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Room-Temperature Thermal Resistance Measurements of New and Existing Materials for Shipboard Air Duct Systems

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Thermal resistance measurements of conventional and composite material insulation for shipboard air duct systems are described. Conventional shipboard air ducts are constructed of metal walls insulated externally with fibrous-glass board. Composite materials are being considered as replacements for these duct walls. Thermal measurements were conducted using the National Bureau of Standards 1-metre Guarded Hot Plate at a mean temperature of 23.9°C (75°F). Measurements of the fibrous-glass board specimens were within 3% of certified values of NBS SRM 1450a, fibrous-glass board. Measurements of two aramid-fiber honeycomb specimens were approximately one-half the thermal resistance of the fibrous-glass board specimens.

Key words: aramid fiber; composite materials; fibrous-glass insulation; guarded hot plate; polyimide foam; thermal resistance

1 INTRODUCTION

Composite materials are being considered as replacement materials for shipboard air duct systems. Currently, shipboard ducts utilize a heavy metal wall construction insulated externally with fibrous-glass board insulation. Thermal resistance measurements of these materials, both existing and new, are necessary to determine the thermal performance of the duct wall. The thermal resistance of two specimens from existing shipboard ducts and three specimens of composite materials were measured using the National Bureau of Standards (NBS) 1-metre Guarded Hot Plate (GHP). This report details results of thermal measurements for the first set of five insulation specimens provided by the U.S. Navy.

2 NBS 1-METRE GUARDED HOT PLATE

The NBS 1-m Guarded Hot Plate consists of three temperature-controlled plates of anodized aluminum, each 1.016 m (40 in.) in diameter. The temperature-controlled plates are housed within a large, six-sided rectangular environmental chamber, 1.4 by 1.4 by 1.6 m high (4.6 × 4.6 × 5.3 ft). Two sets of double-doors, both front and back, allow access to the apparatus plates. Air is conditioned and circulated within the chamber by a small heat exchanger consisting of a chilled-water coil, electric-resistance heater and blower. The apparatus is illustrated in Figure 1.

A schematic diagram illustrating the principle of measurement for the NBS 1-m Guarded Hot Plate is shown in Figure 2. In a two-sided mode of operation, two similar homogeneous specimens are brought into intimate thermal contact with the plates. A steady temperature difference (ΔT) is produced across the specimens, until a steady heat flow (Q) is achieved through the specimens. A differential thermopile across the gap is used to null the gap temperature difference, minimizing lateral heat flow (Q_{gap}) at the gap. The net effect of the specimen edge losses (Q_{edge}) are minimized by the large specimen diameter to thickness ratio and by controlling the ambient air temperature the same as the mean specimen temperature.

The NBS 1-m Guarded Hot Plate is operated in a one-sided mode of operation when only one test specimen is available. In a one-sided configuration, a steady temperature difference is maintained across the specimen using the hot plate and one cold plate. Another insulating material, known as the backflow specimen, is inserted between the hot plate and the second cold plate. The second cold plate is maintained at the same temperature as the hot plate thereby reducing the heat flow (Q_b) through the backflow specimen to about zero. The remainder of the test proceeds exactly as the two-sided test described above. Further information on the design and operation of the NBS 1-m GHP is available in references [2] and [3].

3 SPECIMEN DESCRIPTION

A total of five specimens was received from David Taylor Naval Ship Research And Development Center. Specimen composition and physical dimensions are listed in Table 1.

Table 1. Specimen identification and physical dimensions

Sample	Specimen	Thickness (mm)	Thickness (in)	Area (mm × mm)	Area (in × in)
01	Galvanized-steel panel insulated with fibrous-glass board	29.5	1.16	610 × 610	24 × 24
02	Aluminum panel insulated with fibrous-glass board	32.0	1.26	605 × 600	24 × 24
03	Aramid-fiber honeycomb panel with air in the honeycomb	26.1	1.03	614 × 610	24 × 24
04	Aramid-fiber honeycomb panel with polyimide foam in the honeycomb	26.2	1.03	611 × 611	24 × 24
05	Phenolic-resin panel reinforced with glass-filaments	6.1	0.24	609 × 509	24 × 20

3.1 Fibrous-Glass Board Specimens (Samples 01 and 02)

The insulated galvanized-steel and aluminum panels, samples 01 and 02, were removed from shipboard air ducts. The specimens consisted of a metal substrate (the duct wall) with a nominal 25 mm thick (1 in.) fibrous-glass board laminated to the metal substrate. The fibrous-glass board was finished with a thin sheet (0.08 mm; 0.003 in.) of glass-cloth lagging.

For the thermal measurements, the fibrous-glass boards with lagging were removed from their respective metal substrate. The specimens were placed in an oven at 90°C (194°F) for 24 hours prior to measurement. Measurement of the specimen mass indicated a moisture content of less than 1% (by mass) for both specimens before drying.

3.2 Aramid-Fiber Honeycomb Panels (Samples 03 and 04)

The aramid-fiber honeycomb specimens, samples 03 and 04, were smooth, rigid panels, both approximately 26 mm (1 in.) thick. The top and bottom surfaces of both panels were finished with three plies of glass and resin. The interior of each panel consisted of a honeycomb lattice for structural support. Individual cells of the honeycomb were hexagonal in geometry and the walls of the cells were comprised of an aramid-fiber paper. The cells traversed the entire thickness of each specimen. Details of a panel are illustrated in Figure 3.

The two specimens, while similar in construction, used different materials to fill the honeycomb cells. Sample 03 had air in the cells, while sample 04 had polyimide foam foamed in the honeycomb cells during the manufacture of the panel.

3.3 Phenolic-Resin Panel (Sample 05)

The phenolic-resin panel, sample 05, was a thin (6.1 mm), rigid panel of phenolic resin reinforced with filament-wound glass fibers. The filaments of glass-fiber were wound at alternating angles of approximately ±80° in parallel layers within the resin. The specimen surface of the phenolic-resin panel contained many irregularities, i.e., small pock marks and ridges of resin. The specimen was also slightly warped. The effect of these irregularities on the thermal measurements are discussed in Section 4.

4 THERMAL RESISTANCE MEASUREMENTS

For tests reported here, the NBS 1-m GHP was operated in a one-sided mode of operation with heat flow (Q) in the vertical direction (up). Tests were performed in accordance with procedures described in ASTM test method C-177 and practice C-1044 [4,5]. The backflow specimen was a 101.6 mm thick (4 in.) sample of expanded polystyrene, molded beads. Thermal measurements were conducted at a mean specimen temperature (T_m) of 23.9°C (75°F). Tests were conducted under atmospheric conditions with air as the ambient fill-gas in the environmental chamber. The relative humidity (rh) of the laboratory ambient was controlled at 38% ±2% rh.

As mentioned, the fibrous-glass specimens were conditioned in a hot-air oven at 90°C (194°F) and uncontrolled humidity for 24 hours prior to thermal measurement. Mass measurements prior to thermal measurement indicated a moisture content of less than 1% (by mass) for the specimens.

The composite-material specimens were conditioned at 21°C (70°F), 38% rh for a minimum of 6 days prior to thermal measurements. Measurements of the specimen mass made before and after thermal testing indicated no significant change (less than 0.05%) in the mass of these specimens during thermal measurements.

The thermal resistance measurement of the phenolic-resin panel posed several difficulties, not only due to surface irregularities, but also because the thickness (see Table 1) was less than can be tested directly with the NBS 1-m GHP (19.1 mm; 0.75 in.). The resistance was instead determined by the "difference principle" described previously by NBS [6]. In this method, the phenolic-resin panel was sandwiched between two specimens of five-year old, extruded polystyrene and the thermal resistance for the stacked assembly measured. The two stacked specimens of polystyrene were then measured alone. The difference between the two measurements provided the thermal resistance of the phenolic-resin panel, but also included the effect of contact resistance between the composite board and polystyrene.

The thermal resistance (R-value), thickness (L), bulk density (ρ), plate temperatures (T_H and T_C), mean temperature (T_m), and the change in mass (ΔM) for the five specimens are summarized in Table 2. The uncertainties of the resistance measurement for the fibrous-glass board and aramid-fiber honeycomb panels were estimated to be ±0.5% [3] and ±1.0%, respectively. The uncertainty in the value of thermal resistance of the phenolic-resin panel was estimated within ±5% due to the contact resistance.

5 DISCUSSION

5.1 Fibrous-Glass Board Specimens (Samples 01 and 02)

The thermal resistance of the fibrous-glass board specimens was compared with the certified values of NBS Fibrous-Glass Board, SRM 1450a [7]. From the NBS SRM 1450a certificate, the following equation was used;

$$R = \frac{L}{\lambda(\rho,T)} = \frac{L}{(a_0 + a_1\rho + a_2 T_m{}^3)} \qquad (1)$$

where,

R = thermal resistance, ($m^2 \cdot K/W$)
L = thickness, (m)
$\lambda(\rho,T)$ = apparent thermal conductivity, ($W/m \cdot K$)
ρ = bulk density, (kg/m^3), and
T_m = mean specimen temperature, (K).

The values of the coefficients used were;

$a_0 = 1.930 \times 10^{-2}$ ($W/m \cdot K$)
$a_1 = 1.534 \times 10^{-5}$ ($W \cdot m^2/K \cdot kg$)
$a_2 = 4.256 \times 10^{-10}$ ($W/m \cdot K^4$).

For sample 01, the calculated thermal resistance was 0.8065 $m^2 \cdot K/W$ (4.580 $ft^2 \cdot °F \cdot h/Btu$), or within 2.8% of the measurement reported in Table 2. For sample 02, the calculated resistance was 0.7994 $m^2 \cdot K/W$ (4.539 $ft^2 \cdot °F \cdot h/Btu$), or within 0.7% of the measurement reported in Table 2.

5.2 Aramid-Fiber Honeycomb Panels (Samples 03 and 04)

The thermal resistance of the aramid-fiber honeycomb panels was about one-half the thermal resistance of an equivalent 25 mm thick specimen of fibrous-glass board. The resistance measured for the panel having air in the honeycomb cells was 0.355 $m^2 \cdot K/W$ (2.02 $ft^2 \cdot {}^\circ F \cdot h/Btu$). The resistance measured for the panel having polyimide foam in the honeycomb cells was 0.467 $m^2 \cdot K/W$ (2.65 $ft^2 \cdot {}^\circ F \cdot h/Btu$), an increase of 31% over the panel with only air in the honeycomb. A detailed analysis of the heat transfer through the panels is outside the scope of this report, however, a brief explanation for the difference in R-values is presented.

As described previously, the honeycomb cells traversed the thickness of the panel providing the means for thermal bridging through the panel and reducing its thermal performance. Heat transport through an airspace takes place by radiation, and by convection and conduction combined [8]. Thermal measurements indicated replacing the air in the honeycomb with polyimide foam provided a moderate increase (31%) in the thermal resistance of the honeycomb panel. This implies that a significant portion of the over-all heat transport through the panel having air in the honeycomb was by radiation and air convection in the cells. Replacing the air in the cells with foam reduced the radiative and convective heat transport, resulting in the higher R-value for the panel with foam in the honeycomb.

5.3 Phenolic-Resin Panel (Sample 05)

The thermal resistance of the phenolic-resin panel was determined by the difference of the two measurements in Table 2. The resistance was 0.058 $m^2 \cdot K/W$ (0.33 $ft^2 \cdot {}^\circ F \cdot h/Btu$) for a 6.1 mm thick (0.24 in.) panel. Difficulties with the specimen surface and thickness compounded the effort for an accurate (1%) determination of the thermal resistance. An uncertainty of ±5% was estimated for the uncertainty in the resistance measurement of the stacked assembly due to the contact resistance. However, this value is provided as a guide only. Further work is needed to quantify the effect of thermal contact resistance on the specimen measurement.

6 CONCLUSIONS

Thermal resistance measurements of five specimens used in shipboard air duct systems of the U.S. Navy were conducted using the NBS 1-m Guarded Hot Plate. Measurements were conducted at a mean specimen temperature of 23.9°C (75°F) at atmospheric conditions. Specimens of fibrous-glass board were conditioned at 90°C (194°F) prior to measurement. The fibrous-glass boards were found to be the most efficient thermally, having a thermal resistance of 0.79 $m^2 \cdot K/W$ (4.5 $ft^2 \cdot {}^\circ F \cdot h/Btu$) at a thickness of 25.4 mm (1.00 in.). Resistance measurements were in good agreement (3%) with certified values of NBS SRM 1450a, fibrous-glass board.

The thermal resistance of two aramid-fiber honeycomb panels was about one-half the thermal resistance of an equivalent 25 mm thick specimen of fibrous-glass board. The resistance of the panel having air in the cells of the honeycomb was 0.355 $m^2 \cdot K/W$ (2.02 $ft^2 \cdot {}^\circ F \cdot h/Btu$) at a thickness of 26.1 mm (1.03 in.). The resistance of a second panel having polyimide foam in the cells was 0.467 $m^2 \cdot K/W$ (2.65 $ft^2 \cdot {}^\circ F \cdot h/Btu$), an increase of 31% over the panel having air in the honeycomb. These measurements suggest radiative and convective heat transport occurred in the panel having air in the honeycomb cells. Replacing the air with foam in the cells reduced the radiative and convective heat transport in the panel, thereby increasing its R-value. Further work is suggested to analyze the heat transfer through these honeycomb panels.

The fifth specimen was a phenolic-resin panel reinforced with glass filaments. Considerable difficulty in the measurement of thermal resistance was experienced due to the surface condition and specimen thickness. The resistance of the phenolic-resin panel was determined by difference to be 0.058 $m^2 \cdot K/W$ (0.33 $ft^2 \cdot {}^\circ F \cdot h/Btu$) for the 6.1 mm thick (0.24 in.) board. This value contains considerable uncertainty due to contact resistance during the measurement and is discussed in the report.

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8 ACKNOWLEDGEMENTS

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Table 2. Summary of Thermal Resistance Measurements for All Specimens

	L		ρ		T_H		T_C		T_m		R-value		ΔM
	(mm)	(in)	(kg/m^3)	(lb/ft^3)	(°C)	(°F)	(°C)	(°F)	(°C)	(°F)	SI*	IP*	(%)
01	25.37	0.999	65.1	4.07	37.81	100.1	9.94	49.89	23.88	74.98	0.784	4.45	+0.5
02	25.30	0.996	77.9	4.87	37.82	100.1	9.96	49.93	23.89	75.00	0.794	4.51	+0.4
03	26.1	1.03	209.	13.1	37.79	100.0	10.02	50.04	23.91	75.04	0.355	2.02	-0.01
04	26.2	1.04	315.	19.7	37.80	100.0	9.98	49.96	23.89	75.00	0.467	2.65	-0.01
05A	107.8	4.245	----	----	37.82	100.1	9.94	49.89	23.88	74.98	3.584	20.36	-0.01
05B	101.7	4.004	29.6	1.85	37.80	100.0	9.95	49.91	23.88	74.98	3.525	20.02	-0.01

* SI = ($m^2 \cdot K/W$), IP = ($ft^2 \cdot °F \cdot h/Btu$)

Notes:

1). The thermal resistance of the phenolic composite board is the difference between tests 05A and 05B.

2). For test 05A, the phenolic composite board was sandwiched between two five-year old, extruded polystyrene boards. The change in mass (ΔM) for test 05A is for the phenolic composite board, only.

3). For test 05B, the thermal measurement was for two five-year old, extruded polystyrene boards.

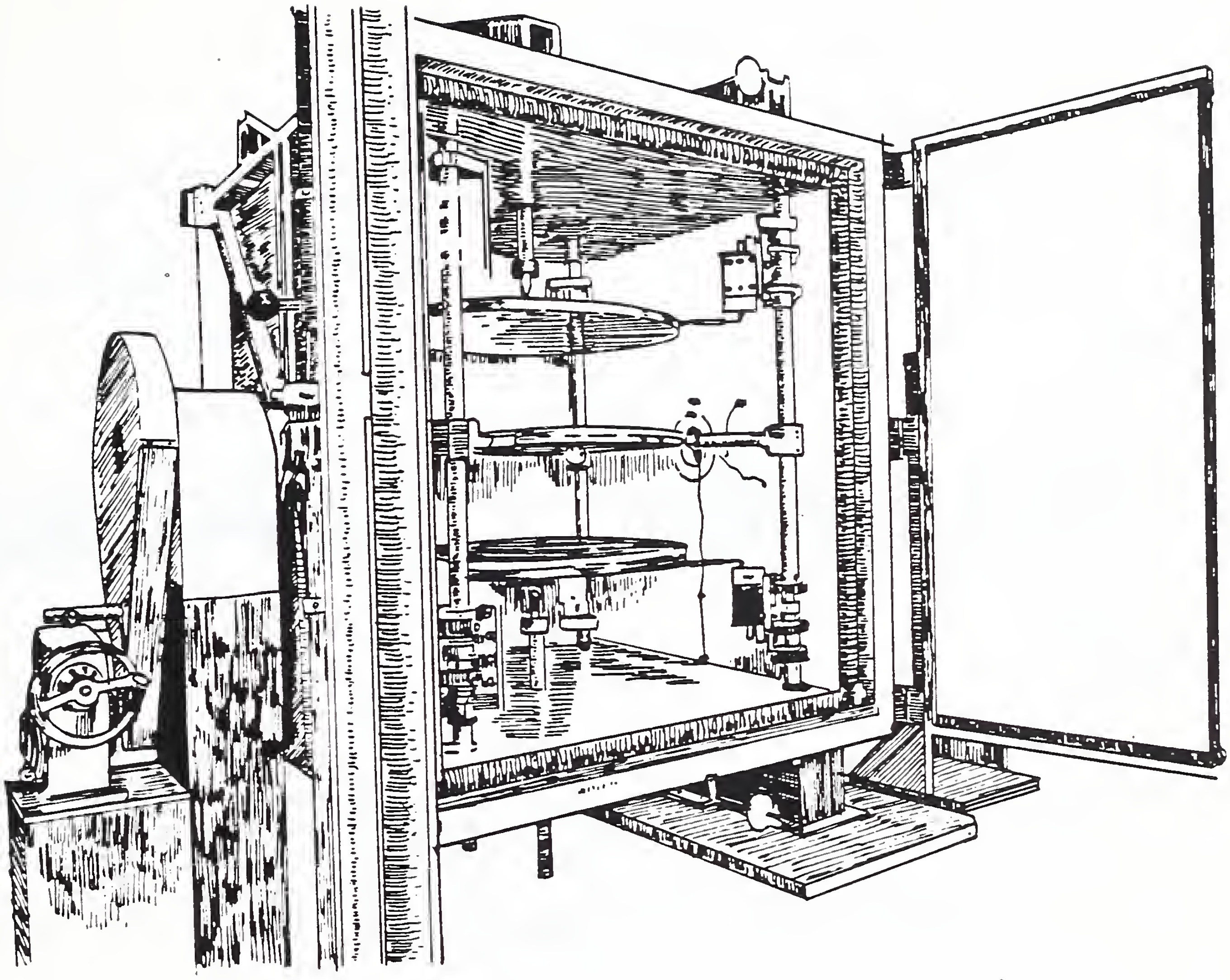

Fig. 1. The NBS 1-metre Guarded Hot Plate.

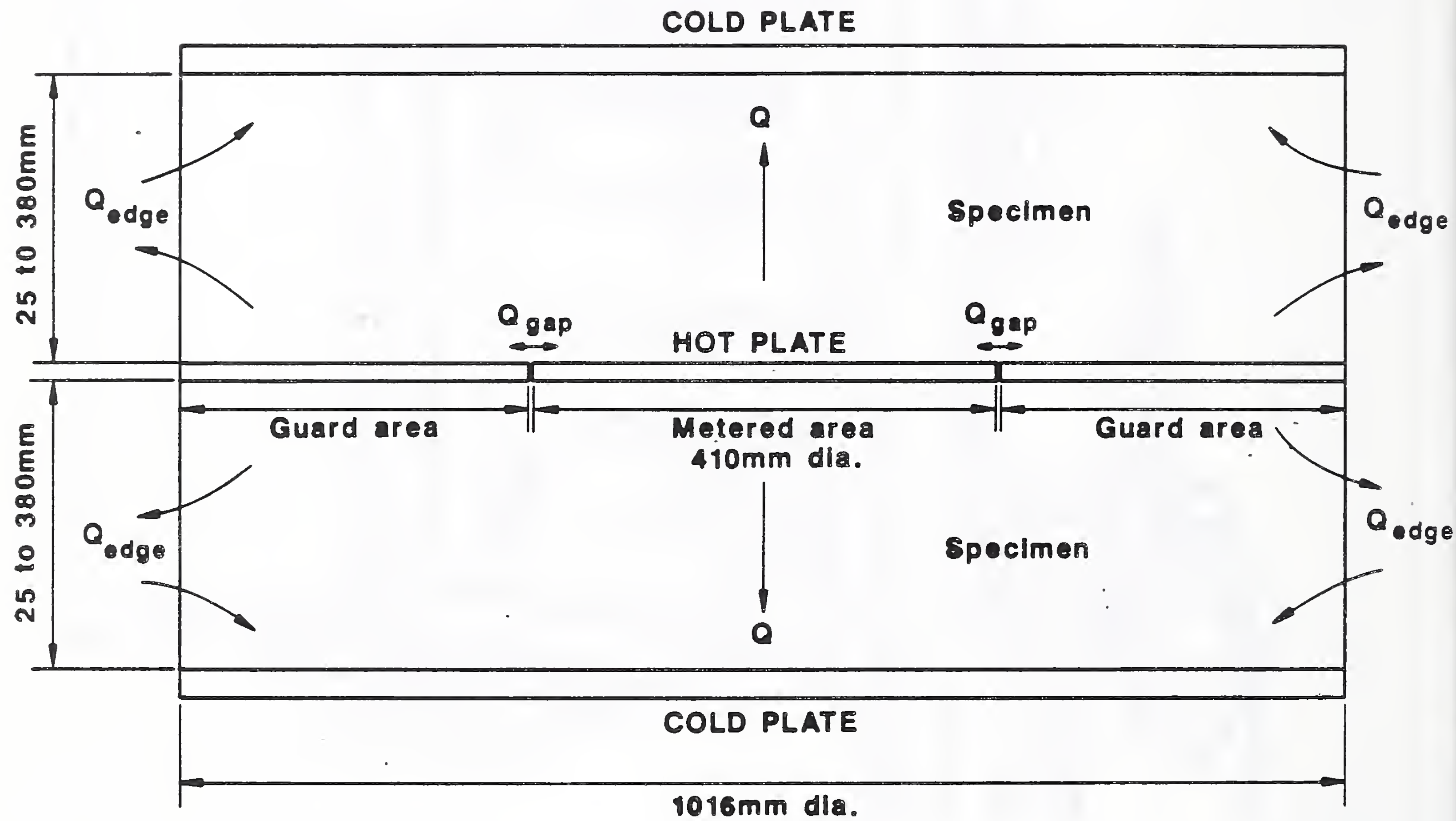

Fig. 2. Principle of measurement for the NBS 1-metre Guarded Hot Plate in a two-sided mode of operation.

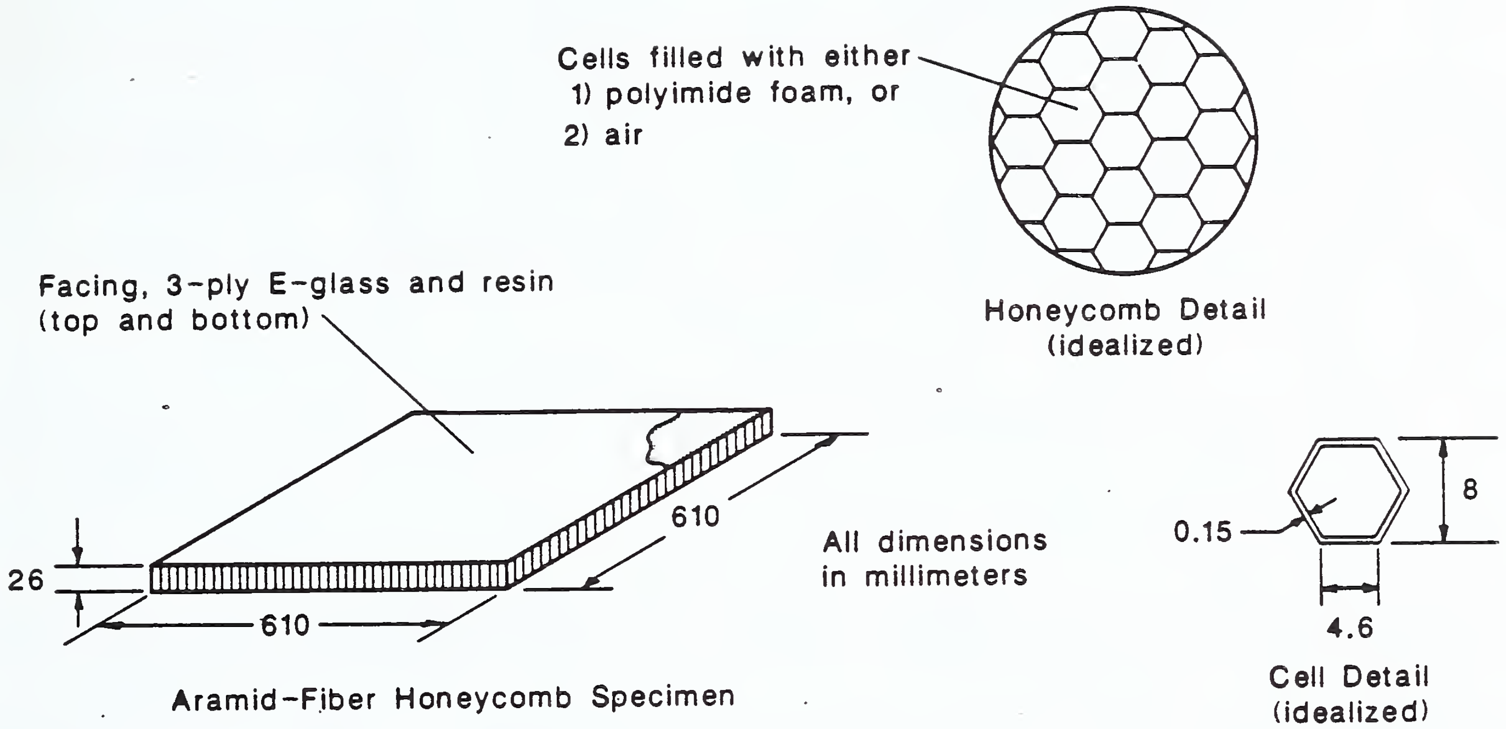

Fig. 3. a) Honeycomb structure of the aramid-fiber honeycomb specimens. Dimensions of the specimen are nominal.
b) Detail of the honeycomb lattice. The cells of the lattice are filled with either polyimide foam or air.
c) Detail of the honeycomb cell.

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Thermal resistance measurements of conventional and composite material insulation for shipboard air duct systems are described. Conventional shipboard air ducts are constructed of metal walls insulated externally with fibrous-glass board. Composite materials are being considered as replacements for these duct walls. Thermal measurements were conducted using the National Bureau of Standards 1-metre Guarded Hot Plate at a mean temperature of 23.9°C (75°F). Measurements of the fibrous-glass board specimens were within 3% of certified values of NBS SRM 1450a, fibrous-glass board. Measurements of two aramid-fiber honeycomb specimens were approximately one-half the thermal resistance of the fibrous-glass board specimens.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

aramid fiber; fibrous-glass insulation; composite materials; guarded-hot-plate apparatus; polyimide foam thermal resistance

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