LOFTID Heat Flux Gauge Calibration: What is Truth?

H. S. Alpert[1], R. A. Miller[2], C. D. Kazemba[2], G. T. Swanson[2], and F. M. Cheatwood[3], [1]AMA Incorporated at NASA Ames Research Center, Moffett Field, CA 94035, [2]NASA Ames Research Center, Moffett Field, CA 94035, [3]NASA Langley Research Center, Hampton, VA 23681

Brief Author Biography: Hannah Alpert received her PhD in Aeronautics and Astronautics from Stanford University. She is currently working as a Systems Engineer for AMA Inc. at NASA Ames Research Center in the Entry Systems and Vehicle Development Branch.

Introduction: The Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) is a demonstration of Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology, which may enable the delivery of heavy payloads to Mars, Venus, and Titan, as well as return to Earth. Unlike rigid aeroshells that are constrained by the size of the rocket's shroud, inflatable aeroshells can be deployed to a much larger scale, thus allowing a spacecraft to begin its deceleration earlier and experience less heating. On LOFTID, there will be 4 total heat flux gauges (HFG) with a range of 70 W/cm^2 and 1 radiometer with a range of 3 W/cm^2, arranged as shown in Fig. 1. Both the radiometer and total HFGs are Schmidt-Boelter gauges purchased from an external vendor.

Radiative calibrations were performed in-house at NASA Ames' Sensors and TPS Advanced Research Laboratories (STAR Labs) before and after environmental testing to investigate how the testing affected the sensors' response. Additional rounds of radiative calibration at STAR Labs were also performed in order to investigate the large uncertainties associated with these tests. For example, a survey of multiple calibration facilities concluded that the uncertainty within a given facility was $\pm 3\%$ [1]. An additional NIST study that calibrated heat flux gauges at 7 different facilities also found the variation in calibration coefficients to be up to $\sim$3% within a given facility, but up to 15% between facilities, suggesting systematic differences between test setups [2]. Finally, the response of heat flux gauges to radiative versus convective heat flux has shown to differ by up to 20% [3], [4]. Because the heat flux gauges on LOFTID will predominantly experience convective heat flux during flight, a convective calibration study was performed at Boeing's Large-Core Arc Tunnel (LCAT) facility.

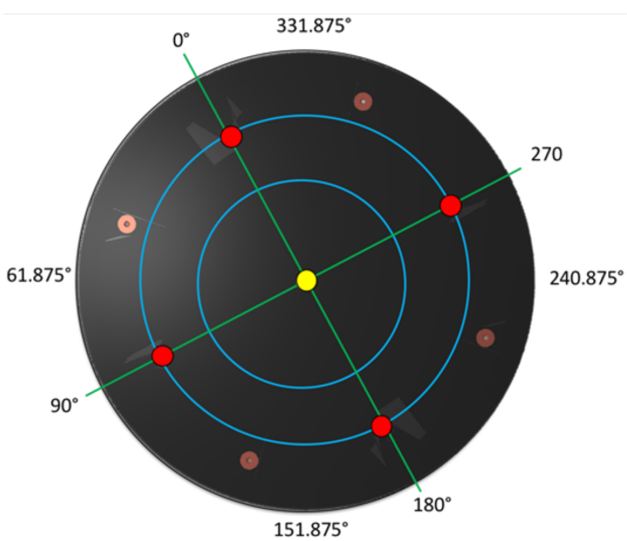

Figure 1. **Arrangement of the total HFGs (red) and the radiometer (yellow) on rigid nose of the aeroshell.**

Radiative Calibration Procedure: The calibrations performed at STAR Labs utilize a quartz lamp bank (QLB) that provides a maximum heat flux of 50 W/cm^2, which bounds the expected LOFTID flight environment. The calibration involves exposing a water-cooled Gardon gauge (reference) and then the unit-under-test (UUT) to 5 different heat fluxes multiple times for 10 seconds each, and then calculating a linear fit. The test setup is shown in Fig. 2.

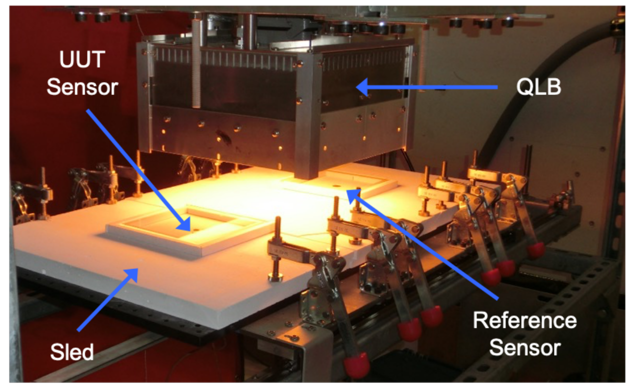

Figure 2. **STAR Labs HFG calibration test setup.**

The total HFGs were calibrated at STAR Labs 3 times, denoted as STAR 1 (before environmental testing), STAR 2 (after protoflight vibration and thermal-vacuum testing), and STAR 3 (no change from previous test). All 8 flight-lot total HFGs showed a decrease in full-scale output from STAR 1 to STAR 2 by between 0.5% and 10%. The first portion of this investigation was to determine whether the change could be due to differences in temperature between the two calibration runs. A typical linear fit to the calibration data was performed using Eq. 1, where q' is the heat flux in W/cm^2, c is the calibration coefficient, and mV is the sensor output.

$$q' = c \times mV \quad (1)$$

To account for temperature, the data were fit to a nonlinear function that included both the sensor output (mV) and the temperature from the thermocouple embedded inside the HFG near the surface (T):

$$q' = \frac{mV}{c_1 \times T + c_0}. \quad (2)$$

The residuals between the fits and the actual data points were calculated for every point, and proven to be much smaller for the temperature-compensated fits than for the linear fits for all sensors. An example is shown in Fig. 3. When the temperature-compensated fits from STAR 1 were applied to the STAR 2 data, the residuals did not improve, suggesting that the change in sensitivity between these two calibration runs was not due to temperature.

A third round of calibration (STAR 3) was conducted to further address the temperature dependence of the total HFGs, and the resulting sensitivities matched closely to STAR 2 (within 2%). Temperature-compensated calibration curves were once again fit to the data. In this case, when the temperature-compensated fits from STAR 3 were applied to

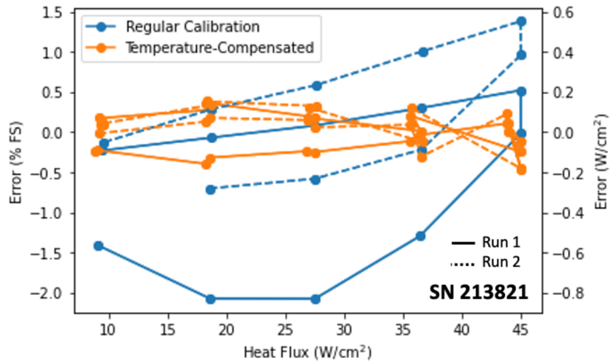

Figure 3. **Residuals for linear and temperature-compensated fits for SN 213821.**

STAR 2 data, the residuals between the fits and STAR 2 data were much lower than the residuals due to the linear fits. This suggests that the changes seen between STAR 1 and STAR 2 were likely due to actual changes in the sensors caused by the environmental testing between the two calibrations.

A modification of the original calibration process, in which the UUT was exposed to each heat flux for just 3 seconds (instead of 10) to reduce the temperature increase during the test, was additionally performed on several of the HFGs. In general, the sensitivities were 1-1.5% lower than from the 10-second tests, but the temperatures were also significantly lower. When the temperature-compensated fits from the 10-second tests were applied to the 3-second test data, the residuals were greatly improved than when just using the linear fits, further suggesting that the temperature-compensated fits may lead to better accuracy than the linear fits in flight.

Convective Calibration: The second portion of this study was to create a mapping between the radiative and convective calibration coefficients. The majority of the heating during flight will be convective, so it is important to understand how the HFG response differs under these conditions. However, there are no standardized methods for convective calibration [5]. Because the TPS aerothermal response models were validated at LCAT, the same facility was chosen for convective calibration of two of the total HFGs (Fig. 4). Preliminary results showed that the full-scale output was 3% and 8% higher in convective heat flux as compared to radiative heat flux. However, tunnel variation may have contributed to noise and uncertainty in the measurements, and more testing and analysis remains to be done.

Scope of Presentation: The presentation will include an overview of the changes seen in HFG calibration before and after environmental testing, differences between radiative and convective calibrations, the modeling work done to aid in understanding the sensor response to varying environments, and recommended future work.

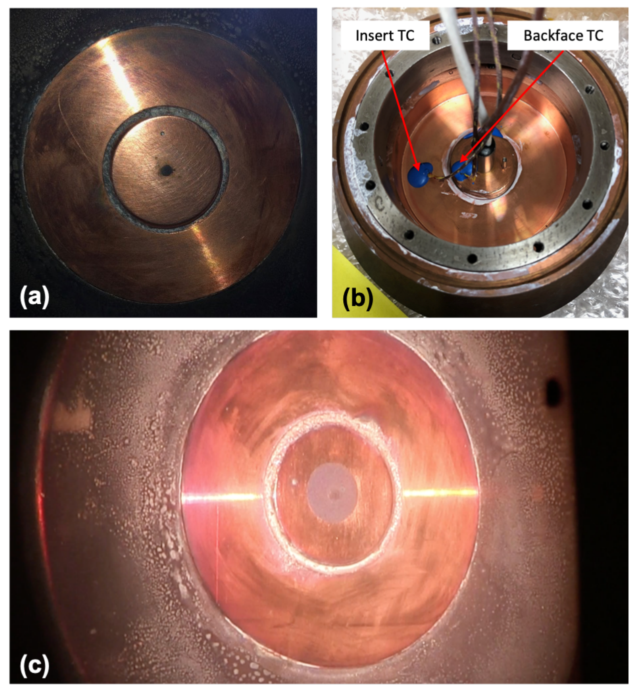

Figure 4. **LCAT convective calibration test setup: (a) front face of HFG, (b) back of HFG, and (c) HFG under test.**

References:

[1] W. L. Grosshandler (1999). NISTIR 6424.

[2] W. M. Pitts, et. al (2006). *Fire Safety Journal, 41*, 459-475.

[3] A. Gifford, A. Hoffie, T. Diller, and S. Huxtable (2010). *J. Heat Transfer, 132*.

[4] C. S. Lam and E. J. Weckman (2009). *Fire and Materials, 33*, 303-321.

[5] ASTM E511-07 (2020).