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Thermal Performance Testing of Cryogenic Multilayer Insulation with Silk Net Spacers

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Abstract. Early comprehensive testing of cryogenic multilayer insulation focused on the use of silk netting as a spacer material. Silk netting was used for multiple test campaigns that were designed to provide baseline thermal performance estimates for cryogenic insulation systems. As more focus was put on larger systems, the cost of silk netting became a deterrent and most aerospace insulation firms were using Dacron (or polyester) netting spacers by the early 1970s. In the midst of the switch away from silk netting there was no attempt to understand the difference between silk and polyester netting, though it was widely believed that the silk netting provided slightly better performance. Without any better reference for thermal performance data, the silk netting performance correlations continued to be used. In order to attempt to quantify the difference between the silk netting and polyester netting, a brief test program was developed. The silk netting material was obtained from Lockheed Martin and was tested on the Cryostat-100 instrument in three different configurations, 20 layers with both single and double netting and 10 layers with single netting only. The data show agreement within 15 – 30 % with the historical silk netting based correlations and show a substantial performance improvement when compared to previous testing performed using polyester netting and aluminum foil/fiberglass paper multilayer insulation. Additionally, the data further reinforce a recently observed trend that the heat flux is not directly proportional to the number of layers installed on a system.

1. Introduction

Early in the development of multilayer insulation (MLI) systems, multiple spacer materials and reflector materials were tested. Different vendors settled on different configurations for manufacturing including using aluminum foil, single aluminized mylar, and double aluminized mylar for reflectors and Dacron tufts, polyester netting, silk netting, and fiberglass paper for spacers [1-4]. For "In-space" applications, eventually double aluminized mylar was settled upon as a consensus reflector, however no consensus in spacer material was developed [5–8]. In the meantime, Lockheed was awarded a contract by NASA for a series of tests to standardize the expected performance of MLI to be used for engineering design. In performing this testing, they used fiberglass paper and silk netting as different spacer materials [8]. As NASA's exploration research continued through the 1980s and 1990s, silk netting was abandoned in favor of the less expensive polyester netting (often referred to as Dacron). Fox, Kiefel, et.al. reported that in 1993, the cost of silk netting was seventeen times higher than polyester netting [9]. While the authors were unable to verify that data point using current prices, they were able to verify a large discrepancy of more than five times the cost, however, the grade of silk netting was not confirmed to be suitable for use in high performance MLI systems. NASA completed multiple test campaigns using a combination of double aluminized mylar and polyester netting [8-11]. The data from these tests always had a significantly higher heat load than was predicted from the correlations previously developed by Lockheed. Lockheed continued to use and perform testing on silk netting due to its established (and presumed slightly better) performance, as the extra cost for small dewars used on science missions was not as significant as the performance benefit [12]. This situation left the aerospace industry in the quandary of having tank-applied MLI data for double aluminized mylar and polyester netting, yet relying on a basic foundational data set built upon double aluminized mylar and silk netting calorimeter testing. There were no comparable data sets between the two material sets and no clear way to assess if the equations developed using silk netting were appropriate for use with polyester netting. At the time there were no means of achieving the desired comparison in a cost effective manner.

2. Experimentation

In order to measure the thermal performance of various insulation systems, NASA Kennedy Space Center's Cryogenic Test Laboratory uses liquid nitrogen boil-off calorimetry for a variety of its instruments. This test program used the Cryostat-100 calorimeter, which is well documented elsewhere [13-15]. Cryostat-100 testing yields absolute thermal performance of the multilayer insulation systems in terms of heat load (Q). The heat load can then be normalized to the logarithmic mean surface area and converted to heat flux (q) in accordance with ASTM C1774, Annex A1. [16]
The objectives of the testing were to measure and compare the thermal performance of silk netting to previously tested polyester netting. Based on these comparisons, the relative performance between the silk netting, polyester netting, and analytical models can be ascertained.

The approach to carrying out the tests was straight forward. The test blankets were built out of previously tested double aluminized mylar sheets (care was taken to ensure no degradation due to previous handling had occured), which were interleaved between the silk netting. Each layer was individually overlapped in order to minimize the effect of seam performance on the test data. A laboratory standard evacuation and bakeout process, including multiple purge cycles with gaseous nitrogen, was performed on all test coupons. In order to maximize utilization of the test time, multiple different warm boundary temperatures (WBT) were used (293 K, 305 K, and 325 K) for better comparison and parameterization of the warm boundary temperature on the first test only. Both high vacuum [$\sim10^{-6}$ torr ($\sim10^{-4}$ Pa)] and degraded vacuum [$\sim10^{-3}$ torr ($\sim10^{-1}$ Pa)] tests were run. In one case no vacuum [760 torr (101 kPa)] tests were also run. While the high vacuum test is mainly of interest for comparisons with the various performance models discussed above, the other vacuum levels serve as points of interest for comparisons with other types or applications of thermal insulation systems. All tests were conducted in cold vacuum pressure (CVP) conditions with a residual gas of nitrogen.

The complete test matrix is shown in Table 1. The first test had 20 layers (n) of double aluminized mylar, each separated by two layers of silk netting. The second and third test had 20 and 10 layers of double aluminized mylar, respectively, that were each separated by a single layer of silk netting. This sequence provided the effect of lowering the layer density (z) from 0.85 layers/mm to 1.3 layers/mm.

Type E thermocouples were placed on selected layers throughout the blankets to provide temperature profiles throughout the thickness of the MLI system. Further details on the preparation steps and nomenclature are found in ASTM C740. [17]

Table 1. Cryostat-100 test matrix and silk netting coupon geometries.

Test Series	# layers [n]	Thickness [x] (mm)	Layer Density [z] (layers/mm)	Effective Area [A_e] (m^2)	CVP Tested (torr)	WBT (K)
A177	20	22.3	0.85	0.343	10^{-6}, 10^{-4}, 10^{-3}, 760	293, 305, 325
A178	20	14.7	1.36	0.330	10^{-6}, 10^{-4}, 10^{-3}	293
A179	10	7.68	1.30	0.318	10^{-6}, 10^{-4}, 10^{-3}	293

3. Results and Discussion

The silk netting results are given in Table 2 and Figure 1. The heat fluxes were in the expected range of approximately 0.3 W/m^2 for the 20 layer tests and just over 0.5 W/m^2 for the 10 layer tests. The difference in the layer density (increase from 0.85 lay/mm to 1.4 layer/mm) caused an increased heat flux of over 10%. Degradation in vacuum level from 4 x 10^{-6} to 1 x 10^{-4} caused nearly a doubling of the heat flux.

The thermocouple data for the layers showed fairly typical temperature profiles through the blanket. The temperature profiles for A177 are shown in Figure 2. As would be expected with radiation heat transfer, the temperature gradient is much steeper closer to the cold boundary. All three warm boundary temperature tests are shown for comparison. The profile gives a curved shape, somewhere between a 2^{nd} and 4^{th} order polynomial.

Table 2. Cryostat-100 test data for MLI systems with silk netting.

Test Series	**CVP (Torr)**	**WBT (K)**	**Q (W)**	**k_e (mW/m/K)**	**q (W/m^2)**
A177	$5*10^{-6}$	293.4	0.105	0.033	0.304
	$1*10^{-4}$	292.5	0.240	0.114	0.696
	$1*10^{-3}$	293.1	0.604	1.00	1.75
	760	284.0	68.9	22.9	200
	$4*10^{-6}$	305.4	0.140	0.042	0.406
	$4*10^{-6}$	325.8	0.185	0.051	0.536
A178	$3*10^{-6}$	293.2	0.113	0.023	0.342
	$1*10^{-4}$	293.0	0.239	0.050	0.724
	$1*10^{-3}$	293.2	0.569	0.117	1.72
A179	$2*10^{-6}$	292.3	0.171	0.019	0.538
	$1*10^{-4}$	293.5	0.246	0.028	0.774
	$1*10^{-3}$	292.8	0.917	0.103	2.884

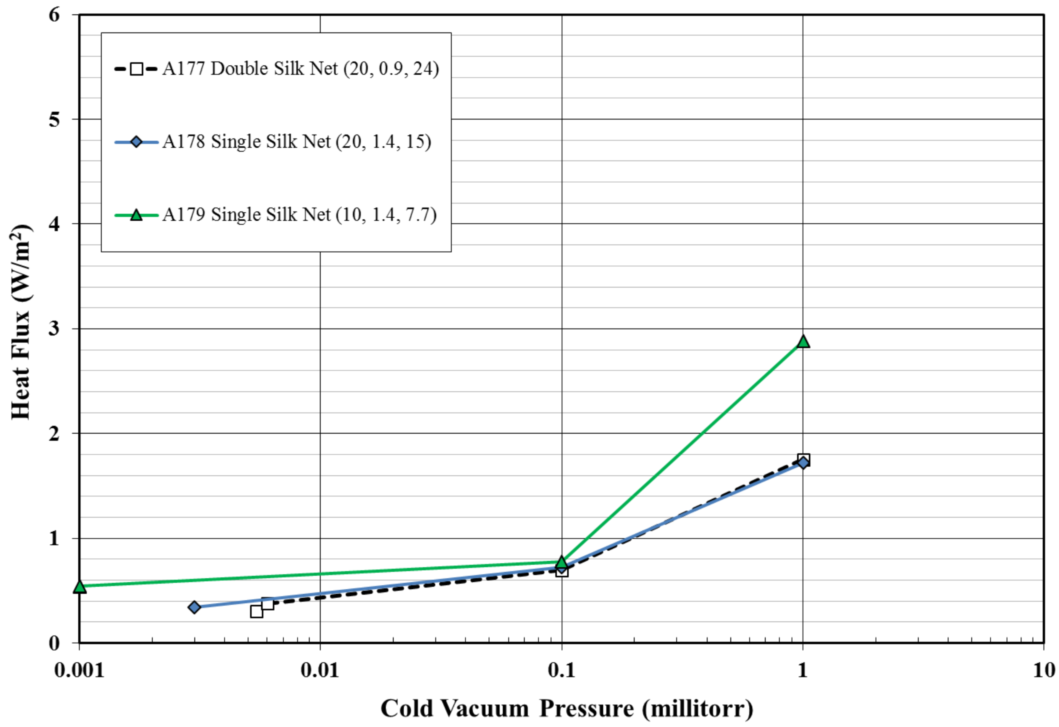

Figure 1. Heat flux (q) as a function of cold vacuum pressure (CVP) for silk netting MLI systems. Legend: (n, z, x).

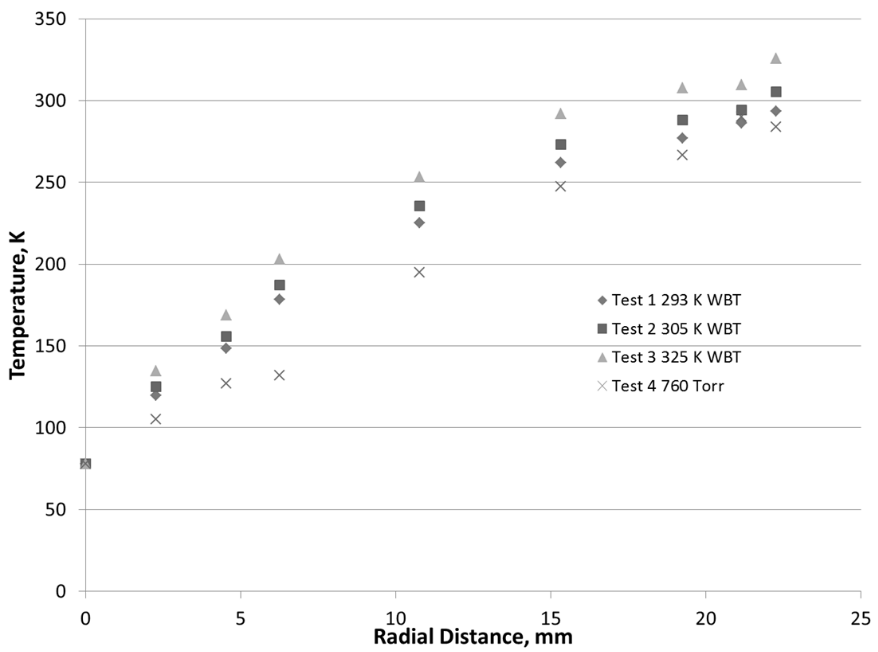

Figure 2. Temperature profiles for test specimen A177 (double silk net).

The silk netting results are compared to polyester netting in both heat load and mass. Table 3 shows that the silk netting when used as a single spacer weighed slightly less than the comparable coupons made with polyester netting [18]. In Table 4, the thermal performance is compared to previous testing performed on Cryostat-100 using many different materials. The silk netting is dramatically better than other material types, with heat fluxes as low as half of that for normal polyester netting. Part of this difference can be attributed to slightly different layer densities and thicknesses; however, the silk netting is still dramatically better across the board, even when accounting for the minor differences.

Table 3. Mass comparison between silk and polyester netting

	Polyester Netting	**Silk Netting**
20 layers (single spacer)	231 g	202 g
10 layers (single spacer)	111 g	105 g

Table 4. Comparison of silk netting and polyester netting thermal performance at high vacuum (all using double aluminized mylar as the reflector material). Comparison data is from reference 18.

Layers	**10 Layers**	**20 Layers**	**20 Layers (double netting)**
Silk netting heat flux (W/m^2)	0.54 (A179)	0.34 (A178)	0.31 (A177)
Polyester netting heat flux (W/m^2)	1.00 (MN154)	0.68 (MN152) 0.37 (60 layers, MN143)	0.53 (MN159) 0.39 (40 layers, MN139)
Polyester fabric heat flux (W/m^2)	0.89 (MF145)		
LB-MLI[a] heat flux (W/m2)	0.92 (MX164)		0.41 (MX142)

[a]Load Bearing MLI (spacers are polymer support posts, not netting or fabric)

Further comparisons of the current data with previous silk netting testing by Lockheed [19] and Stochl [20] are shown in Figure 3. The test data compare well with the previous test data. The current data are slightly better performing than the Stochl data due to the lower layer density as expected. The current data also projects in line with the hallow dot, which was also tested at 290 K. This excellent agreement builds confidence in the calorimeter data. Also of note is the increasing trend shown on the right side of Figure 3 which shows a slightly increasing q*N product (heat flux multiplied by number of layers) with increasing number of layers. This effect was noted by Fesmire and Johnson [17] and is further reinforced here: the heat flux is not inversely proportional with number of layers in a real system as is assumed by most analytical models. The data from this test series is plotted against the previously published data for comparison in Figure 4. Both the LB-MLI and the silk netting show much less propensity for increasing q*N with increasing number of layers, at least on the scale of the previously reported data.

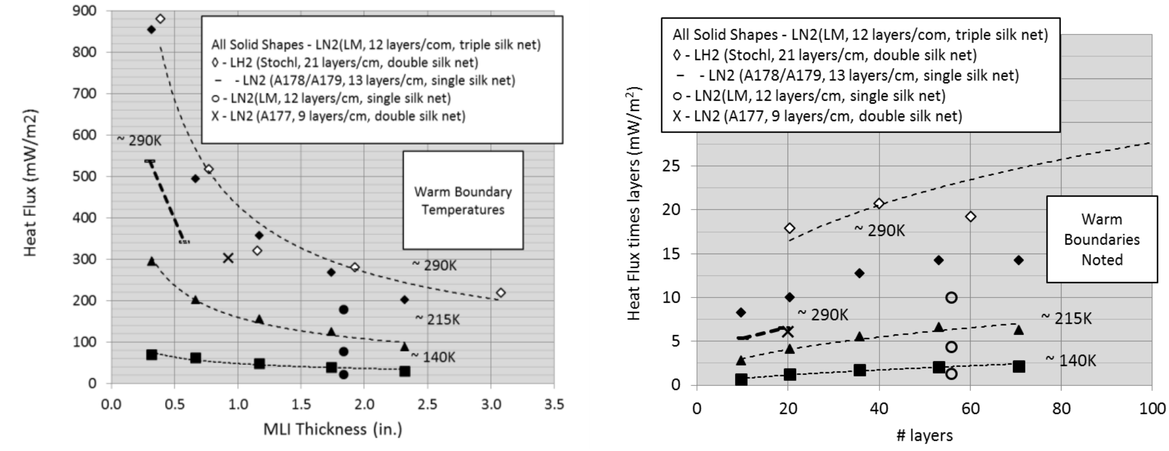

Figure 3. Comparison of Current Data with Historical Data

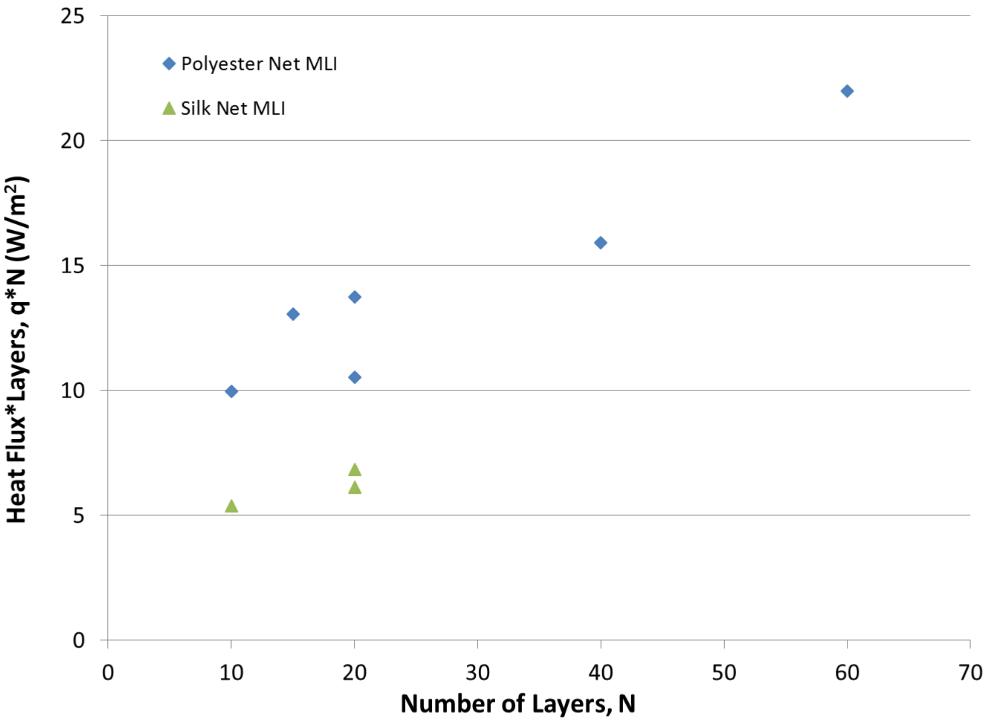

Figure 4. q*N Product versus number of layers for MLI systems.

4. Performance Modelling

In analyzing insulation systems, a widely used MLI equation is the Lockheed Martin Flat Plate equation which includes the effect of boundary temperatures, layer density, and blanket thickness (equation 4-14 of Ref. 7).

$$q = \frac{C_s (z)^{2.56} T_m}{n+1}(T_H - T_c) + \frac{C_r \varepsilon_{RT}}{n}(T_H{}^{4.67} - T_C{}^{4.67})$$

Conduction Radiation

where: q =W/m^2, Cs=8.95E-8, Cr=5.39E-10, z= layers/cm, n = no. of radiation shields, [T] = K, $T_m = (T_H+T_C)/2$, ε_{RT} = room temperature shield emittance (approximately 0.03). This equation was developed with flat plate calorimeter testing using silk net spacers. It includes a conduction and a radiation term and assumes negligible gas conduction. A comparison of the predicted heat flux with the calorimeter tests of this paper is shown in Table 5 below. This work was completed in 1974 and since then a number of tests and analyses have produced variants of coefficients for different materials and layups of the blankets. The heat flux for a silk net spacer system with double aluminized Mylar is lower than that for a system utilizing Dacron netting.

Table 5: Comparison of predicted and measured heat flux for single and double silk net spacers with double aluminized mylar.

Test Series	Net	No. Layers (n)	Layer Density (Layer/cm) (z)	T_{hot} (K) WBT	q measured (mW/m2)	q predicted (mW/m2)
A177	Double Layer	20	8.51	293.4	304	310
A177	Double Layer	20	8.51	305.4	405	370
A177	Double Layer	20	8.51	325.8	536	490
A178	Single Layer	20	13.60	293.2	342	404
A179	Single Layer	10	13.02	292.3	538	759

The comparison between the predicted and measured values is quite good (except for the 10 layer case, which is different by 40 %). In some cases, the measured data is lower than the predicted value. When modelling insulation systems utilizing these equations derived from calorimeter tests, a number of considerations related to layer density control, end effects and attachment techniques can be found in the work of Nast, Frank, and Feller [21].

5. Conclusions

Silk netting was tested on the absolute cylindrical boiloff calorimeter, Cryostat-100, at the NASA Kennedy Space Center between warm boundary temperatures of 293 K, 305 K, or 325 K and a cold boundary temperature of 78 K. The silk netting material was provided by Lockheed Martin from remnants of legacy flight programs. The test results show a dramatically lower heat load with a minimally lower mass than using polyester netting or fiberglass paper but with the same general trend of q*N increasing when increasing number of layers as other MLI systems. The results of this series of test showed that the double silk net did better than single net as expected. Equation 4-14 from reference 7 under predicted the performance by 0-10% for the double net (A177). For the single net the equation over predicted by 15-40% (A178/A179). The mass difference between polyester netting and silk netting is minimal.

The agreement of the current test data with previous testing further strengthens the use of the benchmark thermal performance data from Cryostat-100 along with the recently noticed trends from it.

Due to the cost and availability of silk in general, silk netting may be prohibitive for most applications and spacer materials of polyester netting and fiberglass paper will still be used. However, these test data confirm that there is a significant difference between the silk netting and polyester netting. Silk netting should still be considered in cases where optimum levels of performance are needed and the benefits outweigh the costs.

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References
[1] I. Black, P.E. Glaser, "Progress Report on Development of High-Efficiency Insulation", Advances in Cryogenic Engineering, Vol. 6, Plenum Press, NY, 1961, pp. 32-41.
[2] R.C. Getty, J.P. Clay, et. al., "Initial Evaluation of Some Selected Lightweight Superinsulation for Space Vehicles", Avances in Cryogenic Engineering, Vol. 11, Plenum Press, NY, 1966, pp. 35 – 48.
[3] K. E. Leonard, Cryogenic Insulation Development, Final Report, NASA CR-123938, 1972.
[4] G. O. Fredrickson, M. C. Coes, et al.,Ranking and Selection Insulation Systems for MNV Application, Special Report No. 1, Investigation of High-Performance Insulation Application Problems, NASA CR-112337, 1969.
[5] T. C. Nast, A Review of Multilayer Insulation Theory, Calorimeter Measurements, and Applications, in: J. P. Kelley, J. Goodman, (Eds.), Recent Advances in Cryogenic Engineering - 1993, ASME HTD-Vol. 267, American Society of Mechanical Engineers, New York, 1993, pp. 29-43.
[6] E. H. Hyde, Multilayer Insulation Thermal Protection Systems Technology, Research Achievements IV NASA TM X-64561, 1971, pp. 5-52.
[7] C.W. Keller, G.R. Cunnington, et al.,Thermal Performance of Multi-layer Insulations, Final Report, NASA CR-134477, 1974.
[8] J.J. Martin, and L.J. Hastings, Large Scale Liquid Hydrogen Testing of a Variable Density Multilayer Insulation with a Foam Substrate, NASA TM-2001-211089, 2001.
[9] E.C. Fox, E.R. Kiefel, et. al. "Multipurpose Hydrogen Test Bed – System Definition and Insulated Tank Development", NASA CR-194355, 1993.
[10] R. A. Mohling, H. L. Geir, et al.,Multilayer Insulation Thich Blanket Performance Demonstration, AFAL TR-87-037, Ball Aerospace Systems Group, Boulder, CO, July 1987.
[11] R.H. Knoll, R.J. Stochl, and R. Sanabria, "A Review of Candidate Mulilayer Insulation Systems for Potential Use on Wet-Launched LH2 Tankage for the Space Exploration Initiative Lunar Missions", NASA TM-1991-104493, 1991.
[12] T. Nast, D. Frank, and K. Burns, "Cryogenic Propellant Boil-Off Reduction Approaches", AIAA-2011-806, 2011.
[13] J.E. Fesmire, et al. "Thermal Performance Testing of Cryogenic Insulation Systems". Thermal Conductivity 29. Lancaster, PA : DEStech Publications, 2008. pp. 387-396.
[14] W.L. Johnson, Thermal Performance of Cryogenic Multilayer Insulation at Various Layer Spacings, Master's Thesis, University of Central Florida, Dec. 2010.
[15] J.E. Fesmire, "Standardization in cryogenic insulation systems testing and performance data," International Cryogenic Engineering Conference - 25, Enschede Netherlands, July 2014.
[16] ASTM C1774 - *Standard Guide for Thermal Performance Testing of Cryogenic Insulation Systems*. ASTM International, West Conshohocken, PA, USA (2013).
[17] ASTM C740 - *Standard Guide for Evacuated Reflective Cryogenic Insulation*. ASTM International, West Conshohocken, PA, USA (2013).
[18] J.E. Fesmire and W.L. Johnson, "Thermal Performance Data for Multilayer Insulation Systems Tested between 293 K and 77 K," Space Cryogenics Workshop, Alyeska, AK, June 2013.
[19] T.C. Nast, "A Review of Multilayer Insulation, Theory, Calorimeter Measurements, and Applications", *Recent Advances in Cryogenic Engineering*, Kelley, J.P. and Goodman, J. ed., American Society of Mechanical Engineers, NY, 1993, pg. 29.
[20] R.J. Stochl, *Basic Performance of a Multilayer Insulation System containing 20 to 160 Layers*, NASA TN D-7659, 1974.
[21] T.C. Nast, D.J. Frank and J. Feller, "Multilayer insulation considerations for large propellant tanks", Cryogenics 64 (2014) 105–111.