A Comprehensive Review of Radiant Barrier Research Including Laboratory and Field Experiments

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ABSTRACT

Attic Radiant Barriers (RBs) are proven technologies that significantly reduce the flow of radiant heat across attic spaces. This decreases the heat flow across the ceilings of buildings, which in turn lowers space cooling and heating loads, and produces energy and cost savings. This paper provides a general description of RBs, including installation configurations, the physical principles that make them work, and the laboratory and field experiments used to evaluate their thermal performance. An extensive review of the literature is summarized, highlighting fundamental issues, such as reduced ceiling heat flows, reduced space cooling and heating loads, and changes in attic temperatures produced by the installation of RBs in residential attics. Causes that affect RB performance, such as the influence of attic insulation level and climate, are presented. The data indicate that, on average, RBs reduce summer ceiling heat flows by 23 to 45% depending on the insulation level, whereas winter ceiling heat flow reductions are about 40% of the summer values for the same insulation levels. The data also indicate that RBs reduce space cooling loads by 6 to 20% and that space heating loads reductions are also about 40% of the space cooling load values for the same insulation levels.

INTRODUCTION

The increased pressure to reduce energy use and lower the electrical peak demand that result from building operations have encouraged the increased use, and sometimes the excessive use, of insulation. Although building insulation has played an essential role in making buildings more energy efficient, the amount of insulation that can be added to an attic space is limited by the physical dimensions of the structure. Extra insulation can potentially obstruct attic ventilation, compress itself, and create an excessive weight on the ceiling structure.

Attic Radiant Barriers (RBs) present a different way of increasing the thermal performance of existing or to-be-installed insulation in the space between roofs and ceilings of buildings (e.g., attic spaces in residential buildings or the space between roofs and suspended ceilings in commercial buildings). RBs have received considerable attention because of their potential to reduce radiant heat transfer across vented spaces between roofs and ceilings of buildings. RBs are metalized films or aluminum foil sheets laminated to paper (most commonly to Kraft paper), polymer films, oriented strand board (OSB), or plywood. These films and laminates are characterized by having at least one surface with an emittance of 0.1 or less (ASTM C 1313 2010). In the case of RBs, aluminum is used because it is inexpensive and because its surface, once exposed to air, becomes covered with a layer of a transparent oxide that protects it from the atmosphere and allows it to maintain a low emittance for long periods of time.

RBs are commonly installed in one of the four configurations shown in Figure 1.

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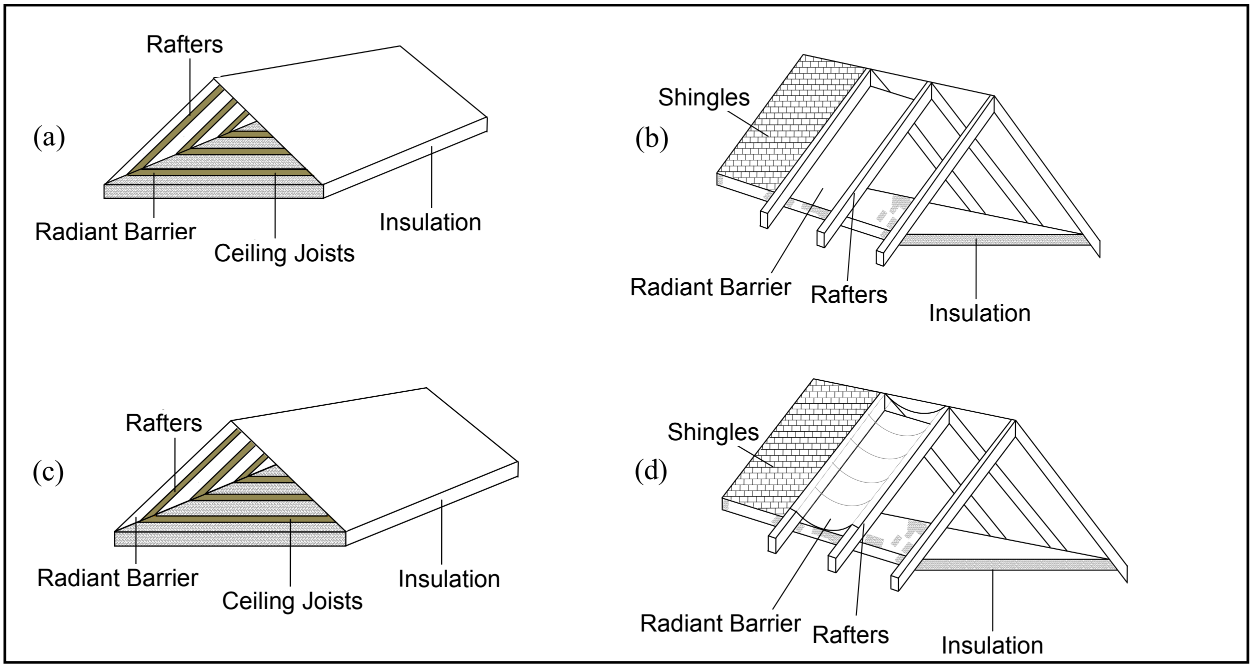

Figure 1. *Common radiant barrier installation configurations: (a) horizontal radiant barrier (HRB), (b) truss radiant barrier (TRB), (c) deck-applied radiant barrier (DARB), (d) draped radiant barrier (DRB).*

In the horizontal radiant barrier (HRB) configuration, the radiant barrier is installed on top of the attic floor insulation. In this case, one low-emittance side must face up towards the air space. The truss radiant barrier (TRB) consists of a radiant barrier installed within the trusses of the attic against the rafters that support the roof deck. In this configuration an extra air space is formed between the radiant barrier and the roof deck. If the radiant barrier has only one low emittance side, it is recommended that the low emittance side face the attic air space. The deck-applied radiant barrier (DARB) consists of aluminum foil bonded to the oriented strand board (OSB) or plywood boards that make up the roof deck. In the draped radiant barrier (DRB), the radiant barrier is attached to the roof deck or held between the roof deck and the rafters where the barrier is allowed to form a "drape-like" configuration, which creates a narrow air space between the deck and the radiant barrier. Similar to the TRB, if the DRB has only one low emittance side, it is recommended that the low emittance side face the attic air space.

Interior Radiation Control Coatings (IRCCs) also decrease the radiant heat flows across attic spaces. IRCCs are low emittance coatings or paints that when applied to a building surface change the emittance of these surfaces to that of the coating, which is 0.25 or less (ASTM C 1321 2009). For the most part, the installation of IRCCs is similar to that of the deck-applied radiant barrier, Fig. 1(c), depending on whether the rafters are coated.

Because of their low emittance values, RBs and IRCCs installed in attic spaces reduce the thermal radiation that is transferred between the roof deck and the top of the insulation, which is usually installed on the floor of the attic. This reduction in radiation heat transfer can be partly explained by Equation (1) (Cengel and Ghajar 2011), which represents the net transfer of heat by radiation between two surfaces (e.g., roof deck, surface 1, and top of the insulation, surface 2)

$$\dot{q}_{12} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{A_1\varepsilon_1} + \frac{1}{A_1F_{12}} + \frac{1-\varepsilon_2}{A_2\varepsilon_2}} \qquad (1)$$

Basically, RBs and IRCCs work by altering the emittance value (ε) of at least one of the surfaces between the roof deck and top of the insulation. Note that Equation (1) is a simplification in many ways, but it presents a snapshot of the physics involved when RBs or IRCCs are installed in attic spaces. For the TRB and DRP configurations, however, other terms must be added to the denominator of Equation (1) because reflective air spaces are created when the radiant barriers are installed.

RADIANT BARRIER PERFORMANCE

There are three well-established and accepted methods that are used for evaluating the performance of RBs and IRCCs. These are laboratory tests, field studies, and computer simulations. Laboratory tests have the advantage that several parameters, such as roof temperature, "solar" intensity, and air speeds, can be controlled, which allows ceiling heat fluxes and attic temperatures to be studied and measured under controlled ranges of conditions. Although laboratory tests are well received and are essential in the study of radiant barriers, they present some drawbacks. One of the shortcomings of laboratory tests is that outdoor (i.e., weather-like) conditions are not entirely reproduced in a laboratory setting. Most laboratory experiments are carried out under steady-state conditions, which are not representative of the conditions in which buildings operate. Field studies tend to be more complex, but offer the advantage that buildings are studied under actual weather conditions. These studies produce data that most accurately represent the conditions in which buildings operate. Field studies also have their own complications and limitations. Complications arise from the fact that under actual weather conditions the climatic variables are not controlled. The most precise results from field studies are produced when side-by-side tests are performed using identical (i.e., same footprint, construction, size, and orientation) unoccupied buildings. In addition to the buildings being identical in all respects, it is important that the buildings' thermal performance be identical or nearly identical prior to the installation of the radiant barriers. In side-by-side testing protocols, control (i.e., standard) and test (i.e., retrofit) buildings operate under the same weather conditions and direct comparisons are possible. The third method used to evaluate the thermal performance of radiant barriers is computer simulation using mathematical models. Although the review of the literature performed for this paper found several computer simulations of buildings with installed radiant barriers, this method will be discussed in a separate paper.

Most of the results are given in terms of ceiling heat fluxes and space cooling and heating load reductions expressed as percentages. This is because comparisons are often made between buildings with and buildings without radiant barriers. Therefore, the effectiveness (i.e., the "thermal performance") of radiant barriers is often an indication of the percent reductions that they produce when buildings with and without RBs are compared.

Review of Experimental Works

Over fifty years (1958-2010) of published papers from various sources were reviewed. The most relevant results are summarized in Tables 1 through 5. The results of Tables 1 through 4 are presented in terms of percent reductions of ceiling heat flows and space cooling and heating loads. The results in Table 5 are presented in terms of attic air temperature reductions, in ^{o}F. For clarity, all percent reductions and temperature data were rounded off to the nearest whole number. The data were divided into cooling or heating season results. For the cooling season, only data collected during June, July, and August were considered. Similarly, for the heating season, only data collected during December, January, and February were considered. Within each table, the results were grouped by insulation level. For the most part, only insulation levels of R-11 (1.94 $m^2 \cdot K/W$), R-19 (3.35 $m^2 \cdot K/W$), and R-30 (5.28 $m^2 \cdot K/W$) were included. Within each table, the percent reductions were also depicted graphically using shaded horizontal clustered bars. Also, because the data were taken from such a diverse pool of experiments that were carried out in various geographical locations, climate conditions, attic ventilation arrangements, in occupied and unoccupied buildings, etc., as much background information as possible is presented in each table entry. This information includes testing protocol (i.e., laboratory controlled, side-by-side, or pre- and post-), location (city and state), cooling and heating degree days (base 65^{o}F), climatic zone (see Figure 2 below), ventilation type (i.e., natural or forced ventilation and vent arrangement), whether the building was occupied during the testing period, and whether the air handlers and ducts were located in the attics. In addition, average values are presented for each data cluster. For testing protocols, laboratory controlled experiments were performed under steady-state conditions. Side-by-side experiments were carried out simultaneously in two or more houses in which one house was used as a control house while the other(s) was (were) retrofit with radiant barriers in one of the four installation configurations. Pre- and post-experiments were carried out using the same buildings at different times, but under comparable weather conditions. That is, data were gathered first with the attic having no radiant barriers. Then, radiant barriers were installed and the monitoring continued. The cooling and heating degree days, as well as DOE climatic zones, for the experimental locations are provided to give a sense of the climate under which the experiments were carried out. All radiant barriers used in the experiments were assumed to be new and clean.

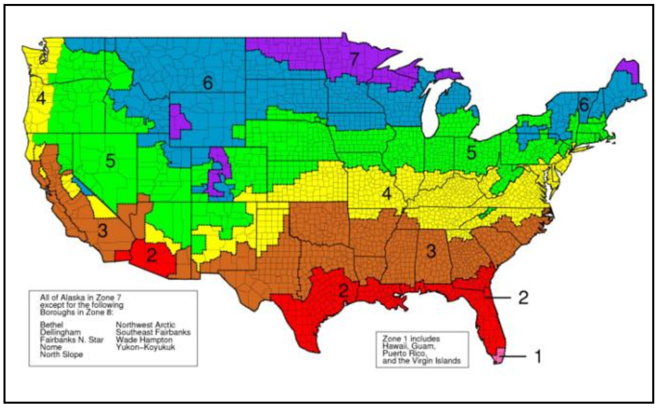

Figure 2. *U.S. climate zone map (ASHRAE Standard 169-2006, 2006)*

Table 1 shows the results of ceiling heat flow reductions produced by RBs and IRCCs during the cooling season. Laboratory-controlled experiments indicated that radiant barriers installed under flat roofs provided greater reductions than those installed below pitched roofs. In both cases, the radiant barriers were installed in HRB configurations. Laboratory-controlled experiments of IRCCs applied in flat roof configurations with R-19 (3.35 m^2·K/W) insulation produced average heat flow reductions of 32% vs. the same system without the application of any coatings. In field experiments, radiant barriers installed in attics with R-11 (1.94 m^2·K/W) insulation produced ceiling heat flow reductions that ranged from 34% to 60%. The 60% reduction corresponded to an attic in which both a HRB and a TRB were installed at the same time. That is, the attic interior was fully lined with a radiant barrier. The average reduction in heat flow produced by radiant barriers in attics with R-11 (1.94 m^2·K/W) insulation was 45%. In attics with insulation levels of R-19 (3.35 m^2·K/W) the reductions ranged from 16% to 43%, with an average value of 30%. The average reduction from installed HRBs was 29%. For installed TRBs the average reduction was 32%. Radiant barriers installed in the draped configuration (DRB) yielded an average of 18% reduction. There seemed to be a slight correlation between percent reductions in ceiling heat flows and the geographical location of the buildings for the referenced experiments, most of which were carried out in DOE Climatic Zones 2 and 4. For example, for the attics with installed HRBs, the highest percentages were observed in Zone 4, but for those attics with installed TRBs and DRBs the maximum reductions were observed in Zone 2. There also seemed to be some correlation between the ceiling heat flow reductions and attic airflow patterns (e.g., soffit/soffit, soffit/gable, and soffit/ridge). For example, the houses that were identified as having soffit vents for attic air intake and exhaust had the largest percent reduction in ceiling heat flows when TRBs were installed. However, there was no clear correlation produced by TRBs in those houses with soffit/ridge or soffit/gable vents arrangements. There were also no clear correlations in ceiling heat flow reduction with attic airflow rate or kind of air flow (i.e., natural or forced) across the attic. The only exception was from a study by Parker and Sherwin (1998) in which the heat flow percent reduction produced by a TRB increased from 26% to 36% when the vent area for natural attic airflow was increased from 1:300 to 1:150. For attics with R-30 (5.28 m^2·K/W) insulation, the reductions ranged from 20% to 25%, with an average value of 23%. These experiments indicated that for TRBs, the highest percent reductions were produced in Zone 2.

Table 1. Ceiling Heat Flow Reductions Produced by RBs and IRCCs (Cooling Season)

Season	Reference	Nominal Insulation Level R-Value	Testing Protocol	Method	Ceiling Heat Flow Reductions Over Test Period (%) Summer														City, St	CDD	Climatic Zone	Ventilation				Occupied		Comments	Average
					-5	0 - 4	5 - 9	10 - 14	15 - 19	20 - 24	25 - 29	30 - 34	35 - 39	40 - 44	45 - 49	50 - 54	55 - 59	60				Vents		FV	NV	N	Y		
Cooling	Joy (1958)	R-7.5	Laboratory Controlled	HRB												50			N/A			S	S	X		X		Flat Roof	41%
	Katipamula & O'Neal (1986)	R-11		HRB											46				N/A			-	-	-	-	X		Flat Roof	
	Yarbrough (2010)	R-13												41					N/A			-	-	-	-	X		Pitched Roof	
	Joy (1958)	R-7.5		HRB							28								N/A			S	S	X		X		Pitched Roof	
	Swami and Fairey (1986)	R-19	Laboratory Controlled	IRCC								32							N/A			-	-	-		X		Flat Roof	32%
	Ashley et al. (1994)	R-11	Side-by-Side	HRB/TRB														60	Kingsville, TX	3,404	2	G	G		X		X	Attic fully wrapped	45%
	Medina (2000a)			TRB										42					College Station, TX	2,938	2	S	G	X		X			
	Hall (1988a)			TRB								34							Chattanooga, TN	1,608	4	S	G		X	X			
	Fairey (1985)	R-19	Side-by-Side	TRB										43					Cape Canaveral, FL	3,300	2	S	S	X		X		5 ACH, 1 AS f/down	30%
	Fairey (1985)			TRB										43					Cape Canaveral, FL	3,300	2	S	S	X		X		5 ACH, 2 AS	
	Hall (1986)			HRB										40					Chattanooga, TN	1,608	4	S	G		X	X			
	Fairey (1990)			TRB									39						Cape Canaveral, FL	3,300	2	-	-		X	X			
	Parker and Sherwin (1998)			TRB									36						Cocoa Beach, FL	3,300	2	S	R		X	X		Vent area = 1:150	
	Levins et al. (1986)			HRB									35						Karns, TN	1,301	4	S	G		X	X			
	Medina (2000a)			TRB								34							College Station, TX	2,938	2	S	G	X		X			
	Levins et al. (1986)			TRB								30							Karns, TN	1,301	4	S	G		X	X			
	Hall (1988a)			TRB								30							Chattanooga, TN	1,608	4	S	G		X	X			
	Medina et al. (1992a)			HRB								30							College Station, TX	2,938	2	S	G	X		X			
	Parker and Sherwin (1998)			TRB							26								Cocoa Beach, FL	3,300	2	S	R		X	X		Vent area = 1:300	
	Hall (1986)			TRB						23									Chattanooga, TN	1,608	4	S	G		X	X			
	McQuiston et al. (1984)			HRB						20									Stillwater, OK	1,881	3	-	-	X		-	-	Curved Roof	
	Ober & Volckhausen (1988)			DRB						20									Orlando, FL	3,428	2	S	G		X	X			
	Fairey (1985)			TRB					19										Cape Canaveral, FL	3,300	2	-	-			X		Unvented Attics	
	Fairey (1985)			HRB					18										Cape Canaveral, FL	3,300	2	-	-			X		Unvented Attics	
	Hall (1986)			DRB					16										Chattanooga, TN	1,608	4	S	G		X	X			
	Medina (2000a)	R-30	Side-by-Side	TRB							25								College Station, TX	2938	2	S	G		X	X			23%
	Hall (1988a)			TRB						20									Chattanooga, TN	1608	4	S	G		X	X			

Legend: CDD = Cooling Degree Days, HDD = Heating Degree Days, HRB = Horizontal Radiant Barrier, TRB = Truss Radiant Barrier, DARB = Deck-Applied Radiant Barrier, DRB = Draped Radiant Barrier, IRCC = Interior Radiation Control Coating, FV= Forced Ventilation, NV= Natural Ventilation, S = Soffit Vent, G = Gable Vent, R = Ridge Vent, P = Power Fan, ACH = Air Changes per Hour, AS = Aluminized Side, f/ = Facing, N/A = Not Applicable, (-) = Not Specified

RBs also showed benefits during the heating season. This is summarized in Table 2. The reductions in ceiling heat flows from the heated conditioned space to the attic ranged from an average value of 13% for attics with R-11 (1.94 $m^2{\cdot}K/W$) insulation to 9% for attics with R-30 (5.28 $m^2{\cdot}K/W$) insulation. For attics with R-19 (3.35 $m^2{\cdot}K/W$) insulation, the average reduction in heat flow was 12%. For attics with R-11 (1.94 $m^2{\cdot}K/W$) insulation, the HRB configuration outperformed the TRB in Zone 4, which was the only zone represented in the R-11 (1.94 $m^2{\cdot}K/W$) pool. That is, attics with HRB had an average reduction of 18% while attics with installed TRBs reduced the heat flow by 7%. For the attics with R-19 (3.35 $m^2{\cdot}K/W$) insulation, however, the TRB outperformed the HRB configuration, 14% to 12%, while the DRB configuration yielded an average reduction of 4%.

Table 2. Ceiling Heat Flow Reductions Produced by RBs and IRCCs (Heating Season)

Season	Reference	Nominal Insulation Level R-Value	Testing Protocol	Method	Ceiling Heat Flow Reductions Over Test Period (%) Winter														City, St	HDD	Climatic Zone	Ventilation				Occupied		Comments	Average
					-5	0 - 4	5 - 9	10 - 14	15 - 19	20 - 24	25 - 29	30 - 34	35 - 39	40 - 44	45 - 49	50 - 54	55 - 59	60				Vents		FV	NV	N	Y		
Heating	Levins and Karnitz (1988)	R-11	Side-by-Side	HRB					19										Karns, TN	3,993	4	S	G		X	X			13%
	Hall (1988)			HRB					17										Chattanooga, TN	3,427	4	S	G		X	X			
	Levins and Karnitz (1988)			TRB			8												Karns, TN	3,993	4	S	G		X	X			
	Hall (1988)			TRB			6												Chattanooga, TN	3,427	4	S	G		X	X			
	Levins and Karnitz (1987b)	R-19	Side-by-Side	TRB								30							Karns, TN	3,993	4	S	G		X	X			12%
	Fairey (1990)			TRB						24									Cape Canaveral, FL	677	2	-	-		X	X			
	Medina et al. (1992b)			HRB					17										College Station, TX	1,616	2	-	-	-	-	X		Non-vented Attics	
	Hall (1986)			HRB					15										Chattanooga, TN	3,427	4	S	G		X	X			
	Medina et al. (1992b)			TRB					15										College Station, TX	1,616	2	-	-	-	-	X		Non-vented Attics	
	Medina et al. (1992b)			HRB				14											College Station, TX	1,616	2	S	G	X		X			
	McQuiston et al. (1984)			HRB				10											Stillwater, OK	3,989	3	-	-	X		-	-	Curved Roof	
	Medina et al. (1992b)			TRB			9												College Station, TX	1,616	2	S	G	X		X			
	Hall (1988a)			HRB			5												Chattanooga, TN	3,427	4	S	G		X	X			
	Hall (1986)			TRB			8												Chattanooga, TN	3,427	4	S	G		X	X			
	Hall (1986)			DRB		4													Chattanooga, TN	3,427	4	S	G		X	X			
	Hall (1988a)			TRB	-5														Chattanooga, TN	3,427	4	S	G		X	X			
	Hall (1988a)	R-30	Side-by-Side	HRB					15										Chattanooga, TN	3,427	4	S	G		X	X			9%
	Levins and Karnitz (1988)			HRB				10											Karns, TN	3,993	4	S	G		X	X			
	Hall (1988a)			TRB			6												Chattanooga, TN	3,427	4	S	G		X	X			
	Levins and Karnitz (1988)			TRB		4													Karns, TN	3,993	4	S	G		X	X			

Legend: CDD = Cooling Degree Days, HDD = Heating Degree Days, HRB = Horizontal Radiant Barrier, TRB = Truss Radiant Barrier, DARB = Deck-Applied Radiant Barrier, DRB = Draped Radiant Barrier, IRCC = Interior Radiation Control Coating, FV= Forced Ventilation, NV= Natural Ventilation, S = Soffit Vent, G = Gable Vent, R = Ridge Vent, P = Power Fan, ACH = Air Changes per Hour, AS = Aluminized Side, f/ = Facing, N/A = Not Applicable, (-) = Not Specified

Buildings located in Zone 2 experienced an average heat flow reduction of 16% while those located in Zone 4 experienced a reduction of 11%. The attics with installed HRBs in Zone 2 experienced an average reduction of 16%, while those in Zones 4 and 3 experienced reductions of 10%. For attics with R-30 (5.28 $m^2{\cdot}K/W$) insulation, the HRB configuration produced larger reductions than the TRB configuration. The average reductions in ceiling heat flow were 13% and 5% for the HRB and TRB configurations, respectively. All the attics with R-30 (5.28 $m^2{\cdot}K/W$) insulation levels were located in Zone 4. Table 3 contains the reported reductions in space cooling load produced by the installation of radiant barriers. In space cooling and heating load reductions the ceiling heat flow represents only one component of the overall enclosure in which the heat flows of each of the other components (e.g., walls, windows, doors, etc.) are also accounted for and contribute to the magnitude of the overall space cooling or heating loads.

Table 3. Space Cooling Load Reductions Produced by RBs

Season	Reference	Nominal Insulation Level R-Value	Testing Protocol	Method	Ceiling Area	Space Load Reduction (%) Cooling								City, St	CDD	Climatic Zone	Ventilation				Occupied		Includes Ducts in the Attic		Average
						-5	0 - 4	5 - 9	10 - 14	15 - 19	20 - 24	25 - 29	30				Vents		FV	NV	N	Y	Y	N	
Cooling	Levins and Karnitz (1987a)	R-11	Side-by-Side	HRB	1,200					16				Karns, TN	1,301	4	S	G		X	X			X	14%
	Levins and Karnitz (1987a)			TRB	1,200				11					Karns, TN	1,301	4	S	G		X	X			X	
	Parker and Sherwin (2002)	R-19	Pre-and Post-	TRB	2,440							27		Orlando, FL	3,428	2	-	-	-	-		X		X	20%
	Levins et al. (1986)		Side-by-Side	HRB	1,200						21			Karns, TN	1,301	4	S	G		X	X			X	
	Parker and Sherwin (2002)		Pre-and Post-	TRB	2,200						20			Largo, FL	3,718	2	-	-	-	-		X	X		
	Levins et al. (1986)		Side-by-Side	TRB	1,200				13					Karns, TN	1,301	4	S	G		X	X			X	
	Parker and Sherwin (2002)	R-30	Pre-and Post-	TRB	1,520					16				Tarpon Springs, FL	3,414	2	-	-	-	-		X			6%
	Davis and Tiller (2009)		Side-by-Side	TRB	3,205				14					Charlotte, NC	1,681	3	S	R		X	X		X		
	Parker and Sherwin (2002)		Pre-and Post-	TRB	1,840			5						Apopka, FL	3,428	2	S	P	X	X		X	X		
	Levins and Karnitz (1987a)		Side-by-Side	HRB	1,200		2							Karns, TN	1,301	4	S	G		X	X			X	
	Parker and Sherwin (2002)		Pre-and Post-	TRB	2,140		0							Orlando, FL	3,428	2	P	P	X			X	Partially		
	Levins and Karnitz (1987a)		Side-by-Side	TRB	1,200	-1								Karns, TN	1,301	4	S	G		X	X			X	

Legend: CDD = Cooling Degree Days, HDD = Heating Degree Days, HRB = Horizontal Radiant Barrier, TRB = Truss Radiant Barrier, DARB = Deck-Applied Radiant Barrier, DRB = Draped Radiant Barrier, IRCC = Interior Radiation Control Coating, FV= Forced Ventilation, NV= Natural Ventilation, S = Soffit Vent, G = Gable Vent, R = Ridge Vent, P = Power Fan, ACH = Air Changes per Hour, AS = Aluminized Side, f/ = Facing, N/A = Not Applicable, (-) = Not Specified

For attics with R-11 (1.94 $m^2 \cdot K/W$) insulation, the range of reductions in space cooling load was from 11% to 16%, with an average of 14%. For the attics with R-19 (3.35 $m^2 \cdot K/W$) insulation, the reductions ranged between 13% and 27%, with an average of 20%. In houses in side-by-side testing, the average reduction in space cooling load was 17% and in houses where pre-and post- testing was performed the reduction was 24%. The side-by-side houses were located in Zone 4 and those in the pre- and post- were in Zone 2. The pre- and post- monitoring were one year apart and these houses were occupied, while the houses used in the side-by-side test were unoccupied. In the R-19 (3.35 $m^2 \cdot K/W$) insulation pool, only one house had the air handling ducts in the attic. Therefore, the effects of having the ducts placed in the attic when RBs were installed could not be determined. For the attics with R-30 (5.28 $m^2 \cdot K/W$) insulation, the range of space cooling load reductions was between -1% and 16%. The negative reduction occurred in one of 12 cases. The average value for space cooling load reductions for attics with R-30 (5.28 $m^2 \cdot K/W$) insulation was 6%. All except one of the houses in this pool had TRBs installed. The houses with air handling ducts in the attics had a space cooling load reduction of 6%. Those without ducts in the attic had an average reduction of 1%.

Table 4 contains the reported space heating load reductions. For attics with R-11 (1.94 $m^2 \cdot K/W$) insulation, the average reduction in space heating load was 5%. For attics with R-19 (3.35 $m^2 \cdot K/W$) and R-30 (5.28 $m^2 \cdot K/W$) insulation, the average reduction values were 4% and 4%, respectively. In each case, except for the R-30 (5.28 $m^2 \cdot K/W$) cluster, the HRB configuration outperformed the TRB configuration.

Table 4. Space Heating Load Reductions Produced by RBs

Season	Reference	Nominal Insulation Level R-Value	Testing Protocol	Method	Ceiling Area	Space Load Reduction (%) Heating								City, St	HDD	Climatic Zone	Ventilation				Occupied		Includes Ducts in the Attic		Average
						-5	0 - 4	5 - 9	10 - 14	15 - 19	20 - 24	25 - 29	30				Vents		FV	NV	N	Y	Y	N	
Heating	Levins and Karnitz (1987b)	R-11	Side-by-Side	HRB	1,200			9						Karns, TN	3,993	4	S	G		X	X			X	5%
	Levins and Karnitz (1987b)			TRB	1,200		0							Karns, TN	3,993	4	S	G		X	X			X	
	Levins et al. (1986)	R-19	Side-by-Side	HRB	1,200				10					Karns, TN	3,993	4	S	G		X	X			X	4%
	Levins et al. (1986)			TRB	1,200	-3								Karns, TN	3,993	4	S	G		X	X			X	
	Levins and Karnitz (1987b)	R-30	Side-by-Side	HRB	1,200		4							Karns, TN	3,993	4	S	G		X	X			X	4%
	Levins and Karnitz (1987b)			TRB	1,200		4							Karns, TN	3,993	4	S	G		X	X			X	

Legend: CDD = Cooling Degree Days, HDD = Heating Degree Days, HRB = Horizontal Radiant Barrier, TRB = Truss Radiant Barrier, DARB = Deck-Applied Radiant Barrier, DRB = Draped Radiant Barrier, IRCC = Interior Radiation Control Coating, FV= Forced Ventilation, NV= Natural Ventilation, S = Soffit Vent, G = Gable Vent, R = Ridge Vent, P = Power Fan, ACH = Air Changes per Hour, AS = Aluminized Side, f/ = Facing, N/A = Not Applicable, (-) = Not Specified

Table 5 contains the reported reductions in attic temperatures produced by radiant barriers. Attics in which TRBs were installed showed temperature reductions from 3°F to 23°F (1.7°C to 12.8°C). When the attics had R-11 (1.94 $m^2 \cdot K/W$) insulation the average temperature reduction was 9°F (5°C). In attics with R-19 (3.35 $m^2 \cdot K/W$) insulation the average temperature reduction was 14°F (7.8°C). It was 11 °F (6.1°C) for attics with R-30 (5.28 $m^2 \cdot K/W$) insulation. For attics with R-19 (3.35 $m^2 \cdot K/W$) insulation, those located in Zone 2 and Zone 4 had average temperature reductions of 14°F (7.8°C) and

13°F (7.2°C), respectively. Two attics in the R-19 (3.35 $m^2 \cdot K/W$) insulation pool had HRBs installed and both were located in Zone 4. In one house the temperature reduction after the installation of an HRB was 8°F (4.4°C) while in the other it was 0°F (0°C). Because of the manner in which sensors (e.g., thermocouples) may have been installed in the attics and the way data were collected and reported, the above temperature reductions represent a mix of attic air temperature reductions and top of insulation temperature reductions.

Table 5. Attic Temperature Reductions Produced by RBs (Cooling Season)

Season	Reference	Nominal Insulation Level R-Value	Testing Protocol	Method	Temperature Reductions (Deg F) Summer														City, St	CDD	Climatic Zone	Ventilation				Occupied		Comments	Average
					0	0 - 2	3 - 4	5 - 6	7 - 8	9 - 10	11 - 12	13 - 14	15 - 16	17 - 18	19 - 20	21 - 22	23 - 24	25 - 26				Vents		FV	NV	N	Y		
Cooling	Hall (1988a)	R-11	Side-by-Side	TRB						10									Chattanooga, TN	1,608	4	S	G		X	X			9 F
	Levins and Karnitz (1987a)		Side-by-Side						7										Karns, TN	1,301	4	S	G		X	X			
	Parker and Sherwin (1998)	R-19	Side-by-Side	TRB											20				Cocoa Beach, FL	3,300	2	S	R		X	X		Vent area = 1:150	14 F
	Parker and Sherwin (2002)		Pre-and Post-										16						Orlando, FL	3,428	2	-	-	-	-		X		
	Parker and Sherwin (2002)		Pre-and Post-										15						Largo, FL	3,718	2	-	-	-	-		X		
	Levins and Karnitz (1986)		Side-by-Side										15						Karns, TN	1,301	4	S	G		X	X			
	Hall (1988a)		Side-by-Side							10									Chattanooga, TN	1,608	4	S	G		X	X			
	Parker and Sherwin (1998)		Side-by-Side					6											Cocoa Beach, FL	3,300	2	S	R		X	X		Vent area = 1:300	
	Hall (1986)		Side-by-Side	HRB					8										Chattanooga, TN	1,608	4	S	G		X	X			4 F
	Levins and Karnitz (1986)		Side-by-Side			0													Karns, TN	1,301	4	S	G		X	X			
	Davis and Tiller (2009)	R-30	Side-by-Side	TRB												23			Charlotte, NC	1,681	3	S	R		X				11 F
	Parker and Sherwin (2002)		Pre-and Post-													22			Tarpon Springs, FL	3,414	2	-	-	-	-		X		
	Parker and Sherwin (2002)		Pre-and Post-								11								Apopka, FL	3,428	2	S	P	X	X		X		
	Hall (1988a)		Side-by-Side							10									Chattanooga, TN	1,608	4	S	G		X	X			
	Levins and Karnitz (1987a)		Side-by-Side						7										Karns, TN	1,301	4	S	G		X	X			
	Parker and Sherwin (2002)		Pre-and Post-				3												Orlando, FL	3,428	2	P	P	X			X		

Legend: CDD = Cooling Degree Days, HDD = Heating Degree Days, HRB = Horizontal Radiant Barrier, TRB = Truss Radiant Barrier, DARB = Deck-Applied Radiant Barrier, DRB = Draped Radiant Barrier, IRCC = Interior Radiation Control Coating, FV= Forced Ventilation, NV= Natural Ventilation, S = Soffit Vent, G = Gable Vent, R = Ridge Vent, P = Power Fan, ACH = Air Changes per Hour, AS = Aluminized Side, f/ = Facing, N/A = Not Applicable, (-) = Not Specified

CONCLUSIONS

There is ample evidence in the literature to conclude that radiant barriers reduce the heat transfer rate across attic spaces in a significant manner. This reduces the space cooling load and to a lesser extent the space heating load. Reductions in ceiling heat flow were primarily affected by RB emittance values, the level of insulation in the attic, and climate. The data indicate that, on average, radiant barriers reduced summer ceiling heat flows by approximately 23 to 45%, depending on the insulation level. Winter ceiling heat flow reductions were approximately 40% of the summer values for the same insulation levels. The data also indicate that space cooling loads were reduced between 6 to 20% and space heating load reductions were about 40% of cooling values for the same insulation levels. Data from laboratory controlled experiments indicate that IRCCs with an emittance of 0.25 or less would provide reductions equivalent to 61% of the values produced by the radiant barriers. The data also indicate that DARBs and TRBs would reduce the summer attic air temperature by an average of 13°F (7.2 °C). Radiant barriers installed in the HRB configuration would reduce the attic air temperature by an average of 4°F (2.2 °C).

NOMENCLATURE

A = surface area, ft^2 or m^2
ε = emittance of surface 1 or surface 2
F = configuration factor (a function only of geometry)
q = ceiling heat flux, $Btu/hr\text{-}ft^2$ or W/m^2
σ = Stefan-Boltzmann constant, 0.1713×10^{-8} $Btu/(hr \cdot ft^2 \cdot R^4)$ [5.673×10^{-8} $W/(m^2 \cdot K^4)$]
T = absolute temperature, R or K

REFERENCES

ASHRAE. 2006. *ASHRAE Standard* 169-2006. *Weather Data for Building Design Standards*. Atlanta: American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc.

Ashley, R., Garcia, O., Medina, M.A., and Turner, W.D. 1994. Effects of radiant barrier technology on summer attic heat load in South Texas. *Proceedings of the 9th Symposium on Improving Building Systems in Hot and Humid Climates*, Arlington, TX.

ASTM C1313. 2010. *Standard Specification for Sheet Radiant Barriers for Building Construction Applications*. West Conshohocken: American Society for Testing Materials.

ASTM C1321. 2009. *Standard Practice for Installation and Use of Interior Radiation Control Coating Systems (IRCCS) in Building Construction.* West Conshohocken: American Society for Testing Materials.

Cengel, Y.A. and Ghajar, A.J. 2011. *Heat and Mass Transfer: Fundamentals and Applications*, 4th Ed. Chapter 13, Radiation heat transfer. McGraw Hill.

Davis, B. and Tiller, J. 2009. Radiant barrier impact on selected building performance measurements - Model home case study. Energy Center, Appalachian State University, USA.

Fairey P.W. 1985. The measured side-by-side performance of attic radiant barrier systems in hot, humid climates. *Proceedings of the 19th International Thermal Conductivity Conference*, Cookeville, TN.

Fairey P.W. 1990. Seasonal prediction of roof-mounted attic radiant barrier system performance from measured test data. *Proceedings of the ACEEE 1990 Summer Study on Energy Efficiency in Buildings*, Pacific Grove, CA.

Hall, J. A. 1986. Performance testing of radiant barriers. *Proceedings of the 3rd Symposium on Improving Building Systems in Hot and Humid Climates*, Arlington, TX.

Hall J. A. 1988. Radiant barrier testing to assess effects of dust accumulation, attic ventilation, and other key variables. Report TVA/OP/EDT-88/25, Tennessee Valley Authority, U.S.A.

Hall, J. A. 1988a. Performance testing of radiant barriers (RB) with R-11, R-19, and R-30 cellulose and rock wool insulation. *Proceedings of the 5th Symposium on Improving Building Energy Efficiency in Hot and Humid Climates*, Houston, TX.

Joy F.A. 1958. Improving attic space insulating values. *ASHRAE Transaction* Vol. 64: 251-266.

Katipamula S. and O'Neal D.L. 1986. An evaluation of the placement of radiant barriers on their effectiveness in reducing heat transfer in attics. *Proceedings of the 3rd Symposium on Improving Building Energy Efficiency in Hot and Humid Climates*, Arlington, TX.

Levins W.P. and Karnitz M.A. 1986. Cooling energy measurements of unoccupied single-family houses with attics containing radiant barriers. Report ORNL/CON-200, Oak Ridge National Laboratory, U.S.A.

Levins W.P., Karnitz M.A., and Knight D.K. 1986. Cooling energy measurements of unoccupied single-family houses with attics containing radiant barriers. *Proceedings of the 3rd Symposium on Improving Building Energy Efficiency in Hot and Humid Climates*, Arlington, TX.

Levins W.P. and Karnitz M.A. 1987a. Cooling energy measurements of single-family houses with attics containing radiant barriers in combination with R-11 and R-30 ceiling insulation. Report ORNL/CON-226, Oak Ridge National Laboratory. U.S.A.

Levins W.P. and Karnitz M.A. 1987b. Heating energy measurements of unoccupied single-family houses with attics containing radiant barriers. Report ORNL/CON-213, Oak Ridge National Laboratory. U.S.A.

Levins W.P. and Karnitz M.A. 1988. Heating energy measurements of single-family houses with attics containing radiant barriers in combination with R-11 and R-30 ceiling insulation. Report ORNL/CON-239, Oak Ridge National Laboratory. U.S.A.

McQuiston, F.C., Der, S.L., and Sandoval, S.B. 1984. Thermal simulation of attic and ceiling spaces. *ASHRAE Transactions*, Vol. 90, Pt 1, pp. 139-163.

Medina, M.A., O'Neal, D.L., and Turner, W.D. 1992a. Effect of attic ventilation on the performance of radiant barriers. *ASME Journal of Solar Energy Engineering,* Vol. 114, pp. 234 - 239.

Medina, M.A., O'Neal, D.L., and Turner, W.D. 1992b. Radiant barrier performance during the heating season. *Proceedings of the 8th Symposium on Improving Building Energy Efficiency in Hot and Humid Climates*, Dallas, TX.

Medina, M.A. 2000a. Radiant Barriers: Performance Revealed," *Home Energy Magazine,* September/October issue.

Ober D.G. and Volckhausen T.W. 1988. Radiant barrier insulation performance in full-scale attics with soffit and ridge venting. *Proceedings of the 5th Symposium on Improving Building Energy Efficiency in Hot and Humid Climates*, Houston, TX.

Parker, D. and Sherwin, J. 1998. Comparative summer attic thermal performance of six roof constructions. *Proceedings of the 1998 ASHRAE Annual Meeting*, Toronto, Canada.

Parker, D. and Sherwin, J. 2002. Influence of attic radiant barrier systems on air conditioning demand in a utility pilot project. *Proceedings of the 13th Symposium on Improving Building Systems in Hot and Humid Climates*, Houston, TX.

Swami, M.V., and Fairey, P. 1986. Comparative testing of a low emissivity paint. Report FSEC-CR-155-86, Florida Solar Energy Center, U.S.A.

Yarbrough, D. W. 2010. Measured thermal performance for horizontal radiant barriers installed above attic floor insulation. Report RD10216, R&D Services, U.S.A.