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MEASURED EFFECTS OF DUST ON THE PERFORMANCE OF RADIANT BARRIERS INSTALLED ON TOP OF ATTIC INSULATION

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ABSTRACT

The rate of dust accumulation and the effect of this dust accumulation on a horizontal radiant barrier (HRB) are of special interest because the HRB may perform better in both summer and winter than a truss radiant barrier (TRB), is much easier to install for retrofits in existing homes, and requires less radiant barrier (RB) material than a TRB. However, an HRB has two important potential disadvantages—condensation during winter, which might cause structural damage, and dust accumulation, which could significantly degrade thermal performance. Results of a winter moisture field test were reported previously by the authors of this paper.

Dusted HRB performance was tested in small 48 ft² test cells in the summer of 1987. The dust loadings, resultant HRB emissivity (ϵ), and relative attic heat fluxes were:

Dust Loading	HRB	ϵ	% Reduction in Attic Heat Flux: June Tests	% Reduction in Attic Heat Flux: September Tests
0.00 mg/cm²	no	—	0	0
0.00 mg/cm²	yes	0.05	42	58 (11 a.m.-6 p.m.)
0.70 mg/cm²	yes	0.34	—	41 (11 a.m.-6 p.m.)
1.27 mg/cm²	yes	0.43	25 (all hrs)	—
1.27 mg/cm²	yes	0.43	26 (11 a.m.-6 p.m.)	—
2.54 mg/cm²	yes	0.51	19 (all hrs)	—
2.54 mg/cm²	yes	0.51	20 (11 a.m.-6 p.m.)	—

The above results indicated that dust accumulation may not be a prohibitive problem for HRB installations. However, the researchers believed further study of this subject was needed.

A national laboratory conducted tests on dusted HRBs at three research houses near Oak Ridge, Tennessee, during the summer of 1988. Two dust loadings were tested: 0.34 mg/cm² (ϵ = 0.125) and 0.74 mg/cm² (ϵ = 0.185). Results showed that the lighter dust loading increased total house cooling loads, compared to a clean HRB, by 2.3%. The heavier dust loading increased house cooling loads by 8.4%, again compared to a clean HRB. However, horizontal radiant barriers with these dust loadings still decreased house cooling loads by 7% when compared to the same house with no radiant barrier.

INTRODUCTION

The effect of dust on a horizontal radiant barrier (HRB) is of interest because an HRB may perform better in summer and winter than all other RB locations.[1-12] (It should be noted that more testing is needed to completely resolve this issue.) Also, an HRB is much easier to install and requires less RB material than roof-mounted configurations for retrofits in existing homes.

However, an HRB has two significant problems that could preclude it from being a viable option. The first is the potential for condensation on the underside of an HRB during winter, which could lead to serious attic moisture problems. This subject was addressed in testing during the winter of 1987-88 at three research houses.[6] The second problem is dust accumulation, which may degrade HRB thermal performance.

Tests have shown[9,13] that small amounts of dust significantly raise the emissivity of radiant barriers. The rate at which dust accumulates on an HRB is currently being investigated in Florida.[14] Testing done in the summer of 1986 showed that dust accumulation may not affect the performance of an HRB as much as the increases in emissivity would indicate. This result led to more detailed testing of the effect of dust on HRB performance.

Two major studies are described in this paper. The first was conducted in Chattanooga, Tennessee, during the summer of 1987. The second was conducted at three research houses near Oak Ridge, Tennessee, during the summer of 1988.

The following section summarizes past and current work relating to the HRB/dust issue. The next two sections describe the Chattanooga and Oak Ridge tests. The last section presents conclusions and recommendations.

BACKGROUND

The effect of dust on an HRB can be divided into three areas of concern: (1) the rate of dust accumulation in actual homes, (2) the effect of dust on RB emissivity, and (3) the effect of dust on actual RB performance. Each of these concerns is discussed in the following sections.

Rates of Dust Accumulation in Actual Homes

Two major independent field tests to determine the rate of dust accumulation in attics of actual homes are now under way.

Thirty homes in Tupelo, Mississippi, and 30 homes in Hopkinsville, Kentucky, were retrofitted with RBs in a two-year RB demonstration project. Approximately one-half of the retrofits in each city were HRBs. Small pieces of RB material with an initial emissivity of 0.05 were placed in boxes in each of the homes that had HRBs to allow periodic removal of an HRB sample and measurement of its emissivity. Eight months after installation, one box was removed from each attic of the HRB homes. The highest measured HRB emissivity was 0.10, with an average of about 0.07. It is planned to retrieve boxes and to measure emissivities two more times in these 60 retrofitted homes during this test.

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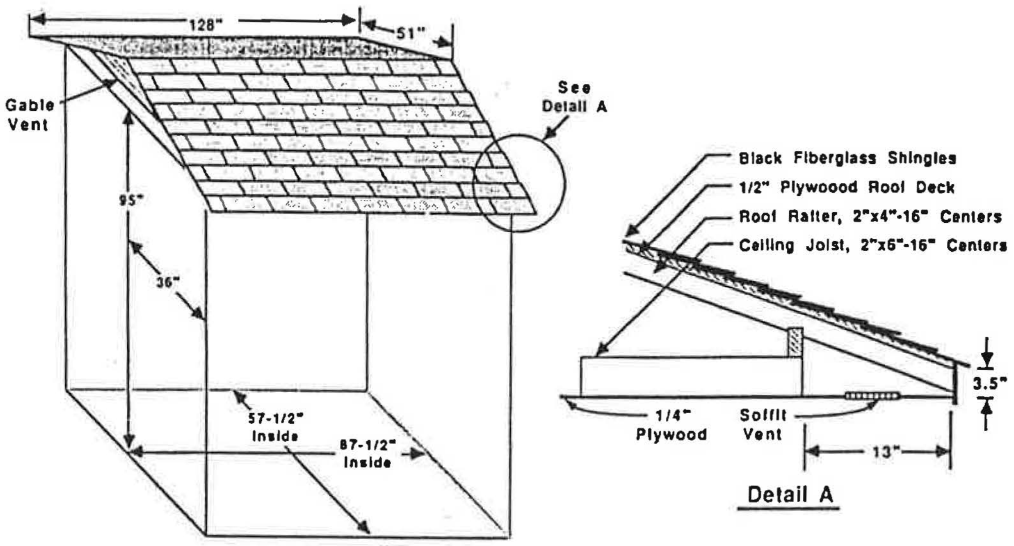

Figure 1 *Radiant barrier test cell*

In the other field test,[14] each attic of 11 homes was retrofitted with an HRB. Again, multiple small boxes containing an RB with an initial emissivity of 0.03 to 0.04 were placed in each of these homes. The boxes were retrieved on a logarithmic time schedule (i.e., more retrievals early in the test than later). After the emissivity was measured, the RB samples were studied with a microscope to determine the percent area covered by dust and then carefully weighed to determine the weight of accumulated dust. Average RB emissivities were also measured. Results after about six months showed HRB emissivities mostly between 0.05 and 0.10, with two samples showing higher emissivities (0.11 and 0.16).

Lotz[15] conducted testing in South Africa in the mid-1960s on HRB dust accumulation in five actual homes. Test results showed that the percent area likely to be covered by dust during one year was 28.6%. The average weight of dust accumulation was 0.69 mg/cm^2. Emissivities resulting from accumulated dust were not measured.

Yarbrough and Cook[13,16] recently collected HRB samples from eight houses in the Chicago area. The samples were carefully cut and transported to the laboratory for study with as little disruption as possible. The RBs had been installed for periods ranging from 39 to 52 months. The average RB emittance from the eight houses was 0.239 (the emissivity of clean RB was 0.03), with values ranging from 0.066 to 0.423. No correlation between emissivity and installed age for the narrow age span was noted.

Two homes in Chattanooga, Tennessee, have had HRBs for an extended period. In one case, the HRB had been installed for more than five years when the emissivity was measured at an average of 0.15. The HRB had been installed in the second house for about 1.5 years and had an average emissivity of 0.10. Initial emissivities were 0.03 to 0.04.

Effect of Dust on RB Emissivity

Testing by Yarbrough[13] in 1987 showed that small amounts of dust cause significant increases in RB emissivity. He measured the emissivities of 46 RB samples containing various amounts of dust taken from the crawl space of a Tennessee residence. Fairey et al.[14] developed the following curve fit for Yarbrough's data:

$$\text{Emissivity } (\epsilon) = 0.02 + 0.829\,[1 - \exp(-0.688 \cdot \text{dust})],$$

where "dust" is the dust loading in mg/cm^2.

Yarbrough and Cook thoroughly investigated the effect of dust on the emissivity of RBs in work conducted in 1988.[16] Three types of dust were used: interior (house) dust, attic dust (vacuumed from attic locations), and Arizona test dust (typically used for air filter testing). The interior dust was applied on an RB by shaking it through a fine sieve. The attic and Arizona dusts were applied by suspending particles in a large chamber with high-velocity air and then allowing the dust to fall freely to the RB surface. Results showed that the three varieties of dust gave different emissivities for the same loadings, with interior dust having the smallest impact.

Effect of Dust on Actual RB Performance

Prior to work discussed in this report, only two efforts had been made to measure actual HRB performance degradation from dust accumulation. The first was in the aforementioned work of Lotz[15] in a roof/ceiling scale model. Degradations in HRB heat flows were about 30% and 60%, respectively, for dust loadings of 0.54 and 1.61 mg/cm^2. The second effort was conducted in a brief test in the summer of 1986. It was found that a complete covering of Arizona dust on an HRB did not significantly degrade the performance of the HRB. This surprising result led to more extensive tests during the summer of 1987.

HRB DUST TESTING

The purpose of this test was to determine the effect that HRB dust accumulation has on the ceiling heat flux.

Test Equipment

Test Cells Five small 48 ft^2 test cells exposed to ambient conditions were used in these tests. The roofs were hinged along the peak so that one side of the roof could be opened to allow easy access to the attics. Attic ventilation was provided by four soffit vents and two gable vents. The minimum net free area (NFA) for each of the test cells, as required by the Department of Housing and Urban Development (HUD) and the Federal Housing Administration (FHA), is about 0.32 ft^2. Figure 1 shows test cell dimensions and details. The actual NFA of the test cells was 0.42 ft^2 (31% more than the minimum FHA/HUD NFA of 0.32 ft^2). The ventilation area was distributed as 0.02 ft^2 in the gables and 0.40 ft^2 in the soffits.

Cooling System A chilled-water recirculation system was used to cool the cells. A thermostat in each cell controlled a diverting valve that rerouted the flow of cool water to a fan coil inside that cell. This system maintained interior summer temperatures of 74°F ±2°F, sometimes dropping below 70°F during cool nights as no heating was supplied.

Instrumentation Heat transfer rates through the attics were measured with five small 2-in. by 2-in. heat flux transducers installed in each cell on the attic side of the plywood ceiling. Before installation, the heat flux transducers were calibrated (with an uncertainty of ±2.25%) in the 1 to 2 Btu/h·ft^2 range. Type-T thermocouples with standard limits of error of ±1.4°F were used.

Data monitored in each test cell consisted of:

- seven insulation temperatures (top, bottom, within)
- six temperatures within the test cell
- seven attic temperatures
- five ceiling heat fluxes
- two roof temperatures
- one cell relative humidity
- two sensors to monitor door and roof status
- five sensors to monitor the chilled-water system.

The following weather data were also monitored:

- two ambient temperatures
- solar radiation
- wind speed and direction.

Data Collection System A data logger recorded (approximately every 10 seconds) and stored values continuously for all data points. Every 15 minutes, the data logger would relay a 15-minute averaged value for each data point to a personal computer so the data could be reviewed daily.

RB and Fibrous Insulation The RB used in all tests was a double-sided RB with 30-pound kraft paper backing, fiberglass scrim reinforcement, and a clean emissivity of 0.05. Conventional R-19 fiberglass batts were used in all tests.

Test Methodology

Two major possible sources of error in these tests were differences in test cells and changes in weather. Past testing had shown that a Latin Square test design would give the best results. In a Latin Square test design (see example in Table 1), each configuration is tested in each test cell and in each phase. Therefore, the effects of cell and weather differences are accounted for and the results will be independent of any such differences. A phase was arbitrarily defined as a time period during which at least one, and preferably two, days with a peak ambient temperature above 85°F occurred. During the latter tests in September and October, the ambient temperature peak was relaxed to 82°F.

Statistical Analysis All heat flux data were analyzed to determine statistically significant differences at the 95% confidence level. This was done using the following procedure. The mean heat flux for each test design "block" (i.e., for each phase and each cell) was determined using the actual experimental data. A model was developed using a linear regression analysis relating heat flux to RB configuration, test phase, and test cell. Effects of other key variables, such as ambient temperature, solar radiation, wind speed, and cell temperature, are not significant because of the Latin Square experimental design. Therefore, these variables are not included in the linear regression model.

The least squares heat flux mean for each RB configuration was calculated using the average values for the test phases and test cells. By comparing the actual mean heat fluxes with linear regression model predictions (i.e., the least squares 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.

The standard error and the least squares mean calculation for each configuration are used to determine whether the differences between the least squares mean heat fluxes are statistically significant. Unless noted otherwise, all references to statistical significance will indicate the 95% confidence level.

Test Setup

Dust was sprinkled as evenly as possible on a 2-in.-square RB sample of known weight. Arizona dust (commonly used for testing air filters) was used. It has a size distribution by weight of 0-5μ, 39%; 5-10μ, 18%; 10-20μ, 16%; 20-40μ, 18%; and 40-80μ, 9%.

An emissometer was used to measure the emissivity of the dusted sample to within ±0.01. When approximately the desired emissivity was reached (0.43), the RB sample with the dust was weighed. Since the weight of the RB sample with no dust was known, the weight of the dust could be determined. Also, since sample area was known, the amount of dust required for the test cells to give the same approximate emissivity could be extrapolated. Fifty-seven grams (1.27 mg/cm^2) of dust were required to give an emissivity of 0.43 in a test cell.

The heavier dust level was obtained by doubling the 57 grams of dust to 114 grams (2.54 mg/cm^2), resulting in an average emissivity of 0.51. Using the Florida equation for Yarbrough's data, the two dust levels used in this testing should yield emissivities of 0.51 and 0.71, respectively. Since the dust used by Yarbrough was not Arizona dust, it would probably be different from the Arizona dust used in these tests, which may account for the differences between measured and calculated emissivities (0.43 vs. 0.51 and 0.51 vs. 0.71).

TABLE 1
TVA Radiant Barrier/Dust—June Data 1
Average Net Ceiling Heat Fluxes for All Hours

Average Net Ceiling Heat Fluxes for All Hours

Test Setup	Dust Load (mg/sq cm)	Emiss.	Heat Flux (BTUHSF)	Reduct. (%)
R-19/No RB	0.00	--	1.18	--
R-19/HRB	1.27	0.43	0.88	25.42
R-19/HRB	2.54	0.51	0.95	19.49

Note: Avg. Ambient Temp = 75.2 F
Avg. Solar Radiation = 75.6 BTUHSF
Avg. Wind Speed = 2.2 mph

TABLE 2
TVA Radiant Barrier/Dust—June Data 2
Average Net Ceiling Heat Fluxes, 11 AM-6 PM

Average Net Ceiling Heat Fluxes 11 AM - 6 PM

Test Setup	Dust Load (mg/sq cm)	Emiss.	Heat Flux (BTUHSF)	Reduct. (%)
R-19/No RB	0.00	--	3.02	--
R-19/HRB	1.27	0.43	2.23	26.16
R-19/HRB	2.54	0.51	2.40	20.53

Note: Avg. Ambient Temp = 83.5 F
Avg. Solar Radiation = 169.6 BTUSFH
Avg. Wind Speed = 3.2 mph

TABLE 3
TVA Radiant Barrier/Dust—June Data 3
Average Net Ceiling Heat Fluxes (OD Air = 90-95°F)

Average Net Ceiling Heat Fluxes (OD Air = 90-95 F)

Test Setup	Dust Load (mg/sq cm)	Emiss.	Heat Flux (BTUHSF)	Reduct. (%)
R-19/No RB	0.00	--	3.97	--
R-19/HRB	1.27	0.43	2.79	29.72
R-19/HRB	2.54	0.51	3.08	22.42

Note: Avg. Ambient Temp = 90.5 F
Avg. Solar Radiation = 253.2 BTUSFH
Avg. Wind Speed = 3.5 mph

Results

Tables 1 through 3 contain the results of a Latin Square analysis using (1) the data from all hours of the day, (2) only data during the hours from 11 a.m. to 6 p.m., and (3) only data when ambient temperatures were extremely hot (between 90°F and 95°F), respectively. These tests were conducted in late June and early July.

For the all-hours analysis, the reductions in averaged ceiling heat flux (25% and 19%) for both dust levels were significantly less than the usual 35% to 40% reductions from a clean HRB. The same holds true for the day-hours reductions in ceiling heat flux from the HRB with dust (26% and 21%) and for the reductions during extremely hot conditions (30% and 22%).

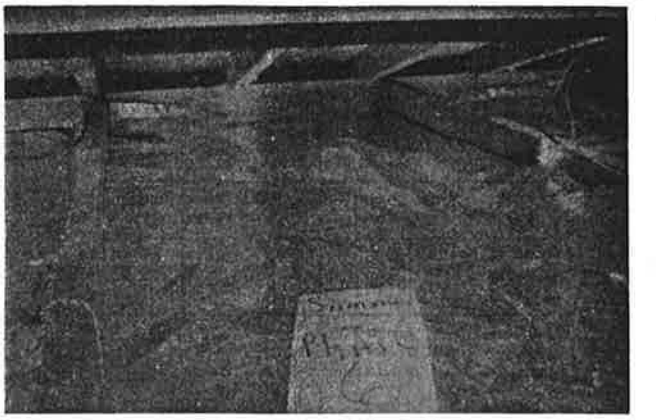

Fig. 2 *Clean HRB (no dust) emissivity = 0.05*

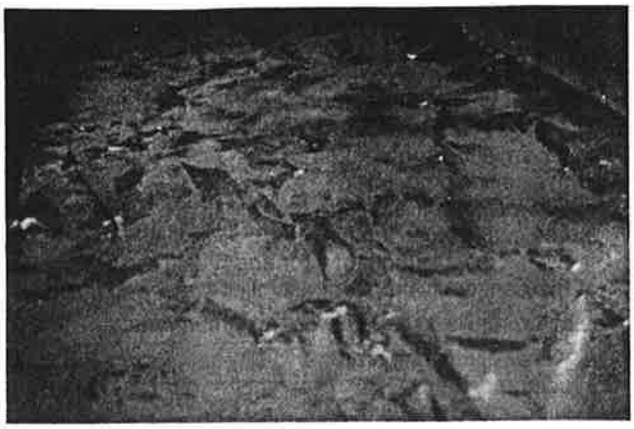

Figure 3 *HRB with dust (1.27 mg/cm²) emissivity = 0.43*

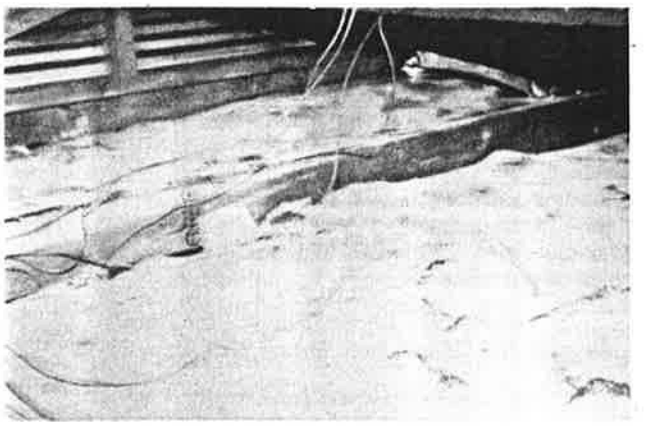

Figure 4 *HRB with dust (2.54 mg/cm²) emissivity = 0.51*

It should be noted that these high dust levels resulted in high emissivities and visually appeared quite excessive. Figures 2 through 4 are photographs showing a "clean" HRB (i.e., no dust), the HRB with 57 grams of dust (1.27 mg/cm^2), and the HRB with 114 grams of dust (2.54 mg/cm^2), respectively. Despite the large amounts of dust, the HRBs still provided sizable and statistically significant reductions in ceiling heat flux in every case shown and in most cases even down to the 75°F to 80°F ambient temperature range.

Figure 5 is a plot of the heat flux vs. time of day for the three configurations tested (all with R-19 fiberglass batt insulation) with no RB and two HRB dust loadings. Also plotted in Figure 5 is a curve representative of the HRB with no dust, so that a comparison can be made of the HRB's performance with and without dust. The HRB without dust was not tested at the same time as the HRB with dust but was tested later during the summer. The curve for the HRB without dust shown in Figure 5 was adjusted to try to account for some minor differences in weather and attic ventilation area between the two test periods.

Figure 5 shows that dust definitely degrades the performance of an HRB. However, even with large amounts of dust, an HRB with dust significantly reduces ceiling heat fluxes from about 10 a.m. to 6 p.m.

Additional Testing

One final test was conducted during the summer of 1987 to determine the effect on the ceiling heat flux of an HRB with a smaller amount of dust than was used in the earlier dusted HRB testing. The attic ventilation area was set at 0.32 ft^2, which is the minimum NFA as specified by FHA/HUD. Soffit/gable ventilation was used in this testing, and the ventilation area was distributed evenly, with 50% in the gables and 50% in the soffits. R-19 insulation was again used throughout the testing.

Thirty-one grams (0.70 mg/cm^2) of Arizona dust were applied on the HRB for this test. This weight of dust is estimated

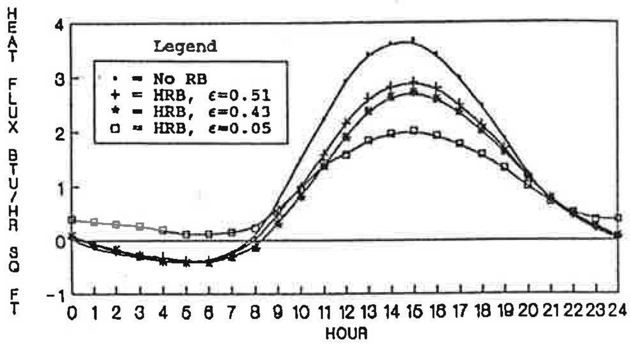

Figure 5 *Attic June 1987 heat flux data—HRB with dust*

TABLE 4
TVA Radiant Barrier/Dust—Sept. Data

Average Net Ceiling Heat Fluxes 11 AM - 6 PM

Test Setup	Dust Load (mg/sq cm)	Emiss.	Heat Flux (BTUHSF)	Reduct. (%)
R-19/No RB	0.00	--	1.69	--
R-19/HRB	0.00	0.05	0.71	57.99
R-19/HRB	0.70	0.34	1.00	40.83

Note: Avg. Ambient Temp = 80.1 F
Avg. Solar Radiation = 132.4 BTUSFH
Avg. Wind Speed = 3.3 mph

to cause a rise in RB emissivity from near 0.05 to 0.34 from laboratory measurements using the same procedure as discussed in the previous RB with dust testing. A 31-gram dust loading also yields an emissivity of 0.34 using the equation for Yarbrough's data.

The results of a Latin Square analysis during the day hours (11 a.m. to 6 p.m.) are shown in Table 4. All the percent reductions in ceiling heat flux are relative to an R-19 with no RB configuration.

Daytime reductions in ceiling heat flux from the HRB, relative to no RB, were quite large (58%). This may be due to the mild ambient temperatures that cause solar radiation to dominate the heat flux and could make an HRB even more effective than usual.

The HRB with dust configuration provided a large (41%), statistically significant reduction in ceiling heat flux compared to no RB with the same ventilation area. Even though the HRB with dust case does exhibit a statistically significant heat flux degradation compared to an HRB with no dust, the HRB with dust case still provides a large reduction in ceiling heat flux (vs. no RB). This result is similar to the findings from the HRB with dust testing discussed earlier.

Figure 6 shows the heat flux vs. time-of-day graph for the HRB with dust. The dust clearly degrades the performance of an HRB compared to an HRB with no dust. However, an HRB

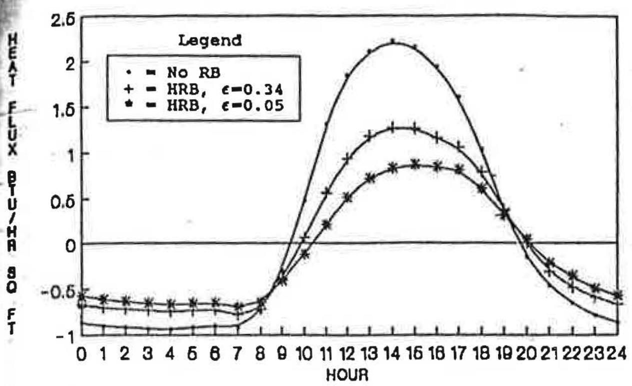

Figure 6 Attic September 1987 heat flux data—HRB with dust

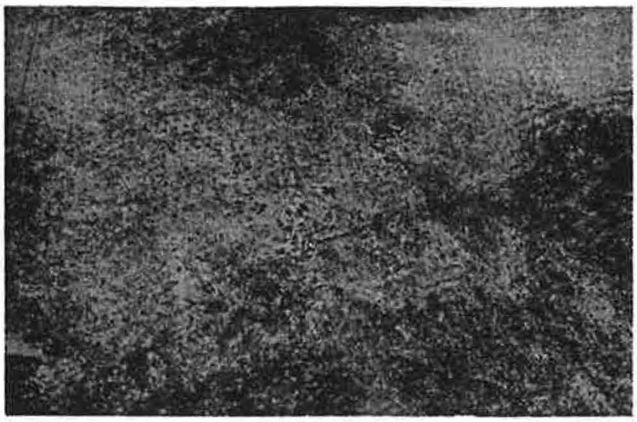

Figure 7 Heavy dust level (0.74 mg/cm²) emissivity = 0.185

Figure 8 Light dust level (0.34 mg/cm²) emissivity = 0.125

Figure 9 Heavy dust level with sample of clean HRB

with dust still provides large reductions (close to 1 Btu/h·ft²) in ceiling heat flux during almost all the daytime hours.

TESTS IN RESEARCH HOUSES

Description of the Research Houses

The research facility consists of three unoccupied single-family ranch-style houses. The conditioned space in each house is 1200 ft² (approximately 40 ft by 30 ft) over a crawl space. The houses are located in Karns, a suburb between Oak Ridge and Knoxville, Tennessee. All three houses were built by the same contractor using standard construction methods. Each house has the same make and model two-ton, single-package residential heat pump. All ductwork is located in the crawl space and is insulated to R-7.6. The houses have soffit-and-gable vents with unfaced R-19 fiberglass batt attic insulation. There is no vapor barrier in the attic. The effective attic ventilation area ratio (AVR) is 1 ft² ventilation area per 150 ft² of attic floor.

Each house is highly instrumented with its own microcomputer-controlled data acquisition system. Approximately 53 data sensors are scanned at 30-second intervals.

Experimental Setup

House 3 was used as the control house in this work. It was operated in the same manner throughout the testing—no RBs were installed in it nor were any other modifications made.

Perforated HRB material was used in the testing. It had an average equivalent hole diameter of 88.2 mils (0.0882 in.) and an open area of 2.31% of the total area. The holes were approximately 5/8-in. on-center in an equilateral triangle pattern.

Cooling results reported by the laboratory in previous experiments[1,3,4] were for nonperforated HRB material. Since the measured emissivity of the HRB material used for this testing (0.055) was higher than the previously used nonperforated RB materials (0.035), one logically could not expect the same performance from the current material as from the others. The perforated HRB was installed in houses 1 and 2 by an insulation contractor.

The testing for this work covered three phases. The first phase was a cooling calibration run among all three houses with no RBs present. The second phase involved a calibration run with clean HRBs in houses 1 and 2. When the calibrations were completed, a heavier dust loading of 0.74 mg/cm² was applied to the HRB in house 1 and a lighter loading of 0.34 mg/cm² was applied to the HRB in house 2. The dust phase of the test was then started.

Dust Measurements

These tests used the same Arizona dust as in the other tests. Based on discussions with the other researchers and a review of their dust experiments, it was decided to use dust levels of 0.34 and 0.74 mg/cm². It was estimated that these dust levels would result in emissivities of about 0.15 and 0.20. The actual measured emissivities from these dust loadings on the perforated RB material used were 0.125 and 0.185, respectively.

Weighed samples of the dust were applied manually over small areas between the roof trusses using salt shakers. The more exotic and easier methods we tried, such as using compressed air, did not work very well.

Figure 7 shows a close-up view of the heavy dust loading on the HRB in house 1, while Figure 8 shows the same view of the lighter dust loading in house 2. Figure 9 shows for comparison purposes a small piece of undusted HRB material atop the more heavily dusted HRB material in house 1.

It became apparent after the artificial dusting was completed that the dust did not cling tightly to the surface of the HRB. It could easily be blown or shaken off the surface. Observations of natural dust on other surfaces in the attic revealed that natural dust appears to adhere to a surface better than Arizona dust. Other airborne pollutants in the attic, such as pollens,

TABLE 5
Summary of Dust Regression Results Using Model Cooling Load (Btu/h) = Constant + (*To* − *Ti*)

House Setup	Dates	No. Hours	REGRESSION LINE					MEAN VALUES			Total Load Normalized @ Int Ld=1692, DT= Avg Wk		
			R^2	Const.	Error	Slope	Error	To-Ti (F Deg)	Tot Load (Btu/h)	Int Load (Btu/h)	(Btu/h)	H#/H3	Norm CF
1 ACCal	6/01-6/29	415	0.848	3898.0	133.3	503.10	10.46	6.69	7262	1836	7328	0.995	1.000
1 HB	7/25-8/01	165	0.910	3795.5	132.6	576.07	14.16	4.81	6568	1948	6658	0.853	0.857
1 HBDL2	8/01-8/15	333	0.926	3535.5	100.8	617.63	9.58	6.52	7562	1912	7759	0.925	0.929
2 ACCal	6/01-6/29	411	0.865	4332.6	153.9	604.25	11.79	6.90	8503	1859	8458	1.148	1.000
2 HB	7/25-8/01	165	0.924	4077.5	162.0	733.26	16.45	5.52	8125	1626	8113	1.039	0.905
2 HBDL1	8/01-8/15	333	0.935	3457.1	123.3	758.66	10.97	7.37	6659	1683	8924	1.064	0.926
3 ACCal	6/01-6/29	415	0.858	3286.0	148.7	549.49	10.99	7.72	7526	1516	7366		
3 ACCal	7/25-8/01	165	0.933	3489.9	166.1	775.03	16.26	5.91	8070	1570	7808		
3 ACCal	8/01-8/15	333	0.936	2726.3	127.9	774.54	11.10	7.69	8684	1600	8390		

Avg Wk (To-Ti) 7.10 F Deg, 5.41, 7.19 — Avg Int Lds 1692 Btu/h

TABLE 6
Summary of Dust Regression Results Using Model A/C Elec. Input (W-h) = Constant + (*To* − *Ti*)

House Setup	Dates	No. Hours	REGRESSION LINE					MEAN VALUES			Total Input Normalized @ Int Ld=496, DT=Avg WkDT		
			R^2	Const.	Error	Slope	Error	To-Ti (F Deg)	A/C Elec (W-Hr)	Int Load (W-Hr)	(W-Hr)	H#/H3	Norm CF
1 ACCal	6/01-6/29	415	0.869	557.3	19.2	79.11	1.51	6.69	1086	537.9	1112.9	0.966	1.000
1 HB	7/25-8/01	29	0.948	554.2	36.4	84.45	3.72	4.81	1022	570.8	999.7	0.877	0.907
1 HBDL2	8/01-8/15	333	0.941	485.6	13.4	92.60	1.28	6.52	1089	560.2	1142.4	0.920	0.952
2 ACCal	6/01-6/29	411	0.885	592.8	20.0	86.23	1.53	6.90	1188	544.7	1198.5	1.041	1.000
2 HB	7/25-8/01	165	0.934	543.8	19.6	96.34	1.99	5.52	1076	476.4	1067.9	0.937	0.900
2 HBDL1	8/01-8/15	333	0.946	461.5	14.7	100.19	1.31	7.37	1200	493.1	1182.7	0.953	0.915
3 ACCal	6/01-6/29	415	0.875	535.6	21.5	85.52	1.59	7.72	1196	444.2	1151.3		
3 ACCal	7/25-8/01	165	0.940	544.4	21.9	109.08	2.14	5.91	1189	460.0	1140.2		
3 ACCal	8/01-8/15	333	0.946	440.4	16.8	110.77	1.46	7.69	1293	468.8	1241.2		

Note: All regressions are done on an hourly basis.
H#/H3 = House Load divided by House 3 Load.
ACCal = A/C Calibration Test.
DL1, DL2 = Dust Levels (0.34 and 0.74 mg/cm²).
Norm CF = Normalized using Calibration Factor.
(To-Ti) = (Outside - Inside) Temp Difference.

Avg Wk (To-Ti) 7.10 F Deg, 5.41, 7.19 — Avg Int Lds 496 WHr

TABLE 7
Differences between House @ Setup and House w/o Setup

House	Attic Setup	Attic Vent Ratio	RB Dust Loading (mg/cm²)	RB Emiss.	% Difference in	
					Btu Load	A/C W-Hr
1	HB	1/150	----	0.055	-14.29	-9.30
1	HBDL2	1/150	0.74	0.185	-7.05	-4.79
2	HB	1/150	----	0.055	-9.51	-10.03
2	HBDL1	1/150	0.34	0.125	-7.38	-8.47

probably provide the mechanism for the better adhesion of the natural dust.

Emissivities of the HRB and the dusted samples were determined by carefully measuring the area of a small box (approximately 3 in. by 5 in.) and weighing samples of the Arizona dust. A weighed dust sample was put in the box and shaken so that the sample was uniformly distributed over the bottom. A piece of RB material the same size as the bottom box surface was placed in the box, the box was inverted and tapped lightly, and the dusted RB sample was removed and placed on the nearby emissometer to measure its emissivity.

It was necessary to measure the emissivity in this manner because the dust on a sample would redistribute itself when a

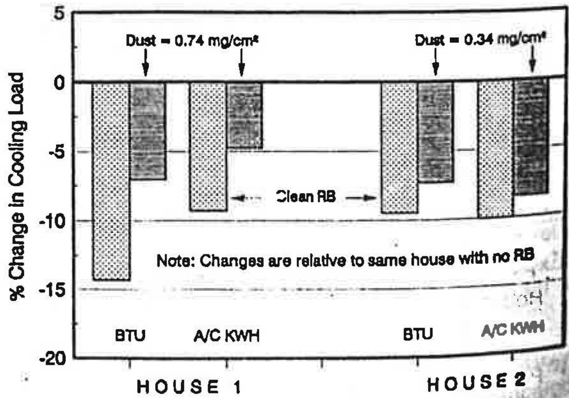

Figure 10 Effect of dust on HRB performance

sample was cut from the attic HRB and brought into the house for a surface emissivity measurement.

Results

Cooling Loads Linear regression modeling was carried out for all three phases of the testing using hourly outdoor minus indoor temperature differences, (*To* − *Ti*), as independent

TABLE 8
Karns Net Attic Heat Flux—HRBs with No Dust

House No./ Insulation	Dates From-To	Hour	Average BTUSFH	Total BTUSF	Ratio H#/H3
#1 R19+HRB	Jul 25-Aug	165	0.53	88.06	0.394
#2 R19+HRB	Jul 25-Aug	165	0.80	131.98	0.591
#3 R-19	Jul 25-Aug	165	1.35	223.34	1.000
#1 R-19+HRB	TOTALS	165	0.53	88.06	0.394
#2 R-19+HRB	TOTALS	165	0.80	131.98	0.591
#3 R-19	TOTALS	165	1.35	223.34	1.000

Notes: Attic Vent Ratio is 1/150 for all houses

TABLE 9
Karns Net Attic Heat Flux—HRBs with Dust

House No./ Insulation	Dates From-To	Hour	Average BTUSFH	Total BTUSF	Ratio H#/H3
#1 R19+HRB	Aug 02-08	144	0.63	91.12	0.515
#2 R19+HRB	Aug 02-08	144	0.83	118.98	0.673
#3 R-19	Aug 02-08	144	1.23	176.84	1.000
#1 R19+HRB	Aug 08-15	167	0.74	123.50	0.500
#2 R19+HRB	Aug 08-15	167	0.98	162.94	0.660
#3 R-19	Aug 08-15	167	1.48	247.00	1.000
#1 R19+HRB	TOTALS	311	0.69	214.62	0.506
#2 R19+HRB	TOTALS	311	0.91	281.92	0.665
#3 R-19	TOTALS	311	1.36	423.84	1.000

Notes: Attic Vent Ratio is 1/150 for all

variables, and hourly cooling inputs as dependent variables. Table 5 contains the cooling load (Btu input to the house) results, and Table 6 contains the electrical input to the air conditioner (A/C) (kWh) results. The results in both tables are made relative to the the control house and normalized to the same mean ($To - Ti$) and internal electrical load that existed during that phase of the testing. This method allowed the comparison to determine the effect of both HRB and dust relative to the same house with no HRB or dust.

Table 7 summarizes the results of Tables 5 and 6 and contains the normalized cooling load and electrical input results relative to R-19 attic insulation with no RBs. Figure 10 depicts the results contained in Table 7 and shows the percent change in cooling loads and in air conditioner electrical inputs relative to houses 1 and 2, respectively, with no HRB installed. The cooling load of house 1 was reduced 14.3% by the addition of a clean HRB, while that of house 2 was reduced only 9.5% by the clean HRB. The corresponding A/C electrical inputs to houses 1 and 2 were reduced by 9.3% and 10.0%, respectively.

House 1 showed a cooling load reduction of 7.1% with a dust loading of 0.74 mg/cm^2 ($\epsilon = 0.185$) compared to no HRB, while the cooling load in house 2, with a dust load of 0.34 mg/cm^2 ($\epsilon = 0.125$), was reduced by 7.4%, compared to no HRB. The corresponding A/C electrical inputs were reduced by 4.8% and 8.5%, respectively.

The effect of dust relative to a clean HRB shows that a heavier dust loading on the HRB in house 1 increased the total cooling load by 8.4% *compared to a clean HRB in house 1.* The lighter HRB dust loading in house 2 increased the total house cooling load by 2.3% *compared to a clean HRB in house 2.* The corresponding effect on air conditioner electrical input was an increase of 4.9% in house 1 and an increase of 1.7% in house 2, *again compared to clean HRBs.*

Attic Heat Flows. Attic heat flows were measured concurrently with house cooling using a small 2-in. by 2-in. heat flow transducer in each house. Table 8 contains the results of net attic heat flow measurements made with clean HRBs in houses 2 and 3. Table 9 contains the results of net attic heat flow measurements with dusted HRBs in houses 2 and 3. Table 10 summarizes and normalizes the results from Tables 8 and 9 and also includes measurements from the no-RB calibration period. It shows that a clean HRB reduces the net attic heat flux by 46.6% in house 1 and 41.4% in house 2, compared to the same houses with no RBs. The heavier dust loading on the HRB in house 1 only reduces the attic heat flux by 31.5%, compared to house 1 with no HRB, or increases it by 28.4% when *compared to that of house 1 with a clean HRB.* The attic heat flow in house 2 with the lighter dust loading is only decreased by 34.1% compared to house 2 with no HRB, or it is increased by 12.6% when *compared to that of house 2 with a clean HRB.*

SUMMARY AND CONCLUSIONS

Heat transfer measurements were made on dusted HRBs installed in the attics of small test cells located at a test site in Chattanooga, Tennessee. RBs were artificially dusted with Arizona dust, which is commonly used for automotive air cleaner testing. R-19 fiberglass batt insulation was in the attics. Dust loadings tested ranged from 0.00 mg/cm^2 (a clean RB) to 2.58 mg/cm^2 (a very dirty RB). Surface emissivities ranged from 0.05 for a clean RB to 0.51 for the dirtiest RB. A Latin Square test design was used, wherein each dust loading was tested in each test cell during the test period, which removed much variability caused by external effects. Test results showed that a clean HRB reduced the net ceiling heat flux by 58% compared to a test cell with no HRB, while the dirtiest HRB reduced the net ceiling heat flux by 19%. These tests showed that dust accumulation on HRBs does not totally eliminate the effectiveness of an HRB and that dust may not be a prohibitive problem for HRB installations.

Tests on HRBs with dust were conducted at three research houses during the following summer. R-19 fiberglass batt insulation was in all attics and Arizona dust was used to load the HRBs. These tests were designed to determine the effect of dusted HRBs on whole-house cooling loads. Attic heat flow measurements were also made. Dust loadings of 0.74 mg/cm^2 ($\epsilon = 0.185$) and 0.34 mg/cm^2 ($\epsilon = 0.125$) were tested. When compared to clean HRBs, the HRB with heavier dust loading increased the house load by 8.4%, and the HRB with lighter dust loading increased the house load by 2.3%. However, when compared to the same houses with no HRBs, the dusted HRBs reduced cooling loads by about 7%.

Attic heat flux measurements with dusted HRBs, when compared to clean HRBs, showed a 28.4% increase for the HRB

Table 10
Comparison of Net Heat Flux Data with and without HRBs

	1/150 Vent Ratio No HRBs			1/150 Vent Ratio No Dust			1/150 Vent Ratio w Dust		
	#1 R-19	#2 R-19	#3 R-19	#1 R19+HB	#2 R19+HB	#3 R-19	#1 R19+HB	#2 R19+HB	#3 R-19
Total Heat Flux (BTUSF)	464.85	634.46	629.06	88.06	131.98	223.34	214.62	281.92	423.84
Relative Total Ht Flux	0.739	1.009	1.000	0.394	0.591	1.000	0.506	0.665	1.000
Normalized Total Ht Flux	---	---	---	0.534	0.586	1.000	0.685	0.659	1.000
% Change from No HB				-46.6%	-41.4%	---	-31.5%	-34.1%	---
% Change from Clean HB							28.4%	12.6%	---

Notes: House #3 is Control House
Horizontal Barrier is Perforated
2.31% Open Area, Dust Free Emissivity = 0.055
House #1 Dust Loading = 0.74 mg/sq cm Emissivity = 0.185
House #2 Dust Loading = 0.34 mg/sq cm Emissivity = 0.125

with heavier dust loading and a 12.6% increase for the HRB with lighter dust loading, respectively. However, the dusted heat fluxes were 31.5% and 34.1% less than no-RB conditions, respectively.

Both sets of tests show that although dust degrades the performance of an HRB in summertime, the degradation is not totally devastating. Dusted HRBs are still effective in reducing both attic heat flows and total house cooling loads. Long-term testing should be done in order to verify the results obtained in these tests as well as to ensure that natural dust does not behave in a more severe manner than Arizona dust.

Research should also be continued on measurements of dust accumulation on HRBs and its effect on surface emissivity.

NOMENCLATURE

AVR	= attic ventilation area ratio (net free area of attic ventilation per ft^2 of attic floor area)
BTUHSF	= Btu/h·ft^2
BTUSF	= Btu/ft^2
ϵ	= emissivity
FHA	= Federal Housing Administration
HB or HRB	= horizontal radiant barrier
HUD	= Department of Housing and Urban Development
NFA	= net free area of attic ventilation
RB	= radiant barrier
R-19, etc.	= R-value of insulation
TRB	= truss radiant barrier

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DISCUSSION

Stanley Boghosian, Mechanical Engineer, Lawrence Berkeley Laboratory, Berkeley, CA: Please compare the truss radiant barrier with the dusted horizontal barrier. Also, what is the correlation between dust loadings used and actual "natural" dust loadings? Are there data on dust accumulation on truss-placed radiant barriers?

J.A. Hall: As far as a comparison of the truss radiant barrier with the dusted horizontal barrier, please refer to the following: W.P. Levins and M.A. Karnitz, 1987, "Energy Measurements of Single-Family Houses with Attics Containing Radiant Barriers," *ASHRAE Transactions*, Vol. 93, Part 2, pp. 182-199, and J.A. Hall, 1986, "Performance Testing of Radiant Barriers," Tennessee Valley Authority, TVA/OP/ED&T-86/25, November. Please refer to work done by D. Yarbrough (Tennessee Technological University) and by the Florida Solar Energy Center for information on dust accumulation rates in the field. To my knowledge, there are no data on dust accumulation on truss-placed radiant barriers.

Louis N. Grounds, Regional Sales Manager, ECCI, Denver, CO: Have you (or will you) take into consideration the effects of nonuniform dust loading?

Hall: This was not considered and we know of no plans to consider nonuniform dust loading.