Designation: C740/C740M – 13

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:*[3]

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,

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[1] This guide is under the jurisdiction of ASTM Committee C16 on Thermal Insulation and is the direct responsibility of Subcommittee C16.40 on Insulation Systems.

Current edition approved Nov. 1, 2013. Published February 2014. Originally approved in 1973. Last previous edition approved in 2009 as C740/C740M – 97(2009). DOI: 10.1520/C0740_C740M-13.

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

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

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.

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

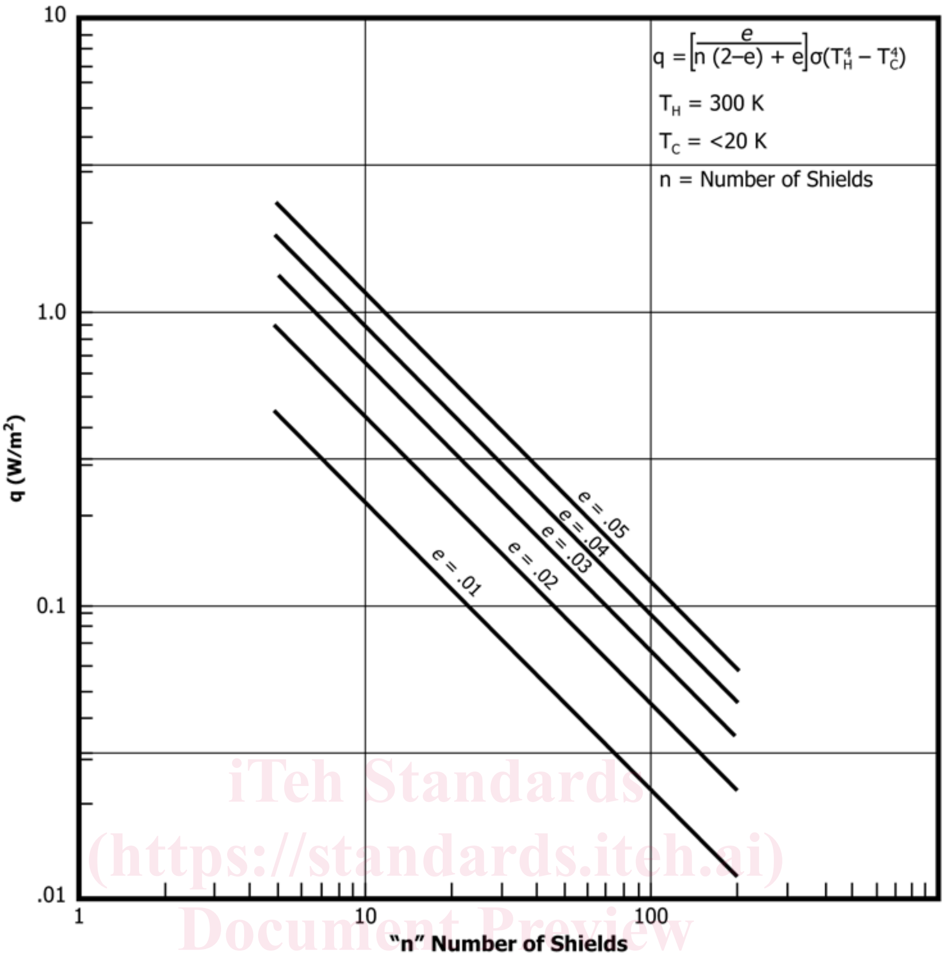


FIG. 1 MLI Theoretical Heat Flow for Various Shield Emittances and 1.0 Boundary Emittance

μ = vacuum level, millitorr (1 μ = 0.1333 Pa)

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:

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

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:

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

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

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

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:

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

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:

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

For values of e ≤ 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 %. 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:

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

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

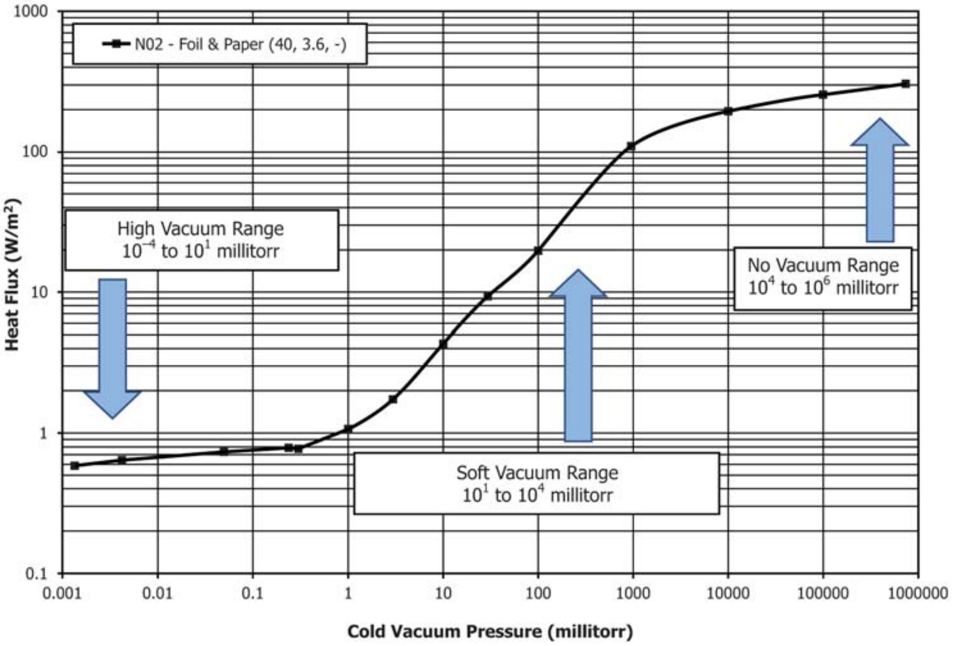


FIG. 2 Variation of Heat Flux with Cold Vacuum Pressure: example MLI system of 40 layers foil and paper with boundary temperatures of 78 K and 293 K and nitrogen as the residual gas. [Note: 1 millitorr = 0.133 Pa]

unit weight of the MLI must therefore be considered for an accurate estimation of actual system thermal performance. (**19, 20**)

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:

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

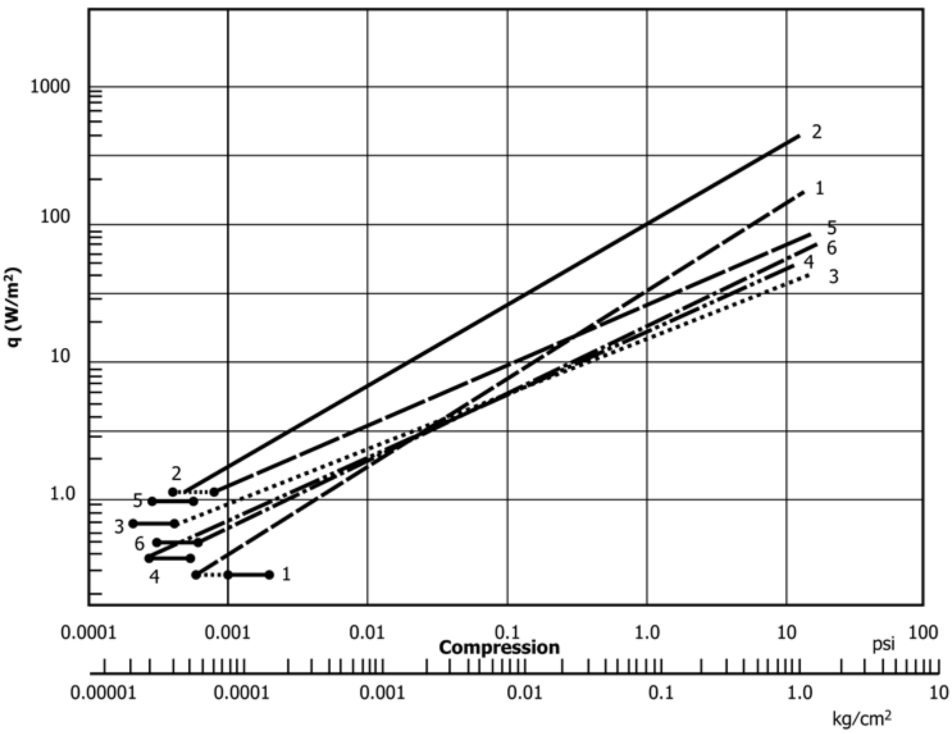
where d_e is taken as the inner diameter of vessel or pipe plus one wall thickness of that same vessel or pipe.

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

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 is chosen to compute the total system heat flux. Accordingly,



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

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.