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

This standard is issued under the fixed designation C740/C740M; 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 guide 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. The technology of evacuated reflective insulation in cryogenic service, or MLI, first came about in the 1950s and 1960s primarily driven by the need to liquefy, store, and transport large quantities of liquid hydrogen and liquid helium. (**1-6**)[2]

1.2 The practice guide covers the use of these MLI systems where the warm boundary temperatures are below approximately 400 K. Cold boundary temperatures typically range from 4 K to 100 K, but any temperature below ambient is applicable.

1.3 Insulation systems of this construction are used when heat flux values well below 10 W/m^2 are needed for an evacuated design. Heat flux values approaching 0.1 W/m^2 are also achievable. For comparison among different systems, as well as for space and weight considerations, the effective thermal conductivity of the system can be calculated for a specific total thickness. Effective thermal conductivities of less than 1 mW/m-K [0.007 Btu·in/h·ft^2·°F or R-value 143] are typical and values on the order of 0.01 mW/m-K have been achieved [0.00007 Btu·in/h·ft^2·°F or R-value 14 300]. (**7**) Thermal performance can also be described in terms of the effective emittance of the system, or E_e.

1.4 These systems are typically used in a high vacuum environment (evacuated), but soft vacuum or no vacuum environments are also applicable.(**8**) A welded metal vacuum-jacketed (VJ) enclosure is often used to provide the vacuum environment.

1.5 The range of residual gas pressures is from <10^{-6} torr to 10^{+3} torr (from <1.33^{-4} Pa to 133 kPa) with or without different purge gases as required. Corresponding to the applications in cryogenic systems, three sub-ranges of vacuum are also defined: from <10^{-6} torr to 10^{-3} torr (from <1.333^{-4} Pa to 0.133 Pa) [high vacuum/free molecular regime], from 10^{-2} torr to 10 torr (from 1.33 Pa to 1333 Pa) [soft vacuum, transition regime], from 100 torr to 1000 torr (from 13.3 kPato 133 kPa) [no vacuum, continuum regime].(**9**)

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 9.

2. Referenced Documents

2.1 *ASTM Standards:*

B571 Practice for Qualitative Adhesion Testing of Metallic Coatings

C168 Terminology Relating to Thermal Insulation

E408 Test Methods for Total Normal Emittance of Surfaces Using Inspection-Meter Techniques

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *cold boundary temperature (CBT)*—The cold boundary temperature, or cold side, of the MLI system is the temperature of the cold surface of the element being insulated. The *CBT* is often assumed to be the liquid saturation temperature of the cryogen. The *CBT* can also be denoted as T_c.

3.1.2 *cold vacuum pressure (CVP)*—The vacuum level under cryogenic temperature conditions during normal operation, but typically measured on the warm side of the insulation. The *CVP* can be from one to three orders of magnitude lower than the *WVP* for a well-designed cryogenic-vacuum system.

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[2] The boldface numbers in parentheses refer to a list of references at the end of this standard.

3.1.3 *effective thermal conductivity (k_e)*—The k_e is the calculated thermal conductivity through the total thickness of the multilayer insulation system between the reported boundary temperatures and in the specific environment.

3.1.4 *evacuated reflective insulation*—Multilayer insulation (MLI) system consisting of reflector layers separated by spacer layers. An MLI system is typically designed to operate in a high vacuum environment but may also be designed for partial vacuum or gas-purged environments up to ambient pressures. Additional components of an MLI system may include tapes and fasteners, and mechanical supports; closeout insulation materials and gap fillers for penetrations and feedthroughs; and getters, adsorbents, and related packaging for maintaining vacuum conditions.

3.1.5 *getters*—The materials included to help maintain a high vacuum condition are called getters. Getters may include chemical getters such as palladium oxide or silver zeolite for hydrogen gas, or adsorbents such a molecular sieve or charcoal for water vapor and other contaminants.

3.1.6 *heat flux*—The heat flux is defined as the time rate of heat flow, under steady-state conditions, through unit area, in a direction perpendicular to the plane of the MLI system. For all geometries, the mean area for heat transfer must be applied.

3.1.7 *high vacuum (HV)*—residual gas pressure from $<10^{-6}$ torr to 10^{-3} torr ($<1.33^{-4}$ Pa to 0.133 Pa) [free molecular regime].

3.1.8 *hot vacuum pressure (HVP)*—The vacuum level of the system under the elevated temperatures during a bake-out operation. SI units: Pa; in conventional units: millitorr (μ); 1 μ = 0.133 Pa.

3.1.9 *layer density (x)*—The layer density is the number of reflector layers divided by the total thickness of the system. The number of reflector layers is generally referred to as the *number of layers (n)* for an MLI system.

3.1.10 *no vacuum (NV)*—residual gas pressure from 100 torr to 1000 torr (13.3 kPa to 133 kPa) [continuum regime].

3.1.11 *ohms per square*—The electrical sheet resistance of a vacuum metalized 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.

3.1.12 *reflector material*—A radiation shield layer composed of a thin metal foil such as aluminum, an aluminized polymeric film, or any other suitable low-emittance film. The reflector may be reflective on one or both sides. The reflector may be smooth, crinkled, or dimpled. The reflector may be unperforated or perforated

3.1.13 *residual gas*—As a perfect vacuum is not possible to produce, any gaseous material inside or around the MLI system is the residual gas. The concentration of residual gases can vary significantly through the thickness of the system of closely spaced layers. The residual gas between the layers is also referred to as interstitial gas.

3.1.14 *soft vacuum (SV)*—residual gas pressure from 10^{-2} torr to 10 torr (1.33 Pa to 1333 Pa) [transition regime].

3.1.15 *spacer material*—A thin insulating layer composed of any suitable low conductivity paper, cellular, powder, netting, or fabric material. A given spacer layer may be a single, double, or more thickness of the material.

3.1.16 *system thermal conductivity (k_s)*—The k_s is the thermal conductivity through the thickness of the total system including insulation materials and all ancillary elements such as packaging, supports, getter packages, and vacuum jacket. As with k_e, the k_s must always be linked with the reported boundary temperatures and in the specific environment.

3.1.17 *warm boundary temperature (WBT)*—The warm boundary temperature, or hot side, of the MLI system is the temperature of the outermost layer of the MLI system. Alternatively, the WBT can be specified as the temperature of the vacuum can or jacket. The WBT can also be denoted as T_h.

3.1.18 *warm vacuum pressure (WVP)*—The vacuum level under ambient temperature conditions

3.2 *Symbols:*

l = mean free path for gas molecular conduction, m
Kn = Knudsen number, ratio of the molecular mean free path length to a representative physical length scale, dimensionless
ξ = diameter of gas molecule, m (nitrogen, 3.14×10^{-10} m)
Q = heat flow per unit time, W
q = heat flux, W/m^2
A = unit area, m^2
k = m^2 thermal conductivity, mW/m·K
k_e = effective thermal conductivity through the total thickness of the insulation system, mW/m-K
k_s = system thermal conductivity through the total thickness of the insulation system and all ancillary elements such as packaging, supports, getter packages, enclosures, etc., mW/m-K
A_e = effective area of heat transfer, m^2
d_e = effective diameter of heat transfer, m
d_i = inner diameter of vessel or piping, m
d_o = outer diameter of vessel or piping, m
L_e = effective length of heat transfer area, m
ρ = bulk density of installed insulation system, kg/m^3
n = number of reflector layers or number of layer pairs (one layer pair = one reflector and one spacer)
z = layer density, n/mm
h_c = solid conductance of spacer material,W/K
k_B = Boltzmann constant, 1.381×10^{-23} J/K
σ = Stefan-Boltzmann constant, 5.67×10^{-8} W/m ^{2}·K4
T = temperature, K; Th at hot boundary, T_c at cold boundary
ΔT = temperature difference, $T_h - T_c$ or $WBT - CBT$
E = emittance factor, dimensionless
E_e = effective emittance of system, dimensionless
e = total hemispherical emittance of a surface, dimensionless; e_h at the hot boundary and e_c at the cold boundary
x = total thickness of the insulation system, mm
I = installation factor, dimensionless
P = mechanical loading pressure, Pa
p = absolute gas pressure, Pa
μ = vacuum level, millitorr (1 μ = 0.1333 Pa)

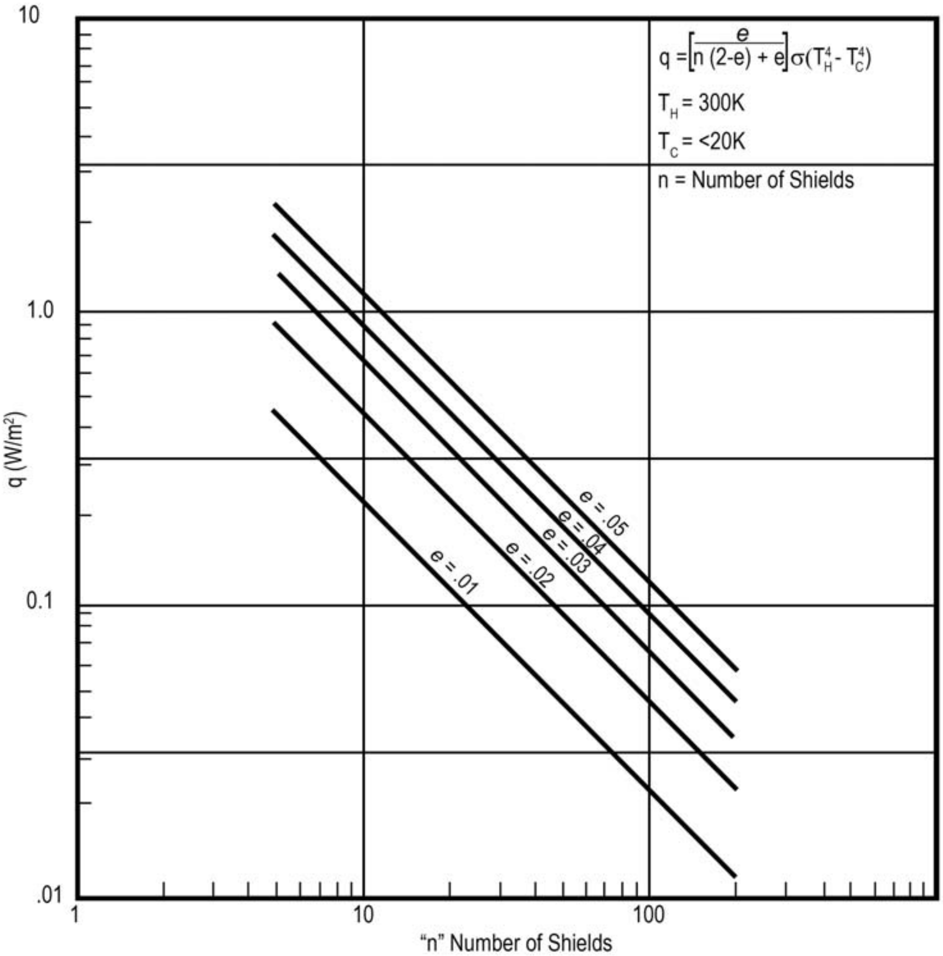


FIG. 1 MLI Theoretical Heat Flow for Various Shield Emittances and 1.0 Boundary Emittance

4. Theroretical Performance and Definition

4.1 *Theoretical Performance:*

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

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

4.1.1.1 The emittance factor, E, is a property of the reflector surfaces facing one another. For parallel reflectors, the emittance factor is determined from the equation:

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

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

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

4.1.2 An MLI of n reflectors is normally isolated in a vacuum environment by inner and outer container walls. When the surface emittances of the reflectors and of the container walls facing the reflectors 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 reflectors.

4.1.3 When the surface emittance of the shields has a value $E < 1.0$ and the boundaries have an emittance of 1.0, representative of a black body, then the emittance factor is given by:

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

For values of e ≤ 0.1, Eq 4 and Eq 5 can be simplified to E = e/[2(n + 1)] and E = e/2n, respectively, and the loss in accuracy will be less than 10 %. Note also that e is a function of temperature. For pure metals, e decreases with temperature. Further considerations include the influence of the spacer on E (for example, the mutual emissivity of two adjacent reflector layers increases when a spacer is present).

4.1.4 Computed values of the theoretical MLI heat flow obtained by using Eq 1 and Eq 5 are presented in Fig. 1.**(10)** Further information on the theory of heat transfer processes associated with MLI systems can be found in the literature.**(11-13)**

4.1.5 Well-designed and carefully fabricated MLI systems tested under ideal laboratory conditions can produce very low heat flux values. In practice, however, several important factors usually combine to significantly degrade the actual performance compared to the theoretical performance. The principal sources of this degradation are listed as follows: *(1)* Composition and pressure level of the interstitial gas between the layers; *(2)* Penetrations such as mechanical supports, piping and wiring; *(3)* Mechanical loading pressure imposed across the insulation boundaries; and *(4)* Localized compression and structural irregularities due to fabrication and installation.**14**,**15**

4.2 *Residual Gas:* Heat transfer by gas conduction within an MLI may be considered negligible if the residual gas pressure under cold conditions (CVP) is below 7.5^{-6} torr (10^{-3} Pa). However, the CVP is typically measured on the warm side and the residual gas pressure between the layers is usually impossible to measure. The vacuum level inside the layers will therefore vary greatly from the vacuum level measured in the surrounding annular space or warm-side vacuum environment. The outer vacuum environment is at a vacuum level corresponding to the WBT while the cold inner surface is at a vacuum level corresponding to the CBT. The CVP, or amount of residual gas, can be imposed by design or can vary in response to the change in boundary temperatures as well as the surface effects of the insulation materials.

4.2.1 For the purposes of this guide, the working definition of *high vacuum (HV)* is a range of residual gas pressure from $<10^{-6}$ torr to 10^{-3} torr ($<1.33^{-4}$ Pa to 0.133 Pa) which represents a free molecular regime of the thermophysical behavior of the gas. In order for free molecular gas conduction to occur, the mean free path of the gas molecules must be larger than the spacing between the two heat transfer surfaces. The ratio of the mean free path to the distance between surfaces is the Knudsen number (Kn). The molecular flow condition is for Kn > 1.0. The mean free path (l) for the gas molecule may be determined from the following equation:

$$l = \frac{k_B T}{\sqrt{2}\pi\xi^2 P} \tag{6}$$

If the mean free path is significantly larger than the separation between the hot side and cold side, then gaseous conduction will be reduced.*16* For many systems, a vacuum pressure of roughly 50 millitorr is the point below which the free molecular range begins. However, some amount of gas conduction still remains until the 10^{-6} torr level is reached. For example, some mean free path values for air at room temperature are approximately 0.1 m for 10^{-3} torr and 100 m for 10^{-6} torr.

4.2.2 The working definition of *soft vacuum (SV)* is a range of residual gas pressure from 10^{-2} torr to 10 torr (1.33 Pa to 1333 Pa) which represents a transition regime of the thermophysical behavior of the gas. The gaseous component of the heat transfer through a material in the SV range is between free molecular conduction and convection. This range is one of sharp transitions and often associated with strong dependencies on the morphology, composition, and construction of the insulation materials. The molecular flow condition is for 1.0 > Kn > 0.01. Thermal insulation systems operating in the soft vacuum range often have all modes of heat transfer working in substantial proportions.

4.2.3 The working definition of *no vacuum (NV)* is a range of residual gas pressure from 100 torr to 1000 torr (13.3 kPa to 133 kPa) which represents a continuum regime of the thermophysical behavior of the gas. The continuum regime is associated with viscous flow and convection heat transfer. The molecular flow condition is for Kn < 0.01. While most MLI systems are designed to operate under high vacuum conditions, other MLI systems may be designed to operate under soft vacuum or no vacuum conditions. In other cases, knowledge of the performance sensitivity due to degraded vacuum or loss-of-vacuum conditions can be crucial for system operation and reliability analysis. The three basic ranges of vacuum levels (high vacuum, soft vacuum, and no vacuum) are depicted in the MLI system performance curve given in Fig. 2.(**17**) In this example, the MLI system is 40 layers of aluminum foil and micro-fiberglass paper under the following conditions: cold boundary temperature of 78 K, warm boundary temperature of 293 K, and gaseous nitrogen as the residual gas.

4.2.4 Cryopumping effects through the innermost layers greatly aid in producing the desired high vacuum levels between the layers by freezing, condensing, and adsorbing the some of the residual gases. The assumption here is that the vacuum environment can be approximately the same as the vacuum between the layers for a properly designed and executed MLI system.

4.2.5 Also important are the type of spacer material used and the layer density. A spacer material that is readily evacuated and very low outgassing is more conducive for obtaining and maintaining the desired high vacuum condition. A lower layer density typically promotes better evacuation and higher ultimate vacuum levels, but an exceptionally low layer density can make maintenance of the high vacuum condition even more critical.

4.2.6 An acceptable CVP is achieved with a well-vented reflector-spacer system that provides communication between the interstitial spaces and the vacuum environment. Failure to provide proper venting can result in serious degradation of thermal performance.

4.3 *Mechanical Loading Pressure:* .

4.3.1 In practice, the reflector layers 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 reflectors producing a more direct conduction heat transfer path between the layers, thereby increasing the total heat flux of the system. The goal in designing any MLI system for high vacuum operation is to minimize the thermal contact as much as possible.

4.3.2 The effects of compression on the heat flux can be obtained experimentally using a flat plate calorimeter.(**18**) Experimental correlations have been obtained for a variety of reflector-spacer combinations that 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. 3 that illustrate this effect. The typical MLI systems listed here provide no significant mechanical strength as the compressive forces should be kept near zero, or less than about 10 Pa (0.001 psi) for optimum performance. The overall configuration of the installed system, whether horizontal or vertical, as well as the unit weight of the MLI must therefore be considered for an accurate estimation of actual system thermal performance. (**19**, **20**)

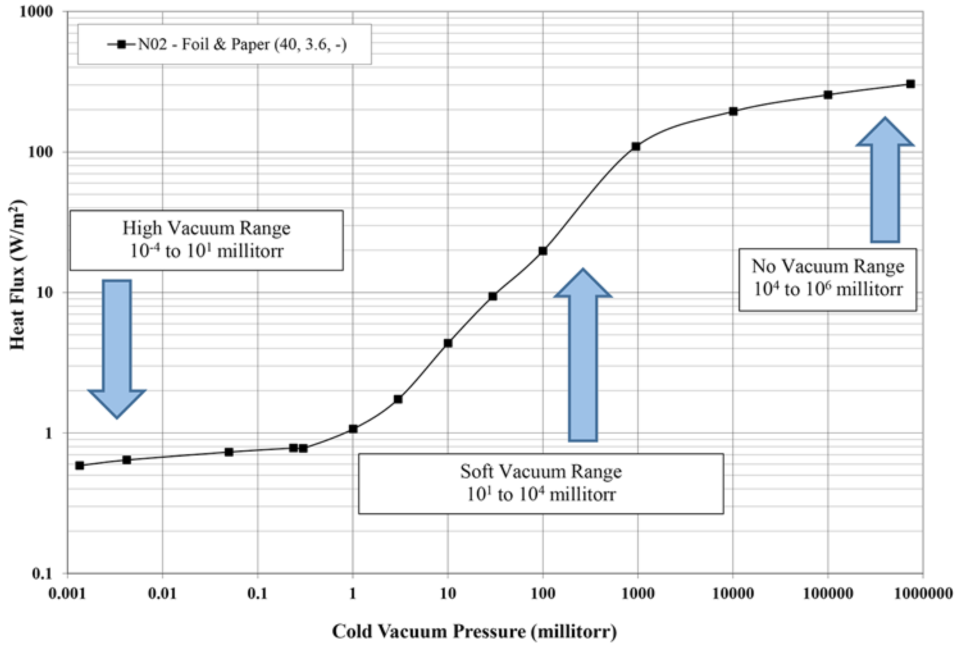


FIG. 2 Variation of Heat Flux with Cold Vacuum Pressure: example MLI system of 40 layers foil and paper with boundary temperatures of 78 K and 293 K and nitrogen as the residual gas. [Note: 1 millitorr = 0.133 Pa]

4.4 *Performance Factors:*

4.4.1 There are three complementary ways of expressing the thermal performance of an MLI system. One way is to express the performance in terms of radiation transfer since these insulations are predominantly radiation controlling. A second way is to calculate the steady-state heat flux. A third way 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 these approaches follow:

4.4.2 *Effective Emittance:*

4.4.2.1 The effective emittance of an MLI has the same meaning as the emittance factor, E_1 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 7. The effective heat transfer areas for both warm and cold surfaces must be applied.

$$E_e = q/\left(\sigma T_{\mathrm{h}}^{4} - \sigma T_{\mathrm{c}}^{4}\right) \tag{7}$$

4.4.2.2 The measured average total effective emittance of a given insulation will have different values depending upon the number of reflectors, the total hemispherical emittance of the reflector materials, the degree of mechanical compression present between layers of the reflectors, 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.

4.4.2.3 *Installation Factor*—The installation factor, *I*, is the ratio of the actual system heat flux to the theoretical system heat flux, that is,

$$I = q_{\mathrm{actual}}/q_{\mathrm{theoretical}} \tag{8}$$

The installation 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. Degradation factors can range from 1.5 to 10 for high vacuum conditions and can be much higher for even moderately degraded vacuum conditions as indicated in Fig. 4. The theoretical system heat flux is not necessarily known, but is generally taken to be the idealized blanket tested under laboratory conditions.

4.4.3 *Heat Flux:*

4.4.3.1 The heat flux, *q*, of a thermal insulation system can be defined by the total heat flow rate divided by the effective area of heat transfer in comparable units as follows:

$$q = Q/A_e \tag{9}$$

The effective heat transfer area, A_e, is the mean area through which heat moves from the hot boundary to the cold boundary and is further defined as follows:

$$\text{For flat disk geometries:} \quad A_e = \frac{\pi}{4} d_e^{2} \tag{10}$$

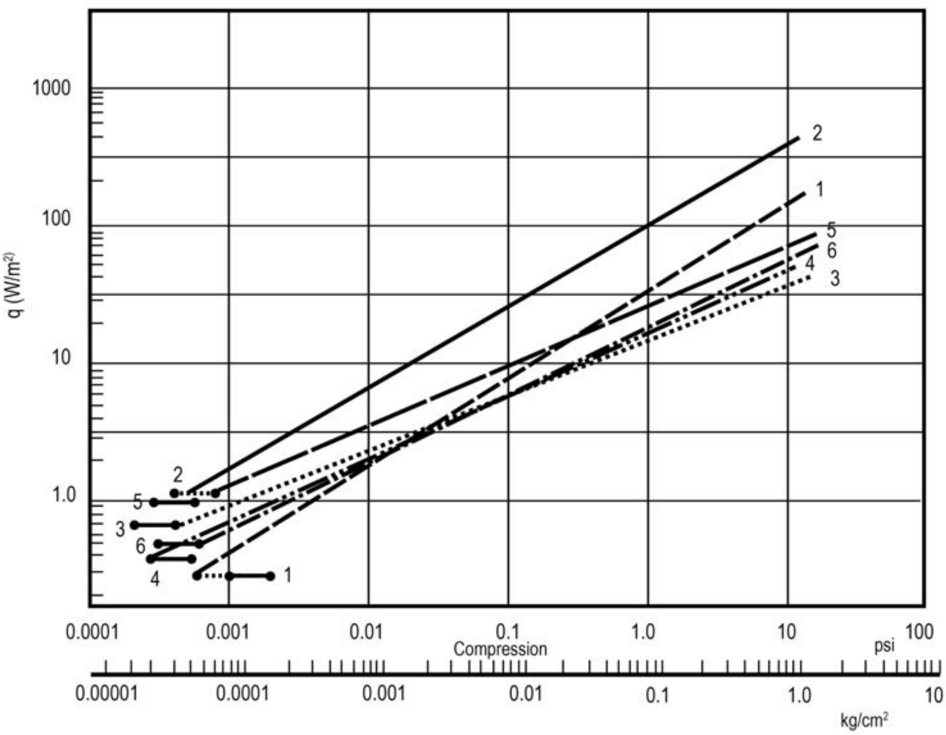
where d_e is taken as the inner diameter of vessel or pipe plus one wall thickness of that same vessel or pipe.

$$\text{For cylindrical geometries:} \quad A_e = 2\pi(L_e)x/1\mathrm{n}\left(\frac{d_o}{d_i}\right) \tag{11}$$

where L_e is the effective heat transfer length of the cylinder and *do* and *di* are the outer and inner diameters, respectively, of the insulation system.

$$\text{For spherical geometries:} \quad A_e = \pi d_o d_i \tag{12}$$

where d_o and d_i are the outer and inner diameters, respectively, of the insulation system. The heat flux can be computed based on the MLI or the total system. For example, the outer diameter of the MLI is chosen for the MLI heat flux while the inner diameter of the vacuum jacket



Curve No.	Numbers of Layers	Reflector	Spacer
1	10	1145—H19 Tempered Aluminum	Nylon Netting (11 layers)
2	10	Aluminized (both sides) Polyester	Glass Fabric (22 layers)
3	10	Aluminized (both sides) Polyester	Silk Netting (33 layers)
4	10	Aluminized (both sides) Polyester	32 kg/m^3 Polyurethane Foam (11 layers)
5	10	Aluminized (both sides) Polyester	Silk Netting with 0.1-mm by 12.7-mm Strips of Glass Mat (11 layers)
6	10	Aluminized (both sides) Polyester	Silk Netting with 0.2-mm by 6.4-mm Strips of Glass Mat (11 layers)

FIG. 3 Effect of Mechanical Compression on Heat Flux

is chosen to compute the total system heat flux. Accordingly, the heat flux should be stated as for the MLI only or for the total system. The basic form using the Fourier rate equation for heat conduction is given as:

$$q = k_e(\Delta T / x) \tag{13}$$

The Lockheed Equation gives an empirical form as follows:

$$q = \frac{C_s * \bar{n}^{2.63}(T_h - T_c) * (T_h + T_c)}{2*(n+1)} + \frac{C_R * e * (T_h^{4.67} - T_c^{4.67})}{n} + \frac{C_G * P * (T_h^{0.52} - T_c^{0.52})}{n} \tag{14}$$

All three modes of heat transfer are accounted for by the leading coefficients: solid conduction (C_S), radiation (C_R), and gaseous conduction (C_G). Even at high vacuum levels, some gas molecules do exist between the layers of radiation shields and spacers necessitating a term for gaseous conduction. The Lockheed Equation (**21**) is based primarily on data from MLI systems comprised of double-aluminized mylar radiation shields with silk net spacers and tested using a flat plate boiloff calorimeter.) Alternatively, the general form for the physics-based equation developed by McIntosh (**22**) is given as follows:

$$q = \frac{\sigma(T_h^4 - T_c^4)}{\left(\frac{1}{\varepsilon_h} + \frac{1}{\varepsilon_c} - 1\right)} + C_G P \alpha (T_h - T_c) + C_s f k \frac{(T_h - T_c)}{x} \tag{15}$$

The McIntosh Equation, as well as the Lockheed Equation, has three terms: one for radiation between shields, one for solid conduction through the spacers, and one for gaseous conduction due to any residual gas molecules among the layers. The term f is the relative density of the spacer compared to the solid form of the material. The use of these or other equations available in the literature requires adequate understanding of all three heat transfer modes as well as the testing methodologies used and the influences of installation for a given application.

4.4.4 *Effective Thermal Conductivity:*

4.4.4.1 The effective thermal conductivity (k_e) 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:

$$k_e = (Q / A_e) \;/\; (\Delta T / x) \tag{16}$$

For highly-evacuated MLI systems, the effective thermal conductivity can be expressed as follows (**23**) :

$$k_e = (N / x)^{-1} / [h_c + \sigma\, e\, (T_h^2 - T_c^2)\, (T_h - T_c) / (2 - e)] \tag{17}$$

The effective thermal conductivity is determined from Fourier's law for heat conduction through a flat plate as given by equation (Eq 18), between concentric cylinders as given by equation (Eq 19), and between concentric spheres as given by equation (Eq 20):

$$\text{Flat Plate: } k_e = \frac{4Qx}{\pi d_e^2 \Delta T} \tag{18}$$

$$\text{Cylindrical: } k_e = \frac{Q\,1\text{n}\left(\frac{d_o}{d_i}\right)}{2\pi L_e \Delta T} \tag{19}$$

$$\text{Spherical: } k_e = \frac{Qx}{\pi d_o d_i \Delta T} \tag{20}$$

4.4.4.2 Because radiation heat transfer within an MLI system produces a nonlinear temperature gradient, k_e will vary approximately as the third power of the mean temperature. Thus, k_e can be properly used for comparison of performance of different MLI systems only when the boundary temperatures are the similar.

4.4.4.3 The total insulation thickness must be carefully defined. Whenever k_e is used to describe the thermal performance of an MLI system, a statement indicating the method used in making the thickness measurement and the accuracy of such measurement is needed. In some cases, an estimate of a range of thicknesses for a given installation may be appropriate. Alternatively, the appropriate diameter of the vacuum can or jacket can be used to establish a thickness for determining an overall system thermal conductivity (k_s).

4.5 *Typical Thermal Performance of MLI*—The thermal performance of MLI systems can vary over a wide range depending largely upon the fabrication techniques, but also upon the materials used for the reflectors and spacers. (**24**) Performance will vary in accordance with different boundary temperatures. Performance can also vary widely for tanks, rigid piping, and flexible piping applications. In all cases, understanding the total system performance, including MLI, supports, attachments, penetrations, getters, etc., is the main point. Testing methods and equipment include a wide range of both boiloff calorimetric and electrical-based techniques.(**25-31**)

5. Practical Performance and Applications

5.1 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.

5.2 *Thermal Performance Data*—Example The typical thermal performance data for a number of MLI systems are given in Fig. 4and Fig. 5.(**9, 14, 17**) These figures show the variation of heat flux with cold vacuum pressure (the residual gas is nitrogen in all cases). The data were obtained using a cylindrical boiloff calorimeter. The thermal performance including the effect of residual gas pressure on effective thermal conductivity is shown in Fig. 6 for nitrogen gas (**9, 14, 17**) and in Fig. 7 for helium gas. (**10**) Table 1 includes the pertinent information concerning the materials, system characteristics, and installation methods. (**9, 10, 14, 17**) Thermal performance is shown for effective emittance, heat flux, and thermal conductivity terms where this information was available. These data are for the boundary temperatures of approximately liquid nitrogen (77 K) and ambient (295 K). Design specifications and thermal performance test results for an example cryogenic MLI system are given in Table 2. (**17**) Additional thermal performance data for different MLI systems can be found in the literature. (**32, 33**)

5.3 *Detailed Performance Considerations:*

5.3.1 *Residual Gas Effects*—The type and amount (vacuum pressure) of residual gas has a strong influence on the resulting thermal performance of MLI systems. The vacuum level, if known, is usually measured at the warm boundary or vacuum enclosure. The vacuum levels between layers are generally unknown and can have significant effects on the thermal performance. Understanding and applying all the available information from the heating, purging, evacuation, and vacuum monitoring steps can help to account for residual gas effects and explain the overall thermal performance results.

5.3.2 *Number of Layers*—The number of layers (n) for MLI systems can be from 1 to 100 or more. If size and weight are not an issue, then more layers are generally better for reducing the heat flux.(**34**) However, sagging in thicker blankets can result in additional compression between the layers and give diminishing returns or even reduced thermal performance.(**35**)

5.3.3 *Layer Density*—The layer density (z) is crucial for estimating the thermal performance of MLI systems. An optimum layer density must be considered in light of the performance targets as well as the practicality of installation techniques. The optimum layer density often varies with different combinations of reflector and spacer materials.(**36**)

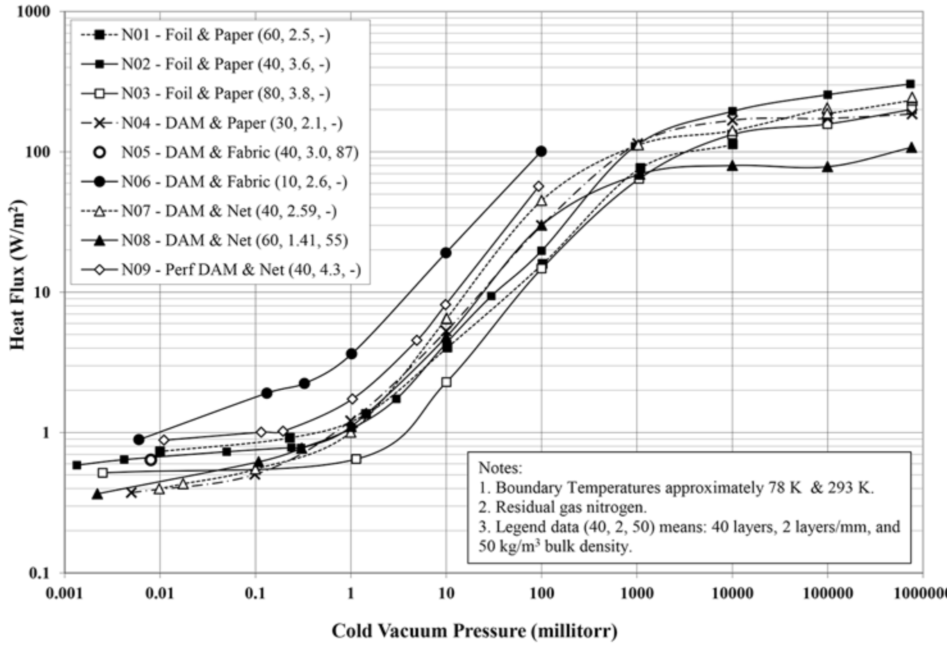


FIG. 4 Variation of Heat Flux with Cold Vacuum Pressure for Various MLI Systems for the Full Vacuum Range [Note: 1 millitorr = 0.133 Pa]

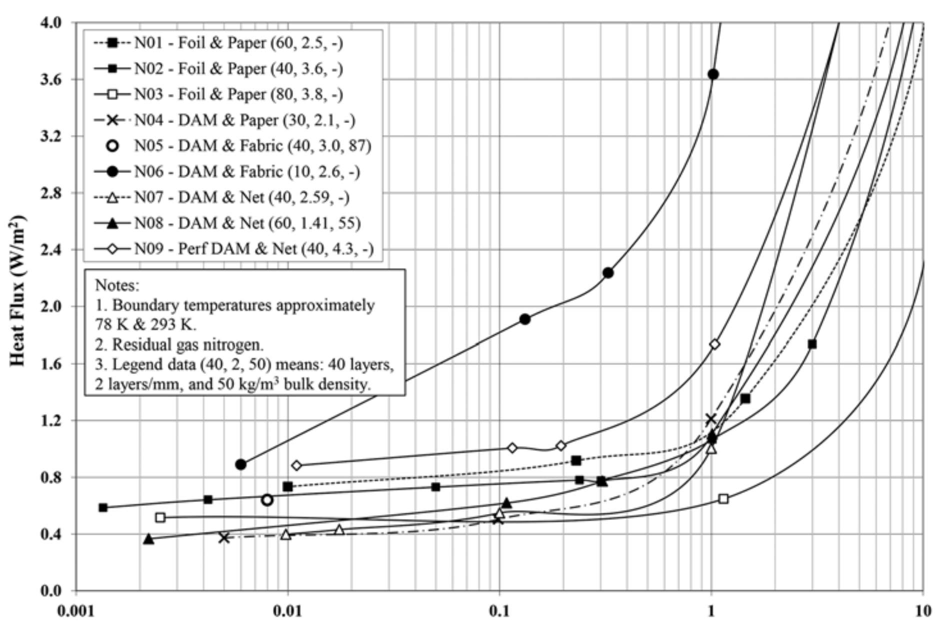


FIG. 5 Variation of Heat Flux with Cold Vacuum Pressure for Various MLI Systems for the High Vacuum Range [Note: 1 millitorr = 0.133 Pa]

Variable density MLI systems, when carefully executed, can provide increased thermal performance.(36-40)

5.3.4 *Cold Boundary Temperature Effects*—The cold boundary temperatures typically range from 111 K for liquefied natural gas to 4 K for liquid helium. Liquid nitrogen at a normal boiling point of 77 K is of course right in the middle of this range and offers a popular test condition for many MLI systems. While the overall change in ΔT is not extremely large going from 77 K to 4 K (only 223 K versus 296 K for a WBT of 300 K), the influence of lower temperature can have profound effects on the cold vacuum pressure and heat transfer mechanisms. Testing and analysis are needed to understand the influence of different CBT. Extrapolations and interpolations of test data are often unavoidable, but such performance predictions should be taken with precaution.

5.3.5 *Very Low Temperature Effects*—The radiative transmissivity of metalized coatings should be considered for cryogenic environments colder than approximately 40 K. At even colder temperatures, for example at liquid helium (4 K), near field thermal radiation effects including the phenomenon

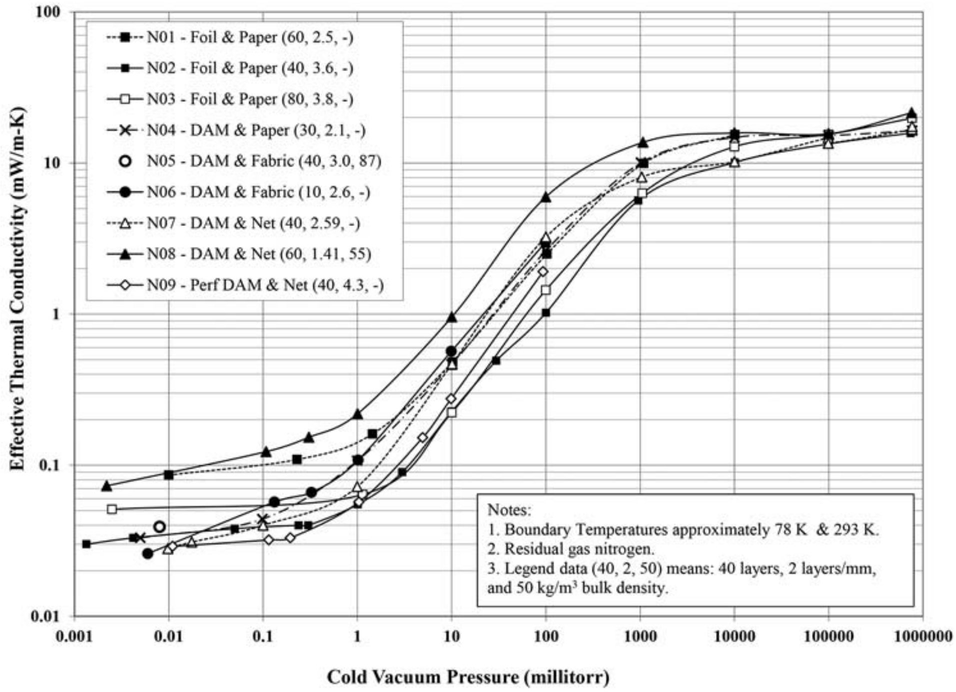


FIG. 6 Variation of Effective Thermal Conductivity with Cold Vacuum Pressure. [Note: 1 millitorr = 0.133 Pa]

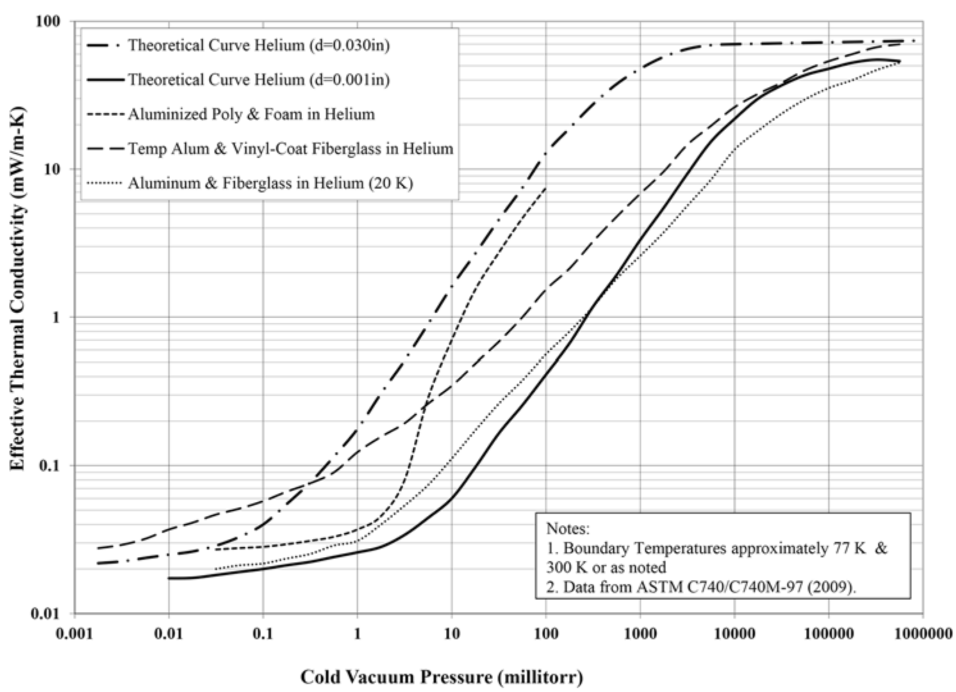


FIG. 7 Variation of Effective Thermal Conductivity with Cold Vacuum Pressure for Helium Residual Gas. [Note: 1 millitorr = 0.133 Pa]

of radiation tunneling may become significant in some cases. For very low temperatures the longer radiation wavelengths can become comparable with the spacing between layers and lead to unexpected consequences in heat transfer.(**41-43**)

5.3.6 *Other Considerations*—System requirements can vary greatly with regard to boundary temperatures, temperature matching among conductive layers, vapor shields, and so forth. Full understanding and delineation of the total system temperature profile, from warmest to coldest temperature, is needed for design the proper MLI system to meet the overall system requirements.

5.4 *System Performance Considerations:*

5.4.1 *Temperatures*—As previously discussed, the warm and cold boundary temperatures are the first and foremost factors in the thermal performance of the system. There are any

TABLE 1 Performance and Weight Summary for Typical Installed MLI Systems

No.[E]	System Characteristics		Installation Data					Thermal Performance				
	Reflector[A,B]	Spacer[C]	n	x	t	Ae	ρ	CVP[D]	CBT	WBT	q	k_e
				n/mm	mm	m^2	kg/m^3	μ	K	K	W/m^2	mW/m-K
N01	Foil	Paper	60	2.5	24.5	0.349	...	0.010	86	295	0.734	0.086
N02	Foil	paper	40	3.6	11.2	0.324	...	0.001	78	293	0.586	0.030
N03	Foil	paper	80	3.8	21.1	0.341		0.003	78	293	0.516	0.051
N04	DAM	paper	30	2.1	19.0	0.338	...	0.001	78	293	0.373	0.033
N05	DAM	Polyester fabric	40	3.0	13.6	0.328	87	0.008	78	300	0.639	0.039
N06	DAM	Polyester fabric	10	1.6	6.4	0.316	...	0.008	78	293	0.557	0.016
N07	DAM	Polyester net	40	2.6	15.5	0.342	...	0.010	78	293	0.398	0.028
N08	DAM	Polyester net	60	1.4	42.6	0.377	55	0.002	78	293	0.366	0.073
N09	DAM	Polyester net	30	4.3	7.0	0.317	...	0.011	78	298	0.883	0.029
P01	Poly film goldized both sides	3 layers silk netting	5	...	...	3.67	...	HV	78	300	1.04	...
P02	DAM	2 layers silk netting	5	...	...	3.67	...	HV	78	300	1.36	...
P03	DAM	2 layers glass fabric	5	...	...	3.67	...	HV	78	300	1.67	...
P04	DAM, 1.9% perforated	2 layers glass fabric	5	...	...	3.67	...	HV	78	300	3.28	...
P05	DAM	0.5-mm polyurethane foam	10	...	...	2.19	...	HV	78	300	1.23	...
P06	DAM	0.9-mm polyurethane foam	37	...	...	2.92	...	HV	78	300	0.54	...
P07	DAM	0.07-mm paper	30	...	...	5.48	...	HV	78	300	1.42	...
P08	DAM	0.013-mm polyester Dimplar Aluminized both sides	36	...	...	...	...	HV	78	300	1.92	...
P09	Crinkled poly film aluminized one side, 0.5% perforated	none	42	...	...	2.69	...	HV	78	300	1.89	...
P10	Foil, 0.006-mm	glass fiber paper	29	...	...	0.16	...	HV	78	300	0.76	0.038
P11	Foil, 0.006-mm	rayon fabric	36	...	...	1.09	...	HV	78	300	0.57	0.033
P12	Foil, 0.006-mm	glass fiber web	21	...	...	0.28	...	HV	78	300	1.83	0.189

[A]Double-Aluminized Mylar (DAM) is polyester film, 0.006-mm (0.25 mil) thick, and metalized on both sides unless otherwise noted.
[B]Foil film is aluminum foil unless otherwise noted.
[C]Paper spacer is micro-fiberglass paper unless otherwise noted.
[D] All CVP for high vacuum condition; where the measurement is unknown, the designation HV is given (assumed to be 0.005 μ on charts). Note: 1μ = 1 millitorr = 0.133 Pa.
[E]Designations starting with an N indicate a cylindrical test configuration; the P designations indicate a flat plate test configuration.

TABLE 2 Design Specifications and Thermal Performance Test Results for an Example Cryogenic MLI System

A245 MLI Baseline (10, 1.6, 6.4) Mylar & Poly Fabric - Original System	Test	CVP (millitorr)	Flow (sccm)	WBT (K)	CBT (K)	Q (W)	q (W/m^2)	k_e (mW/m-K)
Layers = 10 pairs	1	0.004	76	293.1	78	0.316	1.00	0.030
Layer density = 1.6 layers/mm	2	0.050	130	293.0	78	0.536	1.70	0.050
Total thickness = 6.4 mm	3	0.132	146	292.9	78	0.603	1.91	0.057
Ae = 0.316 m^2	4	0.326	171	293.0	78	0.706	2.24	0.066
Total mass = 126 g	5	1.02	277	292.9	78	1.148	3.64	0.108
System density = 53 kg/m^3	6	9.96	1456	292.6	78	6.030	19.10	0.567
Initial Pumping & Heating = 24 hours	7	99	7684	292.8	78	31.80	100.7	2.99

number of combinations of boundary temperatures that may come into play. Some of the more common combinations are listed, for example, as follows in terms of WBT/CBT (in units of K): 293/77, 350/90, 300/20, 300/4, 77/4, 50/2, etc. The two key factors here are the temperature difference and the depth of the cold (that is, the cold boundary temperature). The cold boundary temperature is often determined by the cryogen or cold product to be insulated. The normal boiling points of common cryogens at one atmosphere pressure are summarized as follows: liquid methane (112 K), liquid oxygen (90 K), liquid argon (87 K), liquid nitrogen (77 K), liquid hydrogen (20 K), and liquid helium (4 K). For reference, the boiling point of liquid carbon dioxide is 217 K (at 519 kPa).

5.4.2 *Configuration*—MLI systems are generally designed for either tank or piping configurations. Each configuration will have its own unique requirements and limitations. The design must take into account the basic geometry, the available annular space, support structures, the fabrication and assembly sequence, and the thermal performance requirements. The thermal performance requirement for a long term storage tank will likely be much less stringent than a pipeline providing a high velocity flow. Tanks are generally cylindrical or spherical but also have annular space piping to be insulated. The complex geometries such as ellipsoidal ends of tanks make for additional challenges in the design. Piping systems can be rigid or flexible and each type has its own special requirements and terminations (end assemblies) to consider. Rigid piping assemblies may have complex geometries and angles to address. Flexible piping assemblies can be long lengths with specific requirements for bending as well as unique challenges in fabrication and assembly.

5.4.3 *Effect of Supports*—Support considerations may include the manner of physically supporting the MLI materials themselves, the inner pipe or vessel, or any number of mechanical combinations.(**44, 45**) These support structures or other structural elements used between the warm boundary and the cold boundary can cause increased heat leak in at least three ways. First is the solid conduction of heat through the support itself. This heat leakage rate may be easy to calculate, but the thermal contact resistance at the cold surface is often unknown and difficult to estimate. The second increase in heat leak is any gap or crack that is created underneath or adjacent to the support structure. This gap allows a direct view for radiation heat transfer. The third increase in heat leak is the disruption in continuity of the MLI layers that leads to compressed edges or damage.

5.4.4 *Vacuum Life and Getters*—Both the vacuum level and the operational vacuum life are major factors in the design of MLI systems for vacuum jacketed applications. (**16**) Vacuum retention, maintenance schedule, and getters should be considered for the planned system life cycle. Vacuum retention depends on the leak tightness of the jacket and the outgassing of all materials inside the annular space. Getters may include chemical getters such as palladium oxide or silver zeolite for hydrogen gas, or adsorbents such a molecular sieve or charcoal for water vapor and other contaminants. The amounts, packaging, and placement for the selected getters should be carefully chosen in accordance with life cycle requirements. Any material placed in the annular space should be evaluated for oxygen compatibility requirements.

5.4.5 *Loss of Vacuum / Degraded Vacuum*—The effects of loss of vacuum (**46-49**) or degraded vacuum (**9, 50**) can be a particular concern with most vacuum-jacketed (evacuated) systems. Issues may include safety, increased maintenance, and dramatically reduced thermal insulating effectiveness.

5.4.6 *Valves and Instrumentation*—Vacuum-jacketed applications usually require the use of at least one pressure relief valve (port) that can also serve as the connection for evacuation. Vacuum pressure instrumentation can be incorporated with this port, be made separate, or not used depending on the overall system needs for performance validation. Consideration to the getter replacement or regeneration can also be made in concert with the port design. System life cycle and maintenance requirements, such as vacuum regeneration capability and vacuum monitoring, may define further needs for additional valves, ports, and instrumentation.

5.4.7 *Other Considerations*—The actual system performance may largely depend on the method of manufacture and installation of the MLI materials and ancillary parts. These details are discussed in Section 6. Table 2 gives the design specifications and thermal performance test results for an example cryogenic MLI system.

5.5 *Applications*—MLI systems are generally used when lower heat leakage rates than those obtained with other evacuated insulations are required. Other evacuated insulations include, for example, perlite powder, glass bubbles, or aerogel bulk-fill, which can provide heat flux values in the range of approximately 5 to 20 W/m^2.(**51**) The choice for an MLI system may be dictated by the value of the cryogenic fluid being isolated or by weight or thickness limitations imposed by the particular application. Applications generally fall into the following categories: storage, transfer, thermal protection, and low-temperature processes. Typical storage applications liquid helium dewars, liquid hydrogen storage tanks, liquefied industrial gas vessels including argon and nitrogen, onboard aviation breathing gas, high energy cryostats, and industrial power applications. Transfer applications include hospital oxygen piping systems, welding supply, computer equipment manufacturing, beverage bottling, cryogenic propellant loading systems, railroad tank cars, highway trucks and trailers, liquefied natural gas pipe lines, portable tankage of various sizes, and many other applications. Thermal protection applications include spacecraft thermal control, human habitats for space environments, personnel protection, sensitive equipment protection, and transportation systems. Applications in low-temperature processes include food freezing, medical equipment, surgical operating tools, preservation of biologicals, cooling for superconducting power cables and devices, materials treatment, refrigeration for scientific apparatus, etc. Very low temperature (4 K and below) refrigeration for large-scale superconducting magnets, RF cavities, and other devices is a major technical capability for basic physics research world-wide.**(52-60)**

6. Techniques of Manufacture and Installation

6.1 *General:*

6.1.1 An MLI system requires that each reflector layer (metal or metallized) is separated from the next with minimum solid conduction contact points and with a minimum contact pressure. Reflector layers are made from metal foils or from metal-coated plastics; these materials can smooth or crinkled and with or without perforations or dimples. Spacer layers, if used, are usually a glass, polymer, or natural fiber formed into a fabric, netting, foam, paper, mat, or web to ensure that no direct thermal contact is made. In some cases when a metal-coated plastic is used, the low thermal conductivity plastic also serves as the spacer (see 8.3.2). Small support structures made from low thermal conductivity plastics can also be devised.

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

6.1.2.1 Reduce the solid conduction heat flow by minimizing the compression or thermal contact between the layers.

6.1.2.2 Reduce gas conduction heat flow by providing flow paths within the insulation so that the interstitial gas can be removed by the vacuum environment (or if not high vacuum requirement then a purge gas can be selected to meet the thermal performance criteria), and

6.1.2.3 Reduce the radiation heat flow by utilizing low-emittance reflector materials and by the elimination of gaps, spaces, or openings in each reflector layer. Most importantly, through-thickness gaps or cracks must be eliminated.

6.1.2.4 Select the materials, number of layers, and layer density for the desired thermal performance with additional considerations for space and weight.

6.1.2.5 Provide a design to allow for adequate venting during evacuation and/or purging cycles such that the system remains physically intact with all layers and joints in their proper locations.

6.1.2.6 Minimize particulate and molecular contamination, as required, and provide any necessary gettering and adsorbent materials to maintain the proper high vacuum condition as required for the design life of the overall system.

6.2 *Installation:*

6.2.1 A wide variety of insulation techniques are available. They include, but are not limited to, the spiral-wrap, blanket, layer-by-layer, and filament-wound techniques. As not all geometries or designs allow for wrapping or covering by MLI systems, other insulation materials may also be required for optimum overall system performance. These materials may include foam, fiberglass, aerogel blanket, aerogel bulk-fill, or glass bubbles. For general reference and comparison with MLI systems, thermal performance data for a selected variety of these materials is given in Fig. 8.

6.2.2 *Continuous-Wrap Method:*

6.2.2.1 The continuous-wrap technique is applicable mainly to the cylindrical segments of tanks. The reflectors 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 reflector and spacer material may have the same width as the cylinder or segments of the cylinder. In some cases the reflector 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 reflector segments. Overlaps of 25-50 mm [1-2 in.] are typically used.

6.2.2.2 To obtain the best thermal performance in the case of tanks, the reflectors and spacers of the tank ends are applied individually in a manner such that the end reflectors are interleaved with the side reflectors. In this manner, loft is also enhanced generally resulting in a more favorable (lower) layer density. 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 bulk-fill, powder, open-celled foam, or fibrous insulating material.

6.2.3 *Blanket Method:*

6.2.3.1 MLI blankets can be formed with two or more reflector-spacer layers and can be applied to different 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 has been combined, they are sometimes held together with special attachments such as garment tags at regularly spaced intervals. Ultrasonic spot-welding of small diameter points is another technique that may be used. The blanket is then sheared to the required size and shape and applied to the surface to be insulated. Automated laser cutting processes can also be used to assemble polyester MLI blankets around their cutting edges

6.2.3.2 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

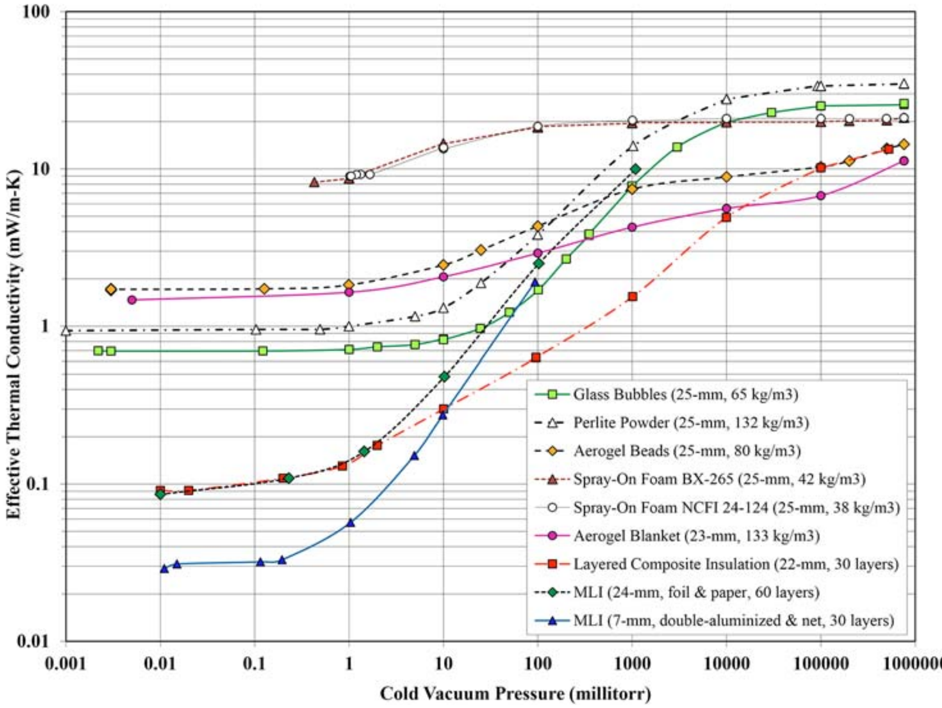


FIG. 8 Variation of Effective Thermal Conductivity with Cold Vacuum Pressure for Different Cryogenic Thermal Insulation Materials. Boundary temperatures 78 K and 293 K; nitrogen residual gas. [Note: 1 millitorr = 0.133 Pa]

be staggered with respect to the joints of the inner layer. Further, the corresponding reflectors in each blanket layer should be appropriately overlapped at the joints. Velcro fasteners are sometimes used in these installations.

6.2.4 *Layer-Layer Method:*

6.2.4.1 MLI systems can be formed to a wide variety of surface geometries by the individual application of the reflectors 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 reflector layer is placed over the entire surface. Again, like the spacer, the reflector 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 reflectors with the alternate application of spacers and reflectors.

6.2.4.2 It is important that there is no mechanical pressure buildup between layers as each successive reflector-spacer layer is applied. This is often accomplished, particularly on articles having the major dimension of a meter or less, by fabricating each layer (reflector-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.

6.2.5 *Sprial-Wrap Method*—This method, also referred to as filament-wound, of installing MLI materials is usually done with automatic machinery. The insulation is applied in the form of a strip up to several inches wide consisting of both the reflector and spacer. The machinery rotates the item to be insulated, positions the reflector 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 reflector is continued until the desired thickness is achieved.

6.3 *Attachment and Support:*

6.3.1 Because MLI systems consist of individual layers of material, a method of securing these layers is often needed so that they will not slip or shift during fabrication, installation, or operation. In the case of flexible piping, the support structure and layering of materials must be evaluated for the effects of localized compression.**(61)**

6.3.2 *Shell Containment*—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.

6.3.3 *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.

6.3.4 *Pinning*—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.

6.3.5 *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 because the lateral conduction along the reflectors will now be added to total heat leakage rate of the system.

6.3.6 *Electrical Grounding*—Depending on the installation configuration, electrical grounding may be required due to the resistances of the metalized layers. Blanketing for spacecraft generally require one or more grounding points to provide an electrical contact between all conductive layers. This electrical contact is then connected to a suitable grounding lead.

6.4 *Joints and Seams:*

6.4.1 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.

6.4.2 Joints can be produced by a number of techniques or combinations of techniques. These methods include overlap, butt-joint, or fold-over. Overlap can be layer-by-layer or by blanket or sub-blanket. Butt joints have been successfully used for sub-blankets where the successive joints are staggered to preclude any through-cracks. Fold-over joints are relatively simple to make and keep the reflector layers thermally isolated. Layer-by-layer techniques can offer the minimum degradation due to seams but can also be the most time-consuming and difficult to install.**(62)**

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

6.4.4 The generous use of tapes, binder clips, garment tags, copper wires, and similar elements are often required during installation and make-up of joints and seams. These elements may or may not be a part of the finished product. Careful consideration must be given to the way these elements are used and applied. For example, the use of tape pieces should avoid thermal bridging of reflector layers. Tape joints should be done with care and precision to minimize the exposure of adhesive to the vacuum space and to avoid the risk of detachment during service.

6.4.5 The types of joints used and the techniques with which they are executed will have a strong influence on the layer density, the variation in layer density through the total thickness, and the overall structural integrity of the MLI system. Therefore, the thermal performance, along with evacuation and outgassing characteristics, will also be strongly affected. Experimental testing to determine the sensitivity of these different joining methods is often necessary to be able to predict thermal performance of the actual system.

6.5 *Penetrations:*

6.5.1 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. The heat leakage rates due to penetrations can be the dominant factor in the total system performance. A thorough thermal analysis for the given temperature and environmental conditions are usually needed to account for the effects of penetrations.**(63)**

6.5.2 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).

6.5.3 Because MLI systems are anisotropic, the best possible thermal isolation of the penetration at the joint is obtained by interleaving the reflectors of the penetration MLI with the main surface MLI. This effect is accomplished by cutting triangular pieces (gores) in the reflectors of the first components at the joint and overlapping the gore segments with the reflectors of the second component. Alternatively, preformed corner reflector can be placed at the corner locations such that they overlap the reflectors in each component.

6.5.4 Alternatively, the corner formed by the two components can be filled with a preformed isotropic insulating material such as foam, fiberglass, aerogel blanket, aerogel bulk-fill, or encapsulated powders.**(64)**

6.6 *Evacuation Rates*—Evacuation of MLI systems, whether by vacuum pumping 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 reflectors must be enhanced.

6.6.1 To prevent damage during evacuation or to enable more complete evacuation among all layers, the reflectors can be perforated to provide broadside flow in addition to the flow provided by the edges. However, the effect of these perforations on the overall thermal efficiency must also be taken into account. The installation methods and the layer density of the system also determine the rate at which the trapped gases can move out.**(65, 66)**

6.6.2 Manufacturing of vacuum-jacketed piping and tanks often involves gaseous nitrogen purge cycles to accelerate the process of establishing the desired high vacuum condition. The repeated vacuum pumping and purging process must be performed without damaging the insulation by too-quick vacuum pumping (may blow off insulation layers) or too-quick purging (may crush insulation layers). A minimum of three purge cycles between approximately 1 torr and 760 torr is usually recommended but as many as 10 purge cycles may be performed depending on the desired final vacuum level and the timeline for evacuation. Although additional purge cycles add time and effort up front, the overall timeline for evacuation can be significantly reduced.

7. Cleanliness

7.1 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.

7.2 If adsorbents or chemical getters are used, it is necessary to protect these materials from contamination prior to evacuation. In most cases, provision should be made for a clean, dry work environment.

7.3 It is recommended that MLI installation always be done in a well-controlled, air-conditioned space or a clean room, and that materials be protected at all times.

7.4 Clean clothing and gloves are recommended wear for persons handling the exposed surfaces of the insulation materials.

7.5 Work surfaces, vacuum jacket surfaces, and tools should be cleaned as required using appropriate solvents. The ultimate vacuum level required may dictate the choice of solvents.

8. Materials Specifications

8.1 MLI systems always have multiple layers of reflector material separated by low thermal conductivity spacer material in any number of different combinations. Reflector materials 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 or deposition onto an appropriate nonmetal. The two most commonly used reflector materials are *(1)* thin aluminum foil, and *(2)* vapor deposited aluminum on a polymeric film. The polymeric film is commonly composed by polyester or polyimide. Some MLI designs do not include spacer materials but instead rely on reducing thermal contact between layers by crinkling the reflector material before installation or reflectors that are metalized only on one side. Test Method E408 gives information on emissivity testing of the reflective materials used in constructing MLI systems.

8.2 *Foils:*

8.2.1 Because these materials must be thin and highly reflective, the foils are usually high-purity metals having high thermal conductivity. Such metals as gold and silver can be used, but the usual choice is obviously aluminum because of cost. The most commonly used aluminum foil is 1145-0. This material has 99.45 % purity, is soft, and can be obtained in thin sheets. Other alloys of aluminum, or even other metals, are acceptable if highly reflective throughout the range of temperatures expected. At least one side should reflect 97.5% of the incident thermal radiation and the emittance at all temperatures of interest should be 0.025 or less. The other side is typically a matte or semi-matte finish. Contaminated or tarnished surfaces can be cause for rejection. The operating temperature of a given foil determines whether the dull side or the shiny side should face the colder surface. Experiments have confirmed that, in the far infared range of radiation, the dull side has the lower emittance.

8.2.2 Mechanical requirements: The foil used should be thin enough to reduce lateral heat conduction. However, even very thin foils can cause serious heat leaks if the system is not designed with proper care to avoid bridging between hot and cold regions (such as struts). The foil material should also give flexibility for easy folding without stiffness. Flexibility is usually assured for such 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 spacer material and cause thermal bridging. A typical material specification reads: 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 a particular design.

8.3 *Metallized Plastic Films:*

8.3.1 Metalized non-metals include aluminized polyester film. Various sheet materials may be vapor deposited (in vacuum) with aluminum, gold, etc., to a thickness sufficient for optical opacity. Vapor deposition on both sides reasonable and superior alternative in many cases. Several methods are available for determining if enough metalizing 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 than some number of ohms, "per square." A typical specification for aluminized polyester film is from 0.5 to 1 ohm per square. A simpler but less reliable test is to hold a sample of the material between the observer and a lighted object. If the lighted object can easily be seen through the material, then the metal coating is probably too thin. Suppliers can be required to verify the emittance or the ohms per square thickness measurement, or both, of any questionable material. 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. One suggested test for tape adhesion is given by Practice B571.

8.3.2 The lateral conduction of metalized plastics is low enough such that they can be used without a spacer material. With this design, 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 through thermal performance testing.

8.3.3 Although various metalized 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. In any case, the materials must not show excessive outgassing in vacuum and must remain somewhat resilient at low temperatures. While theoretically possible to use metalized materials other than plastic films, such materials should be thoroughly tested before using. A typical material specification reads: 6.25 µm [0.00025 in.] polyester sheet, 1.22 m [48 in.] wide, aluminized both sides having a resistance of 0.5 ohm per square on each side. Such a specification will provide for reasonable control over the quality of the material. Suppliers may not be able to readily measure and therefore ensure the emissivity of these metalized films. Coatings with emittance values below 0.025 are available. At least one side should reflect 97.5% of the incident thermal radiation and the emittance at all temperatures of interest should be 0.025 or less.

8.4 *Separator Materials:*

8.4.1 Spacer sheets used between the reflectors need to have a very low thermal conduction in the direction perpendicular to the sheet. Typical examples of such spacers are silk net, polyester net, polyester non-woven cloth, fiberglass woven cloth, fiberglass mats, fiberglass paper, and rayon fiber paper. Frequently, spacer 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. Fibers only a few micrometers in diameter or less are desirable in order to reduce thickness, reduce thermal conduction, and present many points of contact. The use of binder materials in papers increases thermal conduction, so only binderless papers should be used if their mechanical strength is still sufficient for the application

8.4.2 A potentially serious problem with many otherwise (mechanically and thermally) acceptable spacers is vacuum outgassing. Proper bake-out of the system is needed. If substantial outgassing does occur, provision must be made for adequate gettering of these contaminants. A typical spacer 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}].

8.4.3 Particulates can be a produced from some spacer materials. Whether or not particulates are a problem depends on the particular application and overall system design.

8.5 *Vacuum Jacket Materials*—The vacuum jackets, or shells, that contain the insulation must be chosen to minimize outgassing or at least to give off only those gases or vapors which can be conveniently gettered. Characteristically, stainless steel or aluminum is 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 can the problematic. A typical specification for stainless steel reads: 10-gauge 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 manufacturer's designation for that material.

9. Hazards

9.1 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.

9.2 As most MLI systems are designed for a vacuum environment, the hazard with oxygen is usually contingent on an overall system failure including breach of the integrity of the vacuum jacket.

9.3 MLI systems have been impact tested in oxygen with mixed results. For example, foil and fiberglass paper MLI types and have been tested along with aluminized polyester and fiberglass paper MLI types. Of particular interest is the possible safety enhancement provided by thick aluminum foil (15 µm [0.00059 in.]) versus thin aluminum foil (7 µm [0.00028 in.]). However, results are inconclusive and a comprehensive system evaluation remains the recommended approach. The fact that aluminum foil, while harder to ignite compared to polyester, provides a much larger mass of fuel to burn has also been pointed out.

9.4 The vacuum jackets must be designed in accordance with applicable pressure vessel codes to minimize jacket failure and provide failure mode protection, including pressure relief, to the insulation space.

9.5 Fabrication personnel must be provided with suitable protection from reflector materials that can produce bodily cuts due to their small thickness and high-edge velocities during application with certain methods. Fabrication personnel must be protected from glass fibers of respirable size, which are contained in some spacer materials.

9.6 Polyester insulation is flammable and needs to be protected from welding heat.

10. Keywords

10.1 aluminized films; aluminum foil; cryogenic insulation; cold vacuum pressure; effective thermal conductivity; fiberglass paper; layer density; gas conduction; heat flux; heat transfer; multilayer insulation; polyester film; polyester net; radiation; radiation shields; reflectors; reflective insulation; residual gas; spacers; super insulation; thermal insulation system; thermal performance; vacuum environment; vacuum insulation; vacuum jackets

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