#3523

Moisture Measurements in Single-Family Houses with Attics Containing Radiant Barriers

W.P. Levins

M.A. Karnitz, Ph.D.
Member ASHRAE

J.A. Hall

ABSTRACT

A national laboratory tested radiant barriers in attics of three unoccupied research houses located near Knoxville, TN. The purpose of these tests was to determine the effect of moisture condensation on the underside of perforated horizontal radiant barriers during the winter. The houses were operated at high indoor relative humidities (45% and 55% at 70°F). Attic moisture conditions were monitored with both instrumented measurements and visual observations. The observations showed that moisture went through a diurnal cycle at the research houses. Moisture could condense on the bottom surface of the horizontal radiant barrier in weather below 35°F, but it would also dissipate to the attic air during a normal Tennessee winter afternoon, leaving the barrier dry. However, in long periods of subfreezing weather, all condensation did not vaporize and some remained on the surface throughout the day. The data showed that a moisture cycle occurring on a perforated horizontal barrier during a typical Tennessee winter caused no structural, wet insulation, or stained ceiling problems to the research houses, even though the houses were maintained at unusually high indoor relative humidities. Care should be taken in extrapolating the observation of this research to locations with prolonged periods of subfreezing weather where the diurnal moisture cycle under the barrier could be quite different. Further testing of horizontal barriers in cold climates is recommended.

INTRODUCTION

A radiant barrier is a foil material with either or both surfaces coated with a low emittance material (usually aluminum) that works as a subsystem in conjunction with an air space and can theoretically block up to 95% of infrared radiant heat transfer. The experiments were conducted in three unoccupied houses located midway between Oak Ridge and Knoxville, TN. These houses had been used from 1985 to 1987 for heating and cooling space conditioning experiments that measured the energy performance of radiant barriers (Levins and Karnitz 1986, 1987a, 1987b, 1987c, 1988). This paper describes observations of moisture migration in attics of these houses during the winter of 1987-88 (Levins et al.). The objective of this experiment was to determine if moisture condensation can cause problems when horizontal barriers are used in attics of houses with unusually high indoor relative humidities.

The research facility consisted of three single-family, 1200 ft^2, ranch-style houses. The houses have identical floor plans, are oriented with the fronts facing north and all having heat pump space conditioning systems. The ventilation for the attics consists of soffit and gable vents with an effective 1 to 150 area ratio (square feet free ventilation per square feet attic). The houses are thoroughly instrumented with more than 50 data channels in each house. The data recorded consist of temperatures and humidities throughout the house and attic, weather parameters, and heating and cooling electrical consumptions.

Review of Energy Performance Results of Previous Radiant Barrier Experiments

The objective of the previous experiments at these research houses was to quantify the energy performance of radiant barriers with three levels of fiberglass batt attic insulation—R-11, R19, and R-30. Two different methods of installing radiant barriers were also tested. In one configuration, the radiant barrier was laid on top of the fiberglass insulation (horizontal barrier), and in the other, the radiant barrier was attached to the underside of the roof trusses (truss barrier).

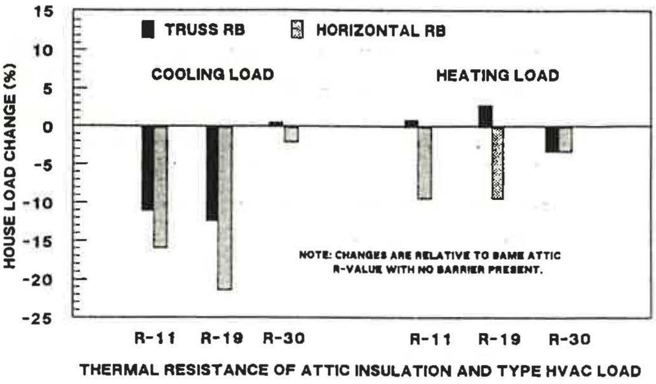


Figure 1 *Summary of radiant barrier performance on research house*

W.P. Levins and **M.A. Karnitz** are on the research staff of Oak Ridge National Laboratory, Oak Ridge, TN; **J.A. Hall** is an engineer with the Tennessee Valley Authority, Chattanooga.

THIS PREPRINT IS FOR DISCUSSION PURPOSES ONLY, FOR INCLUSION IN ASHRAE TRANSACTIONS 1989, V. 95, Pt. 2. Not to be reprinted in whole or in part without written permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, NE, Atlanta, GA 30329. Opinions, findings, conclusions, or recommendations expressed in this paper are those of the author(s) and do not necessarily reflect the views of ASHRAE.

The results of the previous energy performance testing are summarized in Figure 1. The diagram shows that radiant barriers perform better in cooling than in heating, and also are more effective in combination with R-11 and R-19 attic insulation than with R-30. Horizontally installed barriers are more effective than truss-mounted barriers in reducing heating and cooling loads.

The previous work had also shown that moisture can condense on the underside of a horizontal barrier in cold weather and is a potential problem area, even though no deleterious effects were noted in our two heating seasons of operation. Horizontal radiant barriers do not appear to be attic infiltration barriers.

MOISTURE BACKGROUND INFORMATION

Winter Indoor Relative Humidities

Outdoor air is typically very dry during the winter. Outdoor air relative humidities in winter are usually moderate to high, but this is misleading since relative humidities are strongly temperature dependent. Psychrometric charts show 30°F air at 100% relative humidity contains less than half as much moisture per pound of dry air as does air at 70°F and 50% relative humidity. This dry winter air can lead to very low indoor relative humidities because the indoor/outdoor vapor pressure difference drives indoor moisture outdoors.

A literature search was conducted to locate actual relative humidity data. Many references to "proper" and "maximum allowable" indoor relative humidities were located. "Moisture and Home Energy Conservation" (DOE n.d.) states that "prolonged high indoor relative humidity—above about 45%—can cause a wide variety of problems." "Moisture in Homes" (1986) states that "taking condensation control into account, optimum indoor relative humidity is 40% in winter." Product literature for a typical central home humidifier ("Owners Manual") shows the maximum safe recommended indoor relative humidity as a function of temperature. For 10°F, 20°F, and 30°F outside temperatures, the maximum safe recommended indoor humidities are 30%, 35%, and 35%, respectively.

"Residential Moisture Conditions—Facts and Experience" (1982) describes single-point relative humidity data collected during one week in 16 homes located in Utah, Alabama, and Ohio. The results varied widely. The Ohio homes averaged 27% relative humidity at an average outdoor temperature of 23°F. The Utah homes averaged 62% relative humidity with an average outdoor temperature of 31°F. The Alabama homes averaged 66% relative humidity, but the outdoor temperature was much warmer at 55°F.

"Residential Moisture Conditions and Perceived Health Status" (Laquatva and Chi) describes single-point winter humidity measurements in 253 randomly selected houses. A regression analysis of the data estimates the average indoor relative humidity to be 58%. However, the adjusted R^2 for the regression analysis was very low. Also, outdoor temperatures, which would have strongly affected indoor humidities were not measured.

Solar Homes for the Valley Data

Only one source of continuous monitoring of winter relative humidities in several occupied homes was found, and these were data from a public utility's Solar Homes for the Valley (SHFV) Program in the late 1970s and early 1980s. The environmental conditions and energy use of several of these homes were monitored to determine the effectiveness of their passive solar designs. The temperature and humidity data from SHFV that were applicable to this study came from 12 homes monitored from December 1982 to March 1983. However, not all 12 homes had data for the entire four-month period. Data were recorded continuously at 15-minute intervals. All data were normalized to a 70°F indoor dry-bulb temperature. Table 1 summarizes the results of the SHFV relative humidity data.

Based on the literature search and the SHFV data, the following conclusions were made:

- 45% relative humidity during cold weather (below 35°F) is moderately high (more than 80% of relative humidity observations from SHFV data were less than 45%).
- 50% relative humidity during cold weather (below 35°F) is very high (only about 2.7% of SHFV observations were greater than 50%).
- 55% relative humidity during cold weather (below 35°F) is extremely high (less than 1% of SHFV observations were greater than 55%).

TABLE 1
Humidity Data from TVA Solar Homes for the Valley Program

	% Observations in Temperature and Relative Humidity Ranges % Relative Humidity									
Temp. range, °F	**0-35**	**35-40**	**40-45**	**45-50**	**50-55**	**55-60**	**>60**	**Tot. Obs. in temp. range**	**% Obs in temp. range**	**Median % rel. hum.**
0-15	0.0	0.0	33.3	0.0	66.7	0.0	0.0	3	0.01	44.5
15-20	66.0	7.4	11.1	8.6	6.2	0.6	0.0	162	0.33	30.5
20-25	67.9	12.9	12.8	5.2	1.1	0.2	0.0	1292	2.62	31.7
25-30	57.3	20.8	12.2	6.0	3.0	0.6	0.1	3585	7.27	32.8
30-35	52.6	24.5	10.9	6.6	3.3	1.2	0.9	9364	19.00	34.0
35-40	39.1	25.7	11.5	13.3	7.2	1.9	1.3	13125	26.63	36.5
40-45	31.6	23.6	13.6	13.3	10.5	4.1	3.2	11154	22.63	38.0
45-50	28.3	22.1	14.7	12.9	12.2	4.7	5.2	10596	21.50	38.8
Tot obs in %RH range	19624	11570	6224	5503	3856	1343	1161	49281		
% obs in %RH range	39.8	23.5	12.6	11.2	7.8	2.7	2.4		100.00	

MOISTURE EXPERIMENTAL RESULTS FROM THE TESTS OF 1987-88

An experimental plan was devised to test for potential moisture problems with horizontal radiant barriers which was based on the moisture literature search and past winter test experience in the Research House Complex. For the winter test, a perforated radiant barrier material 1.5 mils thickness with an average hole size of 0.039 in and a percent hole area of 0.46% was used. The holes were located on about 5/8 in staggered centers.

House Humidity Control

Humidity was added to the houses by freestanding humidifiers. A 15-gallon plastic jug was placed next to each humidifier to keep the water level in the humidifier at the same approximate level. Two floats were located in the left corner of each humidifier and when approximately 200 ml of water were added to the house air, a small solenoid pump was actuated by the floats so water was pumped from the plastic jug to the humidifier reservoir. The stroke of each solenoid pump was adjusted to give a constant 2 ml per stroke delivery volume. The pump repeatability was very good, and held quite constant throughout the winter. Each stroke of the pump generated a pulse, which was monitored by the data collection system. Table 2 summarizes the conditions under which the houses were maintained along with the dates of operation for each phase of the testing.

It became apparent during the testing that the capacity of one humidifier during cold (less than 25°F) weather (approximately 6 gallons per day) was not sufficient to maintain the indoor relative humidity at 55% at 70°F. Therefore, during the second phase of the testing, house 3 was raised to 55% relative humidity and a second humidifier added to ensure that the high level of indoor relative humidity could be maintained.

The third phase of the testing was designed to test the estimated 25 lb/day/family water generation in a typical home in house 1, while the unfaced R-19 insulation in house 3 was replaced with R19 with a kraft paper vapor barrier facing. The relative humidity in house 1 was therefore allowed to float, and that in house 3 was maintained at 55%. Figure 2 is a time-series plot for approximately a week of the inside relative humidity in house 1 and the outside temperature. It shows the indoor relative humidity at about 35% at 70°F and 55% at 55°F.

TABLE 2
Humidity Operating Summary Research House

Date		Days	Indoor Relative Humidity @ 70°F Dry Bulb		
Start	End		house 1	house 2	house 3
Dec. 04	Jan. 14	41	53%	46%	46%
Jan. 14	Feb. 04	21	53%	46%	55%
Feb. 04	Feb. 18	14	26#/Day	46%	55% (VB*)
Feb. 18	Mar. 24	35	26#/Day	46%/Half Vent	55% (VB*)
		111 Total Days			

*VB signifies vapor barrier present.

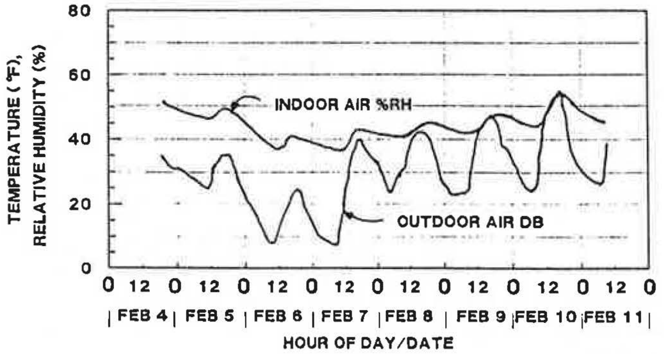
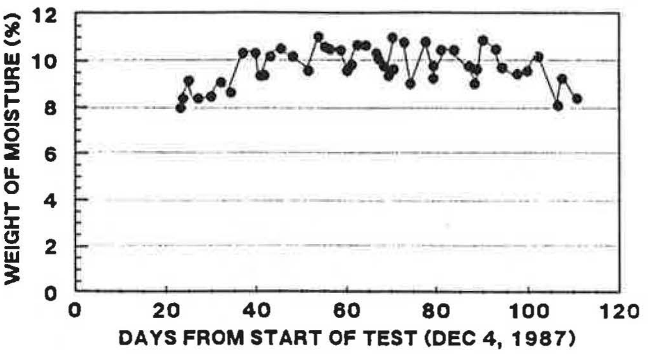
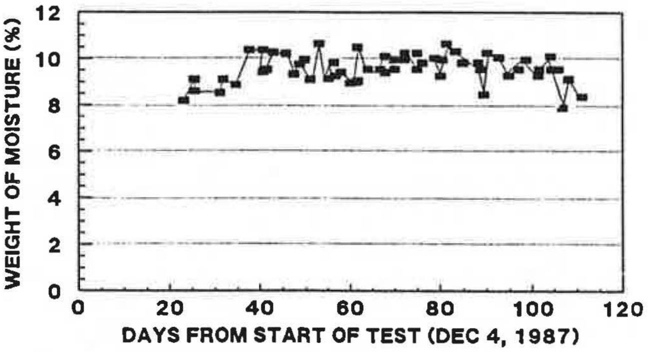


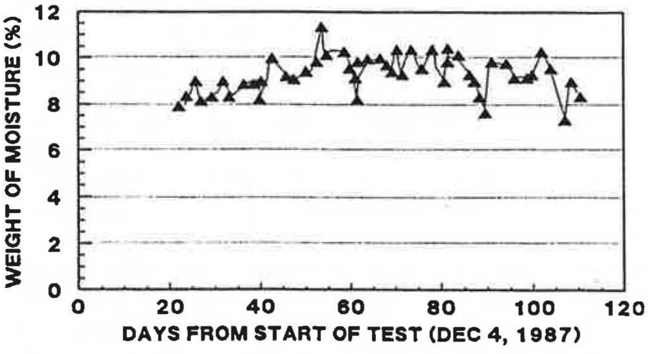
Figure 2 *House 1 indoor relative humidity and outdoor air temperature (constant water generation)*



(a) HOUSE 1



(b) HOUSE 2



(c) HOUSE 3

Figures 3a-c *Measured moisture content in wood truss under horizontal barriers*

TABLE 3
Summary of Humidifier Water Addition and House Relative Humidity

Dates	Outdoor average temp. °F	Water Added Pounds Water/Day Added to			Percent Relative Humidity		
		house 1	house 2	house 3	house 1	house 2	house 3
12/04-11	42.8	25.8	20.2	20.1	54.2	46.8	50.1
12/11-18	40.5	32.6	22.4	24.0	53.7	47.1	47.8
12/18-24	42.6	28.7	16.6	20.0	55.7	48.2	49.9
12/24-31	45.3	19.1	11.6	12.8	55.4	48.0	48.6
01/07	29.8	39.0	34.5	31.4	52.7	46.7	46.1
01/07-14	22.9	47.2	40.4*	38.5	51.0	47.7	45.3
01/14-17	28.8	45.6	36.5*	46.7	54.5	49.1	52.3
01/19-21	49.9	12.5	11.0*	26.4	54.1	55.3	64.2
01/21-28	31.7	47.5	30.0	41.0	55.1	46.1	55.3
02/03	51.9	17.6	10.7	28.1	55.2	46.9	63.5
02/04-11	28.9	31.2	40.2	36.7	46.0	47.4	50.4
02/11-15	30.2	31.3	38.7	39.6	44.0	47.1	53.0
02/16-18	34.3	29.1	30.4	28.8	48.3	49.4	53.8
02/18-25	40.2	28.9	27.7	27.4	51.5	48.4	54.0
03/03	41.3	30.4	32.6	30.6	49.4	48.3	53.2
03/03-10	50.1	25.2	12.6	11.6	59.5	46.7	53.0
03/10-17	38.3	28.5	29.7	27.5	51.6	48.2	54.0
03/17-24	50.6	26.8	18.7	20.9	55.2	47.4	56.7

*Note: Estimated value.

The conditions in houses 2 and 3 were maintained in the fourth phase of the testing. The attic vent area in house 2 was halved (from 1/150 to 1/300 ratio) by blocking off half of the soffit vents and half of each of the two gable vents. The humidity level in house 2 was kept at 46%. Table 3 contains a summary of the daily humidifier water additions to the houses along with dates and average indoor relative humidities.

Wood Moisture Measurements

Moisture measurements of sections of wood truss members, which were under the bottom surface of the radiant barrier, were manually taken throughout the testing. The instrument used ranged from 6% to 30% weight water and was calibrated for Douglas fir at 70°F by the manufacturer. Temperature and wood type (our trusses were made from southern yellow pine) corrections, supplied by the manufacturer, had to be made to all readings before they were meaningful. The manufacturer states an estimated accuracy of +/0.5% for the 6% to 12% weight range. All moisture measurements were taken in approximately the same four locations in each house.

Figures 3a through 3c are plots of the corrected wood moisture measurements made in each of the three houses at one location. The most obvious thing about the plots is that they appear to be very similar. The initial 20 days of data are not plotted because they registered at or just below the lowest (6% uncorrected) range of the meter. However, our best estimate of the corrected moisture content during that period would be about 7.5% to 8.0%. All of the testing periods are plotted, and house 1 at 55% relative humidity appears to be slightly higher than house 2 at 46% relative humidity. Also, the presence of a vapor retarder in house 3 at 55% relative humidity appears to lower the wood content very slightly. The maximum moisture levels peak out at about 11%, which is well below the maximum fiber saturation value of about 28% to 30%. These moisture levels are very similar to those reported for the winter in a New Jersey house (Harrje et al. 1985) with no radiant barriers installed.

Note that random wood moisture readings taken on the upper (above the horizontal barriers) truss members were not significantly different from those below the barrier; on several occasions they were actually higher than those under the barrier. Also, there is a diurnal cycle to the readings, especially those in the open attic—they appeared to be higher in the early morning than in the afternoon. This is probably the result of higher temperatures and increased attic ventilation during the day and colder temperatures and lower ventilation rates at night and in the early morning.

Visual Observations in Attics

Visual observations were made by going up into the attics of each house and physically lifting sections of the barrier in order to see if any condensation was present on the underside of the horizontal barrier and if so how much. The "how much" part of the observation was, of course, qualitative on the part of the observer, but an effort was made to be as consistent as possible. Some observations were made in the morning and some in the afternoon. On many days, both a morning and an afternoon observation was made. The most obvious conclusion from a morning and an afternoon observation is that things change in the course of a day, especially if the sun is shining. Usually when condensed moisture was detected on the bottom surface of a barrier in the morning, it was dry (or at least much less wet) in the afternoon.

A dry circular area surrounded most of the perforations on a moderately wetted barrier. This leads to the conclusion that condensed moisture is being vaporized and passes through the perforations into the attic air. Evidently, perforations in a radiant barrier do facilitate the transfer of moisture from a horizontal radiant barrier to the attic air.

A barrier with a heavy amount of condensation on the underside sometimes showed several large drops of water on the top surface of the insulation. No significant dry areas were visible around the perforations, which would lead one to conclude that moisture is forming much faster than it can be dissipated by the barrier. This means that there is a net accumulation of moisture taking place at that time.

It should be noted, however, that at no time in the course of the experiment was any moisture noticed on the bottom of the insulation, nor were any wet spots noted on either side of the ceiling. Any moisture on the attic insulation appeared to penetrate no deeper than 1/8 in or less. As noted above, moisture shedding conditions (either partial or complete) usually occurred during the warmer afternoon hours.

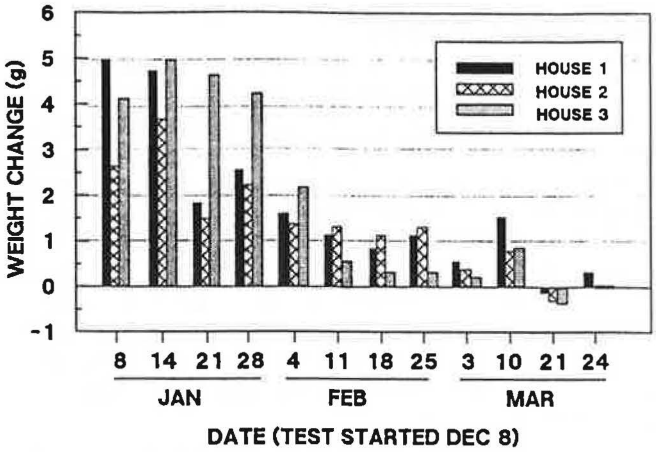
The attics were not uniformly wet during the testing. The central part of the attic over the bathroom area was the most moist area in all three houses. There are more penetrations in this area due to bathroom fans and sewer vent pipes than there are in other parts of the house. The periphery of the houses close to the walls was probably the driest area. Most of the observations showed spotty results, with both dry and wet areas in the same attic.

One particularly cold week during the testing, January 7-14, when the average outside temperature was 23°F, showed the heaviest moisture conditions according to our observations. However, as the weather warmed up in the following weeks, the moisture level decreased significantly.

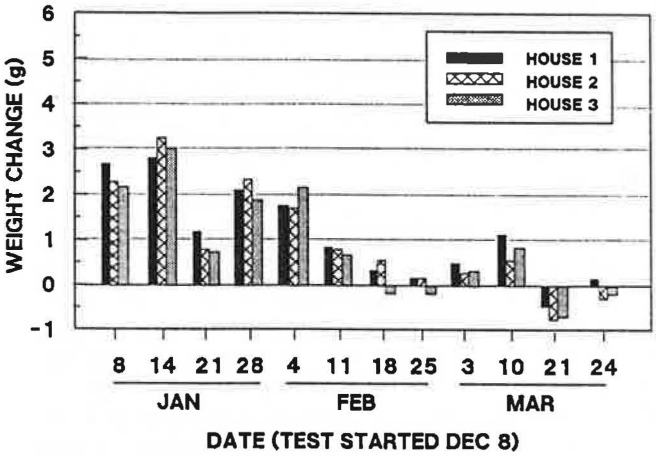
In addition to attic conditions, other observations were made in the houses. One of the more significant was the condition of the windows. Often one could tell how the underside of a radiant barrier would appear by first observing the amount of condensation on the windows. The plaster board on the lower inside of the window frame was extremely moist in house 3 during cold periods. Clearly 55% relative humidity is much too high an indoor humidity to maintain in a house during cold periods.

The unfaced R-19 insulation in house 3 was removed on February 4, and kraft-paper-faced R-19 fiberglass batt insulation was installed in its place. The kraft paper facing is a vapor barrier for this insulation and is intended to impede moisture transport between the house living area and the attic. The relative humidity was maintained at 55% in house 3. The visual observation in house 3 compared favorably with house 2, which was at 46% relative humidity for the remainder of the testing period. The vapor barrier was evidently more effective at keeping moisture transport levels lower in the attic of house 3 than the same R-value insulation without a vapor barrier in house 2.

The humidity level in house 1 was altered from 53% to a constant daily input of approximately 30 pounds. The reason for doing this was to simulate the estimated 25 lb/day of moisture generated in a dwelling by a family of four, as previously mentioned. This was done on February 4, and was accomplished by setting the humidifier in house 1 to run continuously, but at a low fan speed setting. The humidity level in house 1, therefore, fluctuated as a function of the outdoor temperature. Figure 2 shows the variation of the inside relative humidity in house 1 with the outside temperature. Visual observations in the attic showed condensation under the barrier roughly equivalent to house 2 at 46% and house 3 at 55% with a vapor barrier for the same time period.



(a) BLOTTER UNDER HORIZONTAL RADIANT BARRIER



(b) CONTROL BLOTTER

Figures 4a-b *Average weight changes of blotters in research house attics*

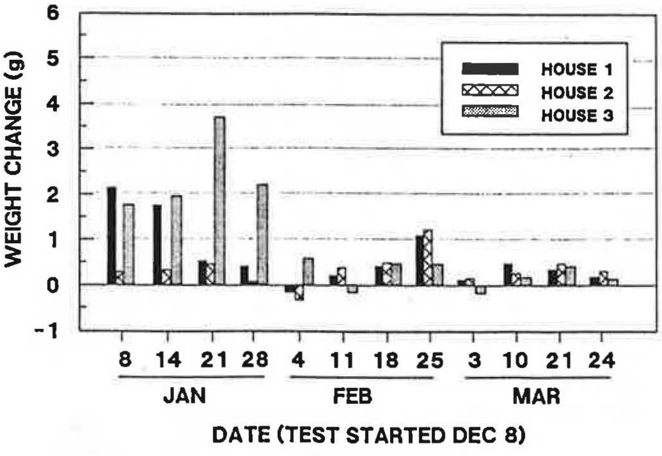


Figure 5 *Difference in weight between blotter under horizontal radiant barrier and control blotter*

Blotting Paper Weighings

Four sections of 12 in × 12 in blotting paper (each section weighed approximately 40 g when dry) were placed in the attics of each house on the top surface of the insulation under the radiant barrier in close proximity to those locations where the wood moisture measurements were made. A fifth control blotter was pinned to an attic truss so that it was exposed to the free attic air space. The blotters were put in the attics because it was thought that they would give some indication of any moisture accumulation that might occur in the insulation under the barriers, with the control blotter acting as a reference point for any changes in blotter weight occurring as a result of natural attic ambient conditions.

The blotters were removed from their locations at approximate one-week intervals, weighed, and then returned to their respective attic locations for another weekly cycle. Figures 4a and 4b depict the weight changes from the original dry weight in bar graph form. Figure 4a graphically shows the weight changes of the blotters under the radiant barrier, while Figure 4b shows the changes of the control blotters. A comparison between the two plots, Figure 5, shows the interesting result that the blotters under the barrier do not change in weight much more than the control blotters.

The period from February 18 to March 24 for house 2 at a reduced attic ventilation area ratio (1/300 compared to the normal 1/150 ft^2 effective vent area per ft^2 attic floor area) shows a slight relative increase compared to house 3 in the blotters under horizontal radiant barrier weights from the preceding two weeks (February 4 to 18), which suggests that the higher attic vent rate may be helpful in reducing the accumulation of moisture in the attic. However, the differences are slight, since the absolute values of the weight gains are small. Colder weather would probably accentuate the difference more.

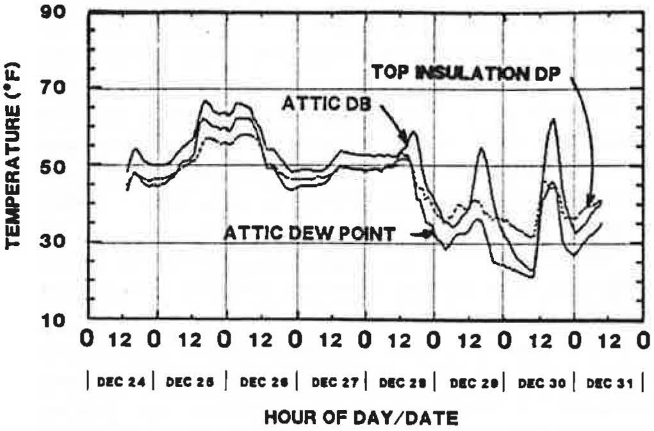
A quantitative interpretation of the blotter weighings is not very straightforward. However, the authors believe that the differences between readings are somewhat close to the actual weights of condensed water which drip from the horizontal radiant barrier to the insulation below it.

Instrument Data

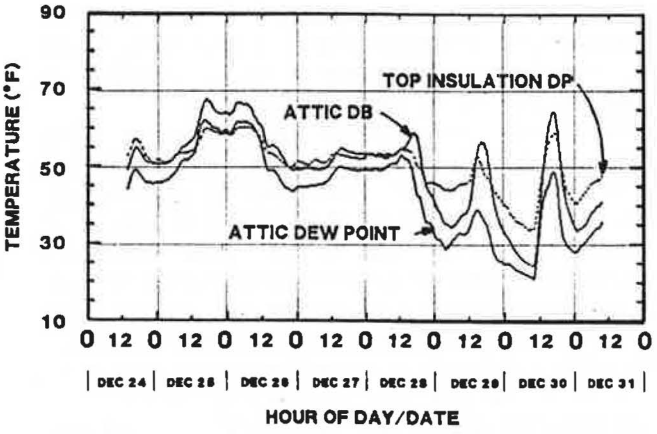
The test houses and their attics were well instrumented, and the data collected from these measurements can quantitatively describe the radiant barrier condensation and vaporization processes that were taking place during the course of the experimental testing. Relative humidity sensors and dry-bulb temperature sensors were located in the attic at the bottom of the insulation, at the top of the insulation under the horizontal radiant barrier, and 12 in above the horizontal radiant barrier in the attic free air space. All sensors were in the same vertical plane approximately above the center of the great room. Figures 6 through 8 are presented to help explain and illustrate the condensation and vaporization of moisture under a horizontal radiant barrier.

Figures 6a and 6b are time-series plots for house 2 (46% relative humidity) and house 1 (56% relative humidity), respectively, on which the attic air dry-bulb, top of insulation under horizontal radiant barrier dew point, and attic air dew point are plotted for the week of December 24 to 31. The average outdoor dry-bulb temperature for this period was 45.3°F, a relatively warm value. The reason for plotting these particular variables is that conditions should be favorable for condensing moisture on the bottom of the horizontal radiant barrier whenever the attic air dry-bulb temperature was less than the dew-point temperature at the top of the attic insulation under the radiant barrier.

Figure 6a shows that the attic air dry-bulb temperature (top solid line) does not go below the top of the insulation dew point temperature (dotted line) until the morning hours of December 29. At this time, moisture can form on the bottom surface of the horizontal radiant barrier. A visual observation confirmed that a light coating of moisture was present under the horizontal radiant barrier in house 2. In the afternoon hours, the attic temperature warmed up and the condensed moisture vaporized from the horizontal radiant barrier into the attic air. Note that, so long as the attic dew point temperature (bottom solid line) is below the dew point temperature on the top surface of the insulation, a water vapor partial pressure driving force exists to promote the transport of water vapor from the horizontal radiant barrier to the attic air through the perforated holes of the horizontal radiant barrier. A log of visual moisture observations was kept, and very good agreement between visual and instrumented moisture conditions was noted.

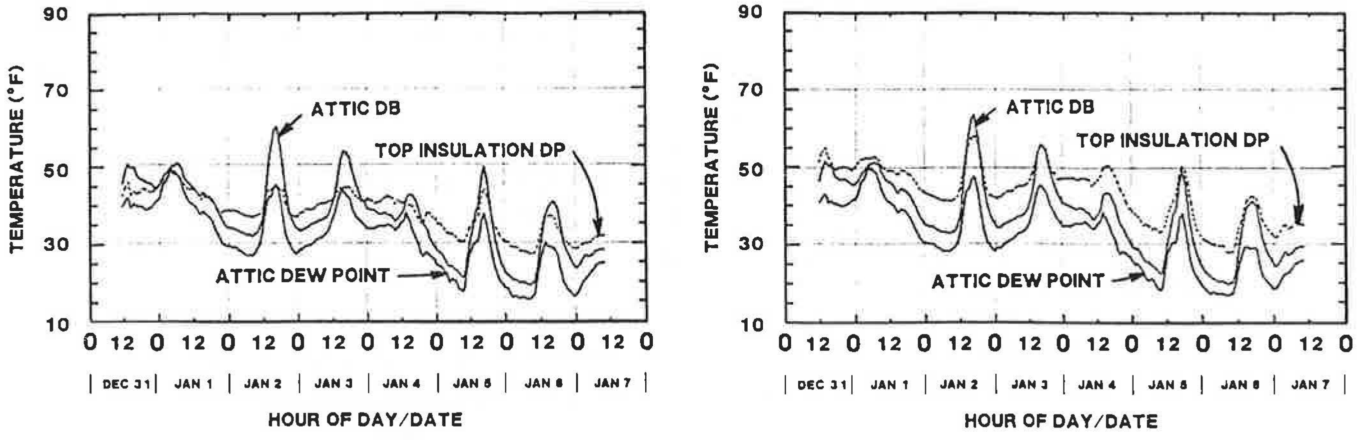


(a) HOUSE 2 (46 % RH)



(b) HOUSE 1 (56 % RH)

Figures 6a-b *Houses 2 and 1—attic dry-bulb, attic dew point, and top of insulation dew point temperatures (December 24-31, 1987)*



(a) HOUSE 2 (46 % RH)

(b) HOUSE 1 (53 % RH)

Figures 7a-b *Houses 2 and 1—attic dry-bulb, attic dew point, and top of insulation dew point temperatures (December 31, 1987 to January 7, 1988)*

The fact that a water vapor partial pressure driving force exists between the bottom surface of the horizontal radiant barrier (assumed to be the same as that of the top surface of the attic insulation) and the adjacent attic air means that moisture can be transported from under the horizontal radiant barrier to the attic air at the same time it is condensing on the horizontal radiant barrier. This explains why condensed moisture does not necessarily accumulate in the attic insulation. Also, since vapor pressure is a logarithmic function of temperature, warmer temperatures can provide greater driving forces for moisture transport.

The size and quantity of the holes in a perforated horizontal radiant barrier provide a resistance to moisture mass transfer from the horizontal radiant barrier to the attic air. Obviously, larger holes will reduce this resistance, but larger holes will also increase convective heat transfer from a horizontal radiant barrier in winter and increase radiant heat transfer to attic insulation in summer. The optimum hole size would appear to be that which is able to dissipate moisture adequately in winter and yet not adversely affect summertime radiant heat transfer reduction. More information must be gathered before an optimum hole size configuration for a horizontal radiant barrier can be suggested.

Returning to Figure 6a, note that condensation occurs again in house 2 from about 6 p.m. on December 29 until about noon on December 30. The outdoor air temperature dropped sharply on December 29 and caused conditions favorable for condensation.

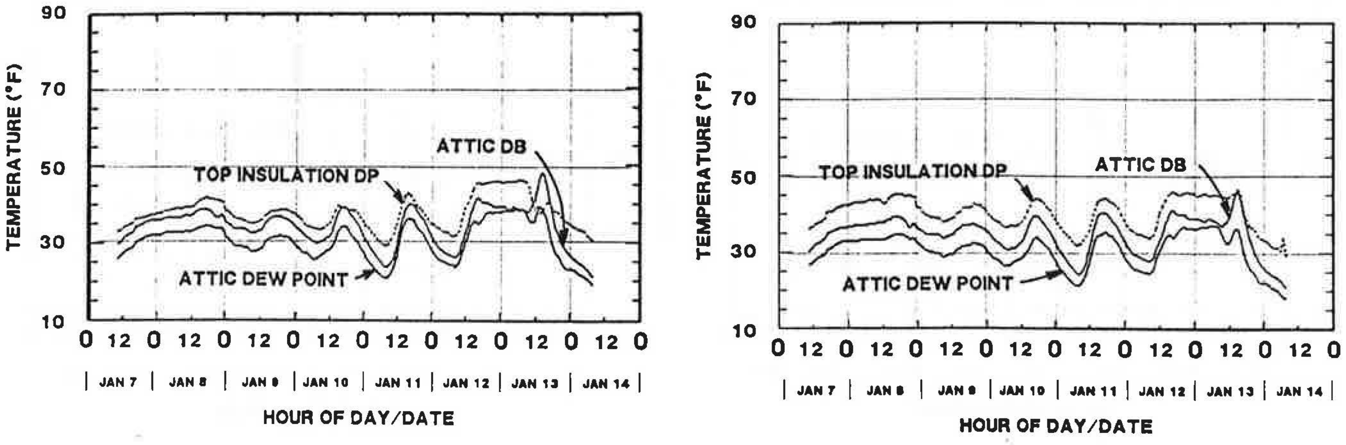
Figure 6b is similar to Figure 6a, the difference being that house 1 at a higher 56% relative humidity is featured. A comparison of the two plots shows that the dew point temperature on top of the insulation in house 1 is usually higher than that in house 2. This means that the attic drybulb temperature is able to cross the horizontal radiant barrier dew point line more often than it could in house 2, which is only logical since more moisture is being generated in house 1.

Figures 7a and 7b, covering December 31 to January 7, are similar to Figures 6a and 6b, the difference being that the average temperature during this week was 29.9°F, somewhat colder than the 45.3°F of the previous week. The relative humidities in both houses are similar to those from the previous week, house 2 at 46% and house 1 at 53%. It is apparent from Figures 7a and 7b that condensation is more likely to form on the horizontal radiant barrier in both houses than during the warmer week depicted in Figures 6a and 6b. House 1, with the higher relative humidity, again shows more tendencies to condense moisture on the horizontal radiant barrier than house 2. The diurnal nature of the condensing and vaporizing moisture cycle is nicely illustrated by Figure 7a.

Figures 8a and 8b, covering January 7 to 14, are similar to the previous two sets of figures, the difference being that the average temperature during this period was 22.9°F, much colder than the previous two weeks. The plots show that the attic drybulb temperature was almost always below the top of the insulation dew point temperature, so that condensation was continually present. Visual observations from Table 3 are in agreement with these data. Note that the humidifier in house 1 could not maintain a relative humidity above 50% during this period. The blotter weight gains discussed in the previous section are extremely high for this week, which suggests that moisture may be forming under the horizontal radiant barrier faster than it is dissipating. This suggests that prolonged cold weather conditions similar to January 7 to 14, which are common in northern climates, may be a cause for concern if a horizontal radiant barrier is installed in a humid northern home. Testing of horizontal radiant barriers in northern climates is definitely recommended. Note, however, that prolonged cold weather is unusual for southern locations and that no permanent ill effects on our houses were noted during our testing.

CONCLUSIONS AND RECOMMENDATIONS

The main conclusion arrived at from this work was that attic moisture appeared to go through a diurnal cycle at the research houses. It could condense on the bottom surface of a horizontal barrier in weather below 35°F, but it could also dissipate during a normal Tennessee winter afternoon, leaving the barrier dry. If the weather was continually in the



(a) HOUSE 2 (48 % RH)

(b) HOUSE 1 (50 % RH)

Figures 8a-b *Houses 2 and 1—attic dry bulb, attic dew point, and top of insulation dew point temperatures (January 7-14, 1988)*

subfreezing range, the condensation would not all dissipate, although it did appear to abate somewhat. However, data showed that the moisture cycle occurring on a perforated horizontal radiant barrier during a typical Tennessee winter did not appear to pose any structural, wet insulation, or stained ceiling problems to the test houses, even though the houses were operated at unusually higher indoor relative humidities.

Other conclusions reached were that a normal range of indoor relative humidity for Tennessee Valley houses at 70°F in winter is 30% to 40%, with the median being about 36%. Houses with indoor relative humidities above 45% in freezing weather are not common, and their windows will contain large amounts of condensed moisture. Perforations in horizontal barriers are effective in providing an outlet for condensed moisture, although an optimum hole size or pattern was not determined. The material used in this study had an average hole diameter of 0.040 in and an open hole area of 0.46%. The vapor pressure of water under a horizontal radiant barrier is usually greater than that in the free attic air, and this difference provides a driving force to convey water vapor from under a barrier into the attic air. We recommend perforations in radiant barrier material used for horizontal installations, but we cannot recommend an optimum hole size or open hole area. More research needs to be done in this area.

More moisture condensed on the barrier of a house at 55% indoor RH than did on a house with 45% relative humidity. We do not recommend installing horizontal radiant barriers in houses with consistent winter indoor relative humidities greater than 50% at 70°F.

Reducing the effective attic ventilation area ratio from 1/150 to 1/300 did not show any significant change in attic moisture parameters. This does not mean that the attic ventilation area is not important, only that a 1/300 ratio may be sufficient at the research houses.

More moisture condensed on barriers in the central portion of the attic than in the periphery. The area over the bathroom, which had holes cut for several plumbing vent pipes and a ventilation fan, was usually the last attic area to become dry. We therefore recommend that holes around vent pipes from a house living area to the attic be sealed with a proper sealant. We also recommend sealing the perimeter of ceiling light fixtures and venting bathroom fans at least to above the top of the attic insulation.

The moisture content of attic truss members under a horizontal barrier started at about 7 weight percent and reached a maximum value of 11 weight percent before returning to lower values and did not appear to be very different from the moisture content of those truss members above the barrier. These numbers are well below the danger point for wood fiber saturation of about 28% to 30%.

We recommend that care be taken in extrapolating the observations of this experimental work to areas with prolonged periods of subfreezing weather. The diurnal moisture cycle under the barrier could be quite different in colder climates. Further testing of horizontal barriers in colder climates is recommended.

REFERENCES

Cuter Information Corporation. 1986. "Moisture in houses: control technology for designers and builder."

DOE. n.d. "Moisture and home energy conservation." Prepared by the National Center for Appropriate Technology for the U.S. Department of Energy.

Harrje, D.T.; Gibson, R.G.; Jacobson, D.I.; Dutt, G.S.; and Hans, G. 1985. "Field measurements of seasonal wood moisture variations in residential attics." PU/CEES Report No. 188.

Johnson, R.J. 1982. "Residential moisture conditions—facts and experience." In: *Moisture Migration in Buildings*, ASTM STP 779, M. Lieff and H.R. Trechsel, eds., pp. 234-240. American Society for Testing and Materials.

Laquatva, J., and Chi, S.K. "Residential moisture conditions and perceived health status." College of Human Ecology, Cornell University.

Levins, W.P., and Karnitz, M.A. 1986. "Cooling energy measurements of unoccupied single-family houses with attics containing radiant barriers." ORNL/CON-200, Oak Ridge National Laboratory.

Levins, W.P., and Karnitz, M.A. 1987a. "Heating energy measurements of unoccupied single-family houses with attics containing radiant barriers." ORNL/CON-213, Oak Ridge National Laboratory.

Levins, W.P., and Karnitz, M.A. 1987b. "Cooling energy measurements of single-family houses with attics containing radiant barriers in combination with R-11 and R-30 ceiling insulation." ORNL/CON-226, Oak Ridge National Laboratory.

Levins, W.P., and Karnitz, M.A. 1987c. "Energy measurements of single-family houses with attics containing radiant barriers." ASHRAE Transactions, Vol. 93, Part 2, pp. 182-199.

Levins, W.P., and Karnitz, M.A. 1988. "Heating energy measurements of single-family houses with attics containing radiant barriers in combination with R-11 and R-30 ceiling insulation." ORNL/CON-239, Oak Ridge National Laboratory.

Levins, W.P.; Karnitz, M.A.; and Hall, J.A. "Moisture measurements in single-family houses with attics containing radiant barriers." ORNL/CON-255, Oak Ridge National Laboratory (to be published).

Owners Manual for Kenmore "3200" 20-Gallon Central Humidifier. Chicago: Sears, Roebuck and Company.