

Investigations of Heat Transfer in Vacuum between Room Temperature and 80 K

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Abstract. The heat transfer between room temperature and 80 K is controlled using various insulating material combinations. The modes of heat transfer are well established to be conduction and thermal radiation when in a vacuum. Multi-Layer Insulation (MLI) in a vacuum has long been the best approach. Typically this layered system is applied to the cold surface. This paper investigates the application of MLI to both the cold and warm surface to see whether there is a significant difference. In addition if MLI is on the warm surface, the cold side of the MLI may be below the critical temperature of some high temperature superconducting (HTS) materials. It has been proposed that HTS materials can serve to block thermal radiation. An experiment is conducted to measure this effect. Boil-off calorimetry is the method of measuring the heat transfer.

1. Introduction

There are many common systems and processes that operate at low temperatures. The storage and transport of liquefied gases such as oxygen, nitrogen, and LNG, the preservation of food by freezing are familiar applications. Many types of superconducting power equipment such as transmission cables, transformers, fault current limiters, and motors are being developed using superconducting materials which need to be cooled to liquid nitrogen temperatures and lower. In all cases, the need exists to minimize heat loads to the cold space, to maximize energy efficiency, to minimize operating expense, and for operational stability of many of these devices. This goal is achieved, in part, through various arrangements of insulation and support systems used to isolate the cold parts from the warm ambient environment.

This work investigates different arrangements of insulation systems used in the application of multi-layer insulation (MLI) or “superinsulation,” for comparing the performance of the various arrangements. There are differing opinions as to whether the MLI system performs better (lower effective thermal conductance and heat flux) when applied to the cold surface. One variation is to apply the MLI on the warm surface. Comparison of the relative performance was done in this study. In addition, it has been proposed that HTS materials may serve as a thermal radiation shield. An experiment to test this hypothesis was conducted and the results included in this paper.

2. Test Facilities, Materials and Equipment

The LeTourneau University Universal Thermal Energy Laboratory (UTEL) includes academic expertise and connects to a number of different industries which are involved in cryogenics and the advancement of the technology for subjects such as energy storage, energy efficiency, and novel thermal material systems targeted for sub-ambient temperature applications. The experimental effort in this work relies on tests using the ‘Cryostat-400’ developed at the Cryogenics Test Laboratory at NASA Kennedy Space



Center [1]. The Cryostat-400 test apparatus is schematically shown in figure 1. It is a comparative, flat-plate instrument, using cryogenic boil-off calorimetry which is relatively simple to operate. Figure 2 shows the Cryostat-400 in operation at LeTourneau. The UTEL at LeTourneau became operational in the performance of thermal materials tests using the Cryostat-400 in 2013 [2].

2.1. Brief discussion of the measurement technique

The measurement technique for the Cryostat-400 was previously described in detail in [1-3]. Briefly, the heat flow rate ($\dot{Q}$) is determined by a direct measurement of the boil-off flow of liquid nitrogen. The rate of heat transfer is the basis for calculating thermal transport properties of the samples. Typically when testing an insulation material the effective thermal conductance (U_o) and heat transfer ($\dot{Q}$) are reported. The calculated value of U_o is a comparative one for the Cryostat-400 instrument and is the reciprocal of the thermal resistance of an insulation construction [4]. The use of an effective thermal conductance to express the thermal performance of a MLI blanket is established in the field [5]. The symbols used for calculation of thermal properties from boil-off testing are given in table 1. This study is not about a single insulation material but is an insulation system consisting of different combinations and arrangements of a multi-layer insulating blanket, aluminium plates, and radiation gap. Therefore the results are more correctly reported as an overall heat transfer coefficient, U_o , that accounts for a series of thermal conductances across a fixed thickness for the insulation system [6].

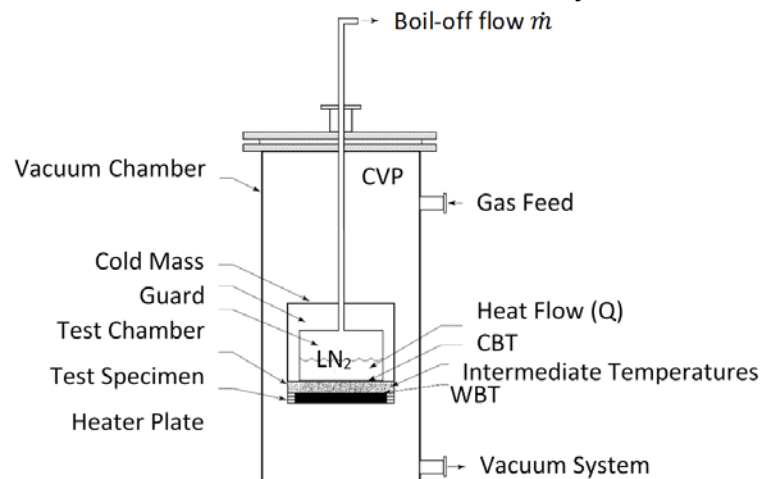


Figure 1. Basic schematic of cryogenic boil-off testing apparatus, flat plate configuration.

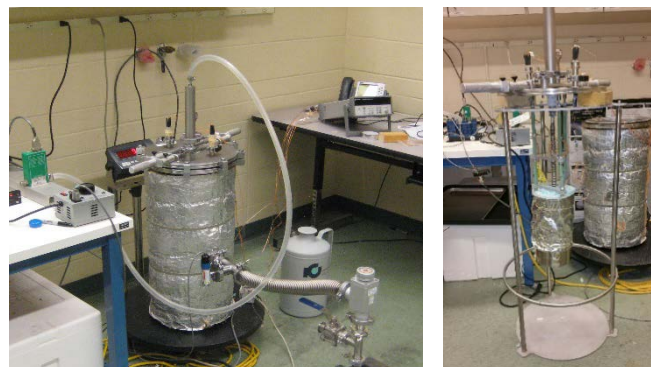


Figure 2. Insulation test instrument Cryostat-400 in the laboratory setting at LeTourneau University.

The effective heat transfer area of the specimen, A_e , is measured, as well as the temperature extremes at the hot and cold boundaries. In some tests, certain inter-layer temperatures to the build of the insulation system are also measured. All insulation system configuration constructions were 0.0254 m

thick. In some of these tests, only the cold boundary temperature (*CBT*) and warm boundary temperature (*WBT*) were measured for simplicity. The effective diameter, d_e , of the test section is 0.1524 m.

Table 1. Symbols used for calculation of thermal properties from boil-off testing

Symbol	Description	Unit
V_{stp}	Volumetric Flow Rate (at STP)	m ³ /s
ρ	Density of Gaseous Nitrogen	kg/m ³
h_{fg}	Heat of Vaporization	J/g
x	Thickness of insulation system	m
d_e	Diameter, effective heat transfer (flat plate)	m
A_e	Area, effective heat transfer area	m ²
ΔT	Temperature difference (<i>WBT</i> – <i>CBT</i>)	K

The rate of heat transfer ($\dot{Q}$) through the insulation system into the cold mass vessel is directly proportional to the liquid nitrogen boil-off rate as shown by Equation (1).

$$\dot{Q} = V_{stp} \rho_{STP} h_{fg} \left(\frac{\rho_f}{\rho_{fg}} \right) \quad (1)$$

Steady-state measurement is achieved by the liquid mass being stratified and stable (a condition promoted by the design features of the cold mass assembly). Measurements of heat transfer are made as the nitrogen is evaporated, with the final test measurement being taken when the vessel is nearly empty. This methodology minimizes any edge effects and ensures a very high level of repeatability in operation. The value of U_o for heat conduction through a flat insulation system arrangement is determined from Fourier's law as given by equation (2). The Cryostat-400 is a comparative instrument, but provides a stable and repeatable platform for a precise and direct measure of the total heat flow.

$$U_o = \dot{Q} / A \Delta T = 4 \dot{Q} / \pi d_e^2 \Delta T \quad (2)$$

For all tests, the insulation stack was isolated from the surroundings using a layer of Cyrolite fiberglass and MLI that were placed around the inside of the C-400 chamber for partial thermal guarding. The same materials were placed on top of the cold mass can to isolate the liquid nitrogen vessel from the surroundings and keep the background heat load to a minimum.

The insulation systems tested in this study were comprised of different stack-up combinations of aluminium 6061 plates, a 32-layer superinsulation blanket, and gaps. Figure 3 shows part of the insulating system used in test 5. It consists of a 32 layer blanket of MLI with a 3.2 mm thick aluminium plate on top which compresses the MLI blanket to approximately 5 mm thick. This assembly was placed on the warm boundary in the test using the high temperature superconductor which is discussed later. The MLI was a double aluminized mylar with a fiber spacer applied to one side. All specimens were approximately 152 mm in diameter. In all tests, the hot boundary did not use an electric heater but relied on heating from the ambient room-temperature condition.

3. Testing of multi-layer insulation on cold versus warm boundary (Tests 1-2)

This series of tests compared a 32 layer MLI insulation blanket on the hot boundary to the case where the MLI is placed against the cold boundary on top of an aluminum plate. For the test with MLI on the warm boundary, the top layer of the MLI was held in place by a string between a flexible metal ring. The thickness of the MLI blanket was approximately 19 mm the un-compressed condition. The insulation system build is provided in table 2 for MLI on both the warm and cold surfaces. Thermocouples were placed on the hot boundary, cold boundary, on top of the cold mass can, in the

middle of the MLI sample, and on top of the MLI sample. The MLI blanket was held in place by a thin string attached to a flexible metal ring that kept the thickness of the blanket to approximately 19 mm or the uncompressed condition. Room and the vacuum chamber temperatures were also monitored. Each test run resulted in a determination of the overall thermal conductance (comparative), U_o , for the thermal insulation system arrangement.

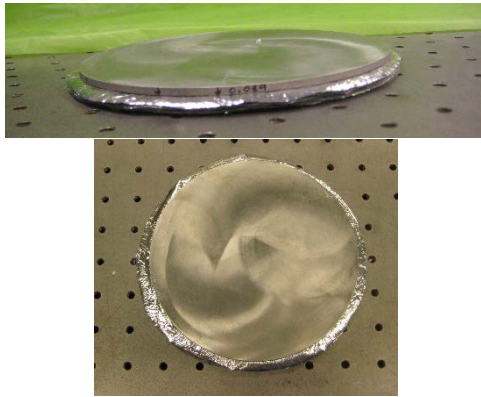


Figure 3. 32-Layer MLI blanket with 3.2 mm thick Al 6061 plate on top used on warm boundary in test with HTS (Test 5).

Table 2. Insulation stack for standard MLI on warm surface (Test 1) and on the cold surface (Test 2)

Test 1 layers	Thickness (mm)	Test 2 layers	Thickness (mm)
Warm boundary	NA	Warm boundary	NA
32 layer MLI blanket	19.1	AL 6061 plate	9.53
Gap	6.35	32 layer MLI blanket	15.9
Cold boundary	NA	Cold boundary	NA

The measured results of boil-off flow rate are provided in figure 4. After an initial cooldown, the liquid nitrogen vessel is refilled at around 2.6 hours into the run. Then the test continues until all the nitrogen boils off. Steady state is reached near the end of the run at around 7.5 hours. The averages of flow and temperatures for the last hour are used in the data reduction.

The typical vacuum level during the test is provided in figure 5. All tests were conducted at a moderate vacuum level. During the liquid nitrogen filling process, a seal in a compression fitting in the fill line is suspected to leak during the thermal transient process. This situation caused an increase in the pressure within the test chamber. The chamber is constantly evacuated by a mechanical vacuum pump during all test runs. In order to assure the leak was not affecting the flow measurement, a flexible diaphragm was placed over the fill/vent tube before filling and after the nitrogen had boiled out of the pot in order to see whether any leakage was occurring to the vacuum space. No leakage was observed and the flow measurements are considered valid.

In figure 4 the initial cool down period can be seen from beginning of the run to around $t=2$ hours. The spikes in the boil-off flow occur when refilling the liquid nitrogen (LN) vessel. After the initial cool down period, the flow gradually decreases until steady state is reached at times near the 8 hour mark. After the supply of nitrogen is depleted, the flow rate drops to zero around hour 9. The vacuum pressure is shown in figure 5. After the initial cooldown period, the vacuum pressure stays relatively constant throughout the entire experiment.

Figure 6 shows of the temperature response during this time period. The boiloff flow tapers off as the liquid level decreases. The temperatures near the cold mass reach a constant value after about 4 hours, but the warmer locations in the insulation system do not stabilize until after 7 hours into the run. Similar response characteristics were measured for all tests conducted in this study.

Figure 7 shows the steady state average temperature distribution for the warm MLI configuration. As shown the temperature profile varied with the material as expected.

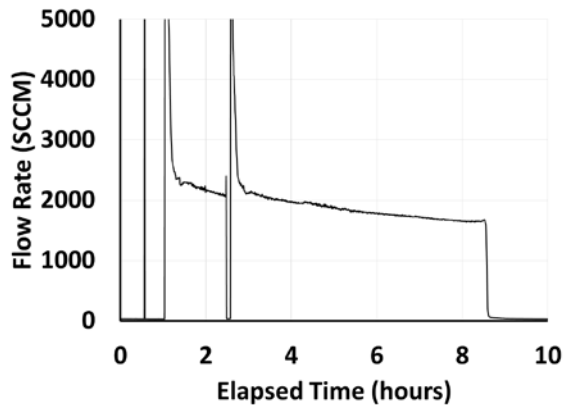


Figure 4. Boil-off flow measurements from standard configuration with MLI on cold surface.

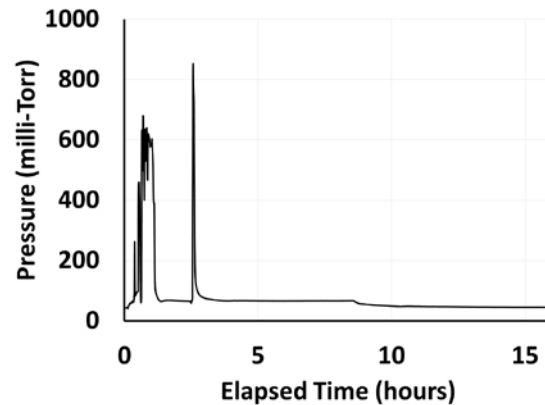


Figure 5. Typical vacuum pressure level during a test run.

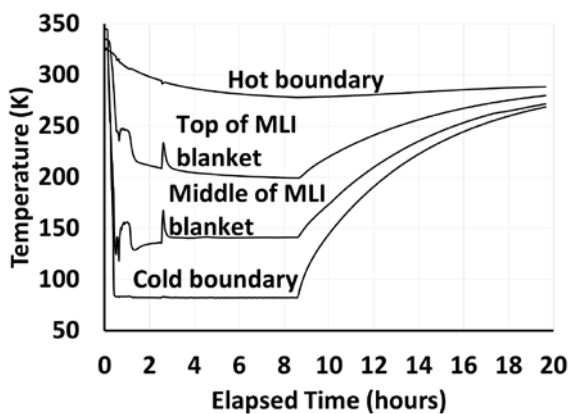


Figure 6. Temperature measurements for the configuration with MLI on cold surface.

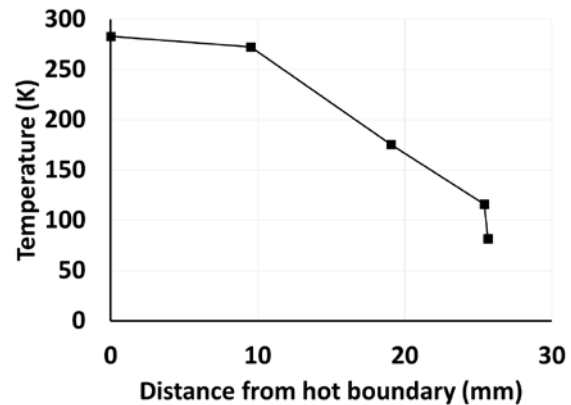


Figure 7. Temperature distribution through the thickness for the configuration with MLI on cold surface.

This test configuration had a 152.4 mm diameter aluminum 6061 plate that was 9.53 mm thick on the hot boundary below the same 32 layer of MLI blanket from the previous test. The MLI blanket made direct contact with the cold boundary. All thermocouples from the previous test were used with an additional thermocouple on top of the aluminum plate.

4. Measurements of MLI with plate (Test 3)

This test was a baseline measurement for the HTS shielding experiment. The MLI blanket was the same one used in the prior tests. A 9.53 mm thick plate was attached to the cold mass with three stainless steel 304 clips. Table 3 shows the construction of this insulation stack. These clips tightly held the aluminum plate next to the cold mass using screws. The 32-layer MLI blanket was on the hot boundary and in contact with the aluminum plate on the cold side. All thermocouples were the same as the warm MLI test with an additional thermocouple being placed on the bottom of the aluminum plate. Cry-con thermal conducting grease was applied between cold boundary and aluminum plate to improve the thermal contact. Figure 9 shows the measured temperature distribution through this blanket.

5. Measurements of high temperature superconductor (Tests 4-5)

In this final test, a piece of bulk high temperature superconductor (HTS) was mounted in the aluminum plate attached to the bottom of the cold mass. Once the HTS drops below its critical temperature, a drop in the reflectivity should be observed [7]. The HTS material is made of YBCO and is similar to bulk materials used in magnetic levitation prototypes [8]. Testing was done with a solid plate attached to the

cold mass and then again with the HTS inserted in the center. The test configuration with the HTS is shown in figure 10. The plate was attached with stainless steel 304 clips as shown in the figure.

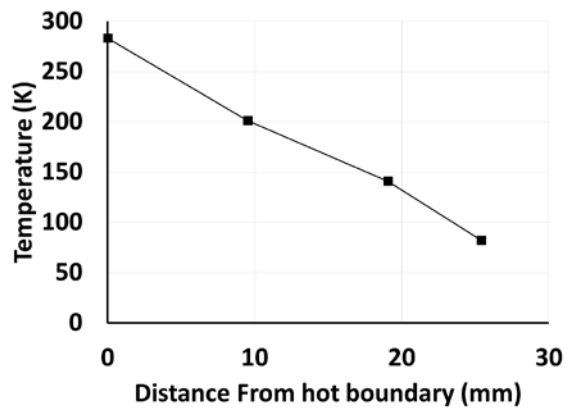


Figure 8. Temperature distribution through the thickness for alternate configuration with MLI on warm surface.

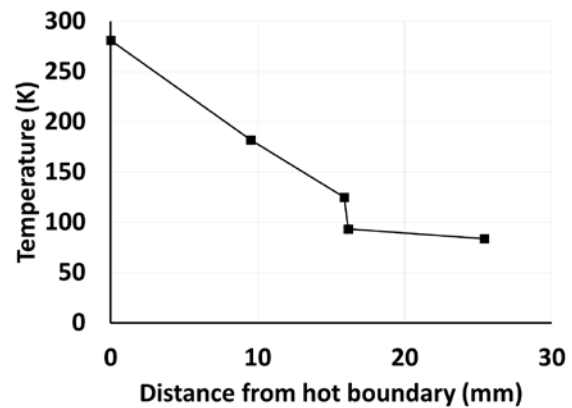


Figure 9. Temperature distribution through the thickness for alternate configuration with MLI on cold surface and aluminum plate.

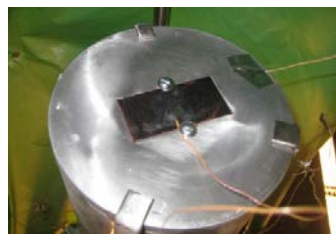


Figure 10. HTS test configuration: Aluminum 6061 plate showing the placement of the HTS material (left) and attachment of HTS and aluminum plate assembly to the bottom of the cold mass (right).

Table 3. Insulation build for test with HTS (Test 4)

Layer	Thickness (mm)
Warm boundary	NA
Uncompressed 32 layer MLI blanket	15.9
AL6061 plate with or without HTS	9.53
Cold boundary	NA

Figure 11 shows the measured temperature distribution for this case. The results of this test did not display any shielding by the HTS, but on the contrary seemed to result in a higher heat transfer. This may have been in part due to the SS304 clips. The temperature of the HTS material was 93.8 K which is slightly above the critical transition temperature, T_{crit} , for the material which is around 92 K for YBCO. The opposing warm surface needs to be below T_{crit} also so that the thermal radiation is at a wavelength that would be reflected by the HTS. Since the material is in the normal state, it would be highly resistive, therefore it would be expected to have a high emissivity. That would result in the sample absorbing radiant energy as opposed to being the radiation shield that was sought. This test needs to be performed again but at conditions where the temperature of the HTS is below T_{crit} in order to possibly observe the thermal radiation shielding. This data point has value in that it can be used for a comparison with data that would be obtained with temperatures only 2 K lower to see if the superconducting transition would reduce the heat transfer.

Table 4. Insulation build for test with HTS and plate on top of MLI (Test 5)

Layer	Thickness (mm)
Warm boundary	NA
32 layer MLI blanket	5.0
Al 6061 plate	3.18
Gap	7.7
AL6061 plate w/ or w/o HTS	9.53
Cold boundary	NA

Table 5 is a summary of the measure boundary temperatures, vacuum pressure levels and heat transfer for all of the runs. Using these parameters and the overall thickness of 25.4 mm, the overall effective heat transfer coefficient for the insulation system was calculated for the different test runs. The lowest value for U_o was obtained for the MLI on the cold surface, which is the conventional approach. It is seen that the HTS measurements resulted in higher thermal conductivities, most likely due in part to the fact that the HTS was in a normal state and not superconducting. In all cases, higher than expected heat transfer was measured due to the soft vacuum levels as provided in table 6. Figure 12 shows the overall heat transfer coefficient, U_o , calculated using the values in the table for all cases.

Table 5. Summary of main measured parameters and calculated heat load

Test Configuration	CBT (K)	WBT (K)	P_{vacuum} (mTorr)	$\dot{Q}$ (W)
1) MLI on warm boundary	82.3	283.4	67	6.750
2) MLI on cold boundary	81.8	283.3	58	6.415
3) Al plate on cold mass w/o HTS	83.7	280.9	59	7.110
4) Al plate on cold mass w/ HTS	84.2	251.5	43	7.790
5) Al plate on cold mass w/ HTS & plate on MLI	84.9	282.2	133	8.745

6. Conclusions and Recommendations for Future Work

Several insulation configurations were tested at the Universal Thermal Energy Laboratory at LeTourneau University to investigate the thermal insulating performance of various insulation systems. The work was conducted based on a calorimetric measurement using the NASA/KSC Cryogenics Test Laboratory Cryostat-400. The comparison between applying MLI on a warm boundary versus a cold boundary showed a slightly better performance when MLI is on the cold boundary. This is not a general conclusion since only one type of blanket was tested. Additional testing of different MLI blanket compositions should be tested.

In addition an attempt was made to measure whether a high temperature superconductor can provide thermal radiation shielding. In order for this to occur, the theory requires that the warm surface facing the HTS material be below the critical temperature of the superconductor and that the superconductor be at a lower temperature than the opposing warm surface. This effect was not observed in these experiments. To ensure that the critical temperature is reached for the entire mass of the superconductor and to reduce the gaseous conduction heat transfer, the vacuum levels in this round of experiments need to have lower pressures (below about 1 milli-Torr for these comparative type measurements) than were reached. Future work should be at conditions where the temperatures are below the critical temperature of the superconductor.

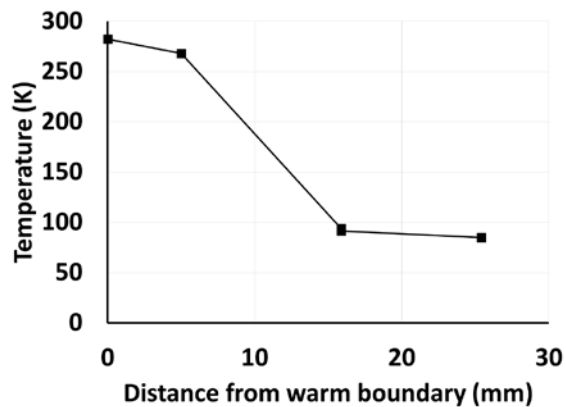


Figure 11. Temperature distributions from test with HTS.

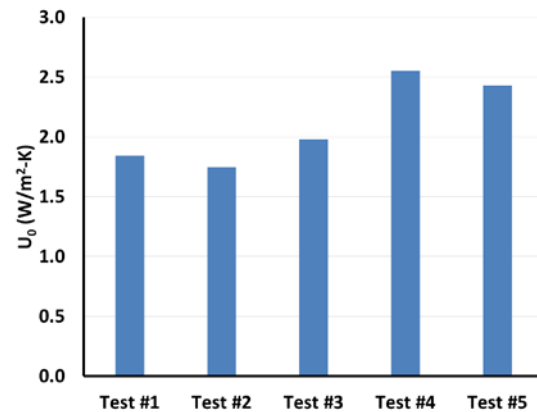


Figure 12. Comparison of calculated U_o for the different insulation system constructions.

7. References

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