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Repeatability of Cryogenic Multilayer Insulation

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Abstract. Due to the variety of requirements across aerospace platforms, and one off projects, the repeatability of cryogenic multilayer insulation (MLI) has never been fully established. The objective of this test program is to provide a more basic understanding of the thermal performance repeatability of MLI systems that are applicable to large scale tanks. There are several different types of repeatability that can be accounted for: these include repeatability between identical blankets, repeatability of installation of the same blanket, and repeatability of a test apparatus. The focus of the work in this report is on the first two types of repeatability. Statistically, repeatability can mean many different things. In simplest form, it refers to the range of performance that a population exhibits and the average of the population. However, as more and more identical components are made (i.e. the population of concern grows), the simple range morphs into a standard deviation from an average performance. Initial repeatability testing on MLI blankets has been completed at Florida State University. Repeatability of five Glenn Research Center (GRC) provided coupons with 25 layers was shown to be +/- 8.4% whereas repeatability of repeatedly installing a single coupon was shown to be +/- 8.0%. A second group of 10 coupons has been fabricated by Yetispace and tested by Florida State University, the repeatability between coupons has been shown to be +/- 15-25%. Based on detailed statistical analysis, the data has been shown to be statistically significant.

1. Introduction

Testing of multilayer insulation (MLI) is a complex process that requires high vacuum conditions and cryogenic boundary temperature which can take a relatively long time to establish. [1,2] Due to the anisotropic properties of MLI (the thermal resistance normal to the blanket is much higher than in the plane of the blanket), proper testing cannot really be done on bench top scale measurement devices, rather chambers for testing are usually at least a meter in one direction to mitigate edge effects. These testing complexities along with the variety of requirements work together to expand the test matrix and test schedule (and thus cost) of any attempted comprehensive test program beyond reasonable measures.

There are several different types of repeatability that can be accounted for. These include repeatability between multiple identical blankets, repeatability of installation of the same blanket, and repeatability of a test apparatus. The focus of the work in this report is on the first two types of repeatability.

Due to the variety of requirements across aerospace platforms, the repeatability of MLI has never been fully established. One study which comes close is a Lockheed effort to produce 10 identical solid methane cryostats. [3] After the performance of the first five cryostats was found to be unsatisfactory, improvements were made and the thermal performance of the last five units were within 25% of each other. However, this performance includes the entire system and not just the MLI system. In another work, Stimpson mentions the repeatability of some coupons being in the 5 – 10% range, but does not go into detail as to the design or numbers of the coupons. [4] The objective of this test program is to provide a more basic understanding of the thermal performance repeatability of MLI systems that are applicable to large scale tanks.

Statistically, repeatability can also mean many different things. In simplest form, it refers to the range of performance that a population exhibits and the average of the population. However, as more and more identical components are made (i.e. the population of concern grows), the simple range morphs into a standard deviation from an average performance.

2. Test Setup

Two different test series were to be run. The first involved coupons provided by NASA directly to Florida State University and the second was under contract to Yetispace who also chose to partner with Florida State University for testing. The main difference between the two sets of coupons was the number of layers. NASA provided 25 layer coupons and Yetispace 10 layer coupons.

2.1. NASA provided test coupons

Previously, NASA had procured 6 identical blankets for similar repeatability testing at GRC. However, the liquid hydrogen calorimeter at Glenn Research Center (GRC) [5] was found to have many irreparable leaks and was scrapped. The blankets were put into storage in 2010. The summer of 2015, the blankets were pulled out again to be modified for this testing.

Each of the blankets was originally 26 layers of quarter mil double aluminized mylar with two layers of B2A Dacron netting in between each layers of double aluminized mylar. The blankets were held together by nylon clothes tags spaced at approximately 12 inches and had Velcro on the inner layers to aid in attachment to the calorimeter. A cover layer of aluminized mylar with a woven backing was added to each side for improved handling characteristics. Average coupon layer density was between 13 and 17 layers per cm.

The original blankets were 1.5 m long and 2.44 m wide. As the Multilayer Insulation Calorimetry Experiment (MIKE) calorimeter at Florida State was to be used [6], the blankets needed to be cut down to fit the smaller test cylinder of approximately 1.2 m long and 197 mm diameter. In order to allow for the increasing diameter of each layer, while still using a blanket, the layers were cut to length in groups of 4 – 6 layers to keep the overlap of each layer between 12 – 37 mm. Instrumentation within the blanket, while originally built in, was not used during testing.

2.2. Yetispace provided test coupons

Yetispace designed and built 10 coupons as two sets of five. Each set of five was from the same material lots and were constructed at the same time, the two sets were constructed several months apart and by different technicians. The blankets were all 12 reflectors of quarter mil mylar, each separated by two layers of B2A Dacron netting. 5 mil aluminized coversheets were used to improve handling characteristics. Type E thermocouples were installed on layers 4 and 8, 180 degrees from the seam. Nominal thickness of the blankets were approximately 0.5 cm thick (a layer density approaching 24 layer/cm). The seams were to be matched at each layer, with the netting sewn together with knots approximately 20 cm apart. The sewing effected the general layup of the blankets, which is fully discussed by Vanderlaan and Stubbs. [7]

The blankets were built to fit on the MIKE calorimeter at Florida State University. All coupon fabrication was performed by Yetispace in their controlled work area.

2.3. Test matrix

The original testing on the NASA coupons was to provide data relevant to liquid hydrogen systems, both in environments close to room temperature and at low temperatures. The test matrix for the NASA coupons is shown in Table 1 and the test matrix for the Yetispace coupons is shown in Table 2.

Table 1: Repeatability Test Matrix for NASA coupons

Test ID	Coupon #	Tc (K)	Th (K)
N1	1	20	293
N2	2	20	293
N3	3	20	293
N4	4	20	293
N5	5	20	293
N6	3	20	293
N7	3	20	293
N8	3	20	293
N9	3	20	293
N10	1	20	100
N11	2	20	100
N12	3	20	100
N13	4	20	100
N14	5	20	100
N15	2	20	100
N16	2	20	100
N17	2	20	100

3. Test Results

The GRC provided coupons have gone through the first half of testing (Tests N1-N9). The Yetispace coupons have finished testing. All repeatability testing was performed at Florida State University (FSU), using the MIKE calorimeter. [6] The calorimeter was recently assembled for use at FSU and has undergone a full uncertainty analysis. Measurement of the heat load is based on conduction down a machined rod that has two temperature sensors on it. The temperature gradient between the two sensors and the known geometry can be used to calculate heat load. However, it is better to use a known heat source to calibrate the rod. In this case, the known heat load is applied and the temperature gradients measured. When multiple different heat loads are applied, a curve for system performance as a function of the temperatures can be developed. Results from the analysis show the uncertainty to range between 1% and 2% depending on the temperature of the measurement rod.

Table 2: Repeatability Test Matrix for Yetispace Coupons

Test Series	Coupon #	Tc (K)	Th (K)
Y1	1	77	293
Y2	2	77	293
Y3	3	77	293
Y4	4	77	293
Y5	5	77	293
Y6	6	77	293
Y7	7	77	293
Y8	8	77	293
Y9	9	77	293
Y10	10	77	293

3.1. Testing between 20 K and 300 K
The first five tests used all five GRC provided coupons and tested each at the same conditions, then coupon 3 was repeated four more times. The test data is reported by Vanderlaan and Stubbs. [7] The data is shown graphically in Figure 1. The layer density was only calculated for a few of the tests, however, the plot of performance versus layer density is shown in Figure 2.

3.2. Testing between 77 K and 293 K
The testing of all ten coupons provided by Yetispace was completed. The test data is reported by Vanderlaan and Stubbs. [7] Figure 3 shows the coupon performances as a function of layer density.

4. Discussion of Results
In order to assess the statistical bearing of the data several steps are needed. First the typical statistical values such as mean (or average), range, and standard deviation can be calculated. The uncertainty was divided by two to give it as a "plus or minus" value. The results of these calculations have been shown in Table 3.

$$\dot{Q}_{mean} = \frac{\sum_{i=0}^{n} \dot{Q}_i}{n} \tag{1}$$

$$\dot{Q}_{st.dev} = \sqrt{\frac{\sum_{i=0}^{n} (\dot{Q}_i - \dot{Q}_{mean})^2}{n}} \tag{2}$$

$$\dot{Q}_{uncer} = \frac{\dot{Q}_{max} - \dot{Q}_{min}}{2\dot{Q}_{mean}} \tag{3}$$

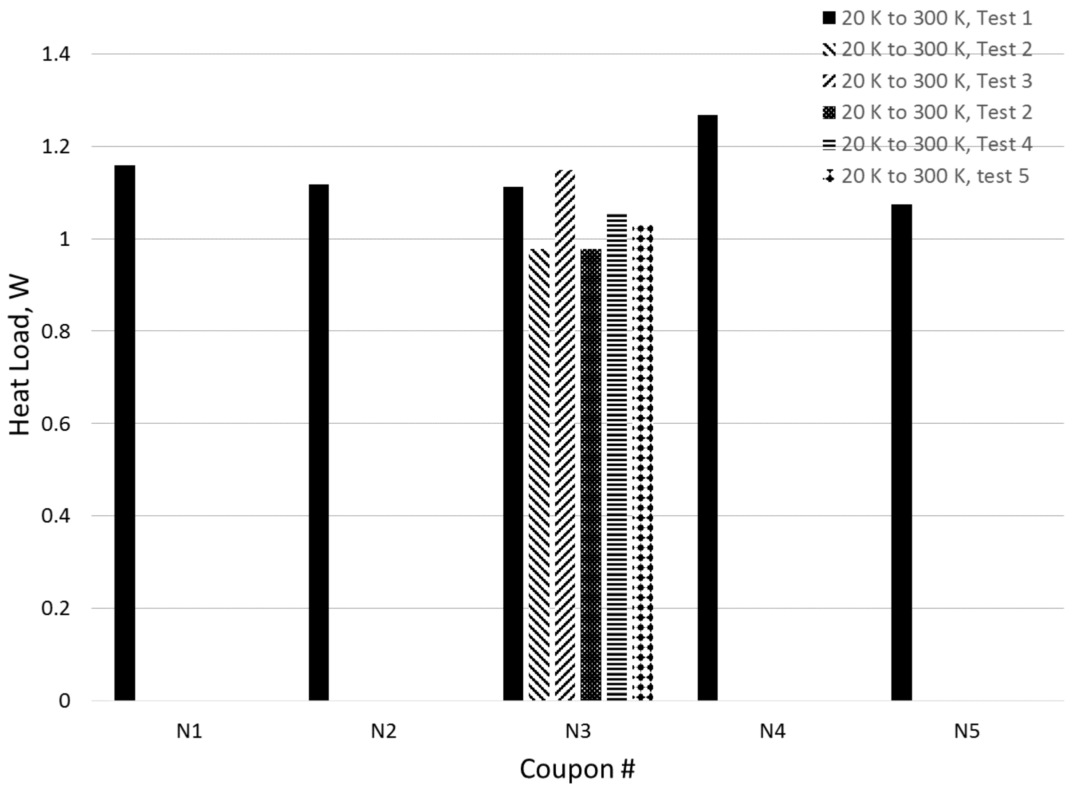

Figure 1: All 20 K to 300 K test data on GRC coupons.

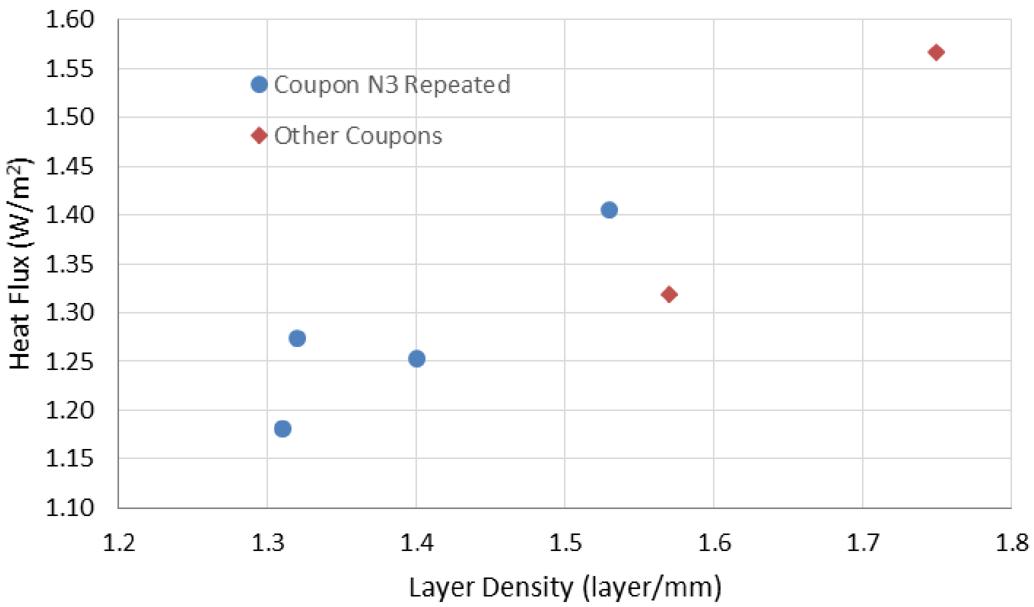

Figure 2: Heat load versus layer density for several installed coupons (outer diameter from which layer density is derived was not measured for all tests).

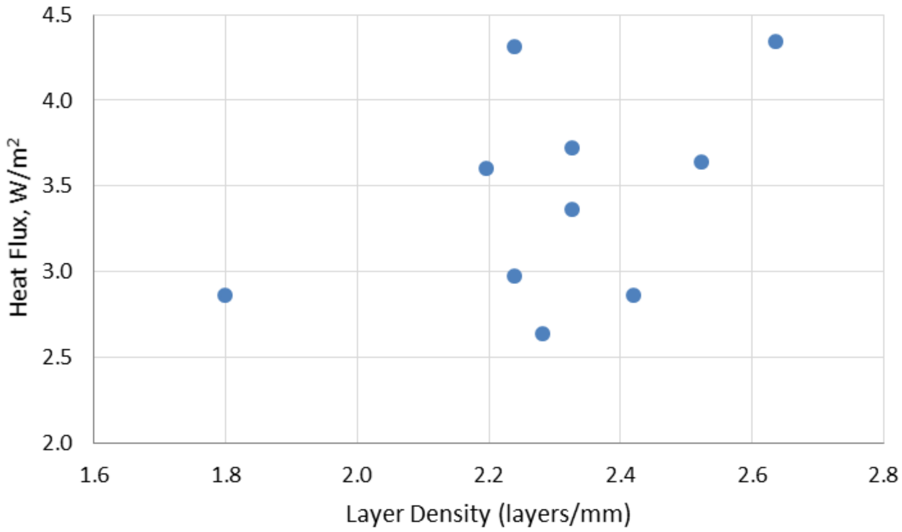

Figure 3: Yetispace coupon data as a function of layer density.

Table 3: Traditional statistical measures.

Test Series	Mean, W	Min, W	Max, W	St. Dev, W	Range, W	Uncertainty
20 K to 300 K, All Five	1.15	1.08	1.27	0.066	0.19	+/-8.4%
20 K to 300 K, Coupon 3	1.06	0.98	1.15	0.061	0.17	+/-8.0%
77K to 293K, First Five	2.40	2.05	2.80	0.27	0.75	+/- 15.6%
77 K to 293 K, Second Five	2.93	2.22	3.36	0.42	1.14	+/- 19.5%
77 K to 293 K, All ten	2.66	2.05	3.36	0.44	1.31	+/- 24.6%

Using ASTM E-2586, further analysis can be done to substantiate the traditional statistical analysis. [8] The authors of ASTM E-2586 have performed Monte-Carlo analysis to approximate what the values of the standard deviation should be as well as the range of errors for both the mean and the standard deviation. In the equations below, se() indicates the standard error of that value. The values of each are shown in Table 4. The data is interpreted as statistically significant if the difference between the "calculated" standard deviation and the "measured" standard deviation is less than the standard error of the standard deviation from ASTM E-2586 (as indicated in the last column of Table 4).

$$\dot{Q}_{st.dev,calc} = \frac{\dot{Q}_{max} - \dot{Q}_{min}}{d_2} \tag{4}$$

Where d2 = 2.326 for n = 5 and d2 = 3.078 for n = 10

$$se(\dot{Q}_{mean}) = \frac{\dot{Q}_{st.dev}}{\sqrt{n}} \tag{5}$$

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$$se\left(\dot{Q}_{st.dev}\right) = \dot{Q}_{st.dev}\sqrt{1 - c_4^2} \tag{6}$$

Where c4 = 0.939986 for n = 5 and c4 = 0.972659 for n = 10

Table 4: Advanced statistical calculations

Test Series	**Mean Standard Error, W**	**Mean Standard Error as Percentage**	**Calculated St. Dev, W**	**St. Dev Standard Error, W**	**St. Dev Calc minus Measured St. Dev, W**	**Statistically Significant?**
20 K to 300 K, All Five	0.017	1.2%	0.083	0.023	0.017	YES
20 K to 300 K, Coupon 3	0.015	1.1%	0.074	0.021	0.013	YES
77K to 293K, First Five	0.064	2.7%	0.322	0.092	0.053	YES
77 K to 293 K, Second Five	0.098	3.3%	0.490	0.143	0.071	YES
77 K to 293 K, All ten	0.044	1.6%	0.426	0.102	-0.015	YES

From the 25 layer coupons, it can be noticed that the range for installing and uninstalling the same coupon is not much smaller than five separate coupons (0.193 W for five coupons and 0.171 W for the same coupon five times, a 13% difference). This suggests that a majority of the range of uncertainty (the remaining 87%) is due to a combination of instrument and installation. Since the published uncertainty for the instrument at hand is on the order of 2% (or about 20 mW, the same as the difference between the two ranges), this leaves the remainder of the uncertainty to be attributed to installation and technician touch labor. This is further reinforced by Figure 2, which shows the MLI performance variations as a function of layer density, which is perhaps the variable most affected during installation.

It is curious that the Yetispace coupons in the second batch performed worse than the first batch. However, upon inspection of the coupons after testing, there was no observable difference between the coupons. Additionally, these coupons did not show as strong of layer density trends as the 25 layer coupons (see Figure 3) though the same trend is there, but with more scatter.

The repeatability of the coupons that were 25 layers were higher than those of 10 layers. Intuitively this makes sense as failure of one layer of a ten layer blanket would result in 10% worse thermal performance (theoretically) and failure of one layer of a twenty-five layer blanket would result in 4% worse thermal performance. However, a direct proportionality is not established as only two data points exist.

5. Conclusions

Repeatability testing on traditional MLI blankets has been completed at Florida State University on coupons provided by both Glenn Research Center and Yetispace. Repeatability of five 25 layer coupons was shown to be +/- 8.4% whereas repeatability of installing a coupon was shown to be +/- 8.0%. Comparatively, the 10 layer coupons showed a repeatability between +/- 15% and +/- 25% depending on the data set. Based on more detailed statistical analysis, the data has been shown to be statistically significant.

The repeatability of the data for the reinstallation of the same blanket vs multiple blankets is very similar. This suggests that most of the uncertainty is due to technician hand labor and installation variables (of which layer density is one). Some of the uncertainty appears to be due to variation in final blanket thickness (and resulting layer density). This further suggest that installation labor is the larger source of uncertainty as opposed to design and fabrication of the blankets.

The combined data with 25 layers and 10 layers suggests the repeatability of the blanket is a function of the number of layers. However, a direct proportionality is not established.

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