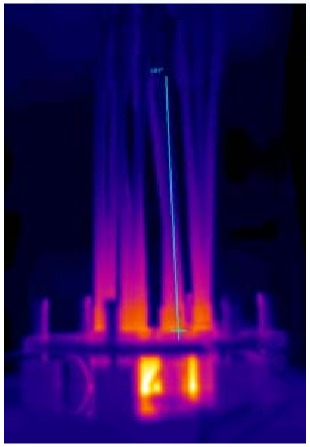
- Captured temperature profiles of heater leads exposed to lab environment
- Heater assemblies were initially suspected of losing an additional 10-15 W during operating tests (compared to insulation loss tests) but turned out to only lose an additional ~3 W



Improved Material Properties



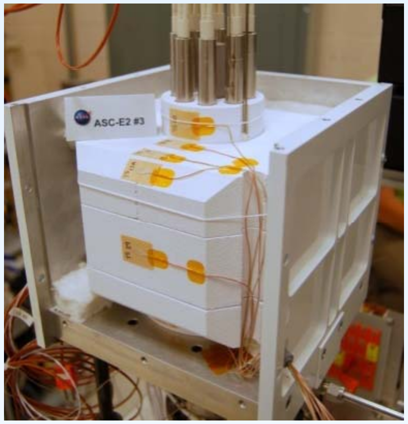
Additional Thermocouples



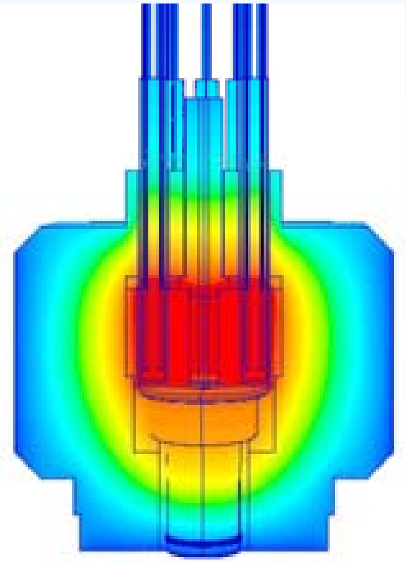
Infrared Data

High Fidelity Models

- Multidimensional numerical models (computational fluid dynamics code) used to predict net heat input of an operating convertor
- Paramount to the convertor modeling effort was the assumption that a predicted temperature profile governed the resulting heat transfer through modeled components
  - Major goal to match predicted temperatures to measured temperatures
  - Adjusted various resistance paths inherent to the materials and component interfaces
  - Resistance paths tuned by adjusting the interface resistance between two mating solid components or by adjusting the thermal conductivity of micro-porous and blanket insulations



ASC-E2 Test Setup


Typical Temperature Contours for operating ASC-E2 test

Model Validation

Mock convertor assembly used to simulate operating convertor temperature profile

Mock Heater Head (discussed next by Schifer)

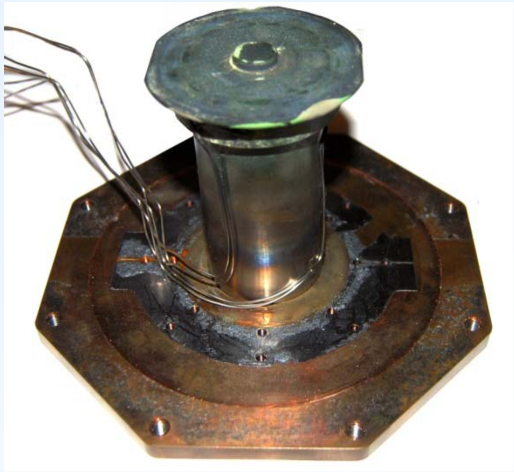
- Existing hardware used to save time
- High-strength copper rod (GRCop-84)

- Proved concept of thermal standard
- Pathfinder for Thermal Standard test
  - Identified selection of materials and coatings
  - Identified desired design features and thermocouple locations
  - Identified preferred test methods

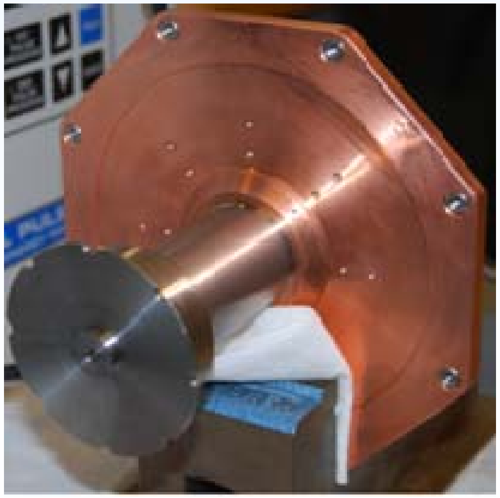
Thermal Standard (discussed next by Schifer)

- Nickel 201/Stainless steel heater head
- High-strength copper rod (GRCop-84)

Both tests allowed direct comparison between predicted and measured values of net heat input



Mock Heater Head Hardware

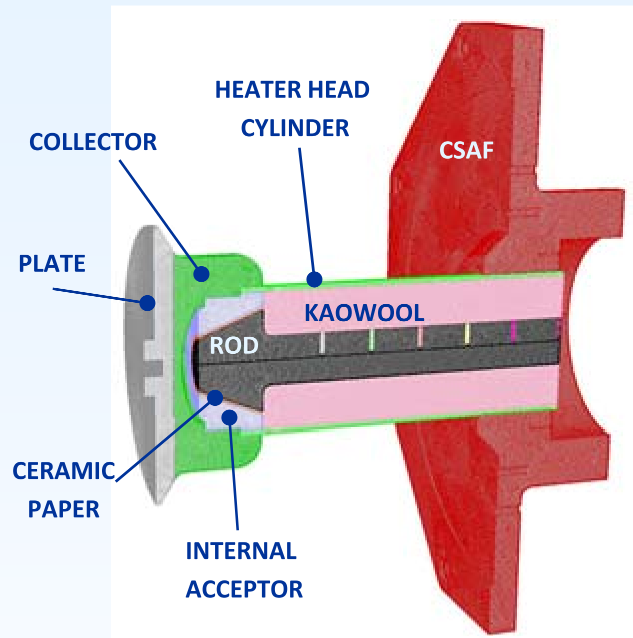


Thermal Standard Validation Hardware

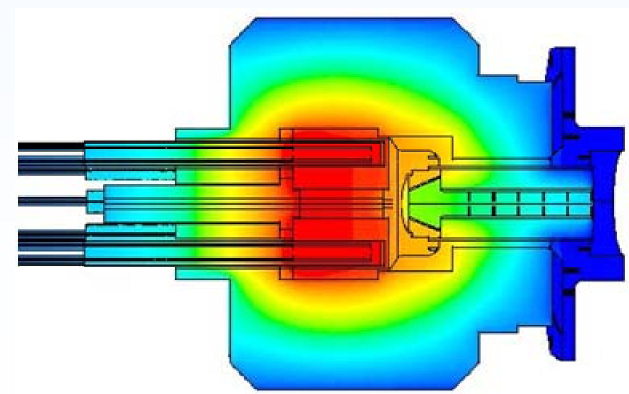
Model Validation

- Thermal Standard was designed to provide validation data for the modeling approach employed in net heat input predictions for convertors
- Thermal Standard test hardware allowed predicted values of net heat input to be compared directly to measured values
- Thermal Standard test using 14 mm dia. rod resulted in net heat input value of 244.4 W
- High fidelity modeling approach resulted in net heat input value of 240.3 W
- Predicted value of net heat input was 1.7 percent less than that measured during testing

Numerical Model Validated



Thermal Standard, modeled components



Temperature Contours from Thermal Standard

Conclusions

- Past methods of predicting net heat input needed to be validated
- Validation effort pursued with several paths including improving model inputs, using test hardware to provide validation data, and validating high fidelity models
- Validation test hardware provided direct measurement of net heat input for comparison to predicted values
- Predicted value of net heat input was 1.7 percent less than measured value and initial calculations of measurement uncertainty were 2.1 percent (under review)
- Lessons learned during validation effort were incorporated into convertor modeling approach which improved predictions of convertor efficiency

Best known method for predicting net heat input

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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.