PERFORMANCE TESTING OF RADIANT BARRIERS (RB) WITH R11, R19, AND R30 CELLULOSE AND ROCK WOOL INSULATION

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ABSTRACT

TVA has previously conducted testing to determine the effects of attic RBs when used with R19 fiberglass insulation during summer and winter conditions[1]. This previous testing, and the testing described in this paper, used five small test cells exposed to ambient conditions. Heat flux transducers measured heat transfer between the attic and conditioned space. The objective of the testing described in this paper was to determine summer and winter RB performance when used with cellulose and rock wool insulations at R-value levels of R11, R19, and R30.

In addition, several summer side-by-side tests were conducted to determine the effects of: dust on RB performance, a low-emissivity paint, a high-emissivity material (black plastic) laid directly on top of the insulation, and a single-sided RB placed on top of the insulation (RBT) with the reflective side down.

INTRODUCTION

Previous work at TVA[1], the University of Mississippi[2], the Florida Solar Energy Center (FSEC)[3], and Oak Ridge National Laboratory (ORNL)[4-7] has shown that RBs can provide significant reductions in summer ceiling heat gain when used with R19 fiberglass. An RB is generally defined as a material with at least one low emissivity surface facing an airspace. Also, previous work [1, 2, 5, 7] has shown that RBs can reduce winter ceiling heat loss when used with R19 fiberglass, although the reduction in ceiling heat flux is much less than during summer. An RB is defined here as a thin, sheet-like material with at least one low emissivity surface facing an air space.

Two key questions emerged from these previous studies:

1. What are the effects of RBs when used with R-values other than R19?
2. What are the effects of RBs when used with insulations other than fiberglass?

These questions were addressed in the testing conducted during the summer of 1986 and the winter of 1986/1987.

As RB testing has progressed, numerous other questions also have been raised. The questions that were addressed in summer, side-by-side tests were:

1. What is the effect of dust on the RBT's ceiling heat flux reduction ?
2. What is the reduction in ceiling heat flux from low-emissivity paints applied to the underside of the roof deck?
3. How much of the reduction in ceiling heat flux from the RBT is due to reduction in infrared radiation and how much to its presence as a barrier to convection heat transfer?

PROJECT DESCRIPTION

OBJECTIVES

The overall objectives of this project were to:

1. Assess the summer and winter performance of RBs when used with R11, R19, and R30 insulation.
2. Assess the summer and winter performance of RBs when used with nonfiberglass insulations --cellulose and rock wool.
3. Address questions concerning low-emissivity paints, the impact of dust on reduction in ceiling heat flux from the RBT, and the effect of a high-emissivity "convection barrier."

TEST METHODOLOGY

Because of the large number of variables in the summer testing (3 R-values, 2 insulation types, and 2 test configurations--no RB and RBT), the Latin Square design used in the previous TVA testing[1] could not be used. Instead, a split-split-plot test design[8] was chosen (see table 1). This design allowed a greater number of variables to be tested but did not completely account for weather differences between phases. This problem was resolved by establishing a weather criteria to be applied to each test phase. This criteria was that each phase should consist of at least 3 days with each day having at least 3 consecutive hours above 85^{o}F ambient temperature. The result was that the test phases were quite similar and any differences that did occur in ambient temperature and other variables such as solar radiation, wind speed, and inside cell temperature were normalized by a linear regression analysis. Cell differences were not a significant concern because the plan called for both the no-RB and RB on the rafters (RBR) configurations to be tested in each cell for a particular insulation type and R-value. For example, in phases 1 and 2 the no-RB configuration is tested in both cells that have cellulose. Also, phases 1-6 were duplicated (phases 7-12) and the insulation types were switched so that each attic configuration and R-value was tested in each cell.

The winter test plan (see table 2) was altered so that the RBT also could be tested. Again a weather criteria and linear regression analysis were used to normalize weather differences between phases. The weather criteria for the winter was that each phase should consist of at least 2 days where the minimum daily temperature was less than 32°F. The cell difference problem was not completely resolved since each attic configuration was not tested in each cell. However, since each attic configuration was tested in the 2 cells in which a given insulation type was installed and since only minor cell differences were noted in past tests, this approach was deemed acceptable. Reference 8 contains discussion on the above experimental designs.

TEST EQUIPMENT

Test Cells. Five small structures or test cells exposed to ambient conditions were used in this testing. Each test cell had a roof which was hinged along the peak so that one side could be opened to allow easy access to the attics. The roof peak was oriented in the north/south direction so that the roof surfaces faced east and west. Figure 1 shows key test cell dimensions and details.

Attic Ventilation. Attic ventilation in each cell was provided by 2 gable and 4 soffit vents. The net free area (NFA) of ventilation in each cell was 0.42 square feet (0.40 square feet in 4 soffit vents and 0.02 square feet in 2 gable vents) which is 31 percent more than the 0.32 square feet minimum NFA as required by the Department of Housing and Urban Development and the Federal Housing Administration for an attic of 48 square feet [9].

Heating and Cooling Systems. Portable 1-kW forced-air electric heaters were used to heat the cells during winter. These heaters were controlled by thermostats in the cells that maintained temperatures of 70°F (± 2°F).

A chilled water recirculation system was used to cool the cells. Two small water chillers delivered water at about 55°F which was stored in three 82-gallon storage tanks to meet peak demands. Water from these tanks flowed continuously in parallel runs of piping to each of the cells. When a thermostat in a cell called for cooling, a diverting valve at the cell re-routed the flow of cool water to a fan/air heat exchange coil located in the cell. When the cooling needs of a cell were satisfied, the diverting valve closed which stopped the flow of water to the fan coil. This system maintained interior summer temperatures of 74°F (typically ± 2°F but on rare occasions dropping to near 70°F).

Instrumentation. The heat transfer rates through the cells' ceiling were measured with heat flux transducers. Before installation, the transducers were calibrated (with an uncertainty of 2.25 percent) by using known heat fluxes in the 1 to 2 Btu/hr-ft^2 range. During both the summer and winter tests, 5 heat flux transducers were installed on the attic side of the ceiling of each cell. These heat flux transducers were approximately 2-inch by 2-inch squares and were located at various places in the attics approximately midway between ceiling joists.

Thirty-six data points were monitored in each test cell. These consisted of:

1. 7 insulation temperatures
2. 6 temperatures within the test cell
3. 7 attic temperatures
4. 5 ceiling heat fluxes
5. 2 roof temperatures (underneath roof shingles)
6. 1 cell relative humidity
7. 1 cell electric energy usage for space heating
8. 2 status sensors (to monitor opening and closing of the door and roof)
9. 5 sensors to determine the cooling effect of the chilled water system

In addition to these 180 data points (36 data points per cell times 5 cells), the following weather data were monitored:

1. Two ambient temperatures
2. Solar radiation
3. Wind speed and direction

The above temperature measurements were made with type-T thermocouples with standard limits of error of ± 1.4°F.

Data Collection System. A data logger continuously recorded (approximately every 10 seconds) and stored values for all data points. Every 15 minutes the data logger would relay a 15-minute "integrated" value for each data point to a magnetic tape. In the winter testing, the data also was transmitted to an IBM Personal Computer so the data could be reviewed daily.

RB and Insulation. For all RB configurations, summer and winter, a double-sided RB with 40-pound kraft paper backing was used. The emissivity of both sides of this RB was approximately 0.05. Because of the large number of variables to be studied in the summer (3 R-values, 2 types of insulation, 2 attic configurations--no RB and RBR), only the RBR was tested in the summer. With a better test design and more experience in handling multiple R-values and insulations, 2 RB cases (RBR and RBT) were tested in the winter. To try to ensure reasonable ventilation above the RB, the RBR was installed with a 3- to 4-inch gap in the RB near the roof peak and with a 2- to 3-inch gap between the RB and the eaves. Figure 2 shows the RBR and RBT installations.

The insulations used throughout the summer and winter testing were cellulose and rock wool which were blown into the cells' attics by an insulation contractor. It should be noted that fiberglass batts (not blown) were used in the previous year's tests. Testing during both summer and winter would begin by having the insulation contractor blow either R11 cellulose or R11 rock wool into each cell. When testing at the R11 level was completed, the insulation contractor would blow additional cellulose or rock wool into each cell to raise the R-value to R19. The same process was repeated for the R30 level. The nominal insulation depths are shown in table 3.

STATISTICAL ANALYSIS

All the heat flux data were analyzed to determine statistically significant differences at the 95-percent confidence level using the following procedure. The mean heat flux (derived from the measured values of the 5 heat flux transducers) for each test design "block" (i.e., for each phase and each cell) was determined. A linear regression analysis model was then developed which equated the heat flux as a function of key variables such as the particular R-value/RB configuration, ambient temperature, solar radiation, wind speed, and cell temperature.

Using this linear regression model, the least square heat flux mean for each R-value/RB configuration is then calculated after normalizing for any differences in the values of the key variables between test design "blocks." By comparing the actual mean heat fluxes with the linear regression model predictions (i.e., the least square means), a standard error for each configuration can be calculated. The standard error is essentially a measure of the degree of variability of the data.

Finally, the standard error and the least square mean calculation for each configuration are used to determine whether the differences between various configurations' least square mean heat fluxes are statistically significant. In the discussion of results, it will be noted when the statistical significance (or nonsignificance) between heat fluxes is especially important. Unless noted otherwise, all references to statistical significance will indicate the 95-percent confidence level.

RESULTS

SUMMER RESULTS

Cellulose and Rock Wool Insulations. One of the main objectives of this work was to assess the performance of RBs when used with two common insulations--rock wool and cellulose. Nearly all past RB testing has used fiberglass insulation, with the exception of some laboratory testing conducted at Texas A&M[10]. Therefore, testing was needed to verify that RBs also provide large ceiling heat transfer reductions when used with cellulose and rock wool.

The first key result was that both the RBR/cellulose and RBR/rock wool R19 combinations yielded large ceiling heat flux reductions similar to the R19/RBR/fiberglass combination. Also, the percentage reduction in ceiling heat flux was very similar to the reduction found with R19 fiberglass insulation.

The second key result was that no statistically significant differences were found in performance between the cellulose and rock wool insulations (with no RB present). Therefore, the summer data could be analyzed as if the cellulose and rock wool insulations were the same and, as a result, all the data for a given R-value and attic configuration (i.e., no RB or RBR), could be combined.

Analysis for All Hours. The data were analyzed using all the data (i.e., all hours of the day) from the "test" days as described in the section on Test Methodology and the results are shown in table 4. The units for heat flux in this and all the following tables are expressed Btu/hr-ft^2. There are two key results evident from this table.

First, when the RBR is added to R11 and R19, a ceiling heat flux reduction of 30 percent or more results. However, when a RBR is added to R30 the percentage and absolute heat flux reduction are much smaller.

The second key result is evident from a comparison of R11/RBR with R19/no RB and from a comparison of R19/RBR with R30/no RB. From the heat flux columns, it is evident that adding a RBR to R11 is nearly equivalent to having R19 insulation, and adding a RBR to R19 is equivalent to having R30 insulation.

With R11 and R19 insulation, the RBR produced statistically significant reductions in ceiling heat flux compared to the no-RB case. However, the reduction in ceiling heat flux from adding a RBR to R30 was not statistically significant.

Analysis for Day Hours. Table 5 gives the results of an analysis using only data recorded during day hours (defined as 11 a.m. to 6 p.m.). The results show that for the RBR at the R11 and R19 insulation levels the percent and absolute reductions in ceiling heat flux are sizable. At R30, the RBR percent and absolute reductions are smaller and not statistically significant.

As with the all hours analysis (Table 4), the ceiling heat flux for the RBR with a given R-value is essentially the same as the ceiling heat flux for the next higher R-value without the RBR.

Analysis for Night Hours. There were no statistically significant differences (at the 90-percent as well as the 95-percent confidence level) in average heat flux among any of the configurations for the night hours between 12 midnight and 7 a.m. These heat fluxes ranged from a high of 0.10 to a low of -0.09 Btu/hr-ft^2. For each R-value the RBRs caused only very small (statistically insignificant) heat flux penalties ($\leq$ 0.13 BTU/hr-ft^2) during the night hours compared to the same R-value, no RB configuration.

Analysis by Temperature Range. Tables 6, 7, and 8 show the average ceiling heat fluxes for each configuration for various ambient temperature ranges. Above 80°F, the RBR, when added to R11 or R19 insulation, provides sizable percent and absolute reductions in ceiling heat flux, and in each case this reduction is statistically significant. Above 80°F, the percent and absolute reduction in ceiling heat flux when adding a RBR to R30 are always less than when adding a RBR to R11 or R19 insulation. In addition, the differences in heat flux between the

R30 RBR and no-RB cases are not statistically significant in any of the temperature ranges. Below 80°F, the RBR did not result in statistically significant reductions in ceiling heat flux for any R-value.

Another interesting result from these tables is the relationship between R11/RBR and R19/no RB and between R19/RBR and R30/no RB (as also is discussed in the sections on Analysis for All Hours and for Day Hours). In nearly every temperature range above 80°F, the lower R-value when combined with the RBR has essentially the same heat flux as the higher R-value with no RB.

Heat Flux versus Time-of-Day Graphs. Figures 3 and 4 are graphs of the average ceiling heat flux (using all the data from phases 1 through 6) versus time of day for the no RB and RBR configurations for R11, R19, and R30.

Figure 3 shows the results for the no RB and RBR configurations for both R11 and R19 insulation. It can be seen from this figure that the RBR's reduction in ceiling heat flux with R11 is much greater than 1 BTU/hr-ft^2 for most of the day hours. This figure also shows that the ceiling heat fluxes for R11/RBR are almost the same as R19/no RB.

Figure 4 shows the results for the no RB and RBR configurations for both R19 and R30 insulation. This figure shows that the reduction in ceiling heat flux from the RBR with R30 is much smaller than with R19. Also, the ceiling heat fluxes for R19/RBR are very nearly the same as for R30/no RB. It should be noted that the Y-axis scale for this figure is different from the scale used in figure 3. The curves for R19 (with and without the RBR) are the same in both figures.

ATTIC TEMPERATURES

In addition to the heat flux, attic air temperatures were examined. Attic air temperatures are of interest since air-conditioning ductwork is sometimes located in attics and any reduction in attic air temperatures by the RBRs will result in a reduction in heat gain by the cool, conditioned air. The attic air temperature sensor was located six inches above the insulation.

For ambient temperatures above 85°F, the decrease in attic air temperature that results from the addition of a RBR is 10°F or more for all R-values. Greater temperature drops are seen for R11 and R19 than for R30 and the attic air temperature decrease resulting from the RBR lessens as the ambient temperature decreases and disappears below 80°F ambient temperature. Decreased heat gain by attic ductwork as a result of the RBR could be significant during ambient temperatures above 85°F.

Roof Temperatures. One of the key questions concerning RBs has been whether they cause higher roof shingle temperatures than normal which could result in shorter roof life. This has been investigated previously by ORNL, FSEC, and TVA. In each case, it was found that RBs, especially the RBR, do cause higher roof temperatures but that the increase is not large. In the worst case, ORNL found increases in roof temperatures of 10°F with the RBR.

Table 9 shows the result of an analysis of roof temperatures for those test periods when the ambient temperature was greater than 88°F and the solar radiation greater than 200 Btu/hr-ft^2. The RBR does increase the average roof temperature at each R-value level during these hot, sunny conditions, but the increase is, at most, 4°F.

Side-by-Side Testing. A series of side-by-side tests was conducted at the end of the primary summer test to do a preliminary investigation of several RB-related questions. Table 10 shows the results of tests of a low emissivity paint and table 11 gives results from side-by-side tests of "miscellaneous" configurations. The results given in tables 10 and 11 are the average heat fluxes for each configuration when ambient temperatures were in the 80°F to 85°F and 85°F to 90°F ranges.

The low-emissivity paint was applied to the underside of the roof deck (including rafters) in one of the test cells. The paint manufacturer claims that the paint can reduce the emissivity of the underside of the roof deck from the usual 0.8 to 0.9 to near 0.2, thereby significantly reducing thermal radiation heat transfer from the roof deck to the top of the insulation. Table 9 shows that the low-emissivity paint provides some small reductions in ceiling heat flux when used with R11 insulation but provides essentially no reduction in ceiling heat flux when used with R19 or R30 insulation. These were simple side-by-side tests with no correction for any possible cell differences and the results should be viewed with appropriate caution.

Table 11 shows the results of the other side-by-side tests. The RBT with dust sprinkled on the RB (line 2) was tested to assess the impact of dust buildup. This is a critical concern for the RBT configuration. Arizona dust was used; this dust is commonly used for testing air filters and has dust micron sizes of: 0-5 microns: 39 percent; 5-10 microns: 18 percent; 10-20 microns: 16 percent; 20-40 microns: 18 percent; 40-80 microns: 9 percent. No attempt was made to weigh the dust applied to the RB but a dust covering was used which by visual observation was similar to that which caused a rise in emissivity of RB samples, as measured by an emissometer, from 0.05 to 0.50. Surprisingly, the dust appeared to have little effect on the effectiveness of the RB. The percent reduction in ceiling heat flux was remarkably similar to that of a RBT with no dust. This issue definitely needs further research, and more detailed testing is planned.

The next configuration tested (line 3) was a single-sided RB placed on top of the insulation with the reflective side facing down. The top side of the RB was Kraft paper with a high emissivity (0.82). This test was an attempt to simulate the case where the RB on top, completely covered by dust, has its top side emissivity drastically increased and would show how much of the reduction in ceiling heat flux is obtained from the low emittance surface that faces down. The third line in table 11 shows that this configuration provided essentially zero reduction in ceiling heat flux compared to R19 only. From these results, it appears that the surprising reduction in ceiling heat flux from the RBT with dust does not result from the low emittance surface facing down.

The last configuration tested was a black plastic placed directly on top of the insulation. The purpose of this test was to examine how much of the reduction in ceiling heat flux from a RB on top is from the creation of a barrier to convection heat transfer. The direction of convection heat transfer is usually upward because of buoyant forces. However, heat transfer by convection from hot attic air to the insulation could possibly occur by forced convection from wind currents entering the attic and moving hot air near the roof downward to the insulation. In other words, the black plastic with its high emissivity should yield little reduction in ceiling heat flux from reflecting thermal radiation; therefore, any reduction should be a result of adding a barrier to convection heat transfer from the hot attic air.

The fourth line in table 11 shows that this configuration also provides essentially no reduction in ceiling heat flux relative to the R19 only case. This result implies that the summer reduction in ceiling heat flux from RBs does stem from a reduction in radiation heat transfer from the roof and not from the RB acting as a "convection" barrier. Again, these were simple side-by-side tests with no correction for any possible cell differences and the results should therefore be viewed with caution.

The results of the black plastic and single-sided RB tests indicate that the reduction in ceiling heat flux from the RBT with dust is not from the reflective side facing down nor from it acting as a convection barrier to heat transfer. The top side of the RB may still reflect large amounts of thermal radiation from the roof deck despite the dust.

WINTER RESULTS

Cellulose and Rock Wool Insulations. As with the summer testing, one of the main objectives of winter testing was to determine whether RBs provided reductions in ceiling heat flux in winter with cellulose and rock wool similar to the reductions with fiberglass. In addition to the no RB and RBR configurations tested in the summer, the RBT also was tested during the 1986/1987 winter (see table 2). A comparison of winter 1986/1987 results with winter 1985/1986 results[1] shows that:

1. The RBT's reduction in ceiling heat flux with cellulose and rock wool was similar in almost all cases to the reductions with fiberglass with the exception of two instances in the All Hours and Day Hours analyses (tables 12 and 14). In the All Hours case, the RBT's reduction in ceiling heat flux with R19 cellulose and rock wool was much lower (5 percent) than with fiberglass (15 percent). In the Day Hours case, the penalty from the RBT with R19 cellulose and rock wool was large (-22 percent), while, with fiberglass, the RBT still showed an 8-percent reduction in ceiling heat flux. These discrepancies possibly could be due to the different attic ventilation areas used in the 2 tests. Attic ventilation area during the winter 1986/1987 tests was much less than during winter 1985/1986 (0.42 versus 1.75 square feet of NFA). Smaller ventilation area could cause much higher attic air temperatures during day hours and, therefore, the potential penalty from the RBT would be increased. This attic ventilation difference would not affect Night Hours since there is no solar radiation and wind speeds are much lower.
2. The RBR's reduction in ceiling heat flux was much lower in almost all cases. Again, the higher penalty for the R19/RBR during Day Hours of the 1986/1987 testing (-30% versus -2% during 1985/1986) could be due to the lower ventilation area as was discussed in the previous paragraph. A theory to explain the much smaller reductions in ceiling heat flux for the RBR for cellulose and rock wool during night hours is not so obvious.

Analysis for All Hours. Table 12 shows the results for all hours of the day. At the R11 insulation level both the RBR and RBT show a reduction in ceiling heat flux. However, only the RBT's reduction is statistically significant and it is much larger (17 percent) than the RBR's reduction (6 percent). At R19 the RBR actually has a higher overall heat flux than the no-RB case while the RBT shows a small reduction in ceiling heat flux. At R30, the RBR shows a small (6 percent) reduction in ceiling heat flux while the RBT shows a large (15 percent) reduction in ceiling heat flux compared to the no-RB case. None of these heat flux differences are statistically significant except for the R11/RBT case mentioned above.

Analysis for Night Hours. Table 13 gives the results of an analysis which examines the effects of RBs during night hours (7 p.m. to 7 a.m.). The reduction in ceiling heat flux during the night hours is larger for both the RBR and RBT cases for each R-value than during all hours of the days. The reduction in ceiling heat flux was greater than 10 percent in all cases except for the RBR with R19 when there was no reduction in ceiling heat flux. However, only the reduction in ceiling heat flux from the RBT with R11 was statistically significant, although the reduction from the RBR with R11 did become significant at the 90-percent confidence level.

Analysis for Day Hours. Table 14 shows the effects of RBs during day hours (11 a.m. to 4 p.m.). As was expected, the RBs cause a heat flux penalty at all R-values because they prevent the warming of the insulation that sometimes occurs from solar radiation raising the temperature of the roof deck. Despite the seemingly large percentage differences, only the difference between the RBR and the no-RB R11 cases was statistically significant.

Analysis by Temperature Range. Tables 15 and 16 give the results for ambient temperatures between 15°F and 25°F and between 25°F and 35°F, respectively. For every R-value, the RBT results in the highest (or best) heat flux and its percentage reduction in ceiling heat flux compared to the no-RB case is usually quite large. The RBR gives very small reductions in ceiling heat flux or a penalty during 15°F to 25°F ambient temperatures. During 25°F to 35°F conditions, the RBR performs somewhat better than the lower temperature case, although the reduction in ceiling heat flux is still small. In every case, the reduction in ceiling heat flux from the RBs decreases as the insulation R-value is increased.

Heat Flux versus Time-of-Day Graphs. Figures 5, 6, and 7 are graphs for R11, R19, and R30, respectively, of the average ceiling heat flux (using all the data) versus time-of-day for all 3 attic configurations. (The Y-axis scales for these 3 figures are different.) With R11 (figure 5), both the RBR and the RBT provide ceiling heat flux increases from 7 p.m. to 9 a.m. It should be noted that unlike summer a heat flux increase is desirable in the winter as less heat is lost from the conditioned space. The RBT's increase in ceiling heat flux is larger (nearly 0.75 versus less than 0.5 Btu/hr-ft^2) than the RBR's throughout hours from 1 p.m. to 4 p.m. The RBT also incurs a heat flux penalty, but it is shorter in duration and smaller in magnitude than with the RBR.

With R19, the RBR provides only small increases in ceiling heat flux from 12 midnight to about 8 a.m. while a large penalty is incurred during the remainder of the hours. The RBT incurs a ceiling heat flux penalty only from 12 noon to 5 p.m. and provides small but consistent increases in ceiling heat flux during all the remaining hours of the day.

With R30, both the RBR and the RBT provide small but consistent increases in ceiling heat flux from 10 p.m. to 9 a.m. During the day hours, however, both RB configurations incur heat flux penalties compared to R30/no RB.

CONCLUSIONS

The following are the key conclusions resulting from the 1986 summer testing:

1. The RBR provides large reductions in ceiling heat flux (as compared with the same R-value, no RB) with cellulose and rock wool insulations, just as with fiberglass.
2. The RBR provides large reductions in ceiling heat flux for insulation R-values of R19 or less. The reductions in ceiling heat flux from the RBR with R30 insulation is much less than with R11 or R19 insulation.
3. Even with significant dust accumulation on the RBT, the RB's performance or reduction in ceiling heat flux may not degrade nearly as much as would be expected from the significant increases in RB emissivity caused by small amounts of dust.
4. Summer heat flux reductions from the RBT do not appear to result from it acting as a "barrier" to convection heat transfer from the hot attic air but appear to stem only from it reducing radiation heat transfer from the roof deck.
5. The RBR reduces attic air temperatures by a significant amount (10°F or more) and this air temperature reduction could result in sizable savings from reduced heat gain by central HVAC ductwork which is sometimes located in attics.

The following are the key conclusions from the 1986/1987 winter testing:

1. The RBT performs somewhat similarly with R19 cellulose and rock wool as with R19 fiberglass.
2. The RBT provides moderate increases (i.e., less heat loss from the conditioned space) in ceiling heat flux at all three R-value levels.
3. The RBR performed quite differently with R19 cellulose and rock wool insulation as compared to R19 fiberglass. Some, but not all, of the performance differences could be explained by the attic ventilation differences between the two tests. Therefore, it is still uncertain whether the RBR performs similarly for cellulose and rock wool insulations as for fiberglass.
4. The reduction in ceiling heat flux from the RBR was much smaller than from the RBT and was near zero or negative in several cases.

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REFERENCES

1. Hall, James A., "Performance Testing of Radiant Barriers." Tennessee Valley Authority, TVA/OP/ED&T-86/25. November 1986.

2. Roux, J. A. and Rish, J. W., "Modelling of Heat Transfer Through Fiberglass Insulation To Assess Attic Radiant Barriers." University of Mississippi. Sponsored by the Tennessee Valley Authority, TVA/OP/EDT-87/15, December 1985.

3. Fairey, Philip W., "Effects of Infrared Radiation Barriers on the Effective Thermal Resistance of Building Envelopes." Florida Solar Energy Center, December 1982.

4. Levins, W. P. and Karnitz, M. A., "Cooling Energy Measurements of Unoccupied Single-Family Houses With Attics Containing Radiant Barriers." Oak Ridge National Laboratory. Sponsored by the Department of Energy and TVA. ORNL/CON-200, July 1986.

5. Levins, W. P. and Karnitz, M. A., "Heating Energy Measurement of Unoccupied Single-Family Houses With Attics Containing Radiant Barriers." Oak Ridge National Laboratory. Sponsored by the Department of Energy and Tennessee Valley Authority. ORNL/CON-213, January 1987.

6. Levins, W. P., and Karnitz, M. A., "Cooling Energy Measurements of Single Family Houses with Attics Containing Radiant Barriers in Combination With R11 and R30 Ceiling Insulation." Oak Ridge National Laboratory, Sponsored by the Department of Energy and Tennessee Valley Authority. ORNL/CON-226, May 1987.

7. Levins, W. E. and Karnitz, M. A., "Heating Energy Measurements of Single-Family Houses with Attics Containing Radiant Barriers in Combination With R11 and R30 Ceiling Insulation." Oak Ridge National Laboratory, Sponsored by the Department of Energy and Tennessee Valley Authority. ORNL/CON-239, March 1988.

8. Mendenhall, William, The Design and Analysis of Experiments. Wadsworth Publishing Company, Inc. Copyright 1968.

9. TVA Material and Installation Standards; Section 6.1, Part C, Home Weatherization; January 1987.

10. Katipamula, S. and O'Neal, D.L. "An Evaluation of the Placement of Radiant Barriers on Their Effectiveness in Reducing Heat Transfer in Attics." Texas A&M University, November 1986.

Table 1: 1986 Summer Test Design

Phase	R Value	Cell C	Cell D	Cell E	Cell F
1	R11	RBR	RBR	no RB	no RB
2	R11	no RB	no RB	RBR	RBR
3	R19	no RB	no RB	RBR	RBR
4	R19	RBR	RBR	no RB	no RB
5	R30	RBR	RBR	no RB	no RB
6	R30	no RB	no RB	RBR	RBR

Notes:
- o RBR stands for RB attached to the underside of the rafters.
- o Phases 7 through 12 were exactly like phases 1 through 6 except cells D and F had cellulose and cells C and E had rock wool insulation.

Table 2: 1986/1987 Winter Test Design

Phase	R Value	Cell C	Cell D	Cell E	Cell F
1	R11	RBR	no RB	no RB	RBT
2	R11	RBT	RBR	RBR	no RB
3	R11	no RB	RBT	RBT	RBR
4	R19	RBT	RBR	RBR	no RB
5	R19	no RB	no RB	RBT	RBT
6	R19	RBR	RBT	no RB	RBR
7	R30	no RB	RBT	RBT	RBR
8	R30	RBT	RBR	RBR	no RB
9	R30	RBR	no RB	no RB	RBT

Notes: RBT stands for RB placed on top of the insulation.

RBR stands for RB attached to the underside of the rafters.

Cells C and E had cellulose.
Cells D and F had rock wool.

Table 3: Insulation Thickness

R-Value	Cellulose	Rock Wool
R11	3.0 inches	3.5 inches
R19	5.1 inches	6.1 inches
R30	7.0 inches	9.6 inches

Table 4: Summer Results - Average Ceiling Heat Fluxes For All Hours[1]

Configuration[2]	Heat Flux (Btu/hr-ft^2)	% Saving (vs same R-value, no RB
R11/no RB	2.38	--
R11/RBR	1.57	34%
R19/no RB	1.45	--
R19/RBR	1.01	30%
R30/no RB	1.06	--
R30/RBR	0.84	20%

[1] Average ambient conditions during these hours were:

Ambient Temperature = 81°F
Solar Radiation = 78 Btu/hr-ft^2
Wind Speed = 2.6 mi/h

[2] Since there were no significant differences in the performances of cellulose and rock wool, the heat flux data for both insulations were combined for each R-value/attic configuration in tables 3 through 8 and 11 through 15.

Table 5: Summer Results - Average Ceiling Heat Fluxes for Day Hours (11 a.m. to 6 p.m.)[1]

Configuration	Heat Flux (Btu/hr-ft^2)	% Saving (vs same R-value, no RB
R11/no RB	5.27	--
R11/RBR	3.22	39%
R19/no RB	3.20	--
R19/RBR	2.06	36%
R30/no RB	2.07	--
R30/RBR	1.57	24%

[1] Average ambient conditions during these hours were:

Ambient Temperature = 89°F
Solar Radiation = 179 Btu/hr-ft^2
Wind Speed = 4.7 mi/h

Table 6: Summer Results - Average Ceiling Heat Fluxes for 80°F-85°F[1] Temperature Range

Configuration	Heat Flux (Btu/hr-ft^2)	% Saving (vs same R-value, no RB
R11/no RB	2.71	--
R11/RBR	1.80	34%
R19/no RB	1.61	--
R19/RBR	1.06	34%
R30/no RB	1.33	--
R30/RBR	1.14	14%

[1] Average ambient conditions during these hours were:

Ambient Temperature = 82.5°F
Solar Radiation = 82 Btu/hr-ft^2
Wind Speed = 2.4 mi/h

Table 7: Summer Results - Average Ceiling Heat Fluxes for 85°F-90°F Temperature Range

Configuration	Heat Flux (Btu/hr-ft^2)	% Saving (vs same R-value, no RB
R/11no RB	4.53	--
R11/RBR	2.90	36%
R19/no RB	2.63	--
R19/RBR	1.68	36%
R30/no RB	1.80	--
R30/RBR	1.40	22%

[1] Average ambient conditions during these hours were:

Ambient Temperature = 87°F
Solar Radiation = 131 Btu/hr-ft^2
Wind Speed = 3.4 mi/h

Table 8: Summer Results - Average Ceiling Heat Fluxes for 90-95°F[1] Temperature Range

Configuration	Heat Flux (Btu/hr-ft^2)	% Saving (vs same R-value, no RB
R11/no RB	5.88	--
R11/RBR	3.68	37%
R19/no RB	3.75	--
R19/RB	2.60	31%
R30/no RB	1.90	--
R30/RBR	1.54	19%

[1] Average ambient conditions during these hours were:

Ambient Temperature = 92°F
Solar Radiation = 179 Btu/hr-ft^2
Wind Speed = 4.9 mi/h

Table 9: Summer Results - Roof Temperatures[1]

Configuration	Temperature
R11/no RBR	155°F
R11/RBR	159°F
R19/no RBR	153°F
R19/RBR	155°F
R30/no RBR	154°F
R30/RBR	156°F

[1] These roof temperatures were determined from test periods when ambient temperatures and solar radiation values were equal to or greater than 88°F and 200 Btu/hr-ft^2 respectively. The actual average weather conditions during these hours were:

Ambient Temperature = 92°F
Solar Radiation = 247 Btu/hr-ft^2
Wind Speed = 5 mi/h

Table 10: Summer Results - Average Ceiling Heat Fluxes With Low-Emissivity Paint

Config.	Heat Flux (80°-85°F)	Heat Flux (85°-90°F)	% Saving (vs Same R-Value no RB Paint)	
			(80°-85°F)	(85°-90°F
R11 Only	4.34	5.02	--	--
R11/RB Paint	3.81	4.73	12%	6%
R19 Only	2.08	2.31	--	--
R19/RB Paint	2.02	2.22	3%	4%
R30 Only	0.96	1.45	--	--
R30/RB Paint	1.00	1.53	-4%	-6%

Table 11: Summer Results - Average Ceiling Heat Fluxes for Miscellaneous Configurations

Config.	Heat Flux (80°-85°F)	Heat Flux (85°-90°F)	% Saving (vs Same R-Value no RB Paint)	
			(80°-85°F)	(85°-90°F
1	2.08	2.31	--	--
2	1.26	1.35	39%	42%
3	2.05	2.23	1%	3%
4	2.17	2.38	-4%	-3%

Configuration:

1: R19 Only
2: R19/RB on Top/With Dust
3: R19/RB on Top/Single Sided/Shiny Side Down
4: R19/Black Plastic on Top of Insulation

Table 12: Winter Results - Average Ceiling Heat Fluxes for All Hours[1]

Configuration	Heat Flux (Btu/hr-ft^2)	% Saving (vs Same R-value, no RB)
R11/no RB	-2.42	-
R11/RBR	-2.28	6%
R11/RBT	-2.02	17%
R19/no RB	-1.49	-
R19/RBR	-1.56	-5%
R19/RBT	-1.41	5%
R30/no RB	-0.96	-
R30/RBR	-0.90	6%
R30/RBT	-0.82	15%

[1] Average ambient conditions during these hours were:

Ambient Temperature = 40.2°F
Solar Radiation = 31.1 Btu/hr-ft^2
Wind Speed = 1.9 mi/h

Table 13: Winter Results - Average Ceiling Heat Fluxes for Night Hours (7 pm to 7 am)[1]

Configuration	Heat Flux (Btu/hr-ft^2)	% Saving (vs Same R-value, no RB)
R11/no RB	-3.04	-
R11/RBR	-2.66	13%
R11/RBT	-2.38	22%
R19/no RB	-1.64	-
R19/RBR	-1.64	0%
R19/RBT	-1.39	15%
R30/no RB	-1.01	-
R30/RBR	-0.86	15%
R30/RBT	-0.76	25%

[1] Average ambient conditions during these hours were:

Ambient Temperature = 37.7°F
Solar Radiation = 0 Btu/hr-ft^2
Wind Speed = 1.5 mi/h

Table 14: Winter Results - Average Ceiling Heat Fluxes for Day Hours (11 am to 4 pm)[1]

Configuration	Heat Flux (Btu/hr-ft^2)	% Saving (vs Same R-value, no RB)
R11/no RB	-0.99	--
R11/RBR	-1.44	-45%
R11/RBT	-1.25	-26%
R19/no RB	-0.98	--
R19/RBR	-1.27	-30%
R19/RBT	-1.20	-22%
R30/no RB	-0.90	--
R30/RBR	-1.12	-24%
R30/RBT	-1.03	-14%

[1] Average ambient conditions during these hours were:

Ambient Temperature = 44.5°F
Solar Radiation = 102.4 Btu/hr-ft^2
Wind Speed = 2.5 mi/h

Table 15: Winter Results - Average Ceiling Heat Fluxes for 15°F-25°F Temperature Range

Configuration	Heat Flux (Btu/hr-ft^2)	% Saving (vs Same R-value, no RB)
R11/no RB	-4.17	--
R11/RBR	-3.62	13%
R11/RBT	-3.27	22%
R19/no RB	-2.42	--
R19/RBR	-2.36	2%
R19/RBT	-2.07	14%
R30/no RB	-1.07	--
R30/RBR	-1.17	-9%
R30/RBT	-1.03	4%

[1] Average ambient conditions during these hours were:

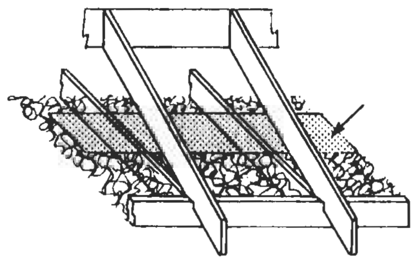
Ambient Temperature = 22.7°F
Solar Radiation = 2.7 Btu/hr-ft^2
Wind Speed = 0.8 mi/h

Table 16: Winter Results -
Average Ceiling Heat Fluxes
for 25°F-35°F[1] Temperature Range

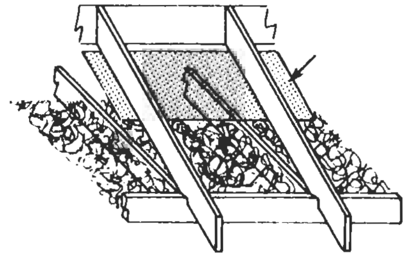
Configuration	Heat Flux (Btu/hr-ft^2)	% Saving (vs Same R-value, no RB)
R11/no RB	-3.42	-
R11/RBR	-3.06	11%
R11/RBT	-2.72	20%
R19/no RB	-2.16	-
R19/RBR	-1.98	8%
R19/RBT	-1.79	17%
R30/no RB	-0.98	-
R30/RBR	-0.90	8%
R30/RBT	-0.85	13%

[1] Average ambient conditions during these hours were:

Ambient Temperature = 30.9°F
Solar Radiation = 21.9 Btu/hr-ft^2
Wind Speed = 1.7 mi/h



Radiant Barrier Located on Top of Ceiling Insulation



Radiant Barrier Located Underneath Rafters

Figure 2. Radiant Barrier Locations

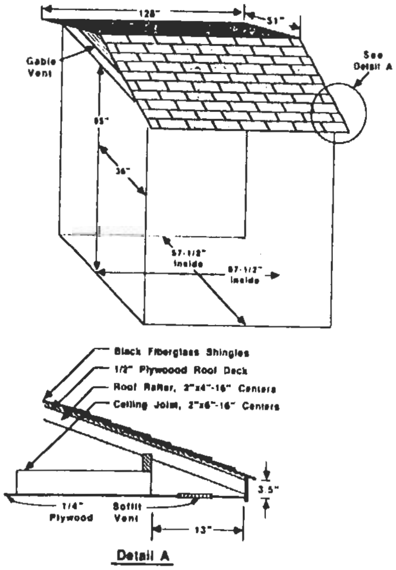


Figure 1. Radiant Barrier Test Cell

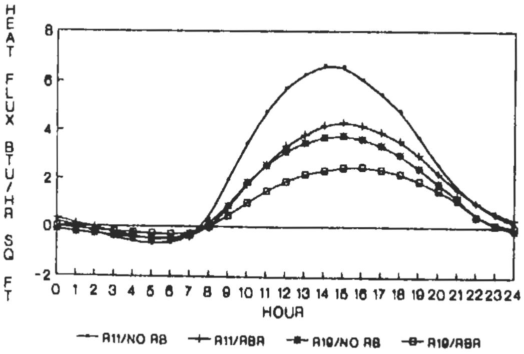


FIGURE 3. AVERAGE SUMMER 86 HEAT FLUX
R11 AND R19 INSULATION

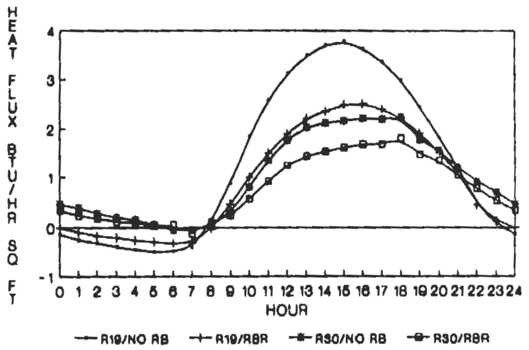


FIGURE 4. AVERAGE SUMMER 86 HEAT FLUX
R19 AND R30 INSULATION

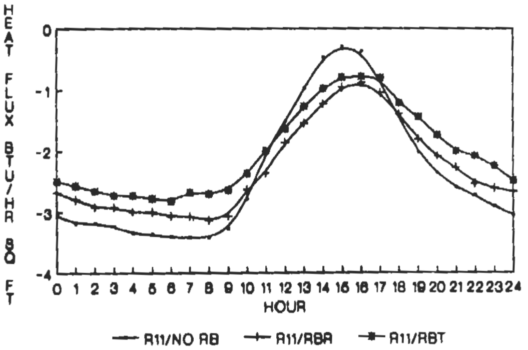


FIGURE 5. AVERAGE WINTER 86/87 HEAT FLUX
R11 INSULATION

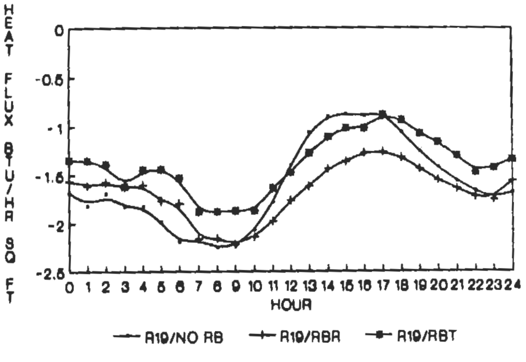


FIGURE 6. AVERAGE WINTER 86/87 HEAT FLU
R19 INSULATION

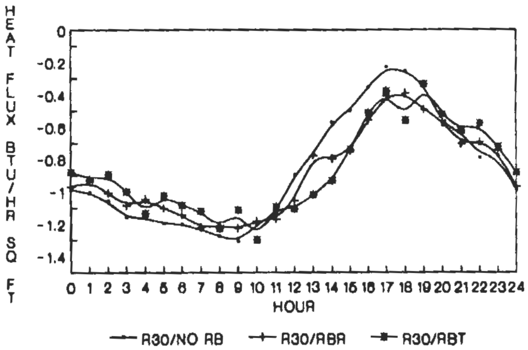


FIGURE 7. AVERAGE WINTER 86/87 HEAT FLUX
R30 INSULATION

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