

Experimental Thermal Performance Testing of Cryogenic Tank Systems and Materials

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Experimental Thermal Performance Testing of Cryogenic Tank Systems and Materials

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A comparative study was conducted to collect and analyze thermal conductivity data on a wide variety of low density materials, as well as thermal performance data on a number of vacuum-jacketed cryogenic tank systems. Although a vast number of these types of materials and cryogenic tank systems exist, the thermal conductivity of insulation materials and the thermal performance of cryogenic tank systems is often difficult to compare because many industrial methods and experimental conditions are available and utilized. The availability of a new thermal conductivity measurement device, the Macroflash Cup Cryostat, which is applicable for assessing a variety of materials, is accessible at NASA's Cryogenic Test Laboratory (CTL) at the Kennedy Space Center (KSC). The convenience of this device has resulted in the ability to rapidly measure the thermal conductivity properties of these materials by using a flat-plate liquid nitrogen (LN₂) boiloff technique that employs a guarded heat flow test methodology in order to determine the effective thermal conductivity (k_e) of a test specimen. As the thermal conductivities are measured at cryogenic temperatures, materials suitable for both future space missions and cryogenic tank systems can be identified and experimentally analyzed. Also recognizable are materials which may help increase energy efficiency by limiting the thermal losses encountered under various environmental conditions. The overall focus of this work consisted of two parts. One part, was to produce and analyze thermal conductivity data on a wide variety of materials with suitable properties conducive to those needed to aid in the production of a calibration curve for the "low end" of the Macroflash instrument. (Low end meaning materials with a thermal conductivity rating below 100 mW/m-K). The second part was to collect and analyze heat transfer data for a variety of small vacuum-jacketed vessels (cryogenic tank systems) in order to compare the thermal performance between them.

Nomenclature

Q	= Heat flow rate (W)
	= Mass flow rate (g/s)
h_{fg}	= Heat of vaporization (J/g)
q	= Heat flux (W/m ²)
A_e	= Effective heat transfer area (m ²)
k_e	= Effective thermal conductivity (mW/m-K)
x	= Thickness of specimen (m)
T	= Temperature difference (K)
Z	= Volumetric boiloff rate (W/L)
	= Density (g/cm ³)
c	= Compressive strength

I. Introduction

The Cryogenics Test Laboratory at Kennedy Space Center was established to develop thermally efficient technologies for a wide range of below-ambient temperature applications. Its overall discipline areas include the study of heat management, energy efficiency, thermal insulation systems, and novel materials. Both novel and conventional means of refrigeration and heat control are being investigated to develop the most suitable thermal management and control systems to meet the needs for propellant process systems, superconducting power device refrigeration, rocket vehicle protection systems, human exploration habitats, cold chain shipping, and biomedical research platforms, to name a few.

In general, one cannot measure how much heat is present in an object, but rather only how much energy is transferred between objects at different temperatures, hot and cold. Early attempts at temperature measurement description of the first modern temperature scale in 1724. A few decades later, J. Black devised an ice calorimeter

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based on his discovery of hidden heat. And by 1822, J. Fourier had published *The Analytical Theory of Heat*, a work that remains the basis of our notions of heat, thermal energy and temperature. The technological development of large-scale systems. To meet this demand and enable the development of multilayer insulation (MLI) and evacuated perelite powder systems, engineers devised different apparatuses to directly measure heat flows from a few milliwatts and up using evaporation of thermal energy. The thermal insulating performances of materials and systems of materials. Gas flow rates measured using boiloff calorimetry enable direct calculation of quantities such as heat flux and thermal conductivity. A particularly useful approach is to use nitrogen for the heat measurement fluid as it is readily available, inert and generally safe to use. Because heat does not flow through a material as a function of temperature but according to a temperature difference, the use of a cryogen such as liquid nitrogen also provides a convenient way to establish the sub-ambient test conditions represented in the wide range of end-use applications. The temperature range from normal boiling point (77.4 K) to ambient (approximately 300 K) represents a wide range of particular needs in construction, transportation, food and beverage, pharmaceuticals, electrical power, electronics, medical imaging, aerospace, industrial processes and so forth, touching on virtually all aspects of modern life.[3]

One of the greatest advantages of using liquid nitrogen boiloff calorimetry is its ultimate simplicity and provision of a direct energy measurement. The liquid provides a stable cold boundary temperature and serves as a sort of power meter. The approach also lends itself to testing under representative conditions (i.e., those that reflect the actual-use or field-installed conditions) afforded by the very large temperature difference established by the liquid nitrogen. Cryogenic boiloff methods provide the means to reliably test the thermal conductivity of materials and the thermal performance of cryogenic tank systems. This method is a direct measurement of the flow of heat and enables the testing of complex materials and systems over a very wide range of conditions. This type of testing will be used for experimental laboratory investigations of both materials and cryogenic tanks. The thermal conductivities of materials will be tested using a Macroflash (Cup Cryostat). The total system thermal performance of small tanks will be tested using a custom developed laboratory methodology.

II. Macroflash Testing of Materials

A. Test Apparatus

The Macroflash Cup Cryostat instrument (shown in Figure 1) is a cryogenic boiloff calorimeter whose data is recorded by a National Instruments LabVIEW Data Acquisition Program. The Macroflash houses a cold mass test chamber centered directly over the test specimen, and wrapped in multiple layers of aerogel blankets to ensure the thermal isolation and stability necessary for accurate steady-state boiloff measurements. The Macroflash is a comparative, flat-plate and determines effective thermal conductivity (k_e) in accordance with ASTM 1774-13 [4]. Boiloff calorimetry provides a way to directly measure the heat flow rate through the test specimen. In Figure 1, the Macroflash system can be seen positioned on a high-sensitivity scale used for measuring the mass change of cryogenic fluid as fluid boil off occurs. The Macroflash system is connected to a heat controller for the hot plate and nitrogen gas for purging of the specimen throughout testing. The nitrogen gas is used to maintain an inert and dry environment, which prevents any moisture condensation on the test specimen. An adjustable compression loading system provides 0.5, 1.5, or 4.5 psi of applied force, ensuring full consolidation and

contact between the test specimen and cold/hot plate boundaries, preventing any void spots that would otherwise alter thermal conductivity results.

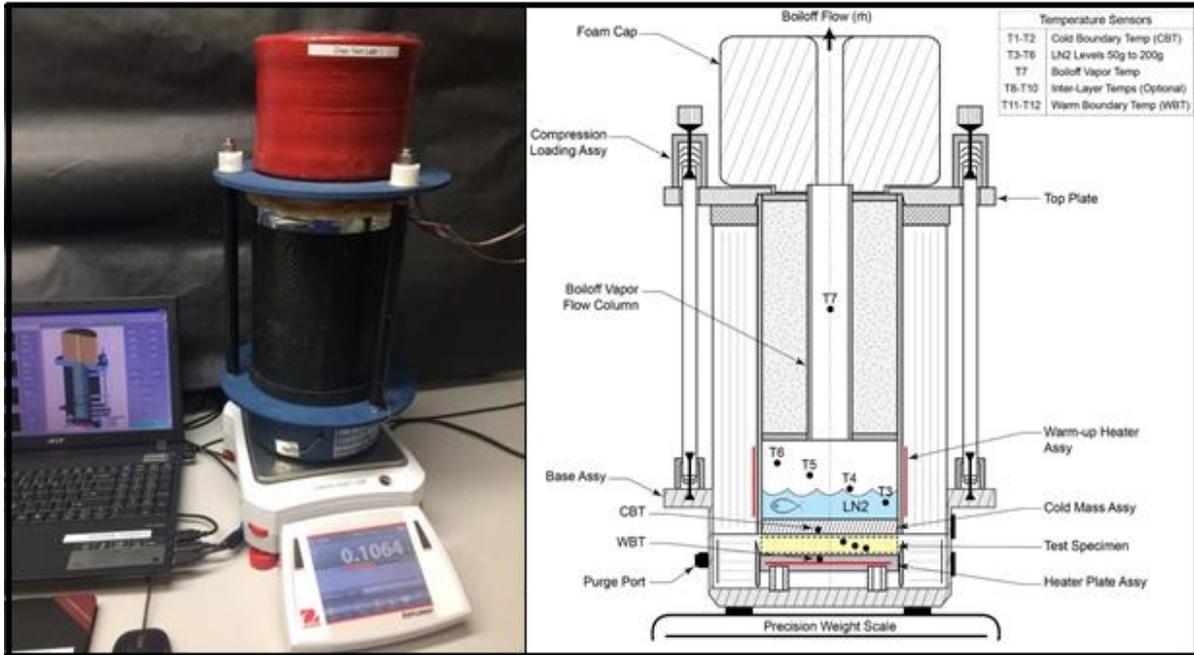


Figure 1. (Left) Assembled Macroflash setup. (Right) Cross sectional schematic for the Macroflash thermal test instrument.

B. Test Method

The test method is comparative and therefore requires calibration with materials of known thermal conductivity data. However, finding these materials with the necessary standard reference data is a difficult challenge. This project builds on the previous five years of work by different colleagues of the NASA Cryogenics Test Laboratory including scientists, engineers, and university researchers and brings in additional testing for a specific range of the spectrum of materials [5, 6].

The test conditions are representative of actual-use cryogenic applications with a warm boundary temperature (WBT) of approximately 293 K and a cold boundary temperature (CBT) of approximately 78 K. The test measurement principle is liquid nitrogen boil-off calorimetry where the mass flow rate of nitrogen gas is directly related to the rate of heat energy transmitted through the material. All tests are performed at an ambient pressure gaseous nitrogen (GN2) condition for consistency. A boiloff calorimetry test is conducted by filling a test chamber with a liquid cryogen which then boils/evaporates at room temperature. A test specimen of pre-determined geometry is affixed to the bottom of the test chamber and put in an environmental apparatus that provides the desired test conditions. The flow of heat through the test sample is directly proportional to the cryogenic fluid boiloff flow rate, measured by a weight scale or mass flow meter, with energy transfer measured as the heat flow rate. This cryogen boiloff rate, or gas flow rate (which can also be measured as mass loss) is directly used for the calculation of heat flux and effective thermal conductivity. Under steady-state flow conditions, the rate of heat flow through the test specimen is constant at all points through the thickness of the specimen. The thermal conductivity can then be easily calculated using a series of equations:

$$= \quad (1)$$

$$= \text{---} \quad (2)$$

$$= \frac{\quad}{(\quad)} \quad (3)$$

The heat flow rate (Q) is the product of boiloff mass flow rate (\dot{m}_{boil}) as shown in the equation above. Knowing the boundary temperatures on either side of the specimen in a set test environment, the heat flux (q) can be calculated. Since the specimen area is also known (A_c), as well as the thickness conductivity (k_c) can then be calculated.

For this testing, liquid nitrogen (LN_2) was used as the cryogen, allowing for a temperature differential from 77 K (nominal boiling point of liquid nitrogen) to 293 K (room temperature) to be created across the thickness of the test specimen (Figure 2). The temperature differential (i.e., the change in temperature from one side of the specimen, chilled by LN_2 , to the other side, maintained at room temperature by a heat controller. Boiloff calorimetry provides the ability to test both simple uniform materials and complicated non-homogeneous, anisotropic, composite materials with equal ease [7]. This method also inherently presents a temperature differential where thermal conductivity is calculated by the mass flow rate of cryogenic fluid boiloff, which is measured through either the system mass loss or boiloff flow rate. The extent of the temperature differential is therefore dependent on the cryogenic fluid and the heat source used, providing high sensitivity for the accurate measurement of highly thermally insulating materials or structural materials alike. Intermediate temperature sensors can also be employed for obtaining thermal conductivity data at different mean temperatures up to the ambient.

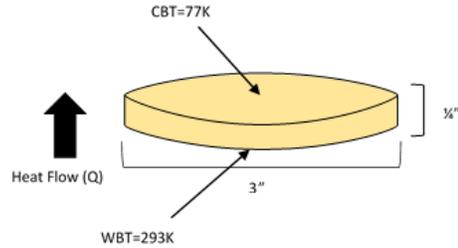


Figure 2. Boundary temperatures on the faces of a test specimen.

C. Materials (Test Specimens)

The test specimens (examples shown in Figure 3) are typically 1/8 inch thickness and should be flat and smooth-faced or easily compressible to insure good thermal contact between the heater assembly and the cold mass. The specimen is placed in the test section between two plates that are maintained at different temperatures during the test. For commercial samples, the compressive properties were obtained from the supplier technical data. For in-house research samples, compression properties were evaluated according to ASTM D695. A complete list of specimens tested and their properties is given in Table 1.



Figure 3. Example test specimens prepared for Macroflash testing: a variety of different thermal insulation materials (left) and five aerogel blanket materials (right).

Table 1. Summary and Properties of Materials Tested

Test Series	Matl Code	Material	Thick mm	Dia. mm	Mass g	Density g/cm ³	Load N	Grease g	Comp. Strength MPa
Z1-138	A	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-139	A	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-140a	A	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-141	A	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-142	A	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-143	L	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-144	A	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-145	P	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-146	P	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-147	P	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-148	A	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-149	A	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-138a	A	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-150	F	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-151	W	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-152	W	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-153	F	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-154	F	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-155	A	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-156	F	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-157a	F	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	0
Z1-158	B	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	1.5
Z1-158a	B	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	1.5
Z1-158b	B	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	1.5
Z1-158c	B	Al-7075-T6	1.5	12.7	2.5	2.81	0	0	1.5

D. Test Results

The thermal conductivities of a large number of test specimens have been evaluated using the Macroflash, as described above. The specimens tested covered a wide variety of materials that met the thermal conductivity requirements. A total of 25 test specimens representing approximately 130 boiloff test runs were performed as part of the current project. The test results are listed in Table 2.

Table 2. Macroflash thermal conductivity test data summary

Test Series	Matl Code	Material	Test Date	Test Runs	Mass Flow	Q	q	K _e - comp	Std Dev	k _e	cal	Comp. Strength	Figure Of Merit
					m ² s ⁻¹	J	W m ⁻²						
Z1-138	A	0.00000001	1/27/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-139	A	0.00000000	1/27/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-140a	A	0.00000000	1/27/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-141	A	0.00000000	1/27/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-142	A	0.00000000	1/27/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-143	L	0.00000000	1/27/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-144	A	0.00000001	1/27/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-145	P	0.00000000	1/27/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-146	P	0.00000000	1/27/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-147	P	0.00000000	1/27/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-148	A	0.00000001 (1.0000)	2/2/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-149	A	0.00000001 (1.0000)	2/2/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-138a	A	0.00000001 (1.0000)	2/2/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-150	F	0.000000	2/2/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-151	W	0.0000 (0.0000) 0.00mm	2/2/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-152	W	0.0000 (0.0000) 0.00mm	2/2/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-153	F	0.000000 0.0000 0.0000	2/2/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-154	F	0.000000001 0.0000	2/2/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-155	A	0.00 0.0000	2/2/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-156	F	0.00000000	2/2/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-157a	F	0.00000000	2/2/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-158	B	0.0000000000 d0.0000 0.0000	2/2/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-158a	B	0.00000000000m0.0000 d0.0000	2/2/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-158b	B	0.00000000000m0.0000 d0.0000	2/2/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Z1-158c	B	0.00000000000m0.0000 d0.0000	2/2/15	2	0.000000	0.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

For example of a range of data for materials with exceptionally low thermal conductivity, Figure 4 shows a comparison of various commercial aerogel insulation materials, which have a thermal conductivity less than 50 mW/m-K, which is specific P FO PO R P M OM M R MNMP B O R FO current project begins with test specimen Z1-148 and goes through Z1-158.to the low end calibration.

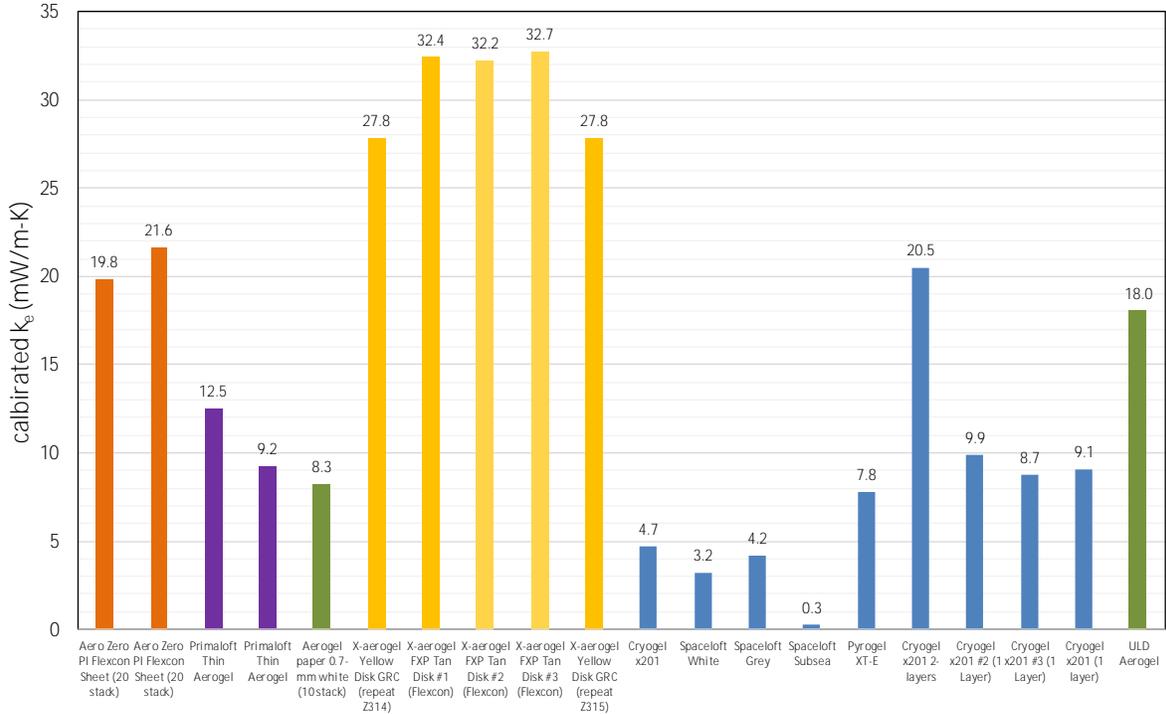


Figure 4. Comparison of various commercial and research Aerogel insulation materials

P M FO Q P ROM P R MO MP M FOM M P
 (FOM) could be derived as a representation of the overall performance. These results are summarized by various categories in Table 2, and the FOM was calculated according to the provided FOM equation:

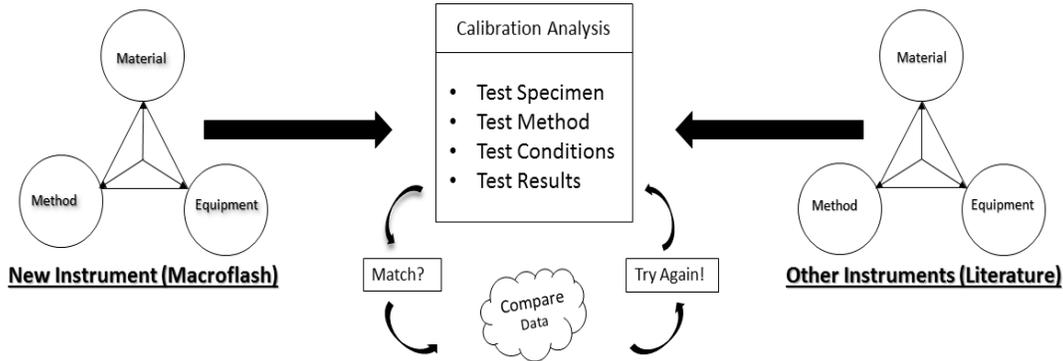
$$= \left(\frac{\text{---}}{\text{---}} \right) \cdot 10^3 \quad (4)$$

RO Q P RO c), effective thermal conductivity (k_e M P RO MP generates values (with units C ROOM QM M MPQ P PM M MP P P M thermal insulation materials. Since low values of thermal conductivity and density are desired, these parameters were placed in the denominator of the FOM equation. The compressive strength was placed in the numerator since large strengths are desired. Combining the desired values in this way allows for a rapidly obtained, quantitative screening parameter to identify potentially high performing structural thermal insulation candidates.

III. Macroflash Analysis and Calibration

Initial Macroflash comparative k_e measurements are reported as raw data that is then calibrated to give the effective k_e values reported in the tables above. The calibration is based off of a linear fit of measured material thermal conductivities to standard reference data for commercial material with a known k_e , such as: Cryogel, SOFI, FoamGlas, Polytetrafluoroethylene (PTFE), and Glass Fiber Reinforced Plastic (G-10CR). The problem here is that the manufacturers reported values for thermal conductivity are not at the necessary warm and cold boundary temperatures of 293 K and 78K, respectively. Most typically, these data are taken at ambient temperature (around 293K) with only a very small temperature difference imposed by the commercial test instruments generally used. The standard reference data therefore have to be derived by careful research and certain selection from the available scientific peer-reviewed published literature of the world some of it from the NASA CTL itself. Figure 5 provides a general

overview of the process and parameters involved in calibrating a comparative type thermal apparatus. Many factors must match up including test specimen type, method, condition, etc.



- 1) Test Specimen: material, density, size, shape, surface finish, etc.
- 2) Test Method: type of apparatus, principal of heat flow calculation, steady state or transient, etc.
- 3) Test Conditions: WBT, CBT, ΔT , calculated T_m , thermal paste, compression load, gas environment, etc.
- 4) Test Results: type of thermal conductivity, large ΔT or small ΔT , T_m , method of calculating thermal conductivity (λ , λ_e , k-value, k_s , k_e , etc.)

Figure 5. Guide for the Calibration of a Comparative Thermal Test Apparatus.

Standard methods of test specimen preparation, testing, thermal performance calculations, data recording and data reporting are all essential. As shown previously in Table 1 and Table 2, the key parameters include density, compression, specimen thickness, diameter, and whether or not thermal contact paste was used.

A. Explanation of Full Range and New Low Range

From the prior work of the NASA CTL over the last 5 years, researchers determined that a full range curve fit worked well except for materials with a $K_e < 50 \text{ mW/m-K}$. This work therefore picks up with the need to add a special low range calibration curve and, if reasonable, update the full range curve as well.

A summary of the special low-end calibration data is given in Table 3 and graphically presented in Figure 6. Together, these five materials through dozens of tests have produced the necessary data sets for bringing a higher fidelity to the Macroflash testing of materials with absolute values of effective thermal conductivity below 50 mW/m-K . The baseline test conditions for this calibration remain as follows: 293 K and 78 K boundary temperatures; ambient pressure gaseous nitrogen environment.

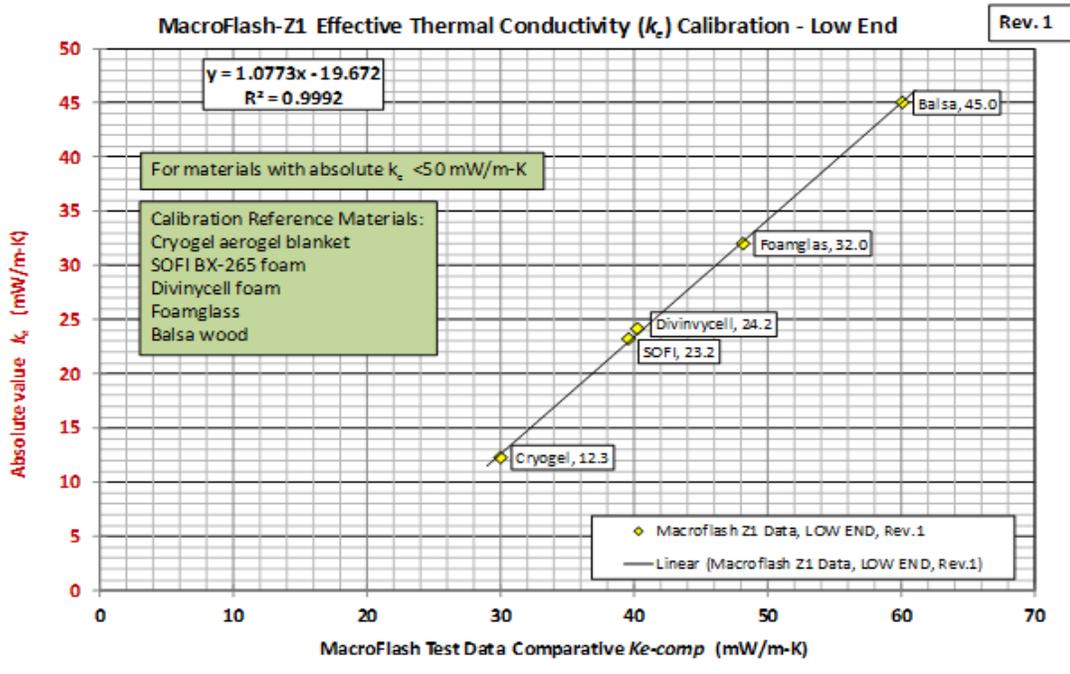


Figure 6. Macroflash- Z1 Effective Thermal Conductivity (k_e) Calibration- Low End.

Table 3. Macroflash Calibration Data- Low End Range

Material	MacroFlash Test Data Comparative k_e -comp (mW/m-K)	Absolute value k_e (mW/m-K)	Reference
Cryogel	12.3	12.3	[1]
SOFI	23.2	23.2	[2]
Divinycell	24.2	24.2	[3]
Foamglas	32.0	32.0	[4]
Balsa	45.0	45.0	[5]

According to the last column of Table 3, the references for the absolute thermal conductivity data for these materials being used as reference materials for the special low-end calibration are listed as follows:

- [1] Cryogel aerogel blanket, NASA Technical Report X-573, 2011.
- [2] SOFI BX-265 foam, NASA Technical Report X-573, 2011.
- [3] Divinycell foam, NASA Technical Report X-573, 2011.
- [4] Foamglass, NASA Technical Report X-573, 2011.
- [5] Balsa wood, NASA Technical Report X-573, 2011.

The low-end is of course only part of the full range of materials from insulators to plastics to composites with thermal conductivities as high as approximately 800 mW/m-K. For completeness, the full range calibration is presented in Figure 7.

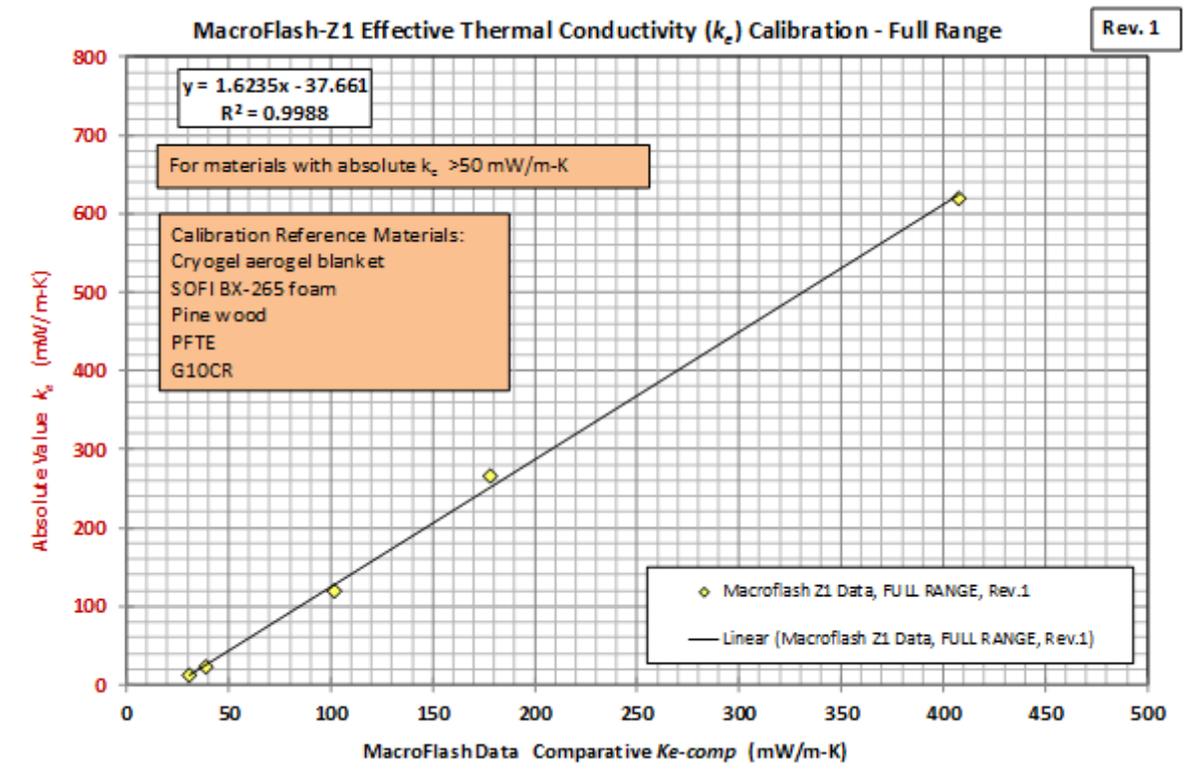


Figure 7. Macroflash-Z1 Effective Thermal Conductivity (k_e) Calibration – Full Range.

B. Software Revisions

Putting all the data together, including the full range of materials for testing over the last five years, the Macroflash software revisions are listed in Table 4. Included are the revised full range equation and the new low-end equation. These equations will be applied to the LabView software of the Macroflash test system. The user will select, up front before each given test, if the material is to be subject to calibration by the full range (above 50 mW/m-K) or low-end (below 50 mW/m-K) calibration. The automated report will be generated accordingly with notice as to which equation was applied for the calibrated data. The Macroflash uses custom designed LabView software by National Instruments. The software will be revised to include the special low-range curve fit as well as an update (from Rev. 0 to Rev. 1) of the full range curve fit. The old and new equations are listed as follows:

Table 4. New low-end and updated full range calibration equations for the Macroflash test system.

<u>Macroflash Calibration Curve-Fit Equations:</u>					<u>Special Low-End Calibration:</u>		
Rev	Date	m	b	R ²	m	b	R ²
0	10/6/2015	1.6301	-39.827	0.9988	n/a	n/a	n/a
1	3/31/2018	1.6235	-37.661	0.9988	1.0773	-19.672	0.9992

With these new equations as a result from the testing and analysis of these low density materials, the calibration columns on the master data sheets have been successfully updated which will result in a k_e measurement that more accurately reflects the literature value. This information will enable more accurate comparisons among materials, whether they be thermal insulation materials or composite structural materials, in each category of research interest. The information also provides valuable data for engineering calculations in the design and construction of future cryogenic tank systems.

IV. Cryogenic Testing of Tanks

A technology demonstration test was conducted as a portion of this project to provide comparative thermal performance data for a variety of small vacuum insulated vessels (cryogenic tank systems) in order to establish good methodology for test and evaluation as well as guide and inform the development of high efficiency, light weight cryogenic tanks of the future. The test articles, shown in Figure 8, range from 8 oz. flasks to 10 liter lab dewars that were custom designed and built to serve as storage tanks for cryogenic fluid. Evaporative (boil-off) calorimeter test protocols using LN₂ were established to provide tank test conditions characteristic of the large storage tanks such as those that support Space Launch System (SLS) hardware and flight operations. The following section provides comparative thermal performance test results for the vessels listed in table 4.



Figure 8. Cryogenic vacuum-jacketed test vessels.

included approximately 40 layers of multilayer insulation (40 reflection layers) within the vacuum space. The next best vessel was the standard laboratory flask with its silvered glass reflection layer within its vacuum space. The remaining small flasks have only the metal surfaces of the inner and outer surfaces of the vacuum annular space which could be polished or not polished, stainless steel only or copper coated. In vacuum, the dominate heat transfer is by radiation thus making the type of number of radiation shields a crucial factor (in addition to a high level of vacuum and a good overall design that minimizes the heat transfer that occurs by solid conduction).

Table 5. Cryogenic Vacuum-Jacketed Tank Test Results

Test ID	Material	Volume (L)	Surface Area (m ²)	Insulation Type	Number of Layers	Boiloff Rate (L/hr)	Boiloff Rate (L/day)	Boiloff Rate (L/month)	Boiloff Rate (L/year)	Notes
1	Aluminum	0.01	0.01	MLI	1	0.001	0.024	0.72	2.73	Standard flask
2	Aluminum	0.01	0.01	MLI	1	0.001	0.024	0.72	2.73	Standard flask
3	Aluminum	0.01	0.01	MLI	2	0.0005	0.012	0.36	1.37	Standard flask
4	Aluminum	0.01	0.01	MLI	2	0.0005	0.012	0.36	1.37	Standard flask
5	Aluminum	0.01	0.01	MLI	2	0.0005	0.012	0.36	1.37	Standard flask
6	Aluminum	0.01	0.01	MLI	2	0.0005	0.012	0.36	1.37	Standard flask
7	Aluminum	0.01	0.01	MLI	2	0.0005	0.012	0.36	1.37	Standard flask
8	Aluminum	0.01	0.01	MLI	2	0.0005	0.012	0.36	1.37	Standard flask
9	Aluminum	0.01	0.01	MLI	2	0.0005	0.012	0.36	1.37	Standard flask
10	Aluminum	0.01	0.01	MLI	2	0.0005	0.012	0.36	1.37	Standard flask

V. Discussion and Recommendations

From the test methodology for materials and tanks, and from the test results and analysis of each, we can begin to inform and guide the design for high efficiency tanks of the future. Structural materials, insulation materials, design and construction must all work together in order to form the basis for a well-made cryogenic storage tank.

IV. Conclusion

A study of the thermal conductivity of materials was performed in order to improve the accuracy of the calibration for the low-end range of the Macroflash thermal test instrument. As a secondary study at the Cryogenics Test Laboratory, the thermal performance testing of different cryogenic tank systems was performed according to a new standard laboratory methodology. A new performance metric called the Z-number, or volumetric boiloff, was developed to compare the wide range of tank test results. Combining aspects of materials science and cryogenic engineering, the experimental data sets include thermal performance comparisons between vacuum-jacketed vessels (cryogenic tank systems) and the effective thermal conductivities of a variety of low density materials. Through multiple liquid nitrogen boiloff calorimetry tests on an extensive array of low density, thermal insulation materials tested using the Macroflash Cup Cryostat a new low-end calibration has been set in place as an updated revision that has improved the data analysis for the test results. From the thermal performance data on the 10 different vacuum-jacketed vessels tested using liquid nitrogen boiloff calorimetry, better informed decisions can be made moving forward on the construction, design and configuration of future cryogenic tank systems.

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