HEAT TRANSFER MEASUREMENT UNCERTAINTY FOR STIRLING HEAT ADDITION PREDICTIONS. S. D. Wilson[1] NASA Glenn Research Center, 21000 Brookpark Rd, 301-2, Cleveland, Ohio, 44135.

Introduction: 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 (GRC).[1] The ASCs convert thermal energy from a radioisotope heat source into electricity. As part of ground testing of these ASCs, different operating points are used to simulate expected mission conditions. These conditions require achieving particular operating parameters for specified alternator power output and heat input from the electrical heat source, commonly used in lab tests. Micro-porous bulk insulation is used to minimize the loss of thermal energy from the electric heat source to the environment. The insulation is characterized before operation to predict how much heat will be lost to the environment and how much will be absorbed by the convertor during operation (net heat input).

Net Heat Input. Stirling convertor net heat input is the heat energy required for the Stirling device to produce a desired power output. Not all heat energy absorbed by the collector makes it to the cycle. Some heat is lost to the cold end of the device (cold-end parasitic losses) and some is lost to the surrounding environment through the insulation. Heat energy is budgeted for the Stirling cycle and cold-end parasitic losses, which sum to be what is referred to here as the net heat input.

Validation Effort. Numerous tasks have been performed that provided a more accurate prediction of net heat input to the Advanced Stirling Convertors (ASCs).[2] These tasks included a) making thermophysical property measurements of test setup materials to provide inputs to the numerical models, b) acquiring additional test data that is collected during convertor tests to provide numerical models with temperature profiles of the test setup, c) using multidimensional numerical models to predict net heat input of an operating convertor, and d) using validation test hardware to provide direct comparison between measured data and numerical results to validate the multidimensional numerical models used to predict convertor net heat input. The validation test effort and uncertainty calculation are discussed here.

Validation Test Hardware: The validation test hardware, known as the Thermal Standard, was designed to simulate an operating Stirling convertor using hardware that replaces the thermodynamic cycle condition heat transfer, which is less expensive and less complicated to model. Figure 1 shows a cross section view of the Thermal Standard hardware. Not shown in the image is the ground support hardware used to mount and contain the micro-porous bulk insulation to the test stand. The gross heat input, heat lost to the insulation, and conduction heat transfer through the wall, insulation plug, and copper rod are shown graphically.

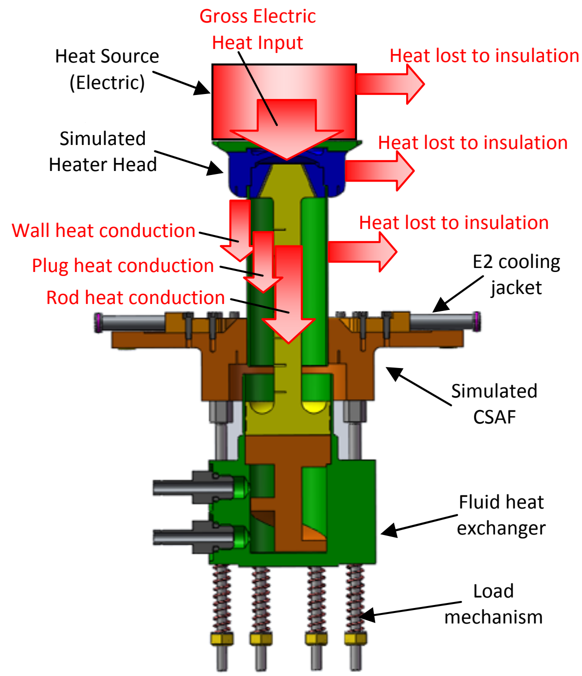

Figure 1. Thermal Standard Hardware.

Test conditions were used that attempted to simulate the temperature profile of an operating convertor using static heat conduction through solid components. This enabled direct calculation of heat transferred through the test setup and provided a comparison to numerical results. This was accomplished by design of conduction paths to simulate those present in convertor testing. The simulated cold side adapter flange (CSAF) was fabricated from oxygen-free high-thermal conductivity copper and the heater head from nickel 201 and stainless steel, which replaced the MarM-247 components in an ASC heater head. A high-strength copper rod, made from GRCop-84, was used to simulate the additional heat absorbed by the Stirling cycle. Testing was carried out over a number of hot end and CSAF temperatures.[3,4]

Measurement Uncertainty: The rod heat transfer was calculated to be 208.7 W for the following inputs: thermal conductivity (k) = 316 W/m/K, rod diameter (D) = .014 m, cross-sectional area (A) = 1.539E–04 m2, temperature difference between the highest and lowest rod temperature (ΔT) = 309 °C, and the distance between temperature measurements (Δx) = .072 m. The same calculation was performed for the stainless steel heater head cylinder wall, which resulted in 35.7 W. The resulting total net heat input value was 244.4 W. Equation 1 shows Fourier's Law, which was used to calculate the conduction heat transfer through the test setup components.

$$q = -kA\frac{\Delta T}{\Delta x} \quad (1)$$

Based on a resulting linear heat conduction trends for both the Stirling rod and the heater head cylinder, an average temperature was used to determine the thermal conductivity for each of the heat transfer calculations performed.

Using the NASA Measurement Quality Assurance Handbook as a guide, the combined standard uncertainty model for the rod conduction heat transfer was formulated.[5] Equation shows the combined uncertainty.

$$U_q = \sqrt{\frac{\partial q}{\partial k}^2 u_k^2 + \frac{\partial q}{\partial A}^2 u_A^2 + \frac{\partial q}{\partial \Delta x}^2 u_{\Delta x}^2 + \frac{\partial q}{\partial \Delta T}^2 u_{\Delta T}^2} \quad (2)$$

The corresponding coefficients are shown below.

$$\frac{\partial q}{\partial k} = \frac{A\Delta T}{\Delta x} = 6.605e-01, \quad \frac{\partial q}{\partial A} = \frac{k\Delta T}{\Delta x} = 1.356e+06,$$

$$\frac{\partial q}{\partial \Delta x} = \frac{kA\Delta T}{\Delta x^2} = 2.899e+03, \quad \frac{\partial q}{\partial \Delta T} = \frac{kA}{\Delta x} = 6.755e-01$$

The error components of the multivariate uncertainty were derived by estimating various measurement process uncertainty contributors, including affects from bias and resolution errors. Random, operator and environmental errors were not included because they were not deemed significant.

The estimated errors contributing to the uncertainty for each of the components shown in Equations 3 through 6.

The insulation was tested to provide temperature dependent thermal conductivity for modeling purposes. The reported total compound relative expanded uncertainty for two standard deviations was ±4%. The average thermal conductivity of the Stirling rod was 316 W/m-K at an average temperature of 355 °C. The uncertainty and average value of thermal conductivity were inputs to Eq. 3.

The uncertainty of the temperature difference was simplified by using the worst case bias error available from the thermocouple vendor (due to wire variation). Also, the higher temperature in the temperature difference calculation has an uncertainty value of ±3.75 °C, as seen in Eq. 6. The same value was chosen to represent both temperatures even though the lower temperature of 300 °C had a corresponding uncertainty of 2.2 °C.

$$u_k = \frac{L}{\Phi^{-1}\left(\frac{1-p}{2}\right)} = \frac{0.04*316}{\Phi^{-1}\left(\frac{1-0.95}{2}\right)} = \pm 6.45\ \frac{W}{m-K}, \quad (3)$$

$$u_A = \sqrt{{u_{Abias}}^2 + {u_{Ares}}^2} = 5.590e-07, \quad (4)$$

$$u_{\Delta x} = \sqrt{{u_{\Delta xbias}}^2 + {u_{\Delta xres}}^2} = 1.393e-05, \quad (5)$$

$$u_{\Delta T} = \frac{3.75}{\Phi^{-1}\left(\frac{1-0.95}{2}\right)} = \pm 1.913\ ^\circ C, \quad (6)$$

$$u_{\Delta xbias} = \frac{2.54e-05}{\Phi^{-1}\left(\frac{1-0.95}{2}\right)} = \pm 1.296e-05\ m, \quad (7)$$

$$u_{\Delta xres} = \frac{1.0e-05}{\Phi^{-1}\left(\frac{1-0.95}{2}\right)} = \pm 5.102e-06\ m, \quad (8)$$

The combined standard uncertainty was calculated to be Uq = 4.516 W using Eq 2. The resulting uncertainty for the rod heat conduction was calculated to be 208.7 ±4.5 watts (± 2.2%).

Conclusion: In an effort to improve the accuracy of the net heat input calculation, validation testing was carried out to provide direct comparison of numerical results and validate net heat input predictions. The validation hardware measurement uncertainty was calcualted to be 2.2 %.

Acknowledgment: 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. The author wished acknowledge the many people who supported this effort including Maxwell Briggs, Wayne Gerber, Terry Reid, Nick Schifer, and Jeff Schreiber.

References: [1] Schreiber J.G., Thieme L.G., and Wong W.A. (2008) AIAA-2008-5790. [2] Wilson S. D. and Reid T. V. (2011) AIAA-2011-5576. [3] Briggs, M.H., Schifer, N.A., (2011) AIAA-2011-5578. [4] Reid, T.V., Wilson, S.D, Schifer, N.A., Briggs, M.H. (2011) AIAA-2011-5579. [5] NASA Measurement Quality Assurance Handbook: ANNEX 3, (2010) NASA-HDBK-8739.19-3, 2010-07-13.