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July 13, 2005

To: Chris Scruton (CEC)
From: Hashem Akbari
Subject: **Cool Roof Colored Materials**: Monthly Progress Report for June 2005
CC: Steve Wiel, Paul Berdahl, Andre Desjarlais, Nancy Jenkins, Bill Miller, Ronnen Levinson

A summary of the status of Tasks and Deliverables as of June 30, 2005 is presented in Attachment 1.

HIGHLIGHTS

- We have completed two reports describing our development of cool nonwhite roofing material prototypes. The first, "Methods of creating solar-reflective nonwhite surfaces and their application to residential roofing materials," was submitted to the journal *Solar Energy Materials & Solar Cells*. The second, "Cool roofing prototype development activities," is a brief summary of our activities. **This completes Task 2.5.2**.
- We have developed preliminary estimates of savings obtained from the installation of cool colored roofs on air conditioned houses in all California climate regions. A short report summarizing these estimates was prepared. **This completes Task 2.7.3**.
- LBNL, MCA Clay Tile, Elk Corporation, and Custom-Bilt Metals showcased cool colored roofing products at an exhibit of California's green energy technologies held in San Francisco's City Hall on the occasion of the United Nation's World Environment Day (June 1) and at the 8th Annual Congressional Renewable Energy/Energy Efficiency EXPO, in Washington DC (June 21).
- The completion date for the deliverables of Tasks 2.5.3, 2.6.4, and 2.7.2 has been postponed to the end of July 2005.
- Elemental analysis of the contaminants soiling the roof samples exposed at the seven CA sites was completed and the results show that samples exposed in Richmond (San Francisco basin area) had the largest amounts of elemental carbon (about 500 ug) as compared to all other weathering sites.

Tasks

1.1 Attend Kick-Off Meeting
Task completed.

1.2 Describe Synergistic Projects
Task completed.

2.1 Establish the Project Advisory Committee (PAC)
Task completed.

2.2 Software Standardization
(No activity.)

2.3 PAC Meetings
Task completed.

2.4 Development of Cool Colored Coatings

2.4.1 Identify and Characterize Pigments with High Solar Reflectance
Task completed.

2.4.2 Develop a Computer Program for Optimal Design of Cool Coatings
Task completed.

2.4.3 Develop a Database of Cool-Colored Pigments
Task completed.

2.5 Development of Prototype Cool-Colored Roofing Materials

2.5.1 Review of Roofing Materials Manufacturing Methods
Task completed.

2.5.2 Design Innovative Methods for Application of Cool Coatings to Roofing Materials
We have completed two reports describing our development of cool nonwhite roofing material prototypes. The first, "Methods of creating solar-reflective nonwhite surfaces and their application to residential roofing materials," is a technical paper that we have submitted to the journal *Solar Energy Materials & Solar Cells*. The second, "Cool roofing prototype development activities," is a brief summary of our activities. These two documents are attached. **Task completed**.

2.5.3 Accelerated Weathering Testing
No activity during June 2005. Work on the manuscript on accelerated weathering is awaiting the completion of the manuscript of Task 2.6.4.

2.6 Field-Testing and Product Useful Life Testing
ORNL's Environmental Science Division (ESD) completed its analysis of the contaminants soiling the roof samples pulled from the seven CA weathering sites. Dr. Susan Pfiffner continues working on the biomass analysis of similar samples. Results of the elemental analysis shows the presence of a wide spread of elements. The seven top elements having highest measured concentrations are shown in Fig. 1. Aluminum and iron are prevalent in all seven sites, with exception of McArthur. The high altitude of McArthur yields little dust and carbon soot pollution (Fig. 1). Richmond and Colton show large amounts of calcium. Elemental carbon was observed largest in Richmond,

probably because of car emissions. Besides Richmond, only Shafter shows noticeable amounts of soot deposition.

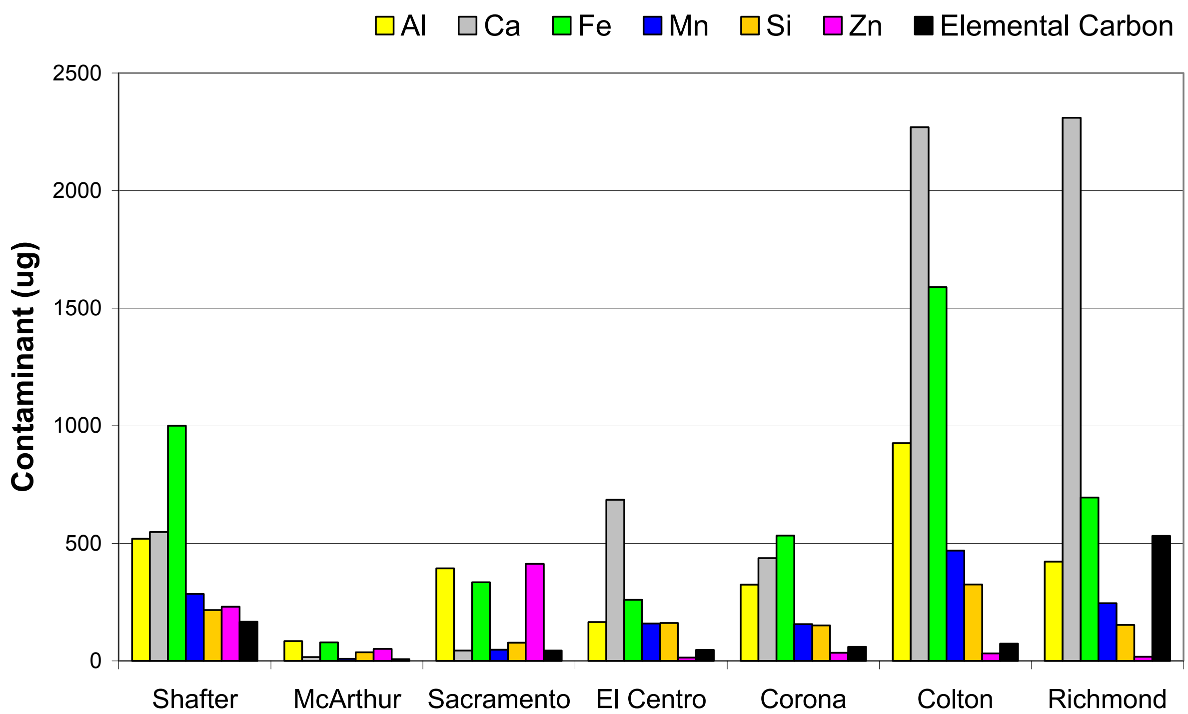

Figure 1. Major elemental contaminants measured on roof samples pulled from CA weathering sites.

2.6.1 Building Energy-Use Measurements at California Demonstration Sites

Shingle Demonstrations: Data collection and data reduction procedures were finalized for the pair of demonstration homes in Redding. We have acquired about 7 weeks of field data.

Painted Metal and Concrete Demonstrations: SMUD forwarded revenue meter readings for the two pair of homes in Fair Oaks, CA. The whole-house power transducer at 4979 Mariah Place appears to have failed. All other meters read within 1% of the revenue meters.

2.6.2 Materials Testing at Weathering Farms in California

Efforts are being made to correlate metered weathered data and contaminant concentrations to formulate an empirical correlation for the drop in solar reflectance of the roof products. The strength of the regression coefficients will help illuminate those parameters most strongly affecting the loss of solar reflectance.

2.6.3 Steep-slope Assembly Testing at ORNL

Efforts are proceeding to measure the airflow rate under the S-Mission clay tile and concrete slate tiles exposed on the Envelope Systems Research Apparatus. A procedure was developed based on tracer gas techniques outlined in ASTM E 741 and also by Lagus et al. 1988, which requires monitoring the decay rate of the tracer gas CO_2 with time. Results will be used to help validate predictions calculated by the attic model AtticSim, which in turn will predict the heat penetrating the roof deck and the heat swept by thermal buoyancy toward the ridge vent.

Various heat transfer correlations were tested against the experimental data for the S-Mission clay and concrete slate tile roofs to determine which correlations reasonably predict temperature and heat flow in the air cavity on the underside of the tile roofs. The correlation formulated by Brinkworth (2000) was found to predict well the heat flow penetrating into the roof deck (Fig. 2). The results are promising and we will therefore use Brinkworth's correlation among others by Hollands in an algorithm formulated in AtticSim to predict heat flow through concrete and clay tile having an air gap on the underside of the tile.

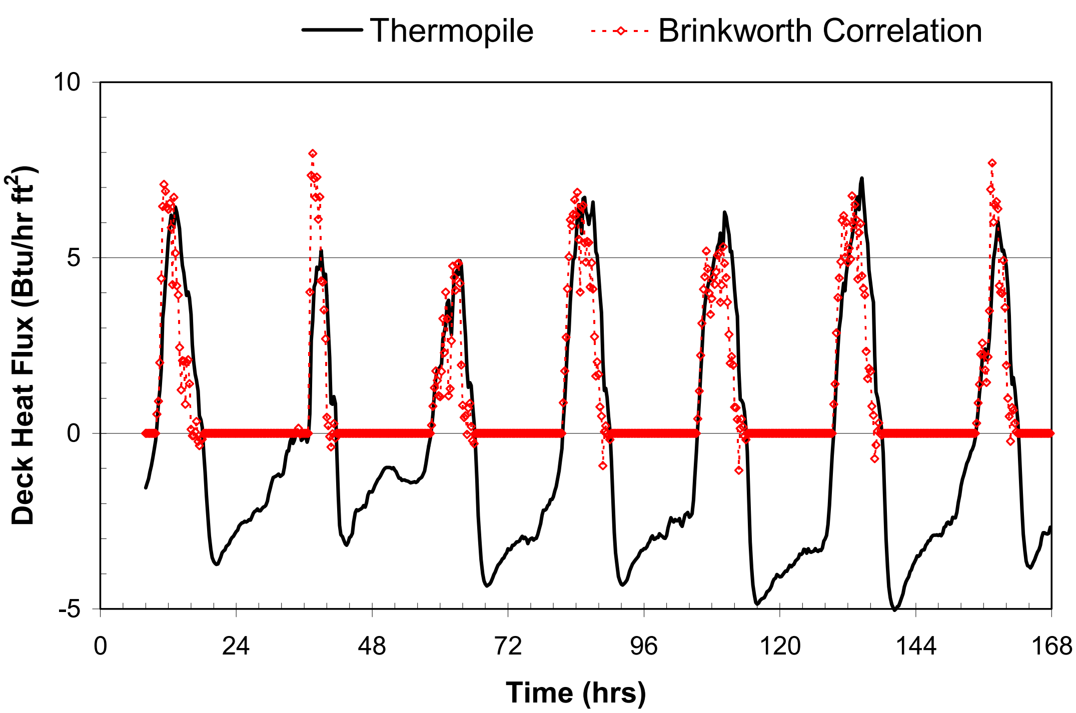

Figure 2. Comparison of heat flow measured by heat flux transducer in OSB deck against heat transfer correlation by Brinkworth (2000).

2.6.4 Product Useful Life Testing

We are currently writing an overview review article on weathering of roofing. The article lists the various physical, chemical, and biological stresses on roofing materials and discusses how manufacturers tailor their manufacturing processes to manage these stresses. The effects of photo-oxidation and the effects of elevated temperatures on roofing materials are featured. Completion of this article is projected in July.

2.7 Technology transfer and market plan

2.7.1 Technology Transfer

LBNL, MCA Clay Tile, Elk Corporation, and Custom-Bilt Metals showcased cool colored roofing products at an exhibit of California's green energy technologies held in San Francisco's City Hall on the occasion of the United Nation's World Environment Day (June 1). Levinson explained and demonstrated the performance of cool colored roofing to California Governor Arnold Schwarzenneger and several visiting mayors. An image of the Governor measuring the temperatures of color-matched cool and conventional metal roofing was distributed worldwide by the Associated Press (http://abcnews.go.com/US/wireStory?id=812675); a full-size version is online at http://CoolColors.LBL.gov

LBNL, Elk Corporation, and Custom-Bilt Metals showcased cool colored roofing products at the 8th Annual Congressional Renewable Energy/Energy Efficiency EXPO - June 21, 2005, in Washington DC. Akbari explained and demonstrated the performance of cool colored roofing to distinguished visitors including the Under Secretary for Energy, Science & Environment of DOE David Garman, Congresswoman from Berkeley Barbara Lee, and many congressman staff and assistances.

W. Miller and A. Desjarlais met with Scichili and Mark Wiebusch of Modern Trade Communications to formulate various strategies for centering attention on the painted metal "Cool Roof" initiative. Wiebusch stated that 67% of all metal building construction was done by design-build firms and that at least 50% of all metal roofs were specified by architects. Wiebusch and Scichili are planning a series of advertisements and articles that will reach about 30,000 architects subscribing to Modern Trade Communications.

Akbari gave a lecture titled "Urban Heat Islands and Mitigation Technologies: An Overview of LBNL Research," at the Architectural Institute of Japan, Tokyo, Japan, May 31, 2005.

Akbari gave a lecture titled "Advances in Development of Cool Colored Roofing Materials," at the Kobe University, Kobe, Japan, June 4, 2005.

Akbari gave a lecture titled "Advances in Development of Cool Colored Roofing Materials," at the Nippon Paint Co., Ltd., Shinagawa office, Japan, June 1, 2005.

Akbari gave a lecture titled "Advances in Development of Cool Pavement Materials," at the Sumitomo Osaka Cement Co., Kobe, Japan, June 3, 2005.

2.7.2 Market Plan

The draft market plan was rewritten per the recommendations of several PAC members and was forward for final review to John McCaskill of Elk Corp., to Bob Scichili, a consultant with Custom-Bilt Metals, to Mark Wiebusch of Modern Trade Communications and to Scott Kriner of Akzo Nobel Coatings Inc. We are in the process of finalizing the document. The completion is expected by July 31, 2005.

2.7.3 Title 24 Code Revisions

Akbari continues working with PG&E and the Energy Commission to develop a plan for code change proposal for sloped-roof residential buildings.

We have developed preliminary estimates of savings obtained from the installation of cool colored roofs on air conditioned houses in all California climate regions. A short report summarizing these estimates is attached. **Task completed**.

Management Issues

- Since the project has been extended through December 2006 to accommodate additional testing (Tasks 2.5.3, 2.6.1, 2.6.2, and 2.6.3), Akbari and Scruton will discuss options to report progress on this testing to the CEC project manager.
- We have not yet obtained the formal approval of the requested no-cost extension (through December 2006) for the project.

Attachment 1

Project Tasks and Schedules (*Approved on May 16, 2002; Revised schedules approved November 2004*)

Task	Task Title and Deliverables	Plan Start Date	Actual Start Date	Plan Finish Date	Actual Finish Date	% Completion as of 6/30/2005
1	**Preliminary Activities**					
1.1	Attend Kick Off Meeting *Deliverables:* • Written documentation of meeting agreements and all pertinent information (**Completed**) • Initial schedule for the Project Advisory Committee meetings (**Completed**) • Initial schedule for the Critical Project Reviews (**Completed**)	5/16/02	5/16/02	6/1/02	6/10/02	100%
1.2	Describe Synergistic Projects *Deliverables:* • A list of relevant on-going projects at LBNL and ORNL (**Completed**)	5/1/02	2/1/02	5/1/02	5/1/02	100%
1.3	Identify Required Permits	N/A		N/A		
1.4	Obtain Required Permits	N/A		N/A		
1.5	Prepare Production Readiness Plan	N/A		N/A		
2	**Technical Tasks**					
2.1	Establish the project advisory committee *Deliverables:* • Proposed Initial PAC Organization Membership List (**Completed**) • Finalize Initial PAC Organization Membership List (**Completed**) • PAC Meeting Schedule (**Completed)** • Letters of Acceptance (**Completed)**	6/1/02	5/17/02	9/1/02	9/1/02	100%
2.2	Software standardization *Deliverables:* • When applicable, all reports will include additional file formats that will be necessary to transfer deliverables to the CEC • When applicable, all reports will include lists of the computer platforms, operating systems and software required to review upcoming software deliverables	N/A		N/A		

Project Tasks and Schedules (contd.)

Task	Task Title and Deliverables	Plan Start Date	Actual Start Date	Plan Finish Date	Actual Finish Date	% Completion as of 6/30/2005
2.3	PAC meetings (**Completed)** *Deliverables:* • Draft PAC meeting agenda(s) with back-up materials for agenda items • Final PAC meeting agenda(s) with back-up materials for agenda items • Schedule of Critical Project Reviews Draft PAC Meeting Summaries • Final PAC Meeting Summaries	9/1/02	6/1/02	6/1/05		100% (6/6)
2.4	Development of cool colored coatings					
2.4.1	Identify and Characterize Pigments with High Solar Reflectance *Deliverables:* • Pigment Characterization Data Report (**Completed)**	6/1/02	6/1/02	12/1/04 → 12/31/04	12/31/04	100%
2.4.2	Develop a Computer Program for Optimal Design of Cool Coatings *Deliverables:* • Computer Program (**Completed)**	11/1/03	11/1/03	12/1/04 → 5/1/05	5/30/05	100%
2.4.3	Develop a Database of Cool-Colored Pigments *Deliverables:* • Electronic-format Pigment Database (**Completed)**	6/1/03	7/1/03	6/1/05 → 12/31/04	12/31/04	100%
2.5	Development of prototype cool-colored roofing materials					
2.5.1	Review of Roofing Materials Manufacturing Methods *Deliverables:* • Methods of Fabrication and Coloring Report (**Completed)**	6/1/02	6/1/02	6/1/03	4/1/05	100%
2.5.2	Design Innovative Methods for Application of Cool Coatings to Roofing Materials *Deliverables:* • Summary Coating Report **(Completed)** • Prototype Performance Report **(Completed)**	6/1/02	6/1/02	12/1/04 → 5/1/05	6/30/05	~ 100%
2.5.3	Accelerated Weathering Testing *Deliverables:* • Accelerated Weathering Testing Report	11/1/02	10/1/02	6/1/05 → 10/1/05		~ 60%

Project Tasks and Schedules (contd.)

Task	Task Title	Plan Start Date	Actual Start Date	Plan Finish Date	Actual Finish Date	% Completion as of 6/30/2005
2.6	Field-testing and product useful life testing					
2.6.1	Building Energy-Use Measurements at California Demonstration Sites *Deliverables:* • Demonstration Site Test Plan (**Completed)** • Test Site Report	6/1/02	9/1/02	10/1/05 → 10/1/06		90%
2.6.2	Materials Testing at Weathering Farms in California *Deliverables:* • Weathering Studies Report	6/1/02	10/1/02	10/1/05 → 10/1/06		88%
2.6.3	Steep-slope Assembly Testing at ORNL *Deliverables:* • Whole-Building Energy Model Validation • Presentation at the Pacific Coast Builders Conference • Steep Slope Assembly Test Report	6/1/02	10/1/02	10/1/05		90%
2.6.4	Product Useful Life Testing *Deliverables:* • Solar Reflectance Test Report **(Draft Prepared)**	5/1/04	5/1/04	6/1/05 → 10/1/05		95%
2.7	Technology transfer and market plan					
2.7.1	Technology Transfer (**Completed)** *Deliverables:* • Publication of results in industry magazines and refereed journal articles • Participation in buildings products exhibition, such as the PCBC Brochure summarizing research results and characterizing the benefits of cool colored roofing materials	6/1/03	6/1/02	6/1/05	6/1/05	100%
2.7.2	Market Plan *Deliverables:* • Market Plan(s) **(Draft Prepared)**	5/1/05	4/1/05	6/1/05		80%
2.7.3	Title 24 Code Revisions *Deliverables:* • Document coordination with Cool Roofs Rating Council in monthly progress reports (**Completed)** • Title 24 Database **(Completed)**	6/1/02	5/16/02	6/1/05	6/30/05	100%

Project Tasks and Schedules (contd.)

Task	Task Title	Plan Start Date	Actual Start Date	Plan Finish Date	Actual Finish Date	% Completion as of 6/30/2005
VII	Critical Project Review(s) *Deliverables:* • Minutes of the CPR meeting					
XII (C)	Monthly Progress Reports *Deliverables:* • Monthly Progress Reports (**Completed**)	6/1/02	6/1/02	6/1/05		103% (37/36)
XII (D)	Final Report *Deliverables:* • Final Report Outline • Final Report	3/1/05 → 3/31/06		10/1/05 → 10/1/06		
	Final Meeting *Deliverables:* • Minutes of the final meeting	10/15/05		10/31/05		

Methods of Creating Solar-Reflective Nonwhite Surfaces and their Application to Residential Roofing Materials

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Abstract

We describe methods for creating solar-reflective nonwhite surfaces and their application to a wide variety of residential roofing materials, including metal, clay tile, concrete tile, wood, and asphalt shingle. Reflectance in the near-infrared (NIR) spectrum (0.7 – 2.5 μm) is maximized by

* Contact author.

coloring a topcoat with pigments that weakly absorb and (optionally) strongly backscatter NIR radiation, adding an NIR-reflective basecoat (e.g., titanium dioxide white) if both the topcoat and the substrate weakly reflect NIR radiation. Coated steel and glazed clay tile roofing products achieved NIR reflectances of up to 0.50 and 0.75, respectively, using only cool topcoats. Gray concrete tiles achieved NIR reflectances as high as 0.60 with coatings colored by NIR-scattering pigments. Such tiles could attain NIR reflectances of up to 0.85 by overlaying a white basecoat with a topcoat colored by NIR-transparent organic pigments. Granule-surfaced asphalt shingles achieved NIR reflectances as high as 0.45 when the granules were covered with a white basecoat and a cool color topcoat.

Introduction

A roof with high solar reflectance (ability to reflect sunlight) and high thermal emittance (ability to radiate heat) stays cool in the sun, reducing demand for cooling power in conditioned buildings and increasing occupant comfort in unconditioned buildings. Nonmetallic surfaces and most polymer-coated metal surfaces have high thermal emittance. Hence, a cool roofing surface may be described as a nonmetal or polymer-coated metal with high solar reflectance.

Visible light (0.4 – 0.7 μm) [1] contains 43% of the power in the air-mass 1.5 global solar irradiance spectrum (0.3 – 2.5 μm) typical of North-American ground-level insolation; the remainder arrives as near-infrared (NIR) radiation (0.7 – 2.5 μm, 52%) or ultraviolet (UV) radiation (0.3 – 0.4 μm, 5%) (ASTM 2003). A clean, smooth, and solar-opaque white surface strongly reflects both visible and NIR radiation, achieving a solar reflectance of about 0.85. This is the coolest type of roofing surface, and is ideal for low-sloped roofs visible neither from ground level nor from taller buildings.

The solar reflectance of a roofing surface (especially that on a home) may be constrained by (a) desire for a nonwhite appearance, which limits visible reflectance; (b) NIR transparency of a thin and/or sparsely pigmented coating; and/or (c) curvature, which can cause light reflected from one face to be absorbed by another face. Nonwhite surfaces can be made as cool as possible by

[1] The spectrum of visible light is typically specified as either 0.38 – 0.78 μm, or 0.40 – 0.70 μm. We choose the simpler range 0.40 to 0.70 μm because phototropic responses to light in the tails (0.38 – 0.40 μm and 0.70 – 0.78 μm) are low (ASTM 2001).

maximizing reflectance in the NIR spectrum, which does not affect color. Smoothing rough surfaces can increase reflectance at all wavelengths.

This study describes the engineering principles for creating a solar-reflective coated surface, and their application to a wide variety of residential roofing materials, including metal, clay tile, concrete tile, wood, and asphalt shingle.

Literature Review

Brady and Wake (1992) present the basic method for creating a coating with high NIR reflectance: color an otherwise transparent topcoat with pigments that weakly absorb and (optionally) strongly backscatter NIR radiation, adding an NIR-reflective basecoat (e.g., titanium dioxide white) if both the topcoat and the substrate weakly reflect NIR radiation (Figure 1). This technique is reprised in whole or in part by U.S. patents and patent applications for creating generic NIR-reflectors (Genjima and Haruhiko 2002; Hugo 2002) and for creating NIR-reflective granules and/or granule-surfaced asphalt shingles (Gross and Graham 2005; Joedicke 2003; Ming et al. 2005a,b).

The authors reviewed current methods of manufacturing metal, clay tile, concrete tile, and asphalt shingle roofing materials in a earlier pair of articles (Akbari et al. 2005a,b).

Methodology

Maximizing solar reflectance of a colored surface

The fraction R of solar radiation incident at wavelengths between λ_0 and λ_1 that is reflected by a surface is the irradiance-weighted average of the surface's spectral reflectance $r(\lambda)$. That is,

$$R_{\lambda_0 \to \lambda_1} = \left(\int_{\lambda_0}^{\lambda_1} r(\lambda)\, i(\lambda)\, d\lambda \right) \Big/ \int_{\lambda_0}^{\lambda_1} i(\lambda)\, d\lambda \,, \tag{1}$$

where $i(\lambda)$ is the solar spectral irradiance. Average reflectances of interest include solar reflectance S (0.3 – 2.5 μm), UV reflectance U (0.3 – 0.4 μm), visible reflectance V (0.4 – 0.7 μm), and NIR reflectance N (0.7 – 2.5 μm).

It follows from Eq. (1) that the solar reflectance of a surface may be computed as the weighted average of its UV, visible, and NIR reflectances. The aforementioned distribution of solar power (5% UV, 43% visible, and 52% NIR) yields

$$S = 0.05\ U + 0.43\ V + 0.52\ N\ . \tag{2}$$

Strong UV absorption by surface-layer pigments (e.g., titanium dioxide rutile white) or aggregate (e.g., granules) is usually desirable to prevent UV damage to lower components of the roofing product, such as the primer layer in a coated metal system or the asphalt in a granule-surfaced asphalt shingle. High UV reflectance would be even better, but is difficult to achieve with nonmetallic surfaces. Hence, we maximize solar reflectance by establishing high reflectances in the visible and NIR spectra that contain 95% of the incident solar radiation.

Since there is usually more than visible spectral reflectance curve (reflectance versus wavelength in the visible spectrum) that will yield a particular color under a particular illuminant, it is possible to maximize visible reflectance by designing to a color, rather to a visible spectral reflectance curve. However, this may yield metamerism, in which the color of the coated surface matches that of another surface under one illuminant (e.g., early morning sun) but not another (e.g., noon sun). Maximizing only NIR reflectance avoids this problem.

Creating a coated surface with high NIR reflectance

When appearance and hence visible reflectance are constrained by design, a "cool" surface is one with high NIR reflectance. Consider a substrate (opaque structural material) with a uniformly pigmented coating. The spectral (wavelength-specific) reflectance of this system depends on the spectral reflectance of the substrate, the thickness of the coating, and on the extent to which light passing through the coating is absorbed (converted to heat) and/or backscattered (reversed in direction) at that wavelength by suspended pigment particles. Reflectance is also influenced by the refractive index of the otherwise-clear coating vehicle. For example, the passage of normally incident collimated light from air (refractive index 1) to a smooth polymer or silicate coating (refractive index 1.5) induces a 4% "first surface" reflection.

Backscattering usually has less effect than does absorption on the reflectance of a substrate with a pigmented coating because some of the light backscattered toward the surface is later backscattered away from the surface. Consider a 25-μm-thick pigmented coating applied to a substrate of reflectance 0.50. Neglecting first surface effects, a nonabsorbing coating with a Kubelka-Munk backscattering coefficient of 5 mm^{-1} will increase system reflectance by 0.03; of 10 mm^{-1}, by 0.06; of 50 mm^{-1}, by 0.19; of 100 mm^{-1}, by 0.28; and of 200 mm^{-1}, by 0.36. A nonscattering coating with a Kubelka-Munk absorption coefficient of 0.5 mm^{-1} will decrease system reflectance by 0.01; of 1 mm^{-1}, by 0.02; of 5 mm^{-1}, by 0.11; of 10 mm^{-1}, by 0.20; and of 20 mm^{-1}, by 0.32 (Levinson et al. 2005a). That is, the reflectance decrease induced by absorption can be comparable to the reflectance increase caused by backscattering an order of magnitude larger. Hence, we classify the backscattering by a pigmented coating as "weak" if its backscattering coefficient is less than 10 mm^{-1}, "moderate" if between 10 and 100 mm^{-1}, or "strong" if greater than 100 mm^{-1}. Absorption by a pigmented coating is labeled "weak" if its absorption coefficient is less than 1 mm^{-1}, "moderate" if between 1 and 10 mm^{-1}, or "strong" if greater than 10 mm^{-1}.

A pigmented coating will typically be designed to exhibit strong absorption and/or strong backscattering in the visible spectrum to hide (and thereby color) the substrate. We describe a pigmented coating as "cool" if it has weak NIR absorption, and "hot" if it has strong NIR absorption.

Our survey of the solar spectral radiative properties of common colorants (Levinson et al. 2005b) determined that only a few pigments—e.g., titanium dioxide rutile, nickel and chrome titanate yellows, aluminum flakes, and mica flakes coated with titanium dioxide—exhibit both strong NIR backscattering and weak NIR absorption when suspended in a vehicle of refractive index 1.5 (Table 1). Some of the nominally cool pigments, such as mixed-metal oxide selective blacks, exhibited both moderate-to-strong backscattering and moderate-to-strong absorption in the NIR. These do not meet our strict requirement (weak NIR absorption) for cool pigments, but may nonetheless be useful for cool applications so long as the coating's NIR reflectance (increased by backscattering, decreased by absorption) is sufficiently high. We note that the manufacturer-reported solar spectral reflectance of a thin (order 25 μm) pigmented coating on an aluminum substrate (N=0.90) tends to exaggerate the solar spectral reflectance that a similar coating achieves when applied to a poor NIR reflector, such as a gray-cement concrete tile (N=0.15).

Most cool pigments surveyed exhibited weak-to-moderate backscattering in a vehicle of refractive index 1.5. A thin (but visibly hiding) coating colored with such pigments may be applied directly over a substrate of high NIR reflectance to produce a colored surface with high NIR reflectance. Some bare roofing materials have NIR reflectances of 0.55 or higher[2], including wood, treated ZINCALUME® steel, treated hot-dipped galvanized (HDG) steel, and natural red clay tile (Table 2). The application of a cool coating to any of these substrates will yield a cool roofing surface with a solar reflectance of at least 0.30. System NIR reflectance will be further increased by NIR backscattering in the cool coating.

Other bare roofing materials, such as gray-cement concrete tiles and gray-rock-surfaced asphalt-shingles, have NIR reflectances in the range of 0.10 to 0.15. These substrates with low NIR reflectance can achieve high NIR reflectance via the application of a 25 to 100 µm thick cool coating pigmented with a moderate-to-strong NIR backscatterer. For example, a smooth, flat dark gray substrate (N=0.10) with a 25-µm thick polymer or silicate coating pigmented with titanium dioxide rutile white (backscattering coefficient about 200 mm^{-1} and absorption coefficient about 0.5 mm^{-1} at wavelength 1 µm) achieves an NIR reflectance of about 0.65. N can be increased to over 0.80 by making the coating at least 100-µm thick (Table 3; Figure 2). A visibly hiding cool topcoat may be applied over this layer to produce an arbitrarily colored system with high NIR reflectance.

Pigmented coatings with moderate-to-high NIR absorption and backscattering tend to yield moderate NIR reflectance over any surface, since the coating is usually NIR opaque. For example, the same gray substrate with a 25-µm thick coating pigmented with an iron oxide red (backscattering coefficient about 100 mm^{-1} and absorption coefficient about 10 mm^{-1} at wavelength 1 µm) achieves an NIR reflectance of about 0.40. Increasing the coating thickness to 100 µm (or greater) yields an NIR reflectance limited to about 0.50.

Creating a color-matched cool coated surface

A cool coated surface of a particular color may be created by using a mixture of cool pigments in the topcoat. The topcoat must exhibit strong visible absorption and/or backscattering to hide the substrate (and basecoat, if present). It is crucial to not to adjust the color with pigments that

[2] Most NIR reflectances presented in this paper are rounded to the nearest 0.05 to avoid unnecessary detail.

strongly absorb light across the entire solar spectrum, such as carbon black, lampblack, iron oxide black, or copper chromite black. The inclusion of any of these NIR-absorbing pigments in the topcoat or basecoat will tend to make the coated surface hot.

Effect of surface curvature on reflectance

Absorption of multiply reflected light can make the net absorptance of a curved, opaque surface exceed the "local" absorptance that would be observed were the surface flat. We plan to quantify in future research the effect of surface curvature on the reflectances of non-flat roofing surfaces, such as S-shaped clay tiles and granule-covered asphalt shingles.

Application to Residential Roofing Materials

Metal

A manufacturer of pigmented polyvinylidene fluoride (PVDF) coatings (BASF Industrial Coatings; Colton, CA) provided (a) four types of steel substrate; (b) seven conventionally coated and seven nominally cool-coated ZINCALUME® steel coupons; (c) a free film of the polyurethane primer layer used between the metal and the color coat; and (d) 27 free films of PDVF coatings colored with different pigments, one pigment per film.

We measured the solar spectral reflectance of each sample from 0.3 to 2.5 µm at 5-nm intervals in accordance with ASTM Standard E903 (ASTM 1996), using a PerkinElmer Lambda 900 UV/visible/NIR spectrometer with a Labsphere 150-mm integrating sphere.

The bare and treated samples of HDG steel (steel coated with zinc) and ZINCALUME® steel (steel coated with a zinc-aluminum alloy) had NIR reflectances ranging from about 0.55 to 0.80 (Table 2; Figure 3). We hypothesize that bare ZINCALUME® steel (N=0.80) is appreciably more NIR-reflective than bare HDG steel (N=0.60) because aluminum is more NIR reflective than zinc. Treatment—cleaning, roughening, and the application of a "conversion layer" to help bind the primer layer to the metal—decreases the NIR reflectance of ZINCALUME® steel by about 0.10 (to N=0.70) and that of HDG steel by about 0.05 (to N=0.55). This suggests that cool coatings on treated ZINCALUME® steel will tend to better reflect NIR radiation than will those on treated HDG steel (N up to 0.15 higher).

Conversion coatings are very thin (typically less than 1 μm) and typically contain mostly transparent, nonabsorbing inorganic phosphate compounds and polymers of refractive index 1.5 (Roland et al. 1998; Hamacher 1994; Mady and Seidel 1996). We hypothesize that the reflectance reduction observed for treated samples stems from surface roughness induced by etching. For example, a polished aluminum surface, while mirror-like, actually has many submicron grooves produced by the polishing-powder particles, and is less reflective than a smooth aluminum film prepared by evaporation in ultrahigh vacuum (Smith et al. 1985). The reflectance loss induced by treatment diminishes with increasing wavelength in the NIR spectrum (Figure 4). This behavior is to be expected because the scale of the roughness (grooves) must be less than the coating thickness, which is itself less than 1 μm. At wavelengths much longer than the roughness scale, the reflectance should approach the high values characteristic of a smooth surface.

Some pretreatments use manganese or chromium ions, which might color the coating. Even a transparent phosphate conversion coating of thickness greater than about 50 nm may introduce color by thin-film interference, though this would be eliminated by the application of a primer layer (thickness order 5 μm).

The NIR absorptance of the 19-μm thick sample of primer (polyurethane pigmented with strontium chromate and titanium dioxide) was about 0.03. Since the primer thickness in the 14 coated ZINCALUME® samples was only about 5 μm, any NIR absorption in the coating systems (primer plus PDVF topcoat) occurred almost entirely in the pigmented PDVF layer.

The NIR reflectances of the seven conventionally coated ZINCALUME® coupons ranged from about 0.05 to 0.25, while those of the seven cool-coated ZINCALUME® coupons ranged from about 0.40 to 0.50 (Figure 5a). This indicates that the nominally cool coatings, while certainly less NIR-absorptive than their color-matched conventional coatings, increased system NIR absorptance by 0.20 to 0.30.

To better understand the nature of the NIR absorptance in the nominally cool pigmented PVDF coatings, and to identify any other pigmented coatings in the manufacturer's product line that might happen to be cool, we characterized the solar spectral radiative properties (reflectance, transmittance, absorptance, backscattering coefficient, and absorption coefficient) of the 27 single-pigment PVDF coatings (Levinson et al. 2005a,b). Many of the nominally cool inorganic pigments exhibited bands of absorption in the NIR induced by the presence of particular elements. For example, pigments that include cobalt were found to have absorption bands centered near wavelength 1.5 μm that cause a 20-μm thick pigmented PVDF coating to absorb about 15 to 40% of NIR radiation. The nominally cool inorganic black pigments containing chromium iron oxide exhibit a gradual, rather than sharp, reduction in absorption from the visible spectrum (where it is desirable) to the NIR spectrum (where it is not), causing a 20-μm coating to absorb 35 to 50% of NIR radiation.

A coating pigmented with an organic cool black (perylene black) was found to absorb about 95% of visible radiation, but only about 5% of NIR radiation. When applied in a coating over ZINCALUME® steel (N=0.70), this weakly scattering pigment can produce a black surface with an NIR reflectance of about 0.65 and a solar reflectance of about 0.35. These values well exceed the NIR (0.35) and solar (0.20) reflectances achieved by ZINCALUME® steel with a cool inorganic black PVDF coating.

The total thickness of the coating system (primer plus topcoat) on a metal substrate is typically limited by the need to keep the metal formable without breaking the coating. This tends to make it difficult to significantly increase the NIR reflectance of the system with a basecoat, since the basecoat would have to be quite thin. The additional pass required to apply a basecoat would also increase the cost and reduce the throughput of coil coating processes originally configured for only two layers (primer plus topcoat).

Clay tile

A manufacturer of clay tile roofing (MCA Clay Tile; Corona, CA) supplied 18 clay tile chips (small cut pieces of tile). The NIR reflectance of bare terracotta (natural red) tile was 0.55, while that of glazed tiles ranged from 0.25 (burnt sienna) to 0.75 (white buff). Only two tiles (glazed with burnt sienna and carbon, respectively) had NIR reflectances less than 0.40, and only four tiles had NIR reflectances less than 0.50 (Figure 5b).

Clay tile is typically composed of transparent crystalline particles (size order 10 μm) with anisotropic (directional) refractive indices. Light propagating through the material is scattered when light passes between two differently oriented crystallites that present different indices of refraction. Bare white tile has high reflectance across the NIR spectrum (N=0.85), while bare terracotta tile contains iron oxide (hematite) and therefore exhibits some NIR absorption (Figure 6).

The high NIR reflectance of bare clay tile and the ability to apply thick glazes make it straightforward to create NIR-reflective glazed clay tiles. It may be possible to modestly increase the NIR reflectance of a glazed tile system by applying and firing a basecoat glaze of white buff before applying and firing the topcoat color glaze. However, it is most important to avoid the use of carbon and other NIR-absorbing pigments in the glaze.

In principle, the solar spectral radiative properties of tile glazes can be characterized in a manner analogous to that used for polymer coatings—i.e., by measurement of the spectral reflectance and transmittance of a glaze applied to a clear substrate, such as quartz, that can withstand firing at 1000ºC. However, since the thermal expansion rate of quartz is several times smaller than that of a silicate glaze, a glaze fired on quartz (rather than clay) will tend to crack. We continue to seek a substrate that is transparent to sunlight, can be fired at high temperature, and thermally expands at a rate compatible with that of the glaze.

We measured the solar spectral reflectances of 20 single-pigment glazes provided at various concentrations on white clay tiles by a manufacturer of tile glazes (Ferro Corporation Frit/Color Division; Los Angeles, CA). These data will be used in our future efforts to improve the NIR reflectances of glazed clay tiles.

Concrete tile

Lawrence Berkeley National Laboratory (LBNL) collaborated with a manufacturer of concrete-tile coatings (American Rooftile Coatings; Brea, CA) to design 25 prototype acrylic coatings on gray-cement concrete tile chips (N=0.15). These included (a) six conventionally pigmented, 100-µm thick coatings applied directly to tile; (b) a matching set of six nominally cool-pigmented, 100-µm thick coatings also applied directly to tile; (c) the same six nominally cool-pigmented coatings applied at a thickness of 50 µm over a 100-µm acrylic white basecoat (N=0.85); and (d) seven “experimental, ” 50-150 µm thick topcoats applied over the white basecoat.

The NIR reflectances of the six conventionally coated chips (set A) ranged from 0.05 to 0.55, while those of the nominally cool coatings applied directly to tile (set B) ranged from 0.35 to 0.60. The conventional blue and all the nominally cool coated chips except the black (N=0.35) had NIR reflectances exceeding 0.50 (Figure 5c).

The white basecoat used in set C increased the NIR reflectances of the six nominally cool coatings by less than 0.05, suggesting that the original line of cool topcoats was essentially NIR opaque. However, some of the seven experimental coatings in set D were NIR transparent, and show potential to achieve high NIR reflectance when applied over a white basecoat. For example, a 50-µm perylene black topcoat applied over the white basecoat achieved an NIR reflectance of 0.55. We note that a 25-µm perylene-black PVDF free film with an opaque white background (N=0.85) prepared in the course of our pigment characterization activities exhibited an NIR reflectance of 0.85. Hence, it is likely that the NIR reflectance of a gray concrete tile with a white basecoat and a perylene black topcoat can be increased from 0.55 to about 0.85 by reformulating the perylene black topcoat.

Wood shake

Light incident on plant material is backscattered as it passes alternately through cell walls of refractive index 1.4 and intracellular air of refractive index 1 (Knipling 1970). This gives plant material high reflectance at all wavelengths, except in those visible bands where lignin and/or chlorophyll absorb light, and in those NIR bands where water absorbs light (Figure 6). Moderately dark bare wood typically has a visible reflectance of 0.20, an NIR reflectance of about 0.70, and a solar reflectance of about 0.45. Hence, bare wood (and wood shakes treated with an NIR-transmissive fire retardant) can be both cool and dark.

A pigment manufacturer (Ferro Corporation Frit/Color Division; Los Angeles, CA) provided 16 samples of wood (N=0.70) with acrylic coatings colored by NIR-scattering inorganic pigments. Each of four pigments (two yellows, one green, and one black) was applied individually to wood in coatings with coverage rates of 150, 125, 100, and 75 ft^2/gal, corresponding to mean thicknesses of 270, 235, 405, and 545 µm, respectively. The thickest yellow coatings increased NIR reflectance to 0.80, while the thickest green coating increased NIR reflectance to 0.75. The thickest black coating reduced NIR reflectance to about 0.55.

When a manufacturer of fire retardants for wood products (Galchem Chemical Inc.; Payson, AZ) added metal-oxide pigments to a fire retardant solution that was pressure-applied to wood shakes, the pigments and some of the fire retardant precipitated out of the solution. Further work in this area is needed to investigate the compatibility of pigments with fire retardants.

Asphalt shingle

Over 97% of the surface of a typical asphalt-soaked fiberglass roofing shingle is covered with a layer of crushed rocks, or "granules" that are about 0.5 to 2 mm in diameter (Akbari et al. 2005a). Hence, the NIR reflectance of an asphalt shingle is determined by that of its granule layer. The NIR reflectance of the granule layer is in turn is limited by (a) the low NIR reflectance of typical gray rock granules (about 0.10 – 0.15); (b) the low mean thickness of a typical granule coating (about 5 to 10 µm); and (c) weak to moderate NIR backscattering by most pigments.

The simplest way to increase the NIR reflectance of individual granules is to use a naturally white (or otherwise light-colored) aggregate. However, some light-colored rocks such as quartz transmit UV light, and would fail to shield the asphalt from solar UV radiation. If a UV-opaque, NIR-reflective aggregate is not available, an NIR-reflective basecoat pigmented with a titanate white, a titanate yellow, titanium-dioxide coated mica flakes, or aluminum flakes can be applied to an NIR-absorbing aggregate to produce an NIR-reflective granule. For example, a 5-µm thick, refractive-index 1.5 coating pigmented with titanium dioxide white can increase the NIR reflectance of a smooth, dark gray surface (N=0.10) to 0.35; a 10-µm coating, to 0.50; and a 25-µm coating, to 0.65 (Table 3; Figure 2). A cool, visibly hiding topcoat can provide color and, optionally, additional NIR backscattering.

The thickness of the coating applied to a granule is limited by the coating process, in which granules are preheated in a tumbler; transferred hot to a rotary mixer for application of the wet pigmented coating (pigments in sodium silicate, hydrated kaolin clay, and water); and then fired in a rotary kiln. If the volume ratio of liquid coating to granules is too high, the granules will tend to fuse together. Multiple passes increase the total coating thickness, but reduce system throughput and increase cost.

LBNL collaborated with a manufacturer of roofing granules (ISP Mineral Products; Hagerstown, MD) to develop approximately 90 prototype shingle coupons and 10 prototype shingle boards. The shingles were surfaced with (a) bare rock granules; (b) granules with thin or thick white coatings; (c) granules with a thin aluminum coating; (d) granules with cool-pigment topcoats over bare rock, rock with an aluminum basecoat, rock with a thin white basecoat, or rock with a thick white basecoat; (e) salt-and-pepper blends of bright-white granules (rock with a thick white coating) and some of the granules described in (d); and (f) blends of granules of varying sizes.

The NIR reflectance of a shingle surface covered with bare granules was about 0.10. Adding a topcoat colored with a black, brown, green, or blue cool pigment increased NIR reflectance to 0.10 – 0.30. A thin (about 15 µm) aluminum basecoat (granulated surface N=0.35) increased NIR reflectances of the colored granules to about 0.25; a thin (about 15 µm) white basecoat (granulated surface N=0.25), to 0.25 – 0.35; and a thick (about 25 µm) white basecoat (granulated surface N=0.45), to 0.30 – 0.45 (Figure 5d).

Adding a basecoat tended to increase both visible and NIR reflectances unless the topcoat was opaque to visible light. For example, a cool inorganic brown pigment over a bare granule produced a shingle with V=0.15 and N=0.28. Adding a thin white basecoat yielded V=0.22 and N=0.35; adding a thick white basecoat yielded V=0.26 and N=0.43. The increases in the visible reflectance of this shingle were comparable to its increases in NIR reflectance—that is, the shingle became lighter in color. However, the shingle was not spectrally gray, in the sense that its NIR reflectance well exceeded its visible reflectance.

Figure 7 illustrates the development of cool black asphalt shingle colored with an inorganic cool black pigment. The granules on a conventional shingle are pigmented with carbon—a hot black with strong absorption across the entire solar spectrum—and have no basecoat. In prototype 1, the carbon is replaced by a cool inorganic black, increasing NIR reflectance from 0.05 to 0.19 and solar reflectance from 0.04 to 0.12. Prototype 2 adds a thin white basecoat below the cool inorganic black topcoat, increasing N to 0.26 and S to 0.16. Prototype 3 replaces the thin white basecoat with a thick white basecoat, increasing N to 0.30 and S to 0.18. The top curve ("performance limit") corresponds to a smooth, 25-µm-thick PDVF film (N=0.43, S=0.25) pigmented with this cool black and backed by an opaque white (N=0.85). Roughness and limits to the thicknesses of the basecoat and topcoat are expected to make the reflectance of any granule-surfaced shingle pigmented with this cool inorganic black less than that achieved by the white-backed smooth film.

The prototype salt-and-pepper blends replaced thinly coated white granules with thickly coated white granules; some also replaced standard color granules with cool color granules. Unsurprisingly, using whiter granules increased both visible and NIR reflectances, resulting in a lighter-colored shingle with higher solar reflectance.

Blending various sizes of granules to make the granule layer smoother did not noticeably increase reflectance.

It may be possible to increase the NIR reflectance of granule-surfaced asphalt shingles by applying the pigmented coating to the shingle after bare granules have been pressed into the asphalt, then baking the granulated surface with radiant heat. This approach would coat only the exposed faces of the granules and might mitigate thickness limits associated with the tumble-coating/kiln-drying processes.

We note that several other roofing manufacturers, including CertainTeed (Valley Forge, PA), 3M Industrial Minerals (St. Paul, MN), and Elk Corporation (Dallas, TX) are engaged in analogous efforts to produce cool nonwhite asphalt shingles. The CertainTeed process applies cool pigments to both the roofing granules and the asphalt substrate (Shiao et al. 2005a,b), while the 3M process applies a solar-reflective basecoat and a cool colored topcoat to the granules (Gross and Graham 2005). The Elk process has not been disclosed.

Summary

Surfaces with high thermal emittance (i.e., nonmetals, and most polymer-coated metals) stay cool in the sun when they have high solar reflectance. When strong UV absorptance is required to shield a substrate, and visible spectral reflectance is fixed to yield a particular color, maximizing NIR reflectance is equivalent to maximizing solar reflectance. The NIR reflectance of a substrate with a pigmented coating generally depends on NIR absorption and backscattering in the pigmented coating, and on the NIR reflectance of the uncoated substrate. Cool coatings should exhibit low NIR absorption. However, some NIR absorption may be acceptable in a coating that also exhibits strong NIR backscattering. A substrate with high NIR reflectance (e.g., metal, clay tile, or wood) can be colored with any cool coating, while a substrate with low NIR reflectance (such as gray concrete tile or gray aggregate) requires significant NIR backscattering in either the cool topcoat or a cool basecoat.

Coated metal and glazed clay tile roofing products achieved NIR reflectances of up to 0.50 and 0.75, respectively, using only a cool topcoat. Topcoats colored with NIR-transparent organic pigments could yield coated metal systems with NIR reflectances as high as 0.65. Gray-cement concrete tiles have low NIR reflectance, but achieved NIR reflectances as high as 0.60 when thickly coated with NIR-scattering pigments. Coated gray-cement concrete tiles with NIR reflectances as high as 0.85 could be obtained by overlaying a titanium-dioxide basecoat with a topcoat colored by NIR-transparent organic pigments. Granule-surfaced asphalt shingles achieved NIR reflectances as high as 0.45 when a cool color topcoat was applied to granules with a thick white basecoat. Bare wood has an NIR reflectance of about 0.70; the application of certain pigments (e.g., metal oxides) may remove fire retardants from wood roofing products, and is not recommended.

Acknowledgements

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Table 1. Classification of cool pigments (those with low NIR absorption) according to strength of NIR backscattering in a vehicle of refractive index 1.5.

Strong NIR backscattering (coefficient > 100 mm^{-1} at 1 μm)	Moderate NIR backscattering (coefficient 10 - 100 mm^{-1} at 1 μm)	Weak NIR backscattering (coefficient < 10 mm^{-1} at 1 μm)
chrome titanate yellow chromium iron oxide black* nickel titanate yellow titanium dioxide (rutile) on mica flakes (interference colors) titanium dioxide white (rutile)	cadmium orange, yellow cobalt chromite blue, green* cobalt titanate green iron titanium brown spinel modified chromium oxide green monastral red red, brown iron oxides	cobalt aluminate blue diarylide yellow dioxazine purple Hansa yellow perylene black phthalocyanine blue, green quinacridone red ultramarine blue

* These pigments exhibit moderate absorption in the NIR and hence are not strictly cool, but have sufficient NIR backscattering to be useful in cool coatings.

Table 2. Typical NIR reflectances (rounded to nearest 0.05) of various clean and uncoated substrates.

Uncoated substrate	NIR reflectance
fresh asphalt	0.05
layer of gray-rock granules	0.10
gray-cement concrete tile	0.15
treated* hot-dipped galvanized steel	0.55
bare hot-dipped galvanized steel	0.60
natural red clay tile	0.70
wood	0.70
treated* ZINCALUME® steel	0.70
bare ZINCALUME® steel	0.80
white ceramic tile	0.85
aluminum foil	0.90

*cleaned and coated with a very thin (about 1 μm) “conversion layer” that helps the primer layer adhere to the metal

Table 3. NIR reflectances (rounded to nearest 0.05) of white* and aluminum-flake coatings on a smooth, dark gray substrate (N=0.10).**

Coating	NIR reflectance of coated substrate
none	0.10
white, 5 µm	0.35
white, 10 µm	0.50
white, 25 µm	0.65
white, 50 µm	0.75
aluminum flake, 25 µm	0.80
white, 100 µm	0.80
white, 200 µm	0.85

* Polyvinylidene fluoride (PVDF) pigmented with titanium dioxide rutile (mean particle size 0.25 µm) at 15% volume concentration. Comparison of measured and computed values of the NIR reflectance of coatings pigmented with titanium dioxide white suggests that these computed values may be slightly (as much as 0.05) too low.

** Silicone pigmented with aluminum flakes. It may be possible to achieve a comparable NIR reflectance with a thinner coating because the aluminum flake coating was NIR opaque at a thickness of about 25 µm.

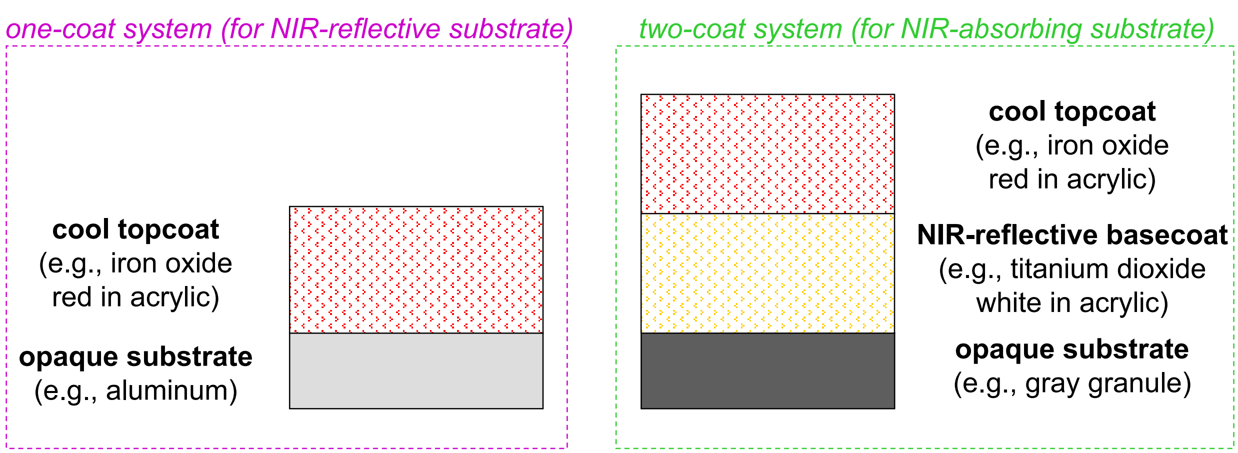

Figure 1. Schematics of one-coat (substrate + topcoat) and two-coat (substrate + basecoat + topcoat) systems. The one-coat system can also be applied over an NIR-absorbing substrate if the topcoat has at least moderate NIR backscattering and is sufficiently thick.

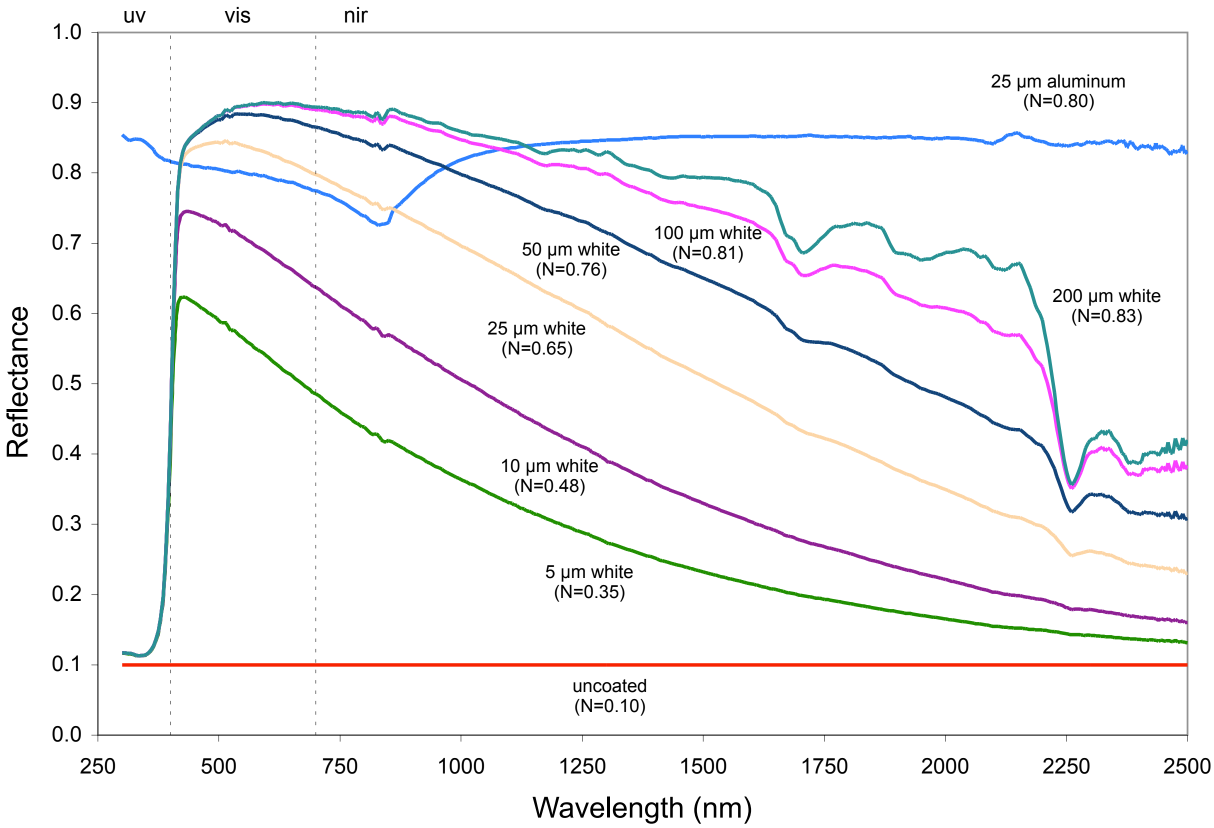

Figure 2. Solar spectral reflectances and NIR reflectances (N) of a smooth, dark gray substrate (reflectance 0.10 at all solar wavelengths) with (a) 5, 10, 25, 50, 100, and 200-µm thick PVDF coatings pigmented with titanium dioxide rutile white at 15% pigment volume concentration; and (b) a 25-µm thick silicone coating pigmented with aluminum flakes (pigment volume concentration unknown). The spectral reflectances of the white-coated surfaces were estimated from absorption and backscattering coefficients computed by Levinson et al. (2005a), while that of the aluminum-flake coated surface was measured.

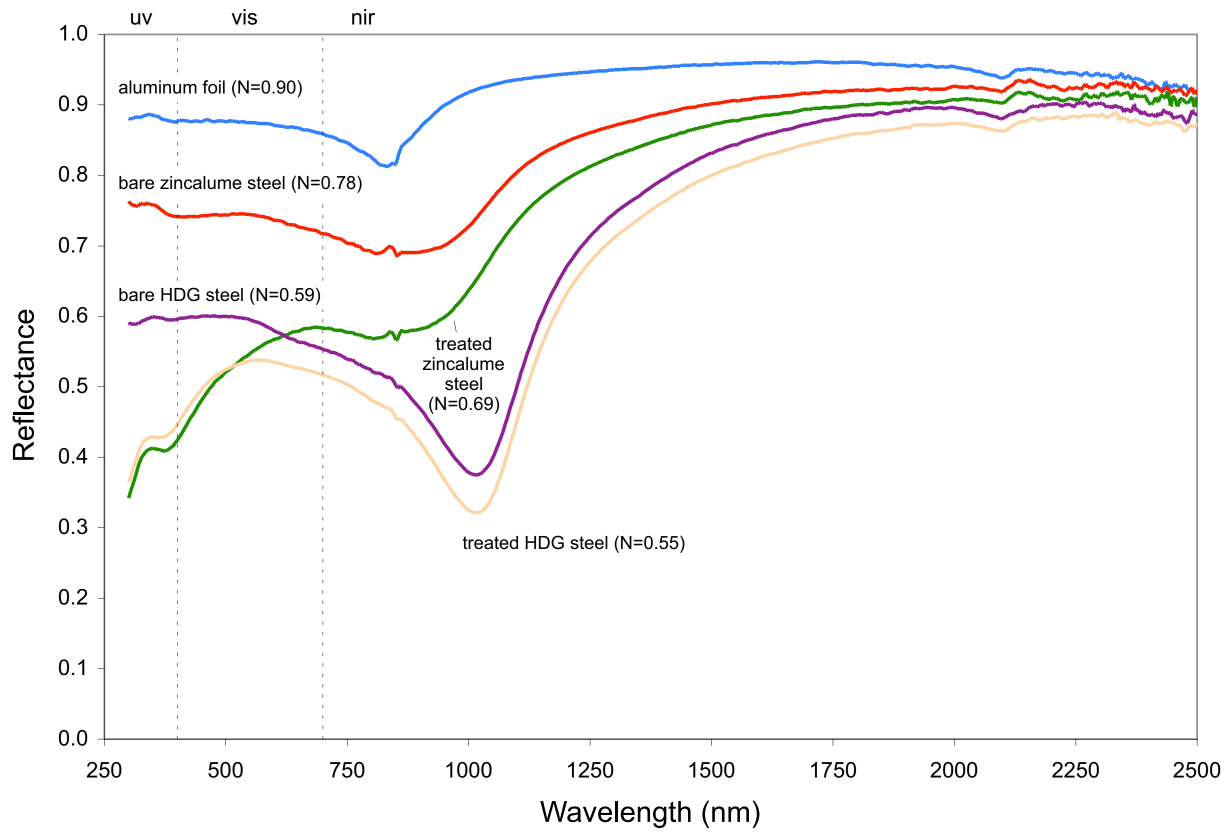

Figure 3. Solar spectral reflectances and NIR reflectances (N) of five uncoated, metallic substrates: aluminum foil, bare and treated ZINCALUME® steels, and bare and treated hot-dipped galvanized (HDG) steels.

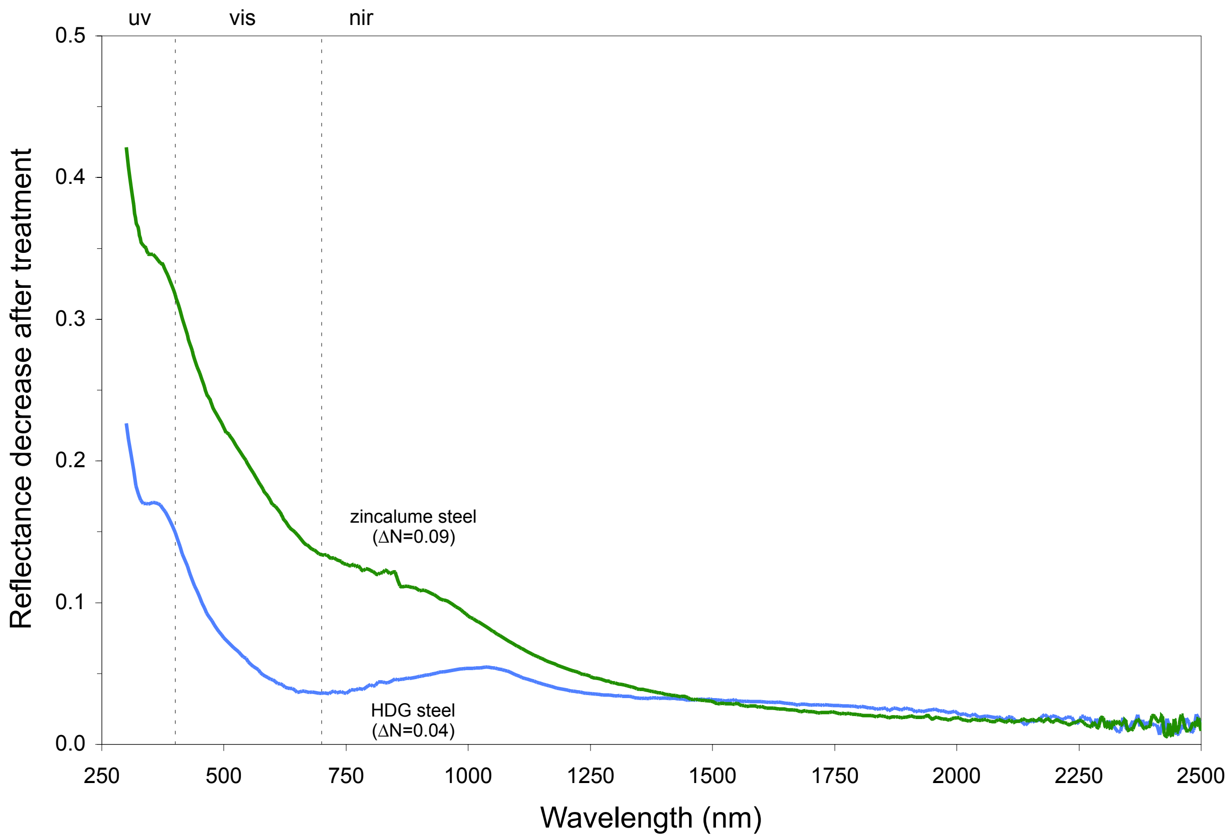

Figure 4. Decreases in spectral reflectance induced by treating ZINCALUME® and hot-dipped galvanized (HDG) steels.

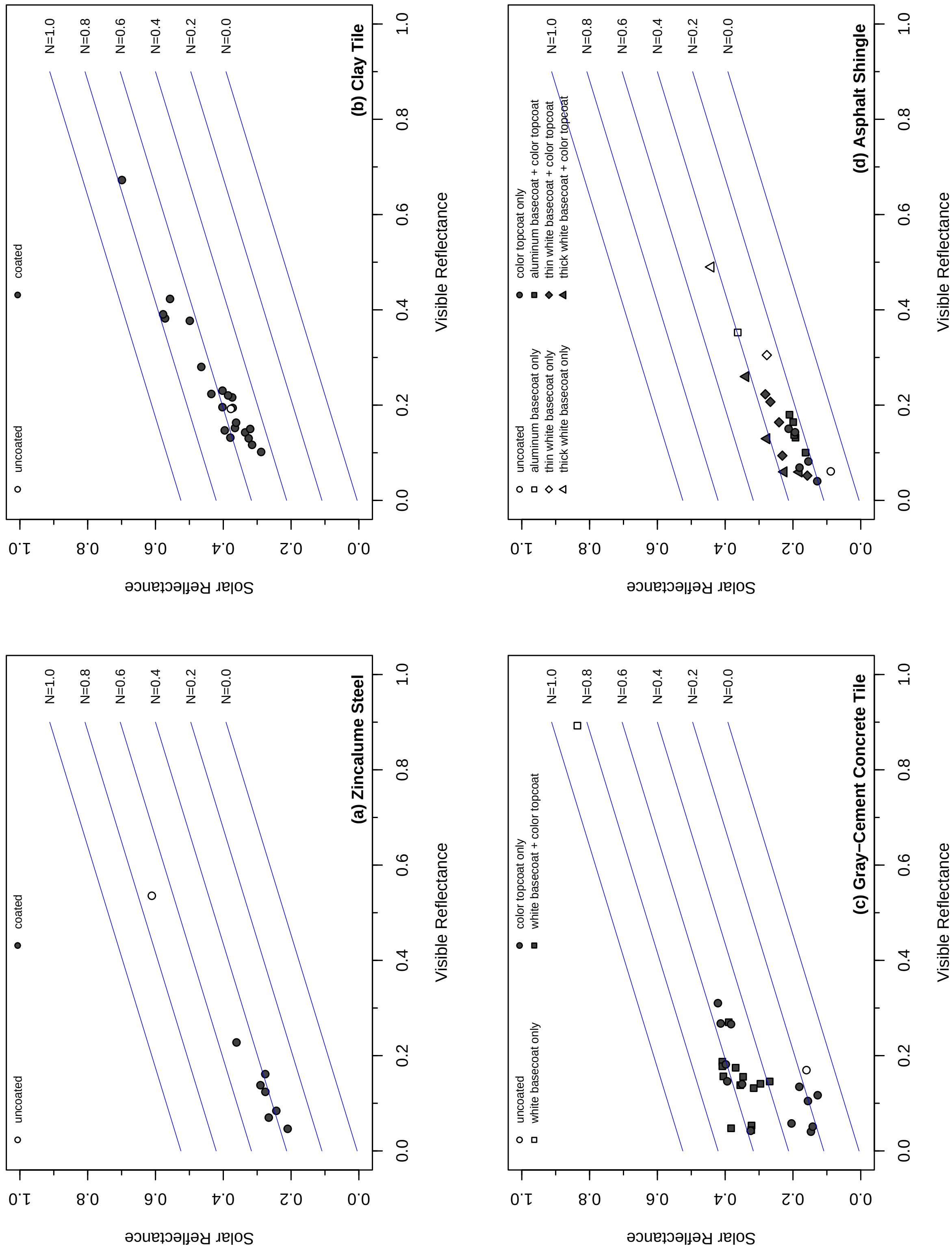

Figure 5. Solar vs. visible reflectances of uncoated and cool-coated samples of (a) treated ZINCALUME® steel, (b) clay tile, (c) gray-cement concrete tile, and (d) granule-surfaced asphalt shingles. Lines of constant NIR-reflectance N assume a UV reflectance of 0.1.

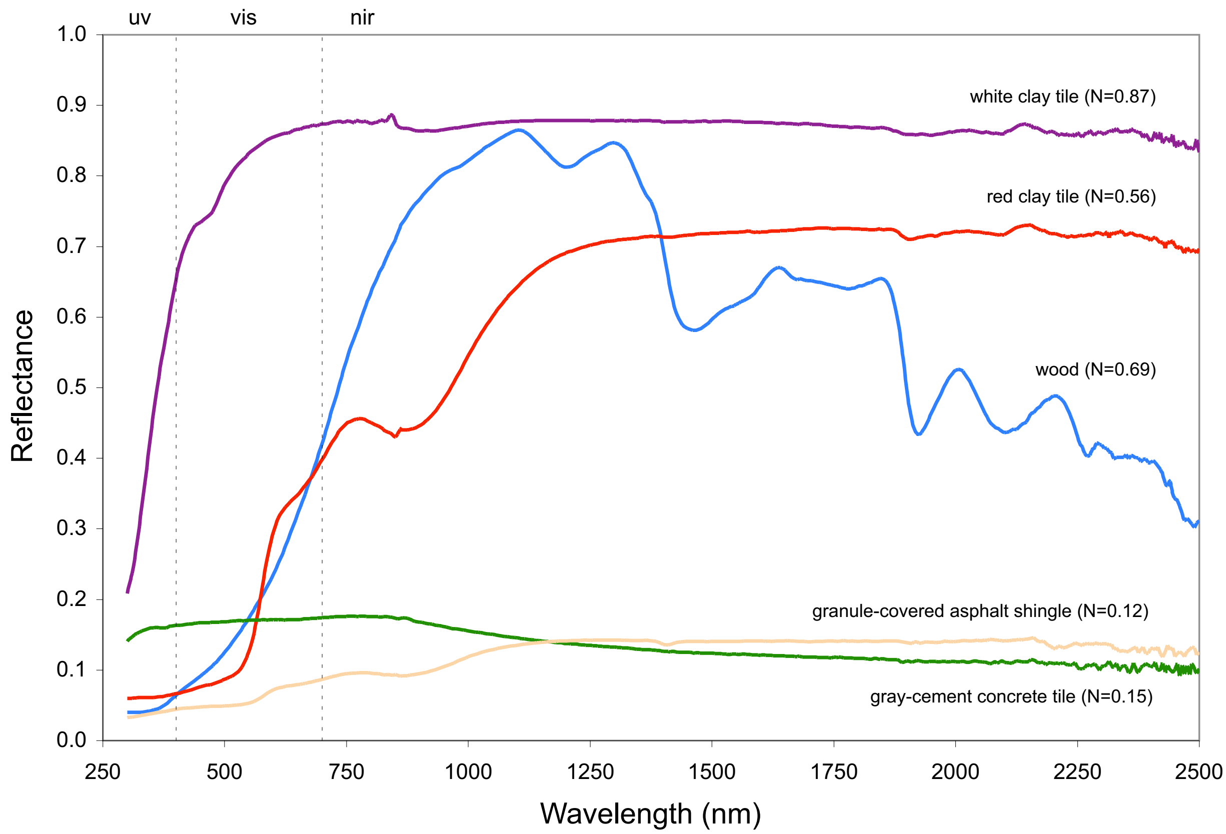

Figure 6. Solar spectral reflectances and NIR reflectances (N) of five uncoated, nonmetallic substrates: white clay tile, red clay tile, wood, granule-covered asphalt shingle, and gray-cement concrete tile.

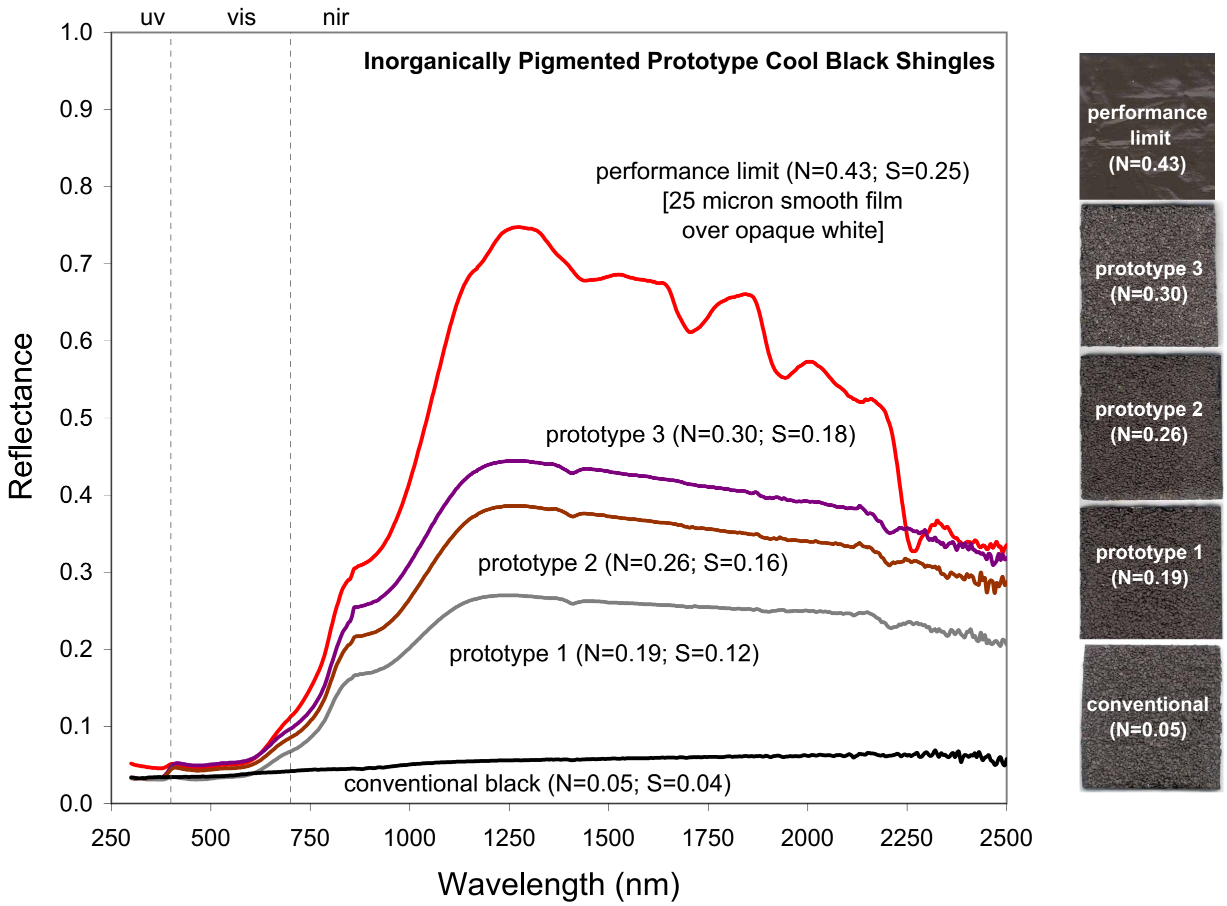

Figure 7. Development of an inorganically pigmented cool black asphalt shingle (N=near-infrared reflectance; S=solar reflectance).

Cool Roofing Prototype Development Activities

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Introduction

From May 2002 to May 2005, the California Energy Commission sponsored the collaboration of Lawrence Berkeley National Laboratory (LBNL), Oak Ridge National Laboratory (ORNL), and 16 industrial partners to create prototypes of cool nonwhite residential roofing products, including metal, clay tile, concrete tile, wood, and asphalt shingle. This report details the activities of the LBNL-ORNL project team and their industrial partners. The engineering methods and prototypes developed in this effort are documented in a separate technical article by Levinson et al. (2005c).

Pigment Characterization

The characterizations of the solar spectral radiative properties of pigmented coatings performed in a parallel task of the Cool Colors project guided the selection of pigments to use in each form of cool roofing. LBNL collaborated with pigment manufacturer Ferro Corporation, pigment manufacturer Shepherd Color Company, and coating manufacturer BASF Industrial Coatings in this activity. The followings are the highlight of the activities:

- LBNL visited a Ferro research facility (Cleveland, OH) in May 2002 to learn about pigments and a BASF Industrial Coatings research facility (Colton, CA) in June 2002 to learn about pigmented coatings.
- Ferro and Shepherd each supplied LBNL with dry pigments, concentrated paints, and technical advice on the preparation of pigmented coatings. BASF Industrial Coatings gave LBNL 26 pigmented free-films, plus an assortment of laboratory instruments used to prepare and characterize coatings.
- LBNL characterized 87 pigmented coatings, including those from Ferro, Shepherd, and BASF Industrial coatings, as well as coatings prepared from artist paints. The theory behind and results of LBNL's extensive pigment characterization efforts are presented in a pair of technical articles by Levinson et al. (2005a,b).

Collaboration with Metal Roofing Industry

LBNL collaborated with coating manufacturer BASF Industrial Coatings, coil coater Steelscape, and metal roofing manufacturer Custom-Bilt Metals to develop cool metal roofing. The followings are the highlights of the activities:

- LBNL visited a BASF Industrial Coatings research facility (Colton, CA) in June 2002 to learn about pigmented coatings for metal systems; a Steelscape factory (Rancho Cucamonga, CA) in April 2003 to learn about the coil coating process; and the Custom-Bilt Metals headquarters (Chino, CA) in March 2005 to learn about metal roofing production. The information obtained in these and other plant visits are documented by Akbari et al. (2005a,b).
- LBNL measured the solar and solar-spectral reflectances (ASTM C1549, ASTM E903) and thermal emittances (ASTM C1371) of approximately 20 conventionally and cool coated metal coupons provided by BASF Industrial Coatings, as well as those of four treated and untreated bare metal coupons supplied by Steelscape. LBNL then extensively characterized the solar spectral properties (reflectance, transmittance, absorptance, backscattering coefficient, and absorption coefficient) of 26

single-pigment topcoats and a primer layer provided by BASF Industrial Coatings. Those pigmented coatings that exhibited weak NIR absorption were classified as "cool," while those with strong NIR absorption were classified as "hot."

- LBNL created and gave to BASF Industrial Coatings a poster comparing the radiative properties and sunlit temperatures of cool metal roofing panels with those of color-matched conventional metal roofing panels.
- The bare metal substrates (ZINCALUME® steel, hot-dipped-galvanized [HDG] steel) were determined to be strong NIR reflectors, though HDG steel was more reflective than ZINCALUME® steel, and the treatment process (needed for good paint adhesion) reduced the NIR reflectance of both substrates. The primer layer was found to be very cool (minimal NIR absorption, moderate NIR backscattering).
- LBNL reported all measured solar and thermal radiative properties to BASF, recommending (a) the use of cool pigments (those inducing weak NIR absorption), (b) the avoidance of hot pigments (those inducing strong NIR absorption), and (c) the use of thicker and/or more heavily pigmented primer layer. Increasing the thickness of the primer layer was determined to be impractical, because thicker coating systems are more likely to break when sharply bent.

BASF Industrial Coatings has launched "Super II Ultra-Cool," a line of cool colored silicone modified polyester coatings that is quickly replacing the more conventional silicone modified polyester coatings. Steelscape has recently introduced Spectrascape MBM, a cool Kynar coating for the metal building industry. Custom-Bilt Metals has switched over 250 of its metal roofing products to cool colors.

Collaboration with Clay Tile Roofing Industry

LBNL collaborated with clay roofing tile manufacturer MCA Tile and pigment manufacturer Ferro Corporation to develop cool clay tile roofing. The followings are the highlights of the activities:

- LBNL visited the MCA Tile factory (Corona, CA) in April 2003 to learn about clay tile production.
- LBNL measured the solar and solar spectral reflectances of 24 bare and glazed clay roofing tiles chips (small pieces of tile) supplied by MCA Tile.
- LBNL's efforts to characterize pigmented glazes in a manner analogous to that used to characterize pigmented polymer coatings were impeded by difficulties identifying a clear substrate with a rate of thermal expansion close to that of a silicate glaze that can also be fired at 1000°C. Instead, LBNL measured the solar spectral reflectances of a set of "concentration ladders" for each of 20 single-pigment glazes provided by Ferro. Each ladder was a set of five or six white ceramic tile chips that had been glazed with various mass concentrations of a particular pigment. This data will be used in future efforts to characterize tile pigmented tile glazes.
- LBNL determined that the bare terracotta tile and most of the glazed tiles had high NIR reflectance. LBNL recommended avoiding the use of certain hot pigments (e.g., carbon black, burnt sienna) in glazes, and suggested that adding a white basecoat beneath the color topcoat might modestly increase the NIR reflectance of a glazed tile. No major action was required other than avoid the use of the hot pigments.

MCA Tile is selling 11 products with solar reflectances exceeding the Energy Star requirement of 0.25.

Collaboration with Concrete Tile Roofing Industry

LBNL collaborated with concrete tile manufacturer MonierLifeTile LLC and concrete tile coating manufacturer American Rooftile Coatings to develop cool concrete roofing tiles. The followings are the highlights of the activities:

- LBNL visited a MonierLifeTile factory (Lathrop, CA) in October 2003 to learn about concrete tile production.
- LBNL measured the solar and solar spectral reflectances of bare gray-cement concrete tile and 25 gray-cement concrete tile chips with pigmented acrylic coatings produced by American Rooftile Coatings.
- LBNL determined that (a) the gray-cement concrete tile had low NIR reflectance; (b) the rooftile coatings colored with nominally cool mixed metal oxide pigments achieved high NIR reflectance over the gray tile; and (c) some, but not all, of the cool coatings could be made significantly more reflective by adding a white basecoat. At LBNL suggestions, American Rooftile Coatings created prototype coating systems with ultramarine blue or perylene black topcoats over white basecoats. LBNL confirmed that these new coating systems were appreciably cooler over a gray tile substrate than similarly colored single-coating systems.

American Rooftile Coatings is expanding its production capacity and plans to sell by fall 2005 cool rooftile coatings in a wide variety of colors.

Collaboration with Wood Roofing Industry

LBNL and ORNL collaborated with pigment manufacturer Ferro Corporation and fire-retardant manufacturer Galchem Chemical Inc. The followings are the highlights of the activities:

- LBNL measured the solar and solar spectral reflectances of bare wood and of 16 Ferro-supplied samples of wood coated with mixed-metal oxide cool paints.
- LBNL determined that the high NIR reflectance of bare wood is somewhat increased by the application of cool yellow and green paints and somewhat decreased by the application of cool black paint. Trials by Galchem Chemical showed that mixed-metal oxide cool pigments tended to draw fire retardant chemicals out of treated wood. Hence, LBNL and ORNL do not recommend the application of mixed-metal oxide cool pigments to wood roofing, and note that bare wood is a cool roofing product.

There are no cool coated wood roofing products under development. However, typical bare wood roofing products are cool.

Collaboration with Asphalt Shingle Roofing Industry

LBNL collaborated with granule manufacturer ISP Minerals Incorporated, granule manufacturer 3M Mineral Products, shingle manufacturer CertainTeed, and shingle manufacturer Elk Corporation. The followings are the highlights of the activities:

- LBNL visited an Elk Corporation factory (Shafter, CA) in February 2003 and the Elk Corporation headquarters (Ennis, TX) in November 2003 to learn about shingle production, and an ISP Minerals factory (Ione, CA) in March 2003 to learn about the granule production.
- LBNL characterized the solar and solar spectral reflectances of over 100 prototype asphalt shingles produced by ISP Minerals, CertainTeed, and Elk. LBNL also developed a technique (now adopted by the Cool Roofing Rating Council) for measuring the mean solar reflectance of a blended-granule

asphalt shingle, and used it to determine the mean solar reflectance of about 20 blended-granule shingle boards. LBNL shared this technique with all its industrial partners, including ISP Minerals, CertainTeed, and Elk.

- LBNL and ISP Minerals iteratively increased the solar reflectance of asphalt shingles by improving the solar reflectances of their granules. Techniques explored included (a) replacing hot pigments by cool pigments; (b) adding NIR reflective basecoats pigmented with titanium dioxide (rutile) or aluminum; (c) blending dark granules with light granules; and (d) blending large and small granules to smooth the granulated surface. Methods (a) and (b) increased the solar reflectance that could be achieved by dark shingles, while method (c) made shingles both lighter in color and more solar reflective. Method (d) did not significantly increase solar reflectance.

  In separate efforts, Elk collaborated with 3M Industrial Minerals to develop cool granules shingles, and CertainTeed increased the solar reflectance of its own granules and shingles. LBNL provided technical suggestions and software tools to Elk, 3M, and CertainTeed, and measured the solar and solar spectral reflectances of some of their prototype shingles.

Elk has announced a small product line of light-gray asphalt shingles with solar reflectances that meet or exceed the Energy Star requirement of 0.25. ISP Minerals and CertainTeed have produced dark black, brown, and green prototype shingles with solar reflectances closer to 0.20. We expect that all three firms will expand their cool-product offerings in the near future.

Summary

LBNL, ORNL, and their 16 industrial partners have collaborated over the past three years to develop cool, nonwhite residential roofing products, including metal, clay tile, concrete tile, wood, and asphalt shingle. Development efforts included plant visits, to learn about production processes; prototype characterization, to determine the radiative properties of existing and experimental products; and prototype refinement, to improve solar reflectance. Clay tile and metal cool roofing products are now in the market, and conventional wood roofing products are already cool. Cool coatings for concrete tiles are expected to be available in production quantities by fall 2005. A limited line of cool asphalt shingles is now available, and more are expected in the near future.

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Estimates of Energy-Savings for Cool Colored Residential Roofs in California

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Estimates of Energy-Savings for Cool Colored Residential Roofs in California

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1. Introduction

Raising the solar reflectance of a roof from a typical value of 0.1–0.2 to an achievable 0.6 can reduce cooling-energy use in buildings by more than 20%. Cool roofs also reduce ambient outside air temperature, thus further decreasing the need for air conditioning and retarding smog formation.

We are collaborating with pigment manufacturers to characterize colorants, and with manufacturers of roofing materials to produce cool colored products, including asphalt shingles, concrete and clay tiles, metal roofing, wood shakes, and coatings. In this collaboration, we have identified and characterized pigments suitable for cool-colored coatings, and developed engineering methods for applying cool coatings to roofing materials. We are also measuring and documenting the laboratory and *in-situ* performances of roofing products. Demonstration of energy savings can accelerate the market penetration of cool-colored roofing materials. Early results from this effort have yielded colored concrete, clay, and metal roofing products with solar reflectances exceeding 0.4. Obtaining equally high reflectances for roofing shingles is more challenging, but some manufacturers have already developed several cost-effective colored shingles with solar reflectances of at least 0.25.

One of the project tasks (Task 2.7.3) was to develop preliminary estimates of cooling electricity savings and potential heating energy penalties resulting from the installation of cool colored roofing materials on residential buildings in California. To accomplish this objective, we simulated the cooling and heating energy use of a prototypical building for 16 California climate zones. This brief report highlights the characteristics of the prototype buildings and summarizes the results of the simulations.

2. Residential Building Descriptions

The prototype residential building was modeled as a single-story single-family detached structure. Changing the reflectance of the roof affects the heat transfer through the roof structure. Therefore, we focused on prototypical simulations of the upper floor, which captures the effects of changes in roof reflectance. The average roof area selected for these prototypical simulations was 1600 ft^2.

The roof was constructed with asphalt shingles on a 20° sloped plywood deck, over a naturally ventilated and unconditioned attic, above a studded ceiling frame with fiberglass insulation (varying by vintage), and with a sheet of drywall beneath. The fractional-leakage-area of the attic and living quarters depended on vintage. Variable air infiltration was modeled by the

Sherman-Grimsrud algorithm (Sherman 1986). The existing solar reflectance of the roof was selected to be 0.1, typical for dark asphalt shingles, and the albedo of the reflective roof was taken to be 0.3. The thermal emittance of each roof was 0.9.

The residence was cooled and heated by a central air-conditioning system with ducts located in the attic space, with a constant volume fan, and without an economizer. Heating was modeled once with a gas furnace and again with an electric heat pump. Cooling by natural ventilation was available by window operation. The systems were sized based on peak cooling and heating loads as determined by DOE-2. System component efficiencies were selected for each vintage. A Seasonal Energy Efficiency Ratio (SEER) of 8.5 and 10 was assumed for the central air-conditioner of the pre-1980 and 1980^+ buildings, respectively. Also a Heating Season Performance Factor (HSPF) of 5 and 7 was assumed for the stock of old and new residential central electric heat pumps.

Modified part-load-ratio curves for a typical air-conditioner, heat pump, and gas furnace were used in place of the standard DOE-2 curves, as they have been shown to model low-energy use more accurately (Henderson 1998). Duct loads were simulated with a validated residential duct function (Parker *et al*. 1998) implemented into DOE-2 to better estimate the thermal interactions between the ducts and space. The function was designed for the residential central system type (RESYS) in DOE-2 and for a single air-conditioned living space with an attic and basement. Since this function greatly improves cooling- and heating-energy use estimates, and the top story of a building receives the bulk of the benefits of a reflective roof, the single-story residential structure was modeled.

Building data for residences are shown in **Table 1** and were obtained from several sources. We used existing data to characterize the existing stock of pre-1980 buildings (Konopacki *et al*., 1997). Characteristics for 1980^+ construction homes were identified from DOE national appliance energy standards (NAECA 1987), California Energy Commission prototypes (CEC 1994), and Energy Star® (USDOE 2001).

3. Solar-Reflectance of Cool Colored Roofs

To simulate the effect of cool colored materials, the values of roof albedo were chosen to be 0.1 for the base case (representing dark colored fiberglass asphalt shingles) and 0.3 for the cool case (representing colored cool shingles). The thermal emittance of each material was 0.9. In DOE-2 the *ABSORPTANCE* keyword for roof construction was 0.9 (solar reflectance 0.1) for the basecase and was changed to 0.7 (solar reflectance 0.3). To estimate savings from increased roof reflectance ($\Delta\rho$) other than the differential specified in the tables, multiply the savings by the ratio $\Delta\rho/0.2$[*].

We estimated the cooling electricity savings and heating energy penalties for various levels of roof insulation: R-5, R-7, R-11, R-19, and R-30 for pre-1980 prototypes; and R-11, R-19, R-30, R38, and R-49 for 1980^+ prototypes.

[*] Linear interpolation can be used to estimate savings or penalties for net changes in roof solar reflectance ($\Delta\rho_2$) other than that used in the simulations ($\Delta\rho_1$) (Konopacki *et al*. 1997). Therefore, these results can be simply multiplied by the ratio $\Delta\rho_2/\Delta\rho_1$ to obtain estimates for other roof reflectance scenarios.

3. Weather Data

We used the California Energy Commission CTZ (California Thermal Zone) climate descriptions to simulate the cool-roof savings from in each of 16 zones. **Table 2** shows the number of cooling and heating degree days in each zone.

4. Simulation results

Tables 3-6 summarize the results of the simulations. For most California climates, the application of cool colored roof yields net savings in the range of 100-400 kWh per 1000 ft^2 per year. The savings are obviously smaller for buildings with higher roof insulation.

The results presented in Tables 3-6 also apply to flat cool colored concrete and clay tiles. For most clay tiles, the base-case solar reflectance is about 0.2 and the cool-case solar reflectance is 0.4.

5. Summary

We have performed building energy simulations for a prototype residential building in 16 California Climate zones. Cool colored roofing materials can increase the solar reflectance of the roofs by about 0.2. Such an increase in solar reflectance of the roof will result in cooling energy savings in the range of 100-400 kWh per 1000 ft^2 per year.

6. Acknowledgement

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Table 1. Prototypical building description for single-family residence.

Single-Family Residence	**Pre-1980**	**1980+**
single-story, non-directional		
roof & floor area (ft^2)	1,600	
Zones		
living (conditioned)		
attic (unconditioned)		
basement (unconditioned)		
Roof Construction		
20° slope		
¼" asphalt shingle		
¾" plywood deck w/ 2" x 6" rafters		
naturally ventilated attic		
¾" plywood deck w/ 2" x 6" rafters (15%)		
fiberglass insulation (85%)	parametric	parametric
½" drywall		
Roof Solar Reflectance		
pre	0.1	
post	0.3	
Roof Thermal Emittance	0.9	
Wall Construction		
brick exterior		
wood frame (15%)		
fiberglass insulation (85%)	R-5	R-13
½" drywall interior		
Windows		
clear with operable shades		
number of panes	1	2
window to wall ratio	0.18	
Fractional Leakage Area (in^2/100 ft^2)		
living	4	2
attic	8	4
Air-conditioning equipment		
central a/c, direct expansion, air-cooled		
seasonal energy efficiency ratio (SEER)	8.5	10
coefficient of performance (COP)	2.5	2.9
cooling setpoint (°F)	78	
natural ventilation available		
Heating Equipment		
1) central forced air gas furnace		
efficiency (%)	70	78
heating setpoint (°F)	70	
11pm - 7am setback (°F)	60	
2) central electric heat pump		
heating season performance factor (HSFP)	5	7
Duct Air Leakage (%)	20	10

Table 2. Heating and Cooling Degree Days (base 65) for each California Thermal Zone (CTZ).

Climate Zone	City	HDD65	CDD65
CTZ1	Arcata	3933	0
CTZ2	Santa Rosa	3073	482
CTZ3	Oakland	2588	50
CTZ4	Sunnyvale	2367	351
CTZ5	Santa Maria	2504	49
CTZ6	Los Angeles	1521	389
CTZ7	San Diego	1292	547
CTZ8	El Toro	1424	808
CTZ9	Pasadena	1361	1035
CTZ10	Riverside	1674	1363
CTZ11	Red Bluff	2709	1408
CTZ12	Sacramento	2675	871
CTZ13	Fresno	2237	2029
CTZ14	China Lake	2979	1858
CTZ15	El Centro	875	4156
CTZ16	Mount Shasta	5414	292

Table 3. Estimates of annual cooling electricity savings (kWh) and heating energy penalties (therms) from installation of cool-colored roofs on pre-1980 single-family detached homes with gas furnace heating systems. All savings and penalties are per 1000 ft^2 of roof area. Solar reflectance change is 0.2 (for fiber glass asphalt shingles: change of the roof reflectance from 0.1 to 0.3; for clay and concrete tiles: change of the roof reflectance 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)	Cooling (kWh)	Heating (therms)	Cooling (kWh)	Heating (therms)	Cooling (kWh)	Heating (therms)	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 4. Estimates of annual cooling electricity savings (kWh) and heating energy penalties (therms) from installation of cool-colored roofs on 1980^+ single-family detached homes with gas furnace heating systems. All savings and penalties are per 1000 ft^2 of roof area. Solar reflectance change is 0.2 (for fiber glass asphalt shingles: change of the roof reflectance from 0.1 to 0.3; for clay and concrete tiles: change of the roof reflectance 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)	Cooling (kWh)	Heating (therms)	Cooling (kWh)	Heating (therms)	Cooling (kWh)	Heating (therms)	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

Table 5. Estimates of annual cooling electricity savings (kWh) from installation of cool-colored roofs on pre-1980 single-family detached homes with electric heat pump heating systems. All savings and penalties are per 1000 ft^2 of roof area. Solar reflectance change is 0.2 (for fiber glass asphalt shingles: change of the roof reflectance from 0.1 to 0.3; for clay and concrete tiles: change of the roof reflectance 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	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)
CTZ1	-178	-184	-189	-185	-181
CTZ2	-79	-90	-100	-105	-108
CTZ3	-168	-174	-179	-177	-174
CTZ4	-106	-115	-124	-127	-128
CTZ5	-168	-175	-180	-177	-174
CTZ6	-98	-108	-118	-121	-122
CTZ7	-66	-77	-89	-95	-98
CTZ8	-12	-26	-41	-51	-58
CTZ9	34	19	1	-14	-23
CTZ10	102	83	61	40	28
CTZ11	111	92	69	48	34
CTZ12	1	-13	-29	-41	-48
CTZ13	239	214	183	150	130
CTZ14	203	180	151	122	103
CTZ15	676	631	572	502	456
CTZ16	-118	-127	-135	-137	-137

Table 6. Estimates of annual cooling electricity savings (kWh) from installation of cool-colored roofs on 1980+ single-family detached homes with electric heat pump heating systems. All savings and penalties are per 1000 ft^2 of roof area. Solar reflectance change is 0.2 (for fiber glass asphalt shingles: change of the roof reflectance from 0.1 to 0.3; for clay and concrete tiles: change of the roof reflectance 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	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)
CTZ1	-75	-70	-64	-62	-59
CTZ2	-28	-30	-30	-29	-28
CTZ3	-70	-66	-61	-58	-55
CTZ4	-41	-41	-39	-38	-36
CTZ5	-70	-66	-61	-58	-56
CTZ6	-37	-38	-36	-35	-34
CTZ7	-22	-24	-25	-25	-24
CTZ8	4	-3	-6	-7	-7
CTZ9	26	16	10	8	7
CTZ10	57	43	34	30	28
CTZ11	62	47	37	33	30
CTZ12	10	2	-2	-3	-4
CTZ13	122	98	82	75	70
CTZ14	105	84	69	64	59
CTZ15	328	274	235	219	204
CTZ16	-47	-46	-43	-42	-40