IOP Conference Series: Materials Science and Engineering

PAPER • **OPEN ACCESS**

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To cite this article: M Vanderlaan *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **278** 012195

IOP Conf. Series: Materials Science and Engineering **278** (2017) 012195 doi:10.1088/1757-899X/278/1/012195

Repeatability Measurements of Apparent Thermal Conductivity of Multilayer Insulation (MLI)

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Abstract: This report presents and discusses the results of repeatability experiments gathered from the multi-layer insulation thermal conductivity experiment (MIKE) for the measurement of the apparent thermal conductivity of multi-layer insulation (MLI) at variable boundary temperatures. Our apparatus uses a calibrated thermal link between the lower temperature shield of a concentric cylinder insulation assembly and the cold head of a cryocooler to measure the heat leak. In addition, thermocouple readings are taken in-between the MLI layers. These measurements are part of a multi-phase NASA-Yetispace-FSU collaboration to better understand the repeatability of thermal conductivity measurements of MLI. NASA provided five 25 layer coupons and requested boundary temperatures of 20 K and 300 K. Yetispace provided ten 12-layer coupons and requested boundary temperatures of 77 K and 293 K. Test conditions must be met for a duration of four hours at a steady state variance of less than 0.1 K/hr on both cylinders. Temperatures from three Cernox® temperature sensors on each of the two cylinders are averaged to determine the boundary temperatures. A high vacuum, less than 10^{-5} torr, is maintained for the duration of testing. Layer density varied from 17.98 – 26.36 layers/cm for Yetispace coupons and 13.05 – 17.45 layers/cm for the NASA coupons. The average measured heat load for the Yetispace coupons was 2.40 W for phase-one and 2.92 W for phase-two. The average measured heat load for the NASA coupons was 1.10 W. This suggests there is still unknown variance of MLI performance. It has been concluded, variations in the insulation installation heavy effect the apparent thermal conductivity and are not solely dependent on layer density.

1. Introduction

In space exploration there is a need for high performance insulation to reduce the heat load to vessels containing cryogens for fuel and respiration. Multilayer insulation (MLI) is chosen for these applications due to its high performance in blocking radiation heat transfer in vacuum environments where, due to there being no medium, radiation dominates. No wide range study has been performed to determine the thermal performance repeatability of MLI and how the performance varies between supposedly identical coupons and between installations of the same coupon.

2. Test series

In collaboration with NASA's Glenn Research Center (GRC), FSU has measured two series of MLI coupons. The first test series was performed with a set of five supposedly identical 25-layer coupons manufactured at GRC. The second series was performed with a set of ten supposedly identical 12-layer coupons manufactured by Yetispace. All coupons where installed using MLI installation guidelines ASTM C740 [1] section 6.2 and analyzed using MLI testing guidelines ASTM C1774 [2] section 6.3.

All tests require the following testing specification and requirements. The cold boundary temperature average shall be +/- 3 K from the desired temperatures. The warm boundary temperature shall be +/- 2 K from the desired temperatures. The warm boundary shall be within 0.5 K of the average warm boundary temperature throughout testing. The vacuum pressure shall be maintained below 10^{-5} torr while system is cold. A minimum of two temperature sensors on both the cold and warm boundaries shall be functional at all times during testing. Steady state for these tests is defined as a temperature rate of change less than 0.1 K/hr for all temperature readings during a minimum of 4 hours with less than 3 % variation of the heat load.

To help install the MLI, structural supports were designed to hold the MLI while it is being taped together. Figure 1 shows their function. Installation technicians were chosen based on availability.

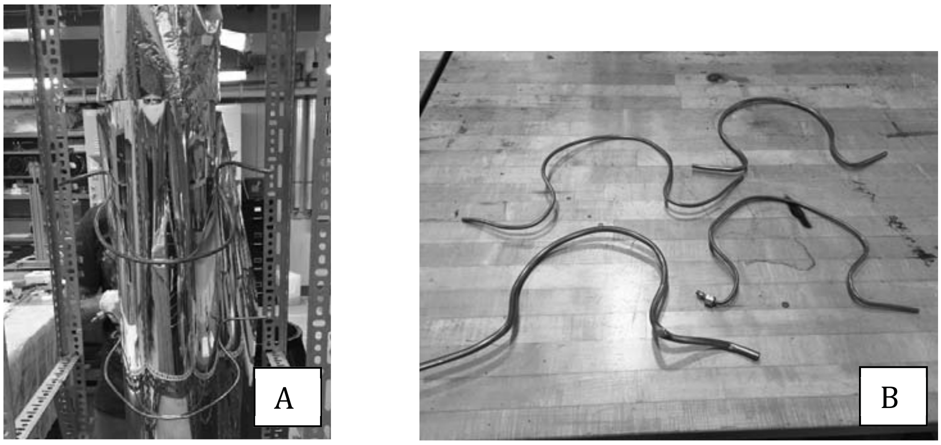

Figure 1. Structural supports hold the MLI in place during installation (A) and individually (B).

2.1 GRC MLI coupons

Five MLI coupons were provided by GRC. Each coupon has 25 layers of alternating double-aluminized 0.25-mil Mylar and two sheets of B2A Dacron® netting. A jacketing sheet made of a thicker aluminized Mylar with a woven back covers the front and back of the alternating layers. Nylon clothes tags are punched through the layers to hold them together. The blankets were cut to fit the multi-layer insulation thermal conductivity experiment (MIKE) and are 121.9 cm long and have an average width of 69.9 cm that increase in steps toward the outer layer to account for an increase in blanket circumference from the first to final layer.

Installation of these blankets includes overlapping the two sides of the coupon along the seam. The Mylar layer is overlapped in the same way and taped together approximately every 30.5 cm. Circumference measurements were made in five equally spaced locations and averaged to determine the coupon thickness, which is then used to calculate layer density.

The NASA test series (Table 1) uses five coupons at temperature boundaries of 20 K and 300 K. Coupons 1 - 5 were each tested once and then coupon 3 was repeatedly tested four additional times. Each time the coupon is fully un-installed and re-installation between tests. Table 1 shows the desired temperatures, test ID, coupon number, and the technician that installed and ran the test. Phase II of NASA coupon testing is not yet complete and will be presented at a later time.

2.2 Yetispace MLI coupons

Ten coupons were provided by Yetispace in two phases. Phase 1 consists of Y1 –Y5 and tests coupons 1 – 5 and phase 2 consists of Y6 –Y10 and tests coupons 6 – 10 (Table 2). Each coupon has 12-layers of alternating quarter mil Mylar and two layer of B2A Dacron netting. A thicker aluminized Mylar covers the front and back layers. No nylon clothing tags were used to hold together the layer so paper binders were used along the outside edge to keep the layer together. The blankets were cut to fit MIKE and are 121.9 cm long and 64.0 cm in width. Additional MLI was applied to cover small exposed sections of the cold cylinder to block the line of sight to the warm cylinder without it making contact with the cold cylinder or testing coupon.

Table 1. NASA test series phase 1

Test ID	Coupon #	Cold temperature Boundary (K)	Warm temperature Boundary (K)	Operator	Cryocooler
N1	1	20	300	Technician 1	CryoMech PT-810
N2	2	20	300	Technician 1	CryoMech PT-810
N3	3	20	300	Technician 1	CryoMech PT-810
N4	4	20	300	Technician 1	CryoMech PT-810
N5	5	20	300	Technician 1	CryoMech PT-810
N6	3	20	300	Technician 1	CryoMech PT-810
N7	3	20	300	Technician 1	CryoMech PT-810
N8	3	20	300	Technician 1	CryoMech PT-810
N9	3	20	300	Technician 1	CryoMech PT-810

The Yetispace coupons were overlapped at the seam and taped similar to the GRC coupons. In addition Kevlar® thread was used to tie the Dacron mesh together every 6 to 8 inches, which increased installation time. Even though the Yetispace coupons had approximately half as many layers as the GRC coupons, they took longer to install. The ties also would create uneven bumps in the coupon. These bumps caused slightly more variation in diameter measurements and may have caused a local layer density reduction.

The Yetispace test series requires the same boundary temperatures for all tests, 77 K and 293 K. The Cryocooler was changed to an AL-230 after the PT-60 got contaminated during a helium recharge.

Table 2. Yetispace test series phase 1 and 2

Test ID	Coupon #	Cold temperature Boundary (K)	Warm temperature Boundary (K)	Operator	Cryocooler
Y1	1	77	293	Technician 1	CryoMech PT-60
Y2	2	77	293	Technician 2	CryoMech PT-60
Y3	3	77	293	Technician 2	CryoMech PT-60
Y4	4	77	293	Technician 2	CryoMech PT-60
Y5	5	77	293	Technician 2	CryoMech AL-230
Y6	6	77	293	Technician 3	CryoMech AL-230
Y7	7	77	293	Technician 3	CryoMech AL-230
Y8	8	77	293	Technician 3	CryoMech AL-230
Y9	9	77	293	Technician 3	CryoMech AL-230
Y10	10	77	293	Technician 3	CryoMech AL-230

3. Apparatus

The apparatus to measure the apparent thermal conductivity of multilayer insulation was created at FSU [3]. This calorimeter utilizes cooling from a cryocooler rather than a cryogen, which allows for more variability in boundary conditions and avoids the use of cryogens. A schematic of the calorimeter is shown in Figure 2.

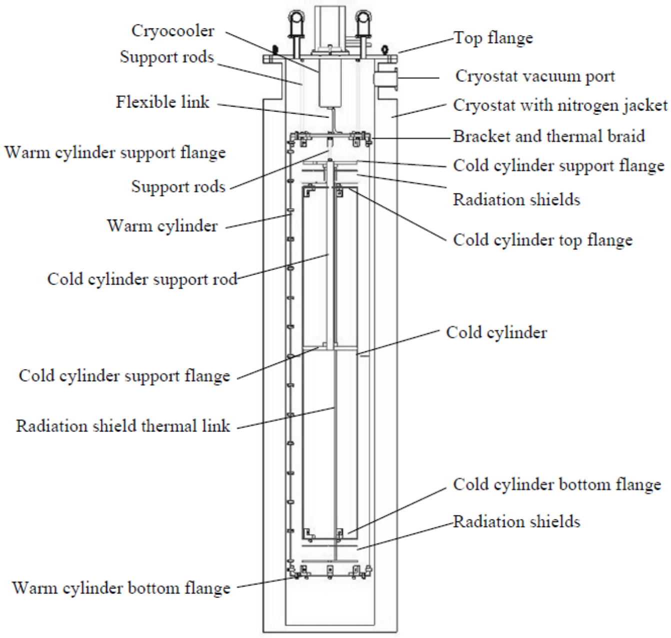

Figure 2. Multi-layer insulation thermal conductivity experiment schematic [3]

The total heat transfer through the blanket is measured by two temperature sensors spaced apart along the cold cylinder support rod. This rod is calibrated at various temperatures by applying a known heat to the rod to determine the calibration parameter in Fourier's Law

$$Q = \theta \cdot \Delta T \quad (1)$$

where Q is the calculated heat, ΔT is the measured temperature difference, and θ is the calibration parameter, which includes the thermal conductivity, rod length, and rod cross-sectional area ($\theta \equiv kA/L$). An error analysis of this calorimeter has shown accuracy of heat load measurements on the order of 1 – 2 % depending on the temperature [4]. The sensitivity of CX-1070 Cernox® goes up at lower temperatures.

The NASA Test Series Phase I specifies a low boundary temperature of 20 K, which required a calibration of the cold cylinder support rod. Due to the temperature dependence of the mean scattering time, there should be a local maximum in the thermal conductivity of 100 RRR copper around 20 K [5]. Figure 3 shows new lower temperature measurements of the rod thermal conductivity were added to the previous calibration [3]. Thermal conductivity reference of 50 RRR and 100 RRR are added for comparison. OFHC 101 copper was used to fabricate the rod, which should have a RRR value between 50 and 700[6]. In figure 3 it appears the rod Cu purity is approximately 80 RRR.

Before the either test series began the cryostat thermometer wiring was rewired using high resistance manganin wire (to reduce thermal leaks) in twisted pairs (to reduce noise) and heat sunk to the cold head (to further reduce thermal leaks).

Before turning on the cryocoolers and reducing the temperature inside the cryostat, the experimental pressure space is evacuated to a pressure below 10^{-5} torr. This pressure limit is below the free molecular regime and the measured heat load has been previously verified to be independent of pressure below this limit [7].

A plot of measured temperatures on the cold cylinder during test ID Y1 is shown in Figure 4. Temperature variation in a single sensor is small compared to variations of temperature of the cold cylinder. The cold middle cylinder is the coldest because it is closest to the cold head. Average cylinder temperature was determined by first averaging the temperature given by a single sensors and then by averaging all the sensors temperature average into one cylinder average.

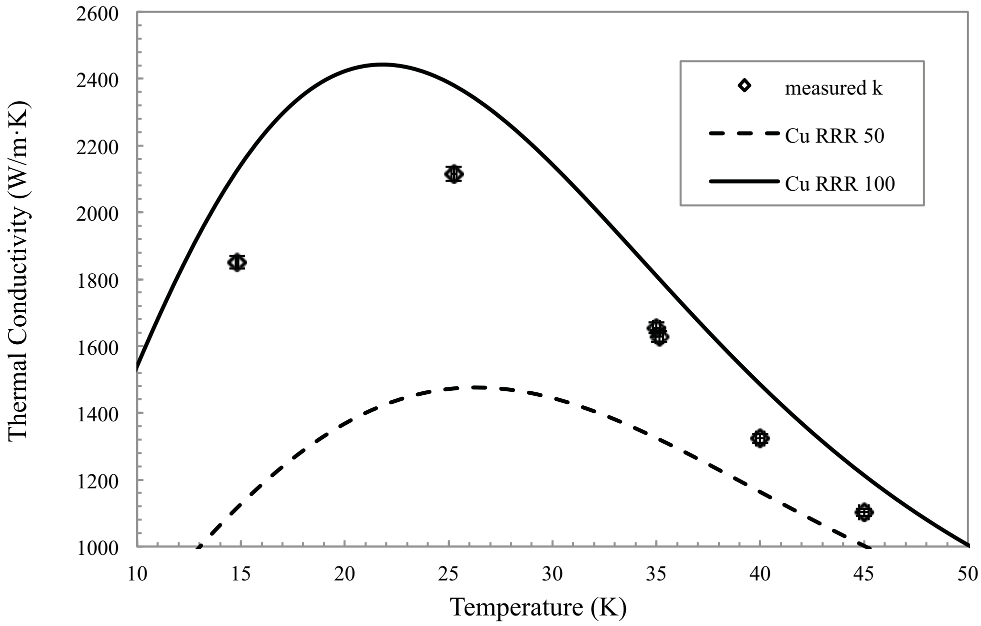

Figure 3. Thermal conductivity of calibrated Cu rod [3] and references or Cu 50 RRR and Cu 100 RRR [6]

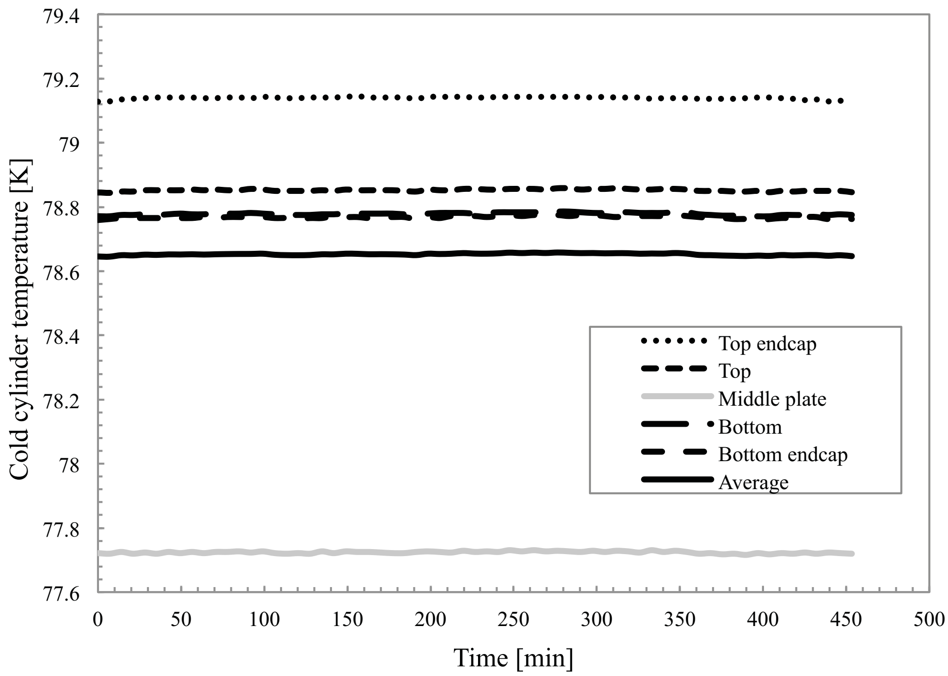

Figure 4. Cold cylinder temperatures during the steady state section of test ID Y1

4. Results

The total heat load error and layer density error is the sum in quadrature for the measurement error and statistical error (standard deviation). A detail examination of the statistical error and relevance is presented in a separate paper in these same proceedings [8].

4.1 GRC coupon results

The first NASA test series boundary temperatures were 20 K for the cold boundary and 300 K for the warm boundary. Due to the unknown heat load and the large temperature difference the PT810 cryocooler was incorrectly identified as being able to meet these boundary specifications. The lowest possible temperature achievable was then used as the new cold boundary temperature goal. In Table 3, the cold boundary temperature varied from 23 K to a little above 27 K with errors of 0.5 K or less. The warm boundary had a smaller range of 298 K to a little above 300 K with errors of about 1 K. Heat loads varied from 0.98 W to 1.27 W for different coupons and varied from 0.98 to 1.15 W in the same coupon (coupon 3). Heat load error of any run was less than 3 %. Unfortunately the coupon circumference was not measured on the first three tests.

Table 3. Measured boundary temperatures, heat loads, and layer density for NASA Phase I

Test ID	Coupon #	Cold temperature boundary (K)	Warm temperature boundary (K)	Heat load (W)	Layer density (layer cm^{-2})
N1	1	24.3 ± 0.3	300.2 ± 0.7	1.16 ± 0.02	-
N2	2	26.7 ± 0.4	300.4 ± 1.0	1.12 ± 0.02	-
N3	3	24.5 ± 0.5	298.0 ± 1.0	1.11 ± 0.02	-
N4	4	26.9 ± 0.4	299.0 ± 1.0	1.27 ± 0.02	17.45 ± 0.07
N5	5	27.2 ± 0.4	300.2 ± 1.0	1.08 ± 0.02	15.65 ± 0.22
N6	3	28.3 ± 0.3	299.3 ± 1.0	0.98 ± 0.02	13.05 ± 0.13
N7	3	23.4 ± 0.4	300.4 ± 1.0	1.15 ± 0.02	15.31 ± 0.10
N8	3	25.6 ± 0.4	300.2 ± 1.0	1.05 ± 0.03	13.22 ± 0.20
N9	3	25.6 ± 0.4	299.2 ± 1.0	1.03 ± 0.02	13.97 ± 0.16

Table 4. Measured boundary temperatures, heat loads, and layer density for Yetispace

Test ID	Coupon #	Cold temperature Boundary (K)	Warm temperature Boundary (K)	Heat load (W)	Layer density (layer/cm)
Y1	1	78.7 ± 0.4	292.4 ± 1.3	2.31 ± 0.05	22.38 ± 0.06
Y2	2	79.4 ± 0.3	292.3 ± 1.2	2.05 ± 0.05	22.81 ± 0.27
Y3	3	79.4 ± 0.3	292.6 ± 0.9	2.80 ± 0.06	21.96 ± 0.07
Y4	4	78.5 ± 0.3	291.5 ± 0.9	2.23 ± 0.05	17.98 ± 0.12
Y5	5	79.0 ± 0.3	291.9 ± 0.6	2.61 ± 0.06	23.26 ± 0.35
Y6	6	78.4 ± 0.3	291.7 ± 0.6	2.22 ± 0.05	24.20 ± 0.28
Y7	7	79.7 ± 0.4	291.5 ± 0.4	2.82 ± 0.06	25.24 ± 0.33
Y8	8	75.8 ± 0.3	291.8 ± 0.6	2.89 ± 0.07	23.26 ± 0.27
Y9	9	76.0 ± 0.4	292.8 ± 0.5	3.36 ± 0.07	26.36 ± 0.32
Y10	10	78.4 ± 0.4	291.7 ± 0.5	3.35 ± 0.09	22.38 ± 0.25

4.2 Yetispace coupon results

All Yetispace test used temperature boundaries of 77 K for the cold boundary and 293 K for the warm boundary. The cold temperature boundaries ranged from 75.8 K to 79.7 K with an error of 0.4 K or less. In Table 4, the warm boundaries ranged from 291.5 K to 292.6 K had a range of error from ± 0.4 K to ± 1.3 K. This variation in error comes from the standard error of the warm temperature sensors. High thermal conductivity copper was used in the boundary cylinders to create a uniform temperature, but variations between sensors were still measured and accounted for in the error. Heat loads varied from 2.05 W to 3.35 W and have errors of less than 3 %.

Interlayer measurements were made using type E thermocouples attached to the coupon with aluminum tape to layers 4 and 8 of each Yetispace coupon (Table 5). All interlayer temperatures have errors of ± 1.7 K. the warm and cold boundary temperature are the same as Table 3.

Table 5. Measured interlayer temperatures in Yetispace coupons

Test ID	WB (K)	L4 (K)	L8 (K)	CB (K)
Y1	292.4	254.3	230.2	78.7
Y2	292.3	248.9	230.1	79.4
Y3	292.6	236.5	210.7	79.4
Y4	291.5	243.9	224.0	78.5
Y5	291.9	250.8	235.3	79.0
Y6	291.7	248.9	227.7	78.4
Y7	291.5	243.2	216.0	79.7
Y8	291.8	243.1	216.7	75.8
Y9	292.8	244.4	214.8	76.0
Y10	291.7	238.6	214.6	78.4

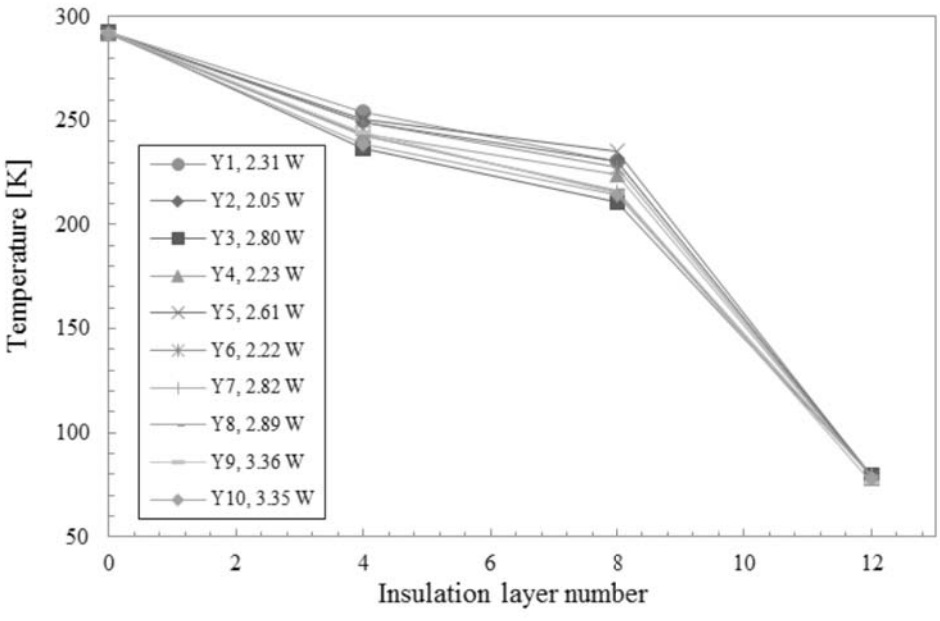

Figure 5. Temperature profile through the MLI

A temperature profile through the coupon is shown in Figure 5. Variations in the warm and cold boundary are small compared the temperature variation inside the coupon. Lines are not used to predict the temperature profile but rather as a guide to connect data from the same coupon. The layer 4 temperature ranged from 236 K to 254 K and layer 8 temperatures ranged from 210 K to 235 K. The largest temperature gradient is near the cold boundary while the smallest temperature gradient was between layers 4 and 8. This could possibly be due to contact resistance between the coupon and the boundary cylinder.

5. Conclusion

The apparent thermal conductivity of fifteen separate coupons was successfully measured in nineteen tests. The calibration rod should be recalibrated after the completion of phase 2 for the GRC coupons to make sure the calibration did not change. Adding a top and bottom radiation shield with a lip may further reduce any small heat leaks to the cold cylinder near the ends of the coupon.

6. References

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Acknowledgements

The authors would like to thank our collaborators Wesley Johnson at NASA-GRC and Jessica Wood at Yetispace, Inc. This research is funded by Yetispace, grant# 227000-524-037894 and NASA, grant# 227000-520-036577. This work was performed at the National High Magnetic Field Laboratory, which is supported by NSF DMR-1157490 and the State of Florida.