Designation: C 740 – 97 (Reapproved 2004)

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

This standard is issued under the fixed designation C 740; 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:

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

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:

$$E = 1/(1/e_h + 1/e_c - 1) = e_h e_c/e_h + (1 - e_h)e_c \quad (2)$$

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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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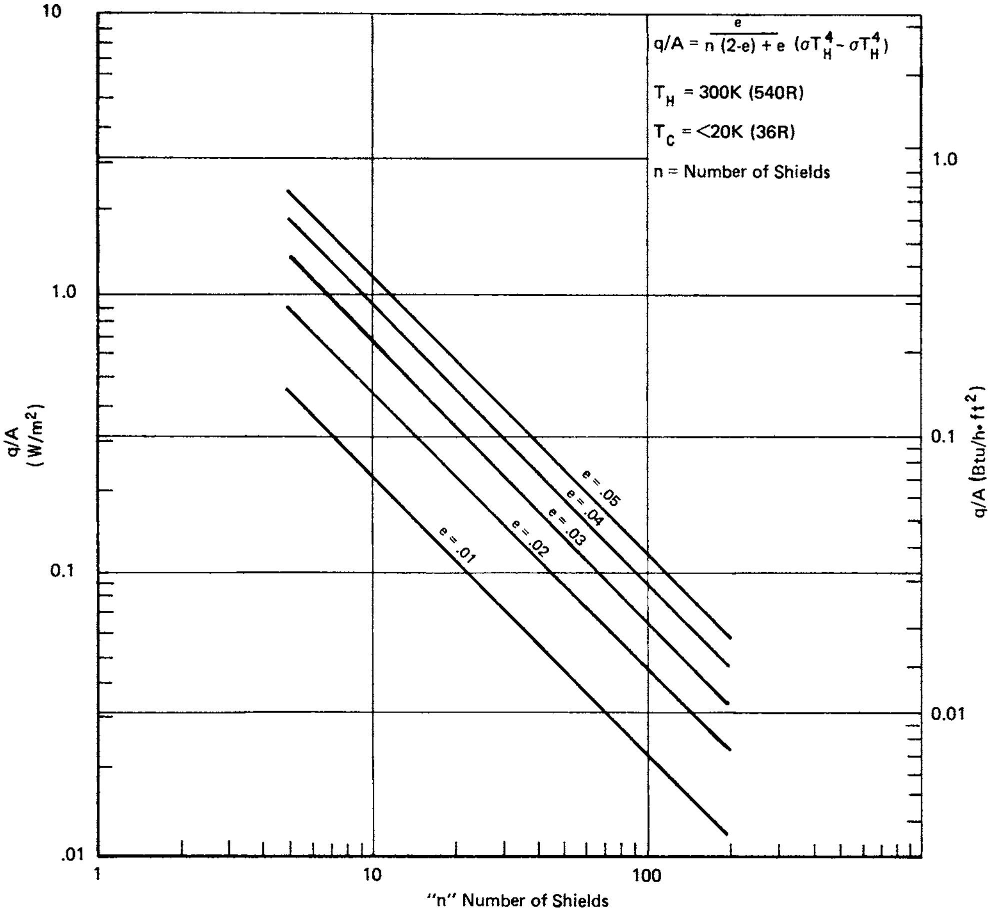

FIG. 1 MLI Theoretical Heat Flow for Various Shield Emittances and 1.0 Boundary Emittance

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

$$E = e/(2 - e) \tag{3}$$

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:

$$E_1 = e/(n + 1)(2 - e) \tag{4}$$

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:

$$E_2 = e/(n\,(2 - e) + e) \tag{5}$$

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.

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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.

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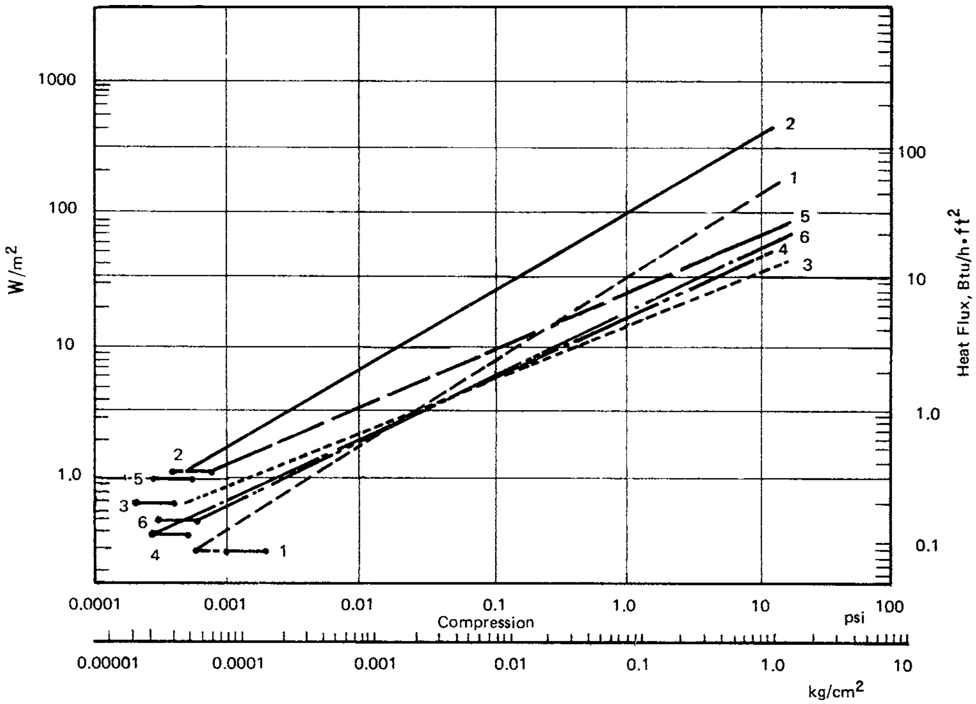

Curve No.	Numbers of Layers	Material
1	10	1145—H19 Tempered Aluminum
	11	Nylon Netting
2	10	Aluminized (both sides) Polyester
	22	Glass Fabric
3	10	Aluminized (both sides) Polyester
	33	Silk Netting
4	10	Aluminized (both sides) Polyester
	11	2 lb/ft^3 Polyurethane Foam
5	10	Aluminized (both sides) Polyester
	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

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:

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.

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

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*:

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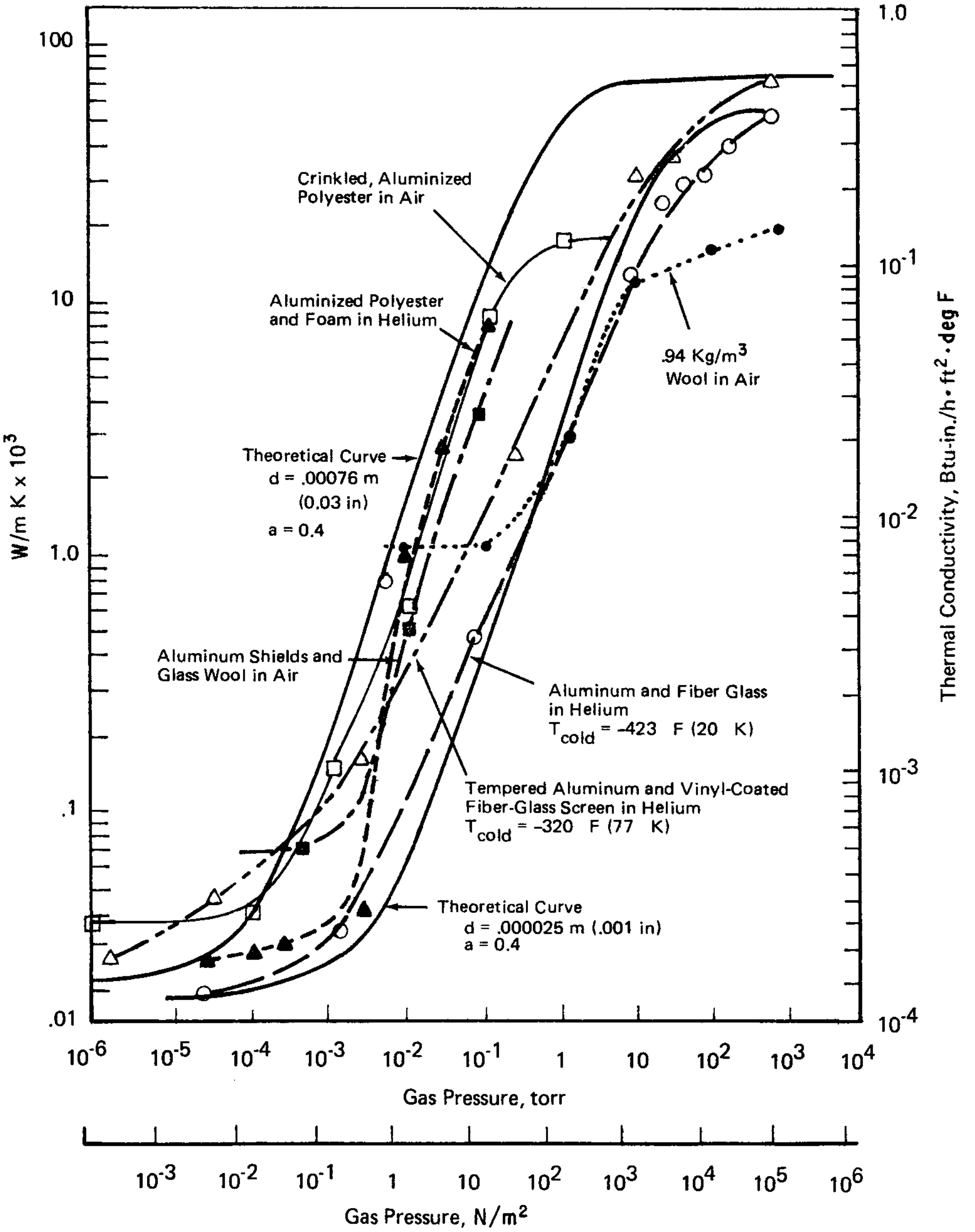

NOTE 1—d = distance between confining surfaces
a = accommodation coefficient (dimensionless)

FIG. 3 Effect of Gas Pressure on Thermal Conductivity

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,

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

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:

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

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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. 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*:

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.

5.2.2 *Spiral-Wrap Method*:

5.2.2.1 The spiral-wrap technique is applicable mainly to the cylindrical segments of tanks. The shields and spacers are applied together from rolls onto the rotating cylinder in a continuous manner until the desired thickness or number of layers is achieved. This method is compatible with automatic manufacturing techniques as well as with manual techniques. The shield and spacer material may have the same width as the cylinder or segments of the cylinder. In some cases the shield segments are butt-joined. It is the recommended and general practice, however, to eliminate the possibility of gaps developing between segments by providing a generous overlap of the shield segments. Overlaps of 51 mm (2 in.) are typically used.

5.2.2.2 To obtain the best thermal performance, the shields and spacers of the tank ends are applied individually in a manner such that the end shields are interleaved with the side shields. An alternative procedure is to apply the MLI onto the cylindrical portion of the vessel so that it extends over the tank end a distance comparable to the radius. The tank ends can then be insulated by folding the extended portion of insulation over the tank end. Alternatively, the extended portion of the insulations can be appropriately gored and then folded over the tank end; or alternatively, the space formed by the extended insulation and the tank end can be filled with a powder, open-celled foam, or fibrous insulating material.

5.2.3 *Blanket Method*:

5.2.3.1 MLI blankets can be formed with two or more shield-spacer layers and can be applied to many surface geometries. The blankets may be formed initially on a flat surface or on a surface that duplicates the curvature of the surface to be insulated. When the desired number of layers have been combined, they are sometimes held together with special attachments at spaced intervals. The blanket is then sheared to the required size and shape and applied to the surface to be insulated.

5.2.3.2 The vessel surface can be insulated with a single blanket or with two or more blanket segments in which the joints are butted together. Additional layers of blankets can be installed over the first layer. The joints of the outer layer should be staggered with respect to the joints of the inner layer. Further, the corresponding shields in each blanket layer should be appropriately overlapped at the joints.

5.2.4 *Single-Layer Method*:

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TABLE 1 Performance and Weight Summary for Typical Installed MLI Systems

System Number	System Characteristics				Installation Data								Thermal Performance		
	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] $\epsilon = [q/A]\sigma T_w^4$

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

[E] NA, not available.

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5.2.4.1 MLIs can be formed to a wide variety of surface geometries by the individual application of the shields and spacers. First, a spacer layer is placed onto the entire surface to be insulated. This layer would be composed of surface segments, which are stitched together at the joints to form a closed and conforming spacer. Next, the shield layer is placed over the entire surface. Again, like the spacer, the shield may be composed of surface segments, and these segments are overlapped at the joints whenever possible. The insulation system is built up to the desired number of shields with the alternate application of spacers and shields.

5.2.4.2 It is important that there is no mechanical pressure buildup between layers as each successive shield-spacer layer is applied. This is often accomplished, particularly on articles having the major dimension of a metre or less, by fabricating each layer (shield-spacer combination) on its own dimensionally accurate form. The layers are then removed from the forms and assembled together onto the insulated article in the appropriate sequence.

5.2.5 *Filament-Wound Method*—This method of insulation is done with automatic machinery. The insulation is applied in the form of a strip up to several inches wide consisting of both the shield and spacer. The machinery rotates the item to be insulated, positions the shield strip relative to the rotating tank, and adjusts the strip tension. Its action is very similar to a filament-winding machine for glass-fiber tank manufacture. Once initiated, the winding of the shield is continued until the desired thickness is achieved.

5.3 *Insulation Attachment and Support*:

5.3.1 Because MLIs consist of separate layers of material, a method of securing these layers in place must be used so that they will not slip or shift during fabrication or use.

5.3.2 *Shell Containment*—The insulation is frequently held in position by containing it between two walls, one the surface being insulated and the other an outer shell. Care must be taken here to space the walls close enough to constrain the insulation material in place and not too closely to overly compress the insulation, thereby degrading the insulation effectiveness.

5.3.3 *Cinch Band*—Another approach to attachment to large objects is to apply narrow cinch bands around the object at a minimum number of positions after it is insulated, thereby applying compression to only a small portion of the insulated surface area. Care must be taken to avoid internal metal-to-metal contact within the insulation system. Allowance must be made to account for the local reduction in insulation performance caused by the application of the bands as well as any possible effect they may have on the allowable evacuation rate.

5.3.4 *Penetration Members*—Layers of MLI can be pinned to the wall of the item being insulated or they can be stitched or quilted together into blankets which can then be attached to the item to be insulated. Again, allowance for the effect of these pins or stitches must be made on the thermal performance of the insulation.

5.3.5 *Shingles*—Application of the material in the form of shingles where one end of each piece of the material is attached directly to the tank wall with adhesives and overlapping an adjacent shingle, is especially attractive where rapid venting of gas between layers is desirable, such as on earth launched space vehicles. In this method, the insulation effectiveness is governed by the length of the shingle since the lateral conduction along the shields will now be added to that of the basic performance of the multilayer configuration.

5.4 *Joints*:

5.4.1 The method of preparing joints between any two segments of MLI is critical to the thermal performance of the system. Continuity of layers shall be maintained to ensure that metal-to-metal contact is avoided and there shall be no significant permanent gaps or openings in the MLI at the joint locations. Any relative motion between the two components produced either by the thermal or the mechanical environments, or both, shall be taken into account during fabrication. Introduce features to prevent gaps and openings from developing.

5.4.2 Gaps can be avoided by generously overlapping the shields at the joint locations. If butt-joining of shield cannot be avoided, then the shields of each component must be restrained to prevent the gap from increasing. Alternatively, a strip of shield material can be placed over the butt joint, overlapping the shields at the joining locations.

5.5 *Penetrations*:

5.5.1 In any practical system, the penetration of the MLI with pipes, supports, and wiring cannot be avoided. These penetrations produce unacceptable thermal shorts unless they are insulated and unless this insulation is properly integrated with the main surface insulations and direct metal-to-metal contact avoided.

5.5.2 Because of the small thicknesses associated with MLI, it is necessary to increase the effective length of the penetration between the cold and warm boundary temperatures. MLI is placed around the penetration and extends from the main surface outward along the penetration several diameters (the exact length to be established by the user).

5.5.3 Because MLIs are anisotropic, the best possible thermal isolation of the penetration at the joint is obtained by interleaving the shields of the penetration MLI with the main surface MLI. This is accomplished by cutting gores in the shields of one of the components at the joint and overlapping the gore segments with the shields of the second component. Alternatively, a preformed corner shield can be placed at the corner locations in a manner that they overlap the shields in each component.

5.5.4 Alternatively, the corner formed by the two components can be filled with a preformed isotropic insulating material such as plastic foam, glass wool, and encapsulated powders.

5.6 *Evacuation Rates*—Evacuation of multilayer reflective insulations, whether by vacuum pump or by ascent through the atmosphere (for example, on space vehicles), must occur without damage to the insulation. During evacuation, a gas pressure gradient will exist within the insulation. The user must either control the evacuation rate such that the pressure gradient does not damage or blow off the insulation, or if this cannot be accomplished, then the rate at which the enclosed gas (air or a purge gas) can escape from between the shields must be enhanced. This is usually done by perforating the shields to provide broadside flow in addition to that via the

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edges. However, the effect of these perforations on the overall thermal efficiency must be taken into account.

6. Cleanliness

6.1 It is essential that the materials used be clean, and that the wrapping area be clean. Dust, organic materials, etc., can cause significant outgassing, and certain foreign materials can corrode reflective surfaces and thereby increase the emittance, that is, reduce the reflectance. Particularly, fingerprints should be avoided, because body acid can cause corrosion of foil, and can even cause the reflective coating of plastics to disappear in time.

6.2 If sorbers or chemical getters are used, it may be necessary to protect these from contamination prior to pump-down. In some cases, insulation rooms should not only be clean, but also dry.

6.3 It is recommended that wrapping always be done in a clean room, and that materials be protected by clean paper wrapping when not actually being applied.

6.4 It is recommended that clean clothing and gloves be worn by any person actually handling the insulation materials.

7. Materials Specifications

7.1 Multilayer reflective insulation systems always have multiple sheets of reflector material, each separated by low conductance separator material. Considering reflector sheets first, these depend on the low emissivity characteristic of clean smooth metal surfaces. The metal can be a sheet of foil, or it can be a coating of some appropriate nonmetal. The two most commonly used materials are (*1*) thin aluminum foil, and (*2*) vapor deposited aluminum on polyester film.

7.2 *Foils*:

7.2.1 Since the materials used must be thin and highly reflective, the foils are usually high-purity metals having high thermal conductivity. Such metals as gold, silver, and aluminum could be used, but the choice is obviously aluminum because of cost. The most commonly used aluminum foil is 1145-0. This material has a 99.45 % purity, is soft, and can be obtained in thin highly reflective sheets. Other alloys of aluminum, or even other metals, are acceptable if highly reflective throughout the range of temperatures expected. One side, at least, should reflect 95 % or more of the thermal radiation incident on it, that is, the emittance at all temperatures of interest should be 0.05 or less. The other side should not differ greatly. A foil with sufficient reflectance will appear bright and shiny on both sides, although perhaps only one of the sides will be mirror-like (normal bright finish), the other having a semi-matte finish. Noticeably dull or tarnished surfaces are cause for rejection. Contamination, such as oil or pigment coatings, or even numerous fingerprints, is also cause for rejection.

7.2.2 Mechanically, there are several requirements. The foil used should be thin enough to restrict lateral heat conduction, and to give flexibility for easy folding without stiffness. The latter property is usually assured for thin enough foils because only soft metal can be cheaply rolled into very thin sheets. As a general rule, aluminum foil should not be more than 12.5 µm (0.0005 in.) thick, although heavier weights have been used. A thickness of 7.5 µm (0.0003 in.) or slightly less is preferable and is near the lower limit for practical manufacturing (rolling) techniques. Finally, it is desirable to order foil from the mill in the widths required, but if it must be trimmed, then the edges must not be left in a sharp and ragged condition, which could tear separator material and cause thermal shorts. A typical material specification might read: Dead soft 1145-0 aluminum foil, 7.5 µm + 0, −1.25 µm (0.00030 in. thick + 0, −0.00005 in.), one side normal bright finish, 1.22-m (45-in.) wide roll, delivered free of oil or other surface contamination, and without splices. These specifications can be varied by the manufacturer to suit his particular design.

7.3 *Metallized Plastics*:

7.3.1 Next, consider metallized non-metals, for example, aluminized polyester film. Various sheet materials may be vapor deposited (in vacuum) with aluminum, gold, etc., to a thickness sufficient for optical opacity. Several methods are available for determining if enough metallizing has been applied to produce a low emittance surface. One simple method is to determine the electrical resistance laterally across a square of the material. The deposit should be thick enough that the resistance is less then some number of ohms, "per square"; many users require enough aluminum deposit (on aluminized plastics) that a resistance of a half to one ohm per square results. The method is certainly open to objections, but is at least a minimum test. A simpler but less reliable test is to hold a sample of the material between the observer and a lighted object (light bulb, the sun, etc.). If the lighted object can easily be seen through the material, then the metal coating is probably too thin. Uncoated areas, such as windows, can be detected by the lighted object test or by the resistance measurement test. Where possible, suppliers should be required to verify the emittance or the ohms per square thickness measurement, or both, of any questionable material. Therefore, it is reasonable, and acceptable, to vapor deposit both sides to give better performance. Coating adhesion is commonly checked by placing a length of transparent adhesive tape, approximately 102 mm (4 in.) long, over the coating and removing it rapidly. The material is not acceptable if any of the coating remains adhered to the tape when it is removed.

7.3.2 The lateral conduction of metallized plastics is so low that sometimes they are used without a separator material. When this is done, crinkling or embossing is required so that only small areas (or points) of contact occur between layers. If reflector materials of this type are to be used, then adequate crinkling or embossing must be assured.

7.3.3 Although various metallized materials may be used for reflectors, aluminized or gold-coated polyester or polyimide are the most common. Naturally, materials chemically equivalent to these plastics are satisfactory. However, other substitute materials must not show excessive outgassing in vacuum, and they must remain somewhat resilient at low temperatures. While it is theoretically possible to use metallized materials besides plastics, such materials should be tested carefully before using. A typical material specification might read: 6.25 µm (0.00025 in.) polyester sheet, 1.22 m (48 in.) wide, aluminized both sides having a resistance of ½ ohm per square on each side. Such a specification will provide for reasonable control over the quality of the material. It has

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generally been found that suppliers are not able to measure and therefore ensure the emissivity of these plated materials. It has been possible to get coatings with emittance as low as 0.025 from a few suppliers. The more usual are in the 0.035 range.

7.4 *Separator Materials*:

7.4.1 Separator sheets used between the reflectors need to have a very low thermal conduction in the direction perpendicular to the sheet. Typical examples of such separators are silk and polyester net, fiberglass woven cloth, fiberglass mats, fiberglass paper, and rayon fiber paper. Frequently, separator materials are papers made of many small, low-conductivity fibers laid together without a binder so that there are many layers of fibers crossed over and over, all lying substantially in the plane of the paper, but randomly oriented within the plane. In order to reduce the thickness of the paper, to reduce thermal conduction, and to present many points of contact, it is desirable to use fibers only a few micrometres in diameter or less. This may be specified in purchasing. The fibers may be of various sizes and may be made of various materials; but as a general rule, larger fibers can be tolerated when the separators are used between sheets of metallized plastic than when used between sheets of metal foil. The use of binder materials in the paper increases thermal conduction, so paper should be ordered without binder. Also, there are differences in the thermal conduction of the various materials when under compressive load. For example, certain organic fibers such as polyester or rayon are not as sensitive to light mechanical loads as is fiberglass paper.

7.4.2 The most serious problem with many mechanically and thermally acceptable separators is their severe vacuum outgassing. If substantial outgassing does occur, provision must be made for adequate gettering of these contaminants. A typical separator material specification might read: glass fiber paper, 75 µm (0.003 in.) thick and weight as close to 21.5 g/m^2 (2 g/ft^2) as possible. Maximum acceptable thickness 100 µm (0.004 in.) and maximum weight 27 g/m^2 (2.5 g/ft^2).

7.5 *Shell Materials*—The shells that contain the insulation must be chosen to prevent excess outgassing, or at least to give off only those gases or vapors which can be conveniently gettered. Characteristically, stainless steel or aluminum are used, the former giving off predominantly hydrogen from the body of the metal. Plastic materials, for example, fiber-glass-epoxy can be used for shells, but porosity and permeation as well as outgassing may become a problem unless the materials are carefully chosen. A typical specification for stainless steel might be specified as 10-gage 304L sheet 1.22 by 2.44 m (48 by 96 in.), delivered clean, without occlusions, and with removable paper protection on the surface. Fiberglass-epoxy and other plastic materials are not normally sold with a guarantee for the limit of either outgassing or gas permeation, but once a particular material has been proved acceptable, then it may be specified in terms of the company designation for that one material (usually proprietary).

8. Hazards

8.1 The temperatures of some cryogens, that is, liquid nitrogen, neon, helium, and hydrogen, are low enough to condense or solidify atmospheric gases. During such behavior, oxygen enrichment of the condensed or solidified gases is likely to occur. Some insulation systems may have organic constituents, which in contact with oxygen-enriched gases constitute a fire and explosion hazard. Caution should be taken to exclude atmospheric gases from these insulations where such oxygen enrichment could occur.

8.2 The vacuum shells used to house vacuum insulations must be designed in accordance with applicable pressure vessel codes to minimize shell failure and provide failure mode protection, such as pressure relief, etc., to the insulation spaces.

8.3 Fabrication personnel must be provided with suitable protection from shield materials that can produce bodily cuts due to their small thickness and high-edge velocities during application with certain methods.

9. Keywords

9.1 cryogenic insulation; insulation; multilayer insulation; radiation; radiation shields; reflective insulation; super insulation; vacuum insulation

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