Designation: C740 – 97 (Reapproved 2004)

Standard Practice for
Evacuated Reflective Insulation In Cryogenic Service[1]

This standard is issued under the fixed designation C740; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers the use of thermal insulations formed by a number of thermal radiation shields positioned perpendicular to the direction of heat flow. These radiation shields consist of alternate layers of a low-emittance metal and an insulating layer combined such that metal-to-metal contact in the heat flow direction is avoided and direct heat conduction is minimized. These are commonly referred to as multilayer insulations (MLI) or super insulations (SI) by the industry.

1.2 The practice covers the use of these insulation constructions where the warm boundary temperatures are below approximately 450 K.

1.3 Insulations of this construction are used when apparent thermal conductivity less than 0.007 W/m·K (0.049 Btu·in./h·ft^2·°F) at 300k are required.

1.4 Insulations of this construction are used in a vacuum environment.

1.5 This practice covers the performance considerations, typical applications, manufacturing methods, material specification, and safety considerations in the use of these insulations in cryogenic service.

1.6 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* For specific safety hazards, see Section 8.

2. Terminology

2.1 *Symbols:*

a = accommodation coefficient, dimensionless
b = exponent, dimensionless
d = distance between confining surfaces, m

q = heat flow per unit time, W
A = unit area, m^2
n = number of radiation shields
σ = Stefan-Boltzmann constant, 5.67×10^{-8} W/m^2·K^4
T = temperature, K; T_h at hot boundary, T_c at cold boundary
E = emittance factor, dimensionless; E_{eff}, system effective emittance
e = total hemispherical emittance of a surface, dimensionless; e_h at hot boundary, e_c at cold boundary
t = distance between the hot boundary and the cold boundary, m
k = thermal conductivity, W/m·K
R = shielding factor, dimensionless; equivalent to $1/E$
D = degradation factor, dimensionless
P = mechanical loading pressure, Pa

2.2 *Definitions:*

2.2.1 *evacuated reflective insulation*—Multilayer composite thermal insulation consisting of radiation shield materials separated by low thermal conductivity insulating spacer material of cellular, powdered, or fibrous nature designed to operate at low ambient pressures.

2.2.2 *ohms per square*—The electrical resistance of a vacuum metallized coating measured on a sample in which the dimensions of the coating width and length are equal. The ohm-per-square measurement is independent of sample dimensions.

3. Insulation Performance

3.1 *Theoretical Performance*:

3.1.1 The lowest possible heat flow is obtained in an MLI when the sole heat transfer mode is by radiation between free floating shields of low emittance and of infinite extent. The heat flow between any two such shields is given by the relation:

$$q/A = E(\sigma T_h^4 - \sigma T_c^4) \tag{1}$$

3.1.1.1 (Refer to Section 2 for symbols and definitions.) The emittance factor, E, is a property of the shield surfaces facing one another. For parallel shields, the emittance factor is determined from the equation:

$$E = 1/(1/e_h + 1/e_c - 1) = e_h e_c/e_h + (1 - e_h)e_c \tag{2}$$

3.1.1.2 When these opposing surfaces have the same total hemispherical emittance, Eq 2 reduces to:

$$q/A = \frac{e}{n(2-e)+e}(\sigma T_H^4 - \sigma T_H^4)$$

$T_H = 300K \ (540R)$
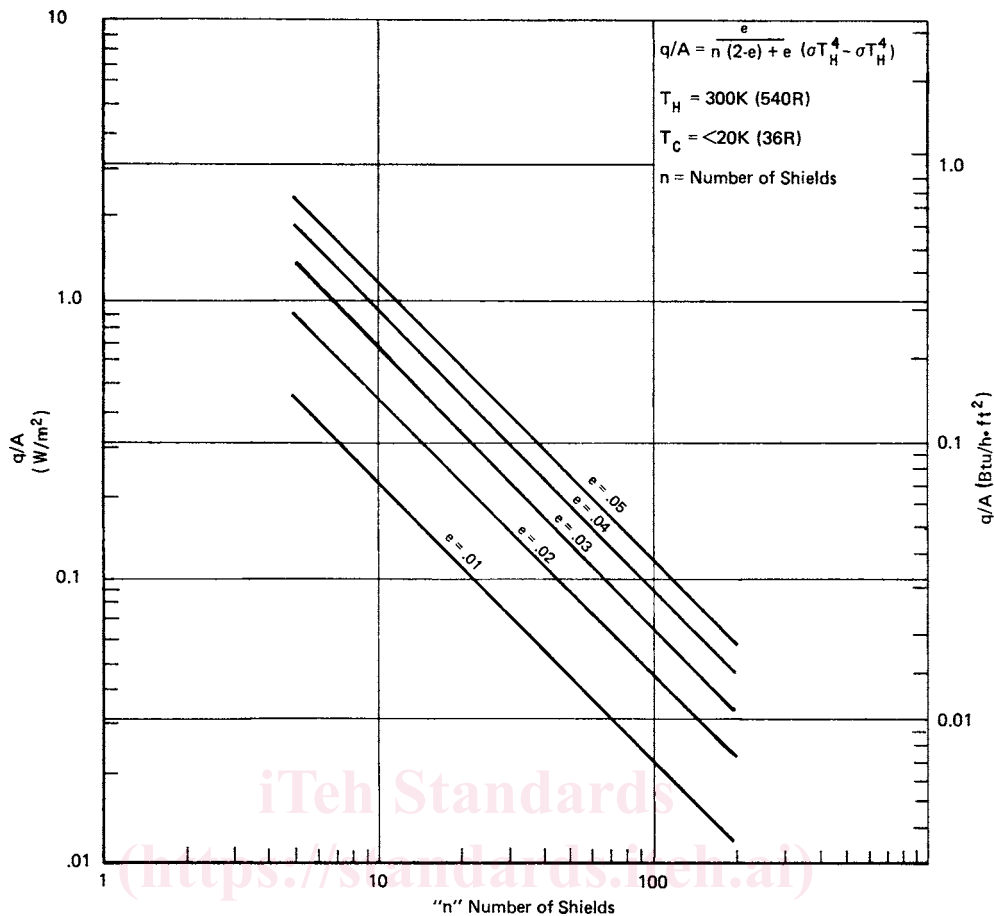
$T_C = <20K \ (36R)$

n = Number of Shields

FIG. 1 MLI Theoretical Heat Flow for Various Shield Emittances and 1.0 Boundary Emittance

$$E = e/(2 - e) \qquad (3)$$

3.1.2 An MLI of n shields is normally isolated in a vacuum environment by inner and outer container walls. When the surface emittance of the shields and of the container walls facing the shields have the same value, then the emittance factor is given by:

$$E_1 = e/(n + 1)(2 - e) \qquad (4)$$

where $(n + 1)$ is the number of successive spaces formed by both the container walls and the shields.

3.1.3 When the surface emittance of the shields has a value $e < 1.0$ and the boundaries have an emittance of 1.0, then the emittance factor is given by:

$$E_2 = e/(n (2 - e) + e) \qquad (5)$$

For values of $e \leq 0.1$, Eq 4 and Eq 5 can be simplified to $E = e/(2 (n + 1))$ and $E = e/2 \ n$, respectively, and the loss in accuracy will be less than 10 %.

3.1.4 Computed values of the theoretical MLI heat flow obtained by using Eq 1 and Eq 5 are presented in Fig. 1.

3.1.5 Well-designed and carefully fabricated MLI systems have produced measured heat flows within approximately 50 % of their theoretical performance. In practice, however, several important factors usually combine to reduce significantly the actual performance compared to the theoretical performance. The principal sources of this degradation are:

3.1.5.1 The mechanical loading pressure imposed across the insulation boundaries,

3.1.5.2 The composition and pressure level of the interstitial gas; and

3.1.5.3 Penetration such as mechanical supports, piping and wiring.

3.2 *Mechanical Loading Pressure*:

3.2.1 In practice, the shields of an MLI are not free-floating. Compression between the layers due to the weight of the insulation or to pressures induced at the boundaries, or both, can cause physical contact between the shields producing a direct conduction heat transfer path between the shields, thereby increasing the total heat flux of the system.

3.2.2 The effects of compression on the heat flux are usually obtained experimentally using a flat plate calorimeter.[2] Experimental correlations have been obtained for a variety of shield-spacer combinations which indicate that the heat flux is proportional to P^b where b varies between 0.5 and 0.66. Typical data for a number of MLI systems are presented in Fig. 2 that illustrate this effect.

---

[2] Black, I. A., Glaser, P. E., and Perkins, P. "A Double-Guarded Cold-Plate Thermal Conductivity Apparatus," *Thermal Conductivity Measurements of Insulating Materials at Cryogenic Temperatures, ASTM STP 411*, ASTM International, 1967.
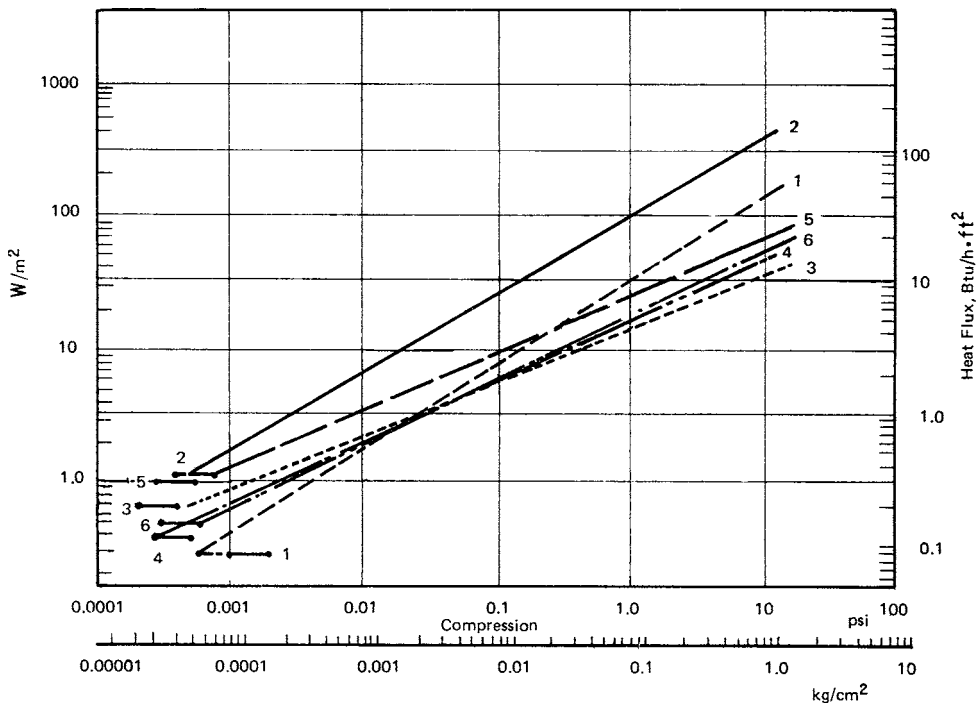
Curve No.	Numbers of Layers	Material
1	10	1145—H19 Tempered Aluminum
	11	Nylon Netting
2	10	Aluminized (both sides) Polyester
	22	Glass Fabric
3	10	Aluminized (both sides) Polyester
	33	Silk Netting
4	10	Aluminized (both sides) Polyester
	11	2 lb/ft^3 Polyurethane Foam
5	10	Aluminized (both sides) Polyester
	11	Silk Netting with 0.004-in. by 0.5-in. Strips of Glass Mat
6	10	Aluminized (both sides) Polyester
	11	Silk Netting with 0.008-in. by 0.25-in. Strips of Glass Mat

FIG. 2 Effect of External Compression on the Heat Flux Through Multilayer Insulations

3.3 *Interstitial Gas*—Heat transfer by gas conduction within an MLI may be considered of negligible importance if the interstitial gas pressure is in the range from 10^{-2} to 10^{-3} Pa depending upon the type of spacer material used. This pressure is achieved with (*a*) a vacuum environment of approximately 10^{-3} to 10^{-4} Pa, and (*b*) with a well-vented shield-spacer system which provides communication between the interstitial spaces and the vacuum environment. Failure to provide these minimal conditions results in a serious increase in the thermal conductance of the insulation system. The effect of excessive gas pressure on conductivity is illustrated for a number of insulation systems in Fig. 3.

3.4 *Performance Factors*:

3.4.1 A number of factors have come into technical usage to fill the need for expressing the thermal performance of an MLI by a single, simple, and meaningful value. Two schools of thought have predominated. One is to express the performance in terms of radiation transfer since these insulations are predominantly radiation controlling. The other is to use the classical thermal conductivity term in spite of the fact that the thermal profile across these insulations is not linear. Elaboration and a discussion of the limitations of these approaches follow:

3.4.2 *Effective Emittance*:

3.4.2.1 The effective emittance of an MLI has the same meaning as the emittance factor, E or E_2, when it is applied to the theoretical performance of the system. The effective emittance of an actual system is given by the ratio of the measured heat flux per unit area to the differences in the black body emissions (per unit area) of the boundaries at their actual temperatures as given by Eq 6.

$$E_{eff} = (q/A)/(\sigma T_h^4 - \sigma T_c^4) \tag{6}$$

3.4.2.2 The measured average total effective emittance of a given insulation will have different values depending upon the number of shields, the total hemispherical emittance of the shield materials, the degree of mechanical compression present between layers of the reflective shields, and the boundary temperatures of the system. This effective emittance factor can be used to compare the thermal performance of different MLI systems under similar boundary temperature conditions.
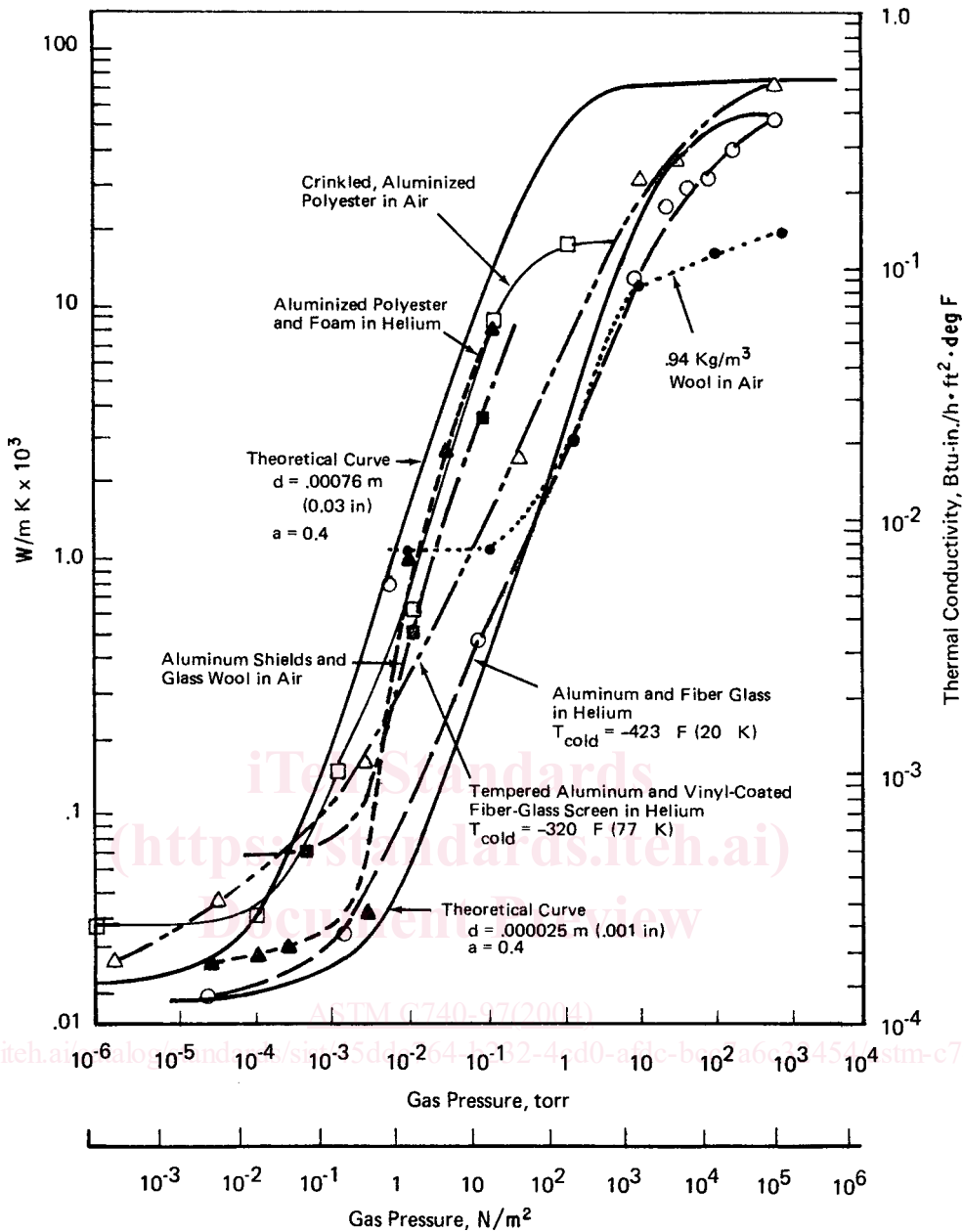
NOTE 1—d = distance between confining surfaces
a = accommodation coefficient (dimensionless)

FIG. 3 Effect of Gas Pressure on Thermal Conductivity

3.4.3 *Shielding Factor*:

3.4.3.1 The theoretical shielding factor, R, is the reciprocal of the emittance factor. This factor can also be obtained by summing the reciprocal emittances of each shield surface as one proceeds from one of the system boundaries to the other and then subtracting 1.0 from the result for each space traversed.

3.4.3.2 The actual system shielding factor is the reciprocal of the effective emittance of the system, that is, $R = 1/E$.

3.4.4 *Degradation Factor*—The degradation factor, D, is the ratio of the actual system heat flux to the theoretical system heat flux, that is,

$$D = (q/A) \text{ actual } / (q/A) \text{ theoretical} \qquad (7)$$

this factor can only have values larger than 1.0. At a value of 1.0 the amount of degradation is zero and the actual performance corresponds to the theoretical performance.

3.4.5 *Thermal Conductivity*:

3.4.5.1 The apparent thermal conductivity of an MLI system can be defined by the ratio of the heat flow per unit area to the average temperature gradient of the system in comparable units as follows:

$$k_a = (q/A)/((T_h - T_c)/t) \qquad (8)$$

3.4.5.2 Since radiative heat transfer present within an MLI system produces a nonlinear temperature gradient, k will vary approximately as the third power of the mean temperature.