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LITERATURE REVIEW OF UNCERTAINTY OF ANALYSIS METHODS

(Cool Roofs)

Report to the
Texas Commission on Environmental Quality

TCEQ

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Disclaimer

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1 Executive Summary

In this literature review, seventy two (72) articles were reviewed from various sources, including: the literature compiled by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); literature listed on the web sites of the Florida Solar Energy Center (FSEC), the Oak Ridge National Laboratory (ORNL), the National Renewal Energy Laboratory (NREL), the Lawrence Berkeley National Laboratory (LBNL), the American Council for an Energy Efficient Economy (ACEEE), and the publications of Elsevier. Keywords searched were: cool roofs, radiant barrier, high-albedo, attic ventilation, duct, as well as the names of the most prolific authors in this area, Dr. Hashem Akbari (LBNL), and Mr. Danny Parker (FSEC).

Twenty-seven of seventy-two papers presented a quantitative cooling energy savings from cool roofs. In these twenty-seven articles cooling energy savings varied from 2% to 44% and averaged about 20%. Ten papers presented quantitative savings as the percent (%) savings of peak cooling energy use, two papers mentioned heating energy savings, or additional amounts of heating required. The literature indicated that the peak cooling energy savings from cool roofs are between 3% and 35%, which depends on ceiling insulation levels, duct placement and attic configuration.

Heating energy savings of 11% through 19% were reported for radiant barrier systems, which can reduce heat fluxes and, as a result, can reduce heat loss to the attic and to the outside of a building in the winter weather condition. One paper reported heating savings of 50%, which was stated to be an impact of the roof re-covering, rather than the cool roof systems alone.

More than half (fifteen) of the papers showing energy savings from cool roofs implemented white roof systems. Eight papers used radiant barrier systems for cool roofs. The applications of the cool roof systems were performed on different building types; eighteen papers were results from residential buildings, seven papers reported results from commercial buildings. No literature could be found on strictly industrial buildings that had quantitative savings. The literature reported that the implementation of cool roof systems was carried out in different climate conditions. However, most of these climates were in hot-humid zones of the United States.

Four of nine papers that reported quantitative results applied the white roof systems and showed heat flux reductions in the 20% to 72% range. Radiant barrier systems, used in four of the papers reviewed, had reduced heat gains from 8% to 98%. Photovoltaic roof systems were even utilized for cool roofs, and were reported to decrease cooling load by as much as 35% on a conventional roof. Applications for most of these papers were to residential buildings (seven of nine papers). One paper applied a white roof system to the commercial buildings along with the residential buildings.

Papers with qualitative analysis for the cool roof systems are also listed. Thirty-five papers showed cooling energy savings, two papers peak cooling savings, and five papers report heating savings from cool roofs. Applications were also mainly to the residential

buildings; seventeen papers to the residential buildings, four papers to the commercial buildings, and two papers to the industrial buildings. Cooling energy savings were also mentioned from the papers that focused primarily on the urban heat island effect. These papers mentioned that the cool roof systems contribute to the reduction of the heat island effect.

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2 Summary

In the United States more than 90% of the roofs covering structures are dark-colored (EPA, 2004). Dark materials absorb more heat from the sun than light-colored materials. The surfaces on these low-reflectance roofs easily reach temperatures of over 180 F, and, as a result, in the summertime considerable heat energy penetrates into the non-ventilated attic, resulting in temperatures as high as 150 F during the peak of summer (Akridge, 1998). These dark roofs can contribute to the reduction of indoor comfort if there are inadequate insulation levels in the ceiling above the conditioned space. Likewise, they can increase of cooling energy and peak electricity demand, and, as a consequence, to the boost in NOx emissions associated with the production of electricity in fossil fuel power plants.

In contrast to the dark roof systems, cool roofs reflect unwanted summer heat and can also radiate away thermal energy after being absorbed in the roofs. Cool roofs consist of a highly reflective roofing surface, which is referred to as a high-albedo or high thermal reflectance surface. In this literature review cool roof systems are discussed in terms of how much cooling and peak cooling energy they have been reported to save when compared to the conventional roofing systems.

To perform this literature review, seventy-two (72) articles were reviewed using several search engines, including: the literature compiled by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); literature listed on the web sites of the Florida Solar Energy Center (FSEC), the Oak Ridge National Laboratory (ORNL), the National Renewal Energy Laboratory (NREL), the Lawrence Berkeley National Laboratory (LBNL), the American Council for an Energy Efficient Economy (ACEEE), and the publications of Elsevier. Keywords searched were: cool roofs, radiant barrier, high-albedo, attic ventilation, duct, as well as the names of the most prolific authors in this area, Dr. Hashem Akbari (LBNL), and Mr. Danny Parker (FSEC).

Twenty-seven of seventy-two papers presented a quantitative cooling energy savings from cool roofs. As shown in Table 1, these cooling energy savings varied from 2% to 44% and averaged about 20%. Ten papers presented quantitative savings for peak cooling energy use, two papers mentioned heating energy savings, or additional amounts of heating required. The literature indicated that the peak cooling energy savings from cool roofs are between 3% and 35%, which depends on ceiling insulation levels, duct placement and attic configuration.

Year	Authors	Methods	Cooling Energy Savings (%)							Peak Cooling Energy Savings (%)							Heating Energy Savings (%)							Applications			Climatic Zones
			10	20	30	40	50	60	70	10	20	30	40	50	60	70	10	20	30	40	50	60	70	Res.	Com.	Ind.	
1995	Parker et al.	Reflective roof coatings	3	---	---	44					22													x			2
1994	Parker et al.	Reflective roof coatings		25	---	43						28												x			2
1997	Parker et al.	Roof coloring		13	---	43																			x		2
1995	Parker et al.	Reflective roof coatings	2	---	---	43					22													x			2
1997	Parker & Barkaszi	Roof coating				40																		x			2
1987	Wu	Radiant barriers				40																		x			2
1998	Hildebrandt et al.	White roofs		17	---	39																			x		3
2002	Sonne et al.	Flexible roofing facility	8	---	---	38																		x			2
1997	Akbari et al.	High-albedo roofs		25	---	35																		x			3
1998	Petrie et al.	Radiant barriers			34																			x			2
1998	Akridge	Albedo roofs	9	---	28																				x		
2002	Parker et al.	Various roofing systems	3	---	26					3	---	---	35											x			2
2000	Parker et al.	Different roofing systems	3	23						5	---	34												x			2
1998	Parker et al.	Reflective roofing systems		19																				x			2
1988	Taha et al.	Heat islands	14	19						14	---	---	35														3
1990	Levins & Herron	Radiant barriers	3	17													11	19						x			3
1996	Hageman & Modera	Low-emissivity roof sheathing		16																				x			2
2003	Parker et al.	Flexible roofing facility	2	15																				x			2
1995	McLain & Christian	Roof re-covering	10																		50				x		
1996	Parker et al.	Roof coloring	10										35												x		2
1998	Parker et al.	White roofs	10									30													x		2
1998	Rosenfeld et al.	Heat islands	10																								3
1998	Moujaes & Brickman	Radiant barriers	9								16													x			2
1999	Moujaes & Brickman	Radiant barriers	9								16													x			2
1990	Levins & Hall	Radiant barriers	7																					x			4
1998	Petrie et al.	Radiation control coatings on roofs	7																						x		2
2000	Parker & Sherwin	Photovoltaic attic ventilator fans	6																					x			2

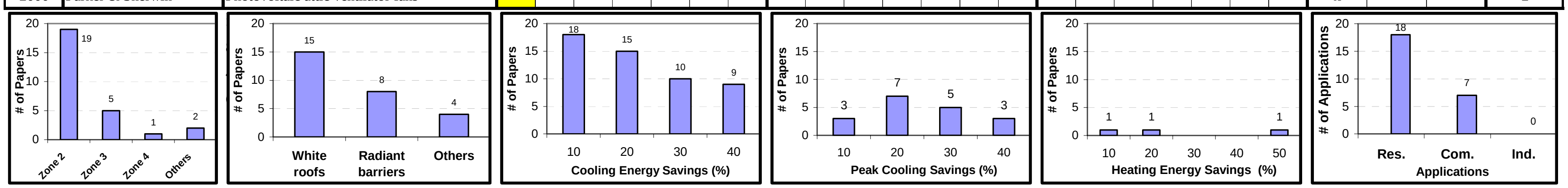


Table 1. Cool Roof Literature Survey Reporting Quantitative Results

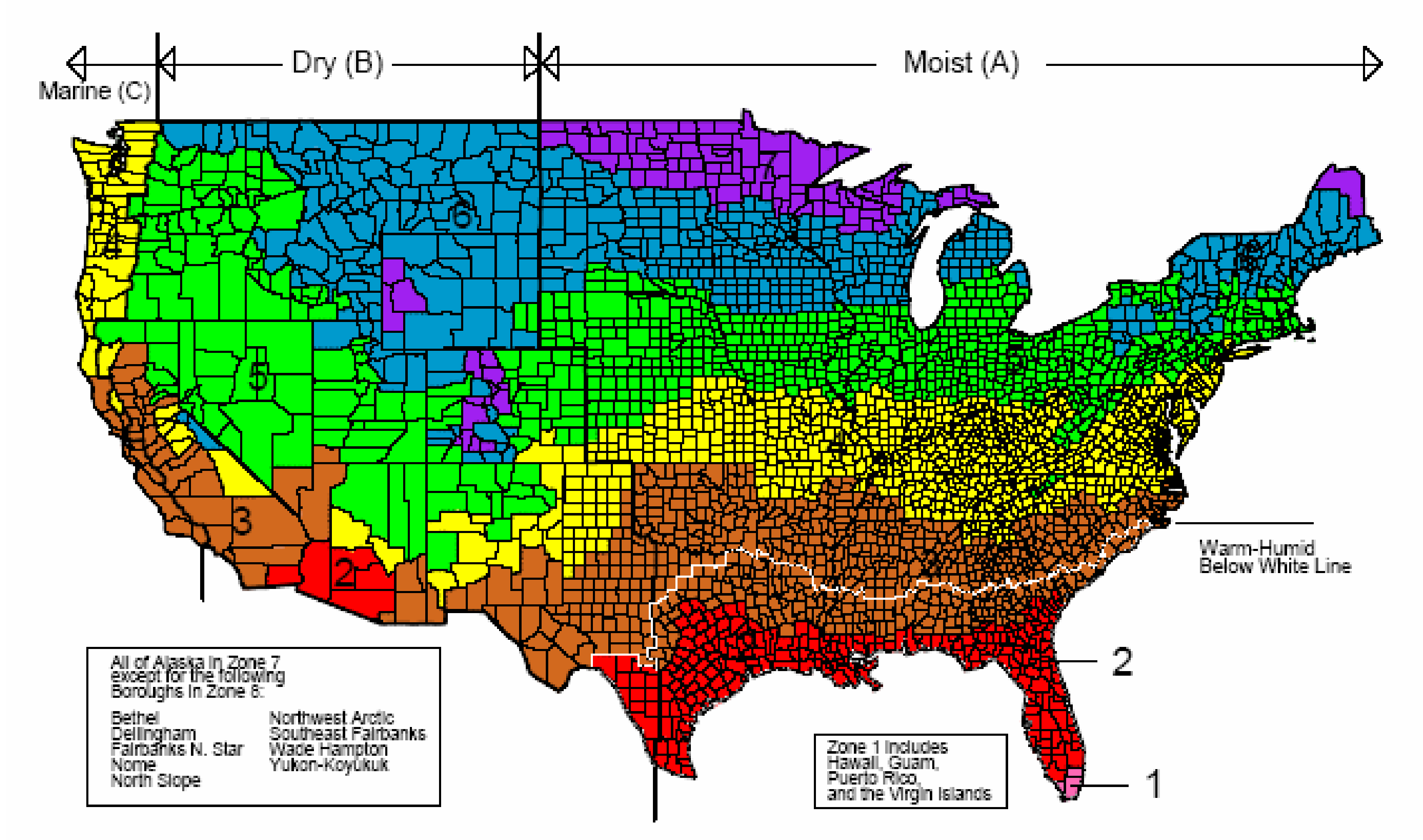


Figure 1. Map of DOE's Proposed Climate Zones (DOE, 2003)

Heating energy savings of 11% through 19% were reported (Levins and Herron, 1990) by implementing radiant barrier systems, which can reduce heat fluxes and, as a result, can reduce heat loss to the attic and to the outside of a building in the winter weather condition. One paper reported heating savings of 50%, which was stated to be an impact of the roof re-covering, rather than the cool roof systems alone.

More than half (fifteen) of the papers showing energy savings from cool roofs implemented white roof systems. Eight papers used radiant barrier systems for cool roofs. The applications of the cool roof systems were performed on different building types; eighteen papers were results from residential buildings, seven papers reported results from commercial buildings. No literature could be found on strictly industrial buildings that had quantitative savings. The implementation of cool roof systems was carried out in different climate conditions. However, as shown in the last column, the majority of the papers were based on Zone 2 – a hot-humid climate, as illustrated in Figure 1, which shows the all seven climate zones in the United States as reported by U.S. Department of Energy.

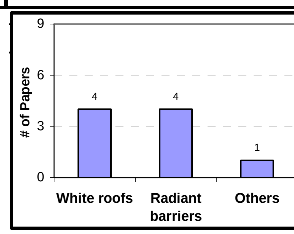
Table 2 shows heat flux/gain reductions from implementing cool roof systems. Four of nine papers that reported quantitative results applied the white roof systems and showed heat flux reductions in the 20% to 72% range. Radiant barrier systems, used in four of the papers reviewed, had reduced heat gains from 8% to 98%. Photovoltaic roof systems were even utilized for cool roofs, and were reported to decrease cooling load by as much as 35% on a conventional roof. Applications for the papers shown in Table 2 were mainly to the residential buildings (seven of nine papers). One paper applied the white roof systems to the commercial buildings along with the residential buildings.

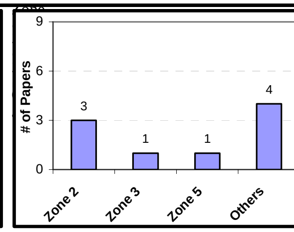
Table 3 is a list of the papers that contained only qualitative results for the cool roof systems. Thirty five papers showed cooling energy savings, two papers peak cooling savings, and five papers heating contained savings from cool roofs. Applications were also mainly to the residential buildings; seventeen papers to the residential buildings, four papers to the commercial buildings, and two papers to the industrial buildings.

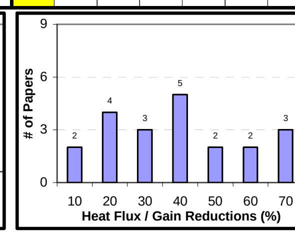
Cooling energy savings were also mentioned from the papers that focused primarily on the urban heat island effect. These papers mentioned that the cool roof systems contribute to the reduction of the heat island effect. Realistically there are many more papers about the heat island effect along with cooling energy savings from the cool roof systems than seven papers shown in Table 3. However, most of the papers focused on the impact that the highly reflective surfaces would have on the surrounding environment, versus the impact on the conditioned space in the building directly below the cool roof. The reader is referred to the Heat Island Group at LBNL for a more details about this analysis.

Figure 2, Figure 3, Figure 4, Figure 5, and Figure 6 are included in this literature review to help illustrate the different heat transfer mechanism at work in an attic.

Year	Authors	Methods	Description of Heat Flux / Gain Reductions	Heat Flux / Gain Reductions (%)							Applications			Climatic Zones
				10	20	30	40	50	60	70	Res.	Com.	Ind.	
2004	Medina	Radiant barriers	Ceiling heat flux reduction from 39.7% to 97.7%				40	---	---	100				3
1998	Akbari & Konopacki	Roof albedo and emissivity	Changing Roof Emissivity from 0.9 to 0.25 (72% reduction)							72	x	x		all
1995	Beal & Chandra	Tile roofs / Attic ventilation	Heat flux reduction of 25% - 66%			25	---	---	---	66	x			2
2000	Medina	Radiant barriers & Attic insulation	Heat flow reduction of 23% - 44%		23	---	44				x			2
1996	Al-Asmar et al.	Radiant barriers	Attic heat gain reduction of 17%-26% (With ventilation) & 24%-42% (Without ventilation)		24	---	42				x			
2001	Yang et al.	Photovoltaic roofs	Cooling load component through a PV roof is about 35% of a conventioanl roof.				35				x			
1998	Parker & Sherwin	White roofs	Average ceiling heat flux reduction of 23%		23						x			2
1999	Holton & Beggs	Plastic shake roofs	20% cooler roof		20						x			5
1993	Wilkes & Childs	Radiant barriers (Winter Condition)	Radiant barrier decreases the ceiling heat flow by 6% to 8%.	8										







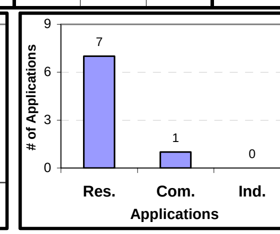
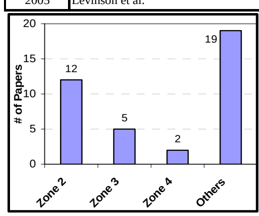
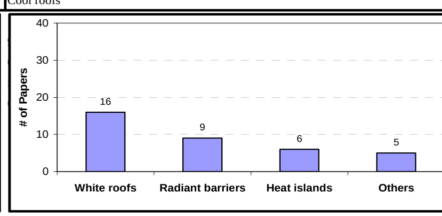
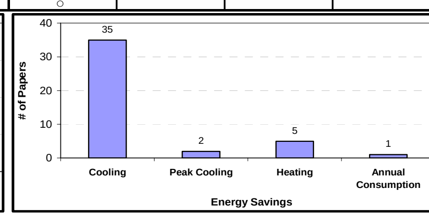


Table 2. Cool Roof Literature Survey Reporting Heat Flux Qualitative Results

Year	Authors	Methods	Energy Savings (●: Qualitative & ○: Mention)				Applications			Heat Island	Climatic Zone
			Cooling	Peak Cooling	Heating	Annual Consumption	Res.	Com.	Ind.		
1985	Griggs & Courville	Roof insulation or coloring	○		○						12 different cities
1987	White et al.	Roof mist spray system	○								
1987	Levins & Karnitz	Radiant barriers	●		●		x				4
1988	Somasundaram & Carrasco	Roof spray cooling	○					x	x		
1989	MacDonald et al.	White roofs	○	○	○	○	x	x	x		all
1989	Wu	Radiant barriers	○				x				2
1989	Ober	Radiant Barrier performance Test	○				x				2
1989	Stewart et al.	Radiant barriers	○								
1989	Wilkes	Radiant barriers	○								
1992	Grondzik	Roof assemblies	○				x				2
1992	Chen et al.	radiant barrier systems in reducing heat loss through the ceiling			○		?				7
1992	Kochhar et al.	Roof coating	○				x				2
1994	Byerley & Christian	Radiation control coatings on roofs	○								
1996	Moujaes S.	Radiant barriers	○				x				
1996	Moujaes	Radiant barriers	○				x				
1996	Gartland et al.	Reflective roofing	○								
1997	Bretz & Akbari	High-albedo roofs	○				x				2 & 3
1998	Akbari	White roofs	○	○			x	x			2 & 3
1998	Parker & Sherwin	White roofs	●				x				2
1998	Rudd & Lstiburek	Attic ventilation	○				x				2
1998	Proctor	Attic ventilation	○				x				4
1998	Parker & Sherwin	Attic temperature measurements with different cool roof systems	○				x				2
1998	Bretz et al.	Heat islands	●							x	3
2000	Parker et al.	Test of roofing materials	○								
2000	Akbari et al.	Reflective roofs	○				x				2
2001	Kriner et al.	White painted roofs	●		●		x	x			2
2001	Rose	Various roof assemblies	○				x				
2002	PG&E	Cool roofs	○								3
2002	Akbari & Pomerantz	Heat islands	○							x	
2002	Dietsch et al.	Heat islands	○							x	
2002	Wong & Mercado	Heat islands	○							x	
2002	Griffiths et al.	Heat islands	○							x	
2002	Miller et al.	Cool color roofs	○								
2003	Miranville et al.	Radiant barriers	○								2
2004	Akbari& Konopacki	Heat islands	●							x	Toronto, Canada
2005	Levinson et al.	Cool roofs	○							x	3







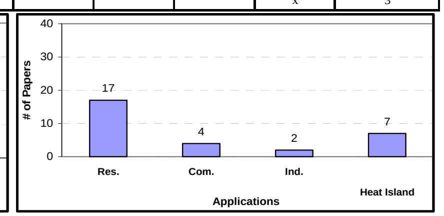


Table 3. Qualitative Analysis of Cool Roof Literature Survey

In Figure 2 from the Whole-building Design Guide (2004), a generalized illustration is provided that shows the basic heat transfer interactions at the roof surface. First, solar radiation is either reflected, or absorbed, depending upon the characteristics of the roof's surface. In the case that solar energy is absorbed, some of this heat is transferred into the inside of the building as "net heat flux", some is re-radiated, or re-emitted to the sky, some is carried away by convection. Clearly, in Figure 2 one can see that there are numerous thermal mechanisms at work in the attic, which is reflected in the diverse results from the literature review.

In Figure 3, from the Florida Solar Energy Center (FSEC 2004a), the heat transfer mechanisms for a roof with an attic are shown. In this figure, the basic heat transfer mechanisms shown in Figure 2 are further complicated by the attic and the ductwork in the attic. First, in the attic it is shown that the insulation is placed above the horizontal ceiling that separates the attic from the living space below. Unfortunately, in many houses this insulating layer is penetrated by the insulated ductwork that delivers the cooling to the space from the air conditioning system. In Figure 3 the cooling unit is shown in the conditioned space. However, in many houses, this unit is also in the attic, which can compound the heat gain from the hot attic. This figure shows why it is important that the researchers identify whether or not there were ducts in the attic, how much insulation those ducts had, and if there was any leakage to/from the duct into the attic. In general, in the studies that showed the most savings from cool roofs, there was either very little insulation in the ceiling, poorly insulated ducts, leaky ducts or some combination of the above. In those studies that showed very little savings from the cool roofs, there was usually significant insulation, insulated and sealed ducts, or the ducts were placed below the insulated ceiling.

In Figure 4 from the Home Energy Magazine (HEM 2004a), a horizontal placement for the radiant barrier is shown. Although this is the easiest placement of the radiant barrier, it suffers the most from dust deposition that can degrade the reflective nature of the radiant barrier. In Figure 5, also from the Home Energy Magazine (HEM 2004b), the most common placement of radiant barriers is shown. In most cases, this is attached to the lower side of the rafters that support the sloped portion of the upper roof. This placement is usually preferred due to its reduced dust deposition that can degrade the reflective nature of the radiant barrier.

In Figure 6 from FSEC (2004b), all three of the most common placement methods are shown, including: 1) the bottom side of the sheathing of the roof decking, 2) attached to the bottom cord of the truss, or 3) in the horizontal position on top of the insulation on the ceiling.

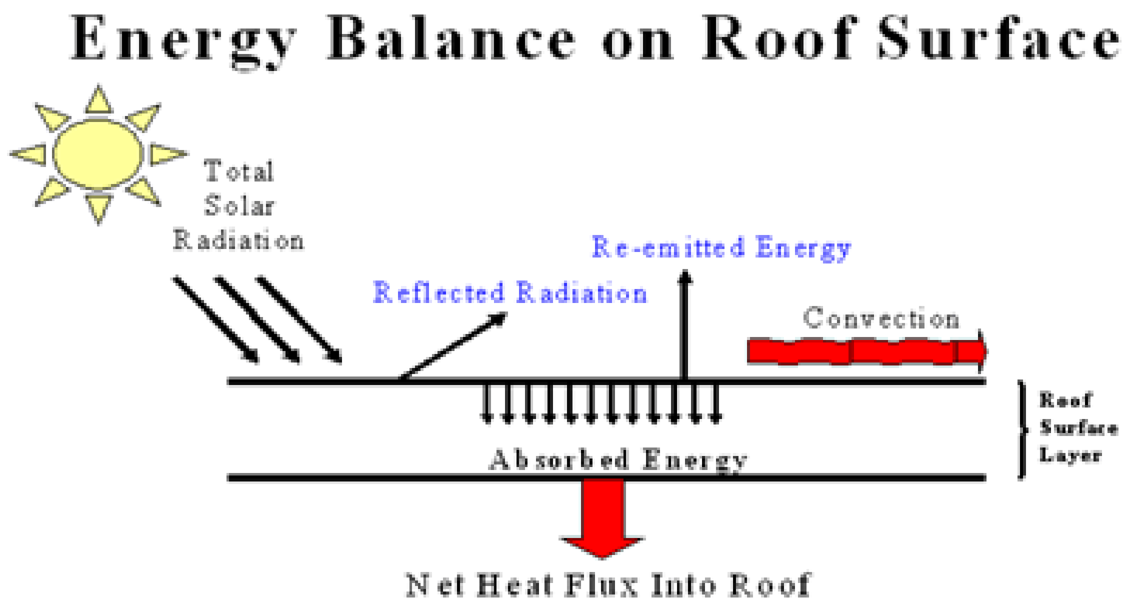


Figure 2. Energy Balance on Roof Surface (WBDG, 2004)

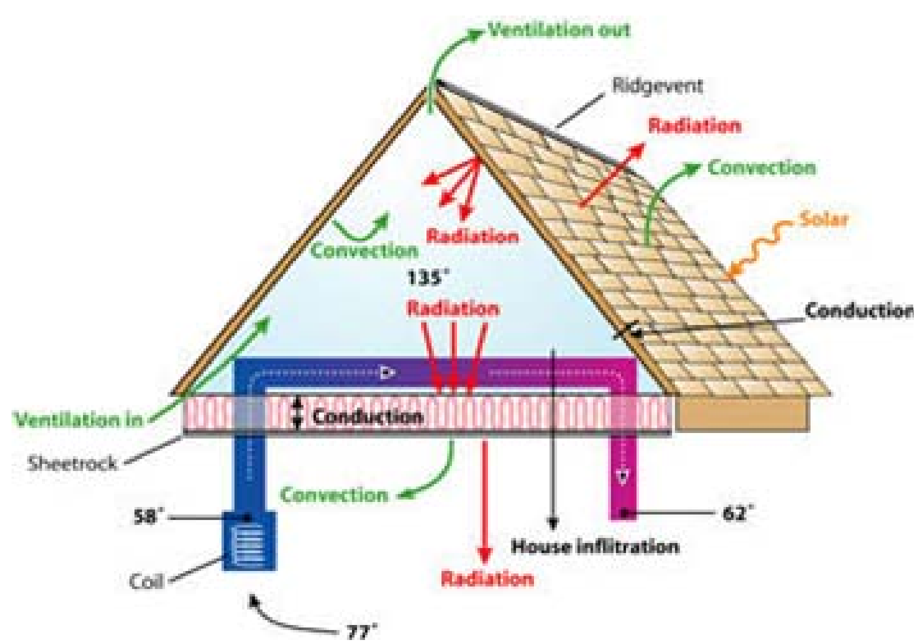


Figure 3. Vented Attic Thermal Processes (FSEC, 2004a)

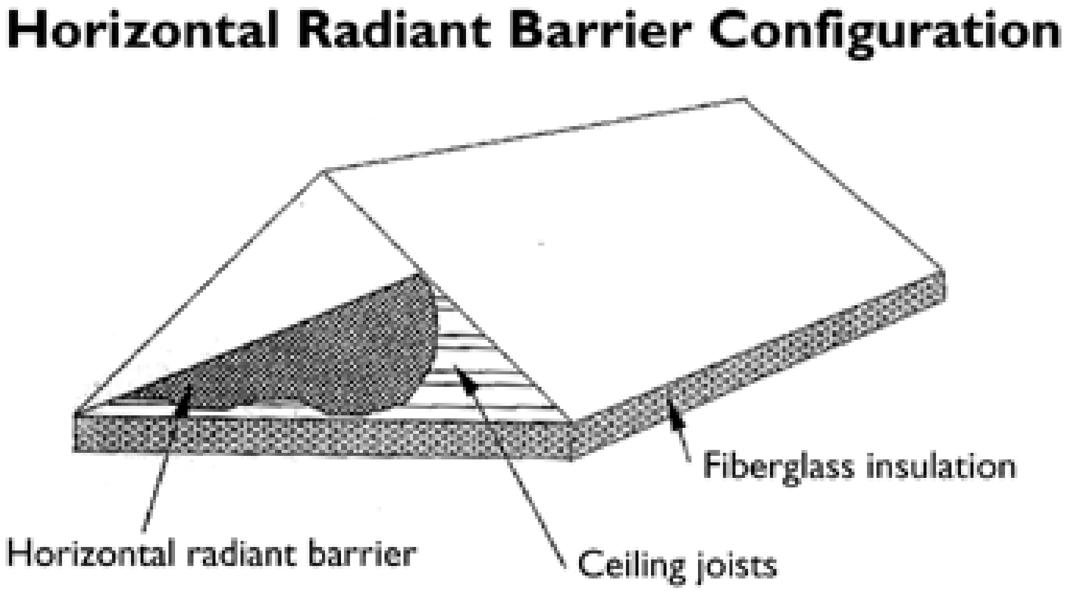


Figure 4. The barrier is installed horizontally over the attic frame. (HEM, 2004a)

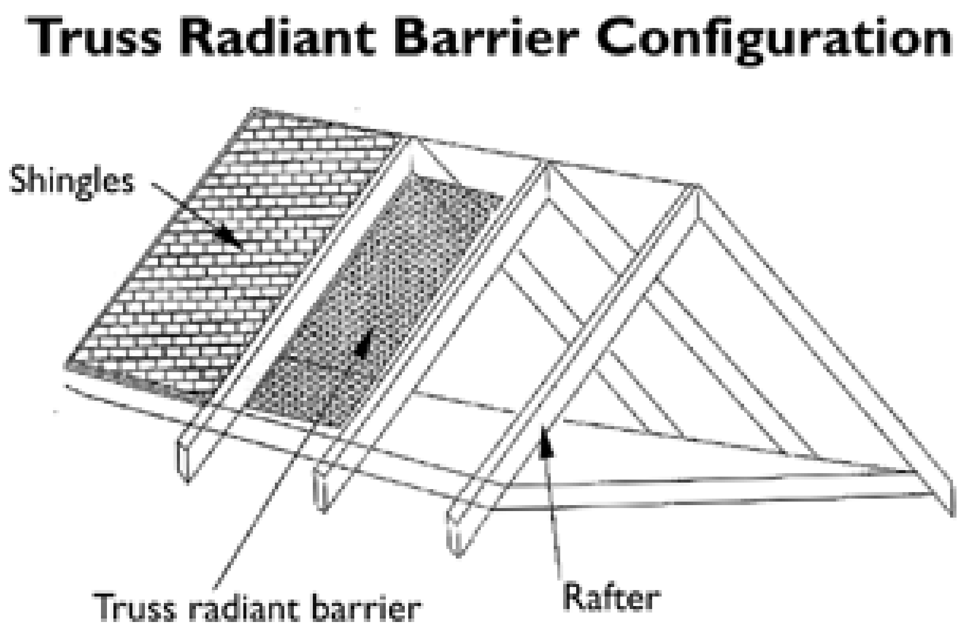


Figure 5. The barrier is attached to the rafters that support the deck. (HEM, 2004b)

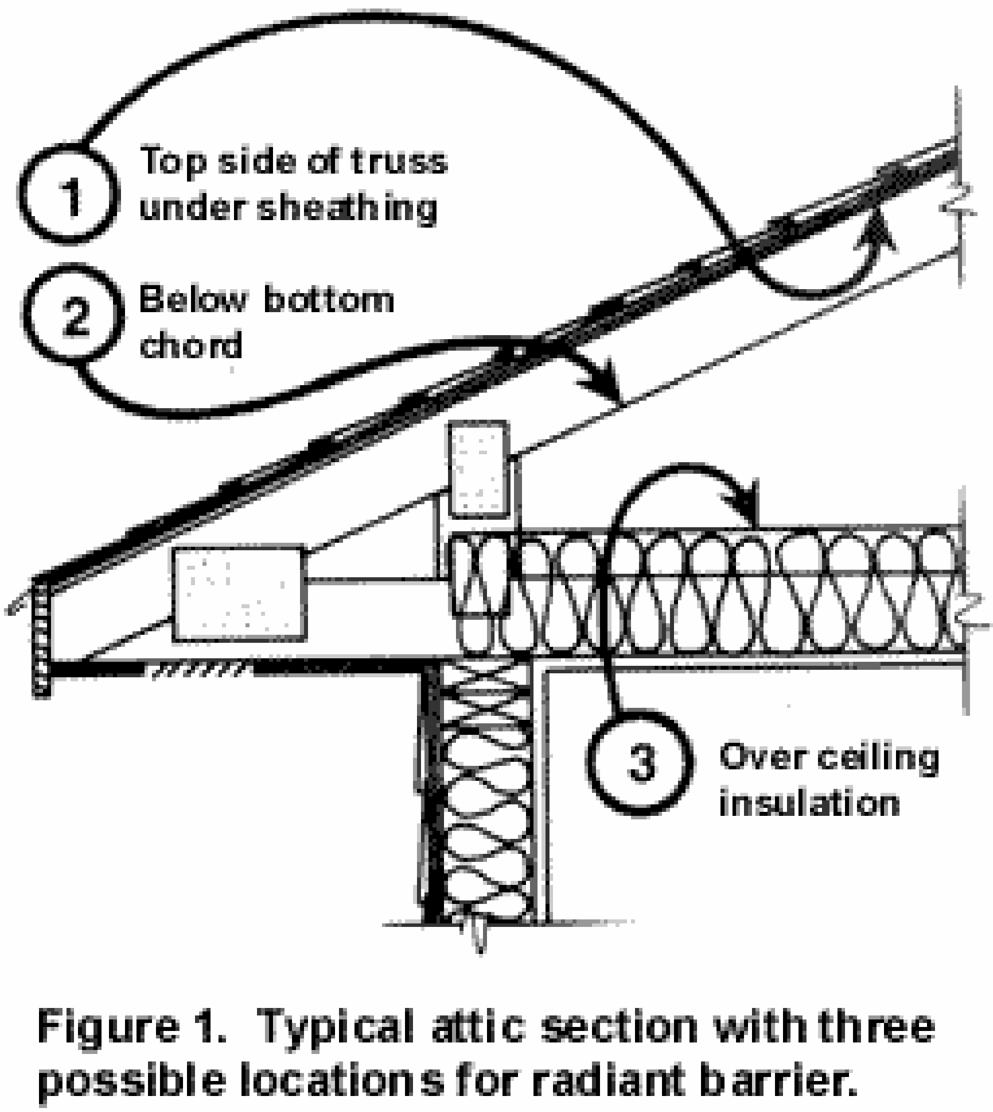


Figure 6. Typical Attic Section with Three Possible Locations for Radiant Barrier. (FSEC, 2004b)

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