Demonstrated Energy Savings Of Cool Roof Coatings And Future Directions For Research

BY DR. LISA M. GARTLAND

INTRODUCTION

A relatively new class of roof coatings has been shown to save significant amounts of cooling energy. Cool roof coatings reflect away the bulk of the sun's energy, allowing the roof surface to stay cooler and transferring less heat to the building underneath. Demonstration projects have shown these coatings can save between 20 and 70% of the cooling energy used in a building. These coatings also have the potential to save money, reduce air pollution, and lessen the need for reroofing. There are still technical and industrial challenges in the way of the widespread adoption of these coatings as the roofing standard.

This paper first reviews the radiative properties of roof materials, then summarizes the results from numerous projects which demonstrate the effectiveness of these coatings at saving cooling energy. The challenges of accurately modeling and predicting the energy savings of cool coatings are discussed. The non-energy benefits of cool coatings are described. Barriers to the implementation of cool coatings are enumerated and the challenges facing researchers and the coating industry are considered.

Radiative Properties of Roofing Materials

The radiative properties of roofing materials are best understood by first studying the energy radiated from the sun. Solar energy is spectral, which means it varies over different wavelengths or spectra. *Figure 1* shows the solar energy reaching the earth's surface on a clear summer day. The amount of energy varies over the wavelength range of 0.3 to 3.0 nanometers, with a peak at around 0.6 nanometers. Solar energy falls into three distinct classes. Three percent of solar energy is in the ultraviolet spectrum, wavelengths responsible for sunburn. Forty percent of solar energy falls in the form of visible light. The remaining 57% of the sun's energy is felt as heat from the infrared spectrum.

The amount of energy any material can reflect—its reflectivity—also varies with wavelength. The coolest roofing materials have high reflectivities over the entire solar spectrum. An overall measure of a material's reflectivity to the sun's energy, called the albedo, is found by taking a weighted average of these reflectivities over the solar spectrum.

Figure 2 plots the reflectivity of typical asphalt shingle roofing materials.[1] Asphalt materials tend to have fairly low, but generally constant reflectivities over the solar spectrum, with lighter colored materials having somewhat

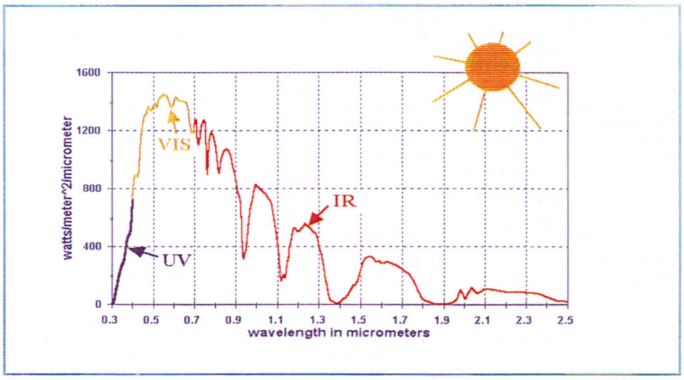

Figure 1. Solar energy versus wavelength, for energy reaching the earth's surface.

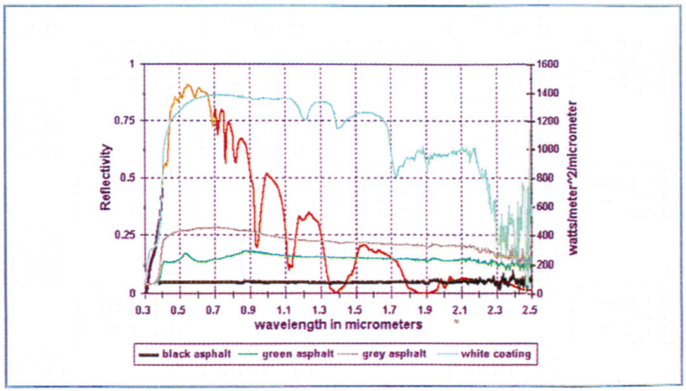

Figure 2. Reflectivity of different roofing materials over the solar spectrum.

Material	Overall Albedo
black asphalt shingle	5%
green asphalt shingle	15%
light gray asphalt shingle	25%
typical white coating	75%

Table 1. Overall albedo of the roofing materials shown in Figure 2.

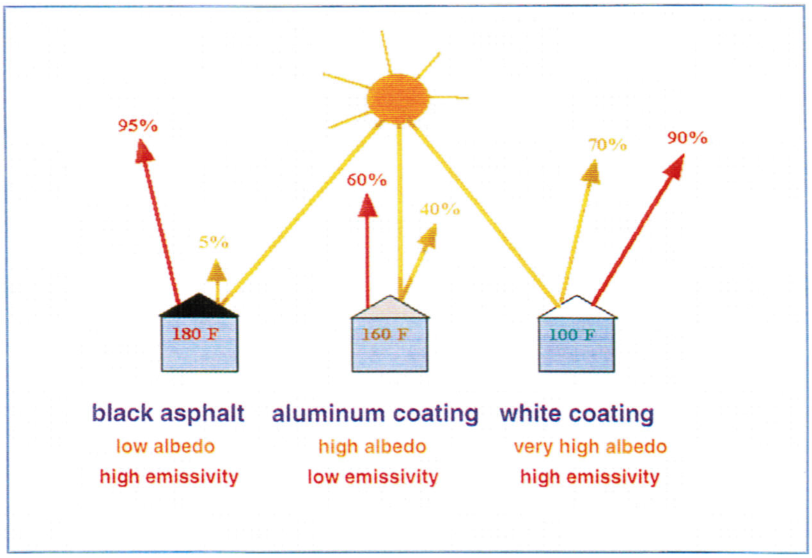

Figure 3. Combined effects of albedo and emissivity in roofing materials.

higher reflectivities. The lightest colored asphalt shingles—very light grays sometimes classified as whites—reflect no more than 25% of the sun's energy from the roof.

Figure 2 also shows the reflectivity of a highly reflective coating. This coating has a peak reflectivity of 0.87 in the visible spectrum, making it a very bright white. The reflectivity of this coating tends to fall off in the infrared spectrum, but the overall albedo of the coating is still 75%, much higher than the albedo of traditional asphalt materials.

The reflectivity and albedo of roofing materials are not the only radiative properties of interest. In order to stay cool, roofing materials must also have high emissivities. The emissivity is the percentage of absorbed energy a material can radiate away from itself. Materials with low emissivities tend to trap any heat they collect. Most roofing materials have emissivities of 0.90 or above, but roofing materials made of metal or metal particles tend to have much lower emissivities, ranging between 0.05 and 0.60, depending on their surface conditions.

Figure 3 shows the effect of albedo and emissivity on roof surface temperature. Black asphalt roofs tend to have the hottest peak temperatures (~180°F) despite their high emissivity, since their low albedo value means they absorb most of the sun's energy. White coatings tend to stay the coolest (~100°F at peak) since they reflect away most of the sun's energy. Aluminum coatings tend to fall somewhere in between. These coatings have albedos of around 40%—higher than traditional asphalt materials, but still quite a bit lower than the highest albedo coatings. Aluminum coatings have fairly low emissivities which don't allow them to radiate away absorbed heat. Aluminum coated roofs tend to be about 20°F cooler than the darkest asphalt roofs, but can still be classed as "hot" roofs.

The most effective way to reduce the surface temperature of a roof is to use a material which has both high albedo and high emissivity. Many publications use the terms "white" or "high-albedo" to describe this type of roofing material. These misnomers can be very confusing. Use of the term "white" implies that all white roofs will have reduced surface temperatures. This is not the case since visible properties of a roof do not indicate its albedo or emissivity. Calling a roof "high-albedo" says nothing about a roof's emissive properties. I have adopted the nomenclature "cool" to describe roofs with very high albedo (over 50%), *and* high emissivity (90% or higher).

Demonstration of Cool Roof Savings

Numerous projects have been undertaken to study the effects of cool roof coatings on roof surface temperature and cooling energy use. All studies confirm the ability of cool coatings to reduce roof surface temperatures dramatically—by 50 to 80°F, and to save significant amounts of cooling energy during the summer months.

Table 2 summarizes the results of five studies per-

Location	Description	Insulation, Roof Slope	Uncoated Albedo	Coated Albedo	Cooling Energy Savings
Sacramento, CA	1-story residence	R-11, flat roof	18%	77%	67%
Sacramento, CA	1-story school	R-19, flat roof	8%	68%	40%
Cocoa Beach, FL	1-story residence	R-11, 22° roof slope	21%	70%	25%
Cocoa Beach, FL	1-story residence	uninsulated, flat roof	20%	73%	43%
Cocoa Beach, FL	1-story school	R-19, flat roof	23%	67%	35%

Table 2. Cooling energy savings from five demonstration projects.

formed in California and Florida.[2] The albedos of all rooftops were raised by 40 to 60 percentage points, well into the range of "very high albedo" (over 50%). Regardless of the level of insulation in the roof, all buildings showed significant reductions in the amount of cooling energy used—reductions from 25% to 67%. These studies were all performed on residences or small school buildings.

Location	Gilroy, CA	Davis, CA	San Jose, CA
Building use	Medical Office	Medical Office	Drug Store
Square footage	~61,000	~31,000	~26,000, plus ~7000 mezzanine
Insulation	R19 in ceiling below roof plenum	R8 in roof above plenum	foil barrier below roof in plenum
Original roof type	lt. gray sheet	lt. gray sheet	tan sheet
Original albedo	25%	24%	16%
Coated albedo	60%	not yet coated	not yet coated

Table 3. Building information for LBNL's ongoing EPA demonstration project.

An ongoing project funded by the Environmental Protection Agency and administered by Lawrence Berkeley National Laboratory is studying the effect of cool coatings on three large, single-story commercial buildings in California.[3] *Table 3* gives information about the use, size and roof conditions of these buildings. As yet only one of the building rooftops has been given a cool coating. The rooftop of the Gilroy, California building was coated during the first week of August 1996, raising its albedo from 25 to 60%. Coatings similar to the white elastomer used on this roof have albedos of 75 to 85% when measured on smooth surfaces in the laboratory. The roughness of the capsheet surface reduces the albedo by increasing the absorption of the reflected solar radiation.

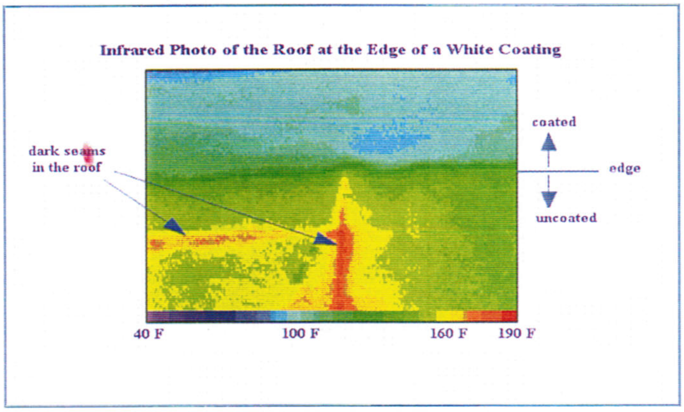

Figure 4. Infrared photograph of the roof of the Gilroy, CA building at the edge of the white coating.

Of the three buildings in this study, the Gilroy building had the highest initial rooftop albedo as well as the greatest amount of roof/ceiling insulation, and its coated albedo was also not extremely high. Nonetheless, this building still showed impressive roof surface temperature reductions and cooling energy savings. *Figure 4* shows an infrared photograph of the Gilroy rooftop taken on a hot summer afternoon during the coating process. This photo shows the coated surface temperature is about 40 to 60°F cooler than the uncoated surface.

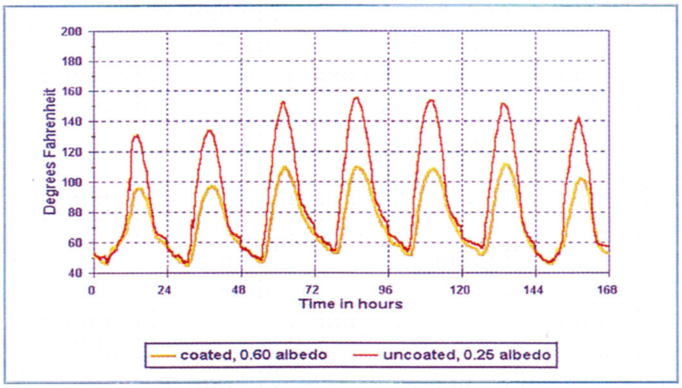

Figure 5. Measured temperature of the coated rooftop and estimated temperature of the roof without coating for the Gilroy, CA building during the week of Aug. 26 to Sept. 1, 1996.

Figure 5 shows measured surface temperatures over the week of Aug. 26 to Sept. 1, 1996 together with estimates of the temperatures that would have occurred without coating. The uncoated temperatures were calculated from a regression equation relating pre-coating surface temperatures to weather and other variables. Peak temperatures of the coated surface are 40-60°F below estimated peaks of the uncoated surface.

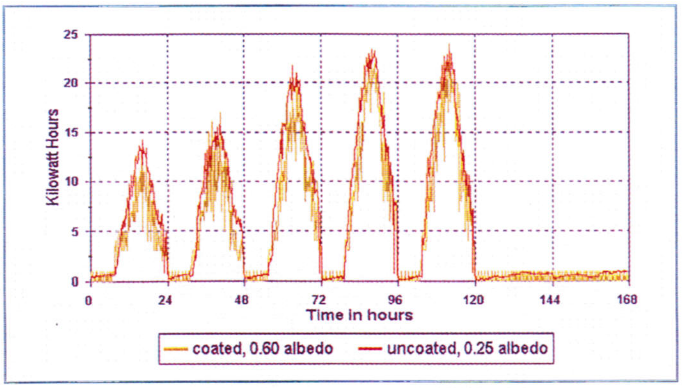

Figure 6. Measured cooling energy use with coated rooftop and estimated cooling energy use without coating for the Gilroy, CA building during the week of Aug. 26 to Sept. 1, 1996.

Figure 6 plots the measured and estimated cooling energy use of the Gilroy building during the week of Aug. 26 to Sept. 1. Estimates were again made from a regression equation relating uncoated energy use to weather and other variables. The decrease in energy use does not look dramatic, but the daily cooling energy load shapes for the coated roof are shorter and narrower than the uncoated shapes, adding up to 21% savings. *Table 4* lists the total cooling energy used for the remaining summer weeks after the coating was applied, along with the estimated cooling energy use for these weeks. The overall summertime cooling energy savings was 5300 kWhr, or 22% of the total estimated uncoated energy use.

Energy Prediction Problems and Solutions

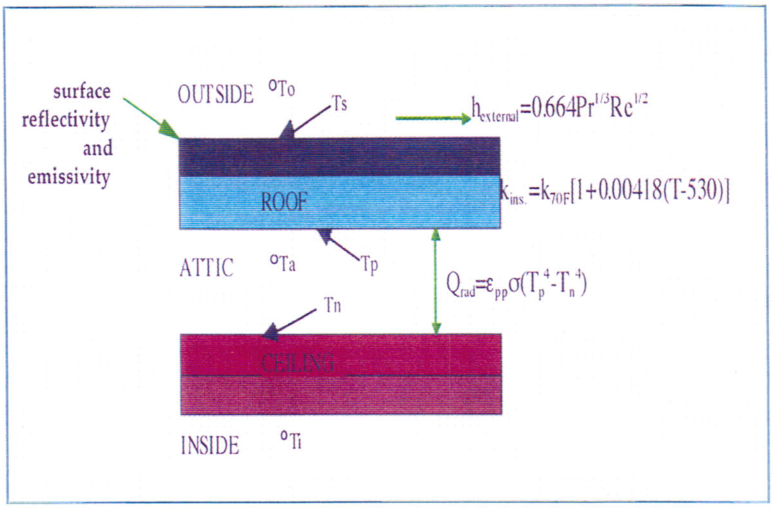

Figure 7. Improvements needed in the DOE-2 building energy model.

The demonstration projects described in the previous section show the enormous potential of cool coatings to reduce the cooling energy used by buildings in warm climate regions. Further work is being done to predict the wintertime penalties and energy savings of cool roofs in various climate regions.[4] Most of this work focuses on using building energy models to make these predictions. Unfortunately, most of these models are not equipped to accurately represent the heat transfer processes that occur in the roof and ceiling.

An example of this inadequacy is found by revisiting the study of the Sacramento, California school bungalow referenced in *Table 2*.[5] The roof of this bungalow began as a galvanized metal roof which was first painted brown (8% albedo), then a couple of weeks later painted white (68% albedo). The cooling energy use of this bungalow was measured through each period, and then compared to determine how much cooling energy was saved by use of the white coating. The measured daily total and daily peak energy savings are recorded in *Table 5*.

Predictions of energy use were also made using the DOE-2 building energy simulation model. DOE-2 is the most widely used tool for building energy predictions. Careful simulations were made using information about indoor temperatures, building occupancy, and the actual weather data in Sacramento during the period of interest. The DOE-2 predictions are also recorded in *Table 5*. DOE-2 is seen to underpredict both the daily total and daily peak cooling energy savings due to use of a cool coating.

The cause of this underprediction is due to three shortcomings in the DOE-2 model, illustrated in *Figure 7*. All three of these modeling problems reduce the heat load from the roof to the building's conditioned space, and lead to DOE-2's underprediction of cooling energy use.

The first problem comes about when the roof and ceiling are modeled as a single layered component. In this case there is no radiative exchange in the plenum, between the underside of the roof and the topside of the ceiling. This means the model does not transfer enough heat to the building conditioned space.

The second problem with DOE-2 is it treats the conductivity of the roof insulation as a constant. In reality, the conductivity of fiberglass insulation varies with temperature,[6] and as we have seen, roof temperatures vary quite a bit. A 60°F change in insulation temperature increases its conductivity by 25%. Since DOE-2 ignores this effect, it once again can underpredict the building load.

Week	Measured Cooling, kWhr (coated)	Estimated Cooling, kWhr (uncoated)	Cooling Energy Savings, kWhr	Percent Savings
Aug 5-11	2827	3485	658	19
Aug 12-18	3769	4587	818	18
Aug 19-25	2397	3211	814	25
Aug 26-Sept 1	3242	4102	860	21
Sept 2-8	1796	2418	622	26
Sept 9-15	2035	2734	699	26
Sept 16-22	2344	3176	832	26
Total	18410	23713	5303	22.4%

Table 4. Measured cooling energy used by the Gilroy building after the roof was coated, compared to cooling energy use estimated without a roof coating, for the summer weeks after the roof was coated.

	Daily Total Energy Savings (kWhr/day)	Daily Peak Energy Savings (kW)
Measured savings	4.6	0.56
DOE-2 predicted savings	2.9	0.28
Difference	-37%	-50%

Table 5. Measured and DOE-2 predicted savings of a white versus a brown roof in a Sacramento, CA school bungalow during the summer of 1992.

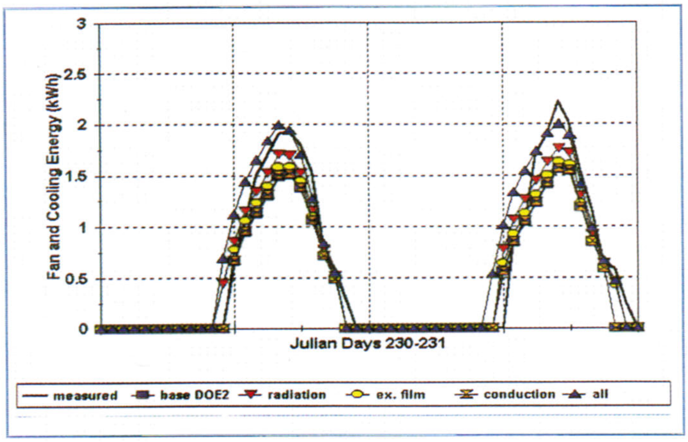

Figure 8. Measured and DOE-2 predicted values of cooling energy use in the Sacramento school bungalow during two days in the summer of 1992 while the roof was painted brown.

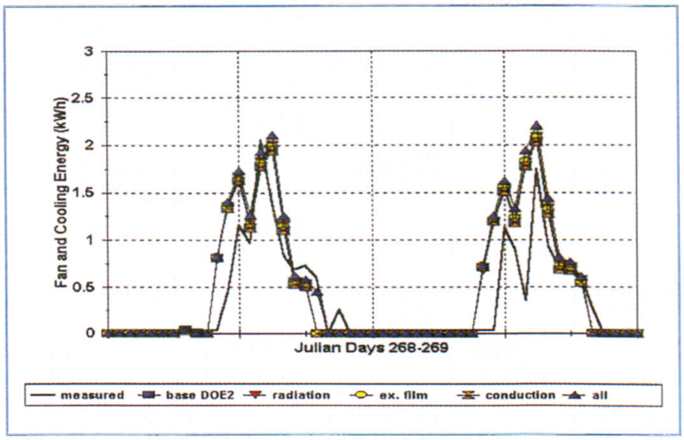

Figure 9. Measured and DOE-2 predicted values of cooling energy use in the Sacramento school bungalow during two days in the summer of 1992 while the roof was painted white.

The third problem is the use of a convection coefficient at the roof's surface that is potentially too high. A high convection coefficient means more heat is carried from the roof surface to the outside air, which in DOE-2 may keep the roof surface temperature artificially cool, again reducing the building heat load.

A function was written to correct all three problems, and was tested using the 1992 Sacramento, CA school bungalow data.[7] *Figure 8* shows both the measured and the DOE-2 predicted cooling energy use over a two day period while the roof was painted brown. The best match to the measured energy use came when the function incorporated all three solutions into the DOE-2 model.

Figure 9 plots the same information during a period while the roof was painted white. Changes to the DOE-2 model have little effect in this case since the high albedo of the roof dominates the heat transfer mechanisms by keeping the roof surface temperature low.

Figure 10 plots daily values of cooling energy use versus the values predicted by DOE-2 using all three model improvements. The DOE-2 cooling energy predictions are higher than the measured values, but the predicted brown and white values are now higher than the measured values by about the same amount. This means the prediction of the difference between the brown and white energy use (the prediction of cooling energy savings) is now much more accurate.

The analysis of the Sacramento school bungalow was extended past the summer cooling season to determine the effect of these modeling improvements on annual building energy use. *Table 6* lists the annual cooling and heating energy values predicted by the standard DOE-2 model and the DOE-2 model with improvements. Both the cooling energy savings and the heating energy penalties are increased with the improved model. But the overall effect of these improvements is a fourfold increase in annual energy savings. This means the standard DOE-2 model, as well as other similar building energy models, may be grossly underpredicting the energy savings due to cool roofing.

		Annual Cooling Energy (kWhr)	Annual Heating Energy (kWhr)	Overall Savings (kWhr)
Standard DOE-2	brown roof	1943	2192	
	white roof	1776	2237	
	savings	+167	-45	+122
Improved DOE-2	brown roof	2750	2325	
	white roof	2108	2473	
	savings	+642	-148	+494

Table 6. Annual energy savings predictions for a cool roof using standard DOE-2 and the improved version of DOE-2 for the Sacramento, CA school bungalow.

	Cool Coating	Conventional Roofing
Initial Cost	+ $0.50/sq ft	+ $3.50/sq ft
Energy Savings over 10 Years	- $0.20 to $0.70/sq ft	none
Recoat/Relayer after 10 Years	+ $0.50/sq ft	+ $1.50/sq ft
Total	$0.30 to $0.80/sq ft	$5.00/sq ft

Table 7. Cost comparison of cool coatings versus the use of conventional roofing.

Non-Energy Benefits of Cool Coatings

There are clearly demonstrated reductions in cooling energy use as well as increasingly reliable predictions of annual energy savings due to the use of cool roof coatings. These coatings also have the benefits of lower cost, reduced air pollution, and reduced waste.

Table 7 compares the cost of using a cool coating on a roof versus using conventional roofing. The comparison studies 10 years of a roof's life with the assumption that initially, under the conventional route, the roof is torn off and replaced while in the cool coating path, the roof can be coated without removal. The cool coated roof can realize an energy savings of 20 to 70% over the next ten years for a monetary savings of 20 to 70¢ a square foot. After 10 years, the conventional roof needs a new layer of roofing, while the coated roof can be recoated at one-third the cost. At the end of only ten years, the cool roof saves more than $4.00 a square foot.

The monetary benefits of the energy savings of cool coatings are not insignificant, but they are much smaller than the potential savings due to reduced roof maintenance costs. Theoretically, these cool coatings can be applied over any roof surface which does not leak. The coatings are assumed to greatly slow down, if not stop, the aging process of the underlying roof materials. Since they are much lighter than a new layer of asphalt, the coatings can be applied indefinitely for decades before having to tear off the old roof materials and replace them.

If these claims about the longevity of roof materials under cool coatings are true, then a substantial amount of waste can be avoided by the use of cool coatings. There are an estimated 11 million tons of asphalt roofing waste going into U.S. landfills every year. Over the last 40 years, 7 to 10% of the landfill space used has been filled with roofing waste from both commercial and residential buildings.[8] Use of cool coatings can greatly increase the life of roof materials, and reduce the amount of torn-off roofing waste going into landfills. The roofing waste that still remains can be recycled into road mixes using existing processes already operating, such as in the RamCo recycling facility in Fort Myers, Florida.[9] These technologies can help turn the roofing industry to a more "green" or "sustainable" path.

Direct and indirect reductions in air pollution can also be attributed to the use of cool roofing materials. Direct reductions come about because less cooling energy is used, so fewer emissions are produced for energy generation. Indirect reductions can result if cool surfaces are used widely throughout an urban area. Cooler surfaces transfer less heat to the air, keeping urban air temperatures lower. Lower urban temperatures again call for less cooling energy, and reduced energy generation emissions.

Lower urban temperatures also reduce smog formation. Ozone formation is highly dependent on temperature, so air temperature reductions slow down the "cooking" of smog on hot summer afternoons. A computer simulation of Los Angeles added cool surfaces and trees to 15% of the possible areas.[10] This simulation indicated summer peak temperature drops of 6°F and smog decreases of 10%. This smog reduction is equivalent to ozone reductions obtained by taking 3 to 5 million cars from the roads of Los Angeles.

Barriers to Implementation of Cool Coatings

Cool rooftop coatings have many benefits, but their implementation is still going slowly. There are many reasons contributing to their slow adoption, including technical confusion, market barriers, and aesthetic barriers.

There is a lot of scientific misinformation leading to a general technical confusion and skepticism about cool coatings. As discussed earlier in this report, the visible properties of a roof material do not necessarily indicate how cool they will stay or how much energy they will save. Materials with higher reflectivities, like aluminum coatings, do not necessarily stay cool. The only way to know if a material will be cool is to know its reflectivity and emissivity. This information is not generally available to roofers or consumers, and its significance would be understood by few people even if it were available. Efforts are underway to adopt a standard called the "solar reflectivity index," a rating combining the reflectivity and emissivity to indicate how cool a material will stay in the sun. The Environmental Protection Agency is also working on rating the energy properties of roofing materials through their *EnergyStar* program. Until one or both of these standards is in common use, the confusion about roofing products will remain.

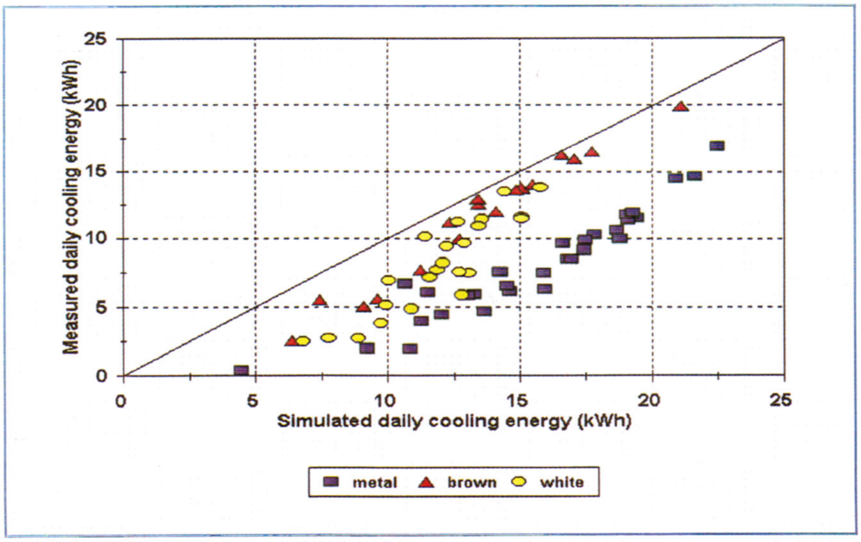

Figure 10. Measured versus predicted values of the daily cooling energy use for the Sacramento, CA school bungalow during the summer of 1992, using all 3 improvements to the DOE-2 model predictions.

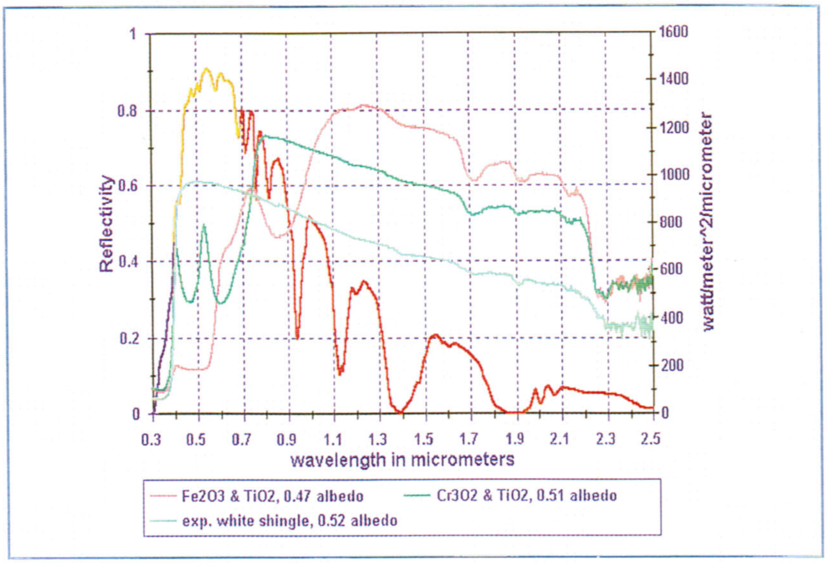

Figure 11. Reflectivity of experimental colored coatings and white residential shingles.

Another area of technical confusion is the effort to classify the benefits of cool coatings into the same terms as the R-value rating for insulation. This is an incorrect analogy which can lead to very wrong conclusions about the behavior of white coatings. If you try to explain the decreased cooling load due to a cool coating in terms of an increased R-value, then you incorrectly assume this coating also decreases the heating load during the winter. The insulation R-value reduces conductive heat transfer through the roof, while cool coatings reduce radiative heat transfer to the roof.

Market barriers to the adoption of cool coatings also exist. Conventional roofing techniques have been used for decades, so there is a relative lack of experience with and availability of cool coatings. Roofing contractors are somewhat skeptical of the claims made about cool coatings and still have many questions about their reliability and longevity. Contractors who must guarantee their work are not about to apply a coating they do not trust. The business of contractors also depends heavily on the relayering, tearing off and replacement of conventional roofing materials. The new cool coating technologies have the potential to upset the market and reduce the demand for these labor- and material-intensive roofing services.

There are also aesthetic concerns to the adoption of cool roofing materials. These materials at this point are all white, which is considered unattractive. White roofs are unacceptable even on some flat rooftops, where the rooftop will not be seen by the majority of people. There are sometimes building codes restricting what can be seen from surrounding hills or taller buildings. There is also a fear of creating glare for airline pilots, which is largely unfounded. The worst glare is created by specular reflections, which bounce off a surface at an angle equal and opposite to the one they came in on. Today's cool surfaces are very bright and reflect the majority of visible light. But they reflect light diffusely, meaning they spread light out in all directions instead of concentrating it in one direction.

Cool white roofing materials also have the problem of showing the buildup of dirt and any biological growth. Most of these products contain agents to make them "self-washing," i.e., to encourage the action of rainwater to remove dirt particles, as well as chemicals to reduce the formation of any algae or mildew. The question of reduced albedo remains, especially in areas of high dust and pollen and low rainfall.[11]

Ongoing and Future Work on Cool Coatings

There are significant research and industry challenges regarding cool coatings which still need to be undertaken. Research challenges include performing systematic demonstrations of the energy savings of cool roofing materials with different roof insulation and constructions, and in varying climate regions. Improvements also need to be made to modeling and prediction programs to get accurate predictions of summertime energy savings and wintertime heating penalties. Research into cool coating materials is now underway at two national laboratories—Lawrence Berkeley National Laboratory and Oak Ridge National Laboratory.

Research at Lawrence Berkeley National Laboratory has been covering many areas. Researchers have been administering demonstration projects of cool coatings in California and Florida (through the Florida Solar Energy Center). Improvements in roof heat transfer modeling are being made to the next generation of DOE-2, the DOE-2.2 and EnergyBase programs. Work is underway to adopt standards rating reflectivity, emissivity and the "solar reflectance index" through ASTM, ASHRAE and the California Energy Commission. Research with the Environmental Protection Agency is ongoing to provide input for *EnergyStar* standards for roofing materials. A roofing materials database has been added to the World Wide Web. Urban climatological and air quality modeling is underway to evaluate the effects of cool surfaces in cities throughout the United States.

Work at Oak Ridge National Laboratory includes testing at a comprehensive roof and attic facility, detailed modeling of the heat transfer mechanisms of roof and attic systems, and investigation of the effects of moisture buildup on roofing materials.

The coatings industry also faces many challenges. Vendors must ascertain the durability and longevity of their products, determine expected failure mechanisms, and quantify the lifetime albedo of their products. To market these products as truly "green" and environmentally friendly, they must evaluate the life cycle costs and externalities of coating products and prove their benefits over traditional materials.

The coatings industry could also potentially profit from the development of new cool materials. Researchers at Lawrence Berkeley National Laboratory have examined colored coatings and residential shingles with albedos of about 0.50 (see Figure 11).[12] These products may have appeal to a broader segment of the roofing market. The development of coatings for residential shingles (probably applied to shingles before they are installed), may also be another profitable area of investigation.

Coatings industry members are challenged to work together to promote the use of their products. Together they can more effectively set and voluntarily adopt standards for classifying their materials, develop a broad research agenda, and pool financial support. There is also a need to educate people about the science behind cool roof coatings, as well as their great potential benefits. The roof construction industry also needs to learn to apply coatings effectively and consistently and must be given the equipment and training to measure coating albedo to ensure they are achieving the targeted value.

Summary

Cool roofing is not a simplistic concept. The development of products and markets for cool coatings faces significant technical and industrial challenges, as well as market and sociological barriers. But cool roof coatings can also provide great benefits. These coatings have the potential to save large amounts of money and energy, and to significantly reduce air pollution and roofing waste.

About The Author

Dr. Lisa Gartland *is currently a post-doctoral fellow in the Building Energy Analysis Program at Lawrence Berkeley National Laboratory, where she has investigated the effects of high albedo roofing on building cooling and heating loads. Prior to obtaining a doctorate in mechanical engineering from the University of Washington in 1995, she designed and analyzed cooling systems for jet engines and nuclear reactors.*

FOOTNOTES

1. Berdahl and Bretz, "Preliminary Survey of the Solar Reflectance of Cool Roofing Materials," *Lawrence Berkeley National Laboratory Report # LBL-36020*, October 1995.

2. Akbari, Bretz, Hanford, Kurn, Fishman, Taha and Bos, "Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area: Data Analysis, Simulations and Results," *Lawrence Berkeley Laboratory Report # LBL-34411*, December 1993.

   Parker, Barkaszi, Chandra, and Beal, "Measured Cooling Energy Savings From Reflective Roofing Systems in Florida: Field and Laboratory Research Results," *Thermal Performance of the Exterior Envelopes of Buildings VI*, pp. 489-500, jointly sponsored by U.S. DOE, ASHRAE, ORNL and the Building Environment and Thermal Envelope Council, December 4-8, 1995, Clearwater, FL.

3. Gartland, "EPA Demonstration Project: Energy Savings of Cool Roof Coatings," draft report for Lawrence Berkeley National Laboratory, January 1997.

4. Konopacki, Akbari, Gabersek, Pomerantz, Gartland and Moezzi, "Energy and Cost Benefits from Light-colored Roofs in 11 U.S. Cities," *Lawrence Berkeley National Laboratory Report # LBL-39433*, October 1996.

5. Akbari et al.

6. Levinson, Akbari and Gartland, "Impact of the Temperature Dependence of Fiberglass Insulation R-Value on Cooling Energy Use in Buildings," *Lawrence Berkeley National Laboratory Report # LBL-38678.*

7. Gartland, Konopacki and Akbari, "Modeling the Effects of Reflective Roofing," *Lawrence Berkeley National Laboratory Report # LBL-38580*, August 1996.

8. "Disposal Costs Go Through the Roof," *RSI*, pp. 30-32, October 1993.

9. "Roofing Debris Recycling, Ten Years and Counting," *Roofer Magazine*, pp. 22-24, July 1996.

10. Akbari, Rosenfeld, Taha and Gartland, "Mitigation of Summer Heat Islands to Save Electricity and Reduce Smog," *Proceedings of the AMS Annual Meeting*, Atlanta, GA, Jan. 28-Feb. 2, 1996; also, *Lawrence Berkeley National Laboratory Report # LBL-37787*.

11. Bretz and Akbari, "Durability of High-albedo Roof Coatings and Implications for Cooling Energy Savings," *Lawrence Berkeley National Laboratory Report # LBL-34974*, June 1994.

12. Berdahl and Bretz.