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Standard Guide for Evacuated Reflective Insulation In Cryogenic Service¹

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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/m² are needed for an evacuated design. Heat flux values approaching 0.1 W/m² 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-ft²·°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-ft²·°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 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.

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

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 kPa to 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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.* For specific safety hazards, see Section 9.

1.8 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

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 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.

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.

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 as 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); $1 \mu = 0.133$ 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, $mW/m \cdot K$
k_e	= effective thermal conductivity through the total thickness of the insulation system, $mW/m \cdot K$
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., $mW/m \cdot K$
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} $W/m^2 \cdot K^4$
T	= temperature, K; T_h 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)

4. Theoretical 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 $e \leq 0.1$, **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 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 $7.5 \cdot 10^{-6}$ 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 ($<1.33 \cdot 10^{-4}$ 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:

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

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.