Effects of Infrared Radiation Barriers on the Effective Thermal Resistance of Building Envelopes

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ABSTRACT

A series of tests and measurements have been conducted to determine the potential effectiveness of infrared radiation barriers (aluminum foil) as heat-flow retarders in building envelopes. Both small-scale hot-box tests and full-scale building tests have been employed. Full-scale testing has been conducted under controlled conditions at the Florida Solar Energy Center's Passive Cooling Laboratory (PCL) and in occupied field residences in Orlando, Florida.

To date, the work has been concerned only with overheated summer conditions. Plans call for continuation of this testing at the PCL under winter heating conditions. This paper addresses the test methods and results and presents a preliminary analysis of the effectiveness of foil radiation barriers used in building envelopes.

TEST PROCEDURES

Hot-Box Tests

A small-scale hot box has been constructed to examine typical attic insulation materials that are exposed to high levels of infrared radiation in summer. The box is used to test two 16in. (406mm) by 36in. (914mm) test sections simultaneously. It is designed to simulate the radiant conditions likely to be found in attic spaces during summer design conditions (see Fig. 1). The heat source consists of 12 25-watt incandescent light bulbs, which can be controlled by a variable-voltage dimmer. The bulbs are separated from the two test sections by a continuous aluminum plate painted with a high-quality, flat-black latex paint on both faces. This plate acts as a radiating surface that simulates the underside of the roof decking found in typical attic spaces.

The test sections are separated from the radiation plate by a 12in. (305mm) air gap. Each test section is bounded by 2in. (51mm) X 6in. (152mm) (nominal dimensions) framing members to simulate normal ceiling framing. The bottom of each test section is composed of one sheet of 1/2in. (12.7mm) thick gypsum board permanently mounted at the bottom edge of the 2in. (51mm) X 6in. (152mm) framing. Below each test section is a 12in. (305mm) airspace that simulates an interior room. The two test sections are separated by 4-1/2in. (14mm) of foil-faced isocyanurate foam insulation. The external sides, bottom, and top also consist of foil-lined isocyanurate.

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Before running comparative side-by-side tests, two sets of null tests were conducted. The initial null test was performed using no insulation in either test section. The results showed agreement of heat-flux meter readings to within 2%. The second null test was conducted using 6in. (152mm) fiberglass batt insulation in each test section. Flux meter readings for this test were in agreement to within 1%.

At the conclusion of the null tests, three sets of side-by-side tests were conducted:

1. plain fiberglass batt R-19 (RSI-3.36) versus single-layer foil,
2. foiled fiberglass batt R-19 (RSI-3.36) versus single-layer foil, and
3. foiled fiberglass batt R-19 (RSI-3.36) versus plain fiberglass batt R-19 (RSI-3.36).

The single layer of nylon-reinforced aluminum-foil product is manufactured by laminating a thin layer of aluminum foil to each face of an equally thin layer of nylon, reinforcing material. The foil product was mounted at the top edge of the 2in. (51mm) X 6in. (152mm) framing member to leave a 5-1/2in. (140mm) airspace between the foil and the gypsum board.

Full-Scale Tests

Controlled full-scale tests have been conducted at the Florida Solar Energy Center PCL. Three occupied residences in Orlando, Florida, also have been retrofitted using various foil radiation-barrier techniques and were monitored for a short period.

PCL Tests

The PCL[1] is an experimental facility located at the Florida Solar Energy Center (FSEC). It was designed so that it can be easily reconfigured. The laboratory was developed specifically to conduct experimental testing and measurement and to support analysis of passive/hybrid cooling designs and construction alternatives in warm, humid climates typical of the southeastern United States.

The permanent structure of the PCL consists of a slab floor and a column-supported roof structure with no intermediate structural walls or ceilings. External support columns stand 2ft (0.60m) outside the exterior wall envelope. This construction allows the walls and ceilings to be easily reconfigured. The normal test-chamber configuration is two side-by-side rooms. The exterior columns also provide attachment surfaces for environmental control chambers; in this way, the interior spaces are affected only by what occurs on the exposed walls.

The roof and structural system are designed to allow for either standard 8ft (2.43m) ceiling heights or cathedral ceilings. This allows testing of various vertical space configurations. Test-space wall partitions are heavily insulated frame walls that are lined on the interior surfaces and that have a continuous vapor and infiltration barrier to prevent air and moisture interchange between test spaces. Ceilings are configured in much the same manner and have continuous vapor and infiltration barriers that form the sealed boundaries of the space. The facility can be configured for a number of simultaneous studies, or the internal partitions can be arranged to allow the laboratory to be used as a single unit.

Radiation barrier tests were conducted in two sections of the PCL (see Fig. 2). The east-facing roof and attic section (over cell A) of the building was used to examine roof radiation barriers, and the west-facing exterior wall (cell E) was used to examine foil radiation barriers in "vent-skin" walls. Vent-skin walls[2] incorporate a vented airspace on the exterior of the building envelope. In theory, these walls protect the building envelope from solar radiation and vent to the ambient air excess heat absorbed by the skin.

For the attic radiant barrier tests, the attic space over test cell A was divided into two 12ft (3.65m) by 9ft (2.8m) side-by-side attic test spaces. (See Fig. 3.) One was insulated in a normal manner with 6in. (152mm) foil-faced fiberglass insulation batt with the foil facing toward the ceiling gypsum board. The other was insulated in the same manner, and a single sheet of "builder's foil" was then stapled to the bottoms of the 2in. (51mm) by 10in. (254mm) roof rafters. Builder's foil is the generic name for a product constructed of kraft paper with a thin layer of aluminum foil laminated to one or both sides of the paper backing. For these tests, single-sided builder's foil was installed with the aluminum foil surface facing the roof and the kraft paper backing facing the ceiling insulation. Both attic sections were unvented.

The attic spaces were subdivided using a product known commercially as "dennyboard." This is a structural laminated-paper sheathing product of approximately 1/8in. (3.04mm) thickness that is faced with aluminum foil. Test space partitions were made by attaching this product to one side of wood-frame partitions. This provides very little conductive thermal resistance between test cells. It was thought, and even desired at the outset of testing, that air temperatures within the attic spaces would remain close. The primary function of the dennyboard was to isolate only the two radiant environments produced by the underside of the roof decks.

Vent-skin wall tests were conducted on the west-facing wall of the PCL. The vent skin was applied to the exterior face of a concrete-block wall (cell E), which was undergoing side-by-side tests with a frame wall (cell D). The vent-skin application consisted of one layer of double-sided builder's foil applied directly to the exterior surface of a raw concrete-block wall surface. 2in. X 2in. (51mm) vertical wooden battens were applied on top of the foil and secured to the wall through the foil. Exterior waterproof gypsum board was then fastened to the vertical batten strips. The exterior of the gypsum board was finished with a 1/8in. (3.04mm) stucco-finish coat. The wall was vented at both top and bottom for some tests, and the vents were sealed for other tests. (See Fig. 4 for construction and instrumentation details.) The exterior surfaces of both the frame and vent-skin walls were then painted with paint identical to that used in the field retrofit studies.

INSTRUMENTATION

The PCL environment and test chambers are closely monitored. FSEC uses a Fluke 2240C data acquisition system, which records data to a Kennedy 360/1600 incremental data recorder. The majority of the PCL analysis and data manipulation is accomplished using the FSEC central computer system and Commodore CBM 8032 microprocessors.

In the instrumentation and measurement systems, every effort was made to assure as much accuracy as possible. Only the highest quality, special-limits-of-error thermocouples and extension wires were used. Data acquisition systems were carefully calibrated with many interesting results. In certain cases, it was found that greater accuracy was achieved by placing acquisition systems on their sides rather than their bases. This technique caused the isothermal input connectors to be horizontal rather than vertical, eliminating the greatest portion of thermal stratification within the input blocks. In some cases, this doubled total system accuracy.

Extensive efforts were made to assure the accuracy of surface temperature measurements[3]. FSEC feels confident of the temperature measurements to within 0.2°F (0.1°C) except when they are mounted on exterior surfaces in the presence of direct solar radiation. In these cases, temperatures can be assumed accurate only to 1.0°F (0.5°C).

All heat-flux meters were recalibrated at temperature and flux rates likely to occur in buildings. The flux-meter calibrations show very good repeatability. Their relative measurements (when used in side-by-side tests and when mounted on identical material in the same manner) appear to be quite accurate. However, their absolute accuracy is highly dependent upon the ratio of the conductivity of the meter to the conductivity of the material to which it is affixed. Under some mounting conditions, absolute inaccuracies can be as great as 300%! For this reason, only their relative accuracy may be considered useful at this time. FSEC is currently performing additional experiments to determine the coefficients that will bring the absolute accuracies of the heat-flux measurements to a high confidence level. All heat-flux data presented here were obtained with flux meters mounted identically on identical surfaces and can be considered to have a high degree of relative accuracy.

RESULTS AND ANALYSIS

The results of these radiation-barrier tests are often surprising and indicate that foil radiation barriers can provide significant resistance to heat transfer during summer design conditions. Although temperature distributions do not directly indicate resistances to heat transfer in buildings, they are often quite instructive as to the thermal processes taking place.

Temperature Distributions

Many building analysts erroneously assume that heat transfer down through attics into buildings is primarily a function of attic air temperature. By this thinking, attic ventilation can significantly reduce heat flow through ceilings. FSEC studies, however, point out that attic air temperatures are not the major driving force of heat flow down through ceilings. In fact, attic air is heated primarily by ceiling insulation rather than hot roof decking. This fact is vividly illustrated by Fig. 5, which shows insulation temperatures higher than attic air temperatures deep in the insulation batt. Under these conditions, heat cannot flow from the attic air to the insulation but must flow from the insulation to the attic air. Therefore, the attic air is not driving the heat transfer to the living space below but is actually helping to cool the overheated attic insulation, even in an unvented attic. Figure 5 also shows temperatures on the radiant barrier side of the attic to be significantly lower than the fiberglass side.

Temperature histories for the hot-box tests show an identical response. The only exception is that the ratio of fiberglass insulation temperatures to air temperatures is even higher. This can be attributed to the virtual elimination of all means of heat transfer other than radiation within the hot-box. The degree to which radiation controls attic air temperatures also can be illustrated through examination of the hot-box temperature distributions (see Fig. 6). The foil test section shows a significant difference between the fiberglass surface and the attic air temperatures, indicating that the greatest portion of air heating in attics is the result of roof radiation being absorbed by the fiberglass insulation and then being re-transferred as heat to the attic air by upward convection.

In essence, what we see through examination of the temperature data is that the greatest component of heat transfer down through attic spaces consists of radiation transfer. The degree to which insulation is effective in buildings is not only a function of the insulation's thermal conductance but also of its emissivity (or long-wave infrared absorptance). For heat transfer down through attic spaces, material emissivity becomes more important than material conductivity, and normal attic insulation and building products compound rather than alleviate the heat transfer problem because they have such high emissivities.

Effective Resistances

Of greatest importance to the building energy analyst is the performance of materials with respect to the rate of heat flow. Heat-flux measurements are often even more surprising than temperature distributions. In some tests, single-layer foil radiation barriers performed better than 6in. (152mm) fiberglass batts installed in the normal manner. (See Figs. 7 and 8.)

For building design and analysis, a composite resistance or conductance is needed to describe heat-transfer rates. It is normal practice to assign resistance values to each component within the composite section and then sum them to arrive at a composite resistance value. Aluminum foil, however, is not a resistor in the classic sense of the term and responds differently to heat flow under differing conditions (i.e., heat flow up versus heat flow down).

In addition, it appears that foil products behave differently than the traditional insulation products to which we assign fixed resistance values. They "reflect" rather than "resist" heat flow and may produce significantly different R-values depending upon the remaining components of the composite section and the direction of heat flow. Effective resistances presented in this paper are not universal and are pertinent only to the composite sections that have been examined.

Analytical Procedures. The effective resistances for foil-faced airspaces of various depths and for various directions of heat flow are given in ASHRAE Handbook--1981 Fundamentals Volume.[4] Effective resistances for ventilated and nonventilated attics with and without reflective barriers also are given in the same publication.[5] (See also Robinson, et al,[6] upon which the ASHRAE tables are based.)

Radiant-barrier measurement data taken by FSEC have been evaluated in terms of in situ effective resistance values. A simple calculation was used to arrive at the effective resistance:

$$R_{eff} = \Sigma\Delta T \ / \ \Sigma Q \qquad (1)$$

where

R_{eff} = effective resistance
ΔT = temperature difference across the composite section (°F)
Q = measured heat flux into interior space (Btu/h·ft²)

Equation 1 represents the steady-state definition of thermal resistance. The summations used in this equation are optimally accumulated over a sufficiently long period of time so that R_{eff} converges on a constant value.

A number of factors affect this convergence[7,8]:

1. mean temperature across the composite,
2. difference in temperature (ΔT) across the composite, and
3. the thermal storage capacitance of the material and its associated time lag.

Differences in mean temperature produce slight variations in material conductivity (k), and, therefore, affect thermal resistance. Large temperature differentials appear to cause more rapid convergence than small ones in massive components.[9] Finally, the thermal storage capacitance and the associated time lag of the composite can have a substantial effect on R_{eff}. The flux, which is affected at the interior wall surface of a building, is a result of a complex process of thermal storage and transfer through the wall system over time. Therefore, the temperature difference that is responsible for a given instantaneous flux occurs at a time previous to that flux. Depending on the thermal makeup of a composite, the time lag associated with this transfer process may be relatively short for frame sections or quite long for massive building components.

It has been shown that calculations of resistance for frame-wall systems converge more rapidly on a constant value when the characteristic wall time lag is used to determine the ΔT value in Eq 1.[10] For more massive components, convergence also occurs more rapidly when the characteristic composite time lag is used in the calculation (see Fig. 9). Part of our effort has been to define the resistance of building components when heat is flowing into the building. Only sunny-day data has been used for this purpose. On days when there is little sunlight or there is rain, both ΔT and Q can approach zero. In this case, the resistance calculation model approaches undefined mathematical regions (zero divided by zero) and the resistance calculations become indeterminant. This is especially true in massive components where thermal storage effects are powerful. Additionally, low ΔTs during these periods lead to less convergence in R_{eff}, and extremely long summations would probably be required for accuracy.

Results. Two sets of results are presented here in tabular format. Table 1 consists of the calculated effective resistances of west-facing vertical-wall tests in the PCL.

It should be pointed out that Tab. 1 contains "effective resistances," which are only accurate in a relative sense. They should not be used for load calculations. They do provide a good relative measure of the block-wall systems that have been tested. The block walls cannot, however, be directly compared to the frame wall because of the differences in conductivity between gypsum drywall and concrete block. This conductivity difference causes the flux meters to respond differently.

Table 2 presents the relative effectiveness of various attic/roof insulation strategies based on hot-box tests. The table is expressed in terms of relative effectiveness, and each ratio, in terms of the effectiveness of R-19 (RSI-3.35) plain fiberglass batt. In other words, the measured heat flux through the plain fiberglass batt is divided by the measured heat flux through each alternative, giving a relative effectiveness for each. If the true resistance of the plain fiberglass batt (with foiled vapor barrier facing down toward the ceiling) is known, the other resistances can be determined by multiplying that resistance by the given effectiveness ratio.

DISCUSSION

Some of the results presented above are not surprising. They parallel results that would be expected for calculations using published ASHRAE thermal performance parameters. Some of the data resulting from the tests employing radiant barriers appear surprising and represent difficult to explain divergences from ASHRAE thermal performance parameters.

It appears that radiant heat transfer, especially in attic spaces, is far more important than previously expected. It also is evident that barriers to radiant transfer are quite efficient separators of differing temperature regimes. These regimes otherwise would be in radiative contact, moving large quantities of energy.

Perhaps these data diverge so drastically from ASHRAE resistance values because of the large values for ΔT that radiation barriers create between themselves and radiating surfaces. Guarded hot-box tests[11] for radiaton barriers have been conducted under steady-state conditions at ΔTs that are not as great as those found in full-scale tests.

Another reason these results appear surprising is because of the relative manner in which they are presented. We do not "expect" one layer of foil to out-perform a 6in. (152.4m) batt. However, in situ attics do not behave in the same manner as guarded hot boxes. The radiation absorptance characteristics of fiberglass are not incorporated in resistances calculated from guarded hot-box or guarded hot-plate data. In a composite roof section, the introduction of an air-bounded radiation barrier changes the entire process of heat transfer rather than simply adding a "constant" resistance value. A simple data set for roof radiation barriers versus normal roof/attic construction (see Fig. 3) are presented in Tab. 3.

Of particular interest is the inability to derive a consistent effective resistance for the foil from the data set. Two sets of resistances are calculated with the foil inside the composite being evaluated. One set uses roof surface temperatures and one set uses the underside temperature of the roof decking to calculate the ΔT term. By logic, one would expect the difference in resistance between the foiled and nonfoiled sides of the attic to be constant. This would allow a simple subtractive technique to define a specific additive value for the effective resistance of the foil. (We were relatively successful with this approach in walls.) This was not the case in roofs. It appears that the radiant barrier does something to the remainder of the composite resistance (in this case it appears to double it) rather than provide a simple additive resistance. If further investigation substantiates this tendency, it will make the definition of radiant barrier thermal performance parameters a very difficult task.

No flux measurements were taken in the field, but temperature measurements taken in occupied residences using vent-skin, radiant-barrier components follow the same relative patterns as observed in the PCL and hot-box tests.

Vent-skin, radiant barrier roof systems employed in the field show rather large temperature differentials across relatively small foil-lined airspaces (50°F (28°C) temperature drop across 1-1/2in. (12.7m) airspace in Schoonmaker house roof (see Fig. 10)). Roof color did not have nearly the same relative effect in radiant-barrier roofs as would be expected without the radiant barrier (Fig. 11).

Vent-skin, radiant-barrier systems that were measured in the field perform in a similar manner to those in the PCL. An interesting phenomenon was the lack of an apparent thermal driving force in the vertical vent-cavity air temperatures (see Fig. 12). At first, the measurements were distrusted; however, when the same patterns occurred in PCL vent-skin tests, the matter was given more thought. It can be hypothesized that local wind pressure differences at vent locations quickly overcome thermal buoyancy forces. Wind turbulence then induces an oscillating pressure differential on the overall system causing a "slug" of air to be pushed back and forth in the center of the vent cavity.

ACKNOWLEDGEMENTS

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Additionally, the author would especially like to thank Mr. Safvat Kalaghchy who has spent many hours instrumenting, collecting data, and programming and running data analysis routines. Without his willing assistance this work would not have been possible.

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5. ASHRAE Handbook, Chapter 23, Table 6.
6. H. E. Robinson, et al, The Thermal Insulating Value of Airspaces (Housing and Home Finance Agency, Housing Research Paper No. 32. (US Government Printing Office, 1954).
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8. S. N. Flanders, and S. J. Marshall, "In Situ Measurement of Masonry Wall Thermal Resistance." ASHRAE Transactions 1 (1982), pp. 677-688.
9. Flanders and Marshall, p. 677
10. Brown and Schuyler, p. 668.
11. Robinson, et al, p. 25-30.

TABLE 1
Effective Resistances of Walls

Wall Type	Measurements From:	To:	T_m	ΔT	Σt	lag	R_{eff}
Uninsul. block	Exterior surface	Interior surface	83.5 (28.3)	5.2 (14.7)	55 (12.6)	4	4.5 (0.79)
Insul. block	Exterior surface	Interior surface	83.2 (28.1)	9.1 (12.5)	44 (6.6)	4	12.7 (2.23)
V-skin block	Exterior surface	Interior surface	82.9 (28.0)	6.9 (13.8)	67 (19.2)	4	13.5 (2.37)
Frame wall	Exterior surface	Interior surface	87.9 (30.7)	16 (8.8)	44 (6.6)	2	5.7 (1.0)

NOTES: T_m = Mean temperature (°F)
ΔT = Mean temperature difference (°F)
Σt = Time period of summation (hours)
lag = Lag time (hrs)
R_{eff} = Effective resistance ($hr.ft^2 \cdot {}^oF \cdot Btu$)

TABLE 2

Effectiveness Ratios of Three Attic/Roof Insulation Strategies

Strategy	Effectiveness Ratio	% Reduction in Heat Transfer
Plain fiberglass batt (R-19) (raw fiberglass facing radiating surface)	1.00	0
Single foil layer (double sided foil with air space on both sides of foil)	1.42	29%
Foil-faced fiberglass batt (with foiled airspace facing radiating surfaces)	1.82	44%

Note: If measured heat flux through the single foil layer is divided by measured heat flux through the foil-faced fiberglass batt, the ratio is 0.91, indicating that the foil provides 91% of the resistance to heat flow. This further indicates that greater than 90% of the heat transfer in attics occurs via radiation.

TABLE 3

Effective Composite Roof Resistance Values

FROM	TO	EFFECTIVE RESISTANCE With foil	No foil
Top surface of ceiling sheet-rock	Bottom surface of ceiling sheetrock	0.27	0.35
Attic air	Top surface of ceiling sheetrock	10.5	10.1
Bottom surface of roof plywood	Top surface of ceiling sheetrock	39.1	18.9
Roof shingles	Top surface of ceiling sheetrock	53.2	26.9

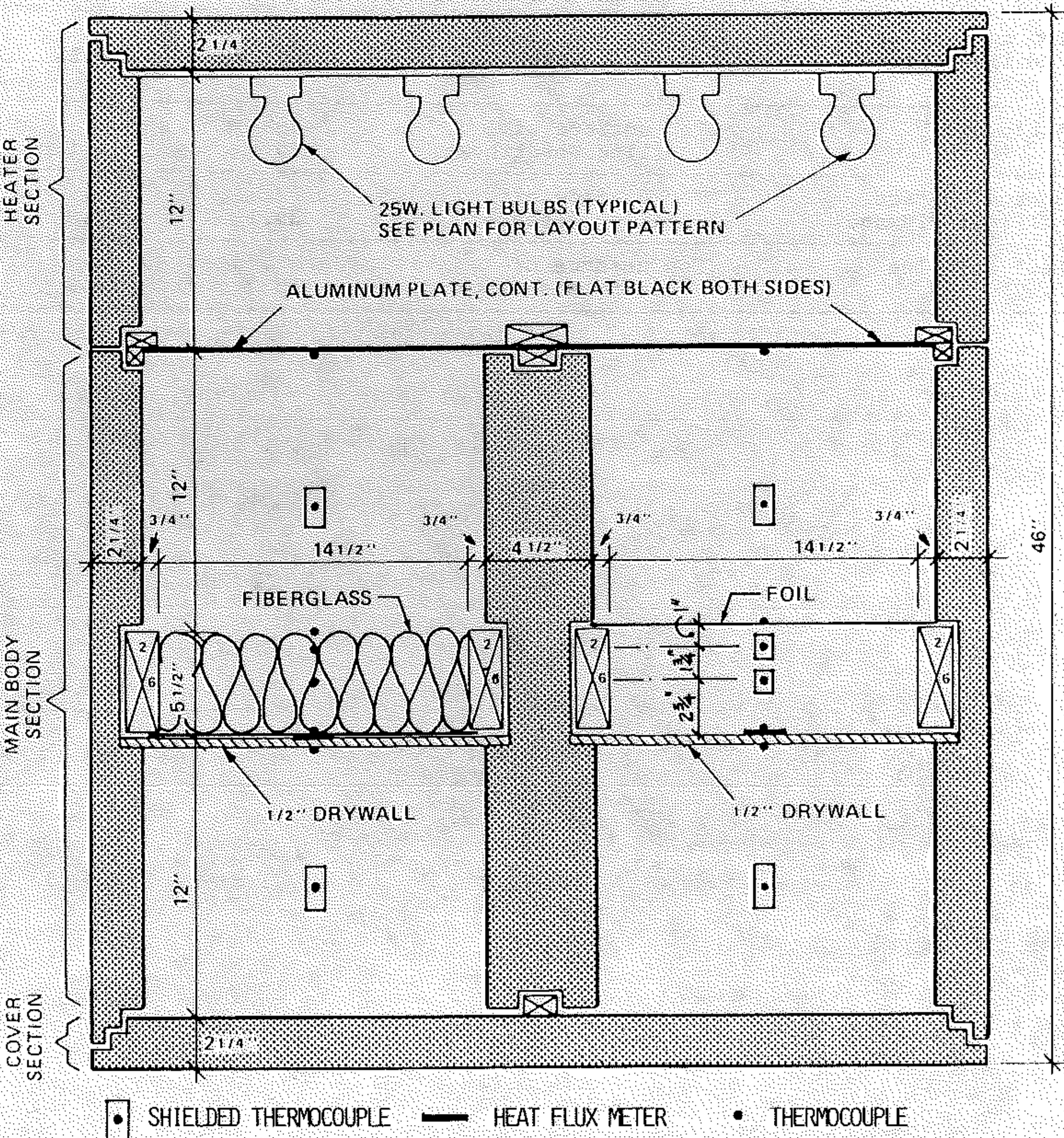

Figure 1. Hot box section showing probe and test section locations for fiberglass insulation versus foil tests

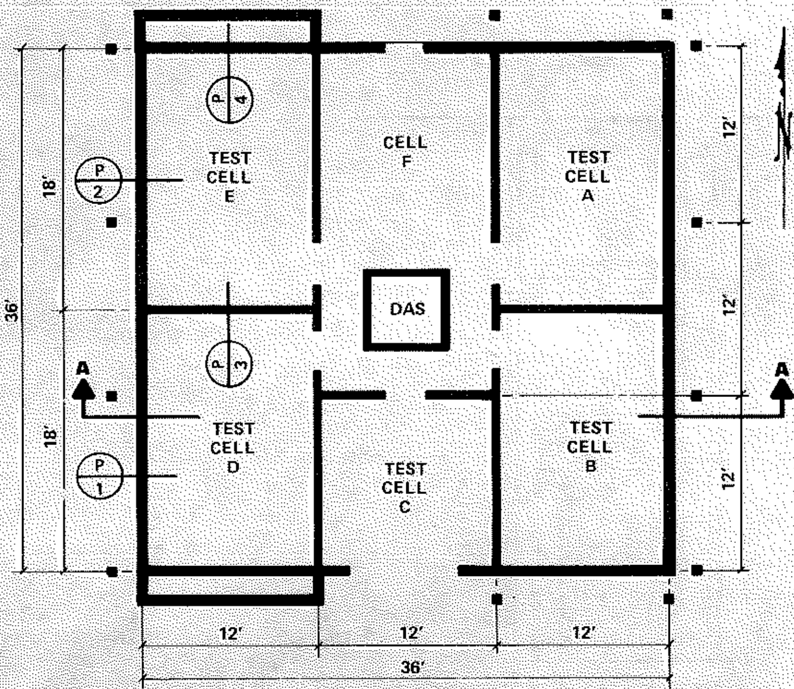

Figure 2. Plan view of FSEC passive cooling lab as configured for wall tests in cells D and E

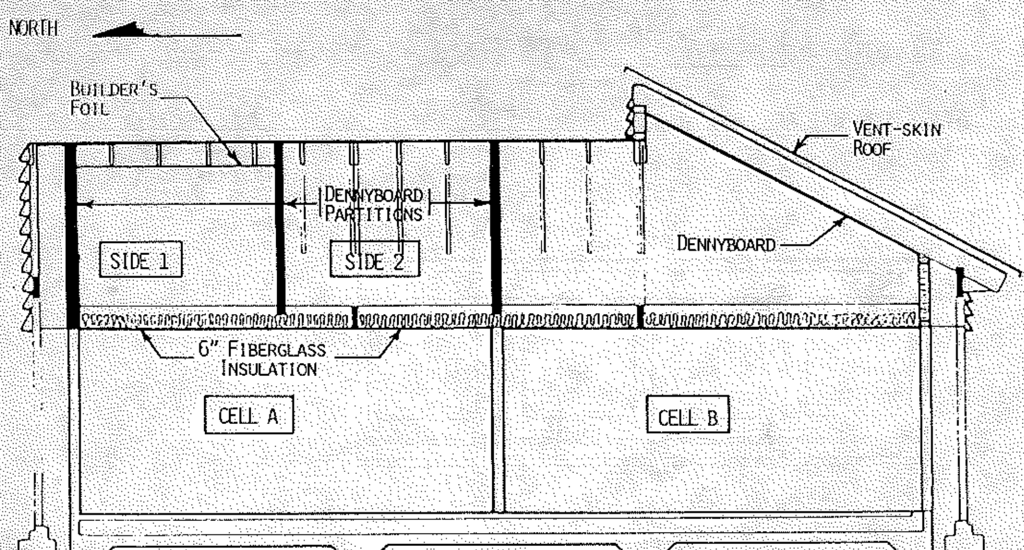

Figure 3. Section view through PCL looking east at side-by-side radiant barrier attic test spaces over cell A

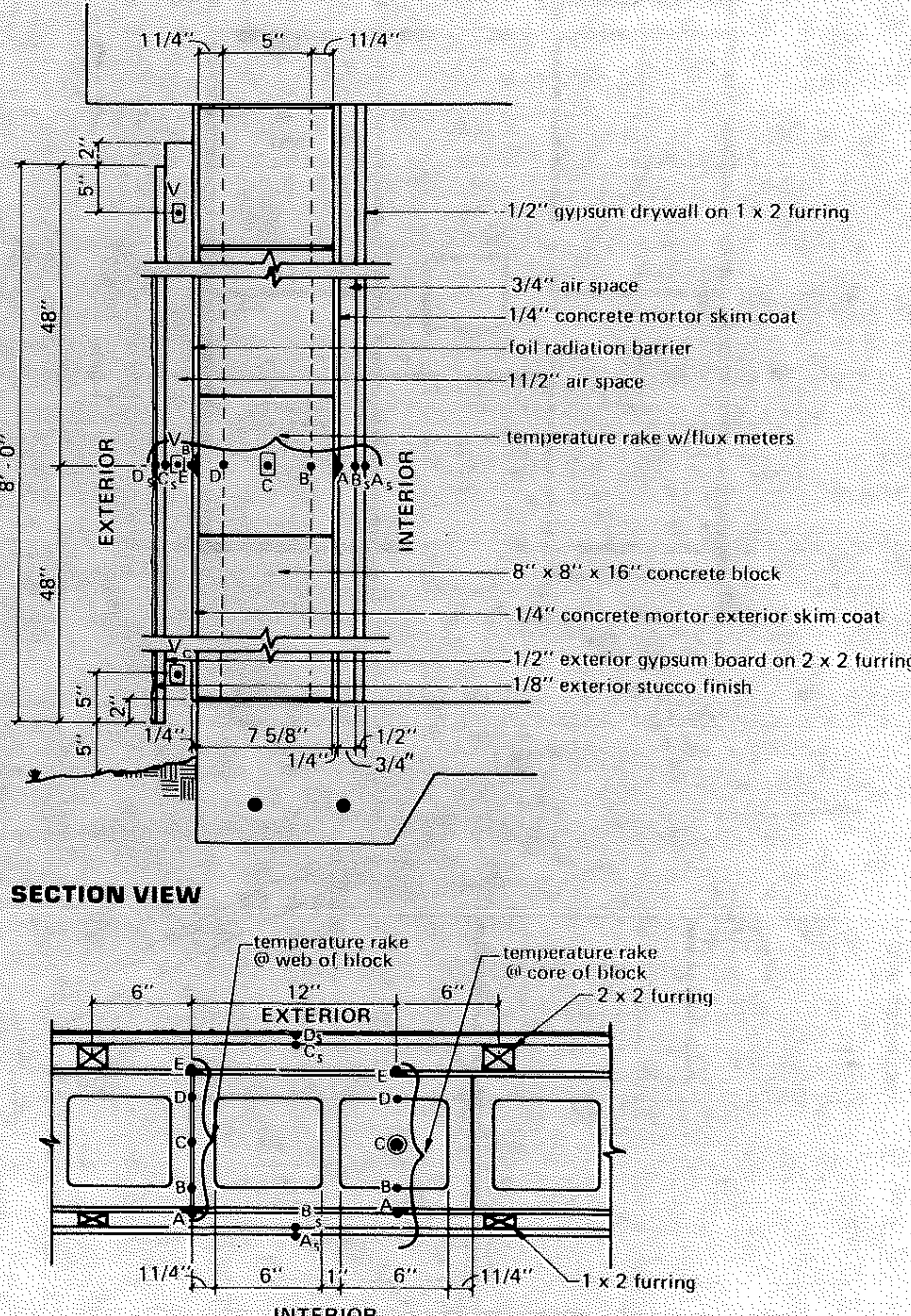

Figure 4. Section view (top) and plan view of vent-skin wall detail showing materials and sensor placement

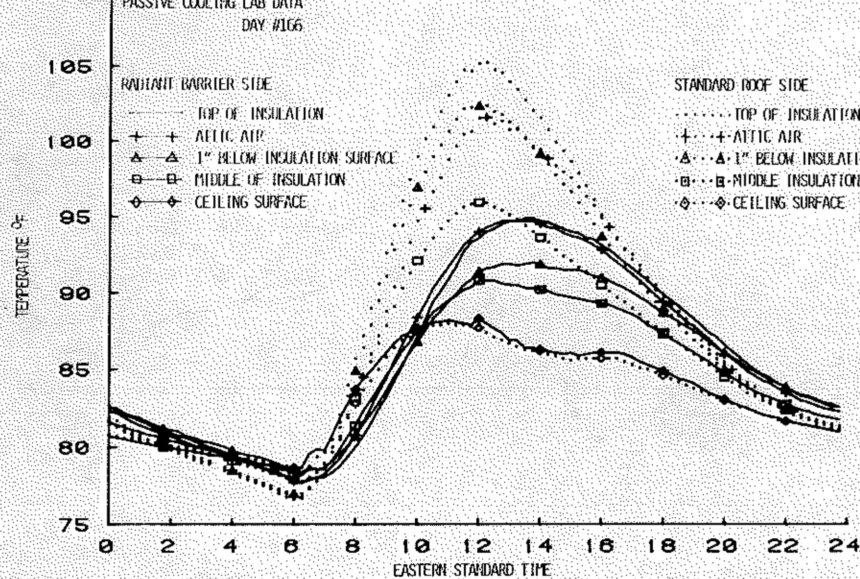

Figure 5. Measured temperature distributions through ceilings for radiant barrier versus standard roof. Both ceilings with R-19 fiberglass insulation, interior space unconditioned

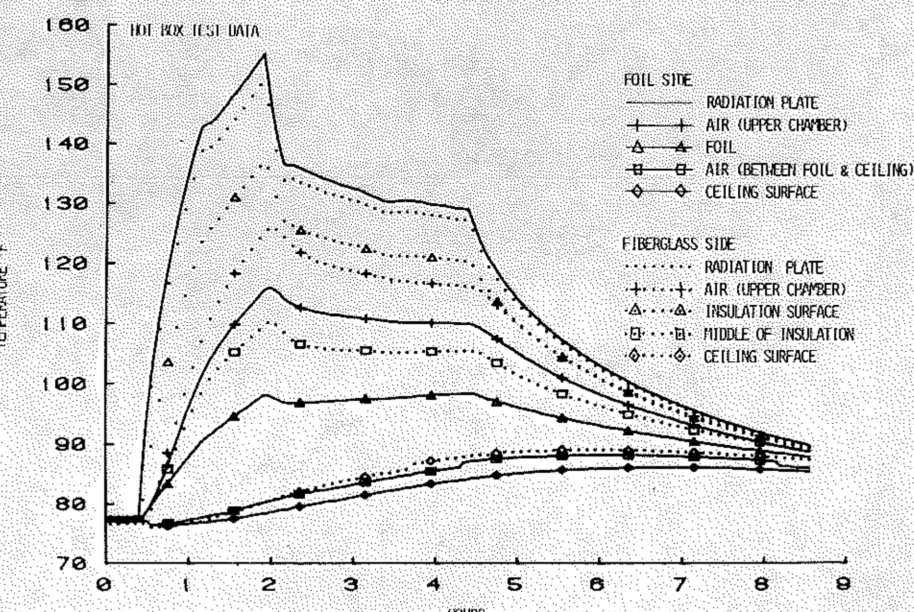

Figure 6. Measured temperature distributions resulting from hot box tests - single layer foil versus R-19 fiberglass batt (see Fig. 1)

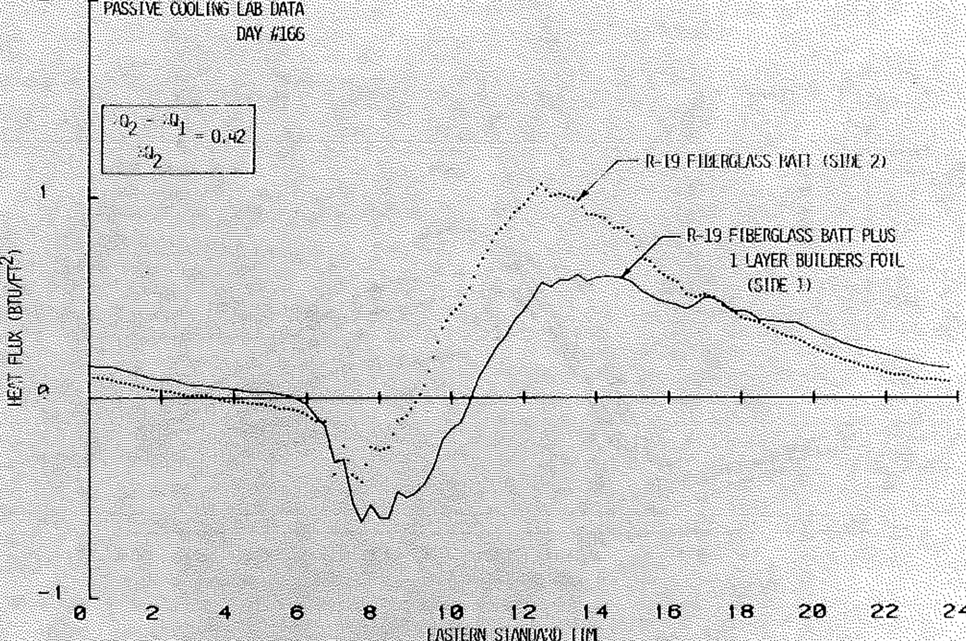

Figure 7. Measured heat flux distributions for full scale side-by-side radiant barrier versus standard attics

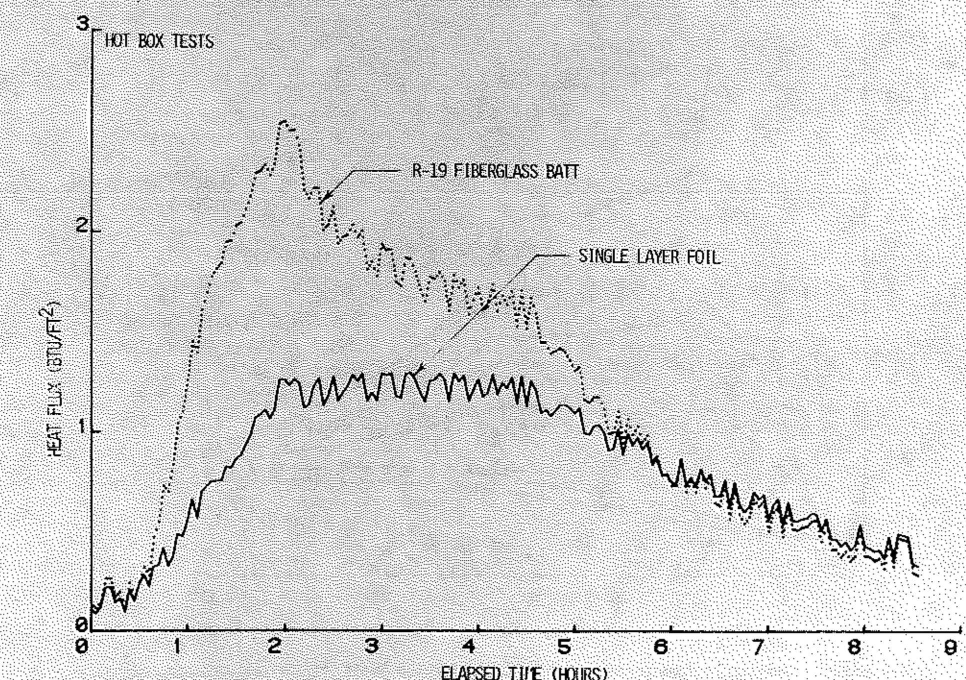

Figure 8. Measured heat flux distributions for side-by-side hot box test - R-19 fiberglass versus single layer foil

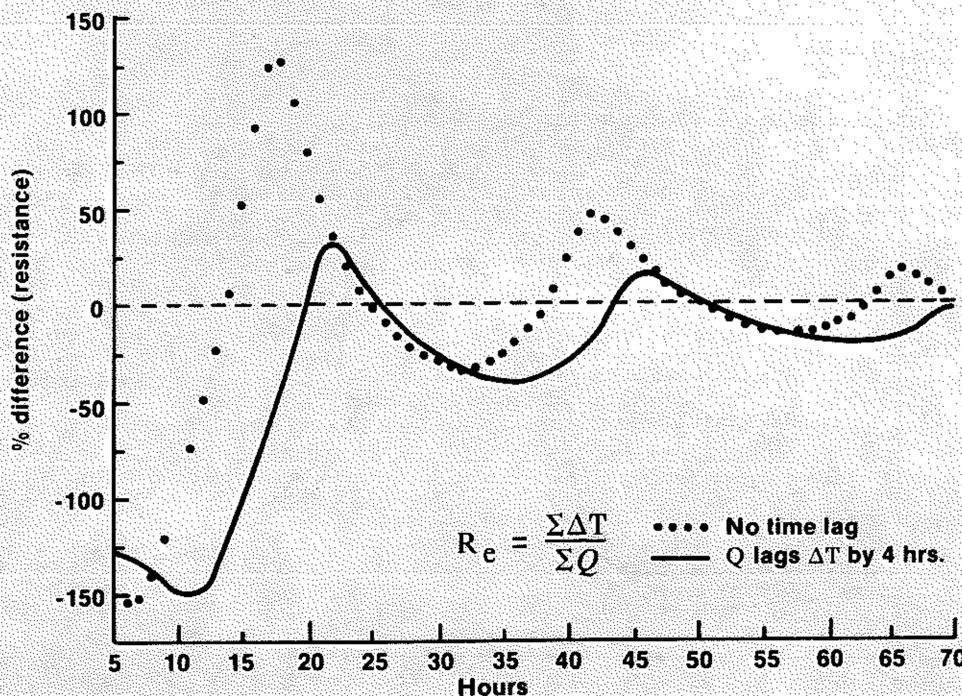

Figure 9. Running resistance calculations from measured concrete block vent-skin radiant barrier wall data showing effective of time lag on calculation results

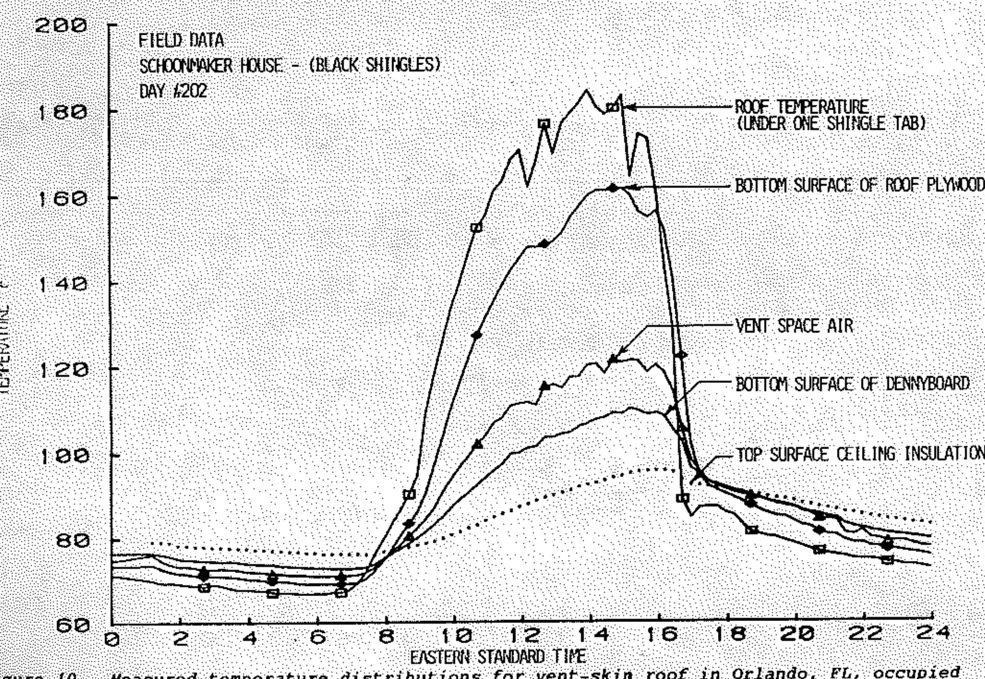

Figure 10. Measured temperature distributions for vent-skin roof in Orlando, FL, occupied residence under design day solar radiation conditions

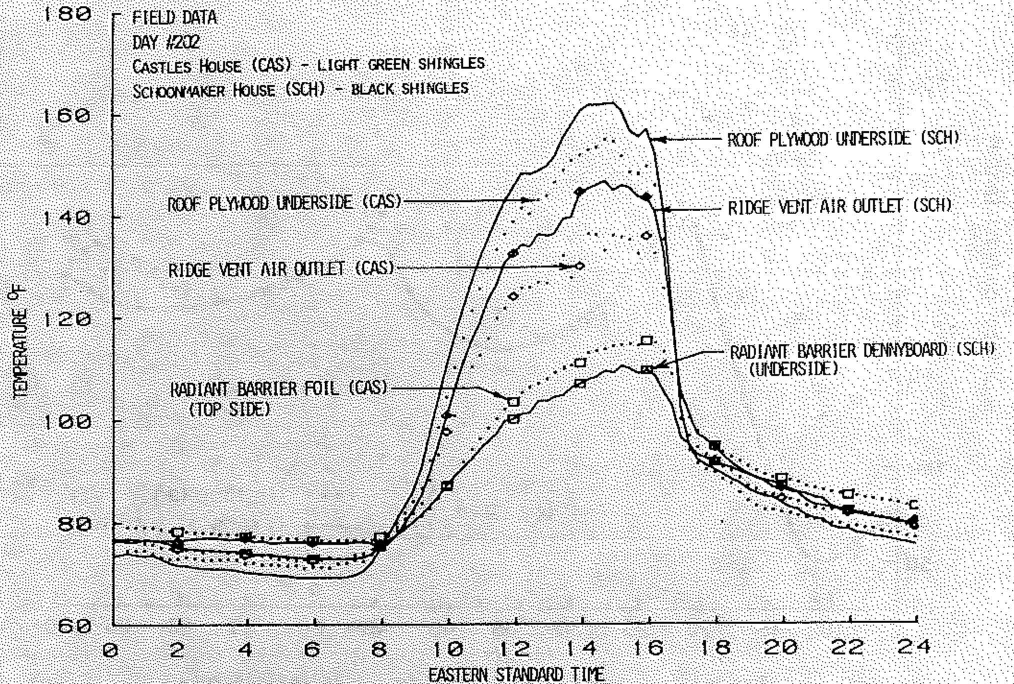

Figure 11. Measured temperature distributions of two very similar vent-skin roofs in Orlando, FL, showing variation by color differences

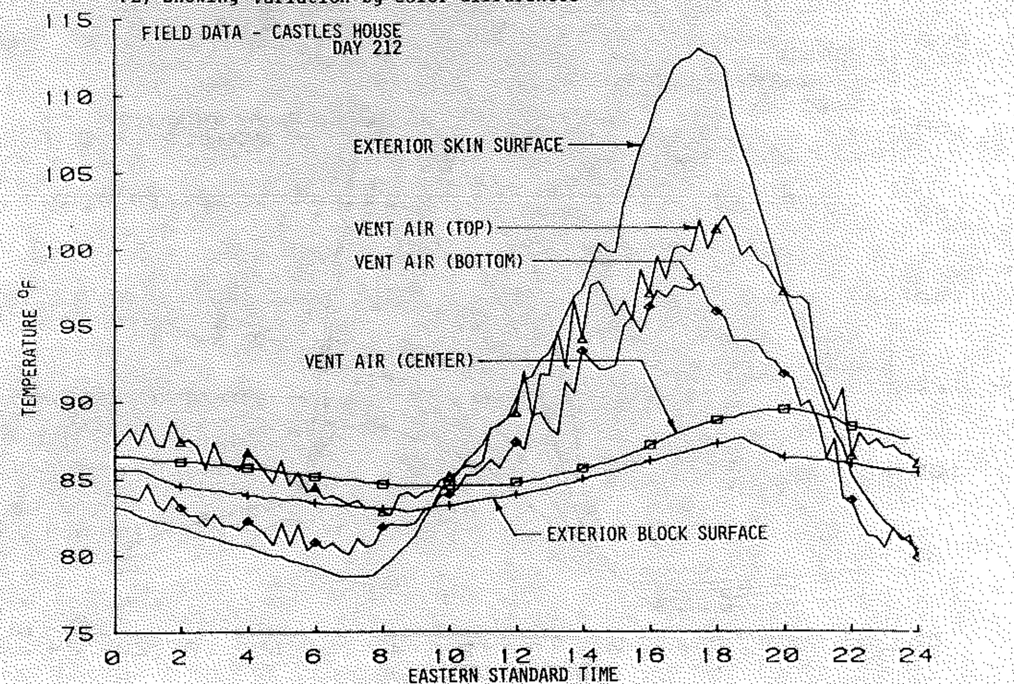

Figure 12. Measured temperature differences in west-facing vent-skin block wall in occupied residence in Orlando, FL, showing unpredictable behavior of vent space air temperatures

Discussion

J.S. England, Washington State University Pullman: Please comment on the maintenance of the effectiveness of the foil reflectance over a period of years.

Fairey: To date we have been unable to uncover evidence which indicates a degredation problem with aluminum foil products. The potential for dust and dirt deposits on the u-per surface of foils installed in a horizontal position does exist, and horizontal foils should probably be installed with a reflective surface and airspace facing down in circumstances where dust and dirt accumulation may be potentially severe. Long term (up to 15 years) emissivity tests on foils installed in harsh salt water environments do not show significant degredations in emissivity.

R.H. McEntire, DAE Engineering, Logan, UT: Please comment on vapor barrier considerations.

P.W. Fairey: In cold climates, the low perm rates of aluminum foil can pose vapor condensation problems if care is not taken. Fortunately, the manufacturers of foil faced products usually distribute a perforated product which can be used under such circumstances. A perforated foil product was used in the full-scale tests which are reportedhere, and it appears that the perforations have little, if any, effect on performance.