

Technical Report

Measuring the R-value of Thermal Insulation at Various Temperatures

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The test results in this report apply only to the specimens tested. The tests conform to the respective test methods except for the report requirements. The report includes summary data but a full complement of data is available upon request. This report shall not be reproduced, except in full, without written approval of R & D Services, Inc. This report must not be used by the client to claim product endorsement by R & D Services, Inc., IAS or any other organization.

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Measuring the R-value of Thermal Insulation at Various Temperatures*Introduction*

Insulation materials of all types provide building owners with resistance to heat flow, called thermal resistance or R-value, to reduce energy costs. In the USA, insulation manufacturers, code officials, building owners and occupiers, etc. have relied on standard test methods for the evaluation of the effectiveness of an insulation material. These standard test methods allow all interested parties to compare the performance of different insulation technologies on an even baseline.

Heat flow can occur via three different modes. The three modes are conduction, convection, and radiation. Conduction occurs when there is a physical path for the energy to pass. Convection is where energy is moved by the transfer of a fluid (air or liquid). Radiation occurs between two bodies of differing temperatures. Radiation can occur in a vacuum.

Heat flow due to conduction is calculated from Fourier's Law given in Equation 1.

$$Q = kA \frac{\Delta T}{\Delta x} \quad (1)$$

Q is defined as the heat flow in BTU/hr.

k is defined as the thermal conductivity in BTU (°F·ft²·h)⁻¹

A is defined as the area in ft²

$\frac{\Delta T}{\Delta x}$ is defined as the temperature difference across the thickness of the material in the direction of heat flow.

All insulation materials that claim an R-value, are required to declare the R-value at the same average temperature, 75°F, according to federal law. All commonly used methods for evaluating insulation require there to be some temperature difference from one side of the insulation to the other to create a heat flow, called the heat flux, that can be measured. From Equation 1, if the temperature difference is 0, then the heat flow is 0. The R-value is reported at the average of the hot and cold side temperature, 75°F in most cases. However, virtually all insulation products show changes in thermal resistance (R-value) with changes in temperature. When measuring the heat flow through porous objects, such as building insulations, it is impossible to quantify the amount of heat transfer that is due to each of the three primary modes of heat transfer. Therefore, the thermal conductivity from Equation 1 is referred to as “apparent thermal conductivity”, k_a which encompasses all three forms of heat transfer into one variable. R-value is determined from thickness, L, and the apparent thermal conductivity, k_a , using the Equation 2:

$$R \text{ value} = \frac{L}{k_a} \quad (2)$$

It is common for insulation materials, such as polyisocyanurate foam board, to be described by the thermal resistivity, or the R per inch (R/in) of material manufactured. The smaller the apparent thermal conductivity, k_a , the larger the potential R-value. The property k_a generally becomes smaller as the mean temperature decreases. This means that generally, as the mean temperature is reduced the R-value increases.

The variation of R-value with temperature can be complex. The relationship of R-value and temperature for some insulation materials is often linear, meaning that the change in R-value changes at a constant rate over the temperature range of use. Compared to the R-value at 75°F, the R-value at lower temperatures will be higher and the R-value at higher temperatures will be lower. If the change in temperature results in physical or chemical changes the changes in thermal resistance can be non-linear. For closed cell foams like polyiso, extreme temperatures can impact the dimensional or cell-gas composition which changes the thermal resistance.

R-value measurements

Heat flow meters (HFM) are commonly used to evaluate the R-value of thermal insulations. Heat flow meters operate under the guidelines of standard test method ASTM C518, “Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus”.

Heat flow meters operated in accordance to ASTM C518 consist of two isothermal plates that are maintained at different temperatures. Each plate has a heat flux transducer located at the center of the plate that measures heat flux. Heat flux is the amount of heat flow per unit area. Typically, the bottom plate is operated at a higher temperature than the top plate creating heat flow in the upward direction. ASTM C518 is known as a comparative test method. Known reference materials are provided by national standards organizations, NIST in the United States, and these known reference materials are used to create calibration files for the HFM. NIST provides users with calibration materials and certificates with the k_a at different average temperatures. The HFM is operated with the known reference materials at the same temperatures as the NIST data. The HFM measures the heat flux at these temperatures and a calibration file is created associating the different heat fluxes with the known k_a . The appropriate calibration files are used to measure unknown materials comparing heat flux data from the calibration material thereby calculating the k_a of the unknown material.

The unknown insulation material is placed between the plates at a known thickness and measured at steady state conditions until the R-value is determined. Both plates contain a heat flux transducer and the measured heat flux of both plates is averaged together for the result. Rearranging Equation 1 allows us to solve for k_a in Equation 3.

$$k_a = \frac{Q \cdot L}{A \cdot \Delta T} \quad (3)$$

The heat flow meter measures each of the components of the right side of Equation 3. The heat flux, Q/A , is measured with the heat flux transducers in the center of the top and bottom plates, the thickness, L , is measured, and the temperature difference, ΔT , between both plates is measured.

The overall process of arriving at R-value involves two steps. The HFM measures the heat flux resulting from a temperature difference across the insulation. Then, the HFM data are analyzed to arrive at values for k_a , R/in. and R-value. The HFM data allows the user to determine the R-value of the insulation specific test conditions such as the temperature difference is across the insulation, the average temperature during the test, and the direction of heat flow. There is an infinite combination for the determination of R-value at different mean temperatures, temperature differences and heat flow directions.

There are two options to characterizing the R-value over the range of use for an insulation material. The first option would be to measure a material at all possible combinations of mean temperatures and temperature differences. This is difficult due to the amount of time and effort it would take to accomplish. The second option is to use the data that comes from the HFM to calculate the R-value for a range of temperatures. Using selective measurements from the HFM, the material R-value is calculated using ASTM C1045, “Standard Practice for Calculating Thermal Transmission Properties Under Steady-State Conditions”.

Calculating R-Value

ASTM C1045 is the uniform procedure for calculating all thermal properties regardless of the test method used to obtain the test data.

There are two common methods for calculating the R-value of insulation materials.

1. The commonly used method includes analysis that is valid when the variation of k_a with temperature is linear. This involves making a minimum of two measurements at the upper and lower temperature use range, fitting the data with a linear curve fit and solving for the equation. Generally additional measurements are made within the temperature range to prove that the variation of k_a is linear for the material. It is recommended that a minimum of four R-value measurements be made for this approach. This is a simplified approach because a linear variation of k_a is valid for many insulations.
2. The second approach allows the user to solve for more complicated equations that describe the changes in thermal performance when the changes in k_a are non-linear over the temperature range. This method of calculating thermal performance is known as the “Thermal Conductivity Integral (TCI) Method”. Any combination of temperature differences and average temperatures can be captured using the TCI method. Additional measurements are required to improve the quality of the fit of the equation to the material thermal performance.

ASTM C1045 recognizes that the HFM determines the average value for k_a over the temperature range T_{cold} to T_{hot} . This fact can be used to describe how R-value varies with temperature and an equation that provides the material R-value for a range of temperatures. The equation used to describe the temperature dependent R-value when the change in R-value is not linear can be a polynomial equation.

The two methods for calculating R-value described above are shown in Figure 1. The blue data points and line in Figure 1 describes a material where the change in R-value over the temperature range is linear. The red data and curve in Figure 1 describes a material where the change in R-value over the temperature range is non-linear. Both materials had measurements performed according to ASTM C518 and the thermal data was evaluated using ASTM C1045. Appendix A contains the full mathematical example for both data sets.

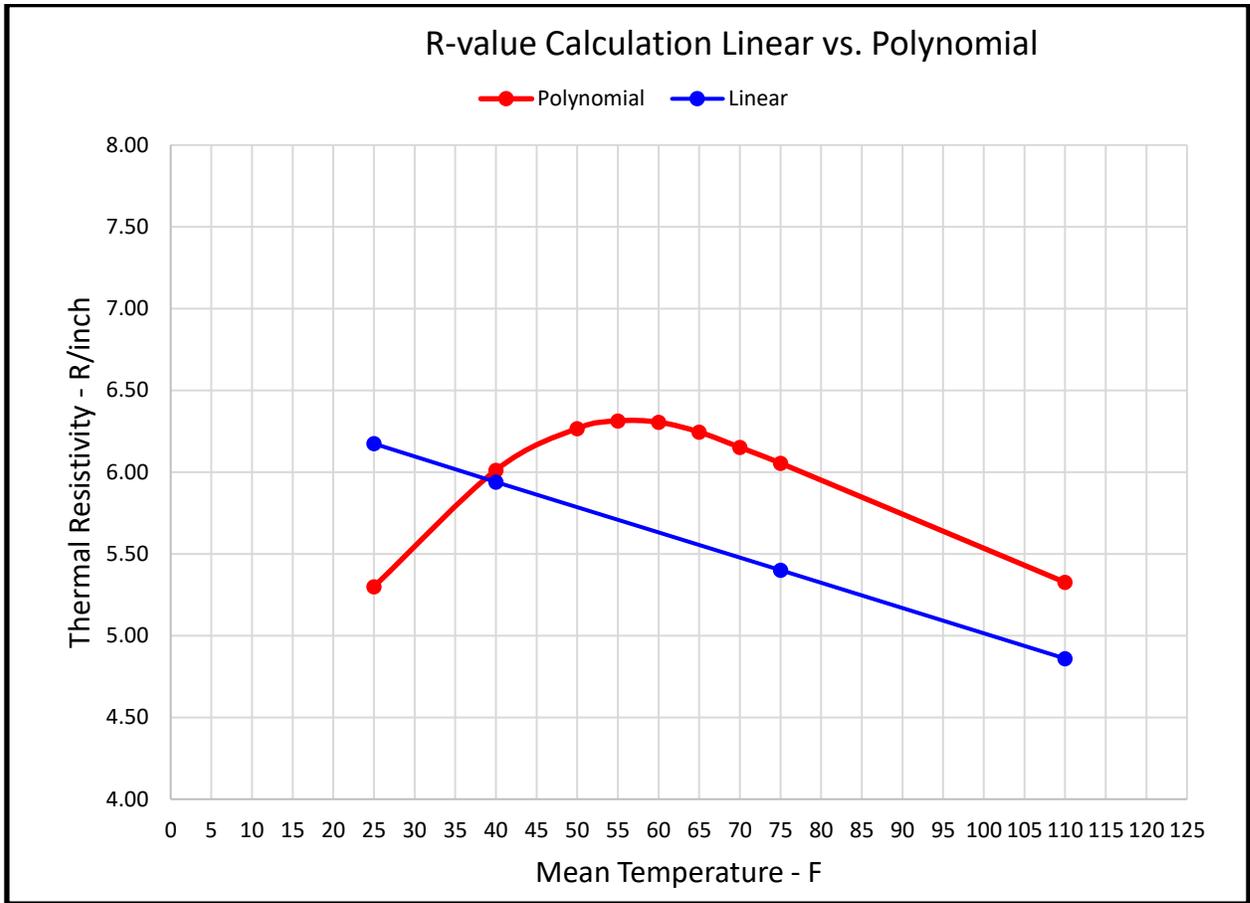


Figure 1 – R-Value of two data sets

Conclusion

Insulation materials are evaluated for thermal performance using widely accepted consensus measurement techniques and are reported in accordance with federal law. All insulation materials have varying thermal performance as the temperature changes. These changes can be linear with respect to temperature where there are no chemical or physical changes or these changes can be more complex when chemical or physical changes do occur. ASTM C1045 is used to calculate the range of thermal performance for all measurement and material types.

ASTM C518 “Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus
ASTM C1045 “Standard Practice for Calculating Thermal Transmission Properties Under Steady-State Conditions”

APPENDIX A

Figure 1 contains data of two materials with curve fit equations derived from ASTM C1045. This appendix contains detailed examples of a curve fit for materials where k_a is linear over the temperature range of use and a curve fit where k_a is nonlinear over the temperature range of use. The examples presented here are in terms of R-value. The procedure would be the same if calculating k_a substituting the apparent thermal conductivity for R-value.

Example when k_a is linear over the temperature range

The set of data in Table 1 was obtained by measuring a material where the relationship of k_a is linear with respect to temperature over the measurement range. Table 1 contains the linear data from Figure 1. \bar{R} and \bar{T} are the average R-value and temperature respectively of the data set.

Test Number	R-value	T _{hot} (°F)	T _{cold} (°F)	Average Temperature (°F)
1	6.86	5	45	25
2	6.60	20	60	40
3	6.00	55	95	75
4	5.40	90	130	110
\bar{R}	6.22		\bar{T}	62.5

Table 1. Selective measurements in accordance to ASTM C518

The equation to calculate R-value with respect to temperature is given in Equation 4 when k_a is linear over the temperature range.

$$R = mT + R_{intercept} \quad (4)$$

The equations for calculating slope, m , and $R_{intercept}$, are given in equations 5 and 6 respectively.

$$m = \frac{\sum(R-\bar{R})(T-\bar{T})}{\sum(R-\bar{R})^2} \quad (5)$$

$$R_{intercept} = \bar{T} - m\bar{R} \quad (6)$$

Using the data from Table 1 and solving equations 5 and 6 and substituting the coefficients, the linear equation for the data set contained in Table 1 is given in Equation 7.

$$R = -0.01717 \cdot T + 7.2879 \quad (7)$$

Example when k_a is nonlinear over the temperature range

ASTM C1045 contains the steps required for the thermal conductivity integral method. Table 2 contains the nonlinear, or polynomial data from Figure 1.

The set of data in Table 2 was obtained by measuring a material where the relationship of k_a is not linear with respect to temperature over the measurement range.

Test Number	R-value	T _{hot} (°F)	T _{cold} (°F)	Average Temperature (°F)
1	5.326	130	90	110
2	6.055	95	55	75
3	6.151	90	50	70
4	6.245	85	45	65
5	6.305	80	40	60
6	6.313	75	35	55
7	6.267	70	30	50
8	6.012	60	20	40
9	5.300	45	5	25

Table 2. Selective measurements in accordance to ASTM C518

A third order equation is typically used to describe the change of R-value versus temperature. The equation is given in Equation 8.

$$R(T) = a_0 + a_1T + a_2T^2 + a_3T^3 \quad (8)$$

The coefficients from equation 8, a_0 , a_1 , a_2 , and a_3 , are solved using the method of least squares. The coefficients are solved by integrating equation 8 and simplifying to get X_1 , X_2 , and X_3 . The terms X_1 , X_2 , and X_3 are calculated from the experimental data for the final regression analysis using equations 9, 10, and 11 respectively. Table 3 contains the coefficients from the experimental data in Table 2 solved using equations 9, 10, and 11.

$$X_1 = \frac{T_h + T_c}{2} \quad (9)$$

$$X_2 = \frac{T_h^2 + 2T_hT_c + T_c^2}{4} \quad (10)$$

$$X_3 = \frac{T_h^3 + 3T_h^2T_c + 3T_hT_c^2 + T_c^3}{8} \quad (11)$$

Test Number	X_1	X_2	X_3
1	110	12100	3647487
2	75	5625	6241219
3	70	4900	4477375
4	65	4225	3114688
5	60	3600	2088000
6	55	3025	1337781
7	50	2500	810125
8	40	1600	235000
9	25	625	17312.5

Table 3. Method of least squares data

Using the data contained in Table 3 to complete the regression, the third order equation for the test data in Table 2 is given in Equation 12.

$$R(T) = 2.750 + 1.345 E^{-1} \cdot T - 1.317 E^{-3} \cdot T^2 + 1.021 E^{-7} T^3 \quad (12)$$

The method of least squares can be used to solve linear test data and solved for in Equation 7.

Using Microsoft Excel to simplify calculation procedures

Microsoft Excel can be used to perform the calculations. For a linear equation the following syntax can be used to solve for the slope and intercept.

=**slope**(known_ys,known_xs)
 =**intercept**(known_ys,known_xs)

In Figure 1 the “known_ys” are the R-values and the “known_xs” are the mean test temperatures.

The regression for the nonlinear example requires an array. The syntax for the regression is given below.

=**linest**(known_ys,known_xs)

The “known_ys” are the R-values and the “known_xs” is the array calculated for the coefficients X_1 , X_2 , and X_3 given in Table 3. The R-values (known ys) and X_1 (known xs) are needed for a linear system, the R-values (known ys) and X_1 and X_2 (known xs) are needed for a second order polynomial fit, and the R-values (known ys) and X_1 , X_2 , and X_3 (known xs) are needed for a third order polynomial fit as shown in Equation 8.

To perform the regression, take the following steps:

Step 1: For a linear, second order, or third order regression, select 2, 3 or 4 cells in a row respectively.

Step 2: Enter the “linest” syntax selecting the appropriate cells for the known xs and known ys

Step 3: Press and hold the Control and Shift keys, then press Enter

The coefficients, are returned in the selected cells in the following order, from left to right; a_3 , a_2 , a_1 and a_0 for a third order polynomial.