PERFORMANCE TESTING OF RADIANT BARRIERS

JAMES A. HALL
TENNESSEE VALLEY AUTHORITY
Chattanooga, Tennessee

ABSTRACT

TVA has conducted a study to determine the effects of radiant barriers (RB) (i.e., a material with a low emissivity surface facing an air space), when used with fiberglass, on attic heat transfer during summer and winter. This study employed five small test cells exposed to ambient conditions and having attics with gable and soffit vents. Three different RB configurations were tested and compared to the non-RB configuration. Heat flux transducers determined the heat transfer between the attic and conditioned space.

The results showed that all RB configurations significantly reduced heat gain through the ceiling during the summer. Reductions in heat gain during daylight and peak electric load hours were especially attractive. Roof temperatures for the RB configurations were only slightly higher than for the non-RB case.

Heat transfer reductions for the RB configurations in the winter were smaller than those for the summer but were still significant in many, but not all, situations. Savings during night and peak electric load hours were especially attractive.

INTRODUCTION

The current approach to reducing residential attic heat gain in the summer and heat loss in the winter is to use fibrous insulation (e.g., fiberglass, cellulose, rock wool) of various thicknesses in the attic. This approach certainly reduces heat transfer through the attic; however, pioneering work at the Florida Solar Energy Center (1) showed that thermal radiation from the roof deck to the fibrous insulation, not convection or conduction, is the primary mode of heat transfer in attics in the summer and that a radiant barrier could significantly reduce the total attic heat transfer. A radiant barrier is defined here as a thin, sheet-like material with a surface of low emissivity or high reflectivity facing an air space.

Heat transfer through a typical residential attic is a relatively complicated series of phenomena. In the summer, high ambient temperatures and solar radiation combine to produce an extremely high roof temperature. On extremely hot summer days, this temperature can reach 170°F in the TVA region. Even on more typical summer days, when the ambient temperature is between 80 F and 90 F, the roof temperature can reach 150°F. Heat transfer then occurs by conduction through the roofing material resulting in a high temperature on the attic side of the roof decking.

At this point, two processes occur. First, heat is transferred down through the attic air by conduction (not convection, since convection involves upward motion of air because of buoyancy). Since the thermal conductivity of air is quite low, this process does not occur at a rapid rate. The second process, thermal radiation from the attic ceiling to the top of the fibrous isulation, accounts for much of the total attic heat transfer. This thermal radiation, which occurs in the far-infrared spectrum (4 to 40 microns), significantly raises the temperature of the top of the fibrous insulation and causes heat transfer through the insulation and into the conditioned space. Previous research (1, 2) has shown that the top of the insulation is heated to such a degree by thermal radiation from the roof that it is at a higher temperature than the attic air and actually heats the attic air.

The heat transfer during the winter begins with the warm ceiling of the conditioned space heating the bottom of the fibrous insulation. Heat is transferred through the insulation, and the top of the insulation loses heat by two processes. First, heat is transferred to and through the attic air by convection; second, heat is transferred to the cold roof deck (which could be slightly below ambient temperature because of radiation heat loss to the night sky) by thermal radiation. Unlike the summer situation, the non-thermal radiation component (i.e., convection) of the total heat transfer is significant, which makes the thermal radiation a smaller percentage of the total heat transfer. Therefore, a radiant barrier could be less beneficial in the winter than in the summer.

PROJECT DESCRIPTION

OBJECTIVES

The overall objectives of this project were to:

- Confirm the significant summer attic heat transfer savings of RBs for the TVA region climate.
- Study the effects of RBs on attic heat transfer in the winter.
- Assess three RB locations (configurations or cases) (see Figure 1):
  - RB placed directly on top of the fibrous insulation (hereafter called RB on top).

- RB attached to the underside of the rafters (hereafter called RB on rafters).
- RB attached directly to the underside of the roof decking (hereafter called RB on roof deck).

o Assess the effects of RBs on summer roof temperatures.

TEST METHODOLOGY

A testing approach was desired that would yield statistically and technically valid results. In any field test, two major sources of potential measurement error are differences in the test structures (if the configurations are tested in different test structures at the same time) and differences in the test periods weather (if the configurations are tested in the same test structure at different times).

A test plan called a Latin Square was chosen to resolve the above concerns (3). In the Latin Square test sequence used, each of the four configurations was tested twice in each of the five test cells, with one duplication in each phase. Since each configuration was tested in each test cell and in each time phase (i.e., each "weather" phase), the differences in cells and phases can be "cancelled out" in the statistical analysis. Summer testing began on June 4, 1985 and ended on September 20, 1985. Winter testing began on December 17, 1985 and ended on March 25, 1986. Figure 2 shows the test schedule for the summer and winter testing. The cell calibration phase, phase 5, was used merely to assist in identifying differences in the test cells.

TEST EQUIPMENT

Test Cells . Five small structures or test cells with exterior dimensions of 8 feet by 6.2 feet and 8.9 feet high (to the ceiling) and exposed to ambient conditions were used in this test. The cells had an interior or conditioned volume of 273 ft^3 and each cell had an attic covered by typical black fiberglass shingles. The attic dimensions were 8.3 feet by 5.8 feet and 2 feet high (to the roof peak). The walls and floors of the cells had R30 insulation. This high value was selected so that heat transferred through the attic would dominate the cells' heating and cooling loads. The cells had no windows and the doors were thoroughly sealed to prevent infiltration. The roofs were hinged along the peak so that one side of the roofs could be opened to allow easy access to the attics. The heating and cooling loads per cell were both estimated to be 1,000 Btu per hour at Chattanooga design conditions (13^oF for heating and 94^oF for cooling).

Attic ventilation in each cell was provided by two gable and four soffit vents. The net free area of the gable and soffit vents were approximately 0.71 and 1.03 square feet, respectively, for a total ventilation area of 1.74. The minimum gable and soffit vent area for each of the test cells, as required by the Department of Housing and Urban Development and Federal Housing Administration, would be only about 0.32 square foot. Therefore, the test cells probably had ventilation rates higher than normal. This probably reduced summer heat fluxes by lowering the attic air temperature. However, winter heat fluxes may have been higher than with normal ventilation since the attic air temperature may have been reduced by the excess ventilation. The exact effects of high ventilation rates are unknown.

Heating and Cooling Systems . Small, 1 kW forced-air electric heaters were used to heat the cells during winter. These heaters were connected to thermostats installed in the cells that maintained interior temperatures of 75^oF (± 2^oF).

Space requirements, small cooling loads, and the desire for precise measurement of the cooling load precluded using conventional air conditioners. Instead, a cooling water recirculation system was installed. Two small water coolers produced cool water at approximately 55^oF which was stored in three 82 gallon storage tanks. Cool water from these tanks was continuously routed to each of the cells in parallel runs of piping. When a thermostat in a cell called for cooling, a diverting valve at the cell rerouted the flow of cool water to a fan heat exchange coil located in that cell. When the cooling needs of a cell were satisfied, the diverting valve closed, stopping the flow of water to the fan coil. This system maintained interior summer temperatures of 65^o (± 4^oF). This cooler-than-normal inside temperature was chosen to increase the relatively small attic heat fluxes to make it easier to detect differences among the various configurations.

Heat Flux Transducers . The heat transfer rates through the attics were measured with heat flux transducers made by Hycal, Inc. Before installation, the heat flux transducers were calibrated (with an uncertainty of ± 2.25 percent) by Dynatech R/D Corporation using heat fluxes in the 1 to 2 Btu/hr-ft^2 range.

During summer phases 1 through 5, five heat flux transducers were installed on the ceiling cell side. Ceiling area beneath joists was avoided. Because of higher than expected air velocities (from the fan coils) across the transducers and a non-integrating data logger (discussed in the following section), the heat flux values recorded every 15 minutes ranged from higher-than expected positive values to much lower-than expected negative values.

When the fan coil began cooling the cell (i.e., when cool water is being circulated through the fan coil), cool air circulated across the bottom of the heat flux sensors causing abnormally high positive heat flux readings (a positive heat flux is heat flow downward or into the cell), since the ceiling with its higher heat capacity was still at the high end of the thermostat deadband. When the fan coil completed its cooling cycle, cool water stopped circulating through the coil but the fan continued to operate. Almost immediately much warmer air began to circulate across the heat flux sensors causing very large negative heat fluxes since the ceiling with its large heat capacity was still at the low end of the thermostat deadband. This problem only occurred when the cooling system cycled on and off and, accordingly, data collected during such periods was not included in our data analysis. The cycling periods turned out to be a small percentage of the total test period, and most of the data was deemed acceptable.

To resolve this problem, some of the heat flux transducers were moved from the cell interior side to the attic-side of the ceiling after phase 5 of the summer test. The sensors on the attic side did not exhibit this problem. During the winter, all five heat flux sensors were placed on the attic-side of the ceiling.

Data Collection System and Thermocouples . A Fluke 2240B data logger was used to collect data. Every 15 minutes the system recorded the instantaneous values of all 170 data points. Data was transferred from the Fluke to a magnetic tape and then to our mainframe computer for analysis. A data collection system that continuously recorded values and gave a 15 minute "integrated" value was preferred but was not available. Future RB testing will be done with such an "integrating" data logger. Type T thermocouples, with limits of error of ± 1.4°F, were used.

RB and Fibrous Insulation . For the RB on top of the insulation and on the rafters, a double-sided RB with 40-pound Kraft Paper backing was used. For the RB attached to the underside of the roof deck, a single-sided, fiber strand reinforced RB with Kraft Paper backing was used. The cost for both of these products was approximately five cents per square foot.

Conventional R19 fiberglass batts (six inches thick) were used in all the attics. The thicknesses of the batts were measured after testing was completed. Some compression of the insulation occurred during the year-long test due to the many configuration changes. However, the average compression over the entire test was only about 0.4 inch.

RESULTS

SUMMER RESULTS

Latin Square Analysis for All Hours . Despite some of the cell-side heat flux data being deleted (as discussed previously), this was still the best data set to use since it covered all phases and was therefore a larger data set, whereas the attic-side readings were taken only during the last half of the summer. A brief breakdown of the weather conditions during this test (summer of 1985) is given in Table 1.

In all the following tables and figures, the heat flux units are Btu/hr-ft^2. Also, the percent savings given in the tables are the savings relative to the non-RB case. The significance column in all the tables shows whether there are statistically significant differences at the 95 percent confidence level. Different letters for two configurations show that there are statistically significant differences between these configurations.

The results of a Latin Square analysis using all the summer data (ie., all hours of all days) are shown in Table 2. The three RB configurations are all statistically different (or better) than the non-RB configuration. In addition, the differences between the RB on top and the other two RB configurations are statistically significant. The percent savings, especially for the RB on top, are quite large.

Latin Square Analysis for Daylight Hours . The results of a Latin Square analysis for only the daylight hours during the summer (8 a.m. to 8 p.m.) are shown in Table 3. As expected because of warmer conditions, the percent savings are higher than for all hours (see Table 2). As in the all hours case, the differences between the non-RB case and the three RB configurations are statistically significant as are the differences between the RB on top and the other RB configurations. The RB on top is again the best performer.

Latin Square Analysis for Night Hours . Table 4 shows the subject results for all data during hours from 8 p.m. to 8 a.m. The RB on rafters and roof deck cases are worse than the non-RB case. This could result from the RBs preventing the radiation of heat away from the hot fibrous insulation at night. Surprisingly, the RB on top has a lower average heat flux than the non-RB case. As the significance column shows, the difference between the RB on top and the non-RB case is statistically significant.

Latin Square Analysis by Temperature Range . Tables 5, 6, and 7 show the heat fluxes for each configuration for various ambient temperature ranges. The significance column again shows whether the differences between the configurations are statistically significant. It is apparent from these tables that the percent savings for the RBs are quite high (and the differences in heat flux are statistically significant) for all three RB configurations for the top four temperature ranges or down to the 75°F to 80°F range. Since the summer cell temperatures were 65°F, this is a temperature difference of 10°F and above. For indoor temperatures typically encountered, say 75°F, the RBs would appear to provide significant savings at ambient temperatures above 85°F.

The RB on top configuration may be superior to the RB on rafters configuration at the higher temperature conditions because the rafter configuration was unvented above the RB. Air trapped above the RB would get quite hot and, through conduction heat transfer downward, could increase the overall attic air temperatures. This could lead to higher ceiling heat fluxes.

Also, configurations 2 and 3, which are doubled-sided RBs, could be superior to configuration 4 because it is only a single-sided RB. As in the analysis for night hours (see Table 4), the RB on top configuration surprisingly shows significant savings even at the lower temperature ranges. This may occur due to the RB functioning as a protective barrier separating the sometimes warm or hot attic air from the fibrous insulation.

The significance lettering for the 85°F to 90°F range can be explained as follows: the difference between configurations 4 and 3 is not statistically significant (both have the letter B) and the difference between configurations 3 and 2 is not statistically significant (both have the letter C). However, the difference between configurations 4 and 2 are statistically significant; (they have the letter B and C, respectively.)

Summer Roof Temperatures . One of the key concerns about RBs is whether they cause higher roof temperatures than normal which could result in shorter roof life. Table 8 shows the roof temperatures for each of the configurations under various conditions. The first breakdown uses only daytime temperature data (8 a.m. to 8 p.m.). The daytime roof temperature differences between the lower temperature configurations (non-RB and RB on top) and the higher temperature configurations (RB on rafters and RB on roof deck) are statistically significant. Despite these statistically significant differences, the RB on rafters and RB on roof deck configurations have only 4°F and 5°F higher overall roof temperatures.

The second breakdown only uses data during very high temperature, high solar insolation conditions. The temperature differences between the last two cases (RB on rafters and RB on roof deck) and the first two cases (non-RB and RB on top) are statistically significant. Even so, the differences are only 6°F and 8°F, respectively.

The last breakdown gives the maximum roof temperature recorded for each configuration. The RB configurations indeed have higher temperatures, but only by 3°F, 8°F, and 5°F for the RB on top, the rafters, and the roof deck configurations, respectively. The RB on rafters configuration would probably have had lower roof temperatures if the air above the RB and under the roof deck had been ventilated. It is likely that this RB configuration (RB on rafters with no ventilation above the RB) is the worst case in terms of high roof temperatures. In actual installations, the air space above the RB on rafters can be easily vented by leaving a small open space at the roof peak so that hot air can be removed by a ridge vent or gable vents.

Heat Flux versus Time-of-Day . Figures 3, 4, and 5 are graphs of the average summer heat flux (for all phases) versus time of day for each RB case versus the non-RB case. These graphs show that from 10 a.m. to 8 p.m. the RBs substantially reduce heat transfer through the attic. The RB on rafters and roof deck cases show either zero or slightly negative savings at night, while the RB on top case does show at least some saving over all 24 hours of the day.

Figure 6 shows the heat flux versus time of day for the day (August 19, 1985) during which TVA's summer peak occurred. TVA's summer peaks last from 10 a.m. to 10 p.m., with the very highest loads occurring around 4 p.m. to 6 p.m. This graph shows that the RB on top significantly reduces attic heat flux during almost all of these hours.

Insulation Temperatures . Temperatures at one-inch intervals within the fibrous insulation were measured with thermocouples (no radiation shields were used) to determine the effects of the RBs on these temperatures. Figures 7 and 8 show one inch interval insulation temperatures versus time of day for August 19, 1985 for the non-RB and the RB on top case. This day had a maximum temperature of 91°F. These graphs clearly show that the RB dramatically reduces insulation temperatures. For this day, the RB reduced the temperature at the top of the insulation by about 20°F, from 112°F to 92°F.

WINTER RESULTS

As in the summer test, the winter test consisted of nine phases (see Figure 2), with the first four phases being duplicated after a cell characterization phase (phase 5). Unfortunately, the weather during the second half of the winter, especially during phases 7 through 9, was extremely mild. For example, the average ambient temperature during the first four phases was 34°F, while for phases 1-4 and 6-9, it was a much higher 42°F. Since the winter heat flux saving for RBs for mild conditions are quite small and the weather during phases 6-9 was quite mild, the overall winter savings would be significantly reduced if the second half of the winter is included in the overall Latin Square. Therefore, to make the results reflect RB performance during cold weather rather than mild weather, the overall Latin Square analyses, Tables 10, 11, and 12, are derived from phases 1 through 4 only. The analyses by temperature range do not have this problem and, therefore, include data from phases 1-4 and 6-9. A brief breakdown of the weather conditions during this test (winter of 1985/1986) is given in Table 9.

Latin Square Analysis for All Hours . Table 10 shows the heat flux Latin Square analysis for all hours. The difference between the RB on top and the non-RB case is statistically significant. The other two RB cases do not show statistically significant differences from the non-RB case.

However, the difference between the RB on rafters and the non-RB case, though not statistically significant at the 95 percent confidence level, is statistically significant at the 90 percent confidence level.

Latin Square Analysis for Daylight Hours . Table 11 shows that the RB on roof deck and RB on rafters have a negative savings during day hours (8 a.m. to 7 p.m.), as might be expected, since heat gain through the attic is reduced, especially during milder, sunny winter days. Statistically, however, there are no significant differences among any of the configurations. Surprisingly, the RB on top does show an 8 percent saving compared to the non-RB case.

Latin Square Analysis for Night Hours . Table 12 shows that the differences between all of the RB cases and the non-RB case are statistically significant during night hours (7 p.m. to 8 a.m.) when heating loads are highest. The percent savings, ranging from 9 to 19 percent, are sizable.

Latin Square Analysis by Temperature Range . Tables 13 and 14 give the heat fluxes for each configuration for 15°F temperature ranges. For the 50°F to 65°F range, there are no statistically significant differences among any of the configurations. In the 35°F to 50°F temperature range, the RB on top does yield a sizable percent saving and the differences between it and the other cases are statistically significant.

In the 20°F to 35°F range, the differences between the RB on top case and all the other cases are statistically significant. Also, the RB on rafters and RB on the underside of the roof deck, while not showing statistically significant differences from the non-RB case, do show some percentage savings. In fact, the RB on the roof deck does show a statistically significant difference from the non-RB case at the 90 percent confidence level, though not at the 95 percent confidence level.

The percent savings for the RBs in the 5°F to 20°F range are quite high and range from 8 percent to 23 percent. However, because of the small amount of data recorded in this temperature range, only the RB on top shows a statistically significant difference from the non-RB case. However, the RB on rafters does show a statistically significant difference from the non-RB case at the 90 percent confidence level. If more cold weather data had been recorded, it is quite likely that all three RB cases would have shown statistically significant differences at the 95 percent confidence level.

Heat Flux versus Time of Day . Figures 9, 10, and 11 are graphs of the average winter heat flux for phases 1-4 versus time-of-day for each RB case versus the non-RB case. Each RB case performs better (i.e., less heat flux or loss) than the non-RB case during the night hours (7 p.m. to 9 a.m.), with the RB on top being the best performer.

During the day hours of about 12 noon to 6 p.m., the RB on rafters and roof deck cases are worse than the non-RB case while the RB on top is only slightly worse.

Figure 12 shows the average heat fluxes versus time-of-day for four of the coldest winter days (one from each of the first four phases) for the RB on top versus the non-RB case. TVA's winter peaks normally occur from 7 a.m. to 9 a.m. and from 5 p.m. to 7 p.m. This graph shows that the RB on top did reduce attic heat flux during TVA's peak periods.

Insulation Temperatures . As in the summer, insulation temperatures were monitored to determine the effects of the RBs on the insulation temperatures. Figures 13 and 14 show the insulation temperatures for the non-RB and RB on top case for the same four cold winter days used in Figure 12. These graphs show a dramatic increase in insulation temperatures for the RB on top. The minimum temperature at the top of the insulation was 15°F higher (30°F compared to 45°F) for the RB on top versus the non-RB case.

CONCLUSIONS

All the RB configurations yielded sizable percent savings (ranging from 16 to 40 percent) and statistically significant reductions in summer attic heat transfer compared to the non-RB case. Also, as the ambient temperature increases, the savings also increase.

The RB on top was the best summer performer. It consistently showed heat flux reductions compared to the non-RB case of about 40 percent for almost all ambient temperatures and even showed savings (20 to 30 percent) during mild temperature and night summer conditions when the other RB configurations actually had negative savings. If the RB on rafters had been ventilated above the RB and below the roof deck, it is possible that its performance would have been better. Nevertheless, above 80°F the RB on rafters yielded heat flux reductions compared to the base case of about 40 percent.

The RB configurations provide statistically significant reductions in winter attic heat fluxes in many, but not all, situations. The percent savings during night hours and during below 35°F conditions, when heating loads are highest, are usually sizable (from 6 to 23 percent) and the differences between the RB configurations and the non-RB case are often statistically significant during these conditions. Again, the RB on top is the best performer.

The RB on top did not show significantly higher summer roof temperatures compared to the non-RB case. In fact, in the worst case, (the maximum observed roof temperatures), the RB on top roof temperature was only 3°F higher than the non-RB case. The higher roof temperatures of the other RB configurations (RB on the roof deck and on the rafters) compared to the non-RB case were statistically significant. Nevertheless, these differences were not excessive and in the worst case (again, the maximum observed roof temperatures) were only 8°F and 5°F, respectively.

All the RB configurations reduced attic heat transfer during TVA's peak load periods, in both summer and winter.

REFERENCES

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

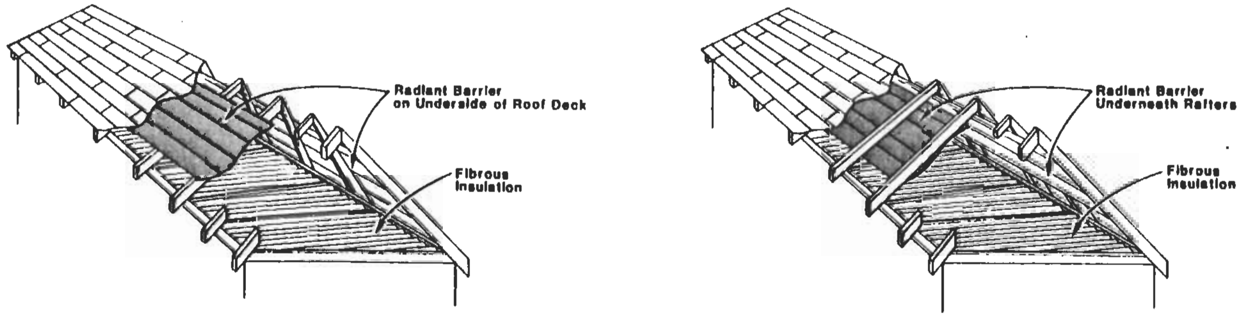
2. Roux, J. A. and J. W. Rish, "Conservation of Radiative Heat Transfer Through Fibrous Insulation." University of Mississippi, Sponsored by Tennessee Valley Authority, Contract TV-64115A, December 1985.

3. Davies, Owen L., "The Design and Analysis of Industrial Experiments, Hafner Publishing Company, New York, 1956.

LEGAL NOTICE

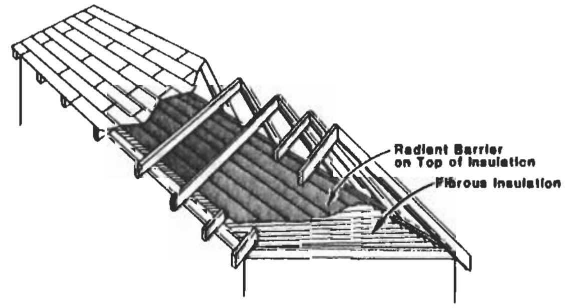
This report was prepared by the Tennessee Valley Authority (TVA) in furtherance of its statutory responsibilities. Neither TVA, the United States, nor any of their agents or employees: (1) make any warranty or representation, express or implied, as to the accuracy, completeness, usefulness, or reliability of any information, apparatus, product, method, or process discussed in this report; (2) assume any liability or responsibility for the use of, or for damages resulting from the use of, any information, apparatus, product, method, or process discussed in this report; or (3) represent that the use of any information, apparatus, product, method, or process discussed in this report would not infringe privately owned rights.

Reference herein to any specific commercial product, process, method, or service by trade name, trademark, manufacturer, or otherwise does not constitute or imply an endorsement or recommendation by TVA, the United States, or any of their agents or employees. The views and opinions of the author expressed herein do not necessarily state or reflect those of TVA.



Radiant Barrier Located on Underside of Roof Deck

Radiant Barrier Located Underneath Rafters



Radiant Barrier Located on Top of Ceiling Insulation

Figure 1. Radiant Barrier Locations or Configurations

Summer Test Schedule[a]

Phase[b]	1	2	3	4	5[c]	6	7	8	9
Test Cell B	4	2	3	1	1	4	2	3	1
Test Cell C	2	3	1	4	1	2	3	1	4
Test Cell D	3	1	4	2	1	3	1	4	2
Test Cell E	1	4	2	3	1	1	4	2	3
Test Cell F	2	4	1	4	1	2	3	1	4

1: Non-RB (fiberglass only)
2: Two-sided RB on top of fiberglass
3: Two-sided RB attached to underside of rafters
4: One-sided RB attached to underside of roof with reflective side down

[a] The winter schedule is exactly like the summer schedule
[b] Each phase lasted approximately 10 days, depending on the weather
[c] Cell calibration period

FIGURE 2. RADIANT BARRIER TEST SCHEDULE

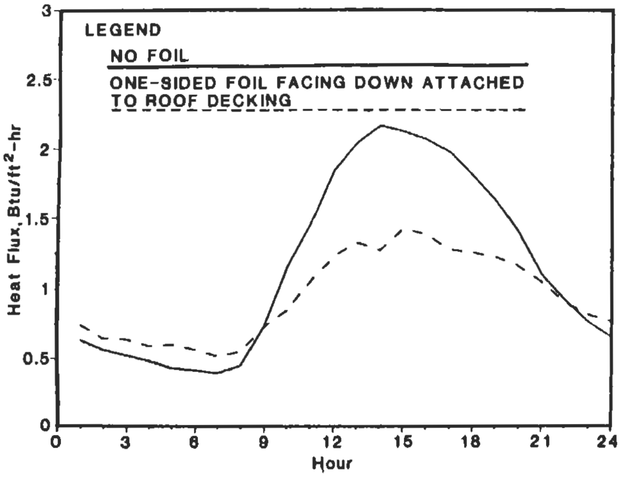


Figure 3. Average Summer Heat Flux, Phases 1-4 and 6-9

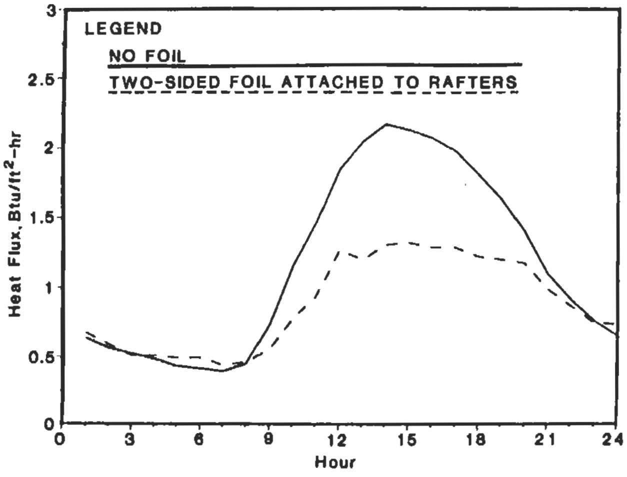


Figure 4. Average Summer Heat Flux, Phases 1-4 and 6-9

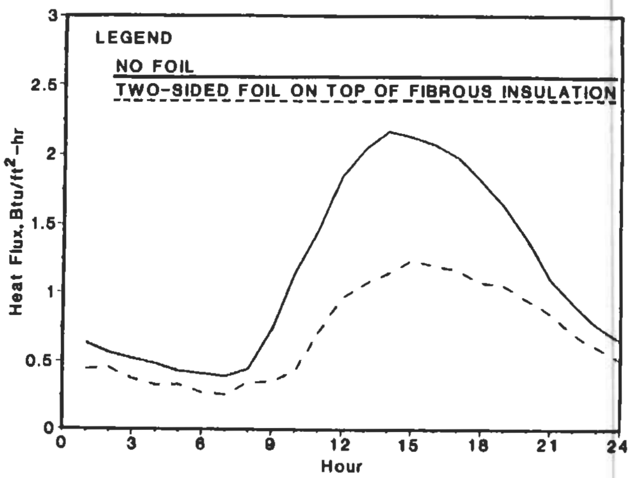


Figure 5. Average Summer Heat Flux, Phases 1-4 and 6-9

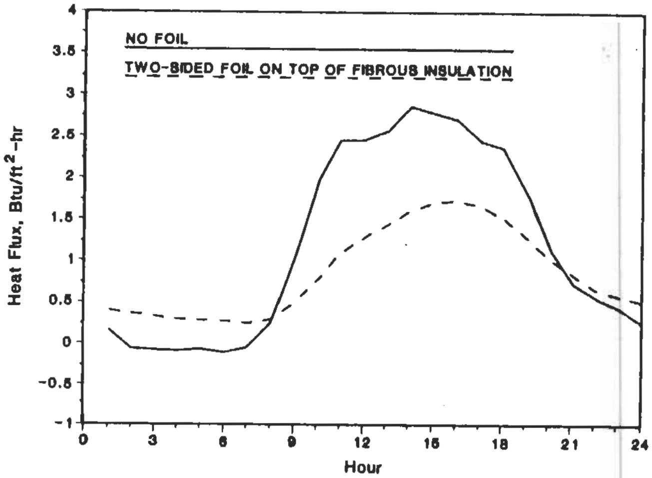


Figure 6. Heat Flux - August 19, 1985

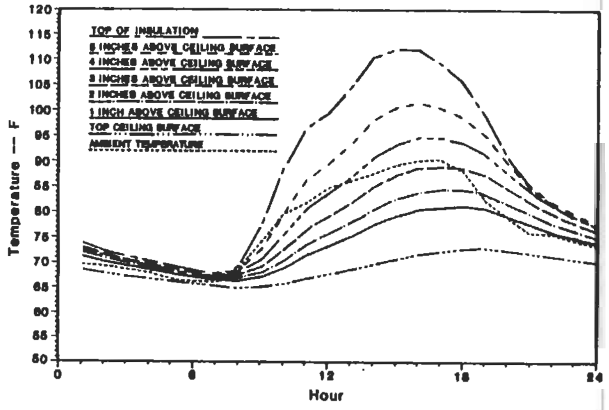


Figure 7. Insulation Temperature Profile - August 19, 1985 - R19 Fiberglass Only

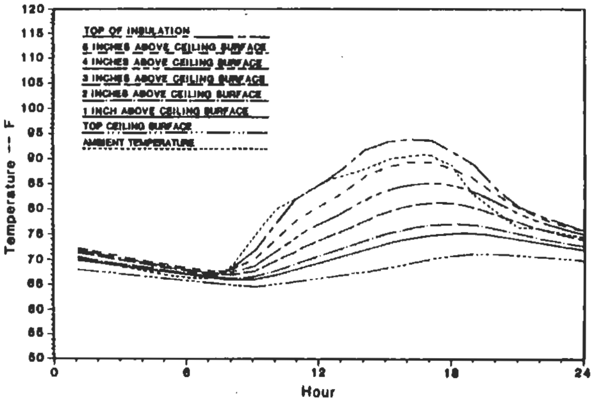


Figure 8. Insulation Temperature Profile - August 19, 1985 - R19 Fiberglass with 2-Sided Foil on Top

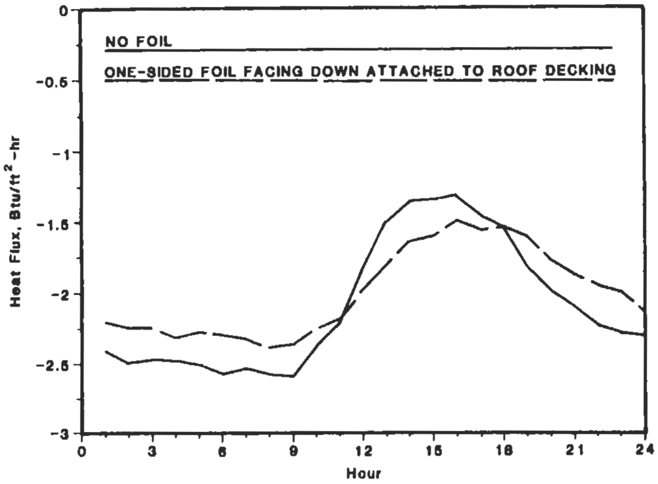


Figure 9. Average Winter Heat Flux, Phases 1-4

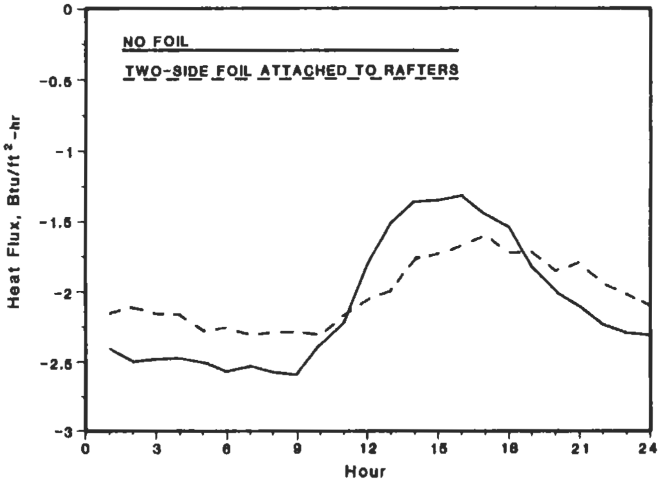


Figure 10. Average Winter Heat Flux, Phases 1-4

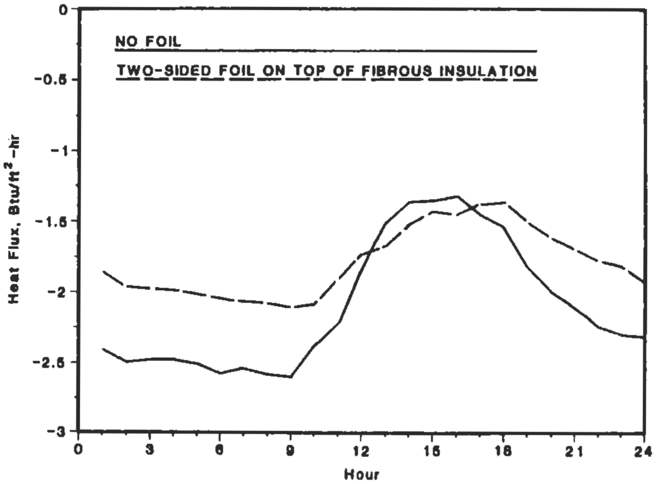


Figure 11. Average Winter Heat Flux, Phases 1-4

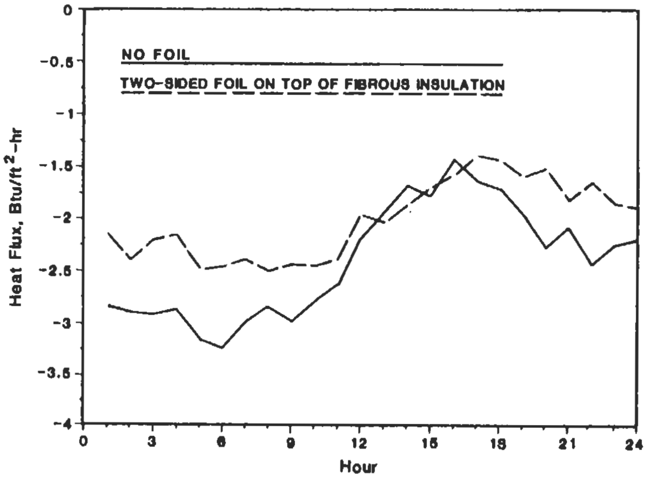


Figure 12. Average Heat Flux from 4 Cold Winter Days

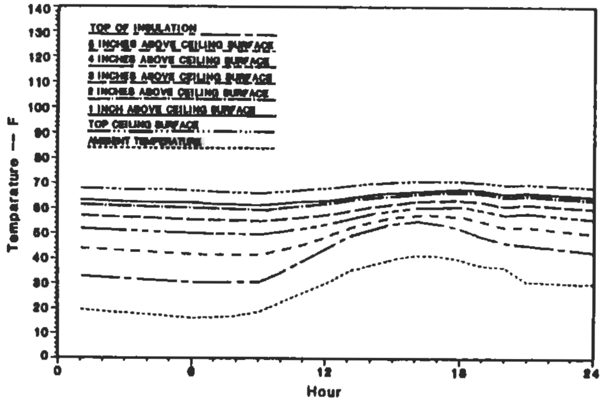


Figure 13. Average Insulation Temperature Profile from 4 Cold Winter Days, R19 Fiberglass Only

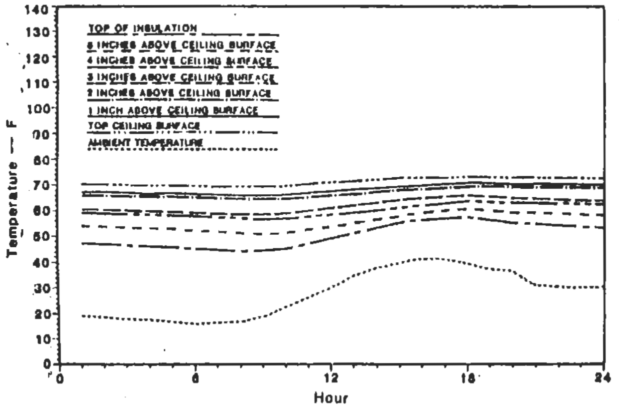


Figure 14. Average Insulation Temperature Profile from 4 Cold Winter Days, R19 Fiberglass with 2-Sided Foil on Top

TABLE 1

SUMMER WEATHER CONDITIONS

Average Daily Temperature = 74°F
Average Daily Maximum Temperature = 84°F
Average Daily Minimum Temperature = 67°F

Average Daily Solar Insolation = 1,240 Btu/ft^2-day
Average Wind Speed = 2.6 MPH

TABLE 2

SUMMER RESULTS

AVERAGE HEAT FLUXES FOR ALL HOURS

CONFIGURATION	HEAT FLUX (Btu/hr-ft^2)	% SAVING	SIGNIFICANCE [1]
NON-RB	1.19	--	A
RB ON ROOF DECK	1.00	16%	B
RB ON RAFTERS	0.91	23%	B
RB ON TOP	0.72	40%	C

TABLE 3

SUMMER RESULTS

AVERAGE HEAT FLUXES FOR DAYLIGHT HOURS

CONFIGURATION	HEAT FLUX	% SAVING	SIGNIFICANCE
NON-RB	1.65	--	A
RB ON ROOF DECK	1.24	25%	B
RB ON RAFTERS	1.11	33%	B
RB ON TOP	0.94	43%	C

TABLE 4

SUMMER RESULTS

AVERAGE HEAT FLUXES FOR NIGHT HOURS

CONFIGURATION	HEAT FLUX	% SAVING	SIGNIFICANCE
RB ON ROOF DECK	0.76	-12%	A
RB ON RAFTERS	0.70	- 3%	A
NON-RB	0.68	--	A
RB ON TOP	0.48	30%	B

TABLE 5

SUMMER RESULTS

SAVINGS BY TEMPERATURE RANGE

AMBIENT TEMP	CONFIGURATION	HEAT FLUX	% SAVING	SIGNIFICANCE
ABOVE 90°F	NON-RB (1)	2.49	--	A
	RB ON ROOF DECK (4)	1.67	31%	B
	RB ON RAFTERS (3)	1.40	40%	B
	RB ON TOP	1.36	44%	B
85°F to 90°F	1	2.28	--	A
	4	1.55	31%	B
	3	1.38	38%	B C
	2	1.28	42%	C

TABLE 6

SUMMER RESULTS

SAVINGS BY TEMPERATURE RANGE

AMBIENT TEMP	CONFIGURATION	HEAT FLUX	% SAVING	SIGNIFICANCE
80°F-85°F	1	2.05	--	A
	4	1.41	31%	B
	3	1.23	40%	B
	2	1.11	46%	B
75°F-80°F	1	1.47	--	A
	4	1.17	20%	B
	3	1.08	27%	B
	2	0.89	39%	C

---

[1] Different letters denote statistically significant differences at the 95 percent confidence level. The 95 percent confidence level also applies to all the following tables.

TABLE 7

SUMMER RESULTS

SAVINGS BY TEMPERATURE RANGE

AMBIENT TEMP	CONFIGURATION	HEAT FLUX	% SAVING	SIGNIFICANCE
70°F-75°F	1	0.94	--	A
	4	0.92	2%	A
	3	0.87	7%	A
	2	0.64	32%	B
BELOW 70°F	4	0.57	-19%	A
	3	0.54	-12%	A
	1	0.48	--	A B
	2	0.37	23%	B

TABLE 8

SUMMER RESULTS

ROOF TEMPERATURES

OVERALL ROOF TEMPERATURES - All Daylight Hours

Configuration	Temperature	Significance
NON-RB	112°F	A
RB ON TOP	113°F	A
RB ON ROOF DECK	116°F	B
RB ON RAFTERS	117°F	B

ROOF TEMPERATURES - SOLAR > 225, AMBT TEMP > 87

Configuration	Temperature	Significance
NON-RB	154°F	A
RB ON TOP	154°F	A
RB ON ROOF DECK	160°F	B
RB ON RAFTERS	162°F	B

MAXIMUM ROOF TEMPERATURES

Configuration	Temperature
NON-RB	170°F
RB ON TOP	173°F
RB ON ROOF DECK	175°F
RB ON RAFTERS	178°F

TABLE 9

WINTER WEATHER CONDITIONS

	Phase 1-4	Phases 1-4 and 6-9
Average Daily Temperature	34°F	42°F
Average Daily Maximum Temperature	44°F	52°F
Average Daily Minimum Temperature	24°F	32°F
Average Daily Solar Insolation	560 Btu/ft^2 day	790 Btu/ft^2 day
Average Wind Speed	3.2 MPH	3.8 MPH

TABLE 10

WINTER RESULTS

AVERAGE HEAT FLUXES FOR ALL HOURS

CONFIGURATION	HEAT FLUX	% SAVING	SIGNIFICANCE
NON-RB	-2.12	--	A
RB ON ROOF DECK	-2.04	4%	A
RB ON RAFTERS[1]	-1.94	8%	A B
RB ON TOP	-1.81	15%	B

[1] The difference between the RB on rafters and non-RB case is statistically significant at the 90 percent confidence level.

TABLE 11

WINTER RESULTS

AVERAGE HEAT FLUXES FOR DAY HOURS

CONFIGURATION	HEAT FLUX	% SAVING	SIGNIFICANCE
RB ON ROOF DECK	-1.92	-4%	A
RB ON RAFTERS	-1.88	-2%	A
NON-RB	-1.85	--	A
RB ON TOP	-1.71	8%	A

TABLE 12

WINTER RESULTS

AVERAGE HEAT FLUXES FOR NIGHT HOURS

CONFIGURATION	HEAT FLUX	% SAVING	SIGNIFICANCE
NON-RB	-2.36	--	A
RB ON ROOF DECK	-2.14	9%	B
RB ON RAFTERS	-2.00	15%	B C
RB ON TOP	-1.90	19%	C

TABLE 13

WINTER RESULTS

SAVINGS BY TEMPERATURE RANGE

AMBIENT TEMP	CONFIGURATION	HEAT FLUX	% SAVING	SIGNIFICANCE
50°F-65°F	RB ON TOP (2)	-1.10	3%	A
	NON-RB (1)	-1.13	--	A
	RB ON ROOF DECK (4)	-1.20	-6%	A
	RB ON RAFTERS (3)	-1.23	-9%	A
35°F-50°F	(2)	-1.53	11%	A
	(1)	-1.71	--	B
	(4)	-1.72	0%	B
	(3)	-1.72	0%	B

TABLE 14

WINTER RESULTS

SAVINGS BY TEMPERATURE RANGE

AMBIENT TEMP	CONFIGURATION	HEAT FLUX	% SAVING	SIGNIFICANCE
20°F-35°F	(2)	-2.00	15%	A
	(4)[†]	-2.18	8%	B
	(3)	-2.22	6%	B
	(1)	-2.36	--	B
5°F-20°F	(2)	-2.29	23%	A
	(3)[†]	-2.60	12%	A B
	(4)	-2.72	8%	A B
	(1)	-2.97	--	B

[†] Statistically significant difference compared to the non-RB case at the 90 percent confidence level.