ANALYSIS OF ANNUAL ENERGY SAVINGS DUE TO RADIANT BARRIERS

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Radiant barriers are receiving increasing attention as an energy conservation measure for residential buildings, especially for warmer climates. They are being actively promoted for use in residential attics, sometimes with exaggerated claims about savings in utility bills that will result from their installation.

In order to provide consumers with factual information that would assist them in deciding upon an investment in a radiant barrier, the Department of Energy, along with an industry advisory panel, has developed a Radiant Barrier Fact Sheet. A major part of this fact sheet is estimates of energy savings that might be expected from radiant barriers in various climates.

This paper presents the details of the methodology underlying the energy savings estimates, and gives a summary of values listed in the Fact Sheet. The energy savings estimates were obtained from calculations using a detailed attic thermal model coupled with DOE-2.1C. A life cycle cost analysis was performed to estimate the present value savings on utility fuel costs. The results show that the fuel cost savings vary significantly with the level of conventional insulation already in the attic and from one climate to another.

INTRODUCTION

Insulation systems based on reflective surfaces have been in existence for many years. However, interest has only recently been focussed on the application of single sheets of reflective materials in the attics of residential buildings, an application that is known as a "radiant barrier" (RB). RBs may be installed in attics in a variety of configurations. They may be laid directly on top of existing conventional attic insulation (the horizontal configuration), attached to the bottoms of the rafters, draped over the tops of the rafters, or attached directly to the underside of the roof decking.

Experiments by a number of groups have demonstrated that radiant barriers can be effective in reducing heat flows through the ceiling, especially under summer cooling conditions (see Wilkes and Yarbrough 1988). However, their benefits are sometimes exaggerated in marketing claims. This, along with the wide range in selling prices, has prompted the U.S. Department of Energy, with the assistance of an industry advisory panel, to develop an Interim Radiant Barrier Fact Sheet to serve as a source of unbiased information for the consumer. The modifier, "Interim", was included because research on radiant barriers is not complete and there will be a need for an updated version.

A major section of the Fact Sheet gives estimates of cooling and heating energy savings. The method chosen by the advisory panel for presenting energy savings estimates is the present value of life cycle energy savings in terms of dollars per square foot of ceiling area. Present-value savings are given for a number of climates, existing insulation levels, and radiant barrier configurations. The consumer can then compare this present value savings with the cost of installing a radiant barrier, which might be obtained as a quote from the installer. This paper presents the methodology that was used to develop the estimates of present-value savings. Work on the Fact Sheet is not yet complete and it does not have unanimous approval of the advisory panel. Therefore, this paper gives the present status of the energy savings estimates; changes may be made before the Fact Sheet is actually issued.

ATTIC/RADIANT BARRIER THERMAL MODEL

Energy savings estimates were obtained using a model for the transient performance of attics. The current model is based on an earlier model that was developed by Peavy at the National Bureau of Standards (Peavy 1979), and that was later extended by Wilkes (1983, 1990a,b). The model includes radiation interchanges among all the surfaces that face the attic space, using the Stefan-Boltzmann (T^4) law, with the idealizations that the surfaces are flat, gray, isothermal, diffusely emitting and reflecting, and have a uniform radiant flux. Each of the surfaces may have a different emissivity (in this paper, the term "emissivity" is used synonymously with the term "emittance"). The model also includes convection to the ventilation air stream, the flow rate of which is calculated from a combination of stack and wind pressure effects. Heat transfer processes at the exterior surfaces include absorption of solar radiation, convection to the outdoor air, and radiation exchanges with the surroundings.

Predictions of the model have been compared with ceiling heat flows measured in a number of laboratory and field tests (Wilkes 1988, 1989, 1990a,b). An example is given in Figure 1, which shows data obtained from a field experiment using full-size houses near Knoxville, Tennessee (Levins and Karnitz 1986). In general, it has been concluded that the model is capable of predicting cumulative ceiling heat flows to within about 10 percent of the measured values. This level of accuracy was judged acceptable to qualify the model for use in generating estimates of the energy savings due to radiant barriers. However, there is a need for further verification of the model, especially in cold climates.

For annual energy analyses, the attic model was driven with hourly weather tapes with the indoor temperature being maintained at a constant value that was midway between the heating and cooling thermostat setpoints. Hourly ceiling heat fluxes computed by the model were brought into the DOE-2.1C model using the FUNCTION command and were substituted for the ceiling heat fluxes that DOE-2 would normally calculate. Adjustments for thermostat settings in DOE-2 being different from the constant indoor air temperature assumed in the attic model, and for the indoor temperature floating between the heating and cooling setpoints were made in the SYSTEMS section of DOE-2. Annual energy savings due to radiant barriers were obtained from model runs on a typical house, the runs being identical except for changes in emissivities of the surfaces facing the attic space.

ENERGY SAVINGS CALCULATION METHOD AND RESULTS

Prototypical House

The energy savings estimates were based on a prototypical ranch style house, which has been used for several studies (for example, Labs et al. 1988). The house is 55 feet long and 28 feet wide, with a floor area of 1540 square feet. The windows are double-glazed and have an area of 184.8 square feet (12 percent of the floor area), and a door on the south wall occupies 19.5 square feet. The walls are wood frame with R-11 insulation and have a solar absorptance of 0.7. The floor is built over a three foot crawl space and has R-19 insulation.

The ceiling is constructed with 2X4 wood joists 24 inches on center, with 1/2 inch gypsum wallboard. The ceiling is insulated with either R-11, R-19, R-30, or R-38 fiberglass batt insulation, and the joists are assumed to be covered with insulation for levels greater than R-11. The roof has a pitch of 5 in 12, a solar absorptance of 0.9, is unshaded, and has the ridge oriented in the east-west direction. (Exploratory calculations show that changing the ridge orientation to the north-south direction affects the load reductions due a RB by only about 5 percent.) Venting of the attic is through soffit and ridge vents, with a total net free area equal to 1/150 of the ceiling area. One-third of the vent area is assumed to be in the ridge vent, and the other two-thirds are assumed to be in the soffit vents, corresponding to typical construction practices

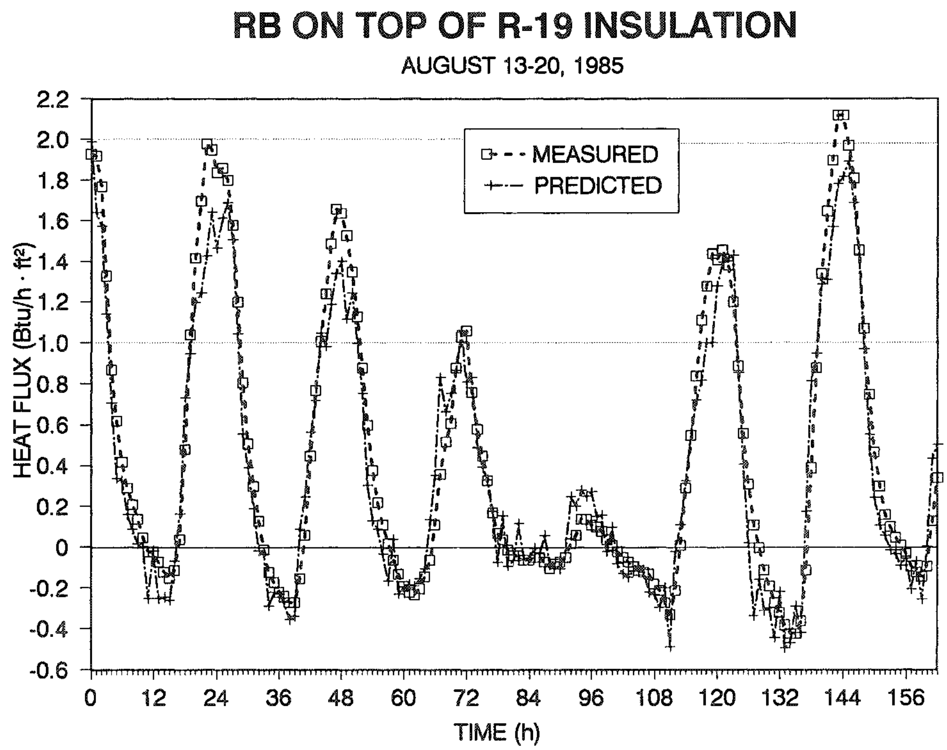

Figure 1. Comparison of Model Predictions with Ceiling Heat Fluxes Measured in Full-size House. Positive heat flows are from attic into house.

(personal communication from B. Howard, 1989). Emissivities of nonreflective surfaces were taken to be 0.9, and the radiant barrier emissivity was taken to be 0.05, except as noted below. (Emissivities of various RB materials range from about 0.03 to about 0.08. An average value of 0.05 was used here.)

The thermostat settings were taken to be 78°F in the summer and 70°F in the winter. During the summer, window venting was assumed when: (1) opening windows provides enough cooling to keep the zone temperature between 68 and 78°F, (2) the outside air enthalpy is lower than the inside air enthalpy, and (3) the air-conditioning load during the hour can be met totally through natural ventilation at 10 air changes per hour. Since occupants typically would not adjust windows after going to bed, a time of day schedule was added to keep windows closed between 11 p.m. and 7 a.m. During the winter, window venting was assumed when the indoor temperatures would rise above 78°F. These operating characteristics are essentially the same as those used by Labs et al. (1988) and Huang et al. (1987). The effect of keeping windows closed at all times has not been explored.

Infiltration was calculated using the Sherman-Grimsrud model for average residential construction in a typical suburban area with low buildings and trees within 30 feet (Sherman and Grimsrud 1980). Internal loads were taken to be 55,100 Btu per day, which corresponds to 3.2 people, 1 kWh per square foot lighting, and average appliance levels. Hourly internal load profiles were taken from a schedule developed by the California Energy Commission (CEC 1984).

If the radiant barrier performance parameter was chosen to be the percentage reduction in energy usage, then many of the above assumptions would be critical. By concentrating on differences in energy usage due to radiant barriers, and by later normalizing the results to a square footage basis, these assumptions should not be as critical, since they should nearly subtract out. For example, consider two houses of equal floor area and similar construction, except that one is a single story house and the other is a two story house. Heating and cooling loads due to the roof will be a smaller percentage of the whole house load for the two story house. Consequently, the percentage reduction in energy usage due to a RB will be smaller for the two story house. However, the difference in energy usage per square foot of ceiling should be similar for the two houses.

Load Reductions for Horizontal RB

Calculations were performed using TMY weather tapes for 26 cities and a California Climate Zone tape for Riverside, California. Figure 2 shows an example of the hour-by-hour ceiling heat fluxes predicted by the attic model (because of plotting software limitations, somewhat less than 8760 hours are shown). The sign convention used is that heat flows from the attic into the house are taken to be positive. This figure clearly shows the significant reductions in peak positive heat fluxes due to the radiant barrier.

The results of the DOE-2.1C model were annual heating and cooling loads on the house. By using differences between similar runs with and without a radiant barrier, the load reduction due to a radiant barrier was obtained. Heating and cooling load reductions for a clean radiant barrier applied directly on top of existing attic insulation are given in Table 1. These results show that both the heating and cooling load reductions are greatest with lower levels of attic insulation, as would be expected. Also as expected, the cooling load reductions are greater for the warmer climates, and the heating load reductions are greater for the colder climates.

For radiant barriers applied directly on top of attic insulation, account was taken of the seemingly inevitable fact that dust will accumulate, resulting in an increasing emissivity and hence a decreasing performance. D. W. Yarbrough (private communication, 1990) has collected the available data on emissivities of radiant barriers that have been installed in attics for various amounts of time (up to five years). A statistical analysis of these data yielded the following 95 percent confidence intervals:

$$e = 0.8 - 0.77 \exp(-0.11127t \pm w) \qquad (1)$$

$$\text{where} \quad w = 1.98 \, [0.0219 + 7.2005 \times 10^{-5} t^2]^{1/2} \qquad (2)$$

where e is the emissivity and t is the time in years. The mean equation (i.e., w = 0) has been constrained to pass through 0.03 at time zero, and to have a long-time asymptote of 0.8. These intercept and asymptote values were determined from laboratory studies of artificially dusted samples of RBs that had emissivities of 0.03 before dusting and 0.8 after a large amount of dusting. After this analysis was performed, an additional house was examined, in which a radiant barrier had been installed for about 23 years. The emissivity was found to be 0.75 to 0.80, in good agreement with the projected curve.

The models have been run with various assumed levels of emissivity for the horizontal RB. Load reductions obtained from these calculations were normalized with respect to the load reductions from a clean horizontal radiant barrier, with the results shown in Table 2. The model predicts that the performance drops off significantly with increasing emissivity, but the normalized reductions do not vary significantly with climate. Empirical equations fit to these results are

$$NRH = 192.2 \, [0.596 - 1/(1 + 0.61/e)] \qquad (3)$$

$$NRC = 162.3 \, [0.8318 - 1/(1 + 0.182/e)] \qquad (4)$$

where NRH and NRC are the normalized heating and cooling load reductions (as percentages of the load reductions for a clean horizontal RB) and e is the radiant barrier emissivity.

Data taken by the Tennessee Valley Authority with test cells having horizontal radiant barriers that were artificially dusted with "Arizona test dust" do not show such a rapid decline in performance as given by NRC (Hall 1988). For these data, the normalized load reductions appear to follow an approximately linear variation with emissivity.

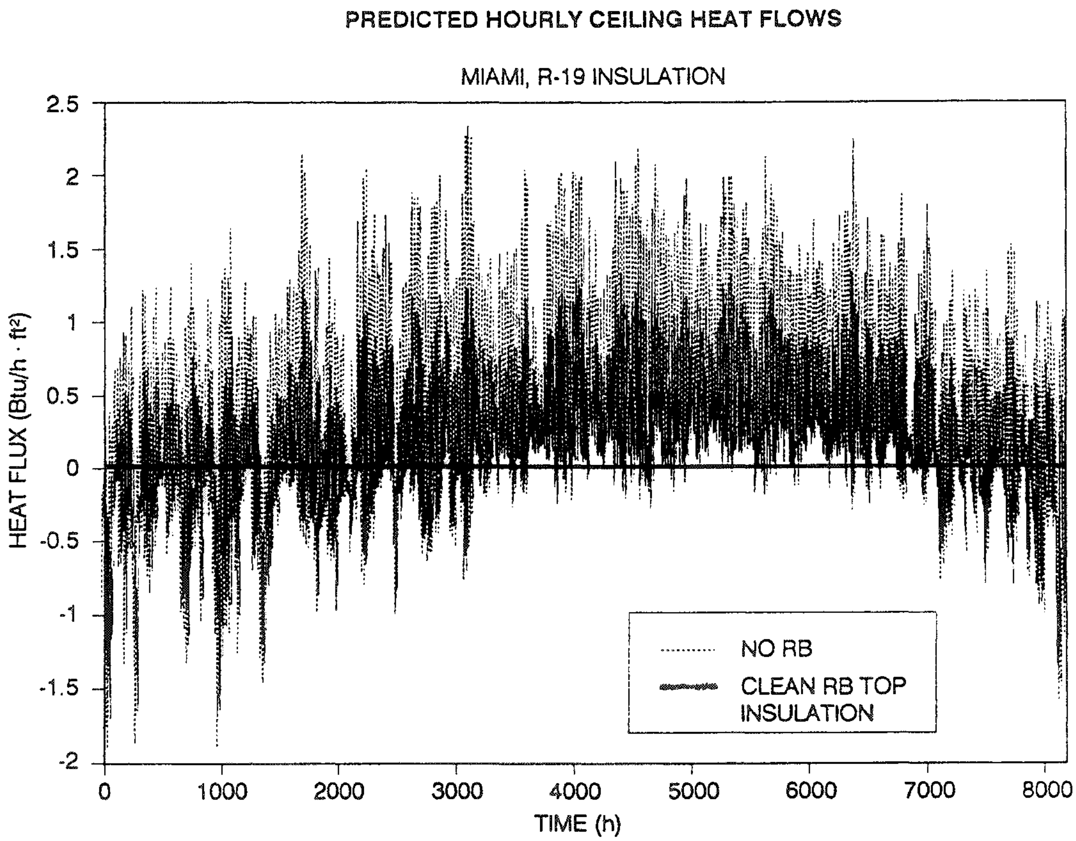

Figure 2. Predicted Hourly Ceiling Heat Fluxes with and Without Clean Radiant Barrier on Top of R-19 Insulation in Miami. Positive heat flows are from attic into house.

The approach used for the Fact Sheet is to present a range of savings for horizontal radiant barriers. The lower end of the range is obtained using the upper level of the confidence interval for emissivity versus time coupled with the model predictions of normalized performance versus emissivity. The upper end of the range is obtained using the lower level of the confidence interval for emissivity versus time coupled with a linear variation of normalized performance versus emissivity.

Load Reductions for Roof RBs

Load reductions for radiant barriers applied near the roof were estimated by running the model with various levels of effective or average emissivities for the underside of the roof. The inside surfaces of the gables were also assigned low emissivities (0.05). Predicted load reductions, normalized to the values for a clean horizontal radiant barrier are given in Table 3. In general, the normalized values do not vary significantly with climate or insulation level, but do vary considerably with roof emissivity and also vary somewhat between the heating and cooling seasons.

For radiant barriers attached to the bottoms of the roof rafters, an effective roof emissivity of 0.08 was used. This value represents a simple area averaging of emissivities of the radiant barrier and a small amount of exposed wood roof deck. For radiant barriers draped over the tops of the rafters or attached directly to the roof deck, an effective roof emissivity of 0.11 was used. This value accounts for additional exposed rafter surfaces. Interpolating in Table 3 for an emissivity of 0.08 gives normalized cooling and heating load reductions of 78 percent and 88 percent. (These load reductions are about 18 percent

Table 1. Annual Load Reductions Due to Clean Horizontal Radiant Barrier

City	Heating Load Reduction, Btu/ft^2				Cooling Load Reduction, Btu/ft^2			
	R-11*	R-19	R-30	R-38	R-11	R-19	R-30	R-38
Albany, NY	929	400	193	140	876	409	259	211
Albuquerque, NM	931	476	299	238	1598	851	522	426
Atlanta, GA	605	282	163	137	1673	832	516	405
Bismarck, ND	1192	513	293	206	706	388	245	191
Chicago, IL	842	377	210	144	960	475	284	229
Denver, CO	989	473	277	236	1020	550	357	294
El Toro, CA	792	378	242	197	1232	636	405	351
Houston, TX	387	182	108	80	2162	1120	672	521
Knoxville, TN	725	337	206	164	1597	823	517	411
Las Vegas, NV	774	438	277	227	2535	1210	703	539
Los Angeles, CA	738	390	227	188	429	256	168	148
Memphis, TN	630	304	180	164	1832	907	555	440
Miami, FL	99	47	28	26	3090	1631	938	727
Minneapolis, MN	1062	447	223	154	769	418	257	204
Orlando, FL	275	130	77	62	2575	1299	832	662
Phoenix, AZ	606	321	191	162	3308	1595	942	738
Portland, ME	1112	490	253	194	297	120	82	62
Portland, OR	937	427	238	186	551	299	178	147
Raleigh, NC	741	342	219	162	1440	738	460	359
Riverside, CA	892	422	248	189	1999	931	556	448
Sacramento, CA	821	397	236	192	1592	849	542	445
Salt Lake City, UT	906	415	223	187	1286	651	409	332
St. Louis, MO	738	324	169	136	1466	757	479	369
Seattle, WA	904	364	197	133	223	119	80	65
Topeka, KS	868	379	219	176	1523	790	512	397
Waco, TX	477	225	138	119	2371	1175	713	552
Washington, D.C.	912	386	212	182	1221	622	386	301

*R-Value of attic insulation.

Table 2. Effect of Emissivity on Load Reductions Due to Horizontal Radiant Barriers with R-11 Insulation

	Percent of Clean Horizontal RB Load Reduction		
Emissivity	Miami, Cooling	Minneapolis, Cooling	Minneapolis, Heating
0.05	100.0	100.0	100.0
0.10	73.4	74.8	87.8
0.20	48.0	50.8	66.7
0.30	33.5	35.7	51.6
0.40	23.4	24.9	38.5
0.50	16.0	17.4	28.0

Table 3. Load Reductions for Truss Radiant Barriers with Low Emissivity (e = 0.05) Gables

			Percent of Clean HRB Load Reduction		
City	Season	Insulation Level	e = 0.05*	e = 0.10	e = 0.15
Miami	Cooling	R-11	92.4	68.2	53.8
		R-19	94.1	70.7	56.8
		R-30	94.5	73.0	58.2
		R-38	94.6	71.8	57.9
Minneapolis	Cooling	R-11	93.2	70.0	56.2
		R-19	95.0	74.5	60.7
Miami	Heating	R-11	95.4	84.9	74.3
		R-19	95.9	83.6	69.9
		R-30	95.3	88.4	76.7
		R-38	97.5	82.5	72.5
Minneapolis	Heating	R-11	96.3	84.2	73.2
		R-19	95.6	80.4	71.2

*Effective emissivity of underside of roof.

and 7 percent less than would be predicted for a roof emissivity of 0.05.) For an emissivity of 0.11, similar normalized factors are 68 percent and 82 percent. Cooling and heating load reductions for the roof RBs were obtained by multiplying the load reductions for a clean horizontal RB by these factors.

An additional factor was applied to the load reductions for roof RBs to account for the influence of a roof RB on decreasing attic air temperatures and hence in decreasing heat gains to air-conditioning ducts that are run in attic spaces. Since the ORNL attic model does not include ducts, the results of modeling work performed by the Davis Energy Group were used to obtain adjustment factors (Bourne and Hoeschele 1988). Their results suggest that the cooling load reductions for attics with air-conditioning ducts should be greater than those without air-conditioning ducts by 26%, 37%, 48%, and 57% for attic insulation levels of R-11, 19, 30, and 38, respectively. Heat gains to ducts are relatively independent of attic insulation level, whereas the heat flow through the ceiling decreases with insulation level. Hence heat gains to the ducts become relatively more important as the attic insulation level is increased. Similar adjustments were not made for heating load reductions, since the effects are expected to be smaller.

For roof applications, two values are used for each case: one that corresponds to the values calculated with the ORNL model and another that is adjusted upwards by the factors derived from the Davis Energy Group work. The first value applies to attics with no A/C ducts, while the second value applies to attics with A/C ducts. There is a need for experimental verification of the proposed duct adjustment factors.

Energy Savings Estimates

Load reductions were converted to energy savings by dividing by equipment efficiencies or coefficients of performance. For the tables of present value savings in the Fact Sheet, average equipment efficiencies of 0.65 for natural gas heating and 2.34 for air-conditioning were used. The energies were then converted to dollars using average fuel prices of $0.527 per therm (100,000 Btu) for natural gas, and $0.0786 per kilowatt-hour for electricity. These values correspond to those used in the development of ASHRAE Standard 90.2P (private communication from D. Ober 1989). The present value of life cycle savings was estimated using a 7 percent real (i.e., over and above general inflation) discount rate, a 25 year life, and national average fuel price escalation rates (Lippiat and Ruegg 1988). The fuel price escalation rates were over and above general inflation, and averaged about 1.7 percent per year for natural gas and 0.16 percent per year for electricity. Table 4 gives estimated present value tables for the horizontal RB and for RBs attached to the bottoms of the rafters. The Fact Sheet also gives present value tables for RBs draped over the rafters or attached to the roof deck. For comparison purposes, tables for adding extra insulation are also given.

Table 4 shows that the savings vary significantly with climate, with larger savings in warmer climates. The tables also show that savings due to radiant barriers decrease greatly as the level of insulation is increased. For any given situation, an investment decision would require comparison of the installed costs per square foot of ceiling with the present value of lifetime savings per square foot of ceiling.

SUMMARY AND RECOMMENDATIONS

A Fact Sheet on radiant barriers is presently being developed. Details have been given of the methods used to estimate the present value of energy savings due to radiant barriers, and examples of present-value savings in the Fact Sheet have been presented. The present-value savings show that radiant barriers are more cost-effective for warmer climates. They are also more cost-effective when they are used in combination with low levels of attic insulation. The present-value savings for RBs attached to the bottoms of the rafters are greater than those for RBs applied directly on top of the attic insulation, when account is taken of the effects of dust accumulation. However, the cost of a RB on the rafters would generally be higher than for a RB on top of the insulation (partly because the total area of the roof and gables is greater than that of the ceiling). Any investment decision would require a comparison of installed costs with the present value of the lifetime savings.

A number of areas have been identified where additional research is needed. First, validation of the ORNL model has been based on data from field tests in warmer climates, such as Florida and Tennessee. There is a need for field experiments in cold climates to validate more fully the accuracy of the model in predicting heating load reductions.

All available data suggest that dust will accumulate fairly rapidly on horizontal RBs. The limited amount of experimental data on the effect of emissivity on performance of horizontal RBs has resulted in a wide variation in present value savings.

Table 4. Present Value Savings for Radiant Barriers

City	Present Value Savings, Cents per Square Foot of Ceiling							
	Dusty RB on Attic Floor**				RB Attached to Bottoms of Rafters***			
	R-11*	R-19	R-30	R-38	R-11	R-19	R-30	R-38
Albany, NY	4-13	2- 6	1- 3	1- 3	17-19	8- 9	4- 5	3- 4
Albuquerque, NM	5-18	3-10	2- 6	1- 5	24-27	12-15	8-10	6- 8
Atlanta, GA	5-17	2- 8	1- 5	1- 4	21-25	10-13	6- 8	5- 7
Bismarck, ND	5-14	2- 6	1- 4	1- 3	18-20	9-10	5- 6	4- 5
Chicago, IL	4-13	2- 6	1- 4	1- 3	17-19	8-10	5- 6	4- 5
Denver, CO	5-15	2- 7	1- 5	1- 4	19-22	10-12	6- 8	5- 7
El Toro, CA	4-15	2- 7	1- 5	1- 4	19-22	10-12	6- 8	5- 7
Houston, TX	5-19	3-10	2- 6	1- 4	23-28	12-15	7-10	5- 8
Knoxville, TN	5-17	2- 8	2- 5	1- 4	22-25	11-13	7- 9	5- 7
Las Vegas, NV	7-24	3-12	2- 7	2- 6	30-36	15-19	9-12	7-10
Los Angeles, CA	3- 8	2- 5	1- 3	1- 2	11-12	6- 7	4- 5	3- 4
Memphis, TN	5-18	2- 9	1- 5	1- 4	23-27	11-14	7- 9	6- 8
Miami, FL	6-23	3-12	2- 7	1- 6	28-36	15-20	9-13	7-10
Minneapolis, MN	4-13	2- 6	1- 3	1- 3	18-19	8-10	5- 6	3- 4
Orlando, FL	5-21	3-10	2- 7	1- 5	26-32	13-17	8-12	7-10
Phoenix, AZ	8-29	4-14	2- 8	2- 7	36-43	17-23	10-14	8-12
Portland, ME	4-10	2- 4	1- 2	1- 2	14-15	6- 6	3- 4	3- 3
Portland, OR	4-11	2- 5	1- 3	1- 2	14-16	7- 8	4- 5	3- 4
Raleigh, NC	5-16	2- 8	1- 5	1- 4	20-24	10-12	6- 8	5- 7
Riverside, CA	6-21	3-10	2- 6	1- 5	27-37	13-17	7-10	6- 8
Sacramento, CA	5-18	3- 9	2- 6	1- 5	23-26	12-14	7-10	6- 8
Salt Lake City, UT	5-16	2- 8	1- 5	1- 4	21-24	10-12	6- 8	5- 7
St. Louis, MO	5-16	2- 8	1- 5	1- 4	21-24	10-13	6- 8	5- 7
Seattle, WA	3- 8	1- 3	1- 2	0- 1	11-12	5- 5	3- 3	2- 2
Topeka, KS	5-17	2- 9	2- 5	1- 4	22-26	11-13	7- 9	5- 7
Waco, TX	6-21	3-10	2- 6	1- 5	26-31	13-17	8-11	6- 9
Washington, D.C.	5-15	2- 7	1- 4	1- 4	20-23	9-12	6- 7	5- 6

*Denotes level of conventional attic insulation.

**Note: Values represent range of savings due to variations in rate of dusting and to uncertainties in effect of dust on heat flows.

***Note: First value applies to houses with no air-conditioning ducts in attics. Second value applies to houses with air-conditioning ducts in attics.

There is a need for additional experimental work to determine a more accurate relationship between emissivity and performance, both for heating and cooling conditions.

Modeling results suggest that roof RBs can have a large effect on heat gains to air-conditioning ducts that are run in attic spaces. Experiments are needed to check the adequacy of the adjustment factors that have been applied to account for duct effects.

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