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

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)

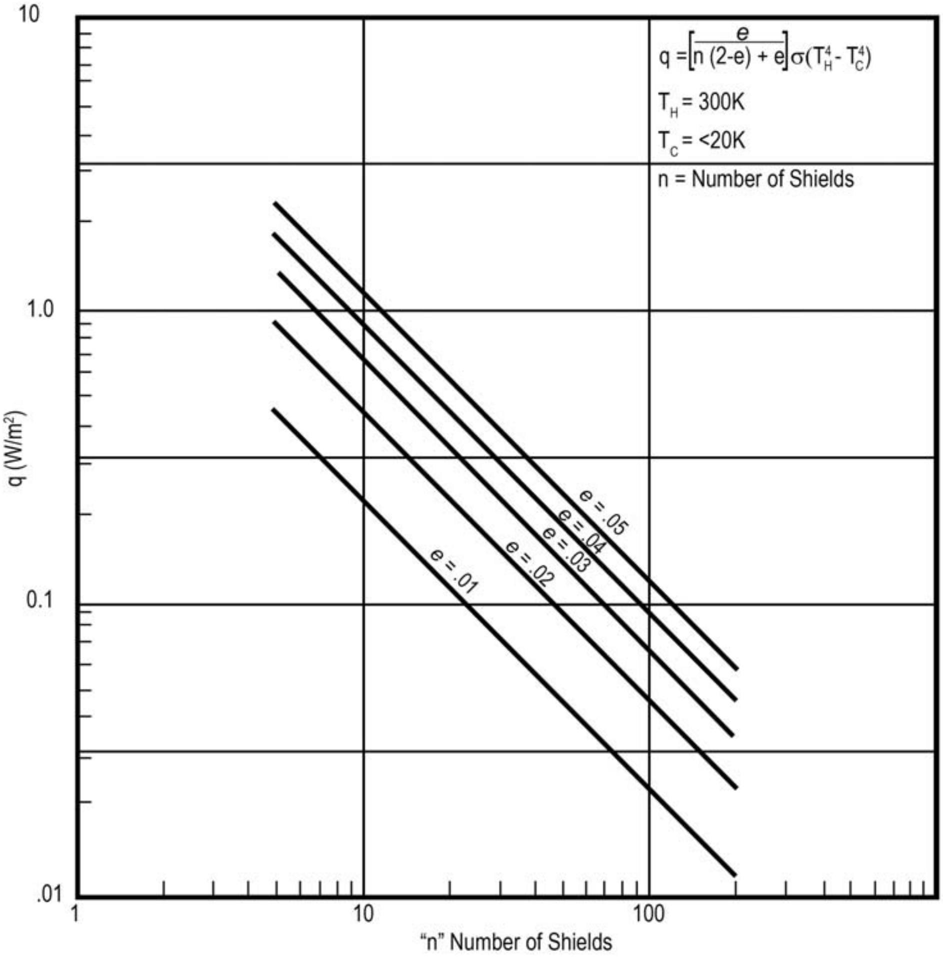

FIG. 1 MLI Theoretical Heat Flow for Various Shield Emittances and 1.0 Boundary Emittance

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 $e \leq 0.1$, 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