Special Infrared Reflective Pigments Make a Dark Roof Reflect Almost Like a White Roof

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ABSTRACT

Pigment colorant researchers are developing new complex inorganic color pigments that exhibit dark color in the visible spectrum and high reflectance in the near infrared portion of the electromagnetic spectrum. The new pigments increase the near infrared reflectance of exterior finishes and paints, thereby dropping the surface temperatures of roofs and walls, which, in turn, reduces the cooling-energy demand of the building. However, determining the effects of climate and solar exposure on the reflectance and the variability in color over time is of paramount importance for promoting these energy efficiency benefits and for accelerating the market penetration of products using the new color pigments.

INTRODUCTION

A new roofing product is about to revolutionize the building industry, bringing relief to homeowners and utilities alike. Cool roof color materials (CRCMs) made from complex inorganic color pigments (CICPs) will reduce the amount of energy needed to cool buildings, helping the power utilities reduce hot weather strain on the electrical grids. The new technology will help mitigate carbon dioxide emissions, reduce the impacts of metropolitan heat buildups and urban smog, and support conservation of water resources otherwise used to clean and process fuel consumed by fossil fuel-driven power plants (Gipe 1995).

The California Energy Commission (CEC) has two national laboratories, Oak Ridge (ORNL) and Lawrence Berkeley (LBNL), working collaboratively on a three-year, $2 million project with the roofing industry to develop and produce new reflective, colored roofing products. The CEC aims to make CRCMs a market reality in the California homebuilding industry within three to five years. For tile, painted metal, and wood shake, the CEC's goal is products with about 0.50 solar reflectance. For residential shingles, the goal is a solar reflectance of at least 0.30.

The Florida Power & Light Company sponsored a field project in Fort Myers, Florida, that compared the energy performance of six identically constructed, side-by-side homes built with various reflective roof products. Parker et al. (2002) showed that a white galvanized metal roof and a white S-shaped cement tile roof caused the respective Fort Myers homes to use 4.2 to 3.0 kilowatt-hours per day less air-conditioning energy than an otherwise identical home with a dark gray asphalt shingle roof. The measurements showed that the white reflective roofs reduced cooling energy consumption by 18% to 26% and peak demand by 28% to 35%. The resultant annual savings for comfort cooling the two homes with white reflective roofs was reported at roughly $120, or about 6.7¢ per square foot per year, which is very promising. However, in the residential market, the issues of aesthetics and durability are more important to the homeowner than are the potentials for reduced air-conditioning loads and reduced utility bills. To homeowners, dark roofs simply look better than their counterpart, a highly reflective "white" roof. What the public does not know, however, is that the aesthetically pleasing dark roof can be made to reflect like a "white" roof in the near infrared spectrum.

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Therefore, a combined experimental and analytical approach is in progress with field data just coming available, some of which we are reporting along with preliminary results of computer simulations showing the potential energy savings throughout the U.S. for residential homes having CRCM roofs. A roof covered with CRCMs absorbs less solar energy and we believe can reduce home air-conditioning energy ~20%, which, in turn, reduces the national primary energy consumption by ~0.5 quads per year.

COOL ROOF COLORED MATERIALS (CRCMS)

Dark roofing can be formulated to reflect like a highly reflective "white" roof in the near infrared (NIR) portion of the solar spectrum (700 to 2,500 nm). For years the vinyl siding industry has formulated different colors in the same polyvinyl chloride base by incorporating titantium dioxide (TiO_2) and black NIR-reflective paint pigments to produce dark siding that is cool in temperature (Ravinovitch and Summers 1984). Researchers discovered that a dark color is not necessarily dark in the infrared. Brady and Wake (1992) found that 10 µm particles of TiO_2, when combined with colorants such as red and yellow iron oxides, phthalocyanine blue, and paliogen black, could be used to formulate fairly dark colors with near infrared reflectances of 0.3 and higher. Researchers working with the Department of Defense added complex inorganic color pigments (CICPs) to paints used for military camouflage and matched the reflectance of background foliage in the visible and NIR spectra. At 750 nm the chlorophyll[1] in foliage naturally boosts the reflectance of a plant leaf from 0.1 to about 0.9, which explains why a dark green leaf remains cool on a hot summer day. Tailoring CICPs for high NIR reflectance similar to that of chlorophyll provides an excellent passive energy-saving opportunity for exterior residential surfaces such as walls and roofs. A CICP consisting of a mixture of the black pigments chromic oxide (Cr_2O_3) and ferric oxide (Fe_2O_3) increases the solar reflectance of a standard black pigment from 0.05 to 0.26 (Sliwinski et al. 2001).

Identification and Characterization of Pigments

We are working with pigment manufacturers to optimize the solar reflectance of a pigmented surface by identifying and characterizing pigments with optical properties suitable for cool roof color materials (CRCMs). LBNL characterized some 83 single-pigment paints as reported by Levinson et al. (2004b) and used the data to formulate and validate an algorithm for predicting the spectral irradiative properties (Levinson et al. 2004a). LBNL also characterized various coating additives such as "transparent" mineral fillers (e.g., mica, clay, silica, talc) and binders (e.g., polymeric resins, silicates) to identify deleterious absorptions in the near infrared. The maximum amount of each material is then determined so that it will not impair the near infrared reflectance of the pigmented surface. The spectral solar reflectance and transmittance; pigment chemistry, name, and measured film thickness; computed absorption and backscattering coefficients; and many ancillary values are planned for public dissemination for the 83 single-pigment paints from the Cool Roof Web site (http://coolcolors.lbl.gov). Further discussion of the pigment identification and characterization work is reported by Akbari et al. (2004).

Application of Pigments to Roof Products

Identifying, characterizing, and then optimizing the reflectance of a pigmented coating is only part of the job for making dark, yet highly reflective, roof products. The application of the CRCMs varies among the different roof products, and the laboratories are working with industry to develop engineering methods for successfully applying them to the sundry roof systems. Each roofing type has its own specific challenges. For composition shingles, the application of pigmented coatings to roofing granules appears to be the critical process because the solar reflectance is predominately determined by the granules, which cover ~97% of a shingle's surface. Coating the granules with CRCMs helps increase reflectance, but some pigments are partly transparent to NIR light and therefore any NIR light not reflected by the cool pigment is transmitted to the dark substrate, where it is absorbed as heat. Multiple layers of coatings can be applied to increase reflectance; however, each additional coating increases cost. A two-step, two-layer process has proven more cost-effective. In the first step, the granule is pre-coated with an inexpensive white pigment that is highly reflective to NIR light. In the second step, the cool-colored pigment is applied to the pre-coated granules.

A slurry coating process is used to add color to the surface of a clay tile. Once coated, the clay is kiln-fired, and the firing temperature, the atmosphere, and the pigments affect the final color and solar reflectance. However, for concrete tile, the colorants are included throughout the bulk of the tile or are applied as a slurry coat to the surface. The addition of CRCMs to the material bulk requires too much pigment and makes the process too expensive. Coating the tile has been successfully demonstrated by American Rooftile Coatings who applied their COOL TILE IR COATING™ to several samples of concrete tiles of different colors (Figure 1). The solar reflectance for all colors tested exceeded 0.40. Most dramatic is the effect of the dark colors. The black coating increased the solar reflectance from 0.04 to 0.41, while the chocolate brown coating increased from 0.12 to 0.41, a 250% increase in solar reflectance! Because solar heat gain is proportional to solar absorptance, the COOL TILE IR COATING™ reduces the solar heat gain roughly 33% of the standard color, which is very promising. The coating can certainly help tile roof products pass the Environmental Protection Agency's Energy Star

[1] Chlorophyll, the photosynthetic coloring material in plants, naturally reflects near IR radiation.

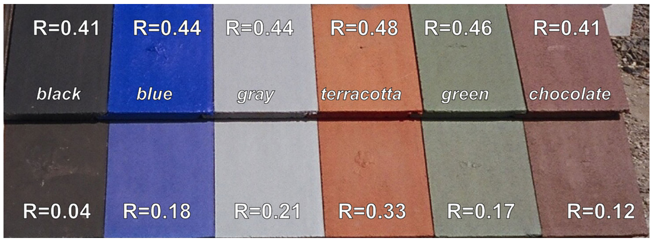

Figure 1 *Solar reflectance of concrete tile roofs with CRCMs (top row) and without CRCMs (bottom row). The COOL TILE IR COATING™ technology was developed by Joe Riley of American Rooftile Coating.*

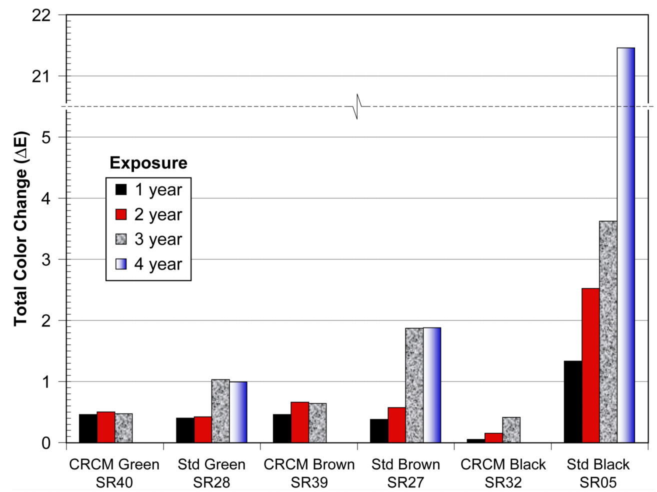

Figure 2 *Three years of natural sunlight exposure in Florida shows that the CRCMs have improved the fade resistance of the painted PVDF metals.*

0.25 solar reflectance criterion as well as California's Title 24 pending criterion[2] for steep-slope roofing.

Premium coil-coated metal roofing probably has the best opportunity for applying CRCMs because the paint coating is reasonably thick (~25 micron) and because the substrate has high NIR reflectance (ρ_{nir} ~ 0.55 to 0.7). The coatings for metal shingles are durable polymer materials, and many metal roof manufacturers have introduced the CRCM pigments in their complete line of painted metal roof products. The additional cost of the pigments is only about 5¢ per square foot of finished metal product (Chiovare 2002). Success of the new CRCM metal products is evident in the market share recently captured by the metal roof industry. Historically metal roofs have had a smaller share of only about 4% in the residential market. The architectural appeal, flexibility, and durability, due in part to the CICPs pigments, has steadily increased the sales of painted metal roofing, and, as of 2002, its sales volume has doubled since 1999 to 8% of the residential market, making it the fastest growing residential roofing product (Dodge 2002).

FADE RESISTANCE OF ROOF PRODUCTS WITH CRCMS

The color of a roof product must remain fade-resistant or the product will not sell. Industry judges fade resistance by measuring the spectral reflectance and transmittance of a painted surface and converting the measures to color-scale values based on the procedures in ASTM E308-02 (ASTM 2001). The color-scale values are compared to standard colors and the color differences (ΔL, Δa, and Δb), which represent the luminance of color, are calculated from:

ΔL = $L_{Batch} - L_{Standard}$, where $\Delta L > 0$ is lighter and a $\Delta L < 0$ is darker;

Δa = $a_{Batch} - a_{Standard}$, where $\Delta a > 0$ is redder and a $\Delta a < 0$ is greener

Δb = $b_{Batch} - b_{Standard}$, where $\Delta b > 0$ is more yellow and $\Delta b < 0$ is bluer.

Manufacturers of premium coil-coated metal use a total color difference (ΔE) to specify the permissible color change between a test specimen and a known standard. The total color difference value is described in ASTM D 2244-02 (ASTM 2002) and is a method adopted by the paint industry to numerically identify variability in color over periods of time. It is calculated by the formula,

$$\Delta E = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]^{1/2} . \quad (1)$$

Typically, premium coil-coated metal roofing is warranted for 20 years or more to have a ΔE of five units or less for that period. ΔE color changes of one unit or less are almost indistinguishable from the original color, and, depending on the hue of color, ΔE of five or less is considered very good.

Fade Resistance Results for Painted PVDF Roofing

To evaluate color changes of CRCMs as compared to standard colors, we used a three-year exposure test to natural sunlight in Florida following ASTM G7-97 (ASTM 1997). Test data showed excellent light fastness of the CRCM masstones[3] exposed in the field (Figure 2). The three color pairs labeled in Figure 2 are identified with their respective unweathered solar reflectance values (e.g., SR40 designation represents a solar reflectance of 0.40 for the CRCM green-painted PVDF metal). Differences in the masstone discoloration occur after two years of exposure for the green and brown

2. Title 24 has legislation pending approval that will require new steep-slope roofs to have a reflectance exceeding the 0.25 Energy Star threshold after 2008.

3. Masstones represents the full color of the pigment while tints are blends of colors.

Table 1. Color Difference for 50/50 Tints of the CRCMs Exposed to Natural Sunlight for Three Years in Florida[*]

	Total Color Difference (ΔE)				
Years	**Green**	**Yellow**	**Brown**	**Black**	**Marine Blue**
1	0.55	0.21	0.47	0.19	0.46
2	0.42	0.25	0.70	0.67	0.50
3	0.53	0.14	0.99	1.51	0.76

[*] ΔE based on International Commission on Illumination (CIE L*A*B) Index.

CRCM coil-coated metals. However, both the green and brown CRCM colors have faded less than their counterpart standard colors. After three years of exposure the standard black has a ΔE~3.5 as compared to the CRCM black with only a 0.5 ΔE. Four years of exposure were also available for the standard colors, and the green and brown masstones were stable, while the black showed a ΔE of 21 (Figure 2). The Florida exposure data are promising and show that over the three-year test period the CRCMs fade less than do the standard masstone colors with known performance characteristics. For the CRCM black masstone, the fade resistance is much improved over the standard color. Tints, especially the blue tints are well known to fade; however, 50/50 tints of the CRCMs field tested in Florida also show excellent fade resistance (Table 1). The highest total color change was observed for the CRCM black tint, which is still indistinguishable from the original color.

The xenon-arc accelerated weathering tests were previously reported by Miller et al. (2002) and showed that after 5000 hours of xenon-arc exposure, all CRCMs were clustered together with $\Delta E < 1.5$, which is considered a very good result.

FIELD TESTING OF ROOFS WITH CRCMS

Experimental field studies are in progress to catalog temperature, heat transmission, solar reflectance, thermal emittance, and color fastness data for CRCMs applied to tile, metal, wood shake, and composition shingle roofs. We are using the data to formulate and validate design tools for predicting the roof energy load during the cooling and heating seasons for residential buildings that use CRCM roof products. A demonstration site in Sacramento, California, has two pairs of identical homes, one pair roofed with concrete tile with and without the CRCMs and the other pair roofed with painted metal shakes with and without CRCMs. All roofs have the same visible dark brown color. A coating was applied to one of the two homes having concrete tile roofs; solar reflectance for the coated roof was a measured 0.41 as compared to the other base house with tile reflectance of only 0.08. Solar reflectance of the painted metal roof with CRCMs was 0.31 versus the roof with standard color metal shingles having 0.08 reflectance.

We are also exposing samples of metal, clay, and concrete tile materials at weathering farms in seven different climate zones of California and are conducting thermal performance testing of several tile roofs of different profile on a fully instrumented roof assembly to help quantify the potential energy savings as compared to asphalt shingles. The Tile Roof Institute (TRI) and its affiliate members are interested in specifying tile roofs as cool roof products using CRCMs. TRI is also interested in knowing the effect of venting the underside of concrete and clay roof tiles. Beal and Chandra (1995) demonstrated a 45% daytime reduction in heat flux for a counter-batten tile roof as compared to a direct nailed shingle roof. The reduced heat flow occurs because of a thermally driven airflow within a channel that is formed by the tile nailed to a counter-batten roof deck. Typically, stone-coated metal and tile coverings are placed on batten and counter-batten supports, yielding complex airflow patterns through the supports. Correctly modeling the heat flow across the air channel is a key hurdle for predicting the thermal performance of tile roofs.

The data for these field studies are just coming on-line and will be reported in future publications. However, for the present work, the results of simulations are presented for quantifying the potential energy savings for residential roofs with CRCMs. The data acquired from the demonstration homes and from the tile roof assemblies will be used to further formulate and validate our simulation tool, AtticSim.

THERMAL PERFORMANCE OF ROOFS WITH CRCMS

The ultimate goal of the pigment identification, characterization, and application work is to increase the solar reflectance of roofing materials upward of 0.50. Present CRCMs pose an excellent opportunity for raising roof reflectance from a typical value of 0.1–0.2 to an achievable 0.4 without compromising the home's exterior décor. The adoption of CRCMs into the roofing market can therefore significantly reduce the 2.0 quadrillion BTUs (quads) of primary electrical energy consumed for the comfort cooling of residential homes (Kelso and Kinzey 2000). To estimate these energy savings we conducted simulations using AtticSim based on two scenarios

- energy savings for CRCM metal products already on the open market and
- energy savings for dark roof products achieving the 0.50 solar reflectance goal.

Table 2. Reflectance and Emittance Values* for PVDF Metal Roofs with and without CRCMs

	Regal White	Surrey Beige	Colonial Red	Chocolate Brown
CRCM	SR75E80	SR65E80	SR45E80	SR30E80
Standard	SR70E80	SR52E80	SR27E80	SR08E80

* The roof colors are described generically using a SRxxEyy designation. “SRxx” states the solar reflectance; “Eyy” defines the thermal emittance. Thus, labeling the standard regal white color as SR70E80 indicates that it has a solar reflectance of 0.70 and an emittance of 0.80.

The Cool Metal Roof Coalition (CMRC) provided measurements of solar reflectance and thermal emittance of painted PVDF metal products. These values are used by AtticSim to answer the first question regarding potential energy savings for available CRCM products. The surface properties are listed in Table 2. The Table 2 reflectance data were verified by a coatings manufacturer (Scichili 2004) and show that the darker the color the greater is the increase in reflectance induced by the CRCMs. ORNL used an emissometer to measure the emittance for several samples of the Table 2 colors and found the emittance to be 0.82 ±0.02. The pigments in the CRCMs do not affect the emittance and, at the request of the CMRC, we fixed emittance at 0.80 for all the simulations.

ATTICSIM SIMULATIONS

AtticSim is a computer tool for predicting the thermal performance of residential attics. It mathematically describes the conduction through the gables, eaves, roof deck, and ceiling; the convection at the exterior and interior surfaces; the radiosity heat exchange between surfaces within the attic enclosure; the heat transfer to the ventilation airstream; and the latent heat effects due to sorption and desorption of moisture at the wood surfaces. Solar reflectance, thermal emittance, and water vapor permeance of the sundry surfaces are input. The model can account for different insulation R-values and/or radiant barriers attached to the various attic surfaces. It also has an algorithm for predicting the effect of air-conditioning ducts placed in the attic (Petrie et al. 2004). The code reads the roof pitch, length, and width and the ridge orientation (azimuth angle with respect to north) and calculates the solar irradiance incident on the roof. Conductive heat transfer through the two roof decks, two gables, and vertical eaves are modeled using the thermal response factor technique (Kusuda 1969), which requires the thermal conductivity, specific heat, density, and thickness of each attic section for calculating conduction transfer functions.

Heat balances at the interior surfaces (facing the attic space) include the conduction, the radiation exchange with other surfaces, the convection, and the latent load contributions. Heat balances at the exterior surfaces balance the heat conducted through the attic surface to the heat convected to the air, the heat radiated to the surroundings, and the heat stored by the surface. Iterative solution of the simultaneous equations describing the heat balances yields the interior and exterior surface temperatures and the attic air temperature at one-hour time steps. The heat flows at the attic’s ceiling, roof sections, gables, and eaves are calculated using the conduction transfer function equations. The tool was validated by Wilkes (1991) against field experiments and is capable of predicting the ceiling heat flows integrated over time to within 10% of the field measurement. AtticSim can predict the thermal performance of attics having direct nailed roof products, but it has not been used to predict the heat flow across a tile roof having a venting occurring on the underside of the roof, between the roof deck and exterior roof cover.

Ventilation In Attic Space

An important issue in our study is the effect of venting the attic. CRCMs are best suited to hot and moderate climates, and in hot climates the primary reason for ventilating an attic is to keep it cool and lessen the burden on the comfort cooling system. Ledger (1996) reported that some roof warranties insist on attic ventilation to protect their roof products against excessive temperatures. CRCMs can help improve the durability and extend the longevity of certain roof products, and the CRCMs will help lower the attic air temperature, thereby reducing the heat penetrating the house.

The AtticSim simulations assumed equal soffit and ridge vent openings with a net free vent area of 1:300[4]. Using a constant ventilation rate is the simple approach to simulating the attic convective heat flows; however, thermal buoyancy affects the surface temperatures of the attic enclosure, which, in turn, causes error in the calculated attic heat flows. This is especially true in climates where there is little to no wind to force air in and out of the vents. Buoyancy, termed by many as *stack effect*, then becomes the sole driving force for attic ventilation.

AtticSim was exercised for a moderately insulated (R-19 $h\cdot ft^2\cdot °F/Btu$) attic exposed in both hot and cold climates in the U.S. Roof pitch was set at 4 in. of rise per 12 in. of run and the ridge vent was oriented east–west. The soffitt and ridge vent areas were made equal and yielded a net free vent area of 1:300. We conducted a regression analysis to derive a correlation of AtticSim’s computed attic ventilation air changes per hour (ACH) as function of the wind velocity and the computed attic air to outdoor ambient air temperature gradient; results

4. Ventilation area is defined as the ratio of the net free vent area to the footprint of the attic floor area.

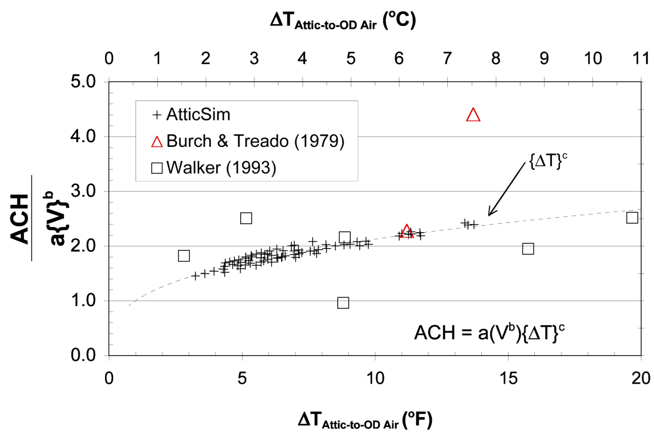

Figure 3 *The air changes per hour (ACH) computed by AtticSim are compared to literature data and show the reasonableness of the predicted ventilation rate.*

are depicted in Figure 3. Summer (June, July, and August) and winter (December, January, and February) seasonal averages were used to fit the correlation. The regression coefficients for the correlation show a stronger dependence on stack effect than on the wind-driven forces. Note that the correlation was not used for computing ACH; rather it was derived to better view both stack and wind effects in a simple two-dimensional plot and for comparing AtticSim's computations to published literature data.

The ordinate of Figure 3 is scaled by the regression parameter $1.1\{V^{0.04}\}$. The curve fit $\{\Delta T\}^{0.33}$is superimposed onto AtticSim's computed ACH values, which as stated are scaled by $1.1\{V^{0.04}\}$. The resultant graph allows direct comparison of the data by Burch and Treado (1979) and by Walker (1993) to AtticSim's output. Burch and Treado (1979) listed field data for soffit and ridge venting of a Houston, Texas, house. A tracer gas technique using sulfur-hexafluoride was released at six-inch levels above the ceiling insulation at eight different attic locations. Sixteen air samples were collected at different attic locations and the dilution of the gas yielded the ACH. They stated the attic ventilation measurements were probably somewhat on the high side; however, their field data for soffitt and ridge venting compares well to the results computed by AtticSim. Walker (1993) studied attic ventilation in Alberta, Canada. His results showed large variations in ventilation rates. We culled his data by selecting some of the measured ACH values for windspeeds not exceeding 4.5 mph (2 m/s). Further, Parker et al. (1991) also measured attic ventilation rates using short-term sulfur hexafluoride tracer gas. Their results under normal summer wind and thermal conditions at Cape Canaveral, Florida, yielded an average of 2.7 ACH over a three-day period with variation from 0.5 to 4.5 ACH. The AtticSim simulations yielded an annual average of 2.9 ACH with variation from 0.2 to 10 ACH. Therefore, the AtticSim code appears consistent with literature data and yields reasonable values of attic ventilation for the soffit and ridge venting being exercised in this report.

Simulation Procedure

Simulations generated the heat flux entering or leaving the conditioned space for a range of roof insulation levels, exterior roof radiation properties, and climates derived from the TMY2 database (NREL 1995). Roof insulation levels ranged from no ceiling insulation through R-49. Simulations assumed painted PVDF metal roofs with and without CRCMs. The roof's solar reflectance and thermal emittance were chosen based on state-of-the-art CRCMs on the open market and also based on our ultimate goal for optimizing solar reflectance (see Table 2). The roofs are assumed direct nailed to the roof deck having only a direct conduction path through the material of the roof deck. The hourly averages of the outdoor ambient dry bulb and specific humidity, the cloud amount and type, the wind speed and direction, and the total horizontal and direct beam solar irradiance were read from the TMY2 database for the climates of Miami, Florida; Dallas, Texas; Burlington, Vermont; and Boulder, Colorado. The hourly ceiling heat flux predicted by AtticSim was used to generate annual cooling and heating loads for the attic and roof combinations. An annual cooling load Q_{Cool} was defined as the time-integrated heat flux entering the conditioned space through the ceiling when the outdoor air temperature exceeded 75°F (24°C). Similarly, the annual heating load Q_{Heat} was defined as the time-integrated heat flux moving upward through the ceiling if the outdoor air temperature dropped below 60°F (16°C).

The output from AtticSim can be coupled to the DOE-2.1E program to model the effect of the ceiling heat flux from the perspective of the whole house energy consumption. However, the multiplicity of residential homes, the diversity of occupant habits, the broad range of exterior surface area-to-house volume, and the internal loading can confound the interpretation of results developed for reflective roofing. Therefore, the reported results center on the heat flows entering and leaving the ceiling of the house. Further analysis of the whole house will be conducted as the data become available from the demonstration sites to validate our results.

Simulation Results

The annual energy savings due to the change in heat penetrating the ceiling is displayed in Figure 4 for the various painted PVDF metals whose solar reflectance and thermal emittance properties are listed in Table 2. The reductions in energy (cooling savings) are based on the difference in ceiling heat flux for the same color roof with and without CRCMs. Potential savings are also shown for a popular chocolate brown roof whose solar reflectance is increased from 0.08 to our ultimate reflectance goal of 0.50.

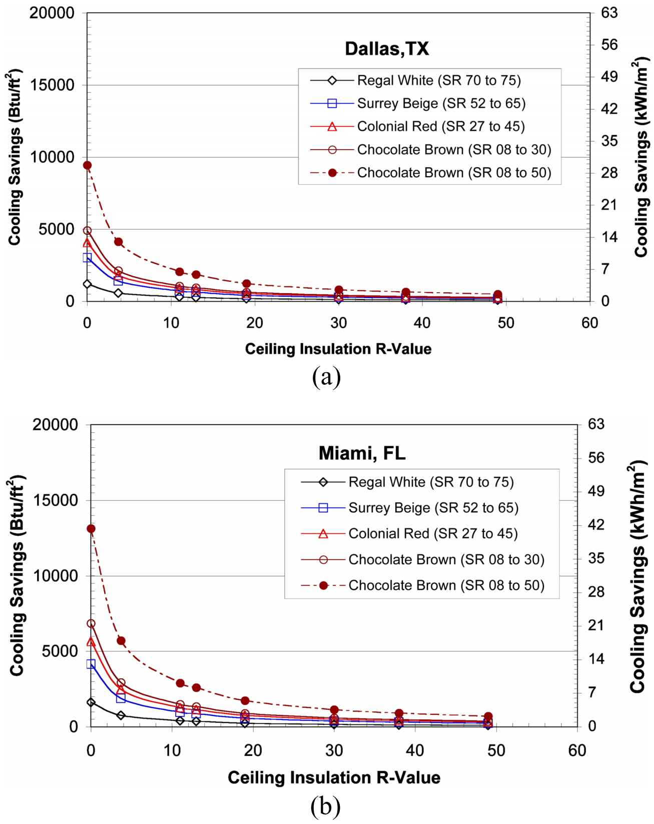

Figure 4 *The reduction in the ceiling heat produced by CRCMs as compared to the same standard color roof.*

A chocolate brown colored roof with 30% reflective CRCMs decreased the consumed cooling energy by 15% of that used for a roof with standard colors exposed in Miami and Dallas; the cooling savings are respectively 623 and 884 Btu per year per square foot of ceiling for an attic having R-19 insulation[5](Figure 4). We believe the pigment optimizations can increase reflectance to the 0.50 mark. In that case, the heat penetrating the ceiling would drop by 30% of that computed for the same standard color roof exposed in Miami and Dallas.

Note that as the roof color lightens, the CRCMs produce less energy savings compared to the same standard pigmented color because the lighter colored standard materials have higher solar reflectance to start with (Figure 4). The increase in solar reflectance caused by CRCMs diminishes as the visible color of the roof lightens from black to brown to a white painted PVDF metal (Figure 4). The CRCMs induce about a 0.05 reflectance point increase for white-painted metal (SR70E80) while a darker chocolate brown roof (SR08E80) increases 0.22 points (Table 2), which is the benefit of the CRCMs. People prefer the darker color roof and the dark colors yield the higher gain in reflectance. The data in Figure 4, therefore, show the level of

[5] The International Energy Conservation Code's recommended ceiling R-value for Dallas is R-19 and for Miami is R-13 for a home having windows covering 12% of the exterior walls.

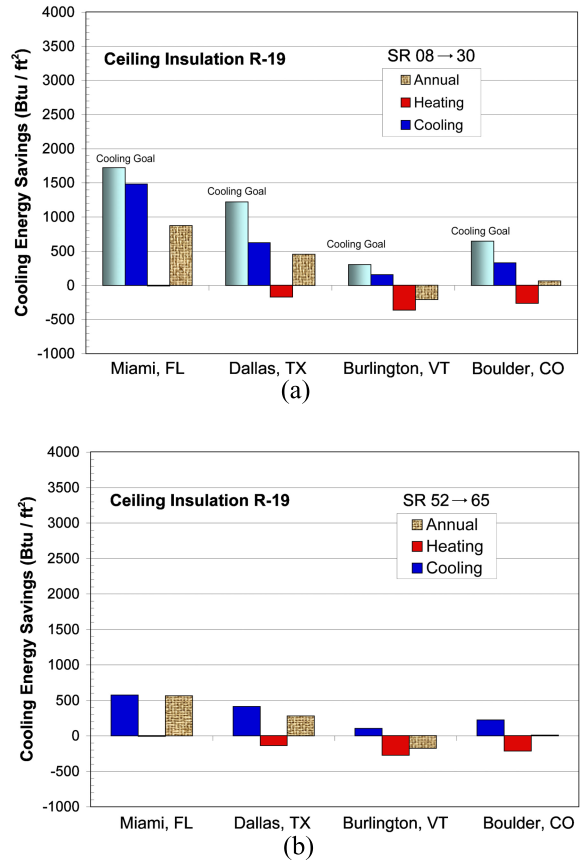

Figure 5 *The cooling, heating, and net annual energy savings achieved by CRCMs as compared to the same standard color roof with R-19 attic insulation, kWh = 0.00315*[Btu/ft^2].*

achievable energy savings with roof color for existing CRCMs being marketed as cool roof products. However, further improvements are achievable! We have successfully demonstrated concrete tile coatings (Figure 1) with reflectances slightly above 0.40 and continue to develop prototype coatings to achieve our solar reflectance goal of 0.50, a ~0.40 increase in solar reflectance over a standard brown color.

Figure 4 compares materials of the same color. However, the lighter the color of the roof, the greater are the energy savings due to less heat penetrating the roof. If the comparison is made between different colors, one can judge the thermal advantage gained by selecting a lighter roof décor. As an example, if the surrey beige with CRCM (SR65E80) is compared to the standard chocolate brown (SR08E80), then the surrey beige reduces the ceiling heat flux 42% of that predicted for the standard brown(SR08E80) roof exposed in Dallas with R-19 attic insulation. In comparison, the same chocolate brown color (SR30E80) saved 15% compared to the same color (SR08E80).

CRCMs in Various Climates

Simulations for attics with R-19 insulation (Figure 5) show the trade-offs between the heating and cooling season. In the

Table 3. Ceiling Insulation Minimum R-Values Recommended by the IECC for Homes with Windows Covering 12% of the Exterior Wall

	Burlington, VT	Boulder, CO	Dallas, TX	Miami, FL
Recommended R-Value	R-49	R-38	R-19	R-13
HDD_{65}	7903	6012	2304	141
CDD_{65}	407	623	2415	4127
Solar flux[1] [Btu/(h·ft^2)]	1194	1467	1559	1557
SR08 Annual Cooling[2] [Btu/yr·ft^2]	335	920	4017	8450
SR50 Annual Cooling [Btu/yr·ft^2]	215	596	2798	5860

[1]Average daily global flux incident on a horizontal surface.
[2]Annual cooling represents the annual energy transfer by attic heat penetrating through the ceiling into the living space.

more moderate climates, there is a heating load penalty that offsets the cooling energy savings and, because higher levels of insulation are required in moderate to cold climates, CRCMs do not yield an energy savings. Burlington, Vermont, is a cold climate and incurs an annual penalty for roofs with CRCMs (Figure 5) regardless of the level of attic insulation. A slight benefit is observed for the climate of Boulder, exposing brown and surry beige colored roofs having CRCMs (Figure 5). Obviously, the hotter the climate, the better is the performance of the CRCMs. In Miami, the net savings are almost 900 Btu per year per square foot for a chocolate brown CRCM covering an attic with R-19 ceiling insulation (Figure 5).

Ceiling Insulation Effects

The most obvious trend shown in Figure 4 is the effect of the ceiling insulation on the reduction of heat penetrating into the conditioned space. The level of attic insulation directly affects the ceiling's thermal load. As an example, for Dallas, Texas, a chocolate brown metal roof (SR30E80) saves about 4902 Btu per year per square foot for an attic having no ceiling insulation (Figure 4). Increasing the insulation to R-19 drops the savings to 623 Btu per year per square foot. R-49 further drops the savings to only 250 Btu per year per square foot. Table 3 lists the International Energy Conservation Code's recommended attic R-values based on the number of heating degree-days (HDD65). The number of cooling degree days (CDD65) and the average daily solar flux are also listed in Table 3. We included our predictions of the attic heat penetrating the ceiling of a house having the chocolate brown painted PVDF metal roof with and without CRCM. The calculations used the recommended attic insulations from the IECC (2000) for each city (Table 3).

In Burlington, Vermont, a house with R-49 attic insulation does not yield enough cooling benefit from the CRCMs to merit their use. In Bolder the cooling benefit is about 164 Btu per year per square foot, and it exceeds the heating penalty by only 23 Btu per year per square foot. In Dallas, the recommended R-19 attic with SR30E80 chocolate brown CRCM dropped the heat flux entering the ceiling by 623 Btu per year per square foot of ceiling. In the still hotter climate of Miami, the CRCM SR30E80 incurs 15% less energy penetrating the ceiling for an R-13 attic. Using the SR60E80 CRCM, the performance improves and about 31% less energy penetrated from the attic into the house.

It is interesting that both Burlington and Boulder, which have moderate cooling demands, also have incident solar irradiance that is almost as much as that for Dallas and Miami (Table 3). Despite the low energy savings in Boulder or Burlington as compared to the hotter climates, the high summer irradiance affects peak demand loads on the electric utility seen in urban areas. CRCMs will help alleviate the demand load as homeowners replace their roof, which they are more apt to do than adding attic insulation.

THE ECONOMICS OF ROOFS WITH CRCMS

We estimated the value of energy savings using the electric and natural gas prices published at the Energy Information Administration's Web site <http://www.eia.doe.gov/>. An electricity cost of $0.10 per kWh and natural gas cost of $10.00 per 1000 ft^3 (about 10^6 Btu or 10 therm) are slightly above the 2001 national average for these energy sources and are assumed for estimating the value of energy savings.

Algorithm for Estimating Savings

The coefficient of performance (COP) describes the performance of the HVAC system in terms of the ratio of the machine's cooling capacity to the power needed to produce the cooling effect. To estimate the value of the electrical energy savings requires systems performance data for the HVAC unit.

$$COP_{HVAC} = \frac{Cooling\ Capacity}{Power_{HVAC}} \tag{2}$$

Because the HVAC unit meets the house load, the heat penetrating the ceiling Q_{Cool} can substitute for the *Cooling Capacity* term of Equation 2 to estimate the power needed to meet the attic's portion of the building load. Cost savings (\$cool) follow from the formula

$$\$cool = \frac{Q_{cool} \cdot \$elec}{COP_{HVAC}} . \tag{3}$$

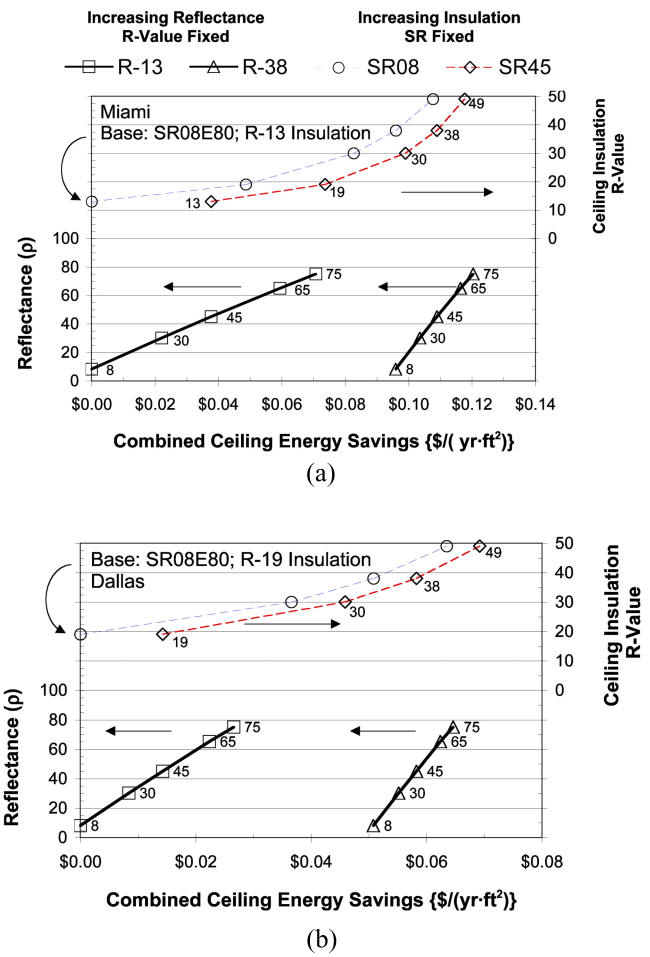

Figure 6 *The energy savings estimates for the combined effects of CRCMs and ceiling insulation. Base of comparisons based on recommended insulation levels and a roof having SR08E80 radiation properties, $\$/(yr \cdot m^2) = 10.764 * \$/(yr \cdot ft^2)$.*

The annual heating energy cost saving (\$heat) requires the efficiency of the furnace and is calculated by the formula

$$\$heat = \frac{Q_{heat} \cdot \$fuel}{\eta_{heat}} . \tag{4}$$

The efficiency of the furnace (η) was set at 0.85 and is relatively constant; however, the cooling COP of HVAC equipment typically drops as the outdoor air temperature increases, as the heat exchangers foul, as mechanical wear occurs on the compressor valves, and especially as the unit leaks refrigerant charge. Hence, what COP should one use to fairly judge cost savings? A conservative approach would be to use the average COP of 2.5 for new HVAC equipment reported by Kelso and Kinzey (2000).

Predicted Savings for CRCMs and Insulation

The more insulation in the attic, the lower is the ceiling heat flow and the less is the benefit of more reflective roofing. Conversely, it is also true that the higher the solar reflectance of the roof, the lower is the ceiling heat flow and the less is the benefit of additional ceiling insulation in cooling-dominant climates. There can, therefore, be a trade-off between the level of ceiling insulation and the solar reflectance of the roof, and the trade-off is constrained by material costs and the value of energy saved by the CRCMs and by the ceiling insulation.

In Miami the recommended ceiling insulation for a house with about 12% exterior window coverage is R-13 (IECC 2000). Dallas requires R-19 ceiling insulation. Typically a dark residential roof has a solar reflectance of about 0.08. We therefore assumed these recommended insulations levels and used SR08E80 as the base for computing the savings in operating energy for incremental increases in both CRCMs and additional insulation for roofs exposed in Miami and Dallas.

We looked at the energy savings from the perspective of increasing the amount of blanket insulation in the ceiling while holding the solar reflectance constant at 0.08 and also at the higher value of 0.45 (plots SR08 and SR45 in Figure 6). R-values 19, 30, 38, and 49 are displayed to help the reader note the savings data listed on the abcissa of Figure 6. The savings are based on the incremental gains over an SR08E80 roof with R-13 insulation in Miami and R-19 insulation in Dallas. An SR08E80 roof in Miami saves ~5 cents per year per square foot if blanket insulation is increased from R-13 to R-19 (see SR08 plot for Miami). For CRCMs having 0.45 solar reflectance, the savings are ~4 cents per year per square foot. The installed cost for R-19 insulation is about \$0.36 per square foot in new construction and is \$0.41 for existing construction (Means 2002). From these data, the additional insulation (R-13 to R-19) is paid for in about seven years for new construction and in about eight years for existing construction for an SR08 roof. In Dallas going from the recommended R-19 to R-38 yields savings of ~\$0.05 per year per square foot, which for new construction pays for itself in about seven years.

Figure 6 also shows the energy savings from the perspective of increasing roof reflectance while holding the ceiling insulation constant at the recommended code level and at the higher level of R-38. The R-13 plot for Miami (Figure 6) shows the cost savings for CRCMs on an attic with R-13 ceiling insulation (SR values are labeled from 0.08 to 0.75). Results show that CRCMs yield savings of about 2.2 cents per year per square foot for the identical color SR30E80 roof compared to the SR08E80 roof with R-13 insulation. As stated earlier, the incremental cost for adding CRCMs to coil-applied metal roofing is ~5 cents per square foot. Hence, the savings in Miami pay for the CRCM technology in about 2½ years. Increasing solar reflectance to 0.50 increases the cost premium and the CRCMs pay for themselves in just one year. In Dallas with R-19 recommended insulation, the SR30E80 roof pays for the added cost of the CRCMs in about 5 years; at 0.50

solar reflectance the premium shortens to ~2½ years. If the ceiling insulation is increased to R-38, the incremental increases in solar reflectance are not as economically effective as seen by the slopes of the R-13 vs. R-38 plots for Miami (Figure 6). The savings in Miami are ~\$0.10 per year per square foot for the SR08E80 roof (R-13 vs. R-8) and diminish to about \$0.06 per year per square foot for a SR75E80 roof (again, R-13 vs. R-38). The comparable savings in Dallas are about half those predicted for Miami (Figure 6).

For the earlier stated fuel prices and the energy savings, the annual cost savings per square foot of ceiling can be as high as \$0.07 per year per square foot in Miami for a house with R-13 ceiling insulation. In Dallas the savings can be as high as \$0.03 per year per square foot for a house with R-19 ceiling insulation. Therefore, the CRCMs have an affordable premium; energy savings easily pay for the roughly 5¢ added expense of the pigments in a CRCM metal roof.

SUMMARY

We have identified and characterized some 83 different complex inorganic pigments and are developing engineering methods to apply them with optimum solar reflectance for the various roof products. Coatings have been developed and demonstrated that match a tile's color and increase the solar reflectance from about 0.08 to over 0.40, a fivefold jump in reflectance. The solar reflectance of painted PVDF metals available on the open market are about three times better with the addition of CRCMs, and we expect further gains as more pigments are identified and new engineering applications are adopted for the production of the metal roof products. Work continues to improve the solar reflectance to our 0.50 goal for tile and painted PVDF metal roofing.

Accelerated weather testing using natural sunlight and xenon-arc weatherometer exposure are proving the CRCMs retain their color. After three years of natural sunlight exposure in southern Florida, the CRCMs show excellent fade resistance and remain colorfast. The CRCMs have excellent discoloration resistance, as proven by the three years of field exposure and the 5000 hours of xenon-arc exposure. Their measure of total color difference was an ΔE value less than 1.5. CRCM 50/50 tints field tested in Florida also showed excellent fade resistance. The highest total color change was observed for the CRCM black tint, which is still indistinguishable from the original color. Therefore, color changes in many of the CRCMs are indistinguishable from their original color.

CRCMs reflect much of the NIR heat and therefore reduce the surface temperature of the roof. The lower exterior temperature leads to energy savings. A chocolate brown roof with 30% reflective CRCMs decreases the consumed cooling energy by 15% of that used for a roof with standard chocolate brown color exposed in Miami and Dallas. If we achieve reflectance measures of 0.50, the energy savings increase to ~30% of the heat flow through an attic having recommended ceiling insulation and the same roof color. The CRCMs also provide an ancillary benefit in older existing houses that have little or no attic insulation and poorly insulated ducts in the attic because the cooler attic temperature leads, in turn, to reduced heat gains to the air-conditioning ductwork.

The cost to the homeowner to achieve this efficiency improvement for coil-applied metal roofing is the incremental cost of about 5¢ per square foot. The CRCMs being sold in coil-applied metal roofing yield savings of about 2.2¢ per year per square foot for the identical color SR30E80 roof compared to the SR08E80 roof with R-13 insulation. Hence, the savings in Miami pay for the CRCM technology in about 2½ years. Increasing solar reflectance to 0.50 increases the cost premium, and the CRCMs would pay for themselves in just one year.

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