Thermal Resistance of Reflective Insulations Installed in a Simulated Wall Cavity

D.W. Yarbrough S.G. Kim

ABSTRACT

The thermal resistances of two types of reflective foil insulation have been measured in an apparatus simulating a wall cavity. The apparatus consisted of a stainless steel screen supported vertically between two water-cooled copper plates. Test materials were installed in the regions between the screen and the copper plates. R-values were determined from the direct current required to maintain a steady-state temperature difference across the test cavities.

Results of the study show that the R-values of the foil insulations in wall cavities decreased 20 to 40% as the temperature difference across the wall was increased from 10°F to 50°F (6°C to 28°C). The measured R-values for a three-foil insulation were higher than the R-values for a two-foil product, but both were below the R-values measured on a mineral-fiber batt. R-values for a wall system were calculated from the experimental data.

INTRODUCTION

The most commonly used thermal insulations in the United States are called mass insulations. This general classification includes mineral fiber and cellulosic materials in loose-fill or batt form, cellular plastics, and a number of loose-fill perlite and vermiculite products.[1] The thermal resistance of these materials is primarily the result of trapping small pockets of air within the body of the insulation. These materials also prevent direct radiative transfer between bounding surfaces. In addition to the mass insulations is a class of materials called reflective foil insulations; these materials use one or more layers of aluminum foil to reduce radiative heat transfer and, in some cases, subdivide the cavity into two or more regions, thus changing the convective heat-transfer characteristics of the cavity. The aluminum foils are often attached to heavy paper or plastic material to provide structural integrity.

The evaluation of insulating materials as thermal barriers commonly involves the determination of an R-value. The R-value is conventionally defined as

$$R = L/k \qquad (1)$$

where

L = thickness, in.

k = apparent thermal conductivity, BTU.in/ft^{2}hr°F

In the case of the mass insulations, the R-value is essentially a material property that can be determined by various measurement techniques.[2,3,4,5] The reflective foil insulations, on the other hand, decrease heat transfer by altering the system in which they are placed. The material itself has negligible resistance to heat transmission.

Since the thermal resistance of the reflective foils is not related directly to apparent thermal conductivity, Fourier's Law is written

$$R = \frac{\Delta T}{(Q/A)} \qquad (2)$$

An experimental determination of R-value based on Eq 2 requires measurement of the one-dimensional steady-state heat flux across a region and the temperature difference required to maintain the heat flux.

The apparent thermal conductivity of the mass-type insulations can be determined as a material property with the R-value calculated from Eq 1. The experimental determination of the R-value for the reflective foil insulations requires a system measurement. A comparison of R-values for the mass insulations with those for the reflective types require, therefore, that the R-value for a system be determined either with mass insulation installed and parallel heat transfer taken into account or by subtraction of parallel heat transfer from the reflective system to obtain an R-value for the region in which the reflective material is installed. In the present work, R-value is determined for a system using Eq 2, and heat transferred along parallel paths is subtracted to obtain an R-value for the installed foil being tested.

Effective thermal resistance values for the reflective foil insulations have been obtained using the guarded hot-box techniques,[6,7] and R-values can be calculated from published convective heat transfer coefficients and a calculation of the heat transfer by radiation.[8,9]

THE EXPERIMENTAL APPARATUS

The experimental apparatus constructed for this study was suggested by the unguarded pipe insulation tester described by Jury et al[10] and by the flat-screen testers described by Moore[11] and McElroy.[12] The apparatus consists of a screen heater, the hot boundary (located between two water cooled copper plates), and the cold boundaries. The test regions between the screen and the copper plates simulate standard wall cavities. A diagram of the apparatus is shown in Fig. 1. The screen heater used in this study was fabricated from 40 mesh stainless steel screen 17.5 in. (44.5 cm) wide by 91.5 in. (232.4 cm) long, mounted vertically with 14.5 in.

(36.8 cm) by 91.5 in. (232.4 cm) of the screen's surface exposed. Approximately 1.5 in. (3.8 cm) of screen extended into the supporting structure along each of the long edges. Rectangular copper strips were fastened along the 14.5 in. (36.8 cm) edges for electrical power input and to provide a means of putting the screen in tension. The screen was mounted in a rectangular frame constructed from two thicknesses of nominal 1.5 by 3.5 in. (3.81 by 8.89 cm) yellow pine lumber. The resulting assembly has test regions on both sides of the screen, with exposed screen dimensions the same as standard 16.0 in. (40.6 cm) wall construction. Copper plates 0.25 in. (6.35 mm) thick, 17.5 in. (44.5 cm) wide, and 96 in. (244 cm) long were mounted vertically with their smooth surfaces parallel to the screen at a distance of 3.5 in. (8.9 cm). The copper plates were painted with a flat black paint to minimize changes in the surface properties with time. Nominal 0.5 in. (1.27 cm) copper tubing was soldered on the outside surfaces of the copper plates to provide fluid for temperature control of the plates. Building water was mixed with a hot water stream to provide a constant temperature fluid for circulation through the tubing attached to the plates. The copper plates were hinged to the main structure for access to the test cavities. Gaskets between the copper plates and the supporting frame provided an air tight seal.

The stainless steel screen was coated with heat transfer cement to prevent air movement between the test cavities. Electrical power to the screen was provided by a 500-amp d.c. power supply. Power to the apparatus was supplied through a resistor bank that provided a load for the power supply. Power to the screen was determined from voltage drop measurements across the screen and a known resistance in series with the screen. Voltage measurements were made with a digital multimeter that was periodically calibrated using a precision potentiometer. Preliminary experimental work established that a.c. ripple in the electrical system was negligible. A correlation of temperature and the resistance of the external resistor used to determine electrical current was established. Screen power determinations, therefore, involved two voltage measurements and a temperature measurement.

The screen and copper plate were instrumented with chromel-alumel thermocouples, Fig. 2. Five 30-gauge thermocouples were attached to the screen by extending one element beyond the thermocouple for attachment to the screen. The screen thermocouples were displaced approximately 0.4 in. (1.0 cm) from the screen but in thermal contact. Each of the copper plates was instrumented with five 18-gauge chromel-alumel thermocouples. Nine 30-gauge chromel-alumel thermocouples were located on the supporting frame of the apparatus to measure temperatures along parallel heatflow paths. The thermocouples were read against an ice bath using the digital multimeter described earlier. Thermocouple readings were converted to temperatures using tables prepared by the National Bureau of Standards.[13]

The structure containing the instrumented screen and copper plates was insulated on top, bottom, and edges with 4 in. (10.2 cm) of expanded polystyrene. Once specimens were mounted in the test cavity, the entire structure was wrapped with mineral-fiber batts to provide edge insulation with a total R-value of 30 $ft^2 \cdot hr \cdot °F/Btu$ (5.3 $K \cdot m^2/W$). The mineral-fiber insulation that was tested filled the test cavity and was in contact with the screen and copper plates. The reflective insulations were mounted so that the center of the insulation coincided with the center of the test cavity.

The determination of specimen R-values from measurements of screen power and temperature difference obtained with the test apparatus required a calculation of heat transport along paths parallel to the test cavities. The thermal conductivity data needed for the calculation were obtained using a cylindrical specimen of the lumber used in the construction. Radial heatflow measurements yielded a thermal conductivity of 0.85 $Btu \cdot in/ft^2 \cdot hr \cdot °F$(0.122 $W/m \cdot K$) for the wood in the temperature range of 80 to 85°F (26.7 to 29.4°C). Additional details concerning the construction and operation of the apparatus are contained in a thesis prepared by Kim.[14]

EXPERIMENTAL RESULTS

A cross-sectional view of the simulated wall cavity, as seen from the top, is shown in Fig. 3; thermocouple locations are shown. Insulation material to be tested was installed in regions 3 and 6. Cold-boundary temperature was taken to be the average of the 10 copper-plate temperature measurements; hot-boundary temperatures were taken to be the average of temperatures G, H, and I. The observed temperature variation on the copper plates was less than 0.45°F (0.25°C) while temperature variations on the screen heater were as large as 2.7°F (1.5°C). The heat flux across the test region was obtained by subtracting calculated values for the heat transported by the wooden members in parallel with the test cavity from the measured screen power.

A number of simplifying assumptions were made in the analysis of the experimental results. The materials in the two test regions were assumed to be identical so that heat transfer across each specimen was one-half the total power corrected for parallel flow. The surfaces A-B-C and O-P-Q were taken to be adiabatic. Heat transport through regions 1, 2, 3, and 4 was taken to be one dimensional. No corrections were made for the top and bottom horizontal wooden members, partly because the screen heater did not extend into these regions. The calculation of steady-state heat transfer along the members parallel to the test cavities were calculated using Fourier's Law and the temperatures identified in Tab. 1. Apparent thermal resistances for the material in the test regions were calculated using Eq 4 with the heat flux across the test regions given by Eq 3.

$$Q_c = Q - Q_w \tag{3}$$

$$R_c = 1.7119\ \Delta T_c/Q_c \tag{4}$$

The constant in Eq 4 is the cavity area perpendicular to the heat flow. The constant is calculated using the cavity width of 14.5 in. (0.3683 m) and height of 91.5 in (2.324 m). The effective R-value for a system R_s consisting of one wall section was calculated using Eqs 5 and 6. The constant in Eq 5 is the product of the cross-grain thermal conductivity of the wood used in the apparatus and the cross-sectional area of the wood; the constant in Eq 6 is two times the area of a wall segment 16 in. (0.4064 m) wide and 91.5 in. (2.324 m) high. Horizontal structure elements were not included in the calculation of Q_s.

$$Q_s = Q_c + 0.2450\ \Delta T_c \tag{5}$$

$$R_s = 1.8890\ \Delta T_c/Q_s \tag{6}$$

Experimental results are summarized in Tabs. 2, 3, 4, and 5. Table 2 contains date obtained with the test region empty and Tab. 3 contains data obtained with a commercial R-11 (1.94 K·m²/W) mineral-fiber batt installed to fill the test cavity. Tables 4 and 5 contain results for two types of reflective foil insulation. Reflective insulation A has two aluminum foils separated by 0.25 in. (0.64 cm) of plastic with trapped air bubbles. Product B was a multifoil insulation with three aluminum foils supported by heavy brown paper. In Tabs. 2, 3, 4, and 5, totals for the heat transfer rates for the two-sided experiment are given in the first three columns. The entry T_{mean} is the average of the temperatures bounding the test region. The ΔT, shown in column five, is the temperature difference across the test region. Two columns of R-values are shown for each test series reported. The first (labeled R_c) is the apparent thermal resistance of the test region; R_s is the apparent thermal resistance for one section of wall. The R-value data have been shown as a function of ΔT_c in Figs. 4 and 5.

A comparison of R_c values in Tab. 2 with R-values calculated using published tables[15] and a bounding surface emissivity of 0.835 showed an average difference of 1.2%. The good agreement between measured and calculated R-values was obtained by adjusting the emissivity of the bounding surfaces. R-values for the mineral-fiber batt insulation tested were calculated from the correlations given by Tye.[16] The average difference between the measured and calculated values for the seven batt measurements was 3.6%. Calculated R-values for the test region with reflective foil installed were higher than the measured values. In the case of product A, the calculated R-values were 16 to 31% higher than the measured values; for product B, the calculated values were 50 to 68% higher than the measured values. A thermal resistance for 0.25 in. (6.4 mm) of air was used in the R-value calculation for product A. In both cases, the best agreement between measured and calculated R-values occurred at the larger ΔT values. A detailed comparison of the experimental and calculated R-values is given by Kim.[17]

The most striking feature of the R-value data shown in Figs. 4 and 5 is the decrease in the R-value of the reflective insulations tested with the increase in the temperature difference across the test cavity. The results shown are consistent with R-values predicted from ASHRAE tables.[18] The decrease in R-value is due partly to increases in the convective heat transfer with increased gap temperature differences.

A detailed analysis of experimental uncertainty in the R-value determination has been carried out by Kim.[19] The results of the analysis of the experimental uncertainty can be summarized as follows. The total R-value uncertainty decreases as ΔT_c increases. The uncertainty calculation includes temperature measurements, power measurements, and uncertainty in the parallel heat transfer rates. No factor has been included for edge losses. The uncertainty in the R-values of the empty cavity ranged from 8.0 to 2.1%. The uncertainty in the mineral-fiber batt measurements ranged from 10.5 to 5.1%. The uncertainty in the reflective foil measurements ranged from 10.9 to 4.0%. Tables 2, 3, 4, and 5 include the estimated uncertainty for each of the reported measurements.

CONCLUSIONS AND RECOMMENDATIONS

The thermal resistance of a standard wall section was measured with the cavity containing air, fiberglass batt insulation, and two kinds of reflective foil insulations. R-values for the empty wall cavity differed from ASHRAE[20] values an average of 1.2%, with boundary emissivity taken to be 0.835. R-value determinations for a mineral-fiber batt showed an average difference of 3.6% from a correlation based on guarded hot-plate data. These observations, combined with the estimated experimental uncertainties indicate that R-value determinations of better than ±10% can be made with the apparatus, except at very low ΔT_c.

The effective thermal resistance of the reflective foil insulated systems decreased from 20 to 40% as ΔT_c was increased from 10°F to 50°F (6°C to 28°C). The R-values measured for the three foil products were about 40% higher than the R-value for the two foil product at low ΔT_c, but the difference decreased as ΔT_c was increased. The R-values measured for the three foil products were about 40% higher than the R-value for the two-foil product at low ΔT_c was increased. The R-values measured for the mineral-fiber batt were higher than those for the reflective insulations and were not sensitive to ΔT_c.

NOMENCLATURE

A = area, in² (cm²)

k = thermal conductivity, BTU·in/ft²·hr·°F (W/cm·K)

L = thickness, in. (cm)

Q = measured screen power, W

Q_c across cavity, Q_s across system, Q_w across wood supports

R = thermal resistance, Btu.in/ft².hr°F (K.m²/W)

R_c for cavity, R_s for system

T = temperature, °F (°C)

ΔT = temperature difference, °F (°C)

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17. Kim, Thermal Resistance, pp. 35-53.

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Table 1.
Data Used to Establish Parallel Path Temperature Differences

Region	Expression for ΔT
1	$(T_B + T_L)/2 - (T_E + T_J)/2$*
2	$(T_G + T_L)/2 - T_J$
4	$(T_I + T_S)/2 - T_J$
5	$(T_S + T_P)/2 - (T_R + T_J)/2$

* This expression is based on TM measurements for one specimen.

Table 2.
Experimental R-Values for a Vertical Empty Wall Cavity

Total Screen Power Q (W)	Cavity Heat Transfer Rate Q_c (W)	System Heat Transfer Rate Q_s (W)	T_{mean} (°C)	ΔT_c (°C)	R_c ($K\cdot m^2/W$)	R_s ($K\cdot m^2/W$)	Exp. Uncertainty in R_c (%)
37.56	35.67	36.56	27.53	3.64	0.175	0.188	8.0
53.08	50.41	51.62	28.79	4.98	0.169	0.182	6.2
75.94	72.61	74.30	28.82	6.91	0.163	0.176	4.7
117.25	111.51	114.08	28.97	10.48	0.161	0.174	3.6
165.17	157.34	160.86	30.33	14.38	0.156	0.169	3.0
216.60	206.24	210.76	28.92	18.44	0.153	0.165	2.6
274.91	262.38	267.96	29.39	22.77	0.149	0.161	2.4
400.25	382.57	390.46	29.49	32.20	0.144	0.156	2.1

To obtain $°F\cdot ft^2\cdot hr/Btu$ multiply $K\cdot m^2/W$ by 5.678

To obtain Btu/hr multiply W by 3.413

Table 3.
Experimental R-Values for a Mineral Fiber Batt Specimen*

Total Screen Power Q (W)	Cavity Heat Transfer Rate Q_c (W)	System Heat Transfer Rate Q_s (W)	T_{mean} (°C)	ΔT_c (°C)	R_c ($K \cdot m^2/W$)	R_s ($K \cdot m^2/W$)	Exp. Uncertainty in R_c (%)
8.45	5.26	6.76	27.98	6.11	1.99	1.71	10.5
13.93	8.70	11.08	27.40	9.70	1.91	1.65	8.0
19.45	11.86	15.16	26.57	13.48	1.95	1.68	6.9
25.11	15.16	19.52	26.53	17.80	2.01	1.72	6.2
30.13	19.11	24.09	28.90	20.32	1.82	1.59	5.6
35.82	22.32	28.36	27.97	24.64	1.89	1.64	5.4
41.98	26.46	33.42	28.19	28.41	1.84	1.61	5.1

* Nominal R-11 mineral fiber batt.

To obtain $°F \cdot ft^2 \cdot hr/Btu$ multiply $K \cdot m^2/W$ by 5.678

To obtain Btu/hr multiply W by 3.413

Table 4.
Experimental R-Values for Reflective Insulation A

Total Screen Power Q (W)	Cavity Heat Transfer Rate Q_c (W)	System Heat Transfer Rate Q_s (W)	T_{mean} (°C)	ΔT_c (°C)	R_c ($K \cdot m^2/W$)	R_s ($K \cdot m^2/W$)	Exp. Uncertainty in R_c (%)
14.03	10.06	11.91	27.90	7.54	1.28	1.20	7.9
22.44	16.21	18.98	28.18	11.29	1.19	1.12	6.2
29.06	21.07	24.55	27.78	14.19	1.15	1.09	5.5
36.10	26.57	30.74	27.55	17.03	1.10	1.05	5.0
48.19	36.23	41.45	27.61	21.32	1.01	0.97	4.4
62.24	47.17	53.71	27.33	26.69	0.97	0.94	4.0

To obtain $°F \cdot ft^2 \cdot hr/Btu$ multiply $K \cdot m^2/W$ by 5.678

To obtain Btu/hr multiply W by 3.413

Table 5.
Experimental R-Values for Reflective Insulation B

Total Screen Power Q (W)	Cavity Heat Transfer Rate Q_c (W)	System Heat Transfer Rate Q_s (W)	T_{mean} (°C)	ΔT_c (°C)	R_c (K·m^2/W)	R_s (K·m^2/W)	Exp. Uncertainty in R_c (%)
8.33	5.27	6.66	27.84	5.68	1.85	1.61	10.9
15.27	10.33	12.57	28.93	9.16	1.52	1.38	7.5
23.06	15.64	18.89	28.79	13.28	1.45	1.33	6.2
30.25	21.18	25.18	28.72	16.33	1.32	1.23	5.4
44.27	32.11	37.48	28.78	21.93	1.17	1.11	4.6
58.60	43.52	50.17	28.63	27.15	1.07	1.02	4.1

To obtain °F·ft²·hr/Btu multiply K·m²/W by 5.678

To obtain Btu/hr multiply W by 3.413

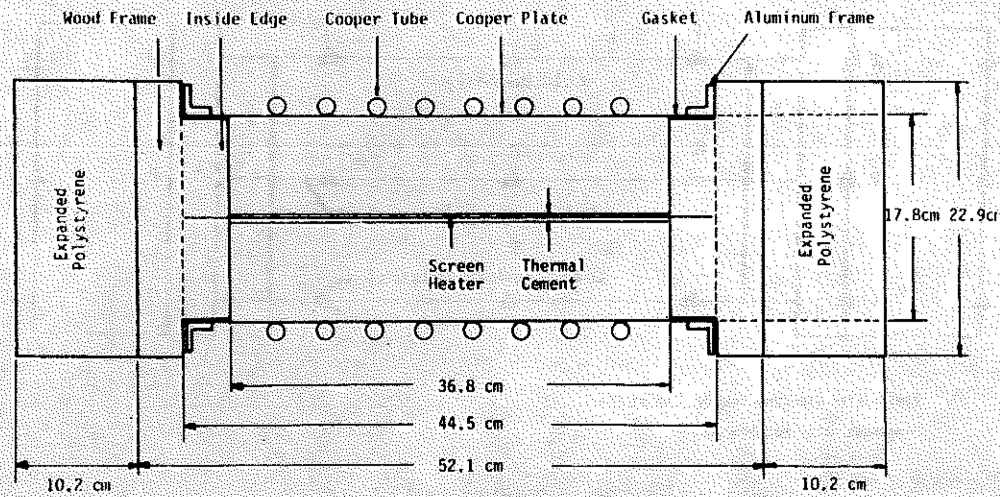

Figure 1. Top view of apparatus

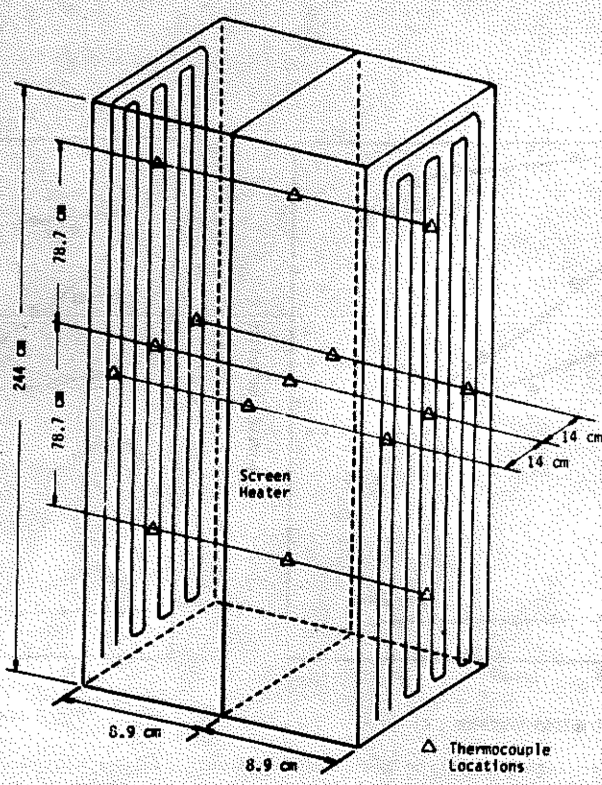

Figure 2. Thermocouple positions on the screen and copper plates

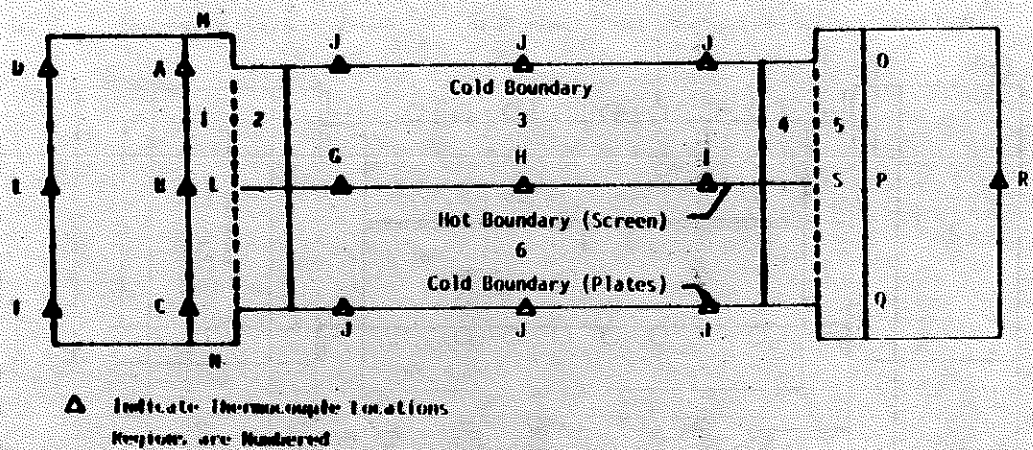

Figure 3. Top view of apparatus with thermocouple locations shown

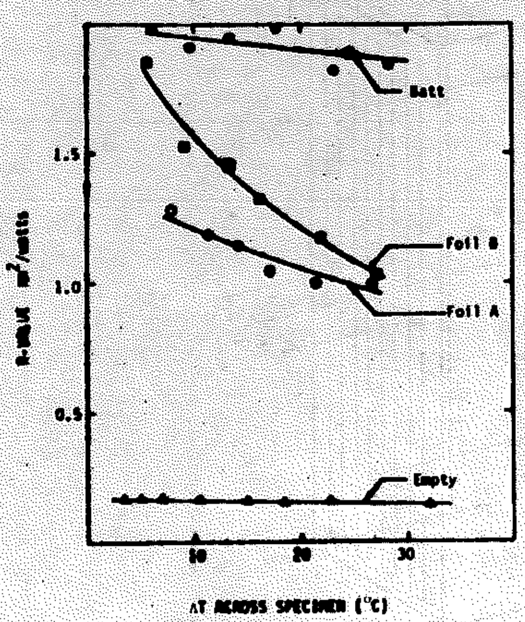

Figure 4. Thermal resistances of the test cavity as a function of temperature difference across the cavity

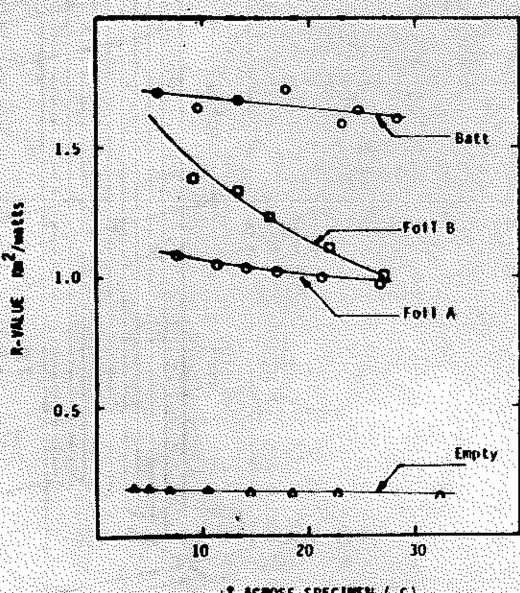

Figure 5. Calculated thermal resistances of a standard wall section as a function of temperature difference across the wall

Discussion

B. Rennex, Physicist, NBS, Washington, DC: How was ϵ measured? Visible-range, measured is not the same as ϵ used in thermal radiation equation (for $\lambda \sim 7 - 30\mu$); ϵ for all paints is $\sim .85$.

Yarbrough: The central screen heater and the copper plates were painted with the same black paint. Epsilon was determined to be 0.835 by treating it as a parameter and adjusting its value to obtain agreement between experimental R-value results for an empty cavity and values calculated using ASHRAE tables (See Ref 9).