

COOL-COLOR ROOFING MATERIAL



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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission) conducts public interest research, development, and demonstration (RD&D) projects to benefit the electricity and natural gas ratepayers in California. The Energy Commission awards up to \$62 million annually in electricity-related RD&D, and up to \$15 million annually for natural gas RD&D.

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/ Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

Cool-color Roofing Material is the final report for the Cool Roofs project, contract number 500-02-021, conducted by Lawrence Berkeley National Laboratory and Oak Ridge National Laboratory. The information from this project contributes to PIER's Buildings End-Use Energy Efficiency program.

For more information on the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier or contact the Energy Commission at (916) 654-5164.

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Abstract

Solar reflective, thermally emissive (cool) roofs decrease demand for building air conditioning power, lower the ambient air temperature, and, by promoting lower ambient air temperatures, retard the formation of smog. For example, raising the solar reflectance of a roof from 0.10 (typical of a conventional dark roof) to 0.35 (typical of a cool dark roof) can reduce building cooling energy use by more than 10 percent. In 2002, suitable cool *white* materials were available for most products, with the notable exception of asphalt shingles, the most widely used roofing material. However, cooler *colored* (nonwhite) materials were needed for all types of roofing, especially in the residential market. The California Energy Commission engaged Lawrence Berkeley National Laboratory and Oak Ridge National Laboratory to work with the roofing industry to develop cool-colored roofing products, with the goal of bringing to market within three to five years roofs that meet the ENERGY STAR qualifying solar reflectance of 0.25. This project led to the development of prototype colored asphalt shingles with solar reflectances of up to 0.35. One manufacturer currently markets colored asphalt shingles with solar reflectance of 0.25. Colored metal, clay tile, and concrete tile roofing materials with solar reflectances of 0.30 to 0.60 are currently sold in California.

Keywords: cool roof, reflectance, building energy, cool-color, energy efficiency, albedo, roofing material manufacture, pigment

Executive Summary

Introduction

Coatings colored with conventional pigments tend to absorb the invisible near-infrared (NIR) radiation that bears more than half of the power in sunlight. Replacing conventional pigments with “cool” pigments that absorb less NIR radiation can yield roofing coatings similar in color to those used in conventional roofs with higher solar reflectance. These cool coatings lower roof surface temperature, which in turn reduces the need for cooling energy in conditioned buildings and makes unconditioned buildings more comfortable. For example, raising the solar reflectance of a residential roof from 0.10 (the typical reflectance of a conventional dark color, to 0.35 (the reflectance of cool dark color) can decrease building cooling-energy use by 7 percent to 15 percent.

In 2002, suitable cool *white* materials were available for most roofing products, with the notable exception of asphalt shingles¹. To respond to the consumer preference for colored roofs, cool *nonwhite* materials are needed for all types of roofing – and especially for asphalt shingles, which account for about 54 percent of the total residential roof market in the western United States.

Purpose

The California Energy Commission engaged Lawrence Berkeley National Laboratory (LBNL) and Oak Ridge National Laboratory (ORNL) – hereafter called the Cool Team – to work with the roofing industry to develop cool-colored roofing products, with the goal of bringing cool roofing products that meet the ENERGY STAR qualifying solar reflectance of 0.25 to market within three to five years.

Project Objectives

- Characterize the optical properties of common and innovative pigments
- Develop a software tool to maximize the solar reflectance of color-specified roofing material
- Work with roofing manufacturers to design innovative cool roofing material production methods
- Measure the energy savings of the cool roofs on demonstration houses and test the performance of conventional and cool roofing systems at ORNL’s steep-slope assembly testing facility
- Characterize the effects of weathering and aging on the cool roofs
- Estimate the energy and demand savings of the new cool roof materials
- Help bring cool roofing products to market within three to five years

Project Outcomes

¹ Shingles marketed as “white” are gray in color with a typical solar reflectance of about 0.25.

Pigment characterization and manufacturing partnership

The Cool Team developed complex inorganic dark colored pigments that are highly reflective in the near-infrared portion of the solar spectrum. The team also created a software tool for designing high-reflectance coatings that match the colors of conventional colored roofing products. The team then worked with a consortium of 16 industry partners – representing most of the major and several minor U.S. roofing manufacturers – to develop novel manufacturing methods, which industry partners then used to manufacture cool roof prototypes and products.

To date and as the direct result of this collaborative effort, manufacturers of roofing materials have introduced cool shingles, cool concrete tile coatings, and cool concrete tiles and have significantly expanded the production of cool clay tiles and cool metal roofs. The manufacturing partners of the two national labs have raised the solar reflectance of commercially available concrete tile, clay tile, and metal roofing products to 0.30–0.45 (up from 0.05–0.25) by reformulating their pigmented coatings.

Test results

Tests of roofs at residential sites that compared the energy performance of cool and conventional roofs yielded these findings:

- The attic air temperature beneath a cool chocolate brown concrete tile roof (solar reflectance 0.41) was 3 to 5 K (5.4 to 9°F) cooler than that below a the same color and type conventional roof (solar reflectance 0.10)
- The attic air temperature beneath the cool brown metal shake roof (solar reflectance 0.31) was 5 to 7 K (9 to 12.6°F) cooler than a similar color and type conventional roof (solar reflectance 0.08).

Material testing showed that long-term change in the solar reflectance of cool roofs – which could compromise the benefits – appears to be driven by particulate matter that sticks to the roofs and resists being washed off by wind or rain.

Steep-slope assembly testing at ORNL suggests that sub-tile venting is just as important as the increase in solar reflectance in reducing the heat flow into the conditioned space of a house. Further, these tests revealed that sub-time venting reduces the small winter heating loss associated with cool-color roofs.

Finally, the accelerated and product useful life testing were promising, showing that novel cool pigmented concrete, clay, painted metal, and asphalt shingle roofs maintain their solar reflectance as well as do their standard production counterparts.

Technology transfer

The Cool Team, in conjunction with respective industry partners, presented research results at appropriate trade shows, and published their results in each industry's appropriate trade magazines. More than 20 journal articles have been published by the Cool Team over the course of the project.

In collaboration with the roofing industry partners, the Cool Team prepared a market plan outlining industry/national lab collaborative efforts that would help the Energy Commission

deploy cool-colored roofing. The plan focuses on six parallel initiatives: regulate; increase product selection; label; educate; provide incentives; and demonstrate performance.

Cool Team estimates of energy and peak demand savings showed that increasing roof solar reflectance from a conventional dark roof of 0.10 to a cool-colored roof of 0.30 yields net savings in the range of 100–600 kWh per 100 m² per year. These data can be used to prepare a protocol for updating the state’s Title 24 building energy code to include cool-colored roofing materials.

Conclusions

By enlisting the partnership of most of the major roofing manufacturers in the United States, the Cool Team exceeded the initial goal of creating dark asphalt shingles with solar reflectances of at least 0.25 and other nonwhite roofing products – including tiles and painted metals – with solar reflectances not less than 0.35.

Many of the products resulting from this work are already in the marketplace. For example, BASF industrial Coatings has launched a line of cool-colored siliconized-polyester coating, MCA Clay Tile is selling 11 products with solar reluctances about 0.25, and Elk Corporation has introduced its Prestique Cool-color Series, a line of light-gray and light-brown asphalt shingle with solar reflectances at or above 0.25. The Cool Team therefore met its commercialization goal of helping to bring products to market in three to five years.

Recommendations

Near the end of the project, the Cool Team’s 16 industrial partners discussed their needs to further develop and successfully market their residential cool roofing products. Their recommendations, summarized below, were used to develop a deployment proposal.

- First and foremost, residential cool roofs need to be credited and recommended in the state’s Title 24 standards that primarily determine what products are used in the construction of new houses and in major remodels.
- More cool materials for all residential (and commercial) sloped roofing systems must be available and appropriately labeled.
- The cool roofing pigment database should be maintained and expanded with new materials to assist the industry in developing new and advanced materials at competitive prices.
- The aging and weathering of cool roofing materials and their effects on the useful life of roofs need to be further studied.
- Appropriate labels on roofing products must be universally applied.
- Architects, designers, builders, roofing material distributors and retailers, and consumers need to learn of the availability and benefits of using cool roofing materials.
- California’s utilities and government can further influence the selection of cool roofs through innovative incentive and rebate programs to accelerate their market penetration.
- For utilities to develop incentive programs and for manufacturers to coordinate their materials development with their marketing efforts, they need to have an industry-consensus calculator to accurately estimate energy and peak demand of cool-colored

roofs. The calculator should account for both the cooling energy savings and potential heating energy penalties of cool roofs.

- Market penetration can be accelerated by enhancing the credibility of retailer and utility marketing claims through large-scale demonstrations of cool roofs to consumers, developer, designers, and roofing contractors.

Benefits to California

Regional climate modeling suggests that the widespread application of cool roofs can reduce urban air temperatures, decreasing cooling peak power demand and smog production. For example, on a warm afternoon in Los Angeles, each 1 K (1.8°F) decrease in the daily maximum temperature lowers peak demand for electric power by about 2 percent to 4 percent and each 1 K (1.8°F) decrease down to 21°C (70°F) reduces smog (specifically, the probability that the maximum concentration of ozone will exceed the California standard of 90 parts per billion) by 5%. A 3 K (5.4°F) reduction in the air temperature of the Los Angeles basin could reduce peak power demand by 200 MW, offer cooling energy savings worth \$21 M/year, and yield a 12% reduction in ozone worth \$104 M/year [Rosenfeld et al. 1998]. More than 450 U.S. counties (including some of the most heavily populated areas of California) had ozone levels that exceeded federal eight-hour standards as of 2004. Widespread adoption of cool roofs could help cities in many of these areas reduce the magnitude of their air quality problem. Table ES1 summarizes many of the benefits of cool roofing, based on findings from a single-family home.

The principal application of cool-color roofing is to provide roofing manufacturers with the tools they need to develop energy-efficient products that benefit their customers and improve the competitive advantage of these U.S roofing products in the marketplace. Cool-color roofing materials provide clear, measured advantages and dollar savings compared to conventional roofing materials at a small cost premium that is paid back within a few years through reduced energy bills.

Table ES1. A comparison of the attributes of cool-colored and standard roofing products *

Feature	Glazed clay tile roofing	Polymer-coated concrete tile roofing	Polymer-coated metal roofing	Asphalt shingle roofing with ceramic-coated granules
Example of conventional roofing product (manufacturer/model/color name)	MCA Clay Tile/Corona Tapered Mission/Burnt Sienna	American Rooftile Coatings/Warm Earthtone Rooftile Coating /Onyx	Custom-Bilt Metals/Titan Select Vail Shingle/ Musket Brown	Elk/Prestique Plus High Definition/ Weatherwood
Example of cool roofing product (manufacturer/model/color)	MCA Clay Tile/Corona Tapered Mission/ Tobacco	American Rooftile Coatings/Cooltile IR Coating™/IR Onyx topcoat over plaster white basecoat	Custom-Bilt Metals/Titan Cool Roof Vail Shingle /Musket Brown	Elk/Prestique Cool-color Series/Cool Weatherwood
Solar reflectance of conventional roofing product sample	0.18	0.04	0.08	0.09
Solar reflectance of cool roofing product sample	0.37	0.38	0.27	0.25
Solar reflectance increase (cool product reflectance–conventional product reflectance) for dark colors (range reflects difference in reflectance for different colors)**	0.18–0.25	0.18–0.34	0.17–0.25	0.10–0.16
Reduction in peak surface temperature on a summer afternoon of the cool roof (K)	10–12	10–17	10–12	7–9
Peak power demand savings of the cool roof (W)	300–400	300–400	400–600	300–350
Annual cooling energy savings of the cool roof (kWh)	150–400	150–400	250–650	190–490
Annual cooling energy savings at \$0.15/kWh of the cool roof (\$)	22–60	22–60	37–97	28–73
Annual heating energy penalty of the cool roof (therms)	1–4	1–4	2–8	1–5
Annual heating energy penalty at \$1.5/therm of the cool roof (\$)	2–6	2–6	3–12	2–7
Net savings provided by the cool roof (\$)	20 –54	20–54	35–85	26–66
Cost premium of the cool roof compared with conventional roof (\$)†	nil	100–500	nil	500
15-year net present value of net energy savings at 3% discount (\$)	240–650	240–650	420–1020	310–790
Simple payback time of the cool roof (years)	0	2–10	0	8–19

* Only the solar reflectances of the cool and conventional products are compared; all other rows enumerate the energy, power, or money saved by the cool roof as compared to a conventional roof on a single-story electrically heated and cooled 200 m² (2,150 ft²) home built after 1980 in Sacramento, CA.

**A dark-colored surface is defined as one that reflects no more than 20% of visible sunlight. Smooth, flat surfaces reflect about 5% of visible sunlight when black; about 10% when dark brown; and about 10–20% when dark red, dark green, or dark blue.

† The cost premium of cool roofs is a matter of industry debate. Specifically, the industry lacks consensus on whether replacing conventional pigments with cool pigments in an existing manufacturing process would introduce a significant cost premium.

1.0 Introduction

1.1. Background

The world is facing disruptive global climate change from greenhouse gas emissions and increasingly expensive and scarce energy supplies. Energy efficiency reduces those emissions and mitigates the rising cost of energy. Cool-color roofing – a new technology that uses solar-reflective pigments to reduce a home’s energy and peak demand – promises a significant leap in energy efficiency.

Coatings colored with conventional pigments tend to absorb the invisible near-infrared (NIR) radiation that bears more than half of the power in sunlight. Replacing conventional pigments with “cool” pigments that absorb less NIR radiation can yield colored coatings similar in color to conventional roofing materials, but with higher solar reflectance (see Figure 1). These cool coatings lower roof surface temperature, which in turn reduces the need for cooling energy in conditioned buildings and makes unconditioned buildings more comfortable.

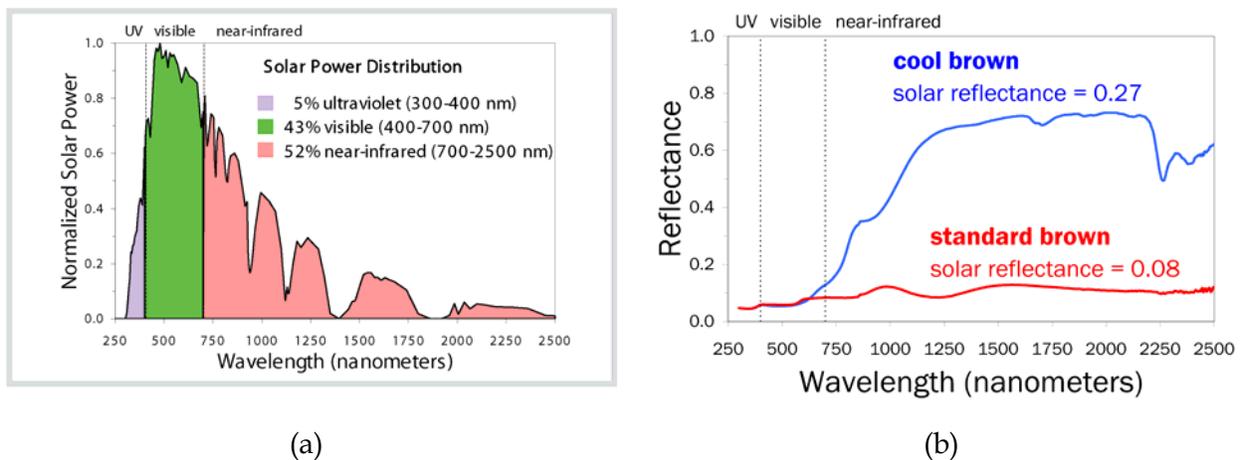


Figure 1. (a) Spectral solar power distribution and (b) solar spectral reflectances of cool and standard brown surfaces

1.1.1. Potential energy and indirect benefits of cool roofs

Field studies in California and Florida have demonstrated cooling energy savings in excess of 20% upon raising the solar reflectance of a roof from the 10–0.20 reflectances typical of conventional roofs to 0.60 (Konopacki and Akbari, 2001; Konopacki et al. 1998; Parker et al. 2002). Energy savings are particularly pronounced in older houses that have little or no attic insulation, especially if the attic contains the air distribution ducts. At 8¢/kWh, the value of potential U.S. net commercial and residential energy savings (cooling savings minus heating penalties) exceeds \$750 million per year (Akbari et al. 1999). Cool roofs also significantly reduce peak electric demand in summer (Akbari et al. 1997; Levinson et al. 2005a).

Further, the widespread installation of cool roofs can lower the ambient air temperature in a neighborhood or city, decreasing the need for air conditioning, retarding smog formation, and improving environmental comfort. These “indirect” benefits of reduced ambient air temperatures have roughly the same economic value as the direct energy savings (Rosenfeld et

al. 1998). Lower surface temperatures may also increase the lifetime of roofing products particularly asphalt shingles), reducing replacement and disposal costs.

1.1.2. The size and value of the western U.S. roofing market

According to *Western Roofing Insulation and Siding* magazine (2002), the total value of the 2002 projected residential roofing market in 14 western U.S. states (AK, AZ, CA, CO, HI, ID, MT, NV, NM, OR, TX, UT, WA, and WY) was about \$3.6 billion (B). The research team estimated that 40% (\$1.4B) of that amount was spent in California. The lion’s share of residential roofing expenditure was for fiberglass asphalt shingle (hereafter, simply “shingle”), which accounted for \$1.7B, or 47% of sales. Concrete and clay roof tiles made up \$0.95B (27%), while wood, metal, and slate roofing collectively represented another \$0.55B (15%). The value of all other roofing projects was about \$0.41B (11%). The team estimates that the roofing market area distribution was 54–58% fiberglass shingle, 8–10% concrete tile, 8–10% clay tile, 7% metal, 3% wood shake, and 3% slate (see Table 1).

Table 1. Projected residential roofing market in the U.S. western region surveyed by Western Roofing (2002). The Western region includes AK, AZ, CA, CO, HI, ID, MT, NV, NM, OR, TX, UT, WA, and WY.

Roofing Type	Market share by \$		Estimated market share by roofing area
	\$B	%	%
Fiberglass Shingle	1.70	47.2	53.6-57.5
Concrete Tile	0.50	13.8	8.4-10.4
Clay Tile	0.45	12.6	7.7-9.5
Metal/Architectural	0.21	5.9	6.7-7.2
Wood Shingle/Shake	0.17	4.7	2.9-3.6
Slate	0.17	4.7	2.9-3.6
Other	0.13	3.6	4.1-4.4
SBC Modified	0.08	2.1	2.4-2.6
APP Modified	0.07	1.9	2.2-2.3
Metal/Structural	0.07	1.9	2.2-2.3
Cementitious	0.04	1.1	1.2-1.3
Organic Shingles	0.02	0.5	0.6
Total	3.60	100	100

The research team estimated that applying cool-colored roofs to houses could achieve a net energy savings in the U.S. worth over \$400 million per year (Konopacki et al. 1997). The

estimated savings in California (in 2005 \$) is about \$100 million per year. Figure 2 shows potential savings of cool-colored residential roofing materials in 11 U.S. metropolitan areas.

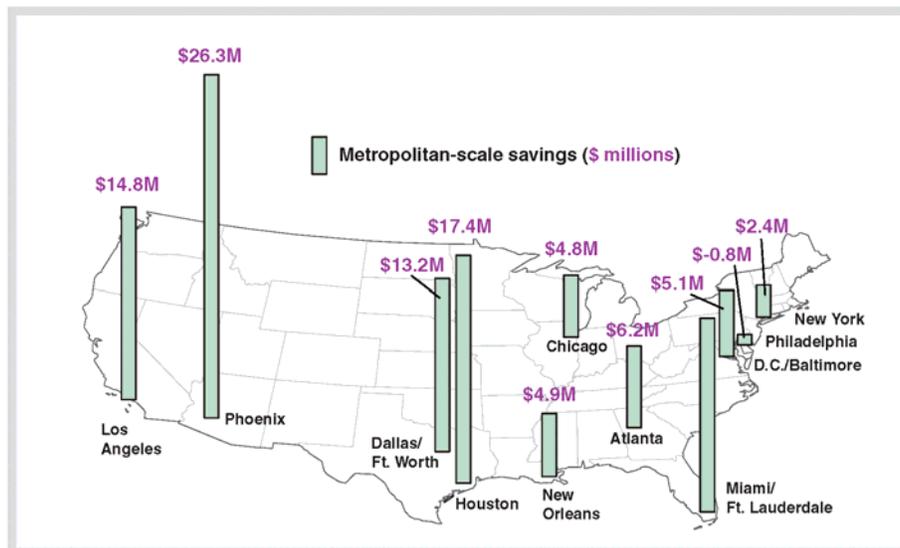


Figure 2. Value of potential annual residential energy savings from cool roofs in 11 U.S. metropolitan areas

1.1.3. The need for cool-color roofing

In 2002, suitable cool *white* materials were available for most roofing products, with the notable exception of asphalt shingles². However, white residential roofing products sell poorly in California, where homeowners prefer the aesthetics of dark-colored roofs. To respond to this market preference, cool nonwhite materials are needed for all types of roofing. Cool color roofing technology makes solar-reflective roofing available in any color (dark or light) by selectively reflecting the invisible component of sunlight in the NIR spectrum.

On a summer day, the peak daily surface temperature of a cool dark roof of solar reflectance 0.35 is about 14 K (25°F) lower than that of a conventional dark roof of solar reflectance 0.10. The cool dark roof conducts about 20–40% less heat into a home’s conditioned space than does a conventional dark roof, reducing the home’s demand for cooling power by about 7–15% in the late afternoon. During these afternoon hours, demand for air conditioning strains the electrical grid and requires utilities to produce additional power using less efficient, more expensive, and more polluting “peak” generators.

1.2. Project Objectives

In May 2002, the California Energy Commission (Energy Commission) sponsored a research project to develop cool nonwhite roofing products that could revolutionize the residential roofing industry. This project – which brought together Lawrence Berkeley National Laboratory (LBNL) and Oak Ridge National Laboratory (ORNL) – aimed to develop complex inorganic color pigments that are dark in color but highly reflective in the NIR portion of the solar

² Shingles marketed as “white” are gray in color with a typical solar reflectance of about 0.25.

spectrum. The high NIR reflectance of coatings formulated with these and other cool pigments – e.g., chromium oxide green, cobalt blue, phthalocyanine blue, Hansa yellow – can be exploited to manufacture roofing materials that reflect more sunlight than conventionally pigmented roofing products.

The cool-color program at LBNL has three elements:

- Measuring the rates at which many common pigmented coatings absorb (convert to heat) and backscatter (reflect) light at wavelengths in the ultraviolet (UV), visible, and NIR spectra
- Using these rates to develop a software tool for the design of color-matched coatings with high solar reflectance
- Working with the roofing industry to develop novel manufacturing methods and encourage the manufacture of cool roof prototypes and products

ORNL was charged with demonstrating the new material to measure both the residential energy savings achieved by use of cool-colored roofing and the extent to which exposure changes the appearance and performance of cool-colored roofing. ORNL also tested several cool roofing products at their facilities at Oak Ridge. In this report, this national labs partnership is referred to as the “Cool Team.”

To complete the project goals, the cool team developed a strong relationship with industry, forming a consortium that included most of the major roofing manufacturers, as well as many smaller manufacturers:

- 3M Company (St. Paul, MN);
- Akzo Nobel (Columbus, OH);
- American Rooftile Coatings (Fullerton, CA);
- BASF Industrial Coatings (Southfield, MI);
- CertainTeed Corporation (Valley Forge, PA);
- Custom-Bilt Metals (Chino, CA);
- Elk Corporation (Ennis, TX);
- Ferro Corporation (Cleveland, OH);
- GAF Materials (Wayne, NJ);
- Hanson Roof Tile (Fontana, CA);
- ISP Minerals (Hagerstown, MD);
- MCA Clay Tile (Corona, CA);
- Monier Lifetile (Thousand Oaks, CA);
- Owens Corning (Granville, OH);
- Shepherd Color Company (Cincinnati, OH); and
- Steelscape Inc. (Kalama, WA).

These partners were needed to help develop new manufacturing processes, develop and eventually commercialize new products, and help develop a commercialization plan.

1.3. Report Organization

This report will summarize the Cool Team activities within each of the project tasks, listed below:

Task 2.4: Development of Cool-colored Coatings

- Task 2.4.1 Identify and Characterize Pigments with High Solar Reflectance
- Task 2.4.2 Develop a Computer Program for Optimal Design of Cool Coatings
- Task 2.4.3 Develop a Database of Cool-Colored Pigments

Task 2.5 Development of Prototype Cool Colored Roofing Materials

- Task 2.5.1 Review of Roofing Materials Manufacturing Methods
- Task 2.5.2 Design Innovative Methods for Application of Cool Coatings to Roofing Materials
- Task 2.5.3 Accelerated Weathering Testing

Task 2.6 Field-Testing and Product Useful Life Testing

- Task 2.6.1 Building Energy-Use Measurements at California Demonstration Sites
- Task 2.6.2 Materials Testing at Weathering Farms in California
- Task 2.6.3 Steep-slope Assembly Testing at ORNL
- Task 2.6.4 Product Useful Life Testing

Task 2.7 Technology Transfer and Market Plan

- Task 2.7.1 Technology Transfer
- Task 2.7.2 Market Plan
- Task 2.7.3 Title 24 Code Revisions

The report ends with a summary of conclusions, recommendations, and benefits of the work to California. Attachments to this report provide additional details on the tasks listed above.

2.0 Technical Tasks

The following is a summary of the work accomplished in each task.

2.1. Task 2.4: Development of Cool-Colored Coatings

To determine how to optimize the solar reflectance of a pigmented coating matching a particular color, and how the performance of a cool-colored roofing material compares to that of a standard material, the Cool Team

- Characterized the optical properties of over 80 single-pigment coatings
- Created a database of pigment characteristics
- Developed a computer model to maximize the solar reflectance of roofing materials for a choice of visible color

2.1.1. Task 2.4.1: Identify and characterize pigments with high solar reflectance

The project team examined pigments in widespread use, with particular emphasis on those that may be useful for formulating nonwhite materials that can reflect the near-infrared portion of sunlight, such as the complex inorganic color pigments (mixed metal oxides).

Pigment characterization begins with measuring the reflectance r and transmittance t of a thin coating (e.g., a 25- μm thick paint film) colored by single pigment, such as iron oxide red. These “spectral,” or wavelength-dependent, properties of the pigmented coating are measured at 441 evenly spaced wavelengths spanning the solar spectrum (300 to 2500 nanometers). Inspection of the film's spectral absorptance (calculated as $1-r-t$) reveals whether a pigmented coating is “cool” (has low NIR absorptance) or “hot” (has high NIR absorptance).

The spectral reflectance and transmittance measurements are used to compute spectral rates of light absorption K and backscattering (reflection) S per unit depth of film. A cool-color is defined by a small absorption coefficient K in the near infrared. For cool-colors, the backscattering coefficient S is small in the visible spectral range for formulating dark colors (or large in the visible spectral range for light colors), and preferably large in the NIR. (Weak backscattering in the NIR is acceptable when a basecoat or the substrate provide high NIR reflectance.) Calculations of S and K employ a variant of the Kubelka-Munk two-flux continuum model of light propagation through a pigmented coating that Berkeley Lab has adapted to account for the reflectance of incompletely diffused light at the air-coating interface. Such “interface reflectances” can significantly alter the reflectance and transmittance of the optically thin pigmented coatings applied to roofing materials.

As a check, the Cool Team found that values of S computed from the Kubelka-Munk model for generic titanium dioxide (rutile) white pigment were in rough agreement with values computed from the Mie theory, supplemented by a simple multiple scattering model.

The optical properties of 87 single-pigment films – 4 white, 21 black or brown, 14 blue or purple, 11 green, 9 red or orange, 14 yellow, and 14 pearlescent – were characterized by computing spectral Kubelka-Munk coefficients from spectral measurements of film reflectance and transmittance. Twenty-six polyvinylidene fluoride (PVDF) resin paint films were provided by a manufacturer of coil-coating paints. Another 34 acrylic paints were purchased as artist colors,

and the remaining 27 coatings were acrylic-base letdowns (dilutions) of cool (primarily metal-oxide) pigment dispersions from pigment manufacturers.

The team identified cool pigments in the white, yellow, black/brown, red/orange, blue/purple, and pearlescent color groupings with NIR thin-film absorptances less than 0.1, as well as other pigments in the black/brown, blue/purple, green, red/orange, yellow and pearlescent groupings with NIR absorptances less than 0.2. Most are NIR transmitting and require an NIR-reflecting background to form a cool coating. Over an opaque white background, some pigments in the pearlescent, white, yellow, black/brown red/orange, green, and blue/purple families offer NIR reflectances of at least 0.7, while other pigments in the blue/purple, black/brown, and green color families have NIR reflectances of at least 0.5. A few members of the white, yellow, black/brown, pearlescent, red/orange, and green color families have NIR scattering sufficiently strong to yield NIR reflectances of at least 0.3 (and up to 0.64) over a black background.

Use of pigments with NIR absorptances approaching unity (e.g., nonselective blacks) should be minimized in cool coatings, as might be the use of certain pearlescent, blue/purple, red/orange, and brown/black pigments with NIR absorptances exceeding 0.5.

Figure 3 illustrates the team's pigment characterization activities, showing (a) images over white and black backgrounds of the 87 single-pigment films; (b) coupons of a pigmented polymer film (an organic red) over white and black backgrounds; and (c) the measured and computed solar spectral reflectances of a pigmented polymer film (an inorganic cool black). The three charts show, from top to bottom, (i) measured reflectance, measured transmittance, and computed absorptance of a free film; (ii) Kubelka-Munk backscattering and absorption coefficients computed from the measured reflectance and transmittance of the free film; and (iii) the measured and computed reflectances of the film over black and white backgrounds, which are used to validate the accuracy of the backscattering and absorption coefficients computed from the free-film properties.

The team has published two milestone papers published in the academic journal *Solar Energy Materials & Solar Cells* (Attachment 1). Feedback from the journal's referees was extremely positive. To wit:

Referee #1: "Great work with extensive detail, I have not seen such detail on pigments since work in the 1960s by the aerospace companies. It is nice to see such a seminal work in one location and with one set of testing methodologies. Please publish."

Referee #2: "...Very nice work, uniform and detailed – the beginnings of a handbook. Very valuable to my industry (paint formulation). If Elsevier puts together a Materials Property Handbook, the results of this work should be in it."

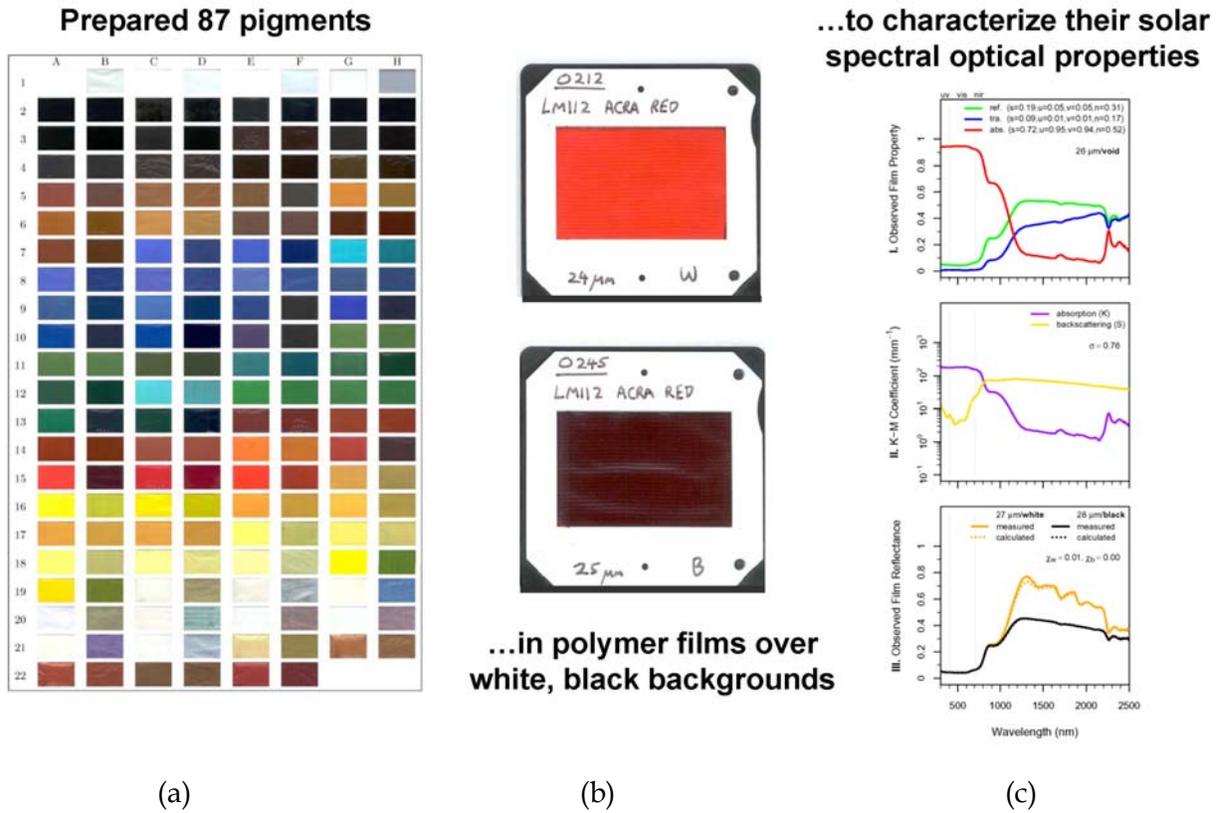


Figure 3. Illustration of the team's pigment characterization activities, showing (a) images over white and black backgrounds of the 87 characterized single-pigment coatings; (b) coupons of a pigmented polymer paint film (an organic red) over white and black backgrounds; and (c) measured and computed solar spectral optical properties of a characterized pigmented paint film (an inorganic black)

2.1.2. Task 2.4.2: Develop a computer program for optimal design of cool coatings

The radiative properties of the pigmented coatings characterized in Task 2.4.1 serve as inputs to Pinwheel™, a software tool for the design of color-matched cool coatings that the LBNL team has developed and shared with its industrial partners.

Pinwheel™ formulates color-matched coatings with high solar reflectance. It models a coated surface with two or three layers: an opaque substrate, an optional basecoat, and a topcoat. The solar spectral reflectance of the substrate; the thickness and colorant composition of the optional basecoat; and the thickness of the topcoat are specified by the coating designer. Pinwheel™ then seeks the topcoat colorant composition that maximizes the solar reflectance of the coated surface while acceptably matching a target visible spectral reflectance. The solar spectral reflectance of a coated surface, and hence its solar reflectance and visible spectral reflectance, are computed by applying to the solar spectral absorption and backscattering coefficients of colorants (a) a two-flux, two-constant model of light propagation through a film and (b) a colorant mixture model. Pinwheel™ has a large library of over 80 colorants whose solar spectral properties have been characterized by LBNL.

This tool differs in three major respects from conventional coating formulation software. First, it predicts solar spectral reflectance (300 to 2500 nm), rather than just visible spectral reflectance (400 to 700 nm). Second, it does not require that coatings be opaque. This permits design of thin coatings that transmit both visible and near-infrared light, as well as thicker coatings that stop visible light but transmit near-infrared light. Third, it contains the solar (and not just visible) spectral properties of the 80+ colorants.

Pinwheel™ executes in R, an interpreted programming environment available as free software for the Windows, Mac OS X, and Unix platforms. The following Pinwheel™ code designs a cool coating that matches a known color (“emerald green”) and combines up to three colorants:

```
design(  
  target="emerald-green",  
  topcoat.colorants=list("U08, G", "W", "Y01, Y10, Y14")  
)
```

The first colorant is to be chosen from the set “U08, G”, where “U08” is a particular blue and “G” can be any of 11 characterized green pigments. The second colorant is to be “W”, which represents any of four characterized white pigments. The third colorant is to be chosen from the set of three characterized yellow pigments “Y01, Y10, Y14”. Each colorant can be present in a volume concentration ranging (by default) from 0 to 30%. The allowable concentrations are among many specifiable parameters with default values.

Figure 4 shows Pinwheel™ seeking the three-colorant combination that will produce the coating with maximum solar reflectance that matches the desired target color to within an acceptable tolerance. Chart a (upper right-hand corner) shows the visible spectral reflectance achieved by a particular set of colorants in a certain vector of concentrations. Chart b (upper left-hand corner) shows the visible spectral reflectance of all acceptable solutions found with all concentration vectors of that particular set of colorants. Chart c (lower left-hand corner) shows the solar reflectance versus match error of all acceptable solutions. The text (lower-right hand corner) shows some of the parameters used in the formulation of this coating.

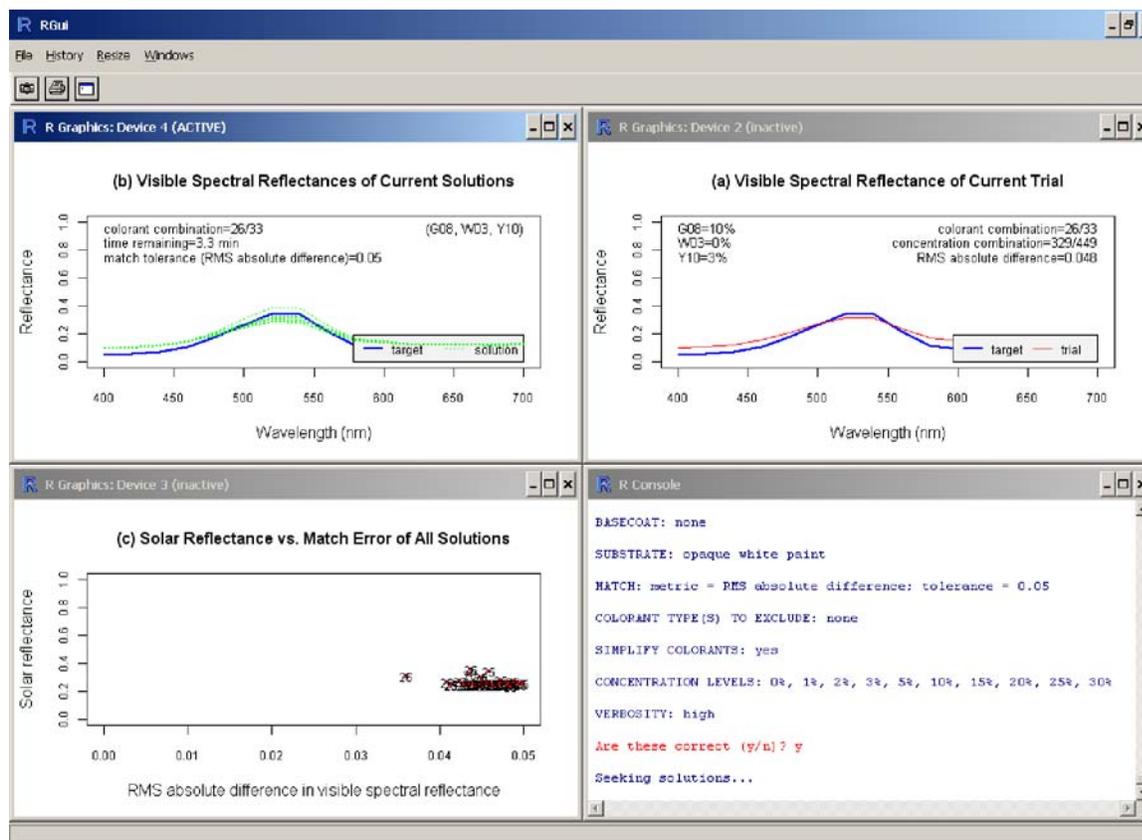


Figure 4. Pinwheel™ screen shot

Figure 5 shows one of 163 acceptable solutions found by Pinwheel™. Solutions are ordered by descending solar reflectance, so solution 2 (shown here) is that with the second highest solar reflectance. It achieves a solar reflectance of 0.38 using volume concentrations of 1% phthalocyanine green and 1% iron oxide yellow in an otherwise clear 25- μm coating over an opaque white substrate.

Pinwheel™ is currently being tested by five manufacturers. Its user manual can be found in Attachment 2.

Solution 2/163

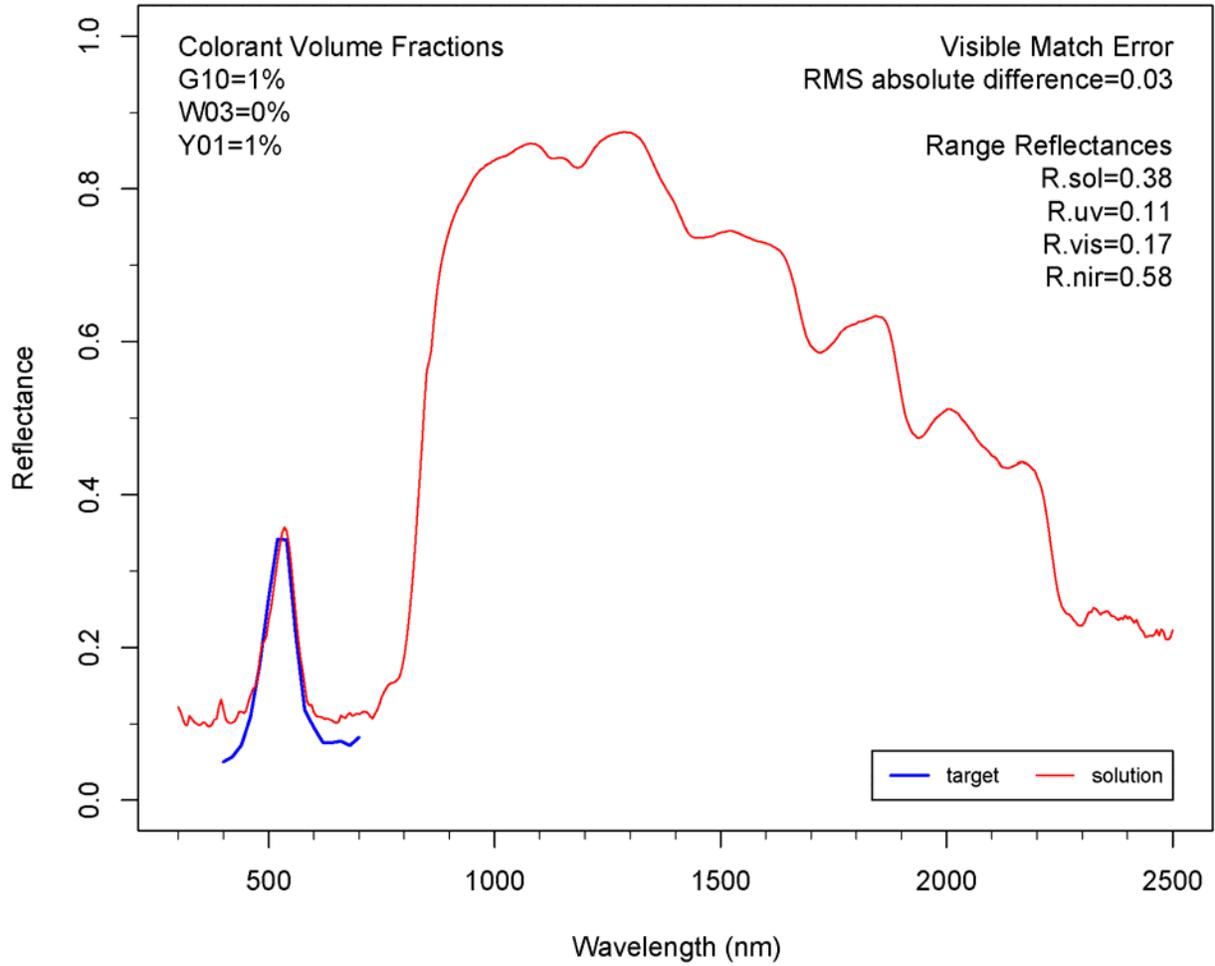


Figure 5. Solar spectral reflectance of a Pinwheel™-formulated cool coating (solution) designed to match the visible spectral reflectance of a particular shade of green (target)

2.1.3. Task 2.4.3: Develop a database of cool-colored pigments

To help the roofing industry identify cool pigments to use and hot pigments to avoid in their coatings, the LBNL researchers have produced a browsable HTML database detailing the solar spectral optical properties of 87 single-colorant (“masstone”) pigmented coatings. It also includes the solar spectral optical properties of 104 tints (mixtures of single colors with white) and 32 binary mixtures of nonwhite colors. The database charts the solar spectral reflectance, transmittance, absorptance, backscattering coefficient, and absorption coefficient of each pigmented coating, and also presents images, commentary, and a chemical description of each pigment (Figure 6). Machine-readable datafiles are also included.

Figure 7 shows the first index page of the online database, including links to detail pages for four white pigments and 21 black/brown pigments. A typical detail page includes the following:

- Links to a datasheet from the pigment’s manufacturer; commentary about the pigment from the LBNL articles produced for Task 2.4.1
- Large images of the pigment’s masstone, tint, and binary nonwhite mixture films
- Charts and tables of the solar spectral properties of these films (Figure 6)

The tabular information available for each pigment is detailed in Table 2. The database is online at <http://Coolcolors.LBL.gov>.

The database summary can be found in Attachment 3.

[R03] Red Iron Oxide (iii)

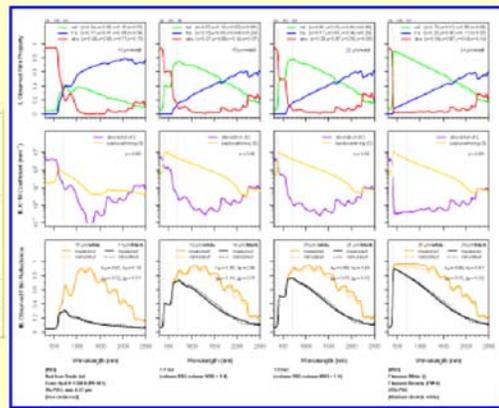
Paint Code	R03
Paint Name	Red Iron Oxide (iii)
Pigment Name	Ferro Red V-13810 (PR 101)
Color Family	Red/Orange
Color Subfamily	iron oxide red
Mean Particle Size (microns)	0.27
Dry Film PVC	3%
Pigment Datasheet	available
Paint Datasheet	unavailable
LBNL Commentary	available

Masstone and Mixtures with White (Tints)

[R03] Red Iron Oxide (iii) +
[W03] Titanium White (i)

image over white				
image over black				
spectral datafile	R03 masstone	R03 tint 1:4	R03 tint 1:9	W03 masstone

[guide to reading spectral datafiles](#)



Mixtures with Nonwhite Colors

[R03] Red Iron Oxide (iii) +
[B16] Iron Titanium Brown Spinel (i)

image over white			
image over black			
spectral datafile	R03 masstone	R03+B16 mixture 1:1	B16 masstone

[guide to reading spectral datafiles](#)

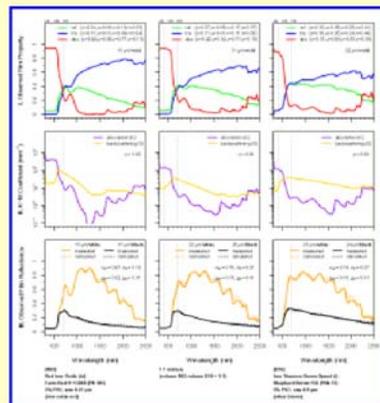


Figure 6. Description of an iron oxide red pigment in the LBNL pigment database



A product of the [Cool Colored Roofing Materials Project](#), a California Energy Commission sponsored collaboration between [Lawrence Berkeley National Laboratory](#), [Oak Ridge National Laboratory](#), and their 16 industrial partners: [3M Industrial Minerals](#), [Akzo-Nobel](#), [American RoofTile Coatings](#), [BASF Industrial Coatings](#), [CertainTeed](#), [Custom-Bilt Metals](#), [Elk Corporation](#), [Ferro Corporation](#), [GAF Materials Corporation](#), [Hanson Roof Tile](#), [ISP Minerals Incorporated](#), [MCA Tile](#), [MonierLifetile LLC](#), [Owens Corning](#), [Shepherd Color Company](#), and [Steelscape Incorporated](#).



Lawrence Berkeley National Laboratory Pigment Database

characterizing the solar spectral radiative properties
of conventional and cool pigmented coatings

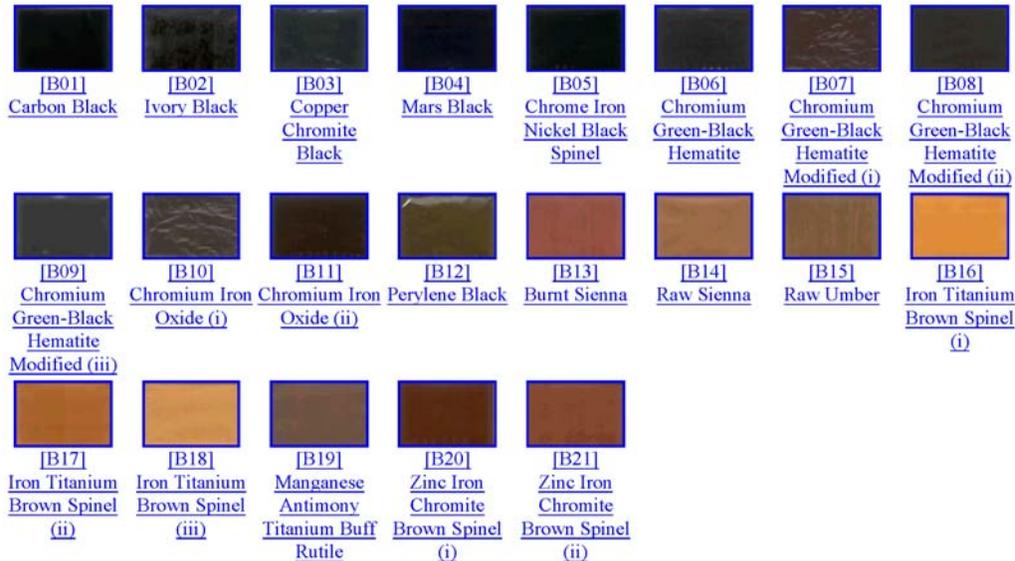
Ronnen Levinson, Paul Berdahl, and Hashem Akbari
Heat Island Group
Lawrence Berkeley National Laboratory
Berkeley, CA
<http://CoolColors.LBL.gov>

White



source: Lawrence Berkeley National Lab

Black/Brown



source: Lawrence Berkeley National Lab

Figure 7. First index page of the LBNL pigment database, including links to the detail pages of 4 white pigments and 21 black/brown pigments. The remaining index pages link to the detail pages of 62 more pigments.

Table 2. Pigment properties tabulated in the LBNL pigment database

instructions	how to view and interpret this datafile
comments	authorship and disclaimer
computation date	when K-M coefficients were calculated
color family	white, black/brown, blue/purple, green, red/orange, yellow, or pearlescent
pigment category	pigment chemistry or characteristic (e.g., cobalt titanate green or non-selective black)
code	used to identify this pigment in our pigment characterization paper (note: this value likely to be replaced)
paint name	assigned by the paint manufacturer
pigment name	assigned by the pigment manufacturer
internal description	LBNL's description of masstone, tint, or mixture
component names	LBNL's description of the paint's components
component ratios	parts by volume of each component
dry-film PVC	pigment volume concentration (volume pigment:volume paint) in dry film
delta.v (microns)	thickness of film sample over void background [exclusive of substrate, if present] (μm)
delta.w (microns)	thickness of film sample over opaque white background [exclusive of background and substrate, if present] (μm)
delta.b (microns)	thickness of film sample over opaque black background [exclusive of background and substrate, if present] (μm)
sigma	non-spectral forward scattering ratio
spectral ranges	definitions of solar, ultraviolet, visible, and near-infrared ranges used in spectral averaging
R.tilde.fv averages	spectrally averaged, irradiance-weighted values of the measured reflectance of the film over a void background
T.tilde.fv averages	spectrally averaged, irradiance-weighted values of the measured transmittance of the film over a void background
A.tilde.fv averages	spectrally averaged, irradiance-weighted values of the measured absorptance of the film over a void background
R.tilde.fw averages	spectrally averaged, irradiance-weighted values of the measured reflectance of the film over an opaque white background
R.tilde.fb averages	spectrally averaged, irradiance-weighted values of the measured reflectance of the film over an opaque black background
R.tilde.ow averages	spectrally averaged, irradiance-weighted values values of the measured reflectance of the opaque white background
lambda (nm)	wavelengths at which spectral values are presented
insolation ($\text{W}/\text{m}^2/\text{nm}$)	air-mass 1.5 hemispherical solar spectral irradiance ($\text{W m}^{-2} \text{nm}^{-1}$)
R.tilde.fv	measured spectral reflectance of the film over a void background
T.tilde.fv	measured spectral transmittance of the film over a void background
A.tilde.fv	measured spectral absorptance of the film over a void background
R.tilde.fw	measured spectral reflectance of the film over an opaque white background
R.tilde.fb	measured spectral reflectance of the film over an opaque black background
K (1/mm)	Kubelka-Munk (K-M) spectral absorption coefficient (mm^{-1})
S (1/mm)	K-M spectral backscattering coefficient (mm^{-1})
R.inf	continuous refractive index (CRI) spectral reflectance of an opaquely thick film
R.tilde.inf	observed spectral reflectance of an opaquely thick film
R.tilde.fw.calc	observed spectral reflectance of the film over an opaque white background, as computed from the K-M coefficients
R.tilde.fb.calc	observed spectral reflectance of the film over an opaque black background, as computed from the K-M coefficients
T.v	internal transmittance of the film
q.i.at.zero	diffuse fraction q of the downflux i exiting the bottom of the film ($z = 0$)
q.j.at.delta	diffuse fraction q of the upflux j exiting the top of the film ($z = \delta$)
omega.i.at.zero	interface reflectance ω to the downflux i exiting the bottom of the film ($z = 0$)
omega.j.at.delta	interface reflectance ω to the upflux j exiting the top of the film ($z = \delta$)

2.2. Task 2.5: Development of Prototype Cool-Colored Roofing Materials

The Cool Team estimates that roofing shingles, tiles, and metal panels comprise more than 80% (by roof area) of the residential roofing market in the western United States. In this project, the Cool Team collaborated with manufacturers of many roofing materials to evaluate the best ways to increase the solar reflectance of these products. The results of this research have been utilized by the manufacturers to produce cool roofing materials. To date and as the direct result of this collaborative effort, manufacturers of roofing materials have introduced cool shingles, cool concrete tile coatings, and cool concrete tiles; and significantly expanded the production of cool clay tiles and cool metal roofs.

2.2.1. Task 2.5.1: Review of roofing material manufacturing methods

The objective of this subtask was to compile information on roofing material manufacturing methods. The Cool Team contacted several representative manufacturers of various roofing materials to obtain information on the processes used to color their products. The team also reviewed literature on the fabrication and coloration of roofing materials.

This analysis suggested that cool-colored roofing materials can be manufactured using the existing equipment in production and manufacturing plants. The three principle ways to improve the solar reflectance of roofing materials include using raw materials with high solar reflectance; using cool pigments in the coating; and applying a two-layered coloring technique using pigmented materials with high solar reflectance as an under-layer. Although all these options are in principle easy to implement, they may require changes to current production techniques that could increase the cost and reduce the market competitiveness of the finished products.

The results of this study were published as a two-part article in *Western Roofing Insulation and Siding* magazine. A copy of the final report for this study is enclosed in Attachment 4.

2.2.2. Task 2.5.2: Design innovative methods for applying cool coatings to roofing materials

In addition to using NIR reflective pigments in the manufacture of cool roofing materials, applying novel engineering techniques can provide a cost-effective way to further enhance the solar reflectance of colored roofing materials. Cool-colored pigmented coatings are partly transparent to NIR light; thus, any NIR light not reflected by the cool pigmented coating is transmitted to its substrate, where it can be absorbed. A reflective basecoat can be used to increase the system's NIR and solar reflectance. This method is referred as a two-layer, or bilayer, technique.

The project team has detailed the innovative engineering methods in an article in press in the academic journal *Solar Energy Materials & Solar Cells*. A prepress draft of this article is included in Attachment 5.

Figure 8 demonstrates the application of the two-layered technique to manufacture cool-colored materials. A thin layer of dioxazine purple (14–27 μm) is applied on four substrates: (a) aluminum foil ($\sim 25 \mu\text{m}$), (b) opaque white paint ($\sim 1000 \mu\text{m}$), (c) non-opaque white paint ($\sim 25 \mu\text{m}$), and (d) opaque black paint ($\sim 25 \mu\text{m}$). As can be seen (and confirmed by the visible reflectance spectrum), the color of the material is black. However, the solar reflectance of the

sample exceeds 0.40 when applied to an opaque white or aluminum foil substrate, while its solar reflectance over a black substrate is only 0.05.

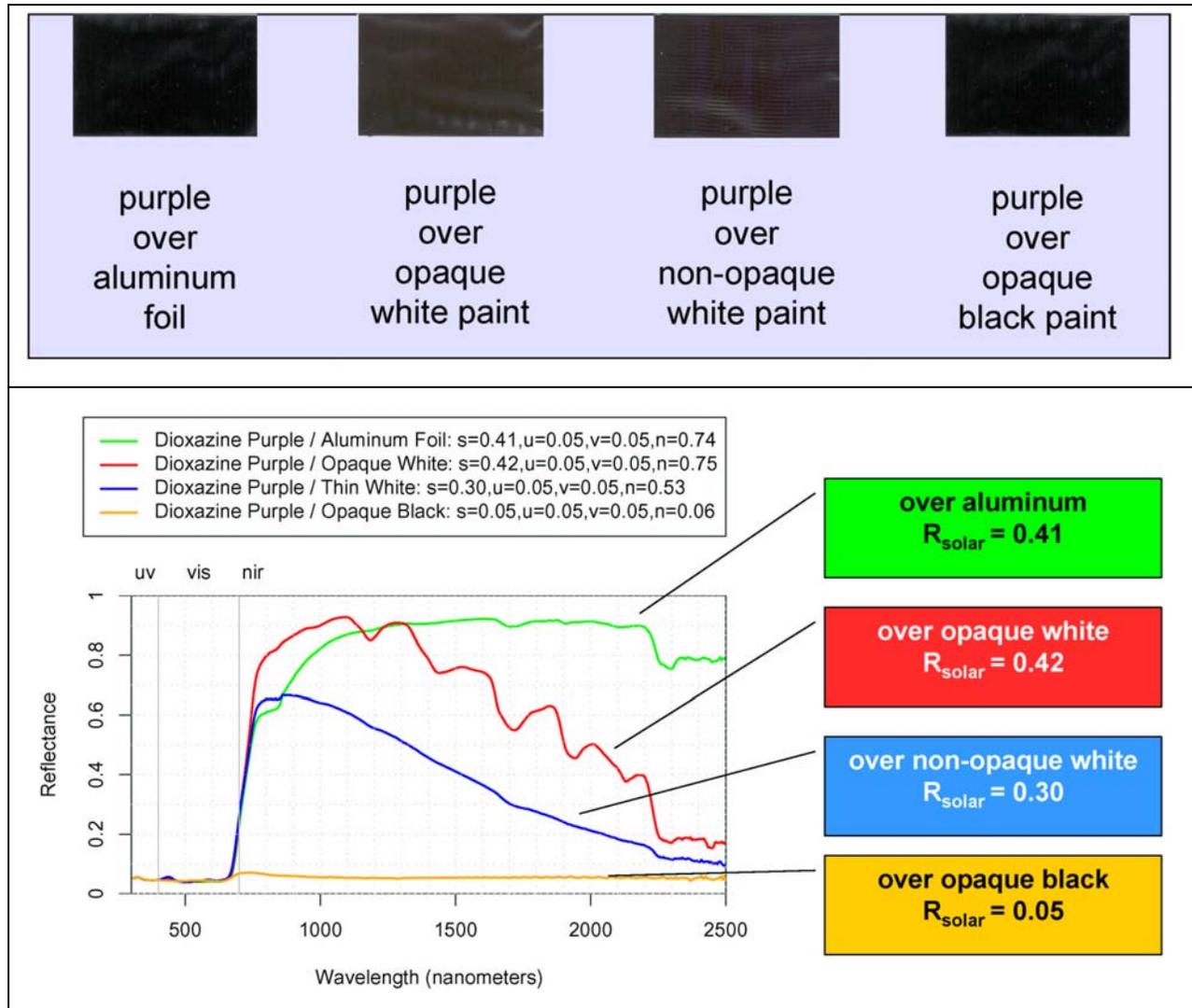


Figure 8. Application of the two-layer technique to manufacture cool-colored materials

2.2.2.1. Shingles

The solar reflectance of a new shingle is, by design, dominated by the solar reflectance of its granules, which cover over 97% of its surface. Until recently, manufacturers produced granules with high solar reflectance by using a coating pigmented with titanium dioxide (TiO_2) rutile white. Because a thin TiO_2 -pigmented coating is reflective but not opaque in the NIR, multiple layers are needed to obtain high solar reflectance. This technique has been used to produce “super-white” (meaning truly white, rather than gray) granulated shingles with solar reflectances exceeding 0.5 (see Figure 9).

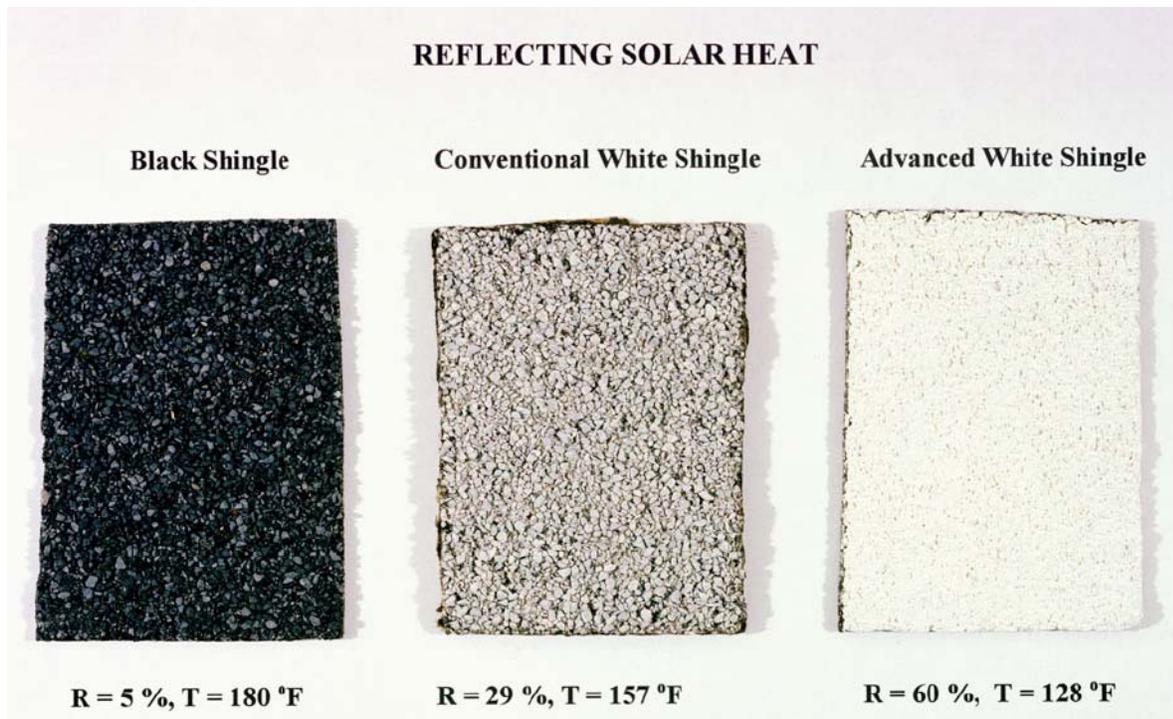
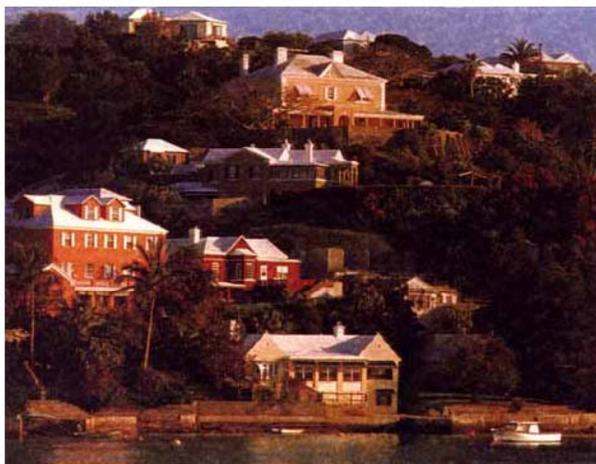
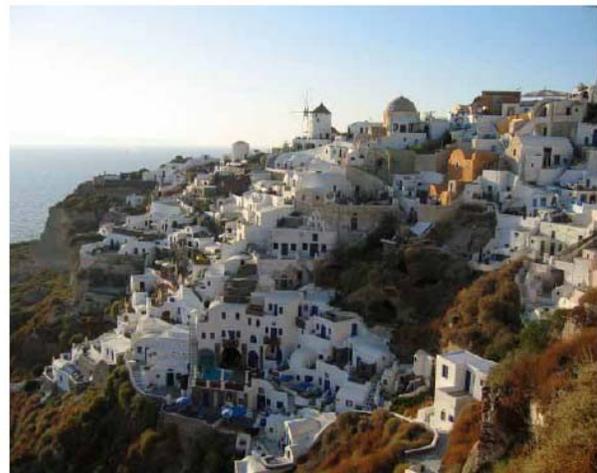


Figure 9. Development of “super-white” shingles

Although white roofing materials are popular in some areas, such as Greece and Bermuda (see Figure 10), many consumers prefer aesthetically pleasing nonwhite roofs. Manufacturers have tried to produce colored granules with high solar reflectance by using nonwhite pigments with high NIR reflectance. To increase the solar reflectance of colored granules with cool pigments, multiple color layers, a reflective undercoating, and/or reflective aggregate should be used. Obviously, each additional coating increases the cost of production.



Bermuda



Santorini (Greece)

Figure 10. White roofs and walls are used in Bermuda and Santorini, Greece

In close collaboration with partners at ISP Minerals, 3M Company, Elk, GAF, and CertainTeed, the labs have developed more than 100 single and multiple-color shingle prototypes. Figure 11 illustrates the iterative development of a cool black shingle prototype by industrial partner ISP Minerals. A conventional black roof shingle has a solar reflectance of about 0.04. Replacing the granule's standard black pigment with a cool NIR-scattering black pigment (prototype 1) increases the solar reflectance of the shingle to 0.12. Incorporating a thin white sublayer (prototype 2) raises the shingle's solar reflectance to 0.16; using a thicker white sublayer (prototype 3) increases the shingle's solar reflectance to 0.18. The figure also shows an approximate performance limit (solar reflectance 0.25) obtained by applying 25-micron NIR-reflective black topcoat over an opaque white background.

Several cool shingles have been developed within the last year. Figure 12 shows examples of prototype cool shingles and compares the solar reflectance of each with a conventionally pigmented counterpart of the same color.

In parallel to the above efforts, two partners (3M and Elk) have developed cool-colored shingles for three popular colored products. On March 2005, Elk announced the availability of the three cool-colored shingles. The Cool Team is currently testing the performance of these cool shingles in two demonstration houses in Redding, CA. Figure 13 shows two houses with cool-colored roofing shingles from Elk.

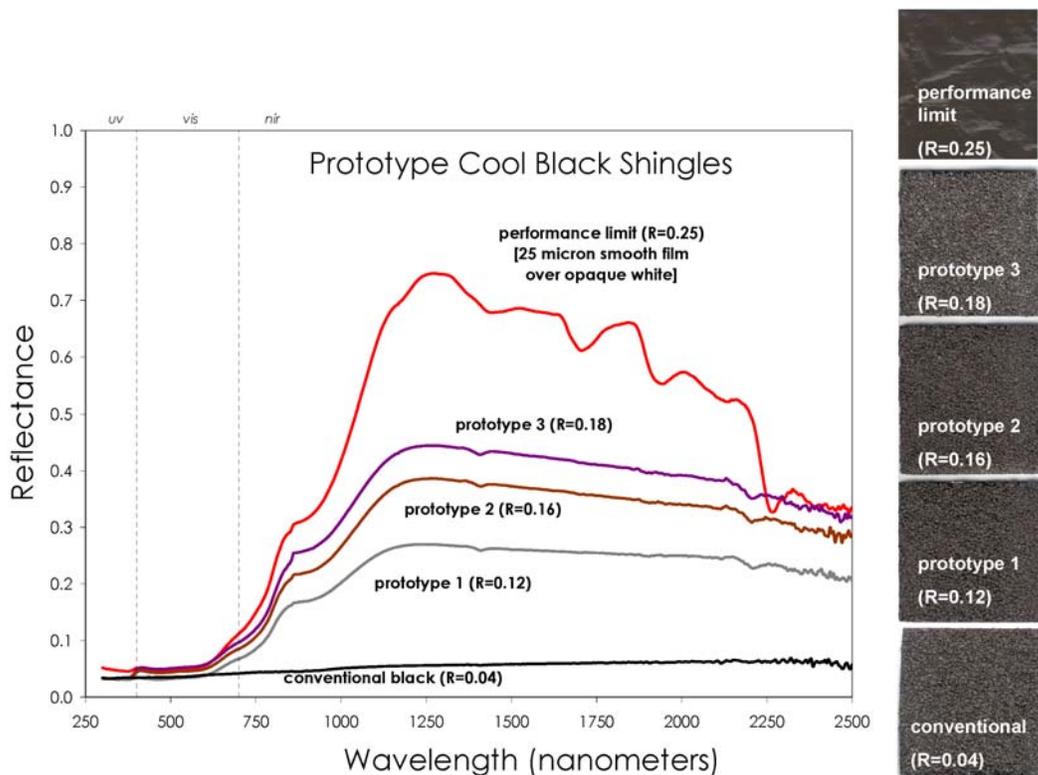


Figure 11. Development of a cool black shingle by industrial partner ISP Minerals. Shown are the solar spectral reflectances, images, and solar reflectances (R) of a conventional black shingle, three prototype cool black shingles, and a smooth cool black film over an opaque white background.

Standard Shingles



R=0.23



R=0.27

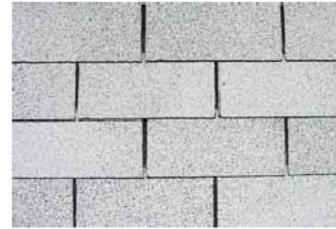


R=0.28

Cool Shingles



R=0.28



R=0.36



R=0.37

Figure 12. Examples of standard and prototype cool shingles; R is solar reflectance



Figure 13. Application of cool-colored roofing shingles on two houses advertised by Elk Corp.

2.2.2.2. Tiles and tile coatings

Clay and concrete tiles are used in many areas around the world. In the United States, clay and concrete tiles are more popular in the hot climate regions. Three methods improve the solar reflectance of colored tiles: (1) use clay or concrete with low concentrations of light-absorbing impurities, such as iron oxides and elemental carbon; (2) color the tile with cool pigments contained in a surface coating or mixed integrally; and/or (3) include an NIR-reflective (e.g., white) basecoat beneath an NIR-transmitting colored topcoat. Although all these options are in principle easy to implement, they may require changes to current production techniques that can increase the cost of the finished products. Colorants can be included throughout the body of the tile, or used in a surface coating. Both methods need to be addressed.

Consortium member American Rooftile Coatings has developed a palette of cool nonwhite coatings for concrete tiles. Each of the COOL TILE IR COATINGS™ shown in the top row of Figure 14 has a solar reflectance better than 0.40. The solar reflectance of each cool coating exceeds that of a color-matched, conventionally pigmented coating by 0.15 (terracotta) to 0.37 (black).

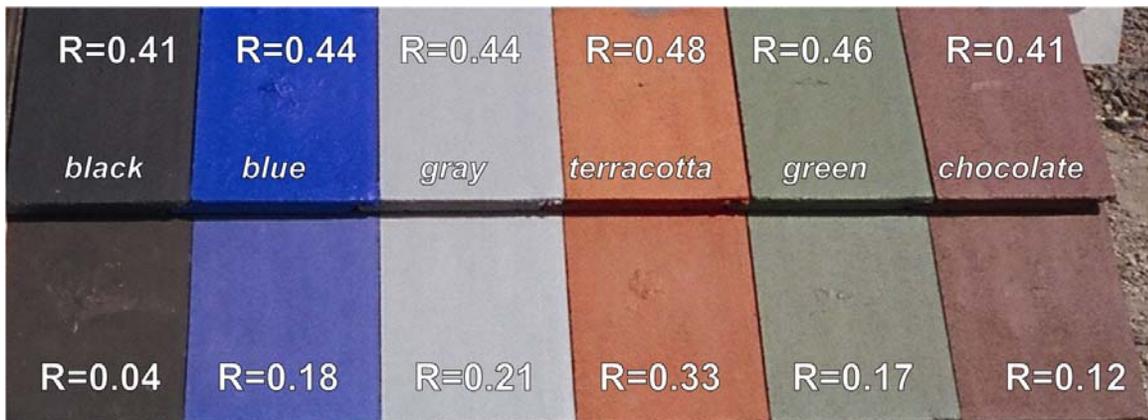


Figure14. Palette of color-matched cool (top row) and conventional (bottom row) roof tile coatings developed by industrial partner American Rooftile Coatings. Shown on each coated tile is its solar reflectance R.

MCA Clay Tile is producing several cool nonwhite clay tile products (Table 3), and MonierLifetile has developed several cool nonwhite concrete tile prototypes. The Cool Team is currently testing a cool-colored concrete tile on a demonstration house in Sacramento and a cool-colored clay tile on the attic test assembly at ORNL.

Table 3. Sample cool-colored clay tiles and their solar reflectances (Source: <http://www.MCA-Tile.com>)

Model	Color	Initial solar reflectance	Solar reflectance after 3 years
Weathered Green Blend		0.43	0.49
Natural Red		0.43	0.38
Brick Red		0.42	0.40
White Buff		0.68	0.56
Tobacco		0.43	0.41
Peach Buff		0.61	0.48
Regency Blue		0.38	0.34
Light Cactus Green		0.51	0.52

2.2.2.3. Metal Panels

Metal roofing materials are installed on a small (but growing) fraction of the U.S. residential roofs. Historically metal roofs have had only about 3% of the residential market. However, the architectural appeal, flexibility, and durability, due in part to the cool-colored pigments, has steadily increased the sales of painted metal roofing, and as of 2002 its sales volume has increased to 8.9% of the residential market, making it the fastest growing residential roofing product (F.W. Dodge 2005). Metal roofs are available in many colors and can simulate the shape and form of many other roofing materials (see Figure 15). Applying cool-colored pigments in metal roofing materials may require fewer production processes changes (and in many cases no changes) than in any other roofing material. In fact, cool pigments have been incorporated into paint systems used for metal roofing since 2002. For example, the BASF Industrial Coatings line of cool coatings for metal includes over 20 cool-colored products (Figure 16).

As in the cases of tile and asphalt shingle, cool pigments can be applied to metal via a single or two-layered technique. If the metal substrate is highly reflective, a single-layered technique may suffice. The coatings for metal shingles are thin, durable polymer materials. These thin layers use materials efficiently, but limit the maximum amount of pigment present. However, the metal substrate can provide some NIR reflectance if the coating is transparent in the NIR. Several manufacturers have developed cool-colored metal roof products.

Cool nonwhite coatings have been enthusiastically adopted by premium coil coaters and metal roofing manufacturers. Metal panels and clay tiles were the first types of roofing to be produced in cool-colors. BASF Industrial Coatings (Southfield, MI) has launched a line of cool-colored siliconized-polyester coatings that is quickly replacing their conventional siliconized-polyester coatings. Steelscape Inc. (Kalama, WA) has recently introduced a cool polyvinylidene fluoride coating for the metal building industry. Custom-Bilt Metals (Chino, CA) has switched more than 250 of its metal roofing products to cool-colors. The Cool Team is currently testing a cool-colored metal roof on a demonstration house in Sacramento.



(a)



(b)



(c)



(d)



(e)



(f)



(g)



(h)



(i)



(j)



(k)



(l)

Figure 15. Simulated roofing products made from metal: (a) Advanta Shingles; (b) Bermuda Shakes; (c) Castle Top; (d) Dutch Seam Panel; (e) Granutile; (f) Perma Shakes; (g) Scan Roof Tile; (h) Snap Seam Tile; (i) Techo Tile; (j) Verona Tile; (k) Oxford Shingles; and (l) Timbercreek Shakes. Products a through j are manufactured by ATAS International, Inc., while products k and l are manufactured by Classic Products, Inc. (Photos courtesy of ATAS International and Classic Products).

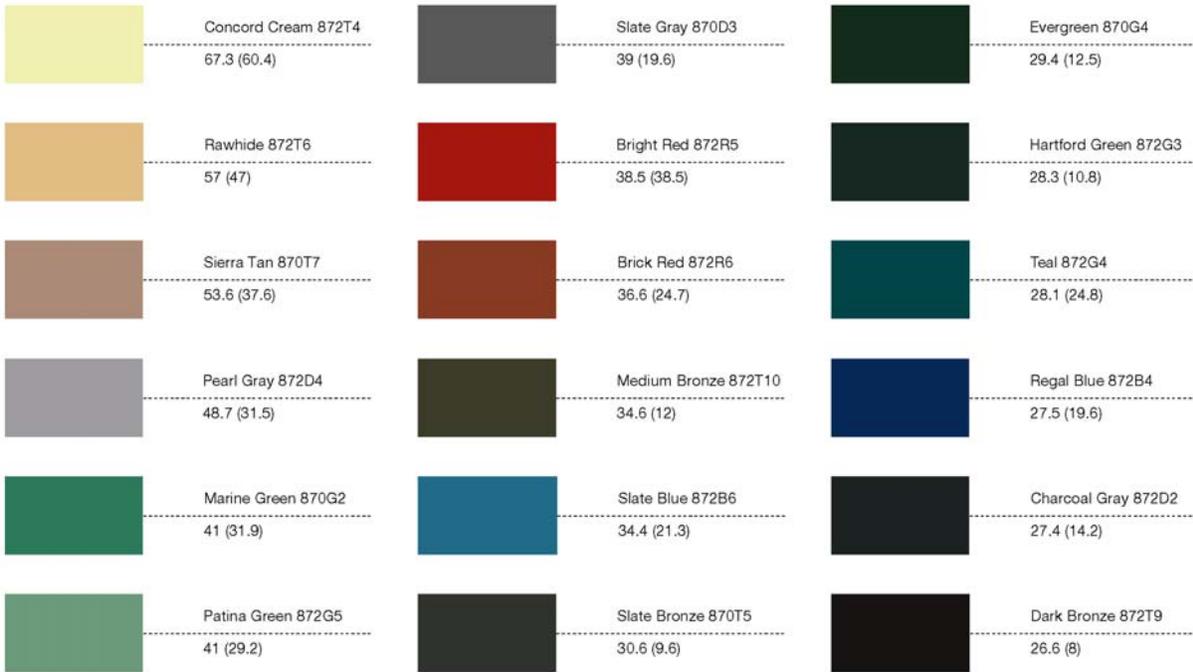


Figure 16. Some of the cool-colored coatings for metal roofing products available from BASF Industrial Coatings. To the right of each color swatch is shown the solar reflectance of the cool formulation, followed (in parentheses) by the solar reflectance of a color-matched standard formulation. (Source: <http://www.basf.com/pdfs/ULTRA-Cool.pdf>).

2.2.3. Task 2.5.3: Accelerated weathering testing (durability of cool nonwhite coatings)

Roofing materials fail mainly because of three processes:

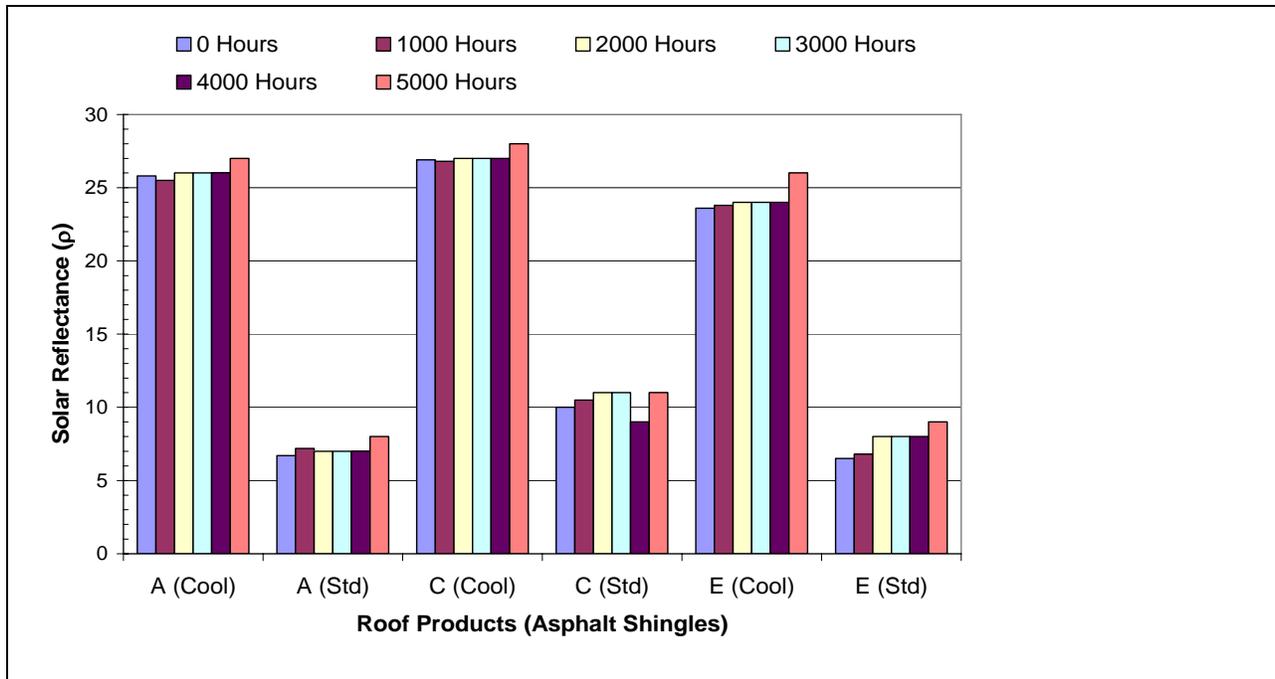
- Gradual changes to physical and chemical composition induced by the absorption of UV light
- Aging and weathering (e.g., loss of plasticizers in polymers and low-molecular-weight components in asphalt), which may accelerate as temperature increases
- Diurnal thermal cycling, which stresses the material by expansion and contraction

The project goal was to clarify the material degradation effects due to UV absorption and to heating. Durability performance must be demonstrated to persuade homebuilders to adopt cool-colored tile and asphalt shingle roof products.

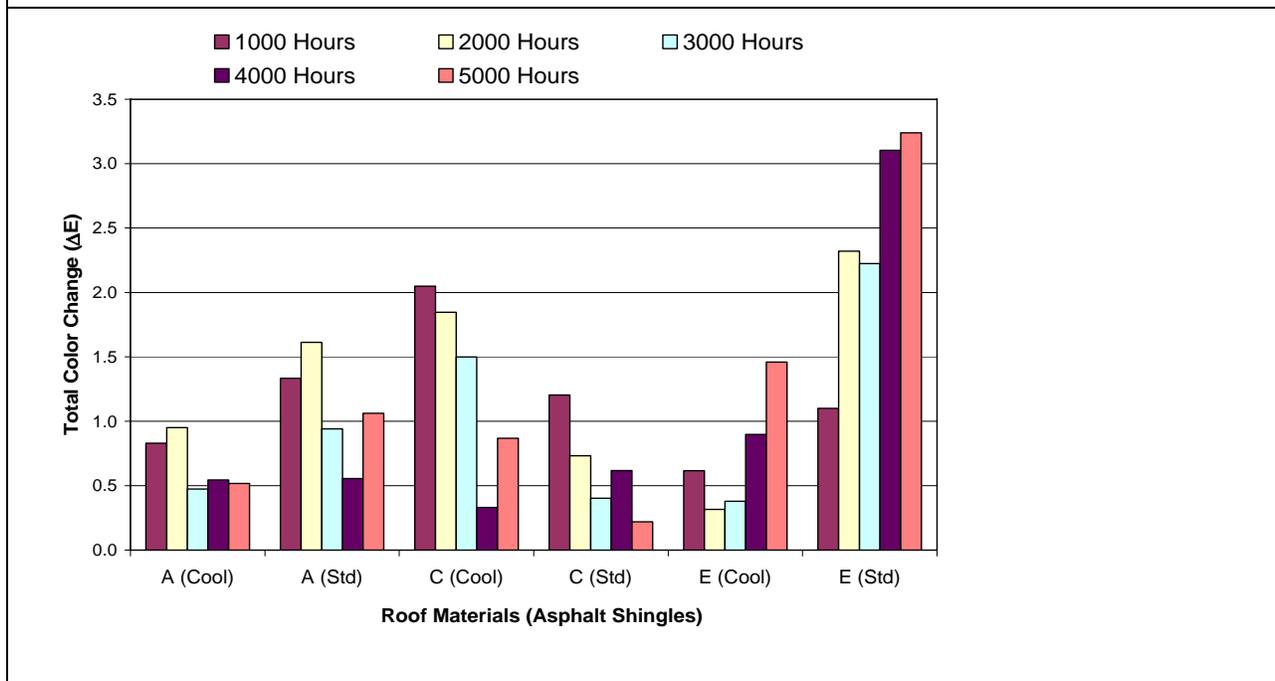
Shepherd Color Company and 3M provided the Cool Team access to their weatherometers for evaluating the effect of fluorescent (UV) light exposure and xenon-arc exposure on the solar reflectance, fading and gloss retention of clay, concrete, painted metal and asphalt shingle roof products. Clay tiles were provided by MCA Clay Tile. Painted PVDF metal samples with and without cool pigmented colors were provided by BASF and Steelscape. Shingles were provided by U.S. companies that wish their products' identities to remain confidential; however, the data for shingles with and without cool pigments are provided in coded format. Details of the accelerated and natural sunlight test results are provided in the Task 2.5.3 report, Attachment 6.

Results of accelerated fluorescent (UV) light exposures show that pigment stability and discoloration resistance of the painted metals, concrete tiles and clay tiles with cool pigments are as good as those of commercially available conventionally pigmented products. Independent UV testing by BASF produced similar findings. They proved that cool pigmented colors retained their gloss just as well as standard production pigments. The fade resistance of painted metal cool-colored blue and yellow masstones is much improved over the respective standard colors. Blue, especially a blue tint, is well known to fade; however, the cool-colored masstone blue shows excellent fade resistance.

Results for asphalt shingles were just as promising and showed no deleterious effects on solar reflectance or total color change after being subjected to 5000 hours of fluorescent or xenon-arc exposures (see Figure 17). Total color change (ΔE) less than 1 is almost indistinguishable and is considered quite good by the industry. Cool-pigmented shingles coded A and E had a total color change (ΔE) less than 1.5 after 5000 hours of UV exposure. In contrast, their conventionally pigmented counterparts had ΔE 's that were 50% higher for Code A and 100% higher for Code E. The ΔE for the Code C shingle with cool-pigments exceeded 2.0 after 1000 hours then dropped below 1.0 after 5000 hours. Reasons for the behavior are unknown; however, overall the data clearly shows that the cool-pigmented shingles when subjected to simulated direct solar UV radiation from a UVB-340 lamp perform just as well as standard products accepted on the open market. The asphalt shingles with cool pigments do not lose solar reflectance, and they remain fade resistant.



a) Solar reflectance of cool-pigmented and standard production shingles.



b) Total color change ΔE for cool-pigmented and standard production shingles.

Figure 17. (a) Solar reflectance (b) and total color change of asphalt shingles exposed to accelerated direct fluorescent UV radiation simulating solar's short-wave irradiance (data courtesy of Shepherd Color Company)

2.3. Task 2.6: Field-Testing and Product Useful Life Testing

2.3.1. Task 2.6.1: Building energy-use measurements at California demonstration sites

The Cool Team set up a residential demonstration site in Fair Oaks, California (near Sacramento), consisting of two pairs of single-family, detached houses roofed with painted metal shakes and concrete tile. The team also set up two houses in Redding, California to demonstrate asphalt shingles. The demonstration pairs each include one building roofed with a cool-pigmented product and a second building roofed with a conventionally pigmented product of nearly the same color. The paired homes are adjacent, and share the same floor plan, roof orientation, and level of blown ceiling insulation (3.4 m²K/W, a.k.a. R-19). All have air-handlers and air-delivery duct work in the attic. Demonstration homes in Fair Oaks have soffit and gable vents, while the homes in Redding are equipped with soffit and ridge vents. The Redding demonstration homes each use two 3½-ton air conditioners for comfort cooling. The homes will be monitored through at least summer 2006.

A data acquisition system continuously logs temperatures at the roof surface, on the underside of the roof deck, in the mid-attic air, at the top of the insulation, on the interior ceiling's sheet-rock surface, and inside the building. Relative humidity in the attic air and the residence are also measured. Heat flux transducers are embedded in the sloped roofs and the attic floor to measure the roof heat flows and the ceiling heat leakage. The Cool Team has instrumented the building to measure the total house and air-conditioning power demands. A fully instrumented meteorological weather station is set up to collect the ambient dry bulb temperature, relative humidity, solar irradiance, and wind speed and direction.

One of the Fair Oaks homes roofed with low-profile concrete tile was colored with a conventional chocolate brown coating (solar reflectance 0.10), while the other was colored with a matching cool chocolate brown with solar reflectance 0.41. The attic air temperature beneath the cool brown tile roof has been measured to be 3 to 5 K (5.4 to 9°F) cooler than that below the conventional brown tile roof during a typical hot summer afternoon. The results for the pair of Fair Oaks homes roofed with painted metal shakes are even more promising. There the attic air temperature beneath the cool brown metal shake roof (solar reflectance 0.31) was measured to be 5 to 7 K (9 to 12.6°F) cooler than that below the conventional brown metal shake roof (solar reflectance 0.08). Attic air temperature below the cool shingle (solar reflectance 0.26) was about 3 K (5.4°F) cooler than the temperature below the conventional pigmented shingle roof (solar reflectance 0.09).

The application of cool-colored coatings reduced the surface temperature of the cool-pigmented roofs, which in turn reduced the average daytime heat flows through the roof deck by 20% for cool pigmented tile, by 32% for cool pigmented painted metal shakes, and by 30% for cool pigmented asphalt shingle roofs as compared to each roof type's conventional counterpart.

The thermal data demonstrated drops in the heat penetrating into the conditioned space, which yields cooling electrical energy savings. Cool pigmented tile and cool pigmented metal shakes reduced the daytime cooling electrical energy by about 2 kWh per day.

As the temperature difference from the outdoor air to the home's interior air (return air) increases, the cooling savings also increase for the pair of shingle-roofed demonstration homes

(Figure 18). At an outdoor air-to-indoor air temperature difference of 10 K (about 32°C outdoor air temperature) the home with cool pigmented asphalt shingles uses about 6.3 kWh per day less electricity than does the other home with conventional shingles. This represents savings of about 0.90 kWh per day per ton of cooling capacity.

It is interesting to note that the hotter the outdoor air temperature, the greater the energy savings for the air-conditioners operating in all demonstration homes with cool pigmented roofs. This small trend could be important in terms of Time Dependent Valuation of energy that places a premium cost on energy consumed during the hottest portion of the day.

The report for Task 2.6.1 documenting the thermal performance and electrical energy savings is provided in Attachment 7.

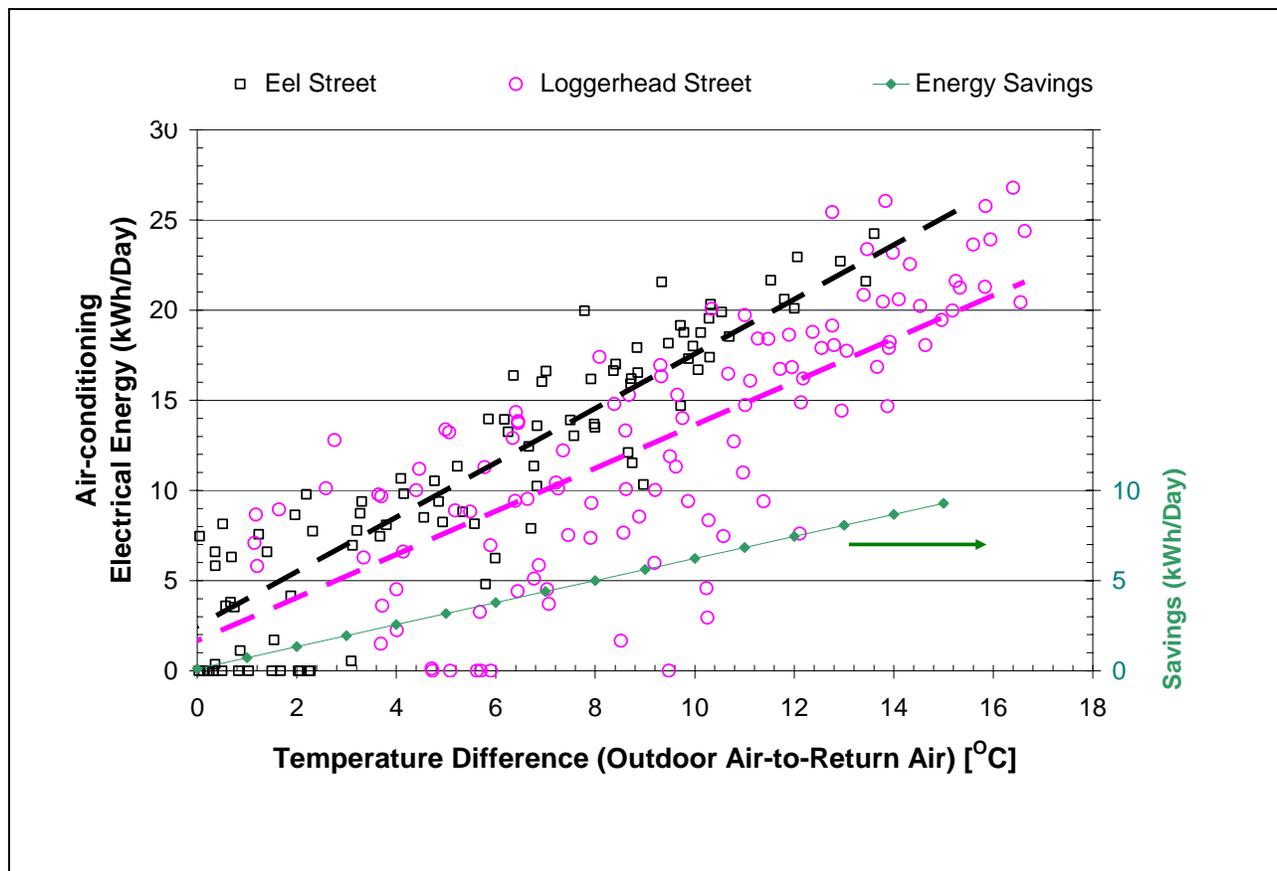


Figure 18. Daily air-conditioning energy consumption and savings, measured during the daylight hours from June through September 2005, for demonstrations with asphalt shingle roofs with and without cool pigments. The Redding demonstration homes each use two 3½ ton air-conditioners for comfort

2.3.2. Task 2.6.2: Materials testing at weathering farms in California

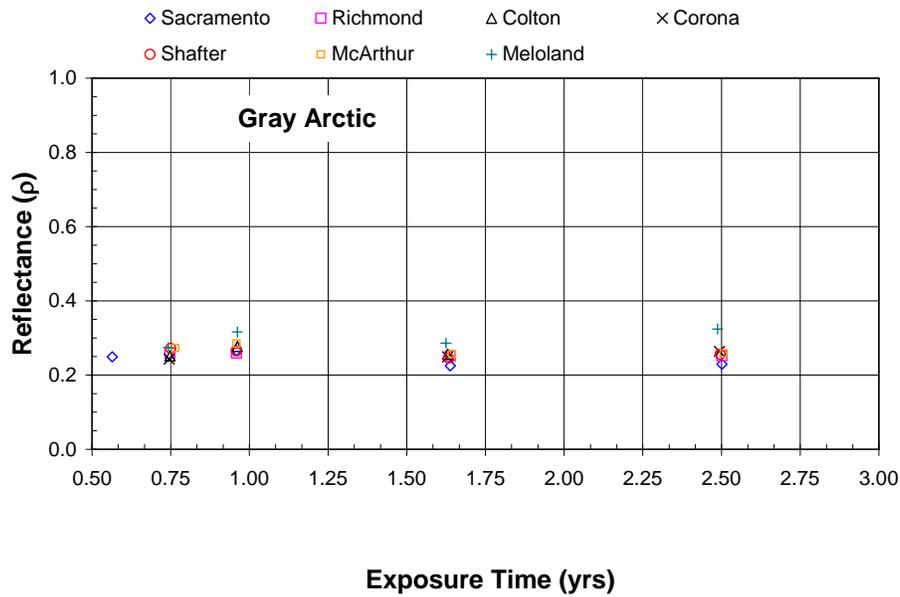
In addition to conducting the laboratory accelerated testing reported in Task 2.5.3, the Cool Team naturally weathered various types of conventional- and cool-pigmented roofing products at seven California sites. (Note that the concrete coupons were placed in the field about 6 months later than were the painted metal and clay coupons.) The final report is contained in Attachment 8 and has been submitted for journal review and publication to document the effect of soiling on the solar reflectance of the conventional- and cool-pigmented roof products.

Airborne particulate matter that settles on a roof can either reflect or absorb incoming solar radiation, depending on the chemistry and size of the particles. These light scattering and absorption processes occur within a few microns of the surface and can affect the solar reflectance of the roof. The long-term change in reflectance appears driven by the ability of the particulate matter to cling to the roof and resist being washed off by wind and or rain.

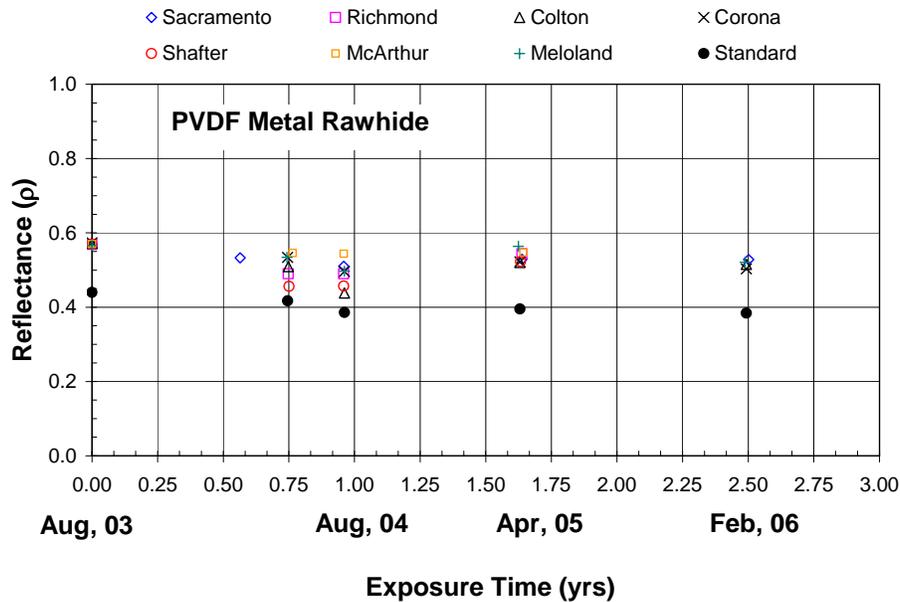
Contaminants collected from samples of roof products exposed at the seven California weathering sites were analyzed to characterize the chemical and/or biological nature of the soil layer on each roof sample and to identify contaminants that degrade or enhance solar reflectance.

The chemical composition of particles deposited on the roof samples was very similar across the state of California; there was no clear distinction from one region to another. Organic and elemental carbon (soot) was detected. However, the elemental carbon was present in concentrations too small to contribute significantly to the loss of solar reflectance. Dust particles (characterized by Ca and Fe) and organic carbon raised the reflectance of low-reflectance samples and lowered the reflectance of the high-reflectance samples.

During this 2½ year time-limited study, the initial solar reflectance for the concrete tile, clay and painted metal coupons dropped about 6% (Figure 19). The solar reflectance of the cool pigmented metal coupons always exceeded that of the standard pigmented coupons (Figure 19b). Climatic soiling did not cause the cool pigmented roof coupons to lose any more solar reflectance points than their standard pigmented counterparts. Figure 19b shows that the reflectance of the samples had decreased significantly by August 2004, toward the end of the dry California summer. By the following April, after winter rains, less soil is present and much of the reflectance has been restored. Increasing the roof slope from 9.5° (2 in 12) to 33.7° (8 in 12) appears to diminish the effect of climatic soiling. Precipitation and or wind sweeping occurring during the winter months helps restore most of the initial solar reflectance. The thermal emittance remained invariant with time and location and was therefore not affected by climatic soiling.



19a) Cool-color light-gray concrete coupons placed in field 6 months later than metal coupons in Figure 19b



19b) Painted PVDF metal coupons (off-white cool-color and standard off-white color)

Figure 19. Solar reflectance of light-gray concrete tile coupons (19a) and painted metal coupons (19b) exposed to climatic soiling at each of the seven CA weathering sites

2.3.3. Task 2.6.3: Steep-slope assembly testing at ORNL

Cool-color pigments and sub-tile venting of clay and concrete tile roofs – achieved by direct nailing or attaching tile roofs to a deck with batten or batten and counter-batten construction – significantly impact the heat flow crossing the roof deck of a steep-sloped roof. The Tile Roofing Institute (TRI) and its affiliate members are keenly interested in documenting the magnitude of the drop in heat flow to obtain solar reflectance credits with state and federal cool roof building efficiency standards. To examine this issue, the Cool Team at ORNL installed S-Mission clay and concrete tile roofs, a medium-profile concrete tile roof, and a flat slate tile roof on fully instrumented attic test assemblies. The team recorded temperature measures of the roof, deck, attic, and ceiling, heat flows, solar reflectance, thermal emittance, and the ambient weather for each of the tile roofs and an adjacent attic cavity covered with a conventional pigmented and direct-nailed asphalt shingle roof. ORNL measured the tile's underside temperature and the bulk air temperature and heat flows just underneath the tile for batten and counter-batten tile systems and compared the results to the conventional asphalt shingle.

The team's measurements showed that the combination of improved solar reflectance afforded by cool pigmented colors and sub-tile venting reduced the peak heat flow crossing the roof deck at noontime for the clay tile roof (solar reflectance 0.54) by 70% compared to the flow crossing the conventional shingle roof (solar reflectance of 0.09). The slate and medium-profile concrete roofs, having nearly the same surface properties as the conventional shingle, reduced the deck heat flow ~45% compared to that crossing the shingle roof because of sub-tile venting. Opening the ridge vent of the attics to allow both attic and sub-tile ventilation caused more heat to be exhausted out the ridge for both the S-Mission clay (solar reflectance 0.54) and the slate tile (solar reflectance 0.13) systems and therefore further improved the performance of the two tile roofs. The effect was more pronounced for the slate tile than for the S-Mission tile because the slate tile has less air leakage between tiles.

Sub-tile venting and use of cool pigments reduce the summertime heat penetrating into the conditioned space; however, in the winter the air gap adds an additional radiation heat transfer resistance. Subsequently, the tile's thermal mass and sub-tile venting have limited the wintertime heat loss to about the same loss observed for the direct nailed asphalt shingle in East Tennessee's climate (Figure 20). Sub-tile venting therefore can lessen the heating penalty associated with cool roof products. The improved summer performance coupled with the reduced heat losses during the winter as compared to a shingle roof show that offset-mounting roofs can provide the roof industry the opportunity to market cool pigmented roofs in climates that are predominated more by heating loads. Typically, the monetary breakeven point for cool roofs occurs where the ratio (cooling degree days/heating degree dates [CDD/HDD])⁶⁵ is about 0.4; however, sub-tile venting can move this climatic boundary of affordable energy cost savings farther north.

A report summarizing and analyzing the experimental data is enclosed in Attachment 9.

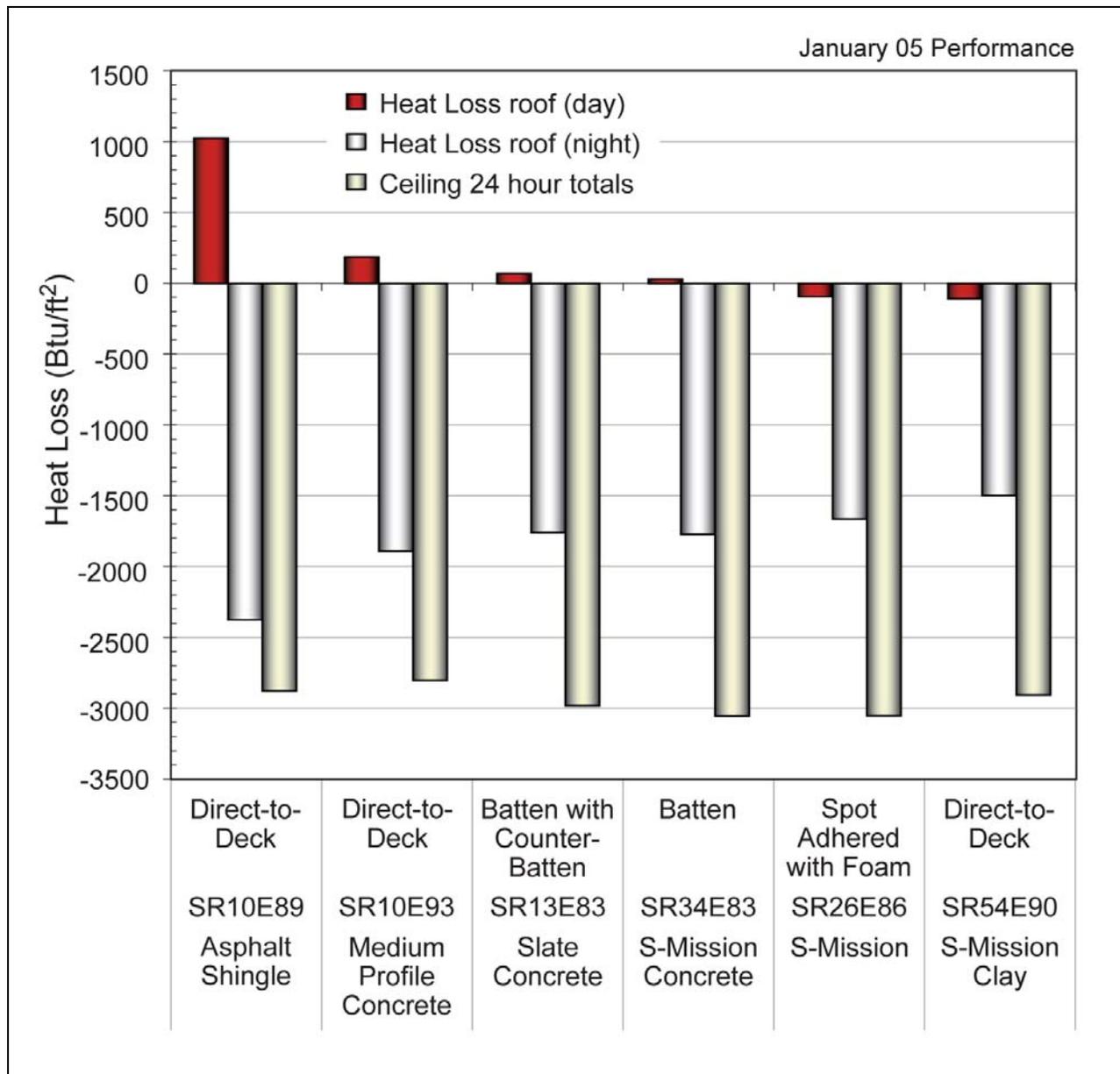


Figure 20. Integrated heat flow measured through the roof deck (heat loss to the sky during the day and during the night) and the attic floor (ceiling 24 hour total heat flow from conditioned space through ceiling into the attic) for all tile and shingle roofs field tested in East Tennessee during the month of January 2005. SR10E89 represents a solar reflectance of 0.10 and a thermal emittance of 0.89.

2.3.4. Task 2.6.4: Product useful life testing

In this task, the project team reviewed several aspects of the weathering of roofing materials. Degradation of materials initiated by ultraviolet radiation affects plastics used in roofing, as well as wood and asphalt. Elevated temperatures accelerate many deleterious chemical reactions and hasten diffusion of material components. Effects of moisture include decay of wood, acceleration of corrosion of metals, staining of clay, and freeze-thaw damage. Soiling of roofing materials causes objectionable stains and reduces the solar reflectance of reflective materials. (Soiling of non-reflective materials can also increase solar reflectance.) Soiling can be attributed to biological growth (e.g., cyanobacteria, fungi, algae), deposits of organic and mineral particles, and to the accumulation of fly ash, hydrocarbons, and soot from combustion. The Cool Team summarized the results of this work in a review article submitted to the journal *Construction and Building Materials*. A copy of the paper is enclosed in Attachment 10. Two specific examples illustrating weathering behavior are given below, taken from this paper.

Most of the ultraviolet-light-induced degradation mechanisms of polymeric roofing materials involve oxidation. That is, the absorption of an UV photon initiates material breakdown, but chemical combination with oxygen is also an essential step. Figure 21 shows how oxygen penetrates polypropylene during photo-oxidation, as evidenced by the carbonyl (C=O) group identified by spectroscopy. After 1200 hours of exposure, it's clear that oxygen has penetrated about 0.3 mm into this plastic. This oxygenated surface region becomes brittle and cracks (crazes). While this specific example utilizes polypropylene, similar behavior is seen in other organic building materials including asphalt, other plastics, and wood.

Ideally, roofing materials are engineered to be impervious to sunlight, moisture, and other elements of the weather. Thus, robust inorganic materials such as metal oxide pigments, minerals (such as the crushed stone for roofing granules), concrete, and clay are employed. Among organic materials, a few fluorinated polymers stand out as durable, and others, such as asphalt, can be used when an overlying ultraviolet-absorbing material provides UV protection. Wood is an example of an organic material that can even be used without a UV-absorbing overlay. Wood does photo-oxidize, changes color, crazes, and is gradually eroded as it weathers. However, the rate of erosion of durable wood species, when kept dry, is very slow, so the lifetime is measured in decades. Figure 22 documents how the spectral reflectance of western red cedar roofing shingles changes as it ages. The color gradually becomes less red. It is interesting that the near-infrared reflectance of wood is larger than the visual (400 to 700 nm) reflectance; wood is naturally cool.

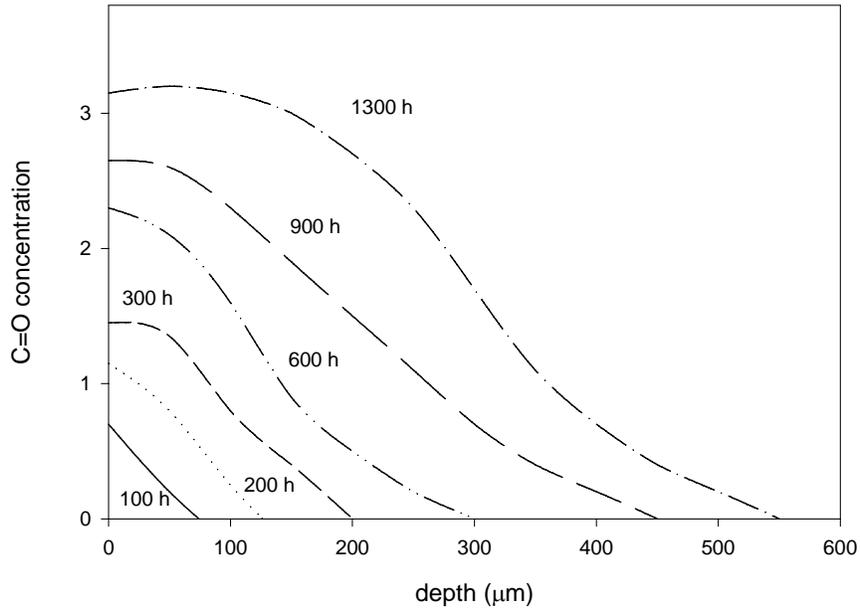


Figure 21. Oxidation (carbonyl) profiles measured during accelerated UV aging of polypropylene

Spectral Reflectance of Western Red Cedar Roofing Shingles
(fire retardant chemically pressure treated)

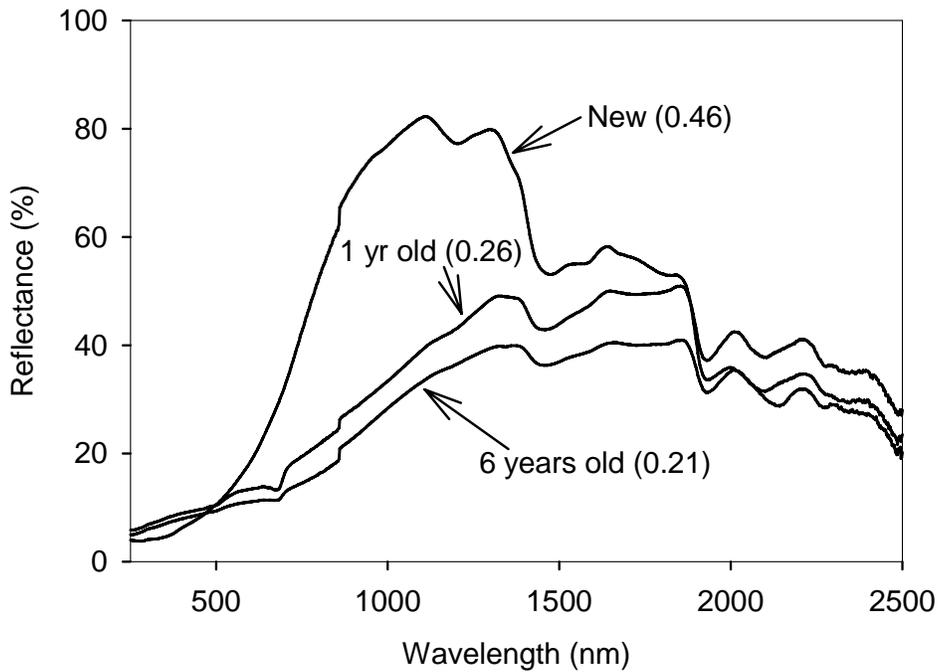


Figure 22. Spectral reflectance of new and weathered western red cedar roofing shingles. The solar reflectance is 0.46 when new and declines to 0.21 after 6 years exposure.

2.4. Task 2.7: Technology Transfer and Market Plan

LBNL, ORNL, color pigment manufacturers and granule manufacturers worked and supported the roofing manufacturers to penetrate the roofing market with new more reflective cool-colored roofing materials. The project team worked with roofing component manufacturers and color pigment manufacturers to introduce prototype cool-colored asphalt shingles, clay and concrete tiles, metal roofing, and wood shake roof products.

2.4.1. Task 2.7.1: Technology transfer

The objective of this task was to support the roofing industry by promoting and accelerating the market penetration of cool-color pigmented roof products. Both laboratories, in conjunction with their respective industry partners, presented research results at appropriate trade shows, and published their results in each industry's appropriate trade magazine. Table 4 below lists articles presented in various trade magazines, conferences, and journals; a copy of each publication can be found in Attachment 11 (or in an earlier attachment).

Table 4: Cool Team articles published or presented in industry magazines, conferences, and journals

Akbari, H. and A. Desjarlais. 2005. Cooling down the house: Residential roofing products soon will boast "cool" surfaces. <i>Professional Roofing</i> , March.
Akbari, H., R. Levinson, and P. Berdahl. 2005. A review of methods for the manufacture of residential roofing materials, Part I." <i>Western Roofing Insulation and Siding</i> . Jan/Feb, p. 54.
Akbari, H., R. Levinson, and P. Berdahl. 2005. A review of methods for the manufacture of residential roofing materials, Part II. <i>Western Roofing Insulation and Siding</i> . Mar/Apr, p. 52.
Akbari, H., R. Levinson, W. Miller, and P. Berdahl. 2005. Cool-colored roofs to save energy and improve air quality. <i>Proceedings of the 1st International Passive and Low Energy Cooling for the Built Environment, Palenc 2005, Vol 1</i> . pp. 89. 19-21 May, Santorini, Greece.
Akbari, H. 2005. Potentials of urban heat island mitigation. <i>Proceedings of the 1st International Passive and Low Energy Cooling for the Built Environment, Palenc 2005, Vol 1</i> . pp. 11. 19-21 May, Santorini, Greece.
Akbari, H., A.A. Berhe, R. Levinson, S. Graveline, K. Foley, A. Delgado, and R. Paroli. 2005. Aging and weathering of cool roofing membranes. <i>Proceedings of Cool Roofing ... Cutting through the Glare</i> . Atlanta GA, May 12-13, RCI Foundation.
Akbari, H., P. Berdahl, R. Levinson, S. Wiel, A. Desjarlais, W. Miller, N. Jenkins, A. Rosenfeld, and C. Scruton. 2004. Cool-colored materials for roofs. <i>Proceedings of the 2004 ACEEE Summer Study on Energy Efficiency in Buildings, Vol. 1</i> . p. 1. Pacific Grove, CA.
Akbari, H., P. Berdahl, R. Levinson, S. Wiel, A. Desjarlais, W. Miller, N. Jenkins, A. Rosenfeld, and C. Scruton. 2004. Cool-colors: a roofing study is developing cool products for residential roofs, <i>Eco-Structure</i> . Sep/Oct, pp. 50-56.
Levinson, R., P. Berdahl, A.A. Berhe, and H. Akbari. 2005. Effects of soiling and cleaning on the reflectance and solar heat gain of a light-colored roofing membrane. <i>Atmospheric Environment</i> , 39 , 7807-7824.

Levinson, R., P. Berdahl, H. Akbari, W. Miller, I. Joedicke, J. Reilly, Y. Suzuki, and M. Vondran. 2005. Methods of creating solar-reflective nonwhite surfaces and their application to residential roofing materials. <i>Solar Energy Materials & Solar Cells</i> (in press).
Levinson, R., P. Berdahl, and H. Akbari. 2005. Solar spectral optical properties of pigments, part I: Model for deriving scattering and absorption coefficients from transmittance and reflectance measurements. <i>Solar Energy Materials & Solar Cells</i> . 89(4), 319-349.
Levinson, R., P. Berdahl, and H. Akbari. 2005. Solar spectral optical properties of pigments, part II: Survey of common colorants. <i>Solar Energy Materials & Solar Cells, Vol 89</i> . 4 pp. 351-389.
Levinson, R., P. Berdahl, and H. Akbari. 2005. Solar spectral optical properties of pigments. Proceedings of <i>Cool Roofing ... Cutting through the Glare</i> . Atlanta GA, May 12-13, RCI Foundation.
Levinson, R., H. Akbari, and J. Reilly. 2004. Cooler tile-roofed buildings with near-infrared-reflective nonwhite coatings. Accepted by <i>Building & Environment</i> .
Miller, W.A., W.M. MacDonald, A.O. Desjarlais, J.A. Atchley, M. Keyhani, R. Olson, and J. Vandewater. 2005. Experimental analysis of the natural convection effects observed within the closed cavity of tile roofs. Proceedings of <i>Cool Roofing ... Cutting through the Glare</i> . Atlanta GA, May 12-13, RCI Foundation.
Miller, W. A., S. Kriner, and D.S.Parker. 2005. Cool metal roofing is topping the building envelope with energy efficiency and sustainability. Proceedings of <i>Cool Roofing ... Cutting through the Glare</i> . Atlanta GA, May 12-13, RCI Foundation.
Miller, W. A., A.O. Desjarlais, H. Akbari, R. Levinson, P. Berdahl, and R.G. Scichili. 2004. Special IR reflective pigments make a dark roof reflect almost like a white roof. <i>Thermal Performance of the Exterior Envelopes of Buildings, IX</i> , proceedings of ASHRAE THERM IX. Clearwater, FL., Dec.
Miller, W. A., A.O. Desjarlais, D.S. Parker, and S. Kriner. 2004. Cool metal roofing tested for energy efficiency and sustainability, <i>International Conference on Building Envelope Systems and Technologies (ICBEST)</i> , proceedings of National Research Council Canada. Toronto Canada, May 2-7.
Miller, W.A., K.T. Loye, A.O. Desjarlais, and R.P. Blonski, 2003. PVDF coatings with special IR reflective pigments. <i>Fluorine in Coatings V</i> , proceedings of Paint Research Association. Orlando, FL., Jan.
Miller, W.A., K.T. Loye, A.O. Desjarlais, and R.P. Blonski. 2002. Cool-color roofs with complex inorganic color pigments. <i>ACEEE Summer Study on Energy Efficiency in Buildings</i> , proceedings of American Council for an Energy Efficient Economy. Asilomar Conference Center in Pacific Grove, CA., Aug.

2.4.2. Task 2.7.2: Market plan

The objective of this subtask was to develop and initiate actions to facilitate the market adoption of cool-pigmented reflective roofing products.

The Energy Commission through this project has dramatically advanced the technology of nonwhite cool roofs that help save energy by exploiting complex inorganic paint pigments to

boost the solar reflectance of clay and concrete tile, painted metal, and asphalt shingle roofing. The project has successfully developed several nonwhite cool-colored roof products for sloped roofs over the past three years and has shown positive energy savings in residential field tests demonstrating pairs of homes roofed in concrete tile, painted metal and asphalt shingles with and without cool pigmented materials. Without further efforts, the accomplishments achieved by the Energy Commission in its Cool Roofs PIER project will creep into the marketplace over the next several decades, slowly bringing the significant energy, cost, smog and carbon savings that the technology promises.

Near the end of the project, the team's 16 industrial partners discussed their needs to further develop and successfully market their residential cool roofing products. Their recommendations and requests, summarized in Table 5, include the following points.

- First and foremost, residential cool roofs need to be credited and recommended in California's Title 24 standards that primarily determine what products are used in the construction of new houses and major remodels.
- More cool materials for all residential (and commercial) sloped roofing systems must be available and appropriately labeled.
- Appropriate labels on roofing products must be universally applied.
- Architects, designers, builders, roofing material distributors and retailers, and consumers need to learn of the availability and benefits of using cool roofing materials.
- California's utilities and government can further influence the selection of cool roofs through innovative incentive and rebate programs to accelerate their market penetration.
- Market penetration can be accelerated by enhancing the credibility of retailer and utility marketing claims through large-scale demonstrations of cool roofs to consumers, developers, designers, and roofing contractors.

In collaboration with the roofing industry partners, the Cool Team prepared a market plan that outlines industry/national labs collaborative efforts to help the CEC in deploying cool-colored roofing. The plan focuses on six parallel initiatives: (1) regulate; (2) increase product selection; (3) label; (4) educate; (5) provide incentives; and (6) demonstrate performance. This market plan is enclosed in Attachment 12.

Table 5. Industry needs to successfully market their cool roof products

Assistance requested in marketing cool roofs	Industry partner requesting assistance
Continuing education for design build firms, architects, utility consumers, construction professionals, and homeowners integrated into seminars offered by the California Association of Building Energy Consultants (CABEC)	Steelscape, BASF, Custom-Bilt, Shepherd
Software to estimate the cooling energy savings and peak demand reduction achieved by installing cool roofs on specific buildings	Steelscape, BASF, Custom-Bilt, Ferro, Elk, ARC
Monitoring of solar reflectance and color change of the materials installed at the California weathering sites	Steelscape, BASF, Custom-Bilt, ISP, Ferro, Elk, ARC
Monitoring of solar reflectance, color change, and thermal performance of materials at ORNL test facilities and the Sacramento test homes	Steelscape, BASF, Custom-Bilt, ISP, Elk, Ferro, ARC
Expansion of the cool coating database	Steelscape, BASF, Custom-Bilt, ISP, Ferro, Shepherd, 3M
Large-scale demonstration of cool roofs	Steelscape, BASF, Custom-Bilt, ISP, Ferro, Elk, ARC
Predictive software for designing cool coatings	Steelscape, BASF, Custom-Bilt, ISP, Ferro, 3M
Research to increase roof material reflectivity and reduce costs	ISP, Ferro, Elk, 3M, Shepherd, ARC
Tools to accurately measure roofing material solar reflectance	ISP, Elk, 3M, ARC
Calculations of weathering benefits of cool roofing	ISP
Identification of new materials and techniques	ISP, Ferro, 3M
Determination of the relationship between granule and ultimate shingle reflectances	3M
Acceleration of cool roof rating criteria by the Cool Roof Rating Council (CRRC) and ENERGY STAR	3M

2.4.3. Task 2.7.3: Title 24 code revisions

The objective of this task was to prepare a preliminary document of energy and peak demand savings for installing cool roofs in various California climates. This data can be further developed to prepare a proposal for updating the Title 24 building energy code to include cool-colored roofing materials.

To estimate the energy savings of cool-colored roofing materials, the project team calculated the annual cooling energy use of a prototypical house for all 16 California climate zones. The team used a simplified model that correlates the cool energy savings to annual cooling degree days (base 18°C ≈ 65°F) (CDD18). The model is developed by regression of simulated cooling energy use against CDD18. The Cool Team performed parametric analysis and simulated the cooling and heating energy use of a prototypical house with varying level of roof insulation (R-0, R-1, R-3, R-5, R-7, R-11, R-19, R-30, R-38, and R-49) and roof reflectance (0.05, 0.1, 0.2, 0.4, 0.6, and 0.8) in more than 250 climate regions, using the DOE-2 building energy use simulation program. For each prototypical analysis, the parametric analysis led to 15,000 DOE-2 simulations. Then the resulting cooling and heating energy use was correlated to CDD18.

The prototypical house used in these calculations is assumed to have roofing insulation of 0.88 to 5.3 m²K/W (R-5 to R-30 insulation). The estimates of savings are for an increase in roof solar reflectance by about 0.2 (change of the roof reflectance from 0.1 to 0.3 for shingles; change of the roof reflectance from 0.2 to 0.4 for clay and concrete tiles). These calculations present the variation in energy savings in 16 California climate zones. This document only reports cooling energy savings and does not account for potential wintertime heating energy penalties. Tables 6 and 7 below show potential cooling energy savings in kWh per year for a house with 100m² of roof area for stock of pre-1980 and post-1980 houses, respectively. The savings can be linearly adjusted for houses with larger or smaller roof areas. For most California climates, the application of cool-colored roof yields net savings in the range of 100–600 kWh per 100 m² per year. The savings are obviously smaller for buildings with higher roof insulation. For houses that are not air conditioned, cool-colored roofing materials offer comfort, typically at very reasonable costs.

Attachment 13 contains the technical document discussing the potential energy savings in a greater detail.

Table 6. Estimates of annual cooling electricity savings (kWh) and heating energy penalties (therms) from installing cool-colored roofs on pre-1980 single-family detached homes with gas furnace heating systems. All savings and penalties are per 100 m² of roof area. Solar reflectance change is 0.2 (shingle roof reflectance change is from 0.1 to 0.3; clay and concrete tiles roof reflectance change is from 0.2 to 0.4). The savings and penalties can be linearly adjusted for other values of changes in solar reflectance.

Roof Insulation	R-5		R-7		R-11		R-19		R-30	
Climate Zone	Cooling (kWh)	Heating (therms)								
CTZ1	110	-11	90	-9	67	-7	47	-5	35	-5
CTZ2	172	-9	149	-7	120	-6	93	-4	76	-3
CTZ3	117	-8	97	-6	73	-5	52	-4	39	-3
CTZ4	155	-7	133	-6	106	-5	80	-3	65	-3
CTZ5	116	-8	96	-6	73	-5	51	-3	39	-3
CTZ6	160	-5	137	-4	110	-3	84	-2	68	-2
CTZ7	181	-5	157	-4	127	-3	99	-2	82	-1
CTZ8	214	-5	188	-4	156	-3	124	-2	104	-1
CTZ9	244	-5	215	-4	180	-3	146	-2	124	-1
CTZ10	286	-6	255	-5	216	-3	177	-2	152	-2
CTZ11	292	-8	260	-7	221	-5	182	-4	156	-3
CTZ12	223	-8	196	-7	162	-5	130	-4	110	-3
CTZ13	372	-7	336	-6	289	-4	241	-3	209	-2
CTZ14	350	-9	315	-7	270	-6	225	-4	195	-3
CTZ15	646	-4	593	-3	521	-2	445	-1	393	-1
CTZ16	148	-14	126	-12	99	-10	75	-8	60	-6

Table 7. Estimates of annual cooling electricity savings (kWh) and heating energy penalties (therms) from installing cool-colored roofs on post-1980 single-family detached homes with gas furnace heating systems. All savings and penalties are per 100 m² of roof area. Solar reflectance change is 0.2 (shingle roof reflectance change is from 0.1 to 0.3; clay and concrete tiles roof reflectance change is from 0.2 to 0.4). The savings and penalties can be linearly adjusted for other values of changes in solar reflectance.

Roof Insulation	R-11		R-19		R-30		R-38		R-49	
Climate Zone	Cooling (kWh)	Heating (therms)								
CTZ1	43	-4	29	-3	21	-2	18	-2	15	-2
CTZ2	73	-3	54	-2	42	-2	38	-2	34	-1
CTZ3	46	-3	32	-2	23	-1	20	-1	17	-1
CTZ4	65	-3	47	-2	36	-1	33	-1	29	-1
CTZ5	46	-3	32	-2	23	-1	20	-1	17	-1
CTZ6	67	-2	49	-1	38	-1	34	-1	30	0
CTZ7	77	-2	58	-1	45	-1	41	0	37	0
CTZ8	93	-2	71	-1	57	-1	51	-1	47	0
CTZ9	107	-2	83	-1	67	-1	61	0	55	0
CTZ10	127	-2	100	-1	81	-1	74	-1	68	-1
CTZ11	130	-3	102	-2	83	-1	76	-1	70	-1
CTZ12	97	-3	74	-2	59	-1	54	-1	49	-1
CTZ13	168	-2	134	-2	111	-1	102	-1	94	-1
CTZ14	158	-3	125	-2	103	-2	95	-1	87	-1
CTZ15	300	-1	244	-1	206	0	190	0	176	0
CTZ16	61	-6	44	-4	34	-3	30	-3	27	-3

3.0 Conclusions and Recommendations

Raising roof reflectivity from an existing 0.10 (conventional dark roof) to about 0.35 (cool dark roof) can reduce cooling energy use in buildings by more than 10%. Cool roofs also result in a lower ambient temperature that further decreases the need for air conditioning and retards smog formation. In 2002, suitable cool *white* materials were available for most roof products, with the notable exception of asphalt shingles; cooler *colored* materials are needed for all types of roofing. To help to fill this gap, the California Energy Commission engaged LBNL and ORNL to work on a three-year project with the roofing industry to develop and produce reflective, colored roofing products. The intended outcome of this project was to make cool-colored roofing materials a market reality within three to five years. For residential shingles, the project team has developed prototype colored-shingles with solar reflectances of up to 0.35. One manufacturer currently markets colored shingles with the ENERGY STAR qualifying solar reflectance of 0.25. Colored metal and clay tile roofing materials with solar reflectances of 0.30 to 0.60 are currently available in the California market.

LBNL and ORNL performed research and development in conjunction with pigment manufacturers and worked with roofing materials manufacturers to reduce the sunlit temperatures of nonwhite asphalt shingles, clay tiles, concrete tiles, metal products, and wood shakes. A significant portion of the effort was devoted to identification and characterization of pigments to include and exclude in cool coating systems, and to the development of engineering methods for effective and economic incorporation of cool pigments in roofing materials. The project also measured and documented the laboratory and in-situ performances of roofing products. The Cool Team also established and monitored three pairs of demonstration homes to measure and showcase the energy-saving benefits of cool roofs. In collaboration with the Energy Commission, the Cool Team convened a Project Advisory Committee, composed of 15 to 20 diverse professionals, to provide strategic guidance to the project.

In order to determine how to optimize the solar reflectance of a pigmented coating matching a particular color, and how the performance of cool-colored roofing products compares to that of a standard material, the project team (1) measured and characterized the optical properties of many standard and innovative pigmentation materials; (2) developed a computer model to maximize the solar reflectance of roofing materials for a choice of visible colors; and (3) created a database of characteristics of cool pigments.

In order to help manufacturers design innovative methods to produce cool-colored roofing materials, the team (1) compiled information on roofing materials manufacturing methods; (2) worked with roofing manufacturers to design innovative production methods for cool-colored materials; and (3) tested the performance of materials in weather-testing facilities.

One of the project objectives was to demonstrate, measure, and document the building energy savings, improved durability, and sustainability attained by use of cool-colored roof materials for key stakeholders (consumers, roofing manufacturers, roofing contractors, and retail home improvement centers). In order to do this, the team (1) monitored buildings at California demonstration sites to measure and document the energy savings of cool-colored roof materials; (2) conducted materials testing at weathering farms in California; (3) conducted thermal testing

at the ORNL Steep-slope Assembly Testing Facility; and (4) performed a detailed study to investigate the effect of solar reflectance on product useful life.

The Cool Team also developed partnerships with various members of the roofing industry. The Cool Team worked through the trade associations to communicate and advertise to their membership new cool-color roof technology and products. This collaboration induced the manufacturers to develop a market plan for California and to provide technical input and support for this activity. Through the industry partners, many California housing developers and contractors have been convinced to install the new cool-colored roofing products.

Re-roofing houses with cool products when roofs are due for replacement and specifying cool roofs in new construction are economically sensible ways to significantly increase energy efficiency. The small price premium of cool roofs is paid back in air conditioning savings within a few years. When a sufficiently large number of home and commercial building owners adopt cool roofs regionally, earlier modeling and field experiments show that urban air temperatures decrease, slowing the rate of smog formation. This improves public health and helps cities meet federally mandated clean air requirements. Finally, cool roofs decrease peak electrical demand on hot summer afternoons, reducing strain on the electrical grid and helping to avoid blackouts and brownouts.

If applied to cars, cool-color technology could improve fuel economy by allowing manufacturers to downsize air conditioning units. These savings could help further reduce greenhouse gas emissions and enhance U.S. energy security by reducing reliance on imported petroleum. For all of these reasons, cool colors on roofs and in other applications have tremendous potential to contribute to the solution of major global problems within a short time, at a reasonable cost.

3.1. Recommendations

The Energy Commission has dramatically advanced the technology of nonwhite cool roofs that exploit cool pigments to boost the solar reflectance of clay tile, concrete tile, painted metal, and shingle roofing. The project has successfully developed several nonwhite cool-colored roof products for sloped roofs over the past three and a half years and has shown positive energy savings in residential field tests demonstrating pairs of homes roofed in concrete tile, painted metal, and asphalt shingles with and without cool pigmented materials. Without further efforts, the accomplishments achieved by the Energy Commission in this project will creep into the marketplace over the next several decades, slowly bringing the significant energy, cost, smog and carbon savings that the technology promises.

The team recommends the following step to rapidly accelerate the uptake of cool roofing materials:

- First and foremost, residential cool roofs need to be credited and recommended in California's Title 24 standards, which primarily determine what products are used in the construction of new houses and major remodels.
- More cool materials for all residential (and commercial) sloped roofing systems must be available and appropriately labeled.
- The cool roofing pigment database should be maintained and expanded with new materials in help the industry develop new and advanced materials at competitive prices.

- The aging and weathering of cool roofing materials and their effects on the useful life of roofs need to be further studied.
- Appropriate labels on roofing products must be universally applied.
- Architects, designers, builders, roofing material distributors and retailers, and consumers need to learn of the availability and benefits of using cool roofing materials.
- California's utilities and government can further influence the selection of cool roofs through innovative incentive and rebate programs to accelerate their market penetration.
- For utilities to develop incentive programs and for manufacturers to coordinate their materials development with their marketing efforts, they need to have an industry-consensus calculator to accurately estimate energy and peak demand of cool-colored roofs. The calculator should account for both the cooling energy savings and potential heating energy penalties of cool roofs.
- Finally, market penetration can be accelerated by enhancing the credibility of retailer and utility marketing claims through large-scale demonstrations of cool roofs to consumers, developers, designers, and roofing contractors.

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5.0 List of Attachments

Attachment Name	Publication Number
Attachment 1: Task 2.4.1 Reports: : Identify and Characterize Pigments with High Solar Reflectance	CEC-500-2006-067-AT1
Attachment 2: Task 2.4.2 Reports: Develop a Computer Program for Optimal Design of Cool Coatings	CEC-500-2006-067-AT2
Attachment 3: Task 2.4.3 Reports: Develop a Database of Cool-Colored Pigments	CEC-500-2006-067-AT3
Attachment 4: Task 2.5.1 Reports: Review of Roofing Materials Manufacturing Methods	CEC-500-2006-067-AT4
Attachment 5: Task 2.5.2 Reports: Design Innovative Methods for Application of Cool Coatings to Roofing Materials	CEC-500-2006-067-AT5
Attachment 6: Task 2.5.3 Reports: Accelerated Weathering Testing	CEC-500-2006-067-AT6
Attachment 7: Task 2.6.1 Reports: Building Energy-Use Measurements at California Demonstration Sites	CEC-500-2006-067-AT7
Attachment 8: Task 2.6.2 Reports: Materials Testing at Weathering Farms in California	CEC-500-2006-067-AT8
Attachment 9: Task 2.6.3 Reports: Steep-slope Assembly Testing at ORNL	CEC-500-2006-067-AT9
Attachment 10: Task 2.6.4 Reports: Product Useful Life Testing	CEC-500-2006-067-AT10
Attachment 11: Task 2.7.1 Reports: Technology Transfer	v CEC-500-2006-067-AT11
Attachment 12: Task 2.7.2 Reports: Market Plan	CEC-500-2006-067-AT12
Attachment 13: Task 2.7.3 Reports: Title 24 Code Revisions	CEC-500-2006-067-AT13

