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

International Energy Conversion Engineering Conference
August 1, 2011

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RPT – Thermal Energy Conversion Branch

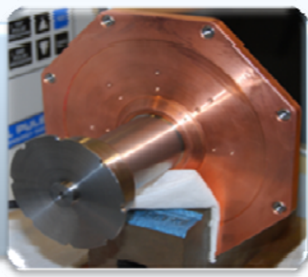
Net Heat Input Session Presentations

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

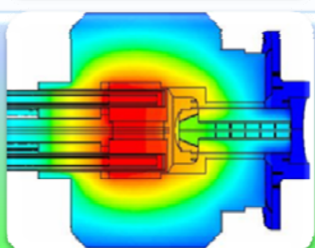
Environmental Loss Characterization of an ASC Insulation Package using a **Mock Heater Head**

- 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



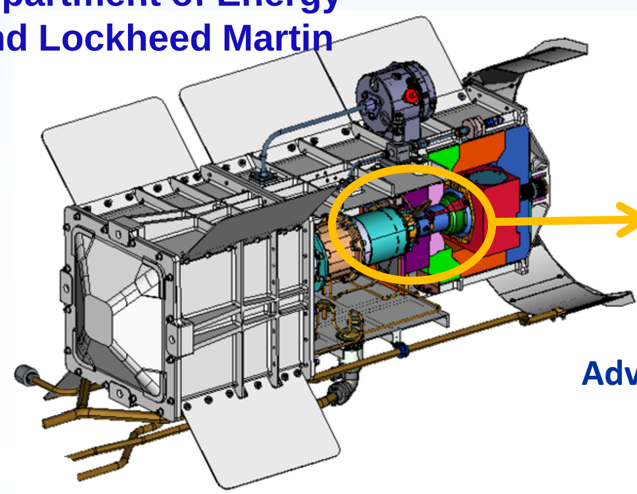
A **Computational Methodology** for Simulating Thermal Loss Testing of the Advanced Stirling Convertor

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

Why is Net Heat Input Needed?

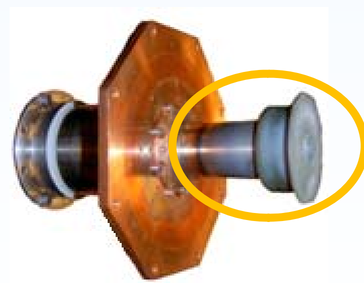
- Problem: Net Heat Input cannot be measured directly during operation
- Net heat input is a key parameter needed in prediction of efficiency for convertor performance
- Efficiency = Electrical Power Output (**Measured**) divided by Net Heat Input (**Calculated**)
- Efficiency is used to compare convertor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

ASRG developed by Department of Energy and Lockheed Martin

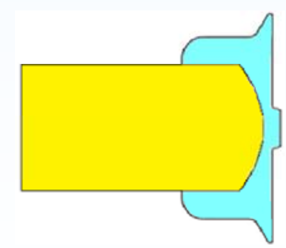


Advanced Stirling Radioisotope Generator (ASRG)

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



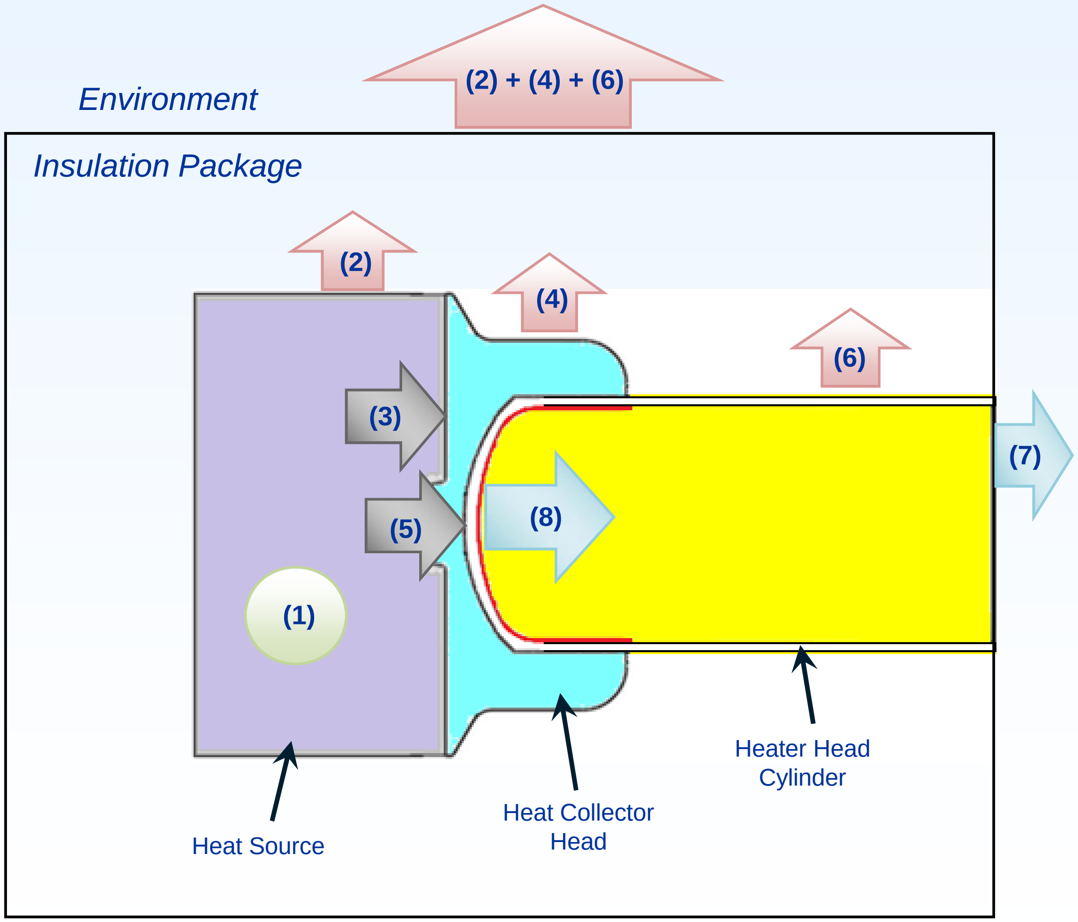
Advanced Stirling Convertor (ASC)



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

- Objective
- Background
- Cluster
- Model details
- Boundary conditions
- Methodology
- Results
- Summary
- Acknowledgments

OBJECTIVE

- Support the Science Mission Directorate and Radioisotope Power System Program Office in developing technologies for space missions.

- Explore the capability of computational modeling to assist in the development of the Advanced Stirling Convertor (ASC).

- Development a methodology that will generate predictions of net heat input for the ASC-E2.

- Verify and validate the prediction methodology.

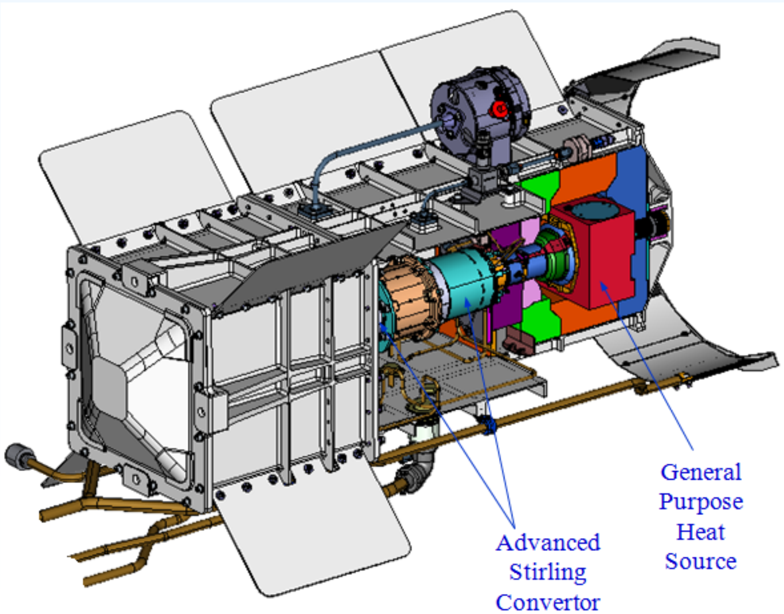
- Baseline computational simulations with available experimental data of the ASC-E2.

BACKGROUND

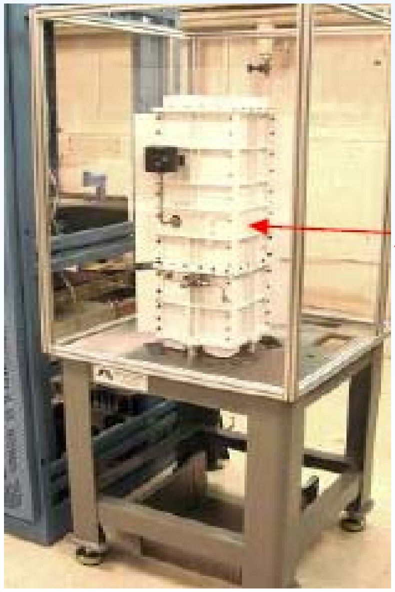
- The ASRG is a viable space flight power system candidate for future deep space and Mars surface missions.

- Each ASRG contains two Advanced Stirling Convertors.

- NASA GRC conducts system and component level testing.



Advanced Stirling Radioisotope Generator

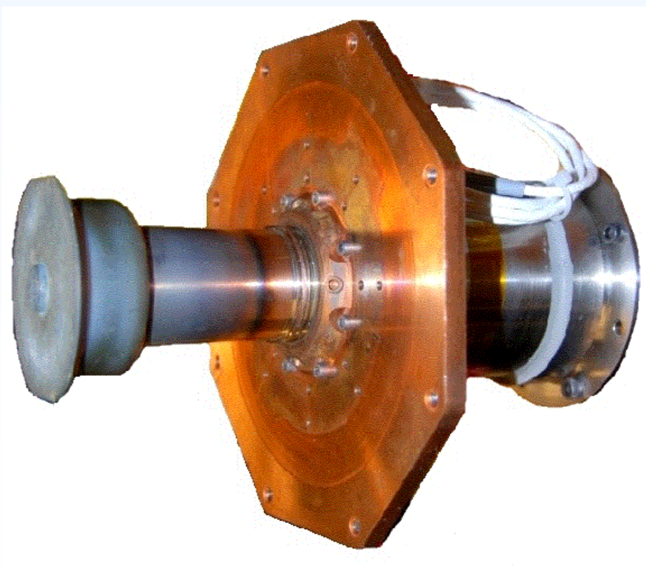


ASRG Testing at NASA GRC

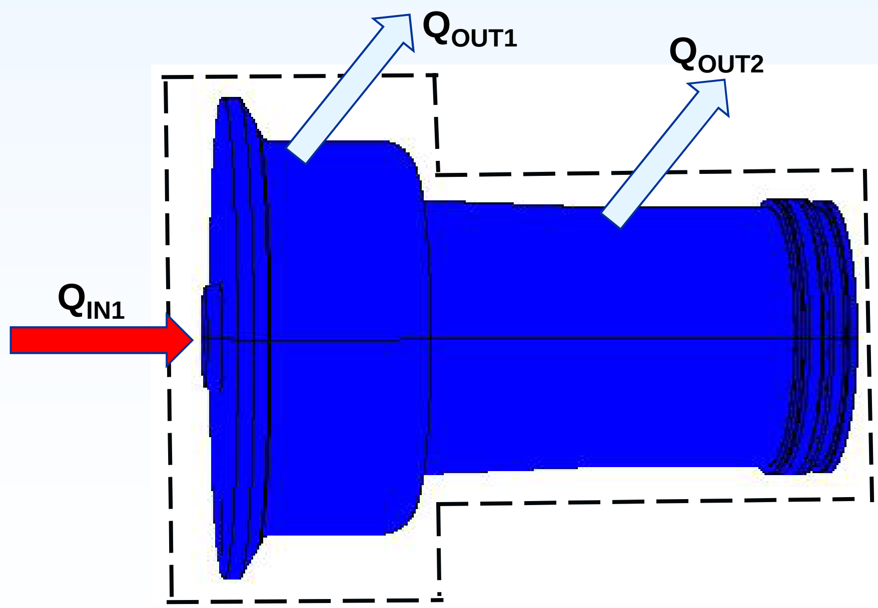
ASC Testing at NASA GRC

BACKGROUND

- ASCs are tested at several conditions to verify performance.
- Computational simulations done to track thermal distributions.
- Methodology developed to predict ASC net heat input.



ASC-E2 Hardware

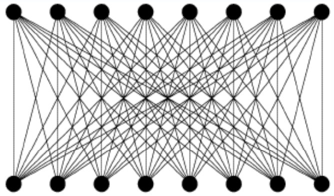


Schematic of heat paths
($Q_{Net\ Heat\ Input} = \Sigma Q_{IN} - \Sigma Q_{OUT}$)

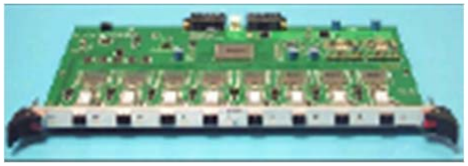
CLUSTER

- Model
  - CFD solver is FLUENT; Model contains 3 million nodes.
  - Typical parallel calculation utilizes 24 processors.

- Hardware
  - Node count: 374 processors, 160 channel Clos network
  - Fiber optic: 1.28 Gb/s Bi-Directional, 600 ns latency
  - Chip design: AMD Opteron 250 & 850, 2- & 4-Way
  - Peak floating point performance: 1.795 TeraFlops
  - Total memory: 4 Terabytes, Total Disk: 31.5 TeraBytes
  - Utilizes 75 KVA Power and 20 Ton Cooling



Clos Network



8-port “leaf “ level of switching in Clos network

128 port Myrinet Clos fiber Optic network switch

NASA GRC Cluster with Myrinet Fiber Optic Communications

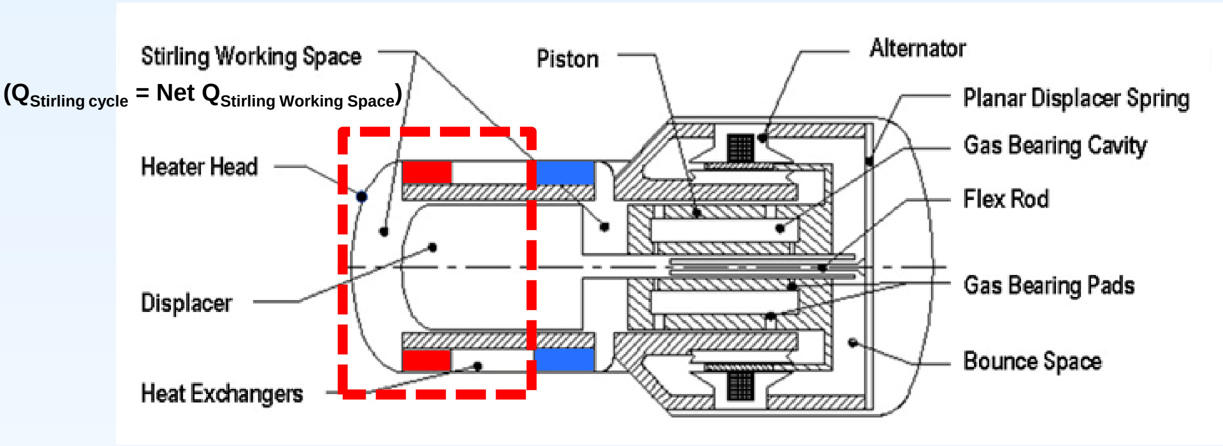
MODEL DETAILS

ASC-E2 model

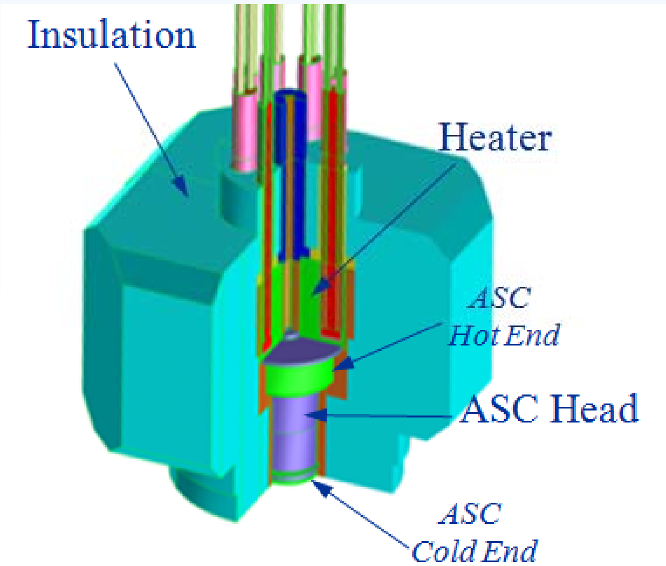
Model comparison

Thermal Standard components

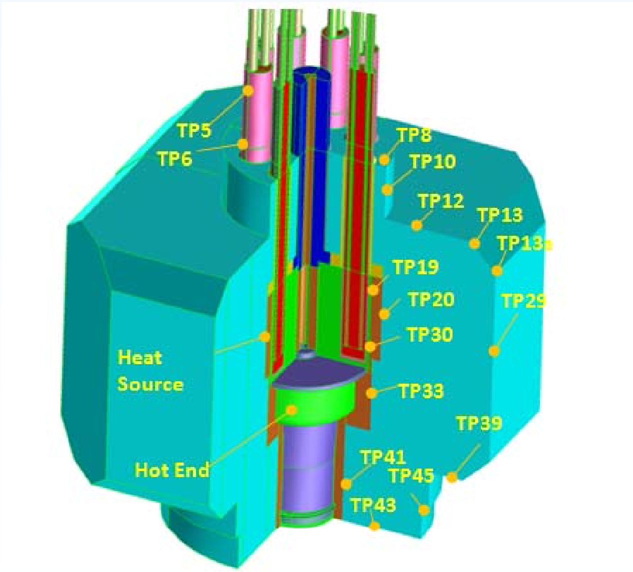
ASC-E2 MODEL



Typical Components in a Stirling Convertor

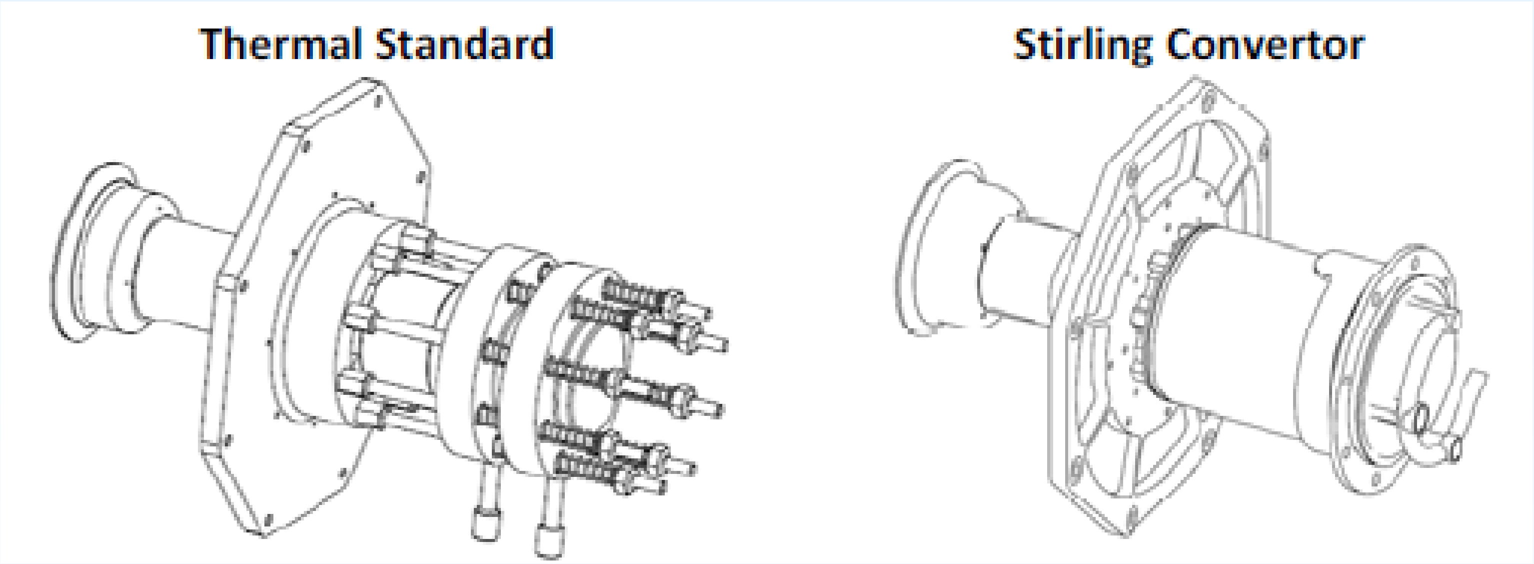


Components in the Computational Model



Measured Temperature Locations

MODEL COMPARISON

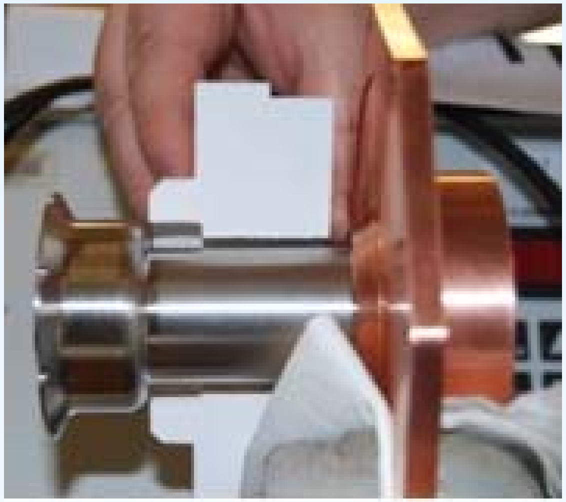


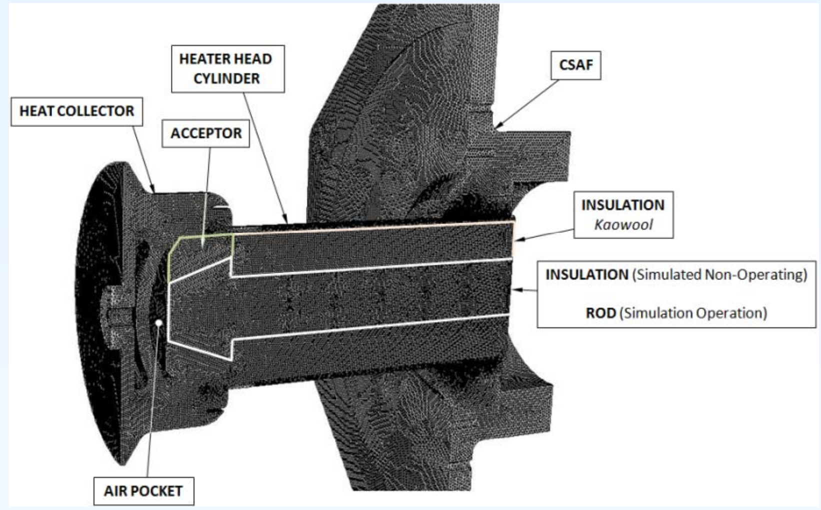
Comparison of Thermal Standard and the Advanced Stirling Convertor

- The Thermal Standard was designed to produce thermal gradients during simulated operating conditions.

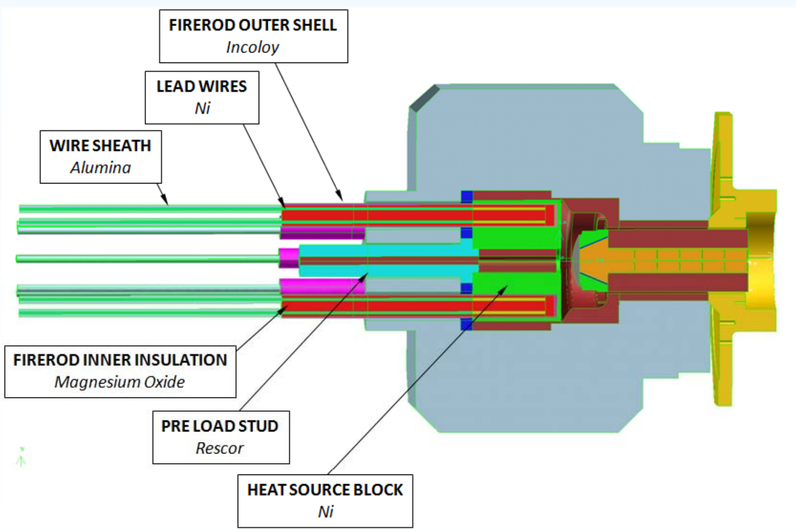
- Instead of converting thermal energy to mechanical energy (characteristic of a Stirling cycle), a highly conductive copper rod removes a comparable quantity of thermal energy from the domain. (*i.e.* $Q_{STIRLING\ CYCLE} \sim Q_{ROD}$)

THERMAL STANDARD COMPONENTS

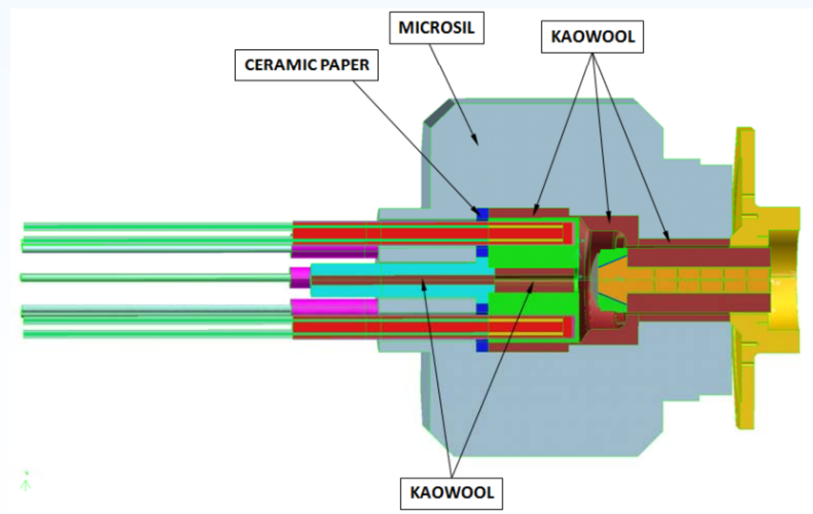




Thermal Standard

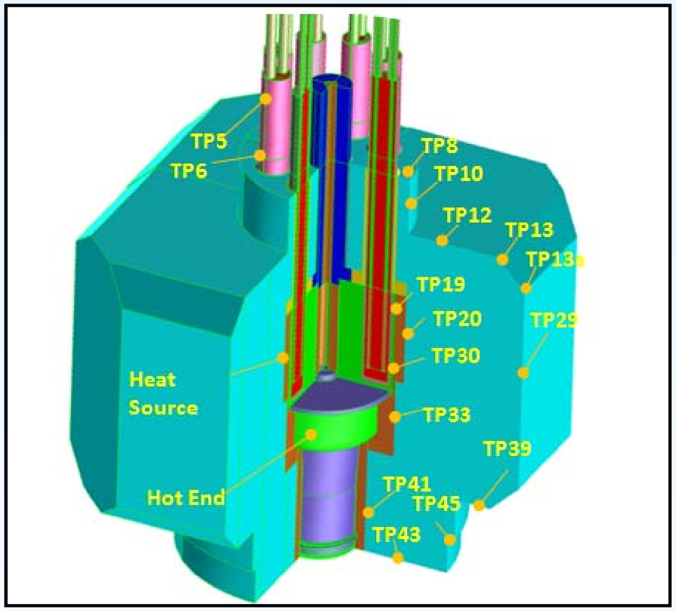


Heating Package

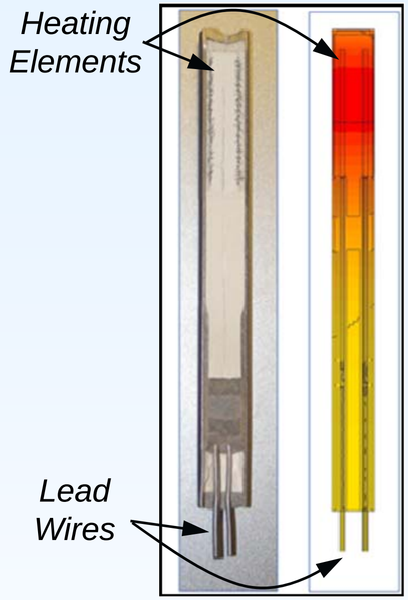


Insulation Package

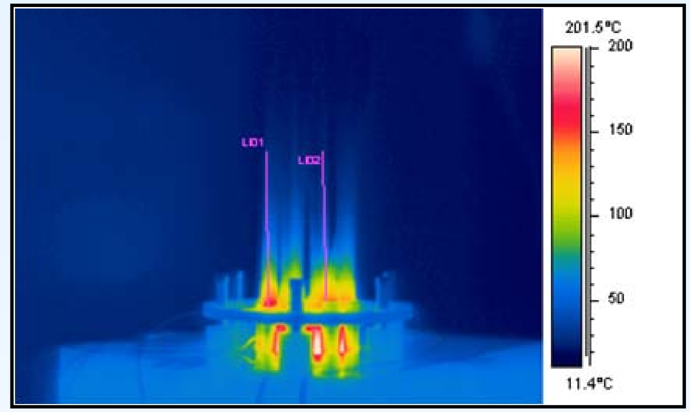
BOUNDARY CONDITIONS



Locations of temperature measurements



FIREROD® components



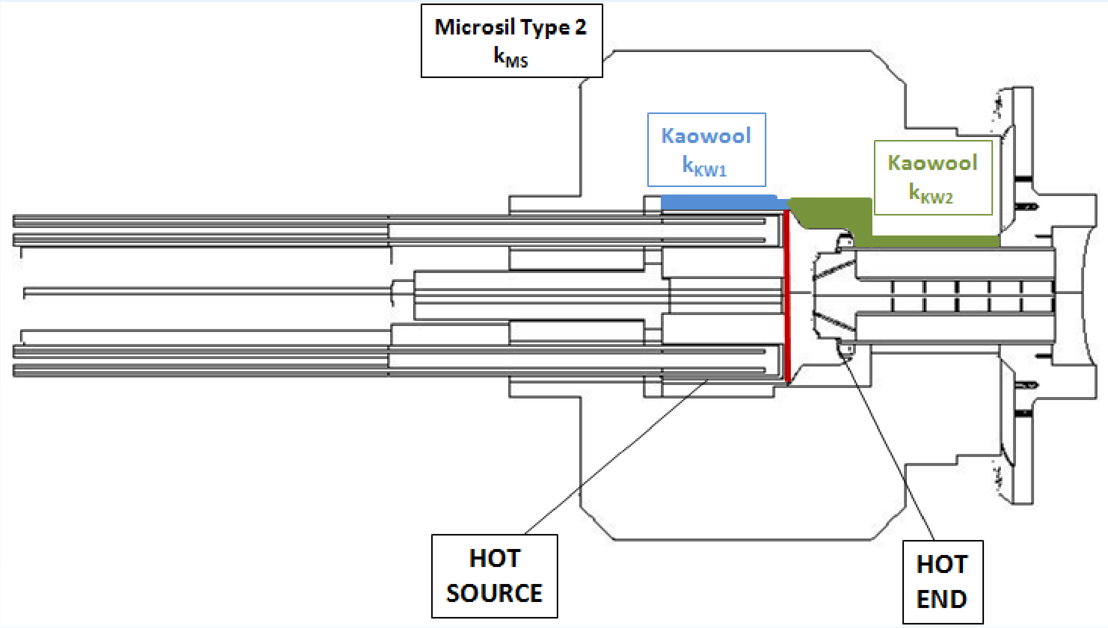
IR image of lead wires

- External Temperature Profiles are applied to the model by mapping measured temperatures to the exterior surface of model in the form of constant, linear or non-linear profiles.

- Gross Heat Input is simulated by the applying a heat generation boundary condition to the heating element.

- For lead wire temperature profile, IR camera used to measure temperature profile,

METHODOLOGY



Observed and modified parameters

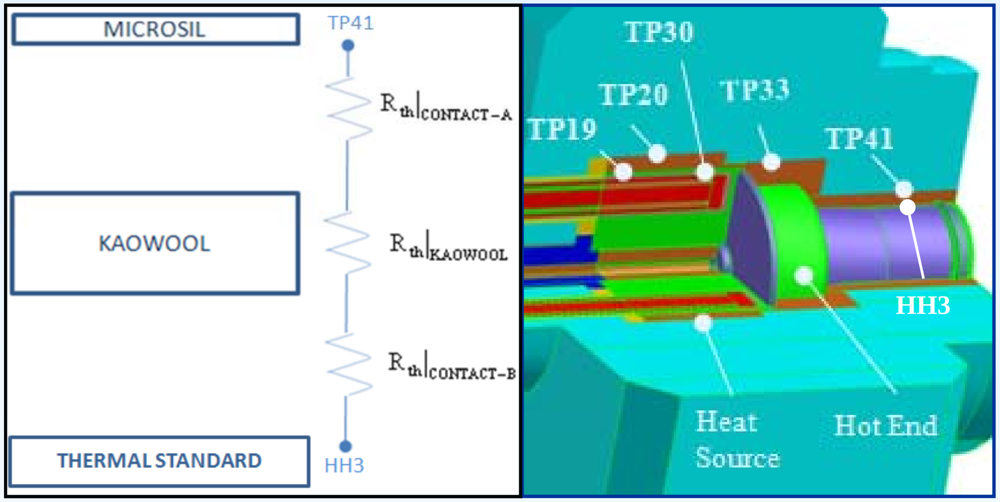
- MICROSIL thermal conductivity profile is modified until Heat Source and Hot End temperatures are in the appropriate range.

Goal: Capture effects of temperature-related shrinkage.

- Adjust thermal conductivity profiles of Kaowool™.

Goal: Capture effects of non-zero thermal contact resistances.

METHODOLOGY



Example of resistance network analogy

$$R_{th} = \frac{\Delta T}{Q} = \frac{\Delta x}{kA}$$

$$k_{effective} = \frac{\Delta x}{A \sum R_{th}}$$

$$= \frac{\Delta x}{A\left(R_{th}\big|_{CONTACT-A} + R_{th}\big|_{KAOWOOL} + R_{th}\big|_{CONTACT-B}\right)}$$

- Computational model includes radial heat transfer between adjacent surfaces with very different thermal conductivity profiles.

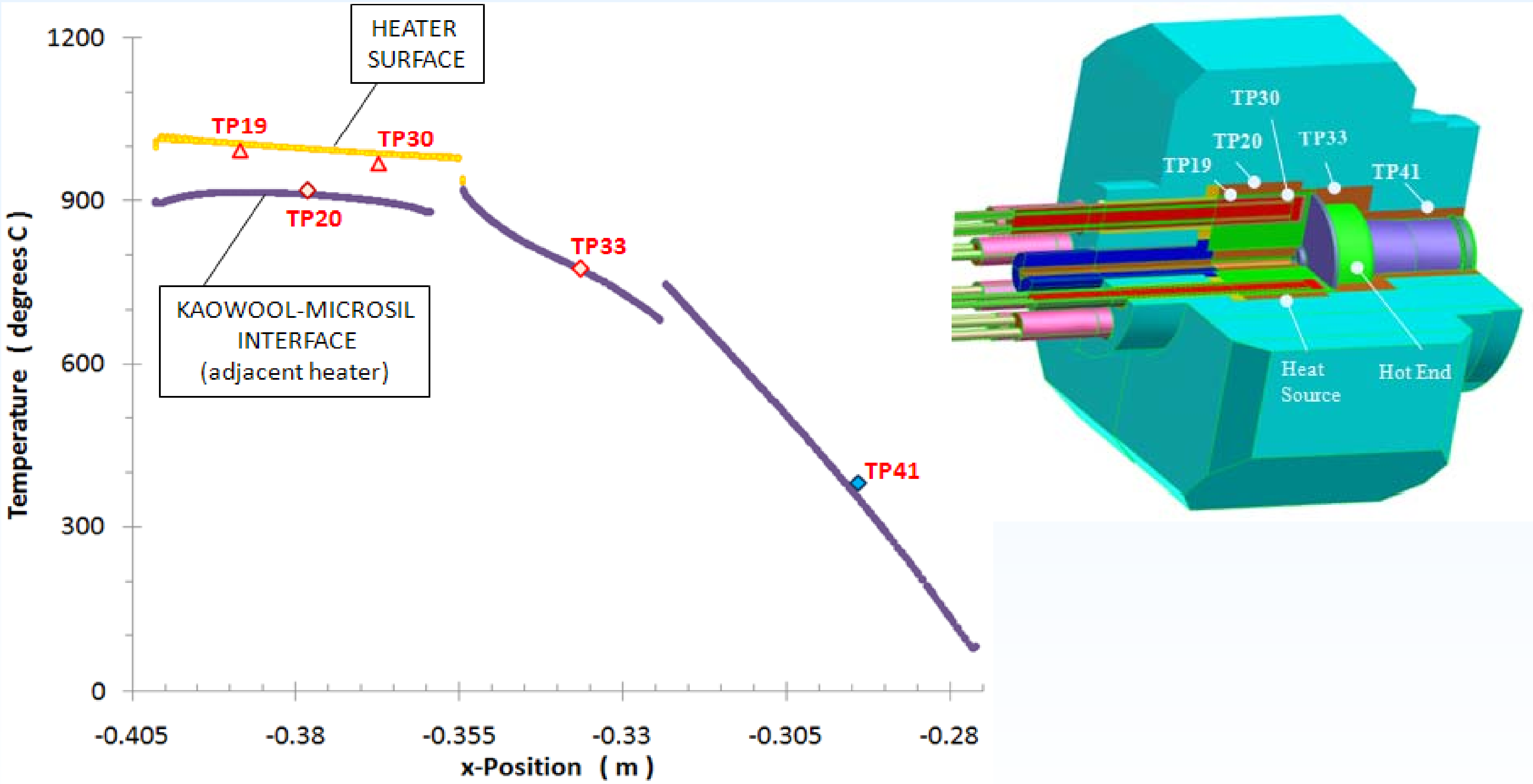
- Model assumes adjacent materials have a contact resistance of zero.

$$k_{effective}(T) = k_{actual}(T)$$

- To estimate the effects of a non-zero contact resistance results in

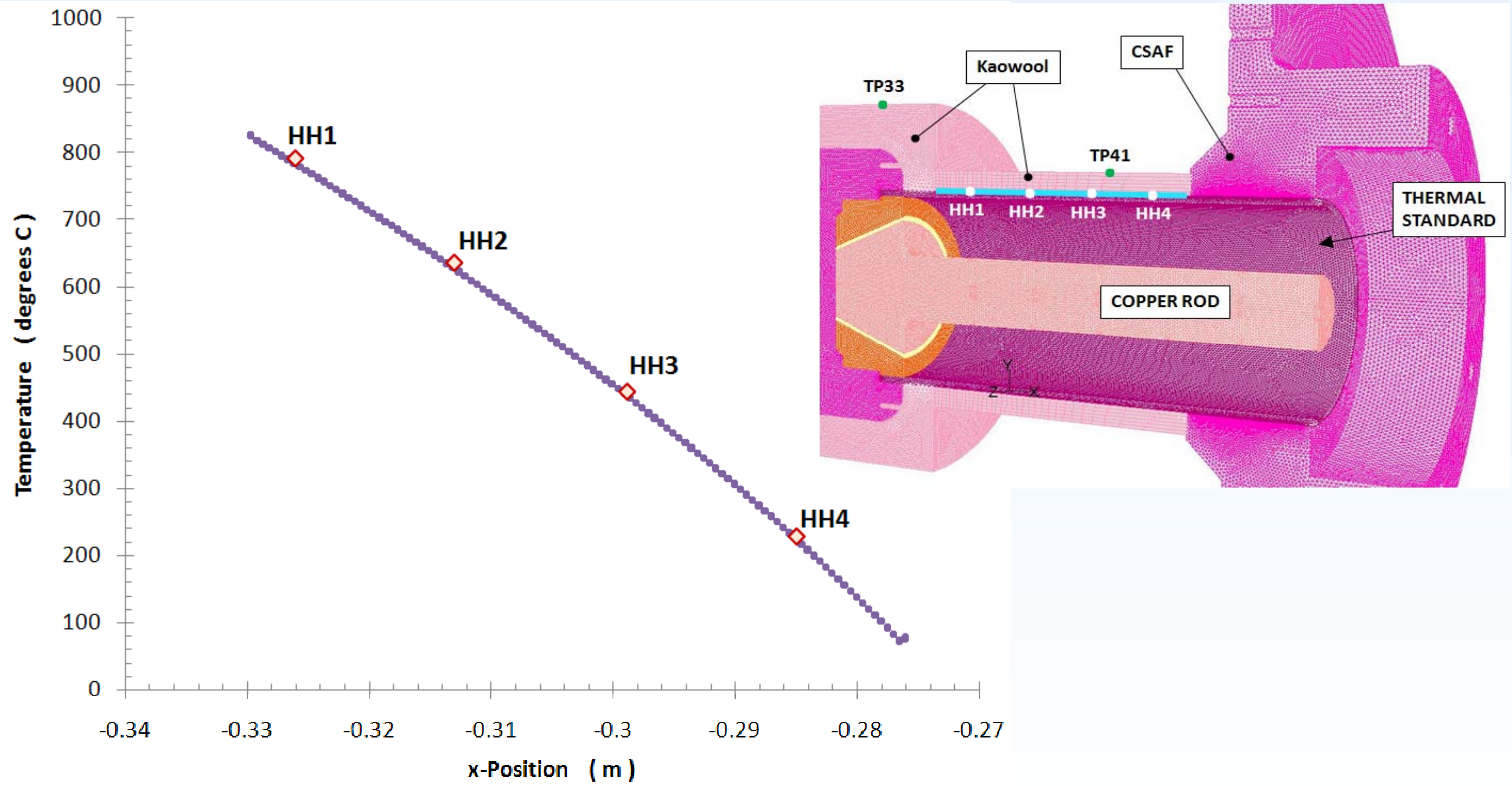
$$k_{effective}(T) < k_{actual}(T)$$

RESULTS



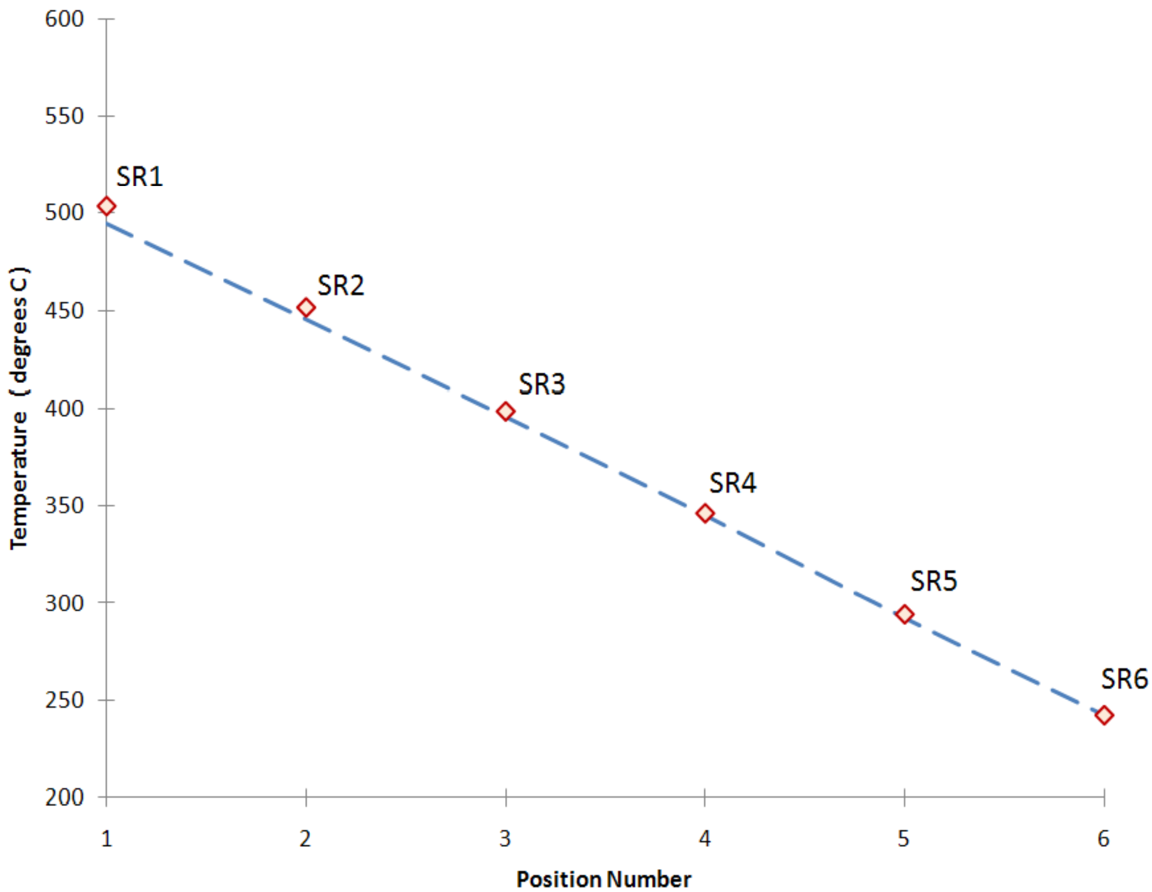
Comparison of predicted (lines) versus measured (symbols) temperatures adjacent heater block

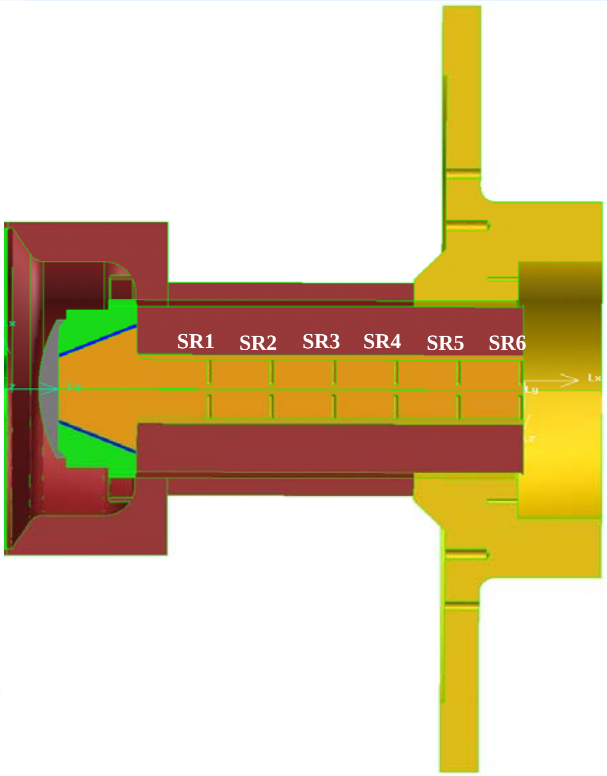
RESULTS



Comparison of predicted (lines) versus measured (symbols) temperatures adjacent heater head

RESULTS

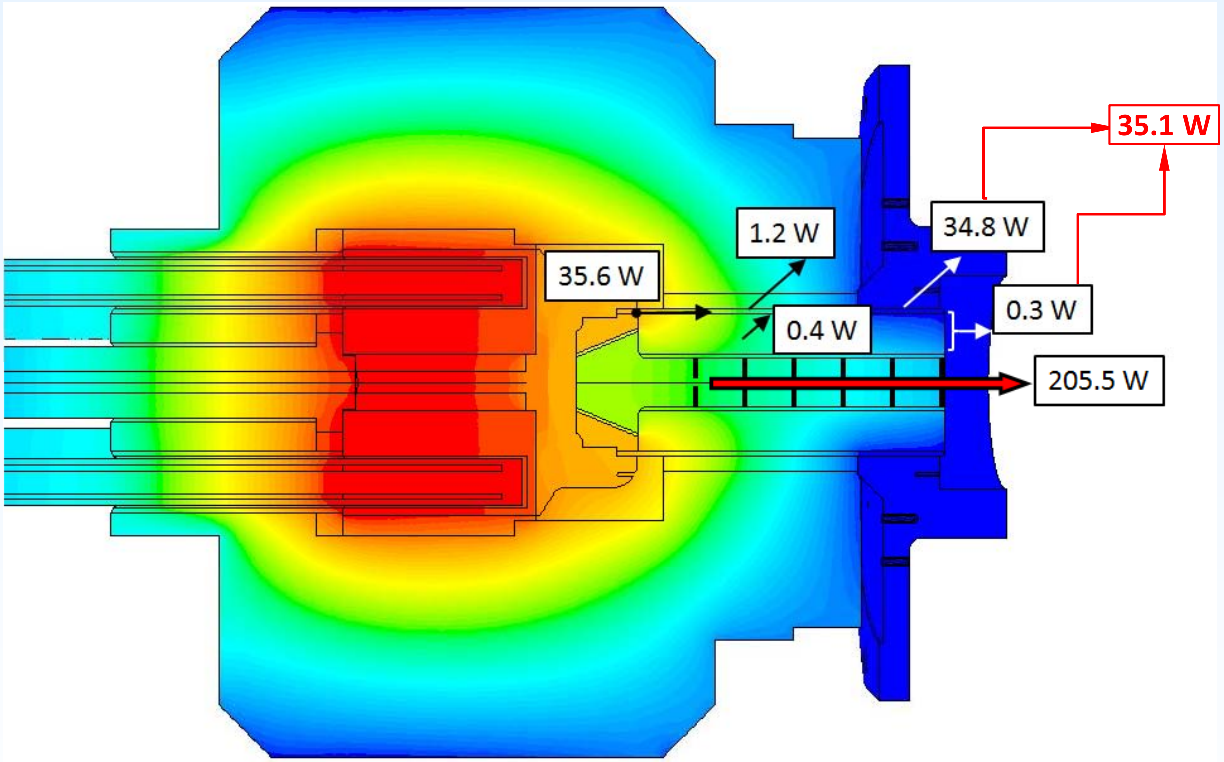




Comparison of predicted (lines) versus measured (symbols) temperatures along copper rod

RESULTS

Heat transfer in Thermal Standard



OPERATION CONDITIONS		COLD END HEAT TRANSFER *watts*	ROD HEAT TRANSFER *watts*	NET HEAT INPUT *watts*
Simulated Operation	measured	35.7	208.7	244.4
14mm ROD	predicted	35.1	205.5	240.6
	% difference	***-1.7***	***-1.5***	***-1.6***

SUMMARY

• Convertor and generator testing is carried out in tests designed to characterize convertor performance when subjected to environments intended to simulate launch and space conditions.

• The value of net heat input must be known in order to calculate convertor efficiency and to validate convertor performance.

• Specially designed test hardware was used to verify and validate a two step methodology for the prediction of net heat input.

• This lessons learned from these simulations have been applied to previous convertor simulations.

ACKNOWLEDGMENTS AND DISCLAIMER

This work is funded through the National Aeronautics and Space Administration (NASA) Science Mission Directorate and the Radioisotope Power Systems Program Office.

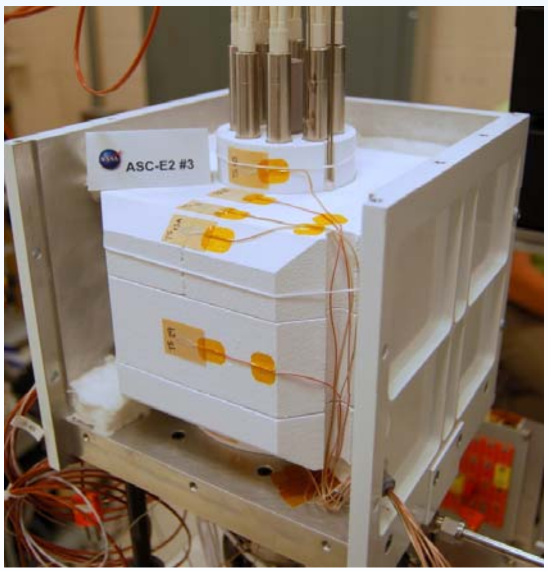
Any opinions, findings, conclusions, or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of NASA.

ADDITIONAL SLIDES

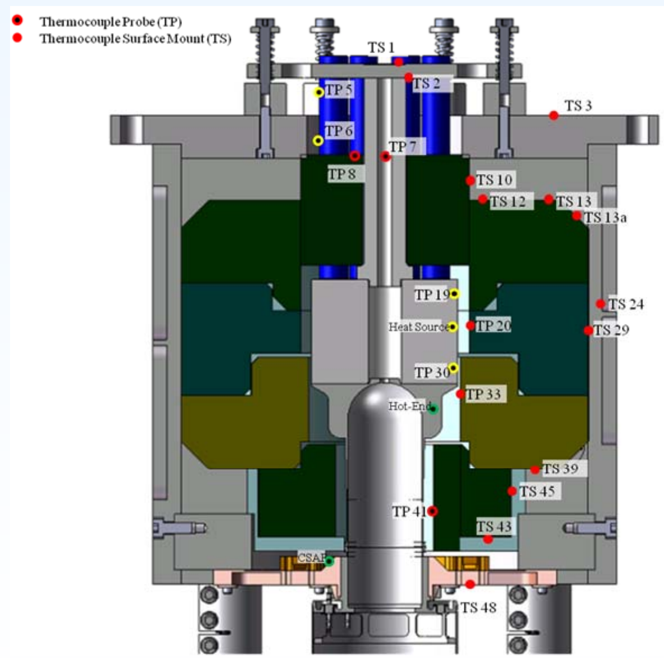
BACKGROUND

• As heat is supplied to the convertors, electric power is produced and measured.

• Net heat input to the convertor is one parameter that will contribute to the calculation of efficiency. This parameter is not measured directly.



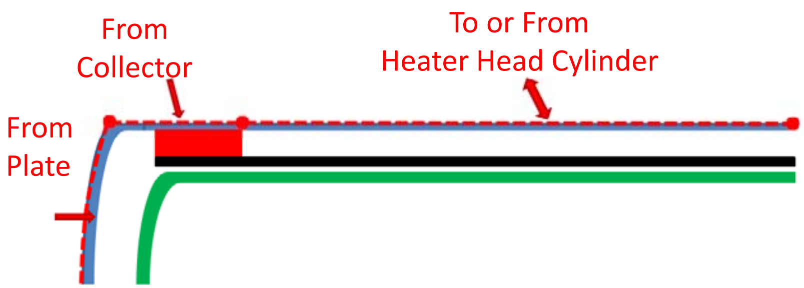
ASC Test Configuration



Measured Temperature Locations

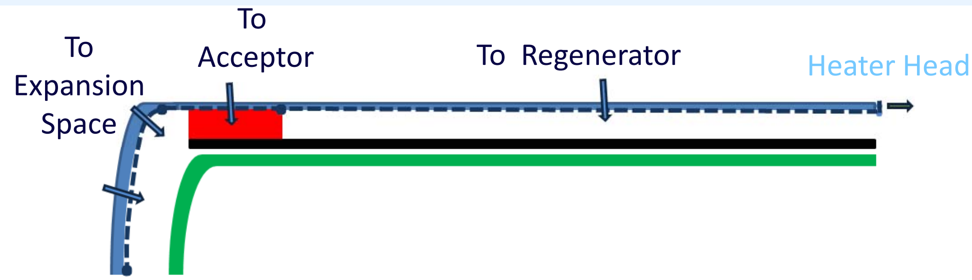
HEATER HEAD ENERGY BALANCE

- Energy Balance around Heater Head



Sum of energy along outer surface of heater head

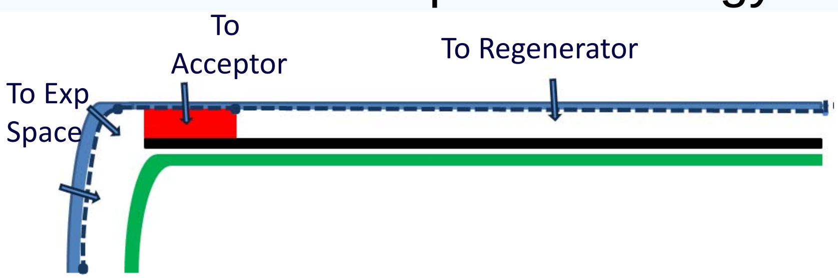
ΣQ_{RED} = Q(plate) + Q(coll) + Q(hh)



Sum of energy along inner surfaces of heater head

ΣQ_{BLUE} = Q(into exp) + Q(acc) + Q(regen) + Q(ex hh)

- Internal Component Energy Balance



Sum of energy along outer surfaces of heater head

Q(into exp) + Q(acc) + Q(regen)

Sum of energy in inner volumes

ΣQ_{ORANGE} = { Q(exp) + Q(tubes) }
+ { Q(reg) + Q(hotcyl) + Q(app gap) + Q(displ wall) + Q(disp gas) }

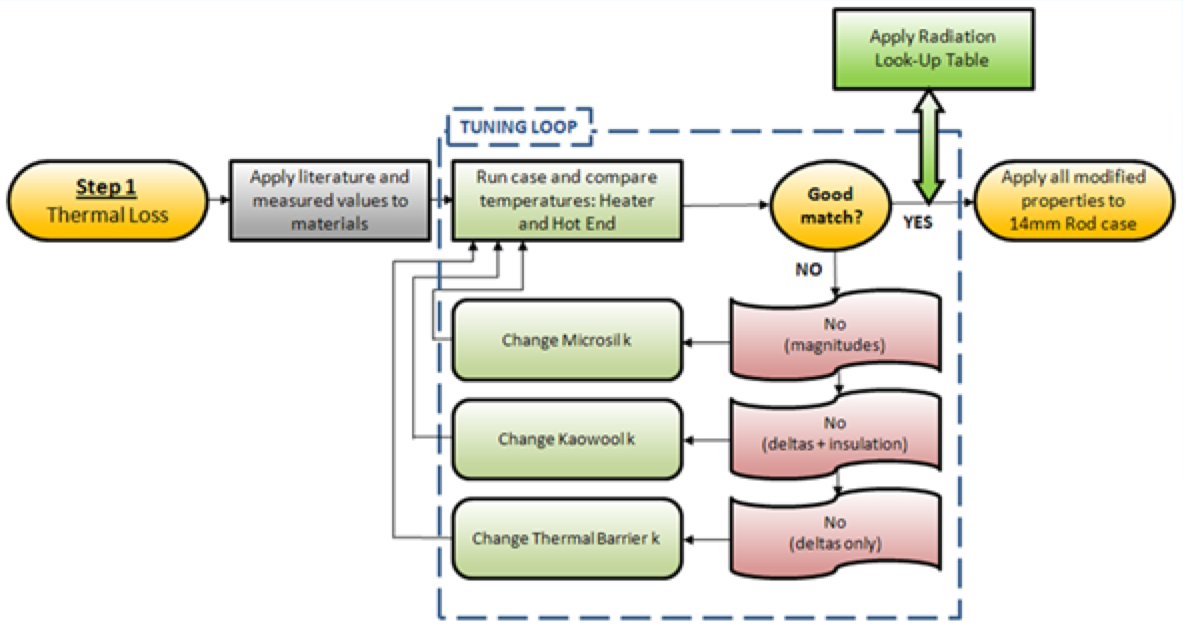
$$Q_{\text{Net Heat Input}} = \Sigma Q_{RED} = \Sigma Q_{BLUE} = \Sigma Q_{ORANGE} + Q(\text{ex hh})$$

METHODOLOGY

• Insulation Loss. Determine the current status of the thermal conductivity of the micro-porous insulation.

- Match heat source and hot end temperatures.

- Match temperature difference across Kaowool™ insulation



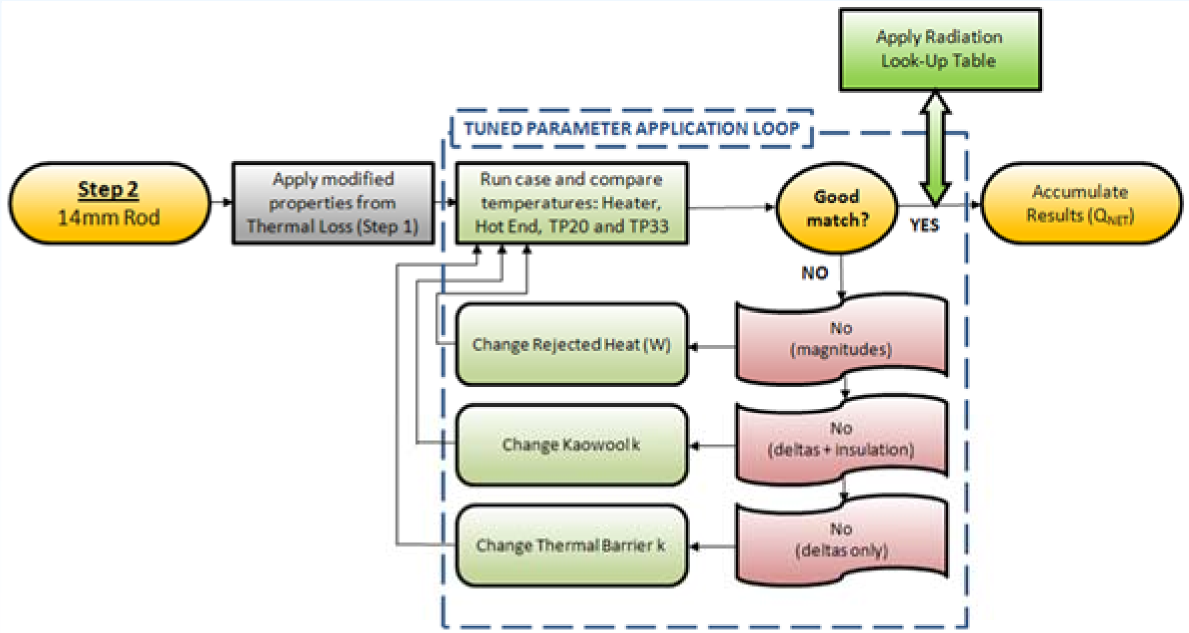
Methodology applied to Insulation Loss calculations

METHODOLOGY

• Simulated Operation. Determine the amount of heat that is rejected by the copper rod.

- Match heat source and hot end temperatures.

- Match temperature difference across KAOWOOL™ insulation



Methodology applied to Simulated Operation calculations