Measured R-Values for Two Horizontal Reflective Cavities in Series

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ABSTRACT

The Large Scale Climate Simulator at the DOE-sponsored Roof Research Center has been used to provide data for steady-state temperatures and heat fluxes in two horizontal reflective cavities in series. The cavities have nominal effective emittances of 0.015 and 0.03 and are relatively narrow. The resulting R-values cover a range of mean air temperatures from -5 F to 135 F and temperature differences from 12 F° to 26 F°. The cavities studied had exposed wood sides. The R-values for heat downflow fall significantly below those for the same nominal emittances in the ASHRAE Handbook of Fundamentals. Values for heat upflow are slightly lower than the ASHRAE data. Analysis of a graybody radiation network for this situation shows that the lower R-values are the effect of non-reflecting sides. It also confirms that the sides should be covered with foil.

INTRODUCTION

Work related to roofing began at Oak Ridge National Laboratory (ORNL) in the late 1970's to carry out the interest of the U.S. Department of Energy in energy efficient yet practical roof systems. The ORNL Roof Research Center was formed to provide roof researchers from industry, academia and governmental agencies with facilities and expertise to test whole roof systems. An outdoor test facility was constructed and began operating in 1984. Called the Roof Thermal Research Apparatus (RTRA), it can dynamically test four panels simultaneously against the weather at the ORNL site. Each panel can be as large as 4 ft by 8 ft and forms part of the roof of a well-insulated, conditioned building housing the instrumentation to acquire data on the behavior of the panels and transmit them to a data storage system.

Experience with the RTRA demonstrated the need for a Large Scale Climate Simulator (LSCS) where wide ranges of weather conditions could be created as needed for steady-state or dynamic tests. An LSCS should accommodate specimens of real roof systems large enough to permit full-scale flashings, fasteners and other features affecting thermal and mechanical performance. Experience with the RTRA also helped to establish the criteria for construction and operation of the LSCS. Construction of the LSCS was completed by August 31, 1987 and debugging of the data acquisition and control system was completed by early 1988.

The initial tests in the LSCS during mid-1988 used larger scale versions of panels tested previously in the RTRA. In the 12 foot by 12 foot diagnostic platform which holds the test specimen in the LSCS, four equal-sized test sections were constructed. Three sections were used to verify and extend the dynamic data obtained with the RTRA on the thermal performance of three common roof insulation materials in board form: expanded polystyrene (EPS), fiberglass and phenolic foam. Data on the

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performance of reflective cavities were obtained from the fourth test section. All tests served to establish and refine operating procedures in preparation for use of the LSCS as a guarded hot box and as an environmental chamber.

This paper reports on the data obtained with the reflective cavities and subsequent analysis of them. The results for the insulation materials have been reported elsewhere (Courville 1989). The LSCS control system imposed a series of steady temperatures above and below the test sections with linear ramps for the transitions. In each interval of steady response, the data yielded the performance of the reflective cavities: their R-values as a function of the difference in the temperatures of the boundary surfaces and the mean temperature of the air between the surfaces.

DETAILS ABOUT THE TEST SECTION

A test section for reflective cavities was designed to get R-values which compare to and extend those presented in Table 22-2 of the 1989 ASHRAE Handbook of Fundamentals (ASHRAE 1989). In particular, an arrangement was constructed to yield two horizontal reflective cavities in series. Figure 1 shows how the 6 foot by 6 foot cross section available for the reflective cavities was filled. In the top view, the spaces for the measurement cavities and the guard cavities look like the spaces beside a standard ceiling joist. Heat flow in the horizontal direction between them is prevented by identical conditions in each side. Heat flow to the side cavities is prevented by the batt insulation. Thus, despite there being only one set of relatively narrow measurement cavities, the dominant heat flow direction is vertical.

The thickest cavity for which data are presented in ASHRAE 1989 is $3\frac{1}{2}$ inches. The nominal $7\frac{1}{2}$ inch high space (formed from standard milled 2x8 framing lumber) was divided in half by ordinary aluminum foil laid dull side up on a horizontal framework of nylon line and taped to the framing lumber to form an air tight divider. Thus, the lower measurement cavity and the upper measurement cavity which were obtained are each $3\frac{3}{4}$ inches high. Corresponding guard cavities were also formed.

The lower measurement and guard cavities had hardboard bottoms and the foil dividers on top, while the upper cavities had foil both on bottom and top. Measurements with an emissometer yielded $\varepsilon_f = 0.03$ for both sides of the dividing foil. Taking the hardboard's emittance as $\varepsilon_h = 0.90$, the lower measurement cavity has a nominal effective emittance $E_l = 0.03$ (from $1/E_l = 1/\varepsilon_f + 1/\varepsilon_h - 1$). The upper cavity has a nominal effective emittance $E_u = 0.015$ (from $1/E_u = 2/\varepsilon_f - 1$). The formulas for the nominal effective emittances assume that the exposed wood sides of the cavities do not participate in the radiation, *i.e.*, the cavities act like they are formed by infinite parallel planes.

STEADY-STATE RESULTS AND DISCUSSION

R-values of air spaces with nominal effective emittances from E = 0.82 to E = 0.03 are available in ASHRAE 1989. Data are given for air gaps of 0.50, 0.75, 1.5 and 3.5 inches positioned horizontally, vertically and at 45° slope for mean temperatures T_m from -50 F to 90 F and for temperature differences ΔT from 10 F° to 30 F°. Moderate extrapolation for air spaces greater than 3.5 inches is allowed by footnote d of the table, but no more than a 1% increase results by a linear extrapolation of the data from 3.5 inches to 3.75 inches. Hence, the data for a gap of 3.5 inches are used directly to compare to the data measured in the lower cavity.

Data measured for the upper cavity where the nominal effective emittance E = 0.015 are a practical extension of the ASHRAE data. The ASHRAE data for a 3.5 inch gap at E's from 0.82 to 0.03 were extrapolated to E = 0.015 for appropriate T_m and ΔT on a log-log plot. Dependence on T_m is inferred from a fit of the data at ΔT = 10 F° of the form $A + B \cdot T_m$. The slope B is held constant for all ΔT's. A, the value at T_m = 0 F and ΔT = 10 F°, is adjusted to reflect the slight decrease in R-value for increased ΔT's of 20 F° and 30 F°. The linear interpolations which result are also permitted by footnote d of the table. The slight extension of the ASHRAE data beyond the upper limit of T_m = 90 F in the table to the upper limit of T_m = 135 F needed for comparison to the measurements is assumed to be valid in the spirit of this footnote. Table 1 summarizes the data to be used for direct comparison to the measurements. The data for E = 0.015 are in parentheses to emphasize that they are extrapolations.

The sketch of the measurement and guard cavities in Figure 1 shows the placement of the thermocouples and heat flux transducer, the data from which allow the R-values to be computed in steady-state by the formula $R = \Delta T/Q$. Temperature differences and heat fluxes are averaged over the time for which they are steady at particular settings of the control temperatures in the upper climate chamber and the lower guard chamber of the LSCS. The three temperatures measured along the middle of the long side of the top foil and the hardboard are averaged spatially and compared to the center value to see if there are any variations in this direction. None were noticed.

Other checks were made to assure that the data are consistent vertically and horizontally. Examples of the working graphs generated for this purpose comprise Figures 2 and 3. The profiles show that nearly 3 hours worth of steady temperatures and heat fluxes sampled every 10 minutes are available for the pair of R-values which result from them. The vertical profiles are all level except for a dip in the guard chamber temperature at the end signaling the start of the excursion to the next control point. The horizontal profiles show that the measurement and guard cavity are at identical conditions, preventing heat flow across the joist between them. However, temperatures at the top of the joist are significantly cooler than the temperatures of the top foil. The guard cavity-side temperature of the middle of the joist is cooler than the temperatures of the mid foil. The measurement cavity-side one is slightly warmer here and is inconsistent for all the horizontal profiles generated. The thermocouple generating this response might have been displaced during assembly of the test section or shorted out at a location away from the middle of the joist. Only the guard cavity-side temperature is used for the middle of the joist.

Joist temperatures which are cooler than the foil temperatures at the same level for heat downflow indicate that the joist presents a lower R-value than the reflective cavities. Data from a heat flux transducer mounted under the joist supported this conclusion. However, since the transducers are 2 inches by 2 inches, the one under the joist protruded slightly into the cavities and could not be used to confirm the tabulated value of the joist R-value alone. Placement of wedges of insulation over this transducer's protrusions was not successful in eliminating cavity effects from its response.

The response of the heat flux transducer in the measurement cavity is shown in Figure 3 on a separate scale. Like the temperatures, it is steady but shows more scatter than them. This is because heat flux transducer signals were amplified before acquisition in this test, an unsatisfactory situation which has since been addressed. Based on the evidence from the horizontal profiles of temperature and the presence of the batt insulation in the side cavities, this heat flux is assigned to both the upper (nominal effective emittance $E = 0.015$) and the lower (nominal effective emittance $E = 0.03$) measurement cavities.

The average heat fluxes for each steady state are divided into the appropriate temperature differences to yield the R-values shown as data points on Figures 4 through 7. The scatter is worse for the upper cavity, reflecting the difficulty of measuring the difference between two foil temperatures rather than between one foil temperature and the hardboard temperature in the lower cavity. A dashed line on each figure shows the best fit of the data by linear regression. It is useful to show the trend of the data with mean temperature.

Each figure also shows the data from Table 1 as a set of solid lines for various effective emittances. The R-values measured for these two horizontal reflective cavities in series show variation with mean temperature which is consistent with the dependence shown in ASHRAE 1989. However, the nominal effective emittance is not a sufficient single additional parameter with which to characterize the behavior. For the cavity with nominal $E = 0.015$, heat downflow is around the $E = 0.03$ line in the ASHRAE data while heat upflow falls between lines for $E = 0.05$ and 0.2. For the cavity with nominal $E = 0.03$, heat downflow and upflow both lie between the ASHRAE data for $E = 0.05$ and $E = 0.2$ but slightly closer to $E = 0.2$. Unfortunately, heat downflow in the cavity with foil on both boundaries shows the exception to the trend. Since it delivers the highest R-value, it is of the most practical interest.

The R-value of a reflective cavity is the inverse of its total conductance. The total conductance, due to the action in parallel of convection and radiation, is the sum of the heat transfer coefficients for each mode acting separately: $1/R = C = Eh_r + h_c$. Footnote a in ASHRAE 1989 gives the following expression for Eh_r:

$$Eh_r \simeq 0.00686 \cdot E \cdot \left[\frac{T_m+460}{100}\right]^3 \qquad (1)$$

where

E = Effective emittance
h_r = Radiation heat transfer coefficient
T_m = Mean air temperature in the cavity

This is suitable for radiation between two gray bodies in the shape of infinite parallel planes or, in practice, two large plates close enough together that the radiation view factor of one from the other approaches 1.0.

The reflective cavities yielding the data in Figures 4 through 7 had exposed wood sides with nominal emittance $\varepsilon \simeq 0.9$. The radiation view factor between the top and bottom of each cavity is only 0.85. Hence, there could be a significant effect on radiation from participation of the sides in the radiation exchange. Since the sides maintain their own thermal communication with the environments maintained above and below the test section, they can be treated in the radiation network as isothermal surfaces at an appropriate temperature. Net radiation absorbed or emitted by the heat flux transducer is part of its response and is, therefore, included in the measured R-values.

At relatively low mean temperatures and relatively large temperature differences, convection-conduction dominates the overall heat transfer. Heat transfer data for natural convection from horizontal plates reflect a complicated heat transfer situation (Lienhard 1987). The ASHRAE data use the results of Robinson, et al. (1954) from actual reflective cavities under various orientations and temperatures. Their guarded hot box tests cover a ratio of air space width w to height l from w/l = 18 to 96. Here $w/l = 6$. Robinson, et al. generated curves of h_c values to fit their data. For a horizontal space with heat flow downward, their curves do not conform within a few percent to their data if the temperature difference multiplied by the cube of height, $\Delta T \cdot l^3 > 300$ F°-in^3. Temperature difference multiplied by the cube of height is a combination which appears in a Rayleigh number for a cavity formed by parallel planes. Here, for heat downflow, $\Delta T \cdot l^3 = 630$ to 1600. Thus, there is some uncertainty in applying the ASHRAE data for convection-conduction to the present situation.

Other correlations exist for heat transfer from horizontal plates, often in the form of the McAdams correlations: $Nu = C \cdot Ra^m$ where C and m are constants to fit the situation and Nu and Ra are the Nusselt and Rayleigh numbers, respectively, based on appropriate length, temperature difference and properties. Use of relevant correlations for the convection on flat plates different from the ones used in the ASHRAE data could show the range of the uncertainty in the R-value due to changes in h_c.

Table 2 explores the possible effect of different Eh_r and h_c values on the R-value for the reflective cavities in series. The conditions selected for the exploration for heat downflow are those shown in Figures 2 and 3: T_m = 131 F in the upper cavity and T_m = 106 F in the lower one. For heat upflow, the conditions chosen are T_m = 31 F and T_m = 48 F in the upper and lower cavities, respectively. The R-values from the ASHRAE data at these conditions are broken down into Eh_r values with Equation 1 and h_c from $1/R - Eh_r$.

For alternate convection coefficients relevant to this study, Incropera and Dewitt (1981) suggest improvements of the McAdams correlations based on a length $L = A_s/P$, where A_s is the surface area and P is the perimeter of the horizontal flat plate. For a plate heated from below or cooled from above (heat upflow), the Nusselt number $Nu_L = 0.54 \cdot Ra_L^{1/4}$ in the range of Rayleigh numbers of interest. For a plate heated from above or cooled from below (heat downflow), $Nu_L = 0.27 \cdot Ra_L^{1/4}$ yielding a heat transfer coefficient half as large as in the unstable heat upflow case. For each case, Rayleigh numbers are generated with air properties at the mean of the surface and air temperatures. The free stream air temperature in each cavity is taken to be halfway between the temperatures of the bounding surfaces. Values of the heat transfer coefficient on each surface, say, h_1 and h_2, respectively, are used to generate an effective h_c for the cavity by $1/h_c = 1/h_1 + 1/h_2$. This h_c is combined with the ASHRAE Eh_r to generate a possible new R-value reflecting an alternate convection correlation.

To explore the possible effect of participation by the cavity sides in the radiation, a two dimensional graybody radiation network is analyzed. The three bodies in the network are the top, bottom and the combined sides of each cavity. The measured foil or hardboard temperatures for each case are specified for the top and bottom of the cavities. The temperatures assigned to the sides are the averages of the joist temperatures measured at the top and bottom edges of the cavities. The enhanced radiation to the hardboard bottom or the foil covered plywood top of the test section is compared to the value for a two body network which models parallel planes. The ASHRAE value of Eh_r is multiplied by the ratio of the radiation heat flow with gray sides to the simple value. The convection coefficient is kept at the ASHRAE value and a possible new R-value is generated reflecting the situation with enhanced radiation.

In heat downflow, cases a and c, the alternate convection correlations decrease the resistance by about a third due to a significant increase in h_c. The resulting R-values are closer to the measured values, but show no difference between the two cavities. The effect of enhanced radiation is more difficult to summarize but does vary from the upper to the lower cavity. Details of the calculations show that the sides of the lower cavity have a significantly larger radiosity than the foil top or the hardboard bottom. The radiosities in the upper cavity are all about equal. Recall that radiosity is

the total radiation leaving a surface including the reflected radiation. The net radiation flux to a surface is its radiation resistance $\varepsilon/(1-\varepsilon)$ multiplied by the difference between its emissive power and radiosity. Emissive power, proportional to the fourth power of the absolute temperature, has about the same value for all the surfaces in a given network. Thus, net radiation heat flows from the sides in case a but to the sides in case c. The result is much more net radiation to the bottom surface in case a than in case c. This causes R-values with enhanced radiation to be nearly the same percentage higher than the measured values: 17½% higher than R = 4.4 measured for case a and 21% higher than R = 7.0 measured for case c.

For heat upflow, cases b and d, the alternate convection correlations produce smaller heat transfer coefficients than the ASHRAE values. Thus, higher R-values are predicted which is opposite to the trend of the measured values. Enhanced radiation again affects the R-values more for the lower cavity than the upper, but not much for either because of the dominant convection. Relative to the heat downflow cases, however, the measured R-values are only slightly smaller than the ASHRAE values. Thus, correction of the ASHRAE data is not critical in heat upflow.

If the wood sides of the joist spaces had been covered by the same foil as formed the middle surface of the reflective cavities in series, the radiation network is affected greatly. Assuming the same measured temperatures as for the cases in Table 2, very little enhanced radiation occurs. The resulting R-values are R = 9.0 vs. ASHRAE's R = 9.3 for heat downflow in the lower cavity (E = 0.03, case a) and R = 9.0 vs. ASHRAE's R = 9.1 for heat downflow in the upper cavity (E = 0.015, case c).

CONCLUSIONS

Measurements have been made of steady-state temperatures and heat fluxes in two horizontal reflective cavities in series to yield R-values over a wide range of mean temperatures for a narrow range of temperature differences across the cavities. Comparison to ASHRAE values for the same nominal effective emittances of 0.015 and 0.03 shows that the measured values are significantly lower for heat downflow and slightly lower for heat upflow. A limited exploration has been made of the possible effects of different Eh_r and h_c values contributing to the overall conductance of the cavity, $C = 1/R = Eh_r + h_c$. The analysis emphasizes the role of radiation in the performance of reflecting cavities. If non-reflecting sides are part of narrow reflective cavities, it is critical to correct for their effect on the radiation heat transfer coefficient. The analysis also shows that it would be better to cover them with foil.

Alternate convection correlations for finite plates do not help to explain the difference between the measured and ASHRAE R-values. The h_c values from the tests of Robinson, et al. (1954) are better than extension of the McAdams correlations for these horizontal reflective cavities in series despite exceeding the limitation of their tests on the width to height ratio w/l, in general, and the Rayleigh number parameter $\Delta T \cdot l^3$ for heat downflow. This is not surprising because the edge effects present in the McAdams correlations for isolated plates are not present in the ASHRAE data for actual cavities with side walls.

A caution accompanies the ASHRAE data, *viz.*, "The National Bureau of Standards Building Materials and Structures Report BMS 151 shows that measured values differ from calculated values for certain insulated constructions." The horizontal reflective cavities in series which were used in this study are such a construction: they require careful correction of the radiation coefficient Eh_r to apply ASHRAE data to them.

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TABLE 1.

ASHRAE R-values ($\frac{ft^2 \cdot hr \cdot F^o}{BTU}$) for $3\frac{1}{2}$ Inch Horizontal Air Gaps

Heat Upflow:

$\Delta T(F^o)$	$T_{mean}(F)$	E=.82	E=.5	E=.2	E=.05	E=.03	(E=.015)
20	-5	1.039	1.318	1.775	2.175	2.251	(2.29)
20	85	0.697	0.972	1.553	2.229	2.378	(2.56)

Heat Downflow:

$\Delta T(F^o)$	$T_{mean}(F)$	E=.82	E=.5	E=.2	E=.05	E=.03	(E=.015)
10-20	60	1.186	1.835	3.817	8.478	10.182	(10.39)
10-20	120	0.664	1.078	2.556	7.056	8.968	(10.03)
20-30	85	0.955	1.488	3.161	7.363	8.958	(9.80)
20-30	135	0.521	0.857	2.110	6.177	7.947	(9.00)

TABLE 2.

Effect of Radiation and Convection on ASHRAE R-values ($\frac{ft^2 \cdot hr \cdot F^o}{BTU}$)

NOTE: Units of Eh_r and h_c are $\frac{BTU}{hr \cdot ft^2 \cdot F^o}$

Case a. Nominal Effective Emittance E = 0.03 at T_m = 106 F; Heat Downflow

ASHRAE	Alternate Convection	Enhanced Radiation	Measured
Eh_r = 0.037 h_c = 0.070 R = 9.3	(Eh_r = 0.037) h_c = 0.133 R = 5.9	Eh_r = 0.144 (h_c = 0.070) R = 4.7	R = 4.4

Case b. Nominal Effective Emittance E = 0.03 at T_m = 48 F; Heat Upflow

ASHRAE	Alternate Convection	Enhanced Radiation	Measured
Eh_r = 0.027 h_c = 0.408 R = 2.3	(Eh_r = 0.027) h_c = 0.263 R = 3.4	Eh_r = 0.085 (h_c = 0.408) R = 2.03	R = 1.9

Case c. Nominal Effective Emittance E = 0.015 at T_m = 131 F; Heat Downflow

ASHRAE	Alternate Convection	Enhanced Radiation	Measured
Eh_r = 0.021 h_c = 0.089 R = 9.1	(Eh_r = 0.021) h_c = 0.147 R = 6.0	Eh_r = 0.028 (h_c = 0.089) R = 8.5	R = 7.0

Case d. Nominal Effective Emittance E = 0.015 at T_m = 31 F; Heat Upflow

ASHRAE	Alternate Convection	Enhanced Radiation	Measured
Eh_r = 0.012 h_c = 0.404 R = 2.4	(Eh_r = 0.012) h_c = 0.272 R = 3.5	Eh_r = 0.017 (h_c = 0.404) R = 2.37	R = 2.1

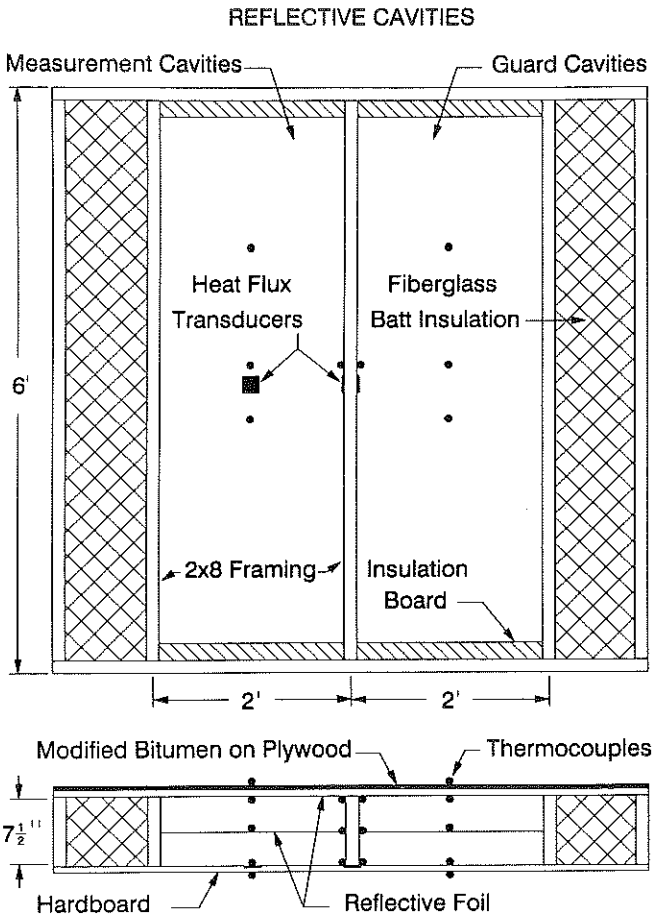

Figure 1. Test section for horizontal reflective cavities in series

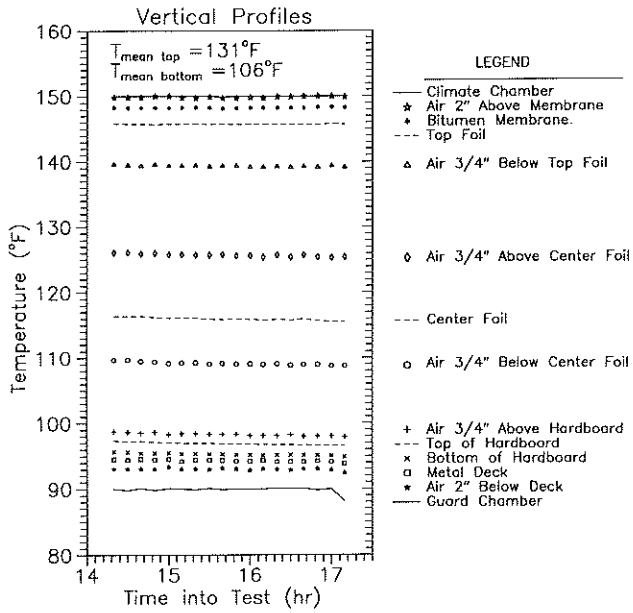

Figure 2. Vertical profiles of temperatures for heat downflow

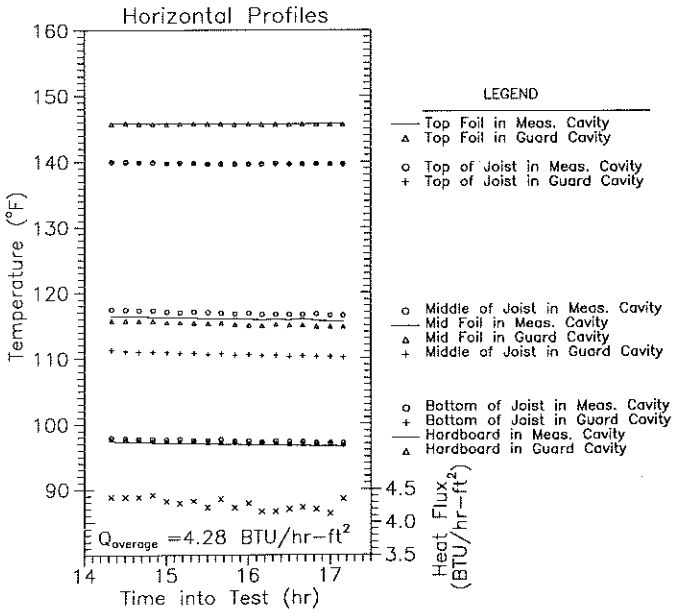

Figure 3. Horizontal profiles of temperatures and heat flux for heat downflow

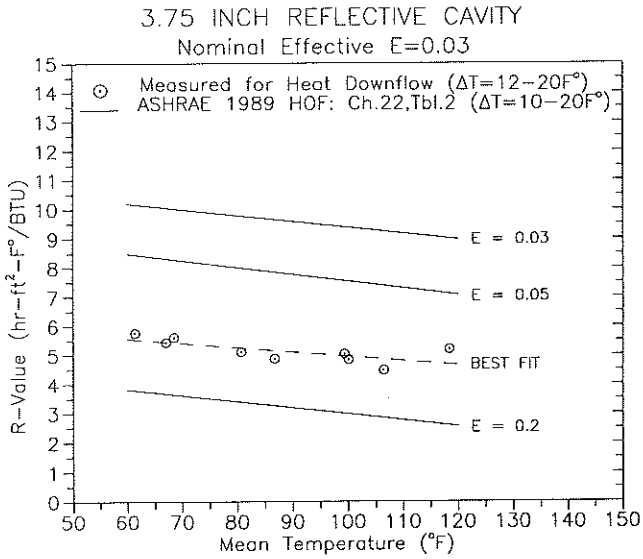

Figure 4. R-values for heat downflow with nominal effective emittance E = 0.03

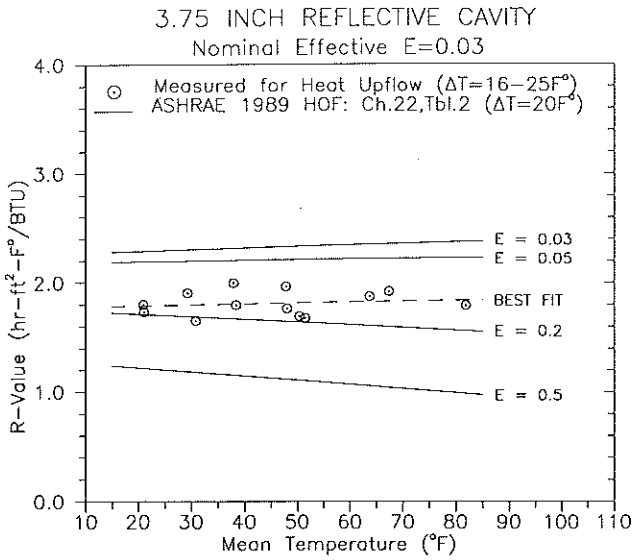

Figure 5. *R-values for heat upflow with nominal effective emittance E = 0.03*

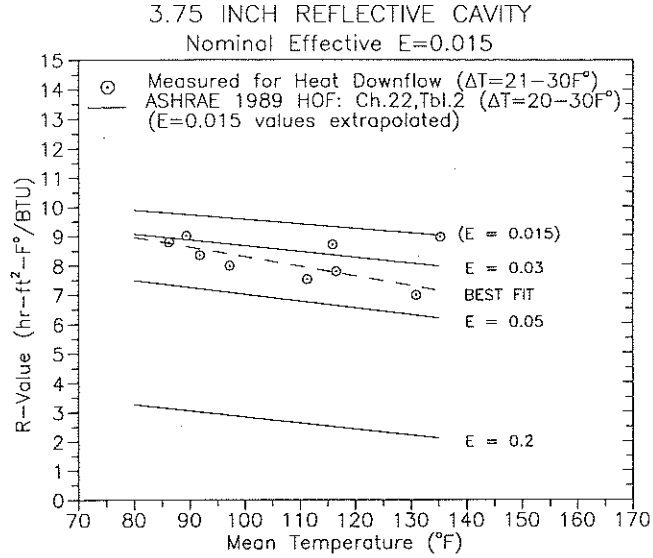

Figure 6. *R-values for heat downflow with nominal effective emittance E = 0.015*

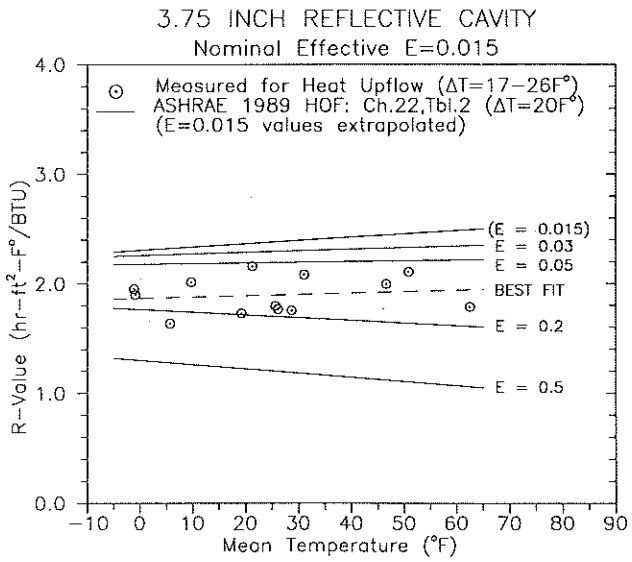

Figure 7. *R-values for heat upflow with nominal effective emittance E = 0.015*