Testing of Heat Flux Sensors at Cryogenic Temperatures

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Abstract. Normally, in order to characterize multilayer insulation installed onto a test tank, the boil-off of the tank is measured and then heat loads from structural and fluid penetrations are calculated from temperature measurements throughout the system. For the Structural Heat Intercept, Insulation, and Vibration Evaluation Rig testing, it was determined that this approach would have significant uncertainties (over 50%) and that another method was needed to characterize the heat load through the blanket. Heat flux sensors are widely used to measure heat loads and characterize insulation systems at room temperature, however, the heat fluxes measured are usually two orders of magnitude higher than high performance MLI. Three different heat flux sensors were initially checked out on a liquid hydrogen calorimeter. One was chosen for actual implementation and 20 sensors were ordered. Of those sensors, calibration was attempted on 7 of the sensors. The results from testing and calibration are discussed.

1. Introduction

Cryogenic propellant tanks are insulated with multilayer insulation (MLI) to minimize radiative heat loads in the space vacuum environment. MLI is constructed with layers of metallized (aluminum, gold) substrate films (Mylar, Kapton), which act as low emissivity radiation shields. Low thermal conductivity spacers separate the layers. The total number of layers is variable, but can be 50 layers or more for long duration missions. Loss of performance in MLI systems due to joints, seams, attachments, and other design details of the insulation blankets has been recognized as a concern since the introduction of MLI. When attempting to insulate large tanks, even more seams may be required as the tank dimensions exceed the roll widths available for insulation materials.

In order to demonstrate the application of MLI and other technologies on a relative scale for upper stages, NASA is developing the Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER) [1]. One of the objectives of SHIIVER is to demonstrate the benefits of MLI as applied to upper stage hydrogen and oxygen applications. The MLI will be tested both thermally and within an acoustic test facility to demonstrate that it can survive structural environments during a rocket launch. As the design and uncertainties due to testing on a more application type tank began to be understood, it became clear that measuring the actual performance of the insulation during the SHIIVER test was not possible using standard test methodologies. These standard test methodologies generally measure the total heat load through boil-off and then subtract out calculated heat loads through structural and fluid connections. However, the structural and fluid connection for SHIIVER in certain test configurations will be much larger than the insulation heat load. As such, it was set out to see what novel methods might prove possible to measure the heat flux of the insulation while installed on the
large scale test tank. These investigations suggested that the best method for measuring the heat load would be to use several heat flux sensors spread out across the tank.

Though no vendors had any data at 20 K, initial investigations on a flat plate calorimeter suggested the heat flux sensors manufactured by Captec and of size 200 mm x 200 mm would be the preferred sensor to use based on the response and sensitivity of the sensors. As such, twenty (20) sensors were ordered (sensitivities of each sensor are shown in table 1). During this time it was also determined that a separate calibration at cryogenic temperatures may be needed to get the best performance out of the sensors during the SHIIVER testing.

| Sensor Number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Sensitivity [µV / (W/m²)] | 326 | 333 | 335 | 346 | 346 | 348 | 353 | 356 | 357 | 358 |

| Sensor Number | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Sensitivity [µV / (W/m²)] | 359 | 359 | 361 | 362 | 363 | 364 | 366 | 367 | 372 | 380 |

2. Heat Flux Meter Test Setups
Two different testing setups were attempted with some success using each. The first attempt at calibration was performed on a purpose made heat flux sensor test rig in the spirit of ASTM C-1130 [2]. While the test setup did not strictly follow to all of the test standard, namely separating the guard and test section of the heating section, the general spirit of the standard was adhered to. Testing in this method ended up taking several hundred hours to get the requisite data points, mainly due to the thermal inertia of the setup. Due to the slow progression of calibration tests with the purpose built rig, an alternative calibration method using ASTM C-1774 [3] was attempted. It was decided to place several sensors on the bottom of the flat plate calorimeter using liquid hydrogen and liquid nitrogen at two different heat fluxes, to get a calibration.

2.1. ASTM C-1130 Test Rig
In the experimental setup (see figure 1), a surface mounted configuration of the heat flux sensor adapted from ASTM C1130-07 [2] at cryogenic temperatures was used. The heat flux sensor was placed on top of a nylon block. The sensor and the nylon block were sandwiched between two copper plates, and bolted together using stainless steel 304 ¼-20 threaded rods and nuts, and Belleville washers. Since nylon contracts more than copper and stainless steel, the Belleville washers acted like springs to ensure that the copper plates and the nylon block do not mechanically separate. To minimize thermal contact resistance, indium foil was placed between the nylon block and the lower copper plate, and thermal grease was applied on the surfaces of the heat flux sensor.

The temperature of the top copper plate was maintained by a temperature controller and heater and are coupled to a cryocooler. A diode (T1) measures the temperature of the top plate. The heat flux sensor, being in contact with the top copper plate, attained the same temperature. Another temperature controller, along with a cartridge heater imbedded in the bottom plate, was used to control the temperature of the bottom copper plate, which was measured by a second diode (T2). Unlike the top copper plate, the bottom plate was not directly coupled to the cryocooler. The temperature T2 was controlled to be higher than T1, creating a heat flow between the two copper plates, regulated by the nylon block, and measured by the heat flux sensor.
Figure 1. Schematic of heat flux sensor test apparatus. The insulator/nylon block (229 mm x 229 mm x 6 mm) and heat flux sensor (200 mm x 200 mm x 0.5 mm) are sandwiched between two copper cold plates (229 mm x 229 mm x 13 mm).

2.1.1. Heat flux meter test matrix: Each sensor was run through a test matrix designed to test temperatures between 20 K and 50 K and between heat fluxes of essentially 0 W/m² and 100 W/m². Once testing began, it became clear that due to time limitations, the test matrix for each sensor could not be fully executed. As such, three heat flux meters (sensors no. 9, 10, and 11) were tested at heat fluxes of approximately 0, 7, 30, and 80 W/m² of heater input at maximum cryocooler power without controlling temperatures.

2.2. ASTM C-1774 calorimeter approach
The flat plate calorimeter is an absolute boil-off calorimeter, operated according to ASTM C-1774, Annex A3 [3]. The heat load measured through the flow meters was assumed to be the total heat load. This was divided by the area of the flat plate calorimeter to determine the average heat flux. The outer diameter of the flat plate is 42 inches with the test tank outer diameter being 38 inches. The calorimeter is designed to be suspended from the lid in the Small Multipurpose Research Facility (SMiRF) vacuum chamber. The SMiRF cold wall was not used and the warm boundary temperature was allowed to vary with the ambient temperature. Six heat flux sensors were installed on the bottom of the calorimeter as shown in figure 2. The original heat flux sensor that was ordered as a sample (hereafter referred to as No 0) in addition to five sensors from the batch of 20 ordered (Nos. 1, 2, 3, 18, and 19). These sensors bounded the sensitivities of the sensors that were installed on SHIIVER and were not immediately required for installation on the SHIIVER test article. The sensors were attached to the calorimeter flat plate with a second surface reflective tape with 3M 966 adhesive. The same boil-off flow meters were used for both liquid hydrogen and liquid nitrogen testing as the thermal coefficient between the two is different by 1%.

Figure 2. Heat flux sensors installed on the bottom of the flat plate calorimeter.
2.2.1. **Calorimeter Test Matrix:** The test matrix is shown in table 2. Two different insulation systems were used. First just a single layer of double aluminized mylar was used to minimize any difference in surface emissivity between the stainless steel plate on the bottom of the calorimeter and the heat flux sensors (appear to be coated in copper, but we did not measure their emissivity). Then a 20 layer MLI blanket built to the diameter of the flat plate calorimeter was installed and tested to drastically lower the heat load. Testing was nominally done at high vacuum (<10^{-6} Torr). However, in order to get a third heat flux, testing was done with gaseous helium in the vacuum chamber at a degraded vacuum (approximately 10 Torr) in order to get a high heat load on the sensors with liquid nitrogen in the calorimeter. High vacuum testing was performed using both liquid hydrogen and liquid nitrogen.

The testing with one reflective layer was referred to as Phase 1. The testing with 20 layers of MLI was referred to as Phase 2. The testing in a soft vacuum was referred to as Phase 3. Phase XA refers to testing with liquid nitrogen and Phase XB refers to testing with liquid hydrogen. A zero heat flux test was run at room temperature.

### Table 2. Calorimeter based test matrix as completed

| Phase/Title | Fluid       | Number of Reflector Layers | Vacuum Pressure |
|-------------|-------------|----------------------------|-----------------|
| Phase 1A    | Liquid Nitrogen | 1                           | < 10^{-6} Torr  |
| Phase 1B    | Liquid Hydrogen | 1                           | < 10^{-6} Torr  |
| Phase 2A    | Liquid Nitrogen | 20                          | < 10^{-6} Torr  |
| Phase 2B    | Liquid Hydrogen | 20                          | < 10^{-6} Torr  |
| Phase 3     | Liquid Nitrogen | 20                          | 12 Torr         |
| Room Temp   | None             | 1                           | 1 ATM           |

3. **Test Results**

The test results from the two test rigs are discussed in the following paragraphs.

3.1. **Test results from heat flux meter test rig**

Tests were performed to calibrate three of the heat flux sensors that were procured – No. 9, No. 10 and No. 11. Much of the data gathered for sensor No. 9 appeared to be transient data. The sensitivity of the heat flux sensor was calculated for one successful test where steady state was attained to be 275 microvolts per watt per square meter. The calculation procedure for the sensitivity used differential heater inputs to calculate out the background radiative heat flux. This radiative heat load passes through the MLI blanket, is absorbed by the test cell, passes through the heat flux sensor, and is ultimately removed from the test cell cold boundary by the cryocooler. The test results for sensor 10 is shown in Table 3 and the results from sensor 11 are shown in table 4. The calculated sensitivities are shown in table 5.

### Table 3. Test data from Heat Flux sensor No. 10

| Start Time (hr) | End Time (hr) | Temp. Diff. (K) | Tavg (K) | T_Hot (K) | T_Cold (K) | HF Sensor (V) | P_Heater (W) |
|----------------|---------------|-----------------|----------|-----------|------------|---------------|--------------|
| 0              | 1             | 36.09           | 60.59    | 78.63     | 42.54      | -1.68E-02     | 0.000        |
| 8.4            | 12.7          | 37.97           | 62.97    | 81.96     | 43.99      | -1.83E-02     | 0.355        |
| 70             | 95            | 66.18           | 112.37   | 145.46    | 79.28      | -4.73E-02     | 4.444        |
| 40             | 48            | 31.49           | 57.94    | 73.68     | 42.18      | -1.73E-02     | 0.000        |
| 62.7           | 67.8          | 33.81           | 61.91    | 78.81     | 45.00      | -1.96E-02     | 0.355        |
| 87.5           | 94.7          | 42.70           | 75.81    | 97.16     | 54.46      | -2.76E-02     | 1.484        |
Table 4. Test data for calibration of heat flux sensor No. 11.

| Start Time (hr) | End Time (hr) | Temp. Diff. (K) | Tavg (K) | T_Hot (K) | T_Cold (K) | HF Sensor (V) | P_Heater (W) |
|-----------------|---------------|-----------------|----------|-----------|------------|---------------|--------------|
| 58              | 68            | 32.94           | 75.16    | 91.63     | 58.69      | 1.76E-02      | 0            |
| 80              | 90            | 35.00           | 78.83    | 96.33     | 61.33      | 1.96E-02      | 0.372        |
| 130             | 140           | 44.43           | 92.15    | 114.36    | 69.93      | 2.66E-02      | 1.480        |
| 175             | 185           | 62.53           | 121.39   | 152.66    | 90.13      | 4.40E-02      | 4.317        |

Table 5. Sensitivities for sensors 9, 10, and 11.

| Sensor | Measured Sensitivity (µV/(W/m²)) | Vendor Sensitivity (µV/(W/m²)) |
|--------|----------------------------------|-------------------------------|
| No. 9  | 275                              | 357                           |
| No. 10 | 359                              | 358                           |
| No. 11 | 321                              | 359                           |

3.2. Results of calorimeter testing

Six sensors – Nos. 1, 2, 3, 18, 19 and 0 were tested on the flat plate calorimeter. The sensor voltages for the Phase 2B testing are shown in figure 3. This response is typical in its stability throughout the duration of the testing. It typically took approximately 30 hours for a steady state to be achieved once a new set of boundary conditions are initiated. The start and stop of the steady state time period from which data is taken, and the calculated heat flux are presented in table 6. While all available flow meter data are shown in the figures, they have different ranges of validity. The average values of the sensor readings, once a steady state is achieved, is shown in table 7.
Table 6. Timing and heat flux data from testing.

| Phase/Title | Start Time (hr) | Stop Time (hr) | Temperature (K) | Heat Flux (W/m$^2$) |
|-------------|----------------|----------------|-----------------|--------------------|
| Phase 1A    | 17.5           | 18.1           | 77.8            | 8.6                |
| Phase 1B    | 27.0           | 32.64          | 20.6            | 4.5                |
| Phase 2A    | 21.0           | 33.0           | 77.8            | 3.2                |
| Phase 2B    | 25.0           | 33.0           | 20.6            | 2.2                |
| Phase 3     | 15.0           | 20.0           | 99.8            | 55.3               |
| Room Temp   | 0.0            | 0.1            | 293.7           | 0.0                |

Table 7. Average sensor data from all testing.

| Phase/Sensor | No. 1 (V) | No. 2 (V) | No. 3 (V) | No. 18 (V) | No. 19 (V) |
|--------------|-----------|-----------|-----------|------------|------------|
| Phase 1A     | -8.39E-04 | -1.86E-03 | -1.81E-03 | -1.89E-03  | -3.46E-03  |
| Phase 1B     | -8.67E-04 | -2.46E-03 | -6.53E-04 | -1.10E-03  | -1.24E-03  |
| Phase 2A     | -4.28E-04 | -4.55E-04 | -4.87E-04 | -6.52E-04  | -7.61E-04  |
| Phase 2B     | -4.53E-04 | -3.47E-04 | -4.76E-04 | -1.10E-03  | -6.20E-04  |
| Phase 3      | -6.73E-03 | -8.57E-03 | -1.34E-02 | -7.24E-03  | -1.09E-02  |
| Room Temp    | -3.37E-04 | -3.72E-04 | -3.27E-04 | -3.46E-04  | -3.75E-04  |

3.3. Uncertainty of heat loads in calorimeter testing

Typically, boil-off calorimeters have uncertainty less than 5% [4]. During testing with the flat plate calorimeter it was determined to check the operational performance and sensitivity of the calorimeter to a few operational procedures. To do so, the calorimeter was run at multiple pressure differentials between the two tanks, the test chamber and the guard chamber. Nominally, this should not affect the performance at all as ideally the test chamber and guard chamber should be as thermally isolated as possible to prevent heat flow between them. In this case the only separation between the two chambers is a 6 mm stainless steel plate. As such, when the differential pressure (and thus slightly differential saturation temperature) across the plate was varied, the boil-off flow responded in a very strong manner (see figure 4). As such, there was clearly a small, yet undetermined parasitic heat load into the test chamber from the guard chamber. Thus the absolute values of the heat flux measured into the test chamber is of question.

![Figure 4. Boil off rate for LN2 with a twenty MLI layers at varying differential pressures](image-url)
4. Discussion of Results
Two specific investigations were conducted, the first attempted to use ASTM C-1130. This approach and testing of this took much longer than desired, mainly due to the thermal impedance of the nylon block. However, it did show that multiple sensors had a similar sensitivity at cryogenic temperatures as at room temperature.

The second approach used a boil-off calorimeter and yielded questionable values. In addition to the aforementioned issues with the boil-off flow, it is interesting in the fact that according to the boil-off flow meters, the hydrogen heat load was much less than then nitrogen heat load. This could be real, or it could be due to different parasitic heat loads at different temperatures (the thermal conductivity of stainless is higher at 77 K than 20 K and nitrogen has a higher slope of the saturation temperature vs. pressure at the same differential pressures). It is interesting that previously, this has been noted by multiple researchers, each with a reason to doubt their data [5, 6]. However, it has also been shown that perhaps the wavelength dependant emissivity and temperature dependant reflectivity of insulation could account for the differences [6, 7].

However, with the six different sensors, it was useful to compare the sensors to each other. As such, a statistical approach was taken to determine how similar the sensors behaved as a group to understand the relative uncertainty using the sensors without a specific calibration.

4.1. Statistical investigation of calorimeter results
A statistical approach was outlined to assess the similarity of the performances of the sensors at low temperatures. Since the sensors chosen were those furthest from the mean of the manufacturing lot, similarity between these sensors should indicate similarity across the lot. Statistical approaches taken are outlined in ASTM E-2586 [8]. The sensor voltage is plotted in figure 5, where the plot is sized such that the difference between sensors as the lower heat fluxes is relevant. It can be seen that there are observable differences between the test data and the room temperature zero heat flux case. The statistical data is shown in table 8. While the statistical uncertainty is much higher than desired, it does provide an order of magnitude answer as well as a baseline for comparison across the multiple SHIIVER tests.

![Figure 5. Sensor voltages for each test sorted by test scenario, enlarged to allow visualization of low heat flux test results.](image-url)
Table 8. Statistical analysis of sensor voltages.

|          | Average   | Min      | Max      | St. Dev   | Range    | Uncertainty |
|----------|-----------|----------|----------|-----------|----------|-------------|
| Phase 1A | -1.97E-03 | -3.46E-03| -3.89E-04| 8.42E-04  | 2.62E-03 | -66%        |
| Phase 1B | -1.26E-03 | -2.46E-03| -6.53E-04| 6.31E-04  | 1.81E-03 | -71%        |
| Phase 2A | -5.56E-04 | -7.61E-04| -6.53E-04| 1.28E-04  | 3.33E-04 | -30%        |
| Phase 2B | -6.00E-04 | -1.10E-03| -3.47E-04| 2.67E-04  | 7.58E-04 | -63%        |
| Phase 3  | -9.37E-03 | -1.34E-02| -6.73E-03| 2.48E-03  | 6.65E-03 | -36%        |
| Room Temp| -3.52E-04 | -3.75E-04| -3.27E-04| 1.92E-05  | 4.82E-05 | -7%         |

5. Conclusions
Heat flux sensors were demonstrated to work at temperatures as low as 20 K. ASTM C-1130 proved to be workable at cryogenic temperatures, but took much longer due to the required use of a thermal insulator between the two copper plates. The results from C-1130 testing showed the sensors to have a cryogenic linear sensitivity very similar to the room temperature values with a zero-flux offset. While there is some concern with the general repeatability of the sensors, they were shown to be in general in line with each other when tested on a flat plate calorimeter with magnitudes approximately in line with the measured heat load. Uncertainty with the heat load onto the flat plate calorimeter prevented a more thorough investigation of the data. As a result of the testing, 16 sensors were installed onto the SHIVER tank for testing expected to begin the summer of 2019. The sensors will provide both a check on the calculated heat flux once removing all the structural heat loads as well as a check between tests to look for damage incurred from the acoustical testing of the test hardware.

6. References
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