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Cooling Season Energy Measurements of Dust and Ventilation Effects on Radiant Barriers

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Energy Division

COOLING SEASON ENERGY MEASUREMENTS OF DUST AND VENTILATION EFFECTS ON RADIANT BARRIERS

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1. W. P. Levins and M. A. Karnitz, Cooling Energy Measurements of Unoccupied Single-Family Houses with Attics Containing Radiant Barriers, ORNL/CON-200, Oak Ridge National Laboratory, July 1986.

2. W. P. Levins and M. A. Karnitz, Heating Energy Measurements of Unoccupied Single-Family Houses with Attics Containing Radiant Barriers, ORNL/CON-213, Oak Ridge National Laboratory, January 1987.

3. W. P. Levins and M. A. Karnitz, Cooling Energy Measurements of Single-Family Houses with Attics Containing Radiant Barriers in Combination with R-11 and R-30 Ceiling Insulation, ORNL/CON-226, Oak Ridge National Laboratory, April 1987.

4. W. P. Levins and M. A. Karnitz, Heating Energy Measurements of Single-Family Houses with Attics Containing Radiant Barriers in Combination with R-11 and R-30 Ceiling Insulation, ORNL/CON-239, Oak Ridge National Laboratory, August 1988.

5. W. P. Levins, M. A. Karnitz, and J. A. Hall, Moisture Measurements in Single-Family Houses with Attics Containing Radiant Barriers, ORNL/CON-255, Oak Ridge National Laboratory, February 1989.

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ABSTRACT

Cooling season tests were conducted in three unoccupied ranch-style houses in Karns, Tennessee, to determine the effects on attic radiant barrier performance incurred by changes in attic ventilation area ratio, attic ventilation type, and the buildup of dust on horizontal radiant barriers. All three houses had R-19 fiberglass batt insulation in their attics.

Horizontal radiant barriers were artificially dusted and the dusted barriers showed measurable performance degradations, although the dusted barriers were still superior to no radiant barriers. Dust loadings of 0.34 and 0.74 mg/cm^2 reduced a clean radiant barrier surface emissivity of 0.055 to 0.125 and 0.185, respectively. Total house cooling load increases amounted to 2.3 and 8.4% compared to house loads with clean horizontal barriers, respectively. When compared to R-19 with no horizontal radiant barrier conditions, the dusted horizontal radiant barriers reduced cooling loads by about 7%.

Testing showed that increasing the attic ventilation area ratio from the minimum recommended of 1/300 (1 ft^2 of effective ventilation area per 300 ft^2 of attic area) to 1/150 had little if any effect on the house cooling load with either truss or horizontal barriers present in the attics. Radiant barriers, however, still reduced the house cooling load.

There was essentially no difference in house cooling load reduction between either ridge/soffit or gable/soffit vent type with a truss radiant barrier, as both reduced cooling loads by about 8% when compared to no radiant barrier conditions. The attic-ventilation-type testing was done with a ventilation area ratio of 1/150.

NOMENCLATURE

Note: The following abbreviations are used in the report body as well as in some of the plots.

Abbreviation	Meaning
AVR	Attic ventilation area ratio
A/C	Air conditioning
BTUSF	Btu/ft^2
BTUSFH or BSFH	$Btu/ft^2/h$
CF	Calibration Factor
DB	Dry bulb temperature
DT, DTemp	Temperature difference
e	Surface emissivity of radiant barrier
FV	Full attic ventilation area, AVR=1/150
GV	Gable vent
Gr Rm, Gr Room	Great Room (combination dining and living)
HB or HRB	Horizontal radiant barrier
HP	Heat pump
HV	Half attic ventilation area, AVR=1/300
HVAC	Heating, ventilating, and air conditioning
IR	Resistance heat
Jan.-Dec.	Months
No. 1, 2, or 3	Houses No. 1, No. 2, No. 3
OD air	Outdoor air
RB	Radiant barrier
RH	Relative humidity
RV	Ridge vent
R-19 or R19	The R-value of insulation
R19 + HRB	Combination of R-19 insulation and a horizontal radiant barrier
TB or TRB	Truss radiant barrier
(To-Ti)	Outdoor air - Indoor air temperature difference
VB	Vapor barrier
WB	Wet bulb temperature

EXECUTIVE SUMMARY

The three main objectives of this work were to determine the effects of attic ventilation area ratio (AVR), attic ventilation type (ridge/soffit and gable/soffit) and dust buildup on radiant barriers (RBs). Three different experiments were run in the unoccupied Karns research houses to obtain data to answer these objectives.

The effect of AVR on truss radiant barriers (TRBs) and horizontal radiant barriers (HRBs) was determined at AVRs of 1/150 and 1/300. The minimum recommended Federal Housing Administration (FHA) AVR is 1/300 for either high/low ventilation (where gable or ridge vents provide high elevation area and soffit vents provide low elevation area) or when a vapor barrier is in the attic on the living area side of the insulation; it is 1/150 when neither of the two previous conditions is met. Since the unoccupied Karns houses originally were equipped with gable and soffit vents (AVR = 1/150) with unfaced R-19 fiberglass batts in the attic, they have twice the FHA minimum recommended AVR of 1/300. Testing was done at AVRs of 1/300 and 1/150, with the 1/300 AVR obtained by blocking off half of the soffit and gable areas with cardboard and tape. A nonperforated TRB was installed in house No. 1, a perforated HRB was installed in house No. 2, and house No. 3 was used as a control (no RB) with an AVR of 1/150. The use of a control house allows normalization of data with respect to the control house. The normalization procedure cancels out small differences between house loads and weather conditions. All houses had R-19 fiberglass batts throughout this summer testing.

The perforated HRB material used throughout the work of this summer (1988) had an open hole area of 2.31%, based on the total surface area, and an emissivity of 0.055. HRB material used in previous summer testing either had been unperforated or perforated with an open hole area of 0.05% (emissivity = 0.035). The hole pattern in perforated RB materials remained the same, only the hole size changed. The increased HRB hole size for this work should be kept in mind when comparing results of this work with previous ORNL work. Another change in methodology took place when TRBs were installed in the attic areas. No RB material covered the ends of the attic under the gable vents in previous TRB work, but some was installed in these end areas for the present TRB testing. The RB material used for TRB testing was nonperforated and had an emissivity of 0.035.

Total (the sum of sensible and latent) cooling load measurements showed that reductions from 7 to 9.5% were obtained for both TRBs and HRBs when compared to no RBs for the two AVRs tested. Electrical inputs to the air conditioning units likewise showed reductions ranging from 6 to 10%. Heat flow reductions caused by both types of RB ranged from 28 to 40%. Since DOE-2 load simulation calculations for a Karns house showed that the percentage of the cooling load from the roof was 26%, heat flow reductions of 28 to 40% should result in cooling load reductions of 7 to 10%. Our load measurements appear to be consistent with our heat flux measurements.

Higher heat flow reductions were measured with HRBs than with TRBs. Higher cooling load reductions were also measured with HRBs installed, but the differences in cooling reductions between the two types of RB were small. It was concluded that doubling the AVR from the minimum of 1/300 to 1/150 has little effect upon either a TRB or an HRB at Karns. Our testing from previous summers had shown HRBs to be substantially more effective than TRBs. The large perforations in the HRB material and the covering of the gable ends of the attics when TRBs were present would help explain the differences between previous work and this work.

The TRB was removed from house No. 1 after the AVR tests and an HRB was installed so that the dusting tests could begin. The HRB in house No. 2 remained in place. A no-dust calibration run was made, with house No. 3 as a control. A heavy dust level of 0.74 mg/cm^2 was applied to the HRB in house No. 1, while a lighter dust level of 0.34 mg/cm^2 was applied on the HRB in house No. 2. The emissivity of clean HRB material was 0.055, that of the heavy (0.74 mg/cm^2) dust loading was 0.185, and that of the light (0.34 mg/cm^2) dust loading was 0.125.

Results from the dust testing showed that total house cooling loads were increased by 2.3% for the light dust loading (house No. 2) and the loads were increased by 8.4% for the heavier dust loading (house No. 1) when compared to a clean HRB. Electrical inputs to each air conditioner were increased by 1.7 and 5.0%, respectively, again compared to those with clean HRBs.

The calibration run with clean HRBs showed reductions in the cooling loads in house No. 1 of 14.3% compared to no RB and of 9.5% in house No. 2 compared to no RB. The measured increases caused by adding dust to the HRBs, therefore, still resulted in savings of about 7% on the total cooling loads when results of dusted HRBs are compared to those of the same houses with no HRBs.

Heat flow measurements in the attics of houses No. 1 and No. 2 show that the heavier dust loading of 0.74 mg/cm^2 increased the attic heat flow by 28.4% compared to a clean HRB. The lighter dust loading of 0.34 mg/cm^2 in house No. 2 resulted in an increase in the attic heat flow of 12.6% when compared to a clean HRB. However, these heat flows are still much less than the heat flows in the same houses with no HRBs. These dust test experiments show that dust does reduce the effectiveness of an HRB, but dirty HRBs are still more effective than no HRBs.

A comparison between the relative performance of a TRB and an HRB in house No. 1 at an AVR of 1/150 using data collected during the first two phases of this work shows an HRB reduced the total cooling load in house No. 1 by 14.3% while a TRB reduced it by 7.0%. This change appears to be significant and agrees with previous summer work at Karns. A comparison of HRB performance using data for house No. 2 shows an HRB cooling load reduction of 9.3% in the first phase and 9.5% in the second phase. This range of 9.3 to 14.3% in load reductions probably indicates the repeatability of data, the assumed stable behavior of all three houses with weather, variability due to differences in the houses or in the weather conditions.

When the dust testing was completed, a ridge vent was installed in house No. 1 by a roofing contractor. The AVR in house No. 1 was approximately 1/150. The gable vents were blocked off with cardboard and taped. HRBs were removed from both houses and TRBs were installed in houses No. 1 and No. 2. After collecting data for two weeks under these conditions, the TRBs were removed and a calibration test was conducted with no RBs in the houses. The results of these tests showed that the TRB/ridge vent combination in house No. 1 reduced the total cooling load by 8.3%, while the TRB/gable vent in house No. 2 reduced the total cooling load by 9.2%, both compared to the same configuration with no TRB.

Results obtained earlier in the summer from house No. 1 with a TRB/gable vent combination showed a cooling load reduction of 7 to 9%. The small difference between the earlier house No. 1 results with a TRB/gable vent setup and the later house No. 1 results with a TRB/ridge vent setup is not deemed to be significant, especially since house No. 2 with a TRB/gable vent appears to be slightly better than house No. 1 during the latter testing. Therefore, it is concluded that at an AVR of 1/150, a TRB/ridge vent combination and a TRB/gable vent combination are equally effective in reducing Karns house total cooling loads. Heat flux data taken during this phase of testing for both house No. 1 and No. 2 show reduced attic heat flows of about 30%, which adds credence to the equal performance conclusion.

Conclusions derived as a result of the summer 1988 testing at Karns concerning the effects of RBs on total cooling loads follow:

1. Dust degrades the performance of an HRB, although a dusted HRB is still more energy efficient than an attic without an HRB.

2. Clean (and even lightly dusted) HRBs appear to outperform TRBs. Long-term dusting effects on HRBs may be able to reverse the situation.

3. TRBs with AVRs of 1/300 and 1/150 behave essentially the same with respect to reductions in attic heat flows, etc.

4. HRBs with AVRs of 1/300 and 1/150 behave essentially the same with respect to reductions in attic heat flows, etc.

5. Equal energy performance was obtained with a combination of a TRB with either a ridge vent or a gable vent at an AVR of 1/150.

1. INTRODUCTION

The Department of Energy (DOE), the Tennessee Valley Authority (TVA), the Electric Power Research Institute (EPRI), and the Reflective Insulation Manufacturers Association (RIMA) have jointly sponsored experiments to measure the effect of ventilation and dust in houses that have radiant barriers (RBs) installed in their attics. A RB is a foil material having either one or both surfaces coated with a low emissivity material such as aluminum. A RB works as a system in conjunction with an air space and theoretically can block up to 95% of infrared radiant heat transfer. These experiments were carried out in three unoccupied houses located in Karns, Tennessee, which is midway between the cities of Oak Ridge and Knoxville. The houses have been used in seasonal space heating and cooling experiments from 1985-88 for measurement of the energy performance of RBs.[1-5] During the winter of 1987-88, an experiment was performed that measured moisture conditions in houses with horizontally installed RBs.[6] The results reported in this paper are those from ventilation and dust experiments performed in the summer of 1988.

1.1 OBJECTIVE OF THIS INVESTIGATION

The objective of this summer experiment was to determine the impact of attic ventilation and dust on the performance of RBs in attics of single-family houses. Both Oak Ridge National Laboratory (ORNL) and TVA testing have shown that locating a radiant barrier on top of attic insulation is the most energy efficient installation method. It is also the easiest method of installing RBs in retrofit situations as well as the one requiring a minimum of RB material. Two potential problem areas with horizontal installation are dust buildup and moisture accumulation. The ORNL winter experiment of 1987-88[6] addressed the moisture accumulation issue. The summer 1988 experiment was an attempt to evaluate the degradation in performance due to dust.

The other primary goal of this experiment was to determine the impact of the amount and type of attic ventilation on the performance of both horizontal RBs (HRB) and truss RBs (TRB).

1.2 DESCRIPTION OF KARNS RESEARCH HOUSES

The Karns Research Facility consists of three unoccupied single-family, ranch-style houses. The conditioned space in each house is 1200 ft^2 (approximately 40 ft x 30 ft) and is over a crawl space. The houses are located on Wilnoty Drive in the Karns community, a suburb between Oak Ridge and Knoxville, Tennessee. The 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 duct work 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. No vapor barrier was in the attic. The effective installed attic ventilation area ratio was 1 ft^2 of open ventilation area per 150 ft^2 of attic floor. Appendix A contains photographs and more detailed construction information about the houses.

Each house is highly instrumented with its own microcomputer-controlled data acquisition system. Approximately 53 data sensors are scanned at 30-second intervals. A listing of the data channels used in this work is in Appendix A (Table A.2).

1.3 REVIEW OF THE PREVIOUS RADIANT BARRIER ENERGY AND MOISTURE EXPERIMENTS AT THE KARNS HOUSE FACILITY

The primary objective of the previous energy experiments (winter of 1987-1988) at these research houses was to quantify the energy performance of RBs with various levels of fiberglass batt attic insulation. The RB tests were done in combination with three levels of attic insulation (R-11, R-19, and R-30). Two different methods of installing RBs were also tested. In one configuration the RB was laid on top of the fiberglass insulation (HRB), and in the other the RB was attached to the underside of the roof trusses (TRB).

Results of the energy performance testing are summarized in Fig. 1.1. All percentage changes in this and the following paragraph are relative to the same R-value with no attic RB present. The cooling results with R-11 attic insulation show that a TRB reduced the house cooling load by 10%, while an HRB reduced the load by 16%. Cooling results with R-19 attic insulation showed that a TRB reduced the cooling by about 12%, while an HRB reduced the load by 21%. Radiant barriers had very little affect when used in combination with R-30 insulation. An HRB tested in the heating mode with R-11 decreased the heating load by an average of 9%, while a TRB showed a slight increase in the load. An HRB with R-19 decreased the heating load by an average of 10%, while a slight increase in the heating load was measured with a TRB and R-19. R-30 with a RB showed a reduction of 3.5% for both HRBs and TRBs. The heating load reduction with R-30 and a TRB is inconsistent with the trends obtained with R-11 and R-19 with TRBs; no explanation is offered for this behavior except that the absolute values of the R-30 load changes are relatively small.

In summary, previous energy testing at Karns showed that RBs work better in cooling than in heating, and they also work better in combination with R-11 and R-19 attic insulation than with R-30. Also, HRBs are more effective than TRBs in reducing heating and cooling loads. Based on measurements of house infiltration rates at Karns, HRBs do not appear to be attic infiltration barriers.

The purpose of the winter test of 1987-88 was to determine the effect of moisture condensation on the underside of perforated HRBs. The experimental plan called for the houses to be operated at high (45 and 58% at 70°F) indoor relative humidities. Attic moisture conditions

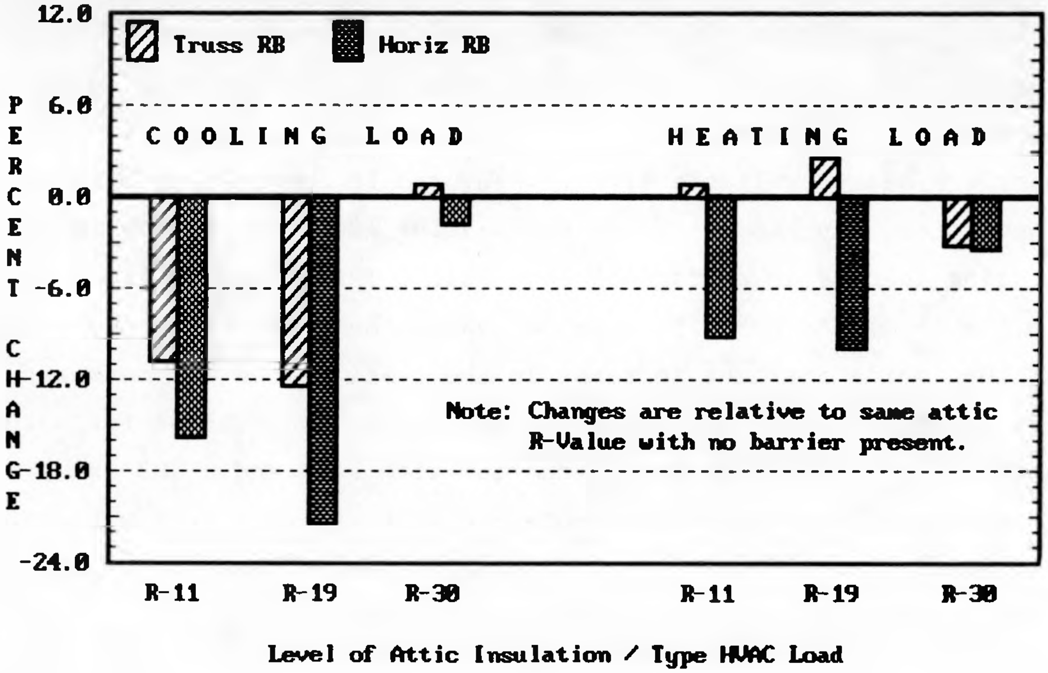


Fig. 1.1 Summary of radiant barrier effects on Karns house loads.

were monitored with both instrumented measurements and visual observations. The results of the testing showed that the moisture went through a diurnal cycle at the Karns research houses. Moisture condensed on the bottom surface of the HRB in cold (below 35°F) weather but dissipated to the attic air during a normal Tennessee afternoon, leaving the barrier dry. In long periods of subfreezing weather, all condensation did not vaporize, with some condensation remaining on the surface of the HRB through the day. However, the testing did show that a moisture cycle occurring on a perforated HRB during a typical Tennessee winter did not cause any problems. There was no structural, wet insulation, or stained ceiling problem to the Karns research houses, even though they were operated at higher than normal indoor relative humidities.

1.4 REVIEW OF OTHER RADIANT BARRIER INVESTIGATIONS

A review of other investigations on the energy performance of RBs has been covered in previous ORNL reports.[1-6] From all the investigations, it can be concluded that RBs can reduce the summer ceiling heat gains. This fact has been demonstrated in work done by TVA,[7-9] Florida Solar Energy Center,[10,11] Texas A&M,[12] the University of Florida,[13] and the Mineral Insulation Manufacturers Association.[14] Another summary of most of these investigations is documented by Wilkes of ORNL.[15]

2. BACKGROUND INFORMATION ON HRB/DUST ISSUES

2.1 INTRODUCTION

The rate of dust accumulation and the effect of this accumulation on an HRB is of special interest. A clean HRB performs better in both summer and winter than a TRB.[1-5, 7-10] Also, installation of an HRB is much easier as a retrofit in existing homes and requires less RB material than a TRB. However, a significant performance degradation caused by dust settling on an HRB over a period of time might make a TRB a better choice.

The effect of dust on an HRB can be divided into three issues: (a) the rate of dust accumulation in actual homes, (b) the effect of dust on RB emissivity, and (c) the effect of dust-induced emissivity change on actual RB performance. Each of these issues is discussed in the following sections.

2.2 FIELD TEST DATA OF DUST ACCUMULATION AND EMISSIVITY CHANGES IN OCCUPIED HOMES

Two major field tests to determine the rate of dust accumulation in attics of occupied homes are now underway. TVA is conducting a two-year RB demonstration project in which 30 homes in Tupelo, Mississippi, and 30 homes in Hopkinsville, Kentucky, were retrofitted with RBs. In each city, approximately one-half of the retrofits were HRBs. Small pieces of clean RB material (emissivity = 0.035) were placed in boxes in the attic of 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 retrofitted homes during this test.

The Florida Solar Energy Center (FSEC) is conducting a field test in which each attic of 11 homes was retrofitted with an HRB. Multiple small boxes containing a RB were placed in each of these attics. The boxes are being retrieved on a logarithmic time schedule (i.e., more retrievals early in the test than later). After emissivities are measured, RB samples are studied with a microscope to determine the percentage area covered by dust, and samples are then carefully weighed to determine the weight of dust accumulation. 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 (0.14 and 0.16).[16]

Lotz[17] conducted testing in South Africa in the middle 1960s on dust accumulation on attic RBs in five occupied homes. His results showed that dust covered clear glass slides in attics at the rate of 28.6% per year. Emissivities were not measured, but the performance degradation due to the dust was analyzed. For dust loadings of 0.54 and 1.61 mg/cm^2, the degradations in RB performance were about 30 and 60%, respectively. Figure 2.1 is a graphical presentation of these results.

Two homes in Chattanooga, Tennessee, have had HRBs in their attics for an extended period. An HRB had been installed for over five years in one house when the emissivity was measured at an average of 0.15. In the second house the HRB had been installed for about 1.5 years and its emissivity measured at an average of 0.10.

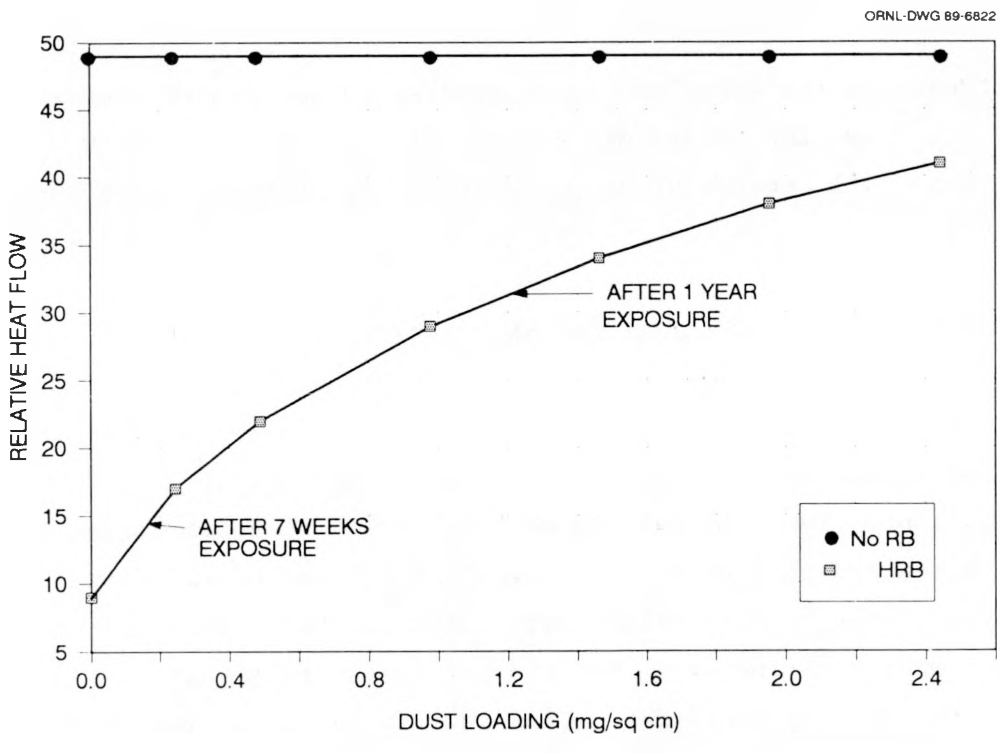


Fig. 2.1. Heat flow data.
Source: Lotz (1964).[17]

2.3 EFFECT OF DUST ON RADIANT BARRIER EMISSIVITY

Testing done by Yarbrough at Tennessee Technological University (18) in 1987 showed that small amounts of dust cause significant increases in RB emissivity. Yarbrough measured the emissivities of 46 RB samples containing various, known amounts of "Tennessee crawl space" dust. FSEC developed the following curve fit for the emissivity as a function of dust loading.

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

where "dust" is the dust loading in milligrams per square centimeter. Figure 2.2 shows the data and the curve fit. Testing at TVA has also shown that small amounts of dust significantly increase an RB's emissivity.

2.4 EFFECT OF DUST ON ACTUAL RADIANT BARRIER PERFORMANCE

Prior to the work discussed in this report, only two efforts had been made to measure actual HRB performance degradation from dust accumulation. The first was the work by Lotz[17] in South Africa in the 1960s, discussed in a previous paragraph. The second effort was conducted by TVA.[8] In a brief summer test in 1986[6] TVA found that a complete dust covering on an HRB did not appear to significantly degrade the HRB's performance. This surprising result led to more extensive tests during the summer of 1987.[9]

The TVA tests in the summer of 1987 used Arizona dust, which is commonly used for testing air filters, to simulate naturally occurring dust accumulation. This dust was sprinkled as evenly as possible on a small RB sample of known weight until an arbitrarily high emissivity (0.43) was reached. The dust weight and the area of the RB sample were

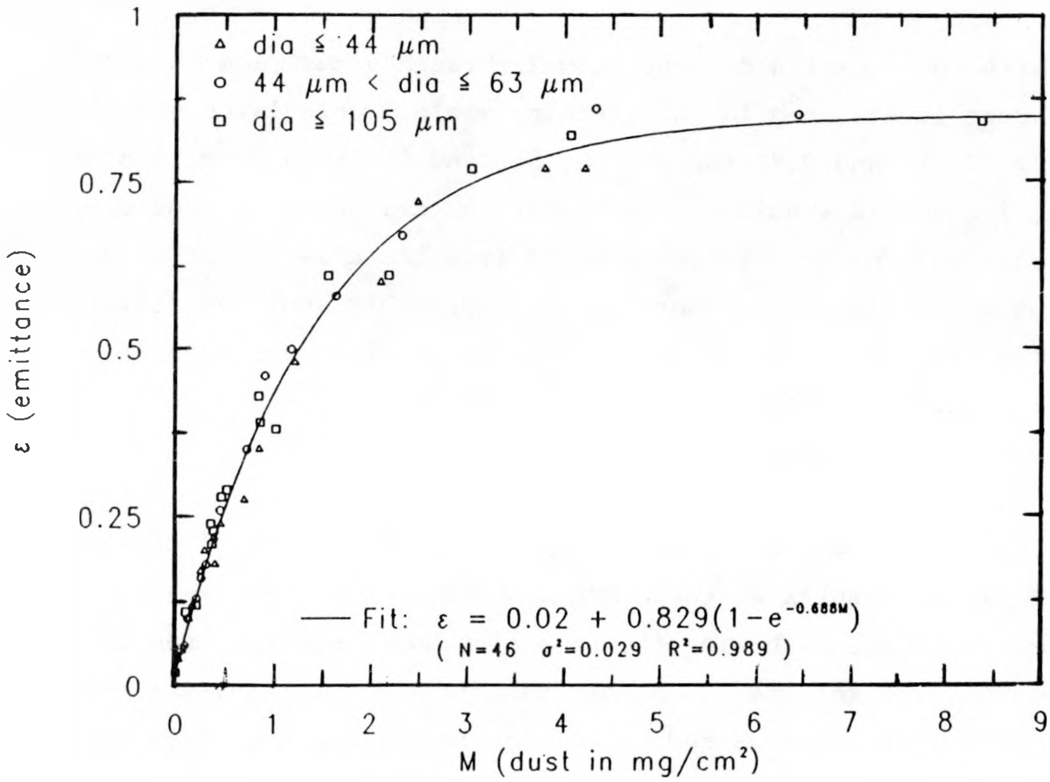


Fig. 2.2. Emissivity vs dust loading data.
Source: Yarbrough (1989).[18]

measured and used to calculate the amount of dust required for each HRB in each TVA test cell to give an HRB emissivity of 0.43. The result was 57 grams of dust for each 48 ft^2 test cell (or 1.28 mg/cm^2).

A heavier dust level was obtained by doubling the 57 grams to 114 grams (or 2.55 mg/cm^2), resulting in an average measured emissivity value of 0.51. A lighter dust loading of 31 grams (or 0.69 mg/cm^2) was also tested and yielded an average emissivity of 0.34.

With the equation derived from Yarbrough's dust and RB data,[16] the three dust levels used in this testing yielded calculated emissivities of 0.34, 0.51, and 0.71 for the 31, 57, and 114 gram dust loadings, respectively. It should be noted that the dust used by Tennessee Technological University was gathered from the crawl space of a Tennessee residence, and that this dust probably would be different from the Arizona dust used in the TVA tests. This variable may account for the emissivity differences (0.43 vs 0.51 and 0.51 vs 0.71) despite similar dust loadings.

Figures 2.3 and 2.4 are ceiling heat flux vs time-of-day graphs that show the results of these HRB and dust tests. Figures 2.5 through 2.7 are photographs showing the excessive dust loadings used in these tests. Results for the two higher dust levels (emissivities = 0.43 and 0.51) show that the measured reductions in ceiling heat flux (25% and 19%) for both dust levels were about half the usual 35-40% reductions from a clean HRB. Results for the lighter dust level (emissivity = 0.34) show that the dust degraded the ceiling heat flux by about one-third when compared to a clean HRB.

However, even with these excessive dust levels, which resulted in very high emissivities, the HRBs provided sizable and statistically significant reductions in the 20% range in ceiling heat flux. An important conclusion from this work is that "large dust accumulations...do degrade the performance of an HRB. Since the

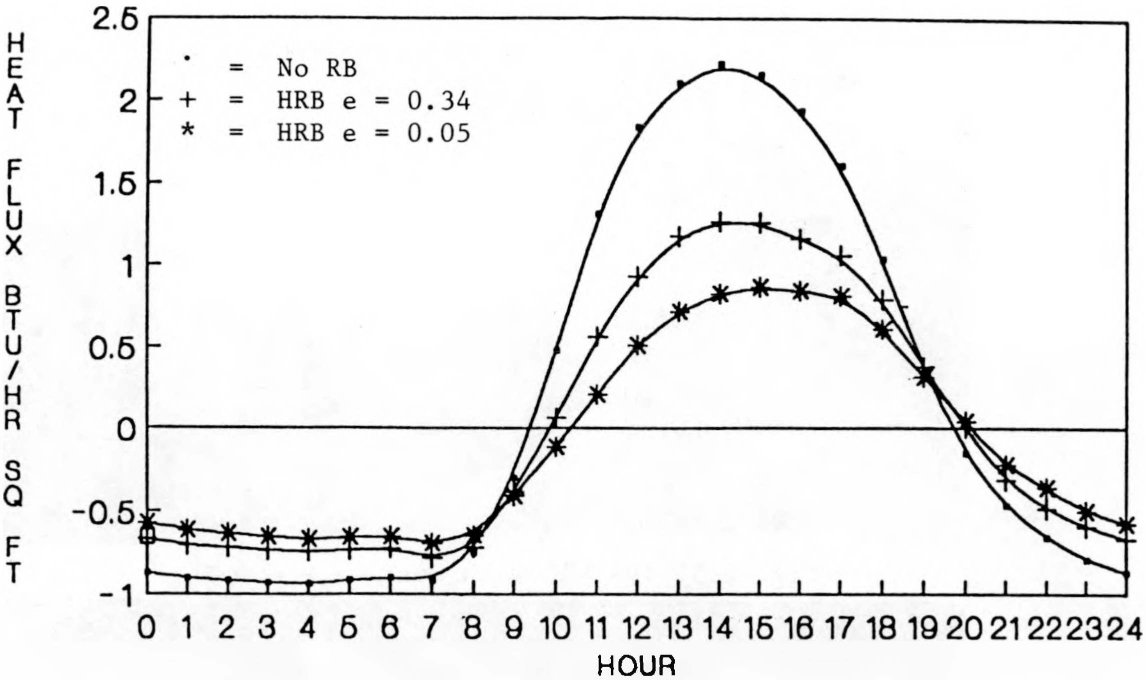


Fig. 2.3. TVA summer of 1987 data - attic heat flux with dusted HRB.

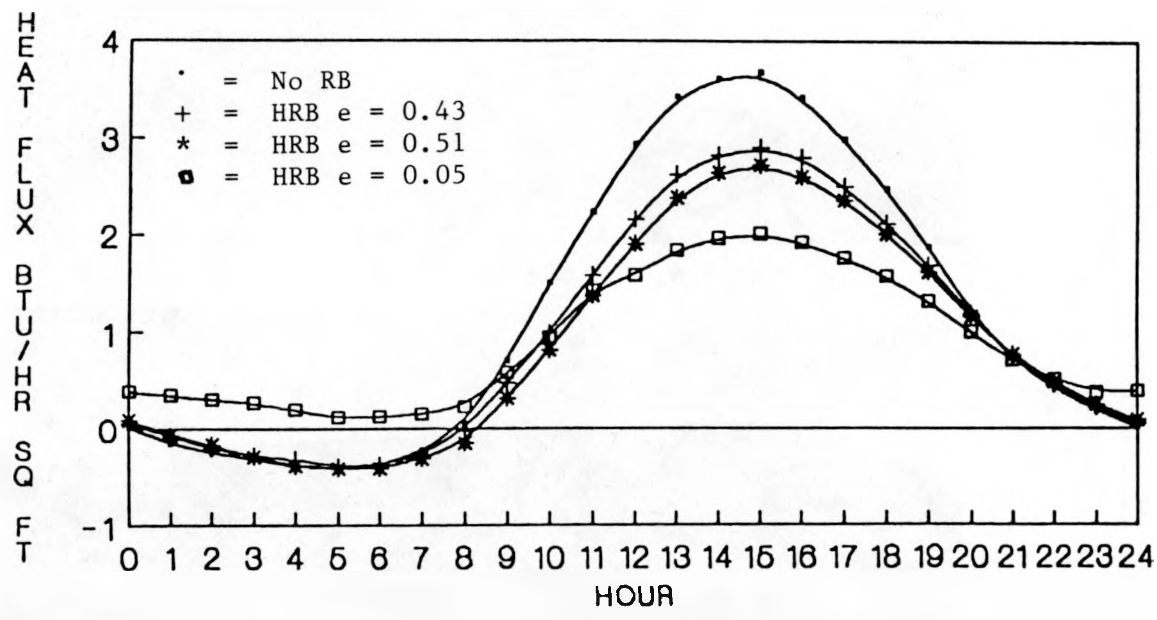


Fig. 2.4. TVA summer of 1987 data - attic heat flux with dusted HRB.

Fig. 2.5. TVA HRB with dust -- e = 0.34.

Fig. 2.6. TVA HRB with dust -- e = 0.43

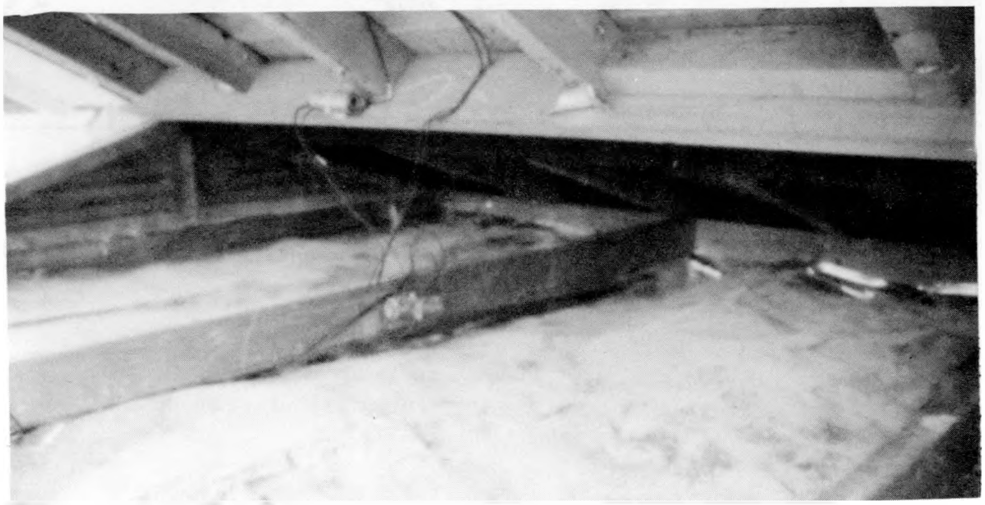


Fig. 2.7. TVA HRB with dust -- e = 0.51.

amounts of dust used resulted in excessive dust coverings, it may be that dust accumulation on an HRB is not a prohibitive problem." TVA researchers generally agreed that further testing was needed to confirm or refute these results.

3. BACKGROUND ON RADIANT BARRIER AND ATTIC VENTILATION ISSUES

3.1 HRB VS TRB PERFORMANCE DIFFERENCES

The various RB tests conducted over the last several years have not shown complete agreement in RB performance as a function of attic location. The following brief paragraphs summarize the pertinent results for performance as a function of RB location.

ORNL summer tests[1,5] have shown that an HRB performs better than a TRB. (This discussion centers on summer performance; thus far there has been no disagreement over winter performance, where an HRB performs better.) During the summer of 1985, tests with R-19 insulation showed that an HRB reduced the whole-house cooling load by 21%, while a TRB reduced the load by a much smaller (relatively) 13%. In the summer of 1986 tests with R-11 insulation, an HRB reduced the whole-house cooling load by 16%, while a TRB reduced the load by 11%.

FSEC tests with R-19 insulation showed that an HRB and a TRB yielded essentially similar results in unvented attics with 18 and 19% reductions in attic heat flux, respectively.[10] Also, other tests at FSEC with vented attics showed a TRB reducing ceiling heat fluxes by 40% or more, which is similar to the performance results found for an HRB (but not a TRB) in TVA and ORNL tests.

Tests at TVA have shown mixed results. During the summer of 1985 TVA tests with R-19,[7] an HRB reduced ceiling heat flux by 40%, while a TRB reduced ceiling heat flux by only 23%. However, in the summer of 1987 tests with R-19[9] HRBs and TRBs performed essentially the same. Relative to R-30, an HRB with R-19 reduced ceiling heat flux by 16%, while a TRB with R-19 reduced ceiling heat flux by 14%.

3.2 THEORIES FOR HRB AND TRB PERFORMANCE DIFFERENCES

In the FSEC tests mentioned above, where the TRB reduced ceiling heat fluxes by 40% or more, or in reductions similar to HRB results of TVA and ORNL tests, ridge/soffit attic ventilation was used. Otherwise, ORNL and TVA used gable/soffit attic ventilation for most of their tests. It was theorized that ridge venting could improve the performance of a TRB and thus account for the differences in test results.

One possible critical difference in the two TVA tests that gave mixed results was the amount of attic ventilation. In the summer of 1985 tests, the attic ventilation area was much higher (by a factor of 5) than the minimum area required by the Federal Housing Administration (FHA). In the summer of 1987 tests, the attic ventilation area was equal to the minimum area required by the FHA, or only 20% of the area used in the 1985 tests. Therefore, it was theorized that an HRB may be superior when attic ventilation area is high, but when the area is near that specified as the minimum by FHA, an HRB performs similarly to a TRB. Results from ORNL appear to partially back this theory as an HRB was superior, and the attic ventilation area of ORNL's houses was about twice the minimum FHA standard. It is difficult to evaluate FSEC's results from this perspective because the attics were vented artificially. However, FSEC did find that the performance of an HRB and a TRB were essentially equal in unvented attics.

4. EXPERIMENTAL SETUP

This section describes the testing setup results of the work done during the summer of 1988 at the Karns research houses. As mentioned earlier in the introduction, information pertaining to the construction and layout of the Karns houses is contained in Appendix A (Table A.1). More detail about the instrumentation used and data analysis methods are documented in references 1-4. A page of Nomenclature is provided at the front of this report to help decipher some of those acronyms and abbreviations which occur in the text, tables, and figures.

Three categories of tests were performed in this period -- attic ventilation area, attic ventilation type, and dust. Two main types of measurements were obtained for each test category -- house cooling load (in latent and sensible Btus, and in Wh electrical input to the air conditioner) and ceiling heat flux between the Great Room (Gr Rm) of each house and the attic above it.

Several important test parameters and techniques used in the testing are described herein. The results are described chronologically in the next section, with ventilation area effects, dust effects, and type of ventilation effects.

4.1 DESCRIPTION OF TEST SETUP

House No. 3 was used as the control house in this work. It was operated in the same manner throughout the testing -- no RBs were installed nor were any other modifications made to the control house. It had a 1/150 attic ventilation area ratio (AVR) with soffit and gable venting.

All houses had unfaced (no vapor barrier) R-19 fiberglass batts in their attics throughout the testing. Radiant barriers were either placed on the surface of the insulation (HRB) or stapled to the roof trusses (TRB), depending on the test requirements. The east and west facing wall ends of the attic under the gable vents were covered with RB material when TRBs were installed, but these walls were not covered when HRBs were installed.

Two types of RB material were used in this testing, and they came from two different sources. The HRB material was perforated, while the TRB material was not. Both materials had a low emissivity surface on each side. The emissivity of the perforated HRB material was 0.055, while that of the nonperforated TRB material was 0.035.

Although perforated HRB material had been used in previous work, the perforations in this current material were larger than those in the two previously tested HRB materials. This material had an average equivalent hole diameter of 88.2 mils (0.0882 in.) and an open area due to the perforations of 2.31% of the total area. The hole pattern in all samples was about the same, with holes approximately 5/8-in. on-center in an equilateral triangle pattern. Figure 4.1 (A-C) are photographs of the three types of HRB material. The material in Fig. 4.1 (C) is the material used in this work. Table 4.1 contains the results of the hole size distribution for the three materials as obtained by surface scan analysis techniques. Figure 4.2 graphically illustrates the hole size distribution for RB material C.

Results reported by ORNL in previous cooling experiments were for nonperforated HRB material, although perforated HRB materials A and B had been used in heating season testing. Since the measured emissivity of HRB material C was higher than either nonperforated or perforated RB materials A and B (0.055 for HRB C vs 0.035 for the other RB materials), logically one could not expect the same performance from material C as from the others.

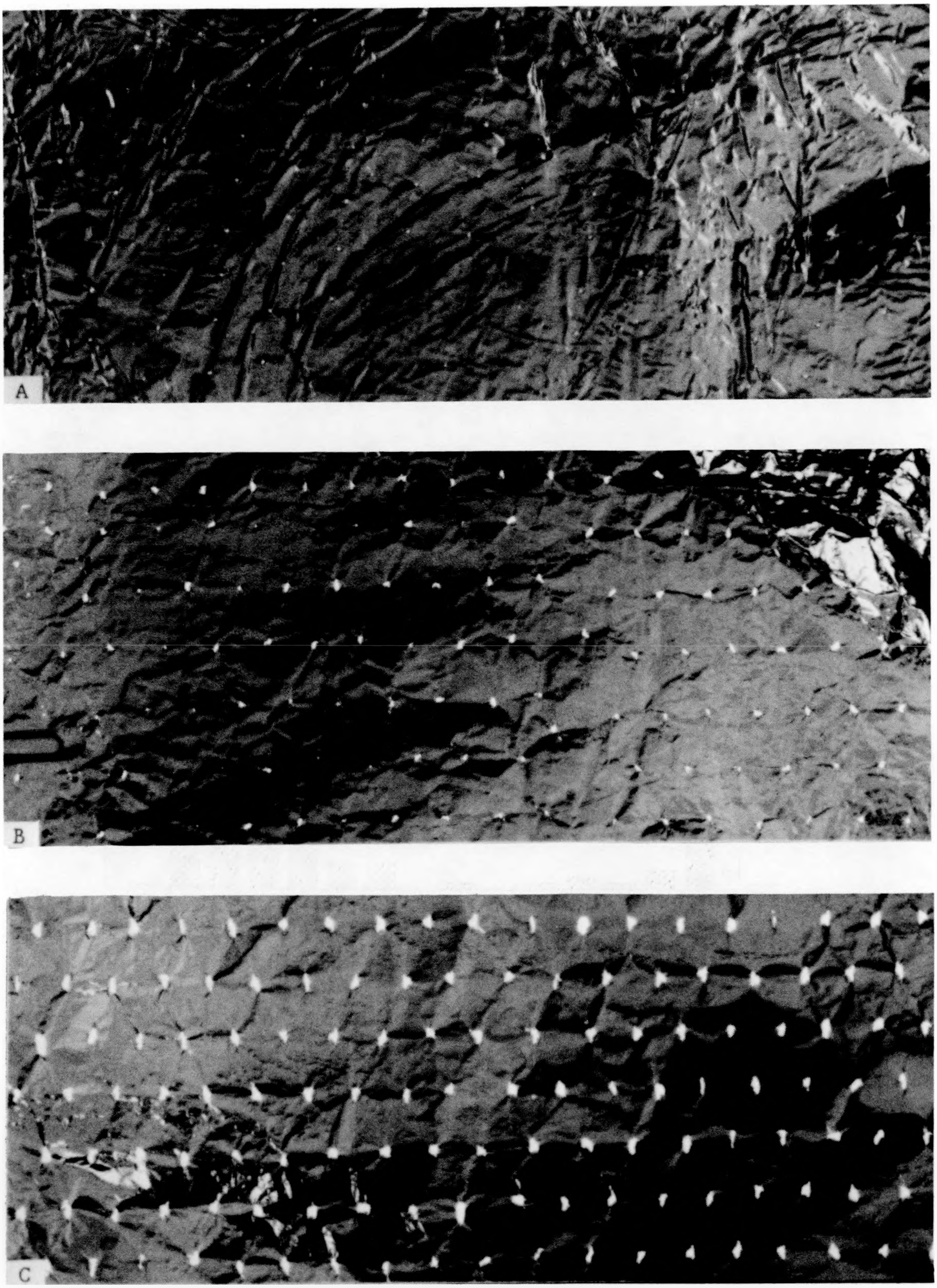


Fig. 4.1. HRB materials used at Karns.

Table 4.1 RESULTS OF SURFACE SCAN ANALYSIS OF RADIANT BARRIER MATERIALS USED IN TESTING AT KARNS

	AVERAGE HOLE SIZE (MILS) DISTRIBUTION (%)															
RB ID	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0	95.0	105.0	115.0	125.0	135.0	145.0	Avg Dia (Mils)	Hole Area (%)
A	52.0	38.0	7.0	3.0												12.7	0.05
B	14.5	19.5	9.5	7.5	9.6	15.8	13.5	8.0	2.1							39.9	0.46
C	20.0	3.0	1.0	2.0	1.0	0.0	1.0	0.0	4.0	4.0	14.0	20.5	20.5	8.0	1.0	88.2	2.31

Notes: Emissivity RB A = 0.035
Emissivity RB B = 0.035
Emissivity RB C = 0.055

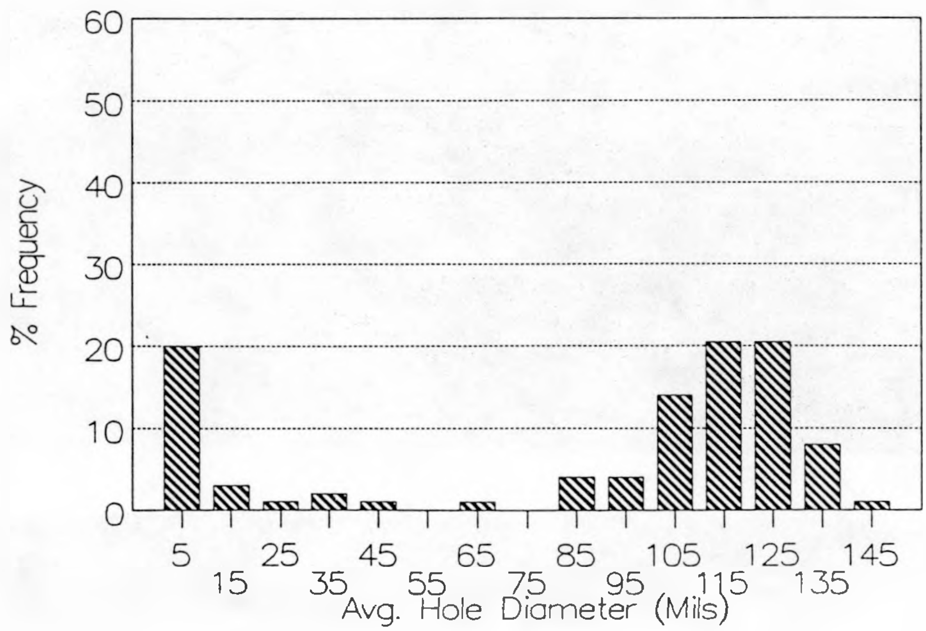


Fig. 4.2. Hole size distribution of radiant barrier material C by surface scan analysis.

Another difference between this testing and previous TRB testing concerned the end walls of the attics under the gable vents. These end walls were not covered with RB material during previous testing, but as mentioned earlier, the east and west facing attic walls were covered with RB material for the current TRB testing.

All heat flux data contained in this report are from a single 2.25 x 2.25-in., Hy-Cal heat flux transducer located in the center of the Great Room in each house on the attic side of the ceiling. The heat flux sensors were under the attic insulation midway between the bottom chords of two roof trusses. The heat flux data therefore are not indicative of the whole attic heat flux but only that well-insulated portion of the attic where the heat flux transducer was located.

The method used to analyze the data collected in this work consisted of fitting linear regression models to each of the three houses, using cooling loads and electrical input to the air conditioner as respective depent variables. In each case the independent variable was the temperature difference between the outside air and the inside air temperatures, (To-Ti). Regression lines were used to normalize the loads for each house using the same mean interior load and (To-Ti) for each respective test period.

Normalized loads were then made relative to the control house by division by the corresponding control house loads. The ratios between the load of each house to that of the control house during the calibration run were used as the calibration factors.

The relative normalized load for each house was then divided by its calibration factor to determine the effect of each modification relative to the same house without the modification.

5. RESULTS

5.1 EFFECTS OF ATTIC VENTILATION AREA RATIO

To make a comparison of the control house with the other two test houses and their retrofits, it was necessary to obtain a calibration comparison among all three houses. The calibration was, therefore, the first series of tests to be performed. All houses were outfitted in the same manner as the control house (i.e., R-19 in the attic, no RBs, 1/150 AVR). Table 5.1 contains the results of the cooling load and electrical usage calibration data, which took place between June 7-29, 1988.

After the calibration tests were completed, house No. 1 was fitted with a nonperforated TRB and house No. 2 with a perforated HRB. The AVRs of houses No. 1 and No. 2 were both reduced from 1/150 to 1/300 by temporarily blocking off half the gable and soffit area with cardboard coverings on each end of each house. The configuration of house No. 3, the control house, was not changed. Table 5.2 contains the results of the cooling load and electrical usage data for this two-week period of testing.

After this testing period the cardboard coverings on the gable and soffit vents were then removed, restoring the AVR of each house back to the original 1/150. The RBs were left in houses No. 1 and No. 2. Another approximately two-week test was run under these conditions, and the results are presented in Table 5.3.

Table 5.4 contains a summary of the results from the data contained in Tables 5.1 through 5.3, which are presented in more detail in Tables 5.21 and 5.23. These normalized results compare the results of the retrofit to the same house results without a retrofit.

Table 5.1. Karns Cooling Calibration Data - No Radiant Barriers

House No./ Insulation	Dates From-To	Sensible Btu	Latent Btu	Total Btu	Electric Watt-hr	Cooling COP	Total Hours
		|<----- Average Hourly Values ----->|					
1 R-19	Jun 07-09	6302	430	6732	1049	1.881	46
2 R-19	Jun 07-09	7995	642	8638	1198	2.112	46
3 R-19	Jun 07-09	6510	445	6955	1155	1.765	46
1 R-19	Jun 13-15	5546	502	6047	926	1.914	48
2 R-19	Jun 13-15	6091	448	6540	919	2.085	48
3 R-19	Jun 13-15	5655	522	6178	992	1.824	48
1 R-19	Jun 15-22	6417	975	7392	1090	1.986	168
2 R-19	Jun 15-22	7426	764	8190	1140	2.105	168
3 R-19	Jun 15-22	6766	819	7584	1198	1.855	168
1 R-19	Jun 22-29	6859	1080	7938	1197	1.943	166
2 R-19	Jun 22-29	8755	1069	9824	1377	2.090	166
3 R-19	Jun 22-29	7347	997	8344	1331	1.837	166
1 R-19	TOTALS	2772599	386950	3159549	474551	1.951	428
2 R-19	TOTALS	3361034	356796	3717831	519327	2.098	428
3 R-19	TOTALS	2927153	348507	3275660	522914	1.835	428

Note: TOTALS are sums of (hourly value x hours) for each period
#3 Sens, Lat, and Total Btu for Jun 07-09 are Estimates
Ventilation Ratio is 1/150 for all houses

Table 5.2. Karns Cooling Data - Radiant Barriers with 1/300 Vent Ratio

House No./ Insulation	Dates From-To	Sensible Btu	Latent Btu	Total Btu	Electric Watt-hr	Cooling COP	Total Hours
		|<----- Average Hourly Values ----->|					
1 R19+TRB	Jun 29-Jul 6	3621	507	4128	598	2.023	163
2 R19+HRB	Jun 29-Jul 6	4710	535	5245	723	2.125	163
3 R-19	Jun 29-Jul 6	4057	564	4621	730	1.854	163
1 R19+TRB	Jul 06-13	6387	801	7188	1120	1.881	166
2 R19+HRB	Jul 06-13	7394	849	8242	1186	2.037	166
3 R-19	Jul 06-13	7258	991	8249	1316	1.836	166
1 R19+TRB	TOTALS	1650513	215692	1866205	283359	1.930	329
2 R19+HRB	TOTALS	1995155	228028	2223182	314752	2.070	329
3 R-19	TOTALS	1866202	256426	2122628	337499	1.843	329

Note: TOTALS are sums of (hourly value x hours) for each period
Ventilation Ratio is 1/300 for House #1,#2; #3 is 1/150

Table 5.3. Karns Cooling Data - Radiant Barriers with 1/150 Vent Ratio

House No./ Insulation	Dates From-To	Sensible Btu	Latent Btu	Total Btu	Electric Watt-hr	Cooling COP	Total Hours
		|<----- Average Hourly Values ----->|					
1 R19+TRB	Jul 13-19	6493	1482	7975	1186	1.970	147
2 R19+HRB	Jul 13-19	7532	1523	9055	1258	2.110	147
3 R-19	Jul 13-19	7204	1539	8742	1379	1.858	147
1 R19+TRB	Jul 19-25	4989	1092	6081	874	2.038	140
2 R19+HRB	Jul 19-25	5924	1204	7128	944	2.213	140
3 R-19	Jul 19-25	5644	1284	6927	1041	1.950	140
1 R19+TRB	TOTALS	1652931	370738	2023669	296784	1.998	287
2 R19+HRB	TOTALS	1936618	392408	2329027	317002	2.153	287
3 R-19	TOTALS	1849074	405869	2254943	348423	1.896	287

Note: TOTALS are sums of (hourly value x hours) for each period
Ventilation Ratio is 1/150 for all houses

Normalized results are obtained by adjusting the regression lines for each house to the same average (To-Ti) during the testing period and also to the same interior loads. These loads are made relative to the control house load for the same period and then divided by the calibration results relative to the control house.

Table 5.4. Summary of Ventilation Testing

House	Attic Setup	Attic AVR	% Difference in: Btu Load	A/C W-Hr
1	TRB HV	1/300	-8.84	-6.28
1	TRB FV	1/150	-7.05	-5.63
2	HRB HV	1/300	-9.31	-8.36
2	HRB FV	1/150	-9.52	-10.42

Table 5.21 shows that the calibration factors for each house are not equal. The calibration factor is defined as the ratio of the total cooling load for a house (with no RB) divided by the total cooling load for house No. 3, the control house. House No. 1 has a load 0.5% lower than that for house No. 3, while house No. 2 has a cooling load 14.5% higher than that for house No. 3. These results are similar to those obtained in previous summer seasons and illustrate the reason why normalization of the test data is necessary.

Table 5.4 shows that a TRB with an AVR of 1/150 reduced the cooling load of house No. 1 by 7.0% compared to house No. 1 with no RB, while the same TRB at an AVR of 1/300 reduced the house No. 1 cooling load by 8.8%.

Table 5.4 also shows that an HRB at an AVR of 1/150 reduced the cooling load of house No. 2 by 9.5% compared to house No. 2 with no RB, while the same HRB at an AVR of 1/300 reduced the house No. 2 cooling load by 9.3%.

Unfortunately, time did not permit a calibration among the houses at a 1/300 AVR, so the results reported in Table 5.4 for RBs with a 1/300 AVR should be viewed with caution. They cannot be directly compared to the 1/150 AVR results, since the 1/300 results are normalized to a 1/150 AVR calibration. What this means is that the 1/300 AVR RB results contain the sum of the effects of both RBs and a 1/300 AVR compared to the same house with an AVR of 1/150 and no RB. However, since these numbers are so close, the best way to interpret them is to say that reducing the AVR at Karns (under the present test setup conditions) from 1/150 (which is twice the recommended minimum AVR for each Karns test house) to 1/300 (which is the recommended minimum ratio) has no effect on the total cooling load. Although there is a large percentage difference between the numbers, the absolute values of the numbers are rather close. We are probably operating near the limits of the experimental measurement accuracy, house behavior, and the normalization assumptions made for testing of this type.

Table 5.4 shows that the HVAC electrical inputs are behaving in a manner similar to the cooling loads, which they should. The TRB input was reduced by 5.6% at 1/150 and 6.3% at 1/300. The HRB input was reduced by 10.4% at 1/150 and 8.4% at 1/300. These numbers are again rather close, and prudence probably would suggest calling things even.

At the Karns testing facility, it appears that a doubling of the AVR from a recommended minimum of 1/300 to 1/150 with soffit and gable venting has little if any effect on reduction of cooling loads or HVAC cooling electrical input by either HRB or TRB installation.

The net heat flux data between the Great Room and the attic area above it during the calibration period are contained in Table 5.5. The heat flux data corresponding to the testing at AVRs of 1/300 and 1/150 with TRBs and HRBs are contained in Tables 5.6 and 5.7, respectively.

Table 5.5. Karns Net Attic Heat Flux - No Radiant Barriers

House No./ Insulation	Dates From-To	Hour	Average BTUSFH	Total BTUSF	Ratio #H/#3
#1 R-19	Jun 07-09	46	1.14	52.25	0.759
#2 R-19	Jun 07-09	46	1.55	71.16	1.033
#3 R-19	Jun 07-09	46	1.50	68.86	1.000
#1 R-19	Jun 13-15	48	1.04	49.77	0.751
#2 R-19	Jun 13-15	48	1.37	65.82	0.993
#3 R-19	Jun 13-15	48	1.38	66.26	1.000
#1 R-19	Jun 15-22	168	1.07	179.32	0.740
#2 R-19	Jun 15-22	168	1.42	237.75	0.981
#3 R-19	Jun 15-22	168	1.44	242.46	1.000
#1 R-19	Jun 22-29	166	1.11	183.51	0.730
#2 R-19	Jun 22-29	166	1.56	259.73	1.033
#3 R-19	Jun 22-29	166	1.51	251.48	1.000
#1 R-19	TOTALS	428	1.09	464.85	0.739
#2 R-19	TOTALS	428	1.48	634.46	1.009
#3 R-19	TOTALS	428	1.47	629.06	1.000

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

Table 5.6. Karns Net Attic Heat Flux – RBs with 1/300 AVR

House No./ Insulation	Dates From-To	Hour	Average BTUSFH	Total BTUSF	Ratio #H/#3
#1 R19+TRB	Jun 29–Jul	163	0.45	73.32	0.583
#2 R19+HRB	Jun 29–Jul	163	0.52	84.53	0.673
#3 R-19	Jun 29–Jul	163	0.77	125.66	1.000
#1 R19+TRB	Jul 06-13	166	0.83	137.95	0.576
#2 R19+HRB	Jul 06-13	166	0.94	156.13	0.652
#3 R-19	Jul 06-13	166	1.44	239.57	1.000
#1 R19+TRB	TOTALS	329	0.64	211.27	0.578
#2 R19+HRB	TOTALS	329	0.73	240.66	0.659
#3 R-19	TOTALS	329	1.11	365.23	1.000

Notes: Attic Vent Ratio is 1/150 for #3

Table 5.7. Karns Net Attic Heat Flux – RBs with 1/150 AVR

House No./ Insulation	Dates From-To	Hour	Average BTUSFH	Total BTUSF	Ratio #H/#3
#1 R19+TB	Jul 13-19	147	0.79	116.56	0.527
#2 R19+HB	Jul 13-19	147	0.92	135.67	0.613
#3 R-19	Jul 13-19	147	1.51	221.37	1.000
#1 R19+TB	Jul 19-25	140	0.59	82.19	0.532
#2 R19+HB	Jul 19-25	140	0.66	92.30	0.598
#3 R-19	Jul 19-25	140	1.10	154.36	1.000
#1 R19+TB	TOTALS	287	0.69	198.74	0.529
#2 R19+HB	TOTALS	287	0.79	227.97	0.607
#3 R-19	TOTALS	287	1.31	375.74	1.000

Notes: Totals are sums of (hourly value x hours)

Table 5.8 is a summary table comparing the heat flux data from Tables 5.5 through 5.7. Figure 5.1 graphically depicts the measured heat flux reductions contained in Table 5.8. The same caveats apply to Table 5.8 as did to Table 5.4.

The heat flux attic calibration factors (no RBs) show house No. 1 to be 26.1% less than house No. 3 (the control house), while house No. 2 is 0.9% higher than house No. 3. Again, keep in mind that the attic heat flux measurements are not an average value but only a measurement for one 2.25 x 2.25-in. area in the attic.

Figure 5.1 shows that a TRB with an AVR of 1/300 reduced the ceiling heat flux by 21.7% compared to no RB, while a TRB with an AVR of 1/150 reduced heat flux by 28.4% compared to no RB.

Figure 5.1 also shows that an HRB with an AVR of 1/300 reduced the ceiling heat flux by 34.7% compared to no RB, while the same HRB with an AVR of 1/150 reduced the heat flux by 39.8% compared to no RB.

The heat flux measurements show that both TRBs and HRBs are more effective at reducing attic heat transfer as the AVR is increased. Both types of RB appear to be 5 to 6 percentage points more effective when the AVR is twice the minimum recommended value. The HRB did not increase in effectiveness any more than the TRB as the AVR was increased.

Although both types of RBs were effective in reducing total house cooling loads and attic heat flow, a direct comparison of the results shows that an HRB is slightly more effective than a TRB in reducing cooling loads. Two things to keep in mind in this comparison follow.

Each heat flux sensor is measuring only one small, well insulated area of the attic and not the average heat flow in the entire attic. Presumably those areas of the ceiling gypsum board with roof truss

Table 5.8. Comparison of Net Heat Flux Data with and without Radiant Barriers

	1/150 Vent Ratio No Barriers			1/150 Vent Ratio W Barriers			1/300 Vent Ratio W Barriers		
	#1 R-19	#2 R-19	#3 R-19	#1 R19+TB	#2 R19+HB	#3 R-19	#1 R19+TB	#2 R19+HB	#3 R-19
Total Heat Flux (BTUSF)	464.85	634.46	629.06	198.74	227.97	375.74	211.27	240.66	365.23
Relative Total Ht Flux	0.739	1.009	1.000	0.529	0.607	1.000	0.578	0.659	1.000
Normalized Total Ht Flux	---	---	---	0.716	0.602	1.000	0.783	0.653	1.000

Notes: House #3 is Control House, AVR kept at 1/150
Horizontal Barrier is Perforated, 2.31% Open Area

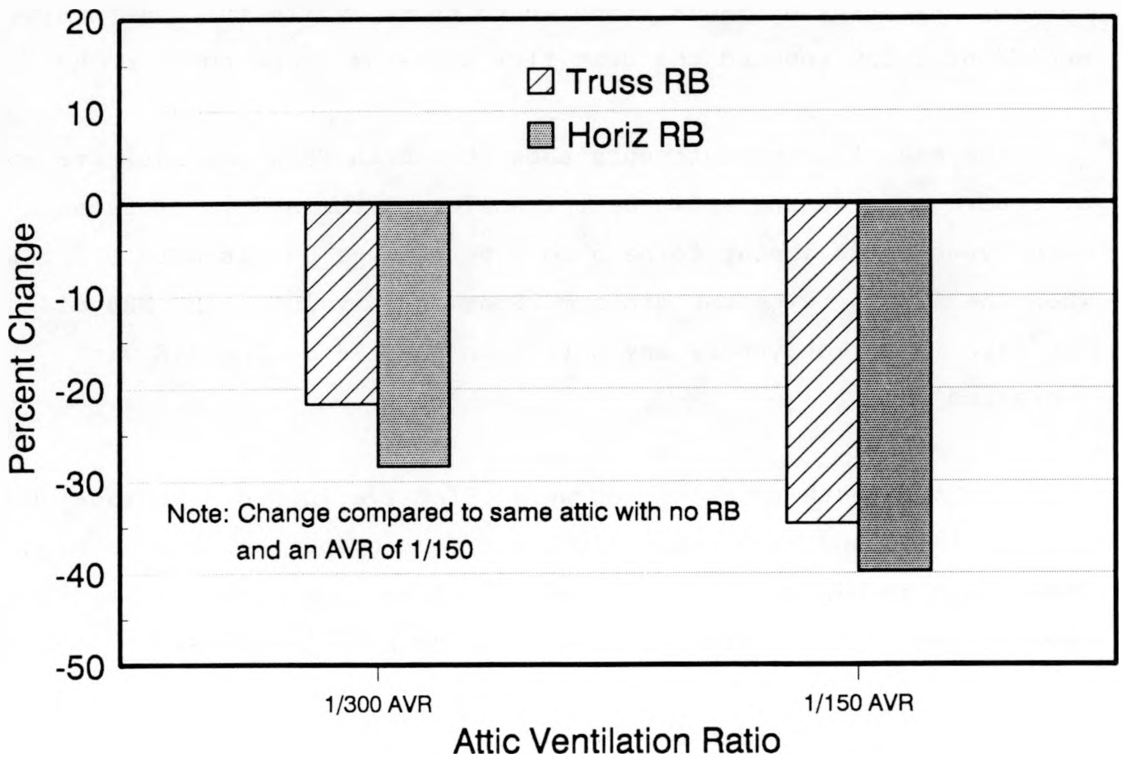


Fig. 5.1. Effect of attic vent ratio/RB type on net attic heat flux.

members over them would conduct more heat and thereby increase the overall attic heat conduction. Also, heat flux sensors only show sensible heat transfer, provided no phase change (condensation or evaporation) takes place in the vicinity of the sensor. The total house load, however, includes both sensible and latent components as seen by the evaporator coil of the air conditioner.

The second factor concerns the percentage of the total cooling load that the roof supplies. DOE-2 simulations of a Karns house with R-19 attic insulation have shown that the roof supplies 25.8% of the total house cooling load.[3] Therefore, total house load reductions should be about one-fourth of the attic heat flow reduction, providing a RB does not change any other house energy load sources such as infiltration, latent loads, etc. Since attic heat flow reductions of 22 to 40% were measured, house cooling load reductions of about 5 to 10% would be expected. The measured load reductions ranged from 7 to 9.5%, so it would appear that heat flows and loads are in the right orders of magnitude for this testing.

Another difficult comparison to make from these data involves the relative effectiveness of TRBs compared to HRBs for this test vs previous ORNL tests. The large perforations (and accompanying higher emissivity) in the HRB are a possible cause of this. Past Karns results were obtained with HRB and TRB materials that had equal emissivities. In the current experiment, the HRB emissivity was significantly higher than that of the TRB (0.055 vs 0.035). Also, the gable end walls of the houses were not covered with RB material for the TRB installation in past Karns tests. The additional RB material added to the attics under the gable ends for the TRB installation most likely increases the TRB effectiveness. This TRB/HRB comparison is discussed again later in the report.

5.2 RESULTS OF DUST EXPERIMENTS

5.2.1 Dust Measurements Setup

TVA ran a series of tests in small test cells in Chattanooga which were described in Sect. 3. An air cleaner dust (commonly called "Arizona dust") was used for their experiments. We decided to use the same dust for our summer 1988 experiments at Karns. Table A.4 in Appendix A contains a characterization of the dust that we used.

Based on discussions with TVA personnel and on their dust experiments, we decided to use levels of 0.34 and 0.74 mg/cm^2. We figured 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 that we used were 0.125 and 0.185, respectively.

Many methods of applying the dust to the HRB were discussed and tried before we decided upon the method that gave the best results. We applied weighed amounts of the dust manually (using salt shakers) over small areas between the roof truss bottom chords. All of the more exotic and easier methods we tried, such as using compressed air, did not work well.

House No. 3 again was used as the control house (no RB). The AVR was returned to 1/150 for all three houses during the dust testing. The R-19 attic fiberglass batt attic insulation in all houses remained unchanged. A perforated HRB was installed in house No. 1 by an insulation contractor (house No. 2 already had an HRB in it from the AVR testing). The first phase of the dust testing involved a calibration run with no dust on the RBs. When calibration testing was completed, the heavier dust loading of 0.74 mg/cm^2 was applied to the

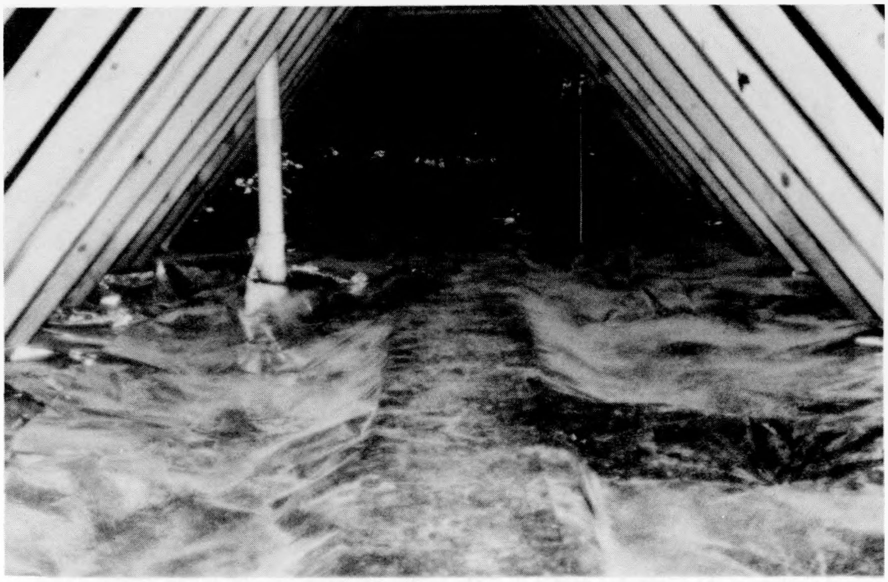
HRB in house No. 1, and the lighter loading of 0.34 mg/cm^2 was applied to the HRB in house No. 2. The dust phase of the test was then started.

Figure 5.2(a) is a photograph of the attic of house No. 1 showing the heavier level of dust on the HRB, while Fig. 5.2(b) shows the attic of house No. 2 with the lighter dust level. Figure 5.3(a) shows a closer view of the heavy dust loading on the HRB in house No. 1, while Fig. 5.3(b) shows a closer view of the lighter dust loading on the HRB in house No. 2. Figure 5.3(c) shows for comparison purposes a small piece of undusted HRB material atop the heavier-dusted HRB material in house No. 1.

After the artificial dusting was completed, it was apparent that the dust did not cling tightly to the surface of the HRB. It could be easily blown or shaken off the surface. Observations of natural dust on other surfaces in the attic reveal that the natural dust appears to adhere to a surface better than the Arizona road dust. Other airborne pollutants in the attic, such as pollens, probably provide the mechanism for the better adhesion.

The emissivities of the HRB and the dust samples were determined by carefully measuring the area of a small box (approximately 3 x 5 in.) and weighing out samples of the Arizona dust. A weighed dust sample was put in the box and the box was shaken so 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 the sample was cut from the attic HRB and brought down from the attic for an emissivity measurement.



(a) Heavy dust level - 0.74 mg/cm^2 - house #1.

(b) Light dust level - 0.34 mg/cm^2 - house #2.

Fig. 5.2. Karns attics after dusting.

5.2.2 Dust Test Results

Table 5.9 contains the results of both the cooling load and electrical input to the air conditioner of the no-dust HRB calibration tests. This test was necessary as a reference point to determine the effect that dust had on HRB performance. Dust loadings of 0.74 mg/cm^2 and 0.34 mg/cm^2 were then added to the HRBs in houses No. 1 and 2, respectively. Table 5.10 contains the cooling load and electrical input results of the dusted HRB testing.

Table 5.11 summarizes the results of Tables 5.9 and 5.10 and contains the normalized experimental cooling load and electrical input results, including the results of the initial calibration runs when no RBs were installed in the houses and the AVR was 1/150. This table, therefore, compares the dust results relative to R-19 attic insulation with no RBs. These data are shown in more detail in Table 5.21 and 5.22. Note that an HRB appears to be more effective in house No. 1 than in house No. 2 as the cooling load of house No. 1 was reduced by 14.3% with the addition of a clean HRB, while that of house No. 2 was reduced only 9.5% with the clean HRB. The corresponding air conditioner electrical inputs to houses No. 1 and No. 2 were reduced by 9.3% and 10.0%, respectively.

House No. 1 showed a cooling load reduction of 7.0% with a dust loading of 0.74 mg/cm^2 (e = 0.185) compared to no HRB, while that in house No. 2 was reduced by 7.4% compared to no HRB after receiving a dust load of 0.34 mg/cm (e = 0.125). The corresponding air conditioning electrical inputs were reduced by 4.8 and 8.5%, respectively.

The effect of dust relative to a clean HRB in the same house may be obtained from Table 5.21, which shows that a heavier dust loading on the HRB in house No. 1 increased the total cooling load by 8.4%. The

Table 5.9. Karns Houses Cooling Data - Horiz Radiant Barriers No Dust

House No./ Insulation	Dates From-To	Average Hourly Values				Cooling COP	Total Hours
		Sensible Btu	Latent Btu	Total Btu	Electric Watt-hr		
1 R19-HB	Jul 25-Aug 1	5498	1069	6568	959	2.007	165
2 R19-HB	Jul 25-Aug 1	6812	1313	8125	1077	2.210	165
3 R19	Jul 25-Aug 1	6534	1536	8070	1189	1.989	165
1 R19-HB	TOTALS	907246	176436	1083682	158199	2.007	165
2 R19-HB	TOTALS	1123958	216687	1340646	177753	2.210	165
3 R-19	TOTALS	1078184	253382	1331566	196185	1.989	165

Note: Ventilation Ratio is 1/150 for all houses

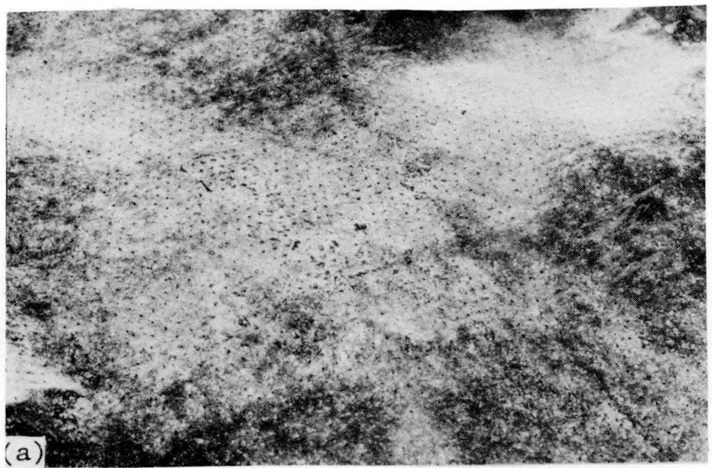
Table 5.10. Karns Houses Cooling Data - Radiant Barriers with Dust

House No./ Insulation	Dates From-To	Average Hourly Values				Cooling COP	Total Hours
		Sensible Btu	Latent Btu	Total Btu	Electric Watt-hr		
1 R19-HB	Aug 1-8	5644	1383	7026	993	2.072	144
2 R19-HB	Aug 1-8	6812	1399	8210	1090	2.207	144
3 R-19	Aug 1-8	6364	1620	7984	1180	1.982	144
1 R19-HB	Aug 8-15	6375	1414	7789	1137	2.007	167
2 R19-HB	Aug 8-15	7922	1549	9471	1252	2.216	167
3 R19	Aug 8-15	7280	1706	8987	1344	1.958	167
1 R19-HB	TOTALS	1877373	435227	2312600	332929	2.035	311
2 R19-HB	TOTALS	2303808	460127	2763934	366047	2.212	311
3 R-19	TOTALS	2132236	518198	2650434	394445	1.969	311

Note: TOTALS are sums of (hourly value x hours) for each period
Ventilation Ratio is 1/150 for all houses
#2 Dust Loading = 0.34 mg/sq cm
#1 Dust Loading = 0.74 mg/sq cm

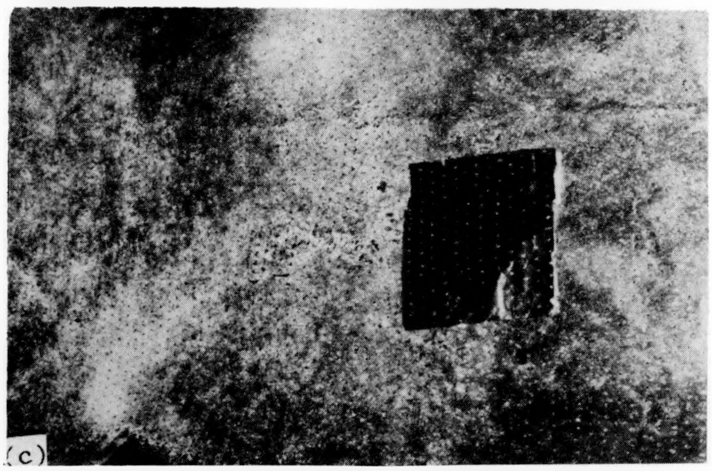
Table 5.11. Summary of Dust Testing

House	Attic Setup	Attic AVR	% Difference in:	
			Btu Load	A/C W-Hr
1	HRB FV	1/150	-14.29	-9.30
1	HRB Dust	1/150	-7.05	-4.79
2	HRB HV	1/300	-9.51	-10.03
2	HRB Dust	1/150	-7.38	-8.47



(a) Heavy dust level - 0.74 mg/cm^2 - house #1.

(b) Light dust level - 0.34 mg/cm^2 - house #2.



(c) Heavy dust level with undusted sample.

Fig. 5.3. Closeup view of dusted HRB at Karns.

lighter HRB dust loading in house No. 2 increased the total house cooling load by 2.3%. The corresponding increase in air conditioner electrical input was 4.9% in house No. 1 and 1.7% in house No. 2.

The weakest result in Table 5.11 involves the reduction in A/C electrical input to House No. 1 in the pre-dust test. Data acquisition problems arose on the channel recording this data, so that only about 15% of the hourly data were valid.

Table 5.13 contains the results of attic heat flow measurements made with clean HRBs in houses No. 2 and No. 3. Table 5.14 contains the results of attic heat flow measurements with dusted HRBs in houses No. 2 and No. 3. Table 5.15 summarizes and normalizes the results from Tables 5.13 and 5.14, showing that the attic heat flow in house No. 1, with the heavier dust loading, is increased by 28.4% compared to that of house No. 1 with a clean HRB. Table 5.15 also shows that the attic heat flow in house No. 2 with the lighter dust loading is only increased by 12.6% compared to that of house No. 2 with a clean HRB.

Using our DOE-2 simulation predictions (25.8%) of cooling load contributions from R-19 attics (as was done in Sect. 5.1), these measured increases in attic heat flows would be expected to increase the total cooling load by about 7 and 3% in houses No. 1 and No. 2, respectively. The measured load increases of 8.4 and 2.3% for the respective houses are close to these values, so we can assume that the data are sufficiently consistent.

5.3 RESULTS OF RIDGE/GABLE VENT TESTING

5.3.1 Ridge/Gable Setup

All three Karns houses initially were built with gable vents. Soffit vents were added to all houses at the beginning of RB testing at

Table 5.12. Karns Net Attic Heat Flux - HRBs with No Dust

House No./ Insulation	Dates From-To	Hour	Average BTUSFH	Total BTUSF	Ratio #H/#3
#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 5.13. Karns Net Attic Heat Flux - HRBs with Dust

House No./ Insulation	Dates From-To	Hour	Average BTUSFH	Total BTUSF	Ratio #H/#3
#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

Table 5.14. Comparison of Net Heat Flux Data with HRB's

	1/150 Vent Ratio No Barriers			1/150 Vent Ratio w Dust		
	#1 R19+HB	#2 R19+HB	#3 R-19	#1 R19+HB	#2 R19+HB	#3 R-19
Total Heat Flux (BTUSF)	88.06	131.98	223.34	214.62	281.92	423.84
Relative Total Ht Flux	0.394	0.591	1.000	0.506	0.665	1.000
Normalized Total Ht Flux	---	---	---	1.284	1.126	1.000

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

Karns in June of 1985. The AVR in each house was 1/150 after the soffit vents were installed. The last phase of the summer 1988 testing was designed to test the effect of the type of attic venting, either ridge/soffit or gable/soffit, on the performance of TRBs. The R-19 fiberglass batt insulation in the attics was not changed.

A roofing contractor who was experienced in retrofitting ridge vents was called in to install a ridge vent in house No. 1. After the ridge vent was in place, our insulation contractor installed nonperforated TRBs in houses No. 1 and No. 2. The gable vents in house No. 1 were blocked off by taping cardboard over them.

The ridge vent installed in house No. 1 had a net free area of 18 $in.^2/ft$ of length. Approximately 42 feet of ridge vent with an net free area of 5.25 ft^2 were installed on house No. 1. Since the effective open area of the soffit vents is 3.52 ft^2, house No. 1 had an AVR of 1/137. This setup makes the AVR in both house No. 1 (ridge/soffit) and house No. 2 (gable/soffit) approximately equal.

5.3.2 Ventilation Type Results

Table 5.15 contains the experimental results of the testing with a TRB and a ridge vent in house No. 1 and a TRB and a gable vent in house No. 2. The TRBs were removed from both houses after these tests, and a calibration run was made comparing the houses without RBs, but with ridge or gable vents in the respective houses. Table 5.16 contains the results of this test. Table 5.17 contains a summary of the normalized results of the data from Tables 5.15 and 5.16, so that they may be compared directly. Tables 5.22 and 5.24 contain more detail than Table 5.17 on the normalization.

Table 5.17 shows that a TRB/ridge vent reduced the cooling load in house No. 1 by 8.3% compared to no RB and a ridge vent, while a TRB/gable vent reduced the cooling load in house No. 2 by 9.2% compared

Table 5.15. Karns Houses Cooling Data - Truss RBs with Ridge and Gable Vents

House No./ Insulation	Dates From-To	Average Hourly Values Sensible Btu	Latent Btu	Total Btu	Electric Watt-hr	Cooling COP	Total Hours
1 R19+RV+TB	Aug 18-25	4867	1163	6030	868	2.035	163
2 R19+GV+TB	Aug 18-25	6168	1324	7492	993	2.211	163
3 R-19	Aug 18-25	5524	1548	7072	1029	2.015	163
1 R19+RV+TB	Aug 25-Sep 1	4127	663	4790	711	1.974	166
2 R19+GV+TB	Aug 25-Sep 1	5217	843	6060	780	2.276	166
3 R-19	Aug 25-Sep 1	4899	855	5753	888	1.897	166
1 R19+RV+TB	Sep 1-3	4170	635	4805	708	1.988	48
2 R19+GV+TB	Sep 1-3	5279	790	6069	782	2.273	48
3 R-19	Sep 1-3	4935	853	5787	883	1.920	48
1 R19+RV+TB	TOTALS	1678579	330155	2008734	293558	2.005	377
2 R19+GV+TB	TOTALS	2124816	393639	2518455	328896	2.244	377
3 R-19	TOTALS	1950420	435171	2385591	357523	1.955	377

Note: TOTALS are sums of (hourly value x hours) for each period
Ventilation Ratio is 1/150 for houses 2,3

Table 5.16. Karns Houses Cooling Data - Calibration with Ridge and Gable Vents

House No./ Insulation	Dates From-To	Average Hourly Values Sensible Btu	Latent Btu	Total Btu	Electric Watt-hr	Cooling COP	Total Hours
1 R19+RV	Sep 9-Sep 13	3380	722	4102	585	2.053	96
2 R19+GV	Sep 9-Sep 13	4381	854	5235	670	2.290	96
3 R-19	Sep 9-Sep 13	3606	821	4427	684	1.896	96
1 R19+RV	Sep 13-16	5159	1194	6353	906	2.055	74
2 R19+GV	Sep 13-16	6781	1407	8189	1034	2.321	74
3 R-19	Sep 13-16	5544	1330	6874	1027	1.962	74
1 R19+RV	TOTALS	706219	157664	863884	123233	2.054	170
2 R19+GV	TOTALS	922352	186168	1108520	140797	2.307	170
3 R-19	TOTALS	756465	177248	933713	141676	1.931	170

Note: TOTALS are sums of (hourly value x hours) for each period
Ventilation Ratio is 1/150 for houses 2,3

Table 5.17. Summary of Dust Testing

House	Attic Setup	Attic AVR	% Difference in: Btu Load	A/C W-Hr
1	TRB RV	1/150	-8.26	-5.12
2	HRB GV	1/150	-9.16	-6.89

to no RB and a gable vent. The electrical input into the air conditioner of house No. 1 with a TRB/ridge vent was reduced by 5.1%, while that of house No. 2 with a TRB/gable vent was reduced by 6.9%. The difference of about 1 percentage point in favor of the gable vents in both measurements is judged as not significant and the results are assumed equal.

Table 5.4 in Sect. 5.1 can be used to expand the results of Table 5.18. Table 5.4 shows that a TRB/gable vent combination in house No. 1 with an AVR of 1/150 caused a total load decrease of 8.8% and an air conditioner electrical input decrease of 6.3% compared to no RB/gable vents. The numbers from Table 5.4 are essentially equal to those from Table 5.18, so it is again concluded that a TRB/ridge vent combination at 1/150 AVR in house No. 1 behaves in a similar manner to a TRB/gable vent combination in that house.

Tables 5.18 and 5.19 contain heat flow data for houses No. 1 and No. 2 corresponding to the test periods contained in Tables 5.16 and 5.17. Table 5.20 summarizes and normalizes the data from Tables 5.18 and 5.19. Table 5.20 shows that the heat flow reduction in both house No. 1 and house No. 2 are essentially equal at about 30%. Therefore, similar savings would be expected from both houses. Table 5.20 reinforces the conclusion that TRB/ridge vent and TRB/gable vent combinations at an AVR of 1/150 are equally effective in reducing house cooling loads.

Table 5.18. Karns Attic Heat Flux - TRBs with Ridge/Gable Vents

House No./ Insulation	Dates From-To	Hour	Average BTUSFH	Total BTUSF	Ratio #H/#3
1 R19+RV+TB	Aug 18-25	163	0.49	79.53	0.495
2 R19+GV+TB	Aug 18-25	163	0.77	126.08	0.784
3 R-19	Aug 18-25	163	0.99	160.72	1.000
1 R19+RV+TB	Aug 25-Sep	166	0.38	63.28	0.417
2 R19+GV+TB	Aug 25-Sep	166	0.67	110.89	0.731
3 R-19	Aug 25-Sep	166	0.91	151.78	1.000
1 R19+RV+TB	Sep 01-03	48	0.39	18.66	0.421
2 R19+GV+TB	Sep 01-03	48	0.64	30.80	0.695
3 R-19	Sep 01-03	48	0.92	44.32	1.000
1 R19+RV+TB	TOTALS	377	0.43	161.48	0.453
2 R19+GV+TB	TOTALS	377	0.71	267.78	0.750
3 R-19	TOTALS	377	0.95	356.82	1.000

Notes: Totals are sums of (hourly value x hours)
Attic Vent Ratio is 1/150 for all

Table 5.19. Karns Attic Heat Flux - No RBs - Ridge/Gable Vents

House No./ Insulation	Dates From-To	Hour	Average BTUSFH	Total BTUSF	Ratio #H/#3
#1 R19+RV	Sep 09-13	96	0.43	41.72	0.664
#2 R19+GV	Sep 09-13	96	0.70	67.51	1.075
#3 R-19	Sep 09-13	96	0.65	62.82	1.000
#1 R19+RV	Sep 13-16	74	0.53	47.95	0.640
#2 R19+GV	Sep 13-16	74	1.07	79.36	1.059
#3 R-19	Sep 13-16	74	1.01	74.96	1.000
#1 R19+RV	TOTALS	170	0.53	89.67	0.651
#2 R19+GV	TOTALS	170	0.86	146.86	1.066
#3 R-19	TOTALS	170	0.81	137.78	1.000

Notes: Totals are sums of (hourly value x hours)
Attic Vent Ratio is 1/150 for all

Table 5.20. Comparison of Heat Flux Data with TRBs and Ridge/Gable Vents

	1/150 Vent Ratio w/o TRB's			1/150 Vent Ratio w TRB's		
	#1 R19+RV	#2 R19+GV	#3 R-19	#1 RV+TRB	#2 GV+TRB	#3 R-19
Total Heat Flux (BTUSF)	89.67	146.86	137.78	161.48	267.78	356.82
Relative Total Ht Flux	0.651	1.000	1.000	0.453	0.750	1.000
Normalized Total Ht Flux	---	---	---	0.695	0.704	1.000

Notes: House #3 is Control House
Truss Barrier is not Perforated
House #1 has Ridge Vent with Gable Vent Blocked Off

The overall conclusion from this attic ventilation type test is that TRBs with ridge vents are no more efficient than TRBs with gable vents on the houses at Karns when the AVR is 1/150.

5.3.3 Regression Modeling

All cooling load and A/C input results for this work were done by using linear regression modeling on the hourly data collected during the course of the various experiments. The linear regression models for each of the three houses used cooling loads and electrical input to the air conditioner as respective depent variables. The independent variable was the temperature difference between the outside air and the inside air temperatures (To-Ti). Regression lines were used to normalize the loads for each house using the same mean internal load and (To-Ti) for each respective test period. Only values of (To-Ti) greater than -15°F were used in the data reduction.

Normalized loads were then made relative to the control house by division by the corresponding control house loads. The ratios between the load of each house to that of the control house during the calibration test period were used as the calibration factors for houses 2 and 3.

The relative normalized load for each house was divided by its calibration factor to determine the effect of each modification relative to the same house without the modification.

Tables 5.21 and 5.22 contain the detailed results of the regression modeling for the cooling loads in Btu/h values, while Tables 5.23 and 5.24 contain the A/C electrical input Wh/h results.

Table 5.21. Summary of Dust and Ventilation Regression Results Using Model Cooling Load (Btu/h) = Constant + (To-Ti)

House Setup	Dates	No. Hours	REGRESSION LINE R^2	Const.	Error	Slope	Error	MEAN VALUES To-Ti (F Deg)	Tot Load (Btu/h)	Int Load (Btu/h)	Total Load Normalized @ Int Ld=1692, DT= Avg Wk (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 TBHV	6/29-7/13	324	0.873	3629.4	106.3	446.25	9.48	4.80	5772	1850	5891	0.907	0.912
1 TBFV	7/13-7/25	287	0.892	3488.0	119.2	552.25	11.34	6.45	7051	1830	7231	0.925	0.930
1 HBFV	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 HBHV	6/29-7/13	325	0.871	4029.4	128.3	514.11	11.00	5.50	6857	1744	6764	1.041	0.907
2 HBFV	7/13-7/25	287	0.885	3478.9	149.7	632.73	13.50	7.16	8005	1493	8124	1.039	0.905
2 HBFV	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	6/29-7/13	323	0.886	3303.4	130.4	550.76	11.03	5.96	6586	1486	6495		
3 ACCal	7/13-7/25	287	0.882	2829.9	165.6	673.10	14.53	7.47	7857	1433	7819		
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) Avg Int Lds
7.10 F Deg 1692 Btu/h
5.42
7.03
5.41
7.19

Table 5.22. Summary of Ridge and Gable Ventilation Regression Results Using Model Cooling Load = Constant + (To-Ti)

House Setup	Dates	No. Hours	REGRESSION LINE R^2	Const.	Error	Slope	Error	MEAN VALUES To-Ti (F Deg)	Tot Load (Btu/h)	Int Load (Btu/h)	Total Load Normalized @ Int Ld=1651, DT= Avg Wk (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	7287	0.995	1.050
1 TBRV	8/18-9/06	444	0.874	4188.8	74.4	470.30	8.50	1.34	4821	1795	4913	0.869	0.917
1 RV	9/06-9/19	327	0.820	4771.6	101.4	553.60	14.37	-1.21	4103	1886	4109	0.947	1.000
2 ACCal	6/01-6/29	411	0.865	4332.6	153.9	604.25	11.79	6.90	8503	1859	8417	1.149	0.959
2 TBGV	8/18-9/06	445	0.884	4829.0	93.7	599.08	10.28	2.09	6080	1434	6152	1.088	0.908
2 GV	9/06-9/19	328	0.831	5672.0	130.1	715.66	17.82	-0.56	5270	1574	5196	1.198	1.000
3 ACCal	6/01-6/29	415	0.858	3286.0	148.7	549.49	10.99	7.72	7526	1516	7324		
3 ACCal	8/18-9/06	450	0.869	4375.6	99.5	589.73	10.80	2.11	5617	1463	5653		
3 ACCal	9/06-9/19	331	0.828	4646.2	110.5	600.03	15.03	-0.55	4317	1497	4336		

Avg Wk (To-Ti) Avg Int Lds
7.10 F Deg 1651 Btu/h
1.85
-0.77

Table 5.23. Summary of Dust and Ventilation Regression Results Using Model A/C Elec Input (W-Hr) = Constant + (To-Ti)

House Setup	Dates	No. Hours	R E G R E S S I O N L I N E					M E A N V A L U E S			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 TBHV	6/29-7/13	324	0.891	524.6	16.0	73.17	1.42	4.80	876	542.0	914.2	0.906	0.937
1 TBFV	7/13-7/25	287	0.909	482.4	16.8	85.51	1.60	6.45	1034	536.2	1077.3	0.912	0.944
1 HBFV	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 HBHV	6/29-7/13	325	0.888	555.5	17.4	75.51	1.49	5.50	971	511.0	962.6	0.954	0.916
2 HBFV	7/13-7/25	287	0.901	467.6	19.4	89.02	1.75	7.16	1105	437.4	1101.2	0.933	0.896
2 HBFV	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	6/29-7/13	323	0.901	533.0	18.8	86.06	1.59	5.96	1046	435.4	1009.0		
3 ACCal	7/13-7/25	287	0.902	454.6	22.6	101.69	1.98	7.47	1214	419.9	1180.9		
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		

Avg (To-Ti) 6.43 F Deg

Avg Int Lds 496 WHr

Avg Wk (To-Ti)
7.10 F Deg
5.42
7.03
5.41
7.19

Table 5.24. Summary of Ridge and Gable Vent Regression Results Using Model A/C Elec Input (W-Hr) = Constant + (To-Ti)

House Setup	Dates	No. Hours	R E G R E S S I O N L I N E					M E A N V A L U E S			Total Input Normalized @ Int Ld=484, DT=Avg WkDT		
			R^2	Const.	Error	Slope	Error	To-Ti (F Deg)	Tot Load (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	1077.1	0.937	1.015
1 TBRV	8/18-9/06	444	0.885	606.2	10.7	71.45	1.23	1.34	702	525.8	732.0	0.876	0.949
1 RV	9/06-9/19	327	0.831	674.8	14.0	79.46	1.99	-1.21	579	552.7	606.0	0.923	1.000
2 ACCal	6/01-6/29	411	0.885	592.8	20.0	86.23	1.53	6.90	1188	544.7	1196.8	1.041	1.047
2 TBGV	8/18-9/06	445	0.895	621.5	11.6	78.20	1.27	2.09	785	420.0	774.1	0.926	0.931
2 GV	9/06-9/19	328	0.841	717.3	15.8	90.23	2.17	-0.56	667	461.0	653.1	0.995	1.000
3 ACCal	6/01-6/29	415	0.875	535.6	21.5	85.52	1.59	7.72	1196	444.2	1149.3		
3 ACCal	8/18-9/06	450	0.874	673.1	13.8	83.67	1.50	2.11	849	428.5	836.0		
3 ACCal	9/06-9/19	331	0.835	712.4	15.2	84.41	2.07	-0.55	666	438.6	656.6		

Avg (To-Ti) 0.55 F Deg

Avg Int Lds 484 W-Hr

Avg Wk (To-Ti)
7.10 F Deg
1.85

6. CONCLUSIONS AND RECOMMENDATIONS

Table 6.1 contains a summary of the normalized results of the all the experiments from this testing. Figures 6.1 and 6.2 depict these results for House No. 1 and No. 2 respectively. Figures 6.3 and 6.4 depict the comparative results for cooling loads and A/C electrical input, respectively. This table and these figures will be used to formulate conclusions and recommendations.

The experiments that were run to determine the effects of AVR on TRB and HRB performance show that all cooling load reductions were within the range of 7 to 9.5%. Therefore, it is concluded that doubling the AVR from a minimum of 1/300 to 1/150 has little, if any, effect on the performance of either TRBs or HRBs. The data also suggest that the increased AVR with no RBs present likewise has little effect on house cooling loads.

Of equal concern is the conclusion drawn from these data that HRBs perform slightly better than TRBs. The increased hole area in the present HRB material compared to that HRB material which we had used in previous summers (it increased from 0.05 to 2.31% of the total surface area) caused us to expect a decrease in HRB performance. We expected an increase in TRB performance also because we attached RB material to the attic ends under the gable vents, which we had not done previously. However, the data appear to show more of a drop in HRB performance than to show a rise in TRB performance. Attic heat flow data in Table 5.8 show the HRB in house No. 2 to perform about 12% better than the TRB in house No. 1, but load data show much less variation. The authors believe that an HRB outperforms a TRB, but the results from Table 6.1 does not show as much difference between TRBs and HRBs as we expected.

Table 6.1
Measured Differences Between House at Setup
Compared to House w/o Setup Conditions

House	Attic Setup	Attic Vent Ratio	RB Dust Loading (mg/cm^2)	RB Emiss.	% Difference in	
					Btu Load	A/C W-Hr
1	TRB HV	1/300	----	0.035	-8.84	-6.28
1	TRB FV	1/150	----	0.035	-7.05	-5.63
1	HRB FV	1/150	----	0.055	-14.29	-9.30
1	HRB DUST	1/150	0.74	0.185	-7.05	-4.79
1	TRB RV	1/150	----	0.035	-8.26	-5.12
2	HRB HV	1/300	----	0.055	-9.31	-8.36
2	HRB FV	1/150	----	0.055	-9.52	-10.42
2	HRB FV	1/150	----	0.055	-9.51	-10.03
2	HRB DUST	1/150	0.34	0.125	-7.38	-8.47
2	TRB GV	1/150	----	0.035	-9.16	-6.89

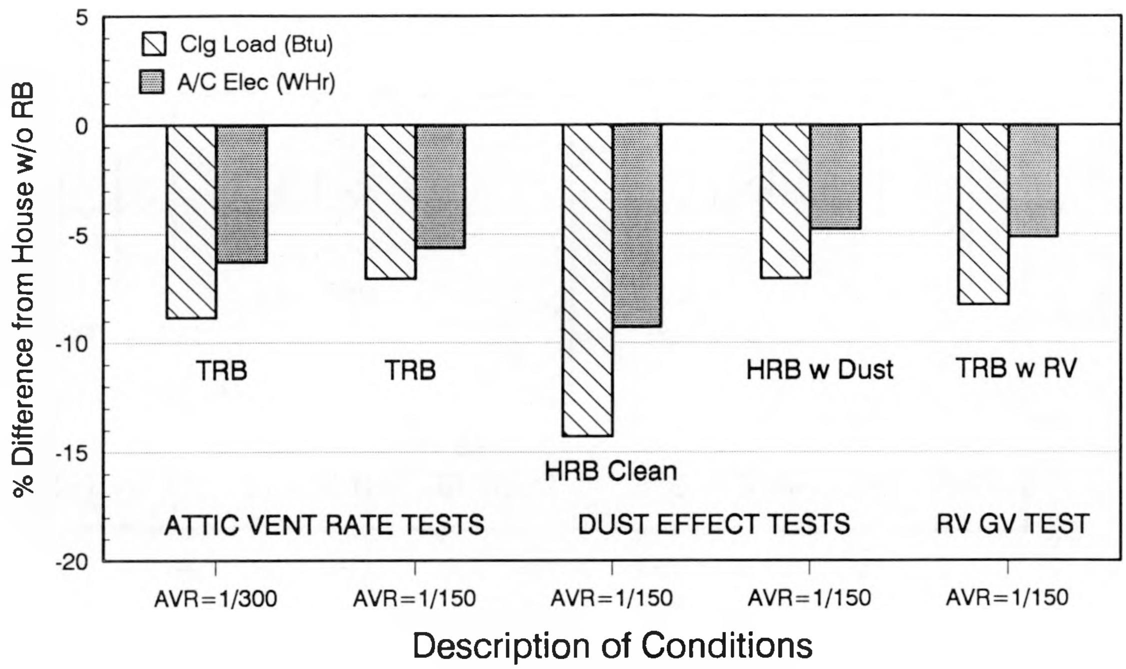


Fig. 6.1. House 1 - Summer of 88 Results Btu and A/C Wh Differences Caused by RB

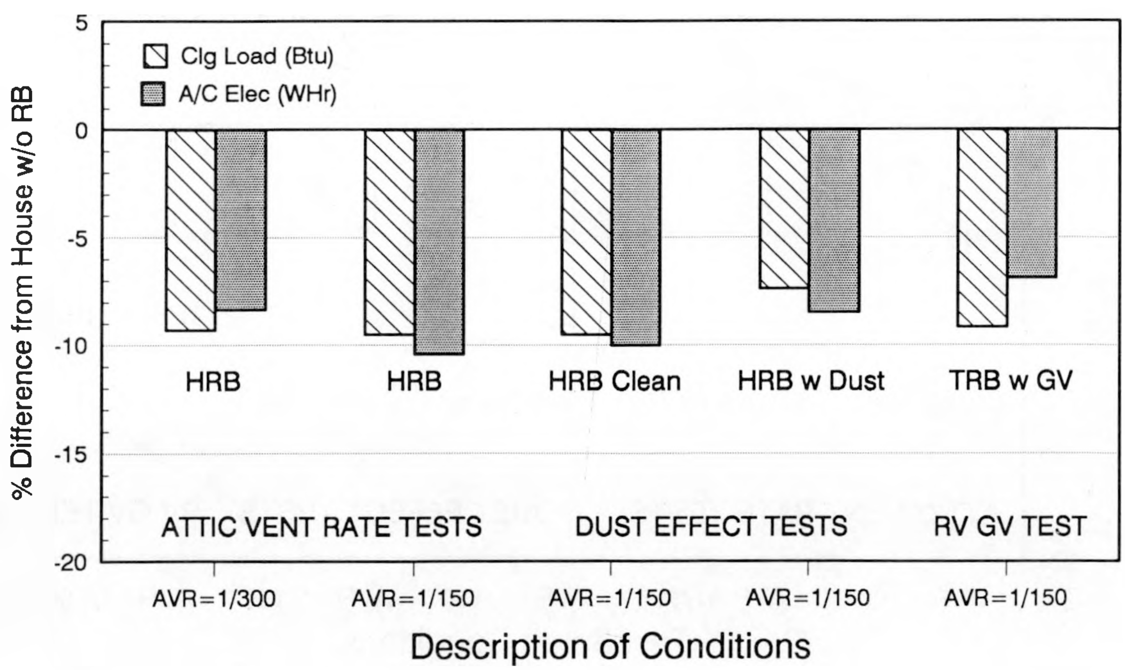


Fig. 6.2. House 2 - Summer of 88 Results Btu and A/C Wh Differences Caused by RB

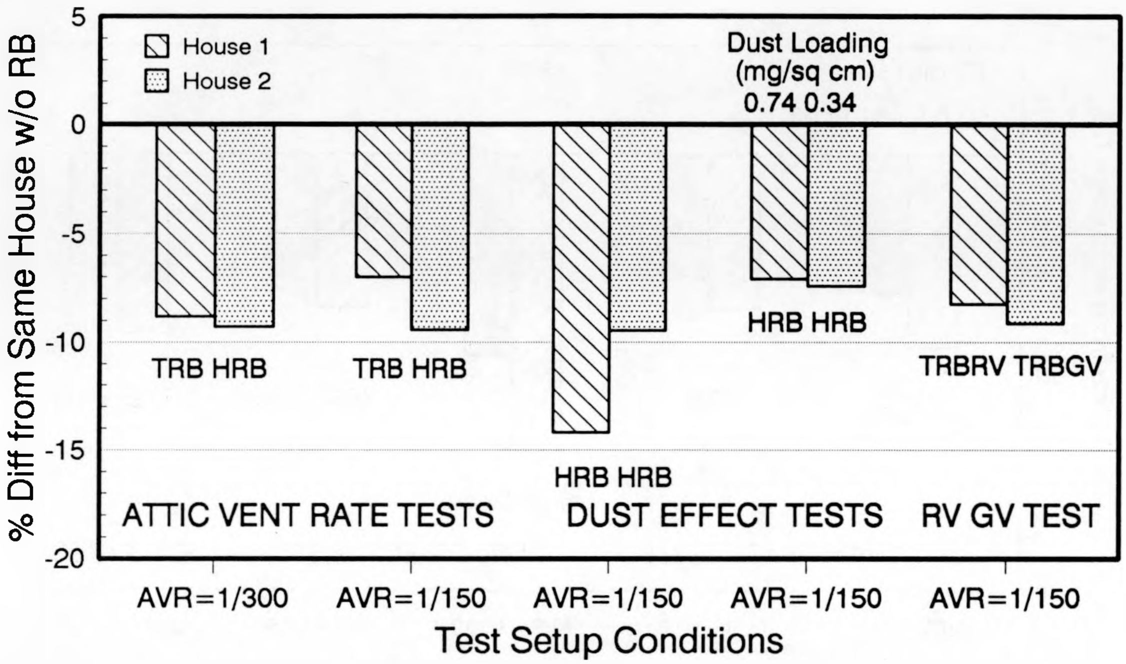


Fig. 6.3. Karns Testing - Summer of 88 Measured Cooling Load Differences

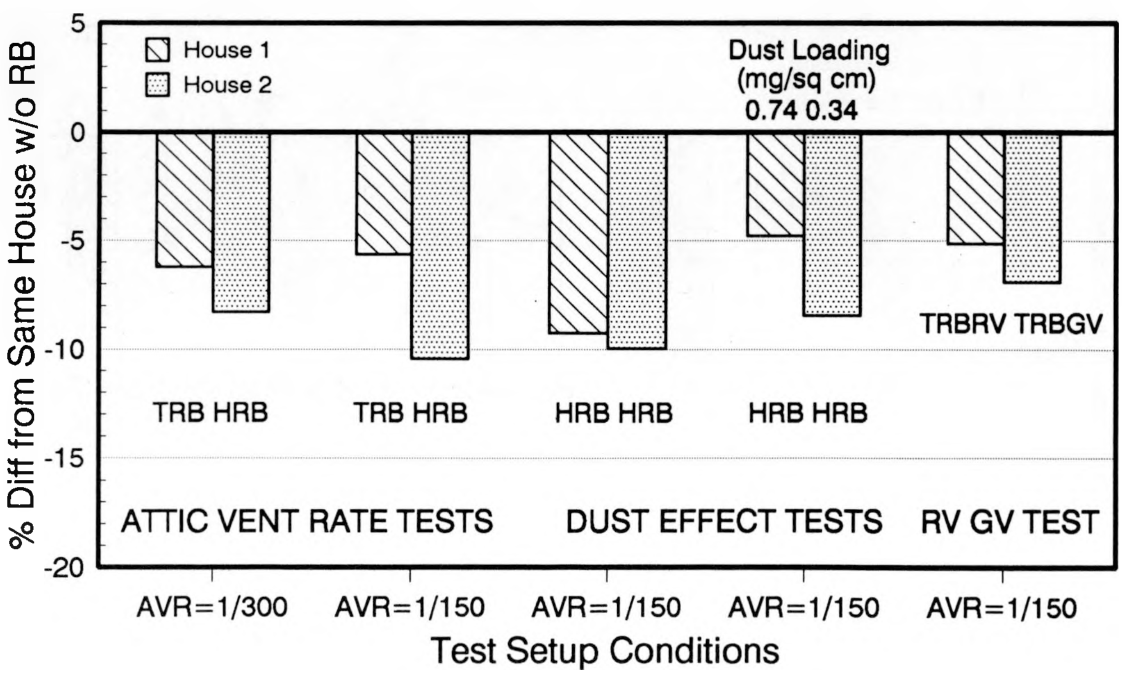


Fig. 6.4. Karns Testing - Summer of 88 Measured A/C Electric Input Differences

Table 6.1 also contains the normalized results for our HRB dust experiments. This table clearly shows that as dust loadings increase, house cooling loads increase at least up to a dust loading of 0.74 mg/cm^2. House cooling loads increased 2.3% by a dust loading of 0.34 mg/cm^2 over that of a clean HRB. A dust loading of 0.74 mg/cm^2 increased the house cooling load by 8.4% over that of a clean HRB. The surface emissivity of a clean perforated HRB sample was 0.055; that of an HRB at 0.34 mg/cm^2 dust loading was 0.125, and that of an HRB at 0.74 mg/cm^2 dust loading was 0.185. Yarbrough's emissivity vs crawl space dust loading data, Fig. 2.2, shows that surface emittance and dust loading have a linear relationship from a dust loading of about 0 to 1 mg/cm^2.

Heat flow results from Table 5.14 agree with the cooling load results from Table 6.1, and the same statements can be made for heat flows as for cooling loads.

The dusted HRB, however, still provides a lower cooling load to a house than the same house would have with no HRB. A secondary question arises here as to how far would the surface emittance of an HRB have to increase before a TRB would outperform a dusted HRB. The answer to this question is not simple, partly because of some results contained in Table 6-1. It shows that a clean HRB reduces the cooling load of house No. 1 by 14.3%, while a TRB reduces the load of that same house No. 1 by only 7%. This house No. 1 comparison shows an HRB as far superior to a TRB. A house No. 2 HRB to house No. 1 TRB comparison, however, shows a much smaller difference (9.5% to 7.1%). The authors are still unable to fully explain this last comparison result.

Results show that TRB/ridge vent and TRB/gable vent combinations perform similarly at an AVR of 1/150 (Table 6.1). Both combinations showed cooling load reductions of about 9%. Time did not permit operating at other AVRs, as summer weather per se ended. We conclude here that TRBs in the Karns houses do not benefit any more from ridge vents than from gable vents when the AVR is 1/150.

Recommendations for future work would encourage the collection of more data at various geographical locations concerning the buildup of dust on HRB as well as TRB surfaces. TVA, FSEC, and Tennessee Tech are in the process of collecting this type of information, but winter conditions as well as summer conditions should be included.

The effect of hole size and pattern on HRBs would also present useful information, both because of summer performance degradation and winter moisture shedding ability.

Testing on houses with various roof shingle colors, various directional orientations, two-story construction, cathedral ceilings, flat roofs, etc., should also be carried out in order to determine their effects on RB performance.

A modeling effort should be implemented using existing data in order to extend its usefulness over a broader spectrum of climates and constructions. Data should also be obtained from controlled conditions and test construction samples in environment chambers to supplement the modeling effort.

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APPENDIX A

Table A.1. Karns House Construction Details

ADDITIONAL INFORMATION ABOUT KARNS HOUSES

ROOF

Roof Pitch	: 12 Horizontal, 5 Vertical
Type Construction	: Asphalt Shingles (Brown, Std Seal-Tab,240#) 15# Felt 1/2 in. CD Plywood Sheathing
Overhang	: 12 in.

EXTERIOR WALLS

Type Siding	: 8 in. Horizontal Hardboard Siding 15# Felt 1/2 in. Sheathing 2x4 Studs @ 16 in. on Center 1/2 in Gypsum Board R-11 Fiberglass Batt Insulation (with kraft paper vapor retarder)

CEILING DETAILS

Construction	: 1/2 in. Gypsum Board Wood 2x4 Trusses @ 24 in. on Center Fiberglass Batt Insulation (R-Value modified during testing)

FLOOR DETAILS

Construction	: 1/2 in. CD Plywood Sub-Floor 2x12 Floor Joists @ 16 in. on Center R-19 Fiberglass Batt Insulation

ATTIC VENTILATION

Types	: Eight 8x16 in. Soffitt Vents (4 Front, 4 Rear) Two Base Louver Gable Vents (7.5 Sq Ft Area) Free Attic Vent Area Ratio (AVR) = 1/141

CRAWL SPACE VENTILATION

Type	: Five 16x8 in FON Vents (Always Closed) Polyethylene Sheeting over Dirt Floor

DUCTING

Type	: Metal Located in Crawl Space
Insulation	: Fiberglass - Double Wrapped to R-7.6

SHADING

Type	: None - No Trees or Other Tall Structures

Table A.2 - Description of Data Channels at Karns

DESCRIPTION OF INSTRUMENTATION AT KARNS HOUSE #2 - Oct 31,1987

Channel Number	Slot Number	Instrumentation Information Number	Location and/or Description	Range	Accuracy (+/-)
000	001	TE-014	Outside Air Temp (Rear)	0-200 F	1F
001	002	TE-082	Great Room Wet Bulb	0-200 F	1F
002	003	TE-083	Great Room Dry Bulb	0-200 F	1F
003	004	RE-070	Pyranometer (Horiz Solar)	500 BSFH	3%
004	005	TE-081	Hall Ceiling Under HMF1	0-200 F	1F
005	006	HFT3	Under Insulation at HFM3	0-200 F	1F
006	007	TE-087	#2 Bedroom Dry Bulb	0-200 F	1F
007	008	HFM3	Ht Flux Mtr #3 - Ctr Gr Room	100 BSFH	5%
008	009	TE-089	#3 Bedroom Dry Bulb	0-200 F	1F
009	010	TE-001	Crawl Space Air Temp	0-200 F	1F
010	011	TE-002	Crawl Space Earth 6 in	0-200 F	1F
011	012	HFT1	Ht Flx Mtr #1 Temp	0-200 F	1F
012	013	HFM1	Ht Flux Mtr #1 - Hall T'stat	100 BSFH	5%
013	014	HFT2	Heat Flux Meter #2 Temp	0-200 F	1F
014	015	HFM2	Ht Flux Mtr #2 - BR #1	100 BSFH	5%
015	016	TE-026	Outside Earth 36 in	0-200 F	1F
016	017	TE-028	Hall Closet (Carpet Top)	0-200 F	1F
017	018	RHM2	RH Mtr #2-Top Ins (Under RB)	20-95 %	5%
018	019	RHM2T	Temp at RHM2	0-200 F	1F
019	020	TE-033	Garage Inside Wall	0-200 F	1F
020	021	TE-034	Great Room Wall	0-200 F	1F
021	022	TE-035	Kitchen Air	0-200 F	1F
022	023	RT1	Roof (Under Shingles)	0-200 F	1F
023	024	TE-037	Attic Top of Insulation	0-200 F	1F
024	025	TE-038	Attic Top of Foil	0-200 F	1F
025	026	TE-039	Attic Air Above Foil	0-200 F	1F
026	027	XE-044	Wind Direction House #2	0-360 DEG	5%
027	028	XE-043	Wind Speed (House #2 Only)	0-30 MPH	5%
028	029	RHM1T	Attic Air Temp over RHM1	0-200 F	1F
029	030	RHM3T	Temp in NE Corner Under GR Ins	0-200 F	1F
030 | 039			Channels not Used		
040	HWI	ME-040	Outside Relative Humidity	10-95 %	2%
041	HWI	ME-041	Crawl Space Rel Humidity	10-95 %	2%
042	HWI	ME-042	Hallway Relative Humidity	10-95 %	2%
043 | 049			Channels not Used		

Table A.2 (cont.)- Description of Data Channels at Karns

Description of Instrumentation at Karns House #2 - Oct 31,1987

Channel Number	Slot Number	Instrumentation Information Number	Location and/or Description	Range	Accuracy (+/-)
050	031	RHM1	Attic Air RH Mtr #1	10-95 %	2%
051	032	RHM3	NE Corner Under Ins RHM #3	10-95 %	2%
052	033	------	Not Used		
053	034	------	Not Used		
054	035	TE-031	HP Indoor Unit Return Air	0-200 F	1F
055	036	TE-032	HP Indoor Unit Supply Air	0-200 F	1F
056	037	TE-027	Thermostat (Hall Air)	0-200 F	1F
057	038	TE-023	Front Ent Outside Air	0-200 F	1F
058	039	------	Not Used		
059	040	------	Not Used		
060	HWI	------	Compressor Cycles	-	.5%
061	HWI	JE-060	Total House W-h	-	.5%
062	HWI	JE-061	Total Heat Pump W-h	-	.5%
063	HWI	JE-062	Total Resistance W-h	-	.5%
064	HWI	JE-063	HP Defrost/Cooling Run Time	-	1 Sec
065	HWI	JE-064	HP Heating Run Time	-	1 Sec
066	HWI	JE-065	HP Defrost/Cooling W-h	-	.5%
067	HWI	JE-066	HP Heating W-h	-	.5%
068	HWI	JE-067	Resistance Defrost W-h	-	.5%
069	HWI	JE-068	Resistance Normal W-h	-	.5%
070	HWI	JE-069	Sensible Heat/Cool Delivered	-	2%
071	---	------	Not Used	-	
072	HWI	------	Latent Load	-	2%
073	HWI	------	Resistance Run Time	-	1 Sec

Table A.3. Average values of various parameters during test periods

Dates	OD Air (Deg F)	OD Air (% RH)	Solar (Btuhsf)	Wind Sp (mph)	HOUSE #1 Gr Rm DB (Deg F)	HOUSE #1 Gr Rm WB (Deg F)	HOUSE #2 Gr Rm DB (Deg F)	HOUSE #2 Gr Rm WB (Deg F)	HOUSE #3 Gr Rm DB (Deg F)	HOUSE #3 Gr Rm WB (Deg F)
Jun 07-09 '88	76.8	55	96.2	1.7	70.1	57.6	70.9	57.7	69.6	57.9
Jun 13-15	74.4	57	99.2	1.2	69.5	57.0	71.1	57.9	69.7	57.7
Jun 15-22	77.8	59	89.0	1.9	70.1	58.1	71.4	58.6	69.9	58.5
Jun 22-29	80.5	55	88.1	2.5	71.1	59.2	71.0	60.7	70.2	59.0
Jun 29-Jul 06	72.0	72	59.4	1.8	71.3	58.7	71.3	59.0	70.8	58.7
Jul 06-13	81.0	59	78.6	2.5	71.3	59.4	71.5	59.4	70.5	59.1
Jul 13-19	81.0	79	76.2	2.2	71.3	60.7	71.3	60.7	70.4	60.5
Jul 19-25	76.2	77	67.6	2.4	71.3	60.4	71.6	60.6	70.5	62.5
Jul 25-Aug 01	77.1	77	76.8	1.4	71.4	60.2	71.6	60.2	70.5	59.6
Aug 02-08	77.5	80	68.2	1.6	71.4	60.4	71.6	60.7	70.6	59.8
Aug 08-15	79.5	73	79.7	1.1	71.3	60.2	71.4	60.3	70.3	59.4
Aug 18-25	77.1	79	51.3	1.7	71.5	60.5	71.6	60.7	70.7	59.8
Aug 25-Sep 01	73.4	69	72.0	2.4	71.4	59.8	71.5	59.9	70.6	58.8
Sep 01-03	73.3	65	73.9	1.5	71.4	59.6	71.8	59.7	70.8	58.6
Sep 08-13	72.6	84	44.2	1.3	71.4	60.3	71.7	60.7	70.8	60.0
Sep 13-16	75.3	74	66.6	1.5	71.4	60.5	71.6	60.9	70.8	60.2

AC Spark Plug

GM

COARSE AIR CLEANER TEST DUST DATA SHEET

BATCH NO. 2804

CHANNEL UPPER LIMIT (MICROMETERS)	CUMULATIVE DATA % SMALLER THAN CHANNEL UPPER LIMIT	% DIFFERENCE BETWEEN CHANNEL & NEXT SMALLER CHANNEL
176	100.0	3.5
125	96.4	10.8
88	85.5	15.1
62	70.4	13.0
44	57.4	12.4
31	44.9	9.3
22	35.6	7.9
16	27.6	5.9
11	21.7	4.1
7.8	17.5	4.4
5.5	13.0	4.4
3.9	8.6	3.3
2.8	5.2	5.2

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L & N MICROTRAC COARSE DUST SPECIFICATION

MICROMETERS	% SMALLER THAN
5.5	13 ±3
11	24 ±3
22	37 ±3
44	56 ±3
88	84 ±3
176	100

ROLLER COARSE TEST DUST SPECIFICATION (FOR REFERENCE ONLY)

MICROMETERS	%
0-5	12 ±2
5-10	12 ±3
10-20	14 ±3
20-40	23 ±3
40-80	30 ±3
80-200	9 ±3

NOTE: MIX DUST WELL BEFORE USING

5-80
25041113

Fig. A.1. Front view of the Karns houses.