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

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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

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

Advanced Stirling Radioisotope Generator (ASRG)
Glenn Research Center

Advanced Stirling Convertor (ASC)

ASC Heater Head Diagram

at Lewis Field
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.

Net Heat Input = (8) + (7)

(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 converter
(8) to Stirling cycle
Outline

• Heat flows in ASC-E2 convertors
  – During nominal operation
  – During insulation loss testing
• Empirical modeling methodology and assumptions
• Thermal Standard
  – Role in model verification
  – Design
  – Test sequence and methods
  – Ability to mimic the ASC-E2
• Evaluation of empirical methods using the Thermal Standard
  – Hot-end temperature correlations
  – Heat-source temperature correlations
  – Multi-parameter fits
• Conclusions
Heat Flow During ASC-E2 Insulation Loss Testing

Gross Heat Input

Insulation Package

Heat Source
Heat Collector
Accepter
Heater Head
Convertor Cold End

Environ. Losses
Environ. Losses
Environ. Losses
Environ. Losses

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Insulation Loss Testing Using an Alumina Disk

During convertor operation heat-source temperature ~1000 °C for a hot-end temperature of 840 °C

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Insulation Loss Testing Using a Thermal Barrier

Insulation tear down required to return convertor to extended operation configuration

Gross Heat Input

Heat Source
~1000 °C

Thermal Barrier

Convertor Hot End
~840 °C

Convertor Cold-End

Matches temperature profile of operating convertor

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Empirical Modeling Methods and Assumptions

- **Method**
  - \( \text{NHI} = \text{GHI} - \text{EL}_{\text{operating}} \)
  - \( \text{EL}_{\text{operating}} = \text{EL}_{\text{Insulation Loss Test}} + \text{Difference} \)
  - \( \text{EL}_{\text{Insulation Loss Test}} = f(\text{HET and/or HST})_{\text{Insulation Loss Test}} \)

- **Assumptions**
  - HET and/or HST characterize the environmental losses during Insulation Loss Testing
    - Examine Goodness of Fit of Environmental Loss Data
  - Correlations based on Environmental Loss data can be applied to operating convertors
    - Compare predicted NHI to measured NHI on the Thermal Standard
The Thermal Standard

• Purpose
  – To evaluate the net heat input predictions of numerical models and empirical correlations using hardware that is representative of the ASC

• Design Objectives
  – Simulate ASC-E2 external geometry
  – Simulate ASC-E2 temperature profiles
  – Simulate ASC-E2 heat flows
  – Simulate both insulation loss testing and nominal operation on ASC-E2 convertors
  – Allow net heat input predictions to be compared to measured values
Thermal Standard Heater Head Design

- Matches external geometry of the ASC-E2 heater head
- Simplifies internal geometry for ease of fabrication and calculation of heat flows
- Super-alloys were replaced with stainless steel to reduce lead times and cost
- Stainless steel has similar conductivity to super-alloys in this temperature range
Simulating Insulation Loss Testing

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Simulating an Operating Convertor

- Fire Rods
- ASC-E2 Insulation Package
- ASC-E2 Insulation Housing
- Conduction Rod
- Heat Exchanger
Comparison of ASC-E2 and Thermal Standard Test Sequences

### ASC-E2 Convertor Test Sequence

<table>
<thead>
<tr>
<th>Test Title</th>
<th>Interface Material</th>
<th>Piston Status</th>
<th>Environmental Loss Calculation Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina disk</td>
<td>Alumina disk</td>
<td>Stalled</td>
<td>Conduction calculation</td>
</tr>
<tr>
<td>Thermal barrier</td>
<td>Ceramic paper</td>
<td>Stalled</td>
<td>Conduction calculation</td>
</tr>
<tr>
<td>Nominal operation</td>
<td>Alumina disk</td>
<td>Moving</td>
<td>Empirical model</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Numerical models</td>
</tr>
</tbody>
</table>

### Thermal Standard Test Sequence

| Simulated alumina disk      | Alumina disk       | No rod        | Conduction calculation                 |
| Simulated thermal barrier   | Ceramic paper      | No rod        | Conduction calculation                 |
| Simulated nominal operation | Alumina disk       | Rod installed | Empirical models                       |
|                             |                    |               | Numerical models                       |
|                             |                    |               | Measured directly                      |
Matching ASC-E2 Temperatures and Heat Flows During Insulation Loss Testing

The Thermal Standard matched both environmental losses and temperature gradients of ASC-E2 convertors.

The mock heater head matched environmental losses well, but did not match ASC-E2 temperature gradients.
Correlations Using Hot-End Temperature Alone

Hot-end temperature correlations do a poor job of fitting insulation loss data.

\[ y = 0.1899x - 26.755 \]

\[ R^2 = 0.8374 \]
Correlations Using Heat Source Temperature Alone

Heat-source temperature correlations provide good fits to insulation loss data. However, heat-source correlations overpredicted environmental losses on the Thermal Standard by ~14 watts bias.
ASC-E2 Convertors Show the Same Behavior

Hot-end temperature correlations do a poor job of fitting ASC-E2 Insulation Loss Data

Heat-source temperature correlations do a good job of fitting ASC-E2 Insulation Loss Data

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Multi-Parameter Correlations

• Weighted Average Temperature / Two Parameter Fit
  – Requires alumina disk and thermal barrier tests
  – Weighting heavily favors heat-source temperature
  – Provides only a modest improvement in predicted environmental losses (overpredicts by 13.5 watts)
Conclusions

- HET correlations should not be used to predict net heat input
- HST correlations based on alumina disk data can be used to predict environmental losses of operating convertors
  - These correlations consistently overestimated environmental losses by 13 – 15 watts.
- Multi-parameter fits provided little benefit over HST correlations
- Thermal barrier testing is unnecessary when using heat source temperature correlations
- The following equation could be used to estimate environmental losses:

\[ EL_{\text{operating ASC}} = f(\text{HST})_{\text{non-operating ASC}} + (\text{Estimated Bias})_{\text{Thermal Standard}} \]

This equation assumes that the estimated bias of correlations as measured on the thermal standard applies to operating convertors.
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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.