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

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~~[0.049 Btu·in./h·ft^2~~·°F)~~·°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.

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

1.6 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

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 *Definitions of Terms Specific to This Standard:*

2.1.1 *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.

2.1.2 *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.

2.2 *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

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[1] This practice is under the jurisdiction of ASTM Committee C16 on Thermal Insulation and is the direct responsibility of Subcommittee C16.21 on Reflective Insulation.

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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:

(1) $q/A = E(\sigma T \text{ h } 4 - \sigma T\text{c } 4)$

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:

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

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:

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:

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.

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:

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[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.

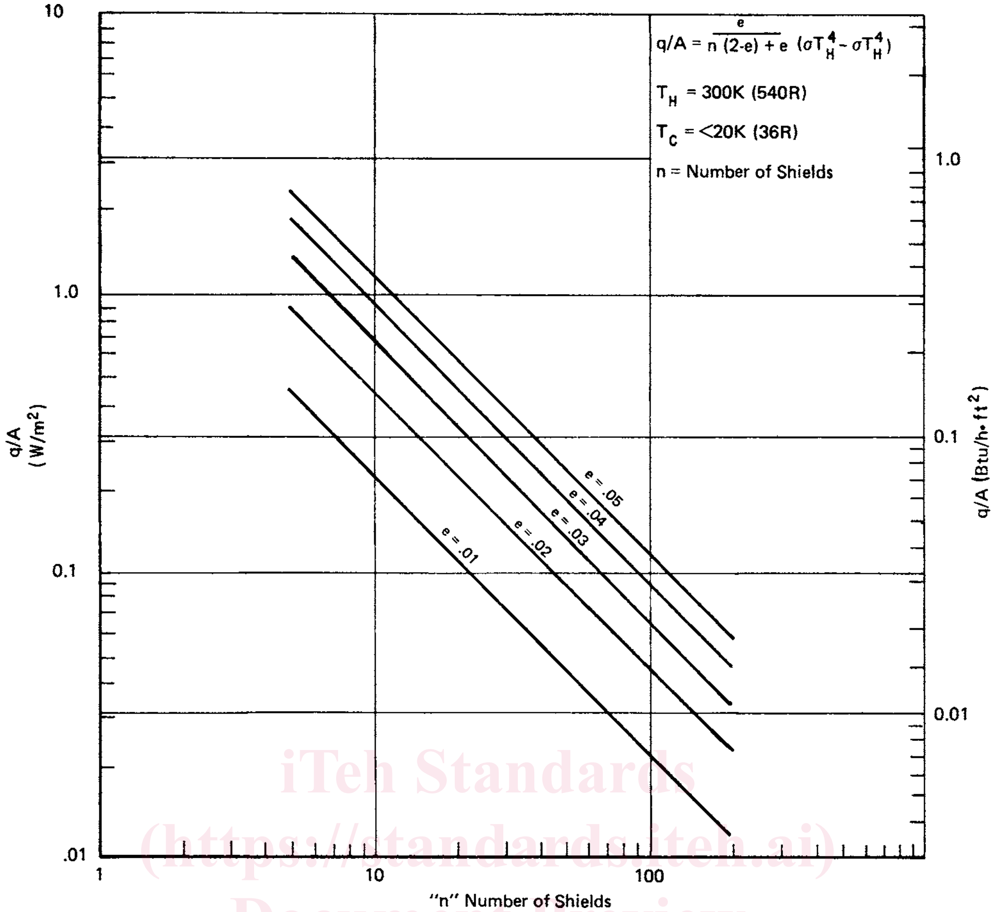


FIG. 1 MLI Theoretical Heat Flow for Various Shield Emittances and 1.0 Boundary Emittance

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.

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.

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,

(7) $D = (q/A)$ actual / (q/A) theoretical

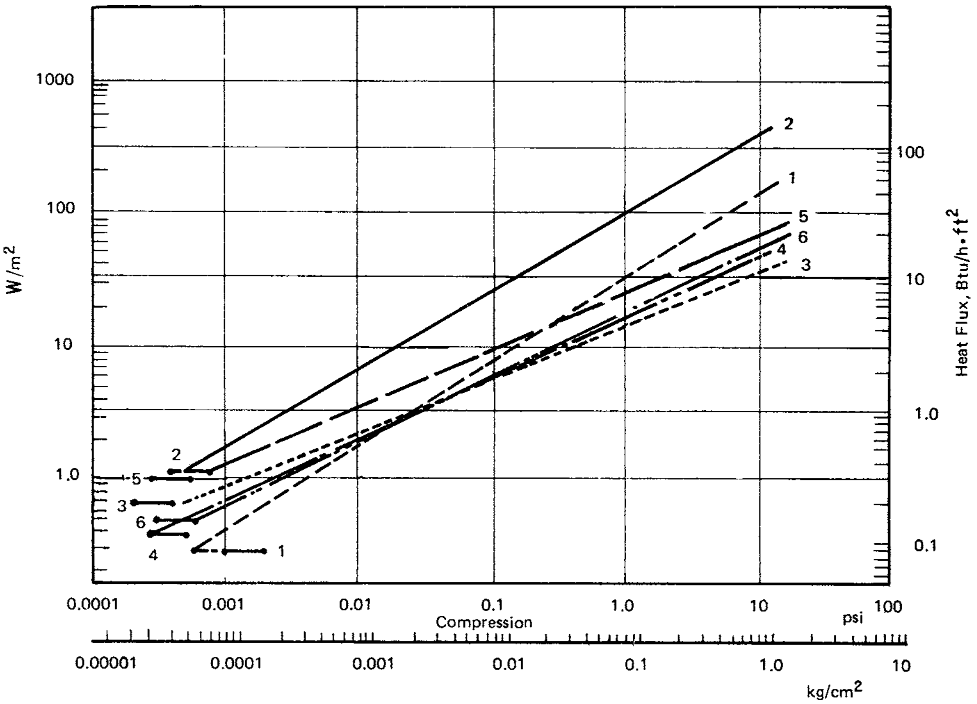
this factor can only have values larger than 1.0. At a value of 1.0 the amount of degradation is zero and the actual performance corresponds to the theoretical performance.

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:

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. Thus, k can be used only for comparison of performance of different MLI systems when the boundary temperatures are the same.

3.4.5.3 A second difficulty associated with the use of a k for MLI systems is the necessity of defining the insulation thickness.



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

This is possible only in certain types of measurement apparatus and in mechanized MLI systems. Thus, whenever *k* is used to describe the thermal performance of an MLI, it should be accompanied by a statement indicating the method used in making the thickness measurement or the accuracy with which such a measurement was made.

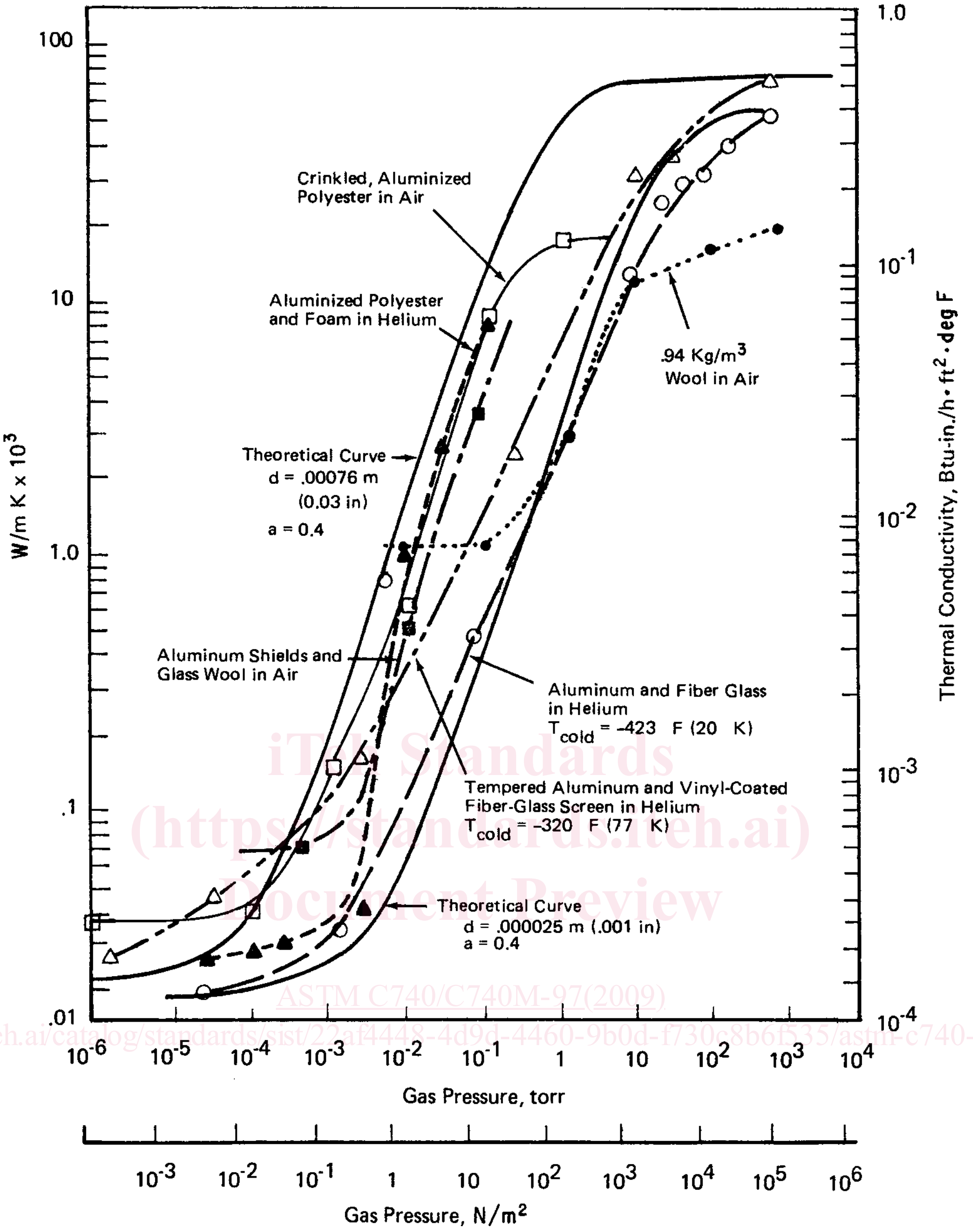
3.5 *Typical Thermal Performance of MLI*—The thermal performance of MLIs can vary over a wide range from system to system depending largely upon the fabrication techniques, but also upon the materials used for the shields and spacers. Typical performance values of installed systems are shown in Table 1 as well as the pertinent information concerning the system characteristics and installation data. Thermal performance for some systems was shown in both the effective emittance and thermal conductivity terms where this information was available.

4. Typical Applications

4.1 Insulations of the type described above are generally used when lower conductivities are required than can be obtained with other evacuated insulations or with gas-filled insulations. This may be dictated by the value of the cryogenic fluid being isolated or by weight or thickness limitations imposed by the particular application. Generally these fall into either a storage or a distribution equipment category. Typical storage applications include the preservation of biologicals, onboard aviation breathing gas, piped-in hospital oxygen systems, welding and heat-treating requirements, distribution storage reservoirs, and industrial users whose requirement cannot be economically met with gas storage. Distribution applications include railroad tank cars, highway trucks and trailers, pipe lines, portable tankage of various sizes, all serving the metal industry, medicine, and space exploration programs. Specialized applications such as surgical operating tools and space vehicle oxidizer and fuel tanks have also seen significant development.

5. Techniques of Manufacture

5.1 *General*:



NOTE 1—d = distance between confining surfaces
a = accommodation coefficient (dimensionless)

FIG. 3 Effect of Gas Pressure on Thermal Conductivity

5.1.1 An MLI requires that each metal layer is separated from the next with a minimum number and size of low conductance contacts and with a minimum contact pressure. Thus each radiation shield is made from metal foils or from metal-coated plastics often crinkled or dimpled, with a separate material, usually a glass, polymer, or natural fiber formed into a fabric, netting, foam, paper, mat, or web to ensure that no direct metal contact is made. In some cases when a metal-coated plastic is used, the low thermal conductivity plastic forms the separator (see 7.3.2).

5.1.2 It is the objective of the MLI manufacturing techniques to:

5.1.2.1 Reduce the solid conduction heat flow by minimizing the compression between the layers.

5.1.2.2 Reduce gas conduction heat flow by providing flow paths within the insulation so that the interstitial gas can be removed by the vacuum environment, and

5.1.2.3 Reduce the radiation heat flow by utilizing low-emittance shield materials and by the elimination of gaps, spaces, or openings in each shield layer.

5.2 *Application*:

5.2.1 The user has a wide variety of application techniques available to him. They include, but are not limited to, the spiral-wrap, blanket, single-layer, and filament-wound techniques.

TABLE 1 Performance and Weight Summary for Typical Installed MLI Systems

	System Characteristics				Installation Data								Thermal Performance		
System Number	Radiation Shield	Spacer	Perforations	No. of Shields	System wt.		System Surface Area		System[A] Thickness		Heat Flux[B]		Effective[C] Total Emittance	Effective Emittance Per Shield	Thermal[D] Conductivity Btu· ft/h· ft^2·° F
					g/m^2	lb/ft^2	m^2	ft^2	cm	in.	W/m^2	Btu/h·ft^2			
1	¼-mil polyester gold-coated both sides	3 layers silk netting per shield	no	5	137	0.028	3.67	39.5	NA[E]	NA	1.04	0.33	2.3×10^{-3}	1.2×10^{-2}	not calculated
2	¼-mil polyester A1 coated both sides	2 layers silk netting per shield	no	5	112	0.023	3.67	39.5	NA	NA	1.36	0.43	3.3×10^{-3}	1.7×10^{-2}	not calculated
3	¼-mil polyester A1 coated both sides	2 layers glass fabric per shield	no	5	288	0.059	3.67	39.5	NA	NA	1.67	0.53	3.6×10^{-3}	1.8×10^{-2}	not calculated
4	1.88% perforated ¼-mil polyester A1 coated both sides	2 layers glass fabric per shield	yes 1.88%	5	288	0.059	3.67	39.5	NA	NA	3.28	1.04	7.1×10^{-3}	3.6×10^{-2}	not calculated
5	¼-mil polyester A1 coated both sides	20-mil open-cell polyurethane foam	no	10	234	0.048	2.19	23.6	NA	NA	1.23	0.39	2.6×10^{-3}	2.6×10^{-2}	not calculated
6	¼-mil polyester A1 coated both sides	35-mil polyurethane foam	no	37	1231	0.252	2.92	31.4	NA	NA	0.54	0.17	1.2×10^{-3}	4.4×10^{-2}	not calculated
7	¼-mil polyester A1 coated both sides	2.8-mil Dexiglas paper	no	30	703	0.144	5.48	59.0	NA	NA	1.42	0.45	3.1×10^{-3}	9.3×10^{-2}	not calculated
8	¼-mil polyester A1 coated both sides	½-mil polyester Dimplar A1 coated both sides	no	36	527	0.108	NA	NA	NA	NA	1.92	0.61	4.2×10^{-3}	15.1×10^{-2}	not calculated
9	3-mil A1 foil	dimpled composite 0.3-mil A1 foil 5-mil fiberglass ¼-mil polyester	no	20	5227	1.07	>2.69	>29	NA	NA	3.09	0.98	6.7×10^{-3}	13.4×10^{-2}	not calculated
10	¼-mil crinkled polyester A1 coated one side	none	yes 0.5%	42	308	0.063	>2.69	>29	NA	NA	1.89	0.60	4.1×10^{-3}	17.2×10^{-2}	not calculated
11	¼-mil A1 foil	glass fiber paper	no	29	977	0.20	0.16	1.76	1.02	0.40	0.76	0.24	1.6×10^{-3}	4.64×10^{-2}	0.022×10^{-3}
12	¼-mil A1 foil	rayon fabric	no	36	1124	0.23	1.09	11.7	1.32	0.52	0.57	0.18	1.2×10^{-3}	4.34×10^{-2}	0.019×10^{-3}
13	¼-mil A1 foil	glass fiber web	no	21	830	0.17	0.28	3.02	2.26	0.89	1.83	0.58	3.9×10^{-3}	8.2×10^{-2}	0.109×10^{-3}

[A] Thickness determined by circumferential tape measurement.

[B] Based on measured heat flux corrected to warm boundary temperature of + 80°F and cold boundary <–320°F.

[C] $\varepsilon = [q/A]\sigma T_w^4$

[D] Between boundary temperature given in footnote *A*.

[E] NA, not available.