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Disclaimer

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Abstract

As the least expensive category of high-slope roofing in the U.S., shingles are found on the roofs of about 80% of U.S. homes, and constitute about 80% (by product area) of this market. Shingles are also among the least reflective high-slope roofing products, with few cool options on the market. The widespread use of cool roofs in the two warmest U.S. climate zones could reduce annual residential cooling energy use in these zones by over 7%. This project targets the development of high-performance cool shingles with initial solar reflectance at least 0.40 and a cost premium not exceeding US\$0.50/ft^2.

Phase 1 of the current study explored three approaches to increasing shingle reflectance. Method A replaces dark bare granules by white bare granules to enhance the near-infrared reflectance attained with cool pigments. Method B applies a white basecoat and a cool-color topcoat to a shingle surfaced with dark bare granules. Method C applies a visually clear, NIR-reflecting surface treatment to a conventionally colored shingle. Method A was the most successful, but our investigation of Method B identified roller coating as a promising top-coating technique, and our study of Method C developed a novel approach based on a nanowire mesh.

Method A yielded red, green, brown, and black faux shingles with solar reflectance up to 0.39 with volumetric coloration. Since the base material is white, these reflectances can readily be increased by using less pigment. The expected cost premium for Method A shingles is less than our target limit of \$0.50/ft^2, and would represent less than a 10% increase in the installed cost of a shingle roof. Using inexpensive but cool (spectrally selective) iron oxide pigments to volumetrically color white limestone synthesized from sequestered carbon and seawater appears to offer high albedo at low cost.

In Phase 2, we plan to refine the cool shingle prototypes, manufacture cool granules, and manufacture and market high-performance cool shingles.

1 Introduction

1.1 Market share

Asphalt shingle roofing is matting, typically fiberglass, coated with asphalt and surfaced with small "granules" of crushed rock (Akbari et al. 2005a,b). Asphalt shingles covered nearly 80% of U.S. homes in 2009 (Table 1), and constituted over 80% (by product area) of the U.S. high-slope roofing market in 2012 (Table 2). The asphalt shingle (hereafter, just "shingle") is the least expensive category of high-slope roofing sold in the U.S. Its material first cost is about 10 – 30% that of the next most common products (metal, wood, clay tile, concrete tile), and its total first cost (material, labor, supplies, and tools) is about 35 – 60% that of these other products (Table 2). Shingles typically weigh only about one-fifth to one-third as much as concrete and clay roofing tiles (Table 3), presenting a lighter structural load.

1.2 Need for higher reflectance, lower cost cool shingles

The use of cool roofing in warm climates is prescribed in energy codes, such as the 2013 California Title 24 Building Energy Efficiency Standards (CEC 2012); credited in green building certification programs, such as LEED 2009 (USGBC 2009); and recognized as an energy efficiency measure by the U.S. Environmental Protection Agency's Energy Star program (US EPA 2015). The key property of a cool roof is high solar reflectance (SR), also known as albedo. California Title 24 prescribes a minimum aged SR of 0.63 for low-slope roofs on nonresidential buildings, but only 0.20 for high-slope roofs on residential buildings. While more reflective than a conventional dark high-slope roofing product (SR 0.05 – 0.10), a roof with aged SR 0.20 absorbs as much sunlight as conventional gray roofing found on commercial buildings. In other words, a high-slope residential roofing product that meets the minimum SR requirement in 2013 California Title 24 is not particularly cool. Similarly, Energy Star cool roof qualification requires an initial SR of 0.65 for low-slope products, but only 0.25 for high-slope products. High-slope roofing SR requirements are modest because energy efficiency standards and labeling programs usually consider not only the benefit and cost of each proposed requirement, but also whether it can be met by commercially available products (Levinson et al. 2005a).

As noted above, the high-slope residential roofing market is dominated by shingles, and most "cool" shingles sold today have initial SR 0.25 – 0.29. Indeed, shingles are among the least reflective high-slope roofing products. For example, as of January 2015, shingles comprise only 4% of the 1,410 metal, tile, and shingle high-slope roofing products in the Rated Products Directory of the Cool Roof Rating Council that could qualify for an Energy Star label by exhibiting an initial SR of at least 0.25. Of the subset of 366 metal, tile, and shingle products in this directory that have initial SR of at least 0.40, fewer than 1% are shingles (Figure 1).

Since about half of the energy in terrestrial sunlight arrives in the invisible near-infrared (NIR) spectrum (Levinson et al. 2010), a very dark "cool colored" roof with high NIR reflectance can attain an albedo of about 0.35 – 0.40 (Levinson et al. 2007). Thus we seek for high-performance cool colored roofs an albedo increase of about 0.30. The minimum aged solar reflectance requirement for all categories of high-slope residential roofing could be raised substantially (perhaps to 0.35) following the introduction to market of high-performance asphalt shingles.

Table 1. Major roofing materials in 2009 U.S. residential roofing stock (US EIA 2013a) and roofing product costs (Homewyse 2015).

				Homewyse cost per roof surface area ($/ft²) [c,d]			
				BASIC GRADE		BETTER GRADE	
Major roofing material [a]	U.S. homes (millions) [a]	Fraction of U.S. homes [b]	Homewyse product category	Material	Total	Material	Total
Composition Shingles [e]	54.1	57%	Asphalt shingle roof [f]	0.72 – 0.90	3.86 – 5.02	0.98 – 1.24	4.15 – 5.38
Asphalt [e]	18.6	20%					
Metal	8.3	8.8%	Metal roof [g]	4.48 – 5.67	6.70 – 8.36	6.12 – 7.74	8.38 – 10.47
Wood Shingles/ Shakes	6.6	7.0%	Wood shake [h]	3.95 – 4.99	7.12 – 8.95	5.39 – 6.82	8.59 – 10.80
Ceramic or Clay Tiles	3.3	3.5%	Clay tile roof [i]	6.47 – 8.18	10.75 – 13.41	8.83 – 11.17	13.14 – 16.43
Concrete Tiles	1.3	1.4%	Concrete tile roof [j]	2.58 – 3.27	6.86 – 8.49	3.53 – 4.46	7.84 – 9.72
Slate or Synthetic Slate	1.3	1.4%	Slate roof [k]	6.26 – 7.92	10.58 – 13.20	8.55 – 10.81	12.91 – 16.13
			Synthetic slate roof [l]	2.74 – 3.46	7.02 – 8.69	3.74 – 4.73	8.05 – 9.99
Other	1.2	1.3%					
Not Asked (Apartments in Buildings With 5 or More Units)	19.1						
Total responses	94.7	100%					

[a] Table HC2.1, RECS 2009 (US EIA 2013a)

[b] Excluding those not asked.

[c] Homewyse (2015). Total costs include material, labor, supplies, and tools. Assumptions: ZIP code 89101 = (Las Vegas); roof surface area = 1,960 ft²; roofing grades = ("Basic – builder grade", "Better – value grade"); labor = "Roofing vendor"; roof layout = "High slope, common shape".

[d] Las Vegas selected because (a) cool roofs are beneficial in that location (Levinson and Akbari 2010) and (b) its "Location Factor" (ratio of local cost to national average cost) was 100.2% for materials and 109.0% for labor in RS Means (2013). Roof surface area of 1,960 ft² was the Homewyse choice closest to average roof area of 1,936 ft² for 1 and 2 story U.S. homes (Table 5).

[e] RECS 2009 categories under "Major Roofing Material" include both "Composition Shingles" and "Asphalt". We interpret both responses as asphalt shingles.

[f] Homewyse lists costs for "Asphalt Shingle Roof", "Composite Shingle Roof", "Composition Shingle Roof", "Dimensional Shingle Roof", and "Fiberglass Shingles". We use "Asphalt Shingle Roof".

[g] Homewyse lists costs for "Aluminum Roof", "Aluminum Shingle Roof", "Metal Roof", "Metal Tile Roof", "Standing Seam Copper Roof","Standing Seam Metal Roof", "Standing Seam Roof", "Copper Roof", "Steel Roof", "Steel Shingle Roof", and "Stone-Coated Steel Roof". We use "Metal Roof".

[h] Homewyse lists costs for "Red Cedar Shingles", "Wood Shake Roof", and "Wood Shingle Roof". We use "Wood Shingle Roof".

[i] Homewyse lists costs for “Clay Tile Roof” and “Terracotta Roof Tile”. We use “Clay Tile Roof”.

[j] Homewyse has only one relevant category, “Concrete Tile Roof”.

[k] Homewyse lists costs for “Slate Roof” and “Slate Roofing Tile”. We use “Slate Roof”.

[l] Homewyse lists costs for “Synthetic Slate Roof” and “Synthetic Slate Roofing Shingle”. We use “Synthetic Slate Roof”.

Table 2. U.S. roofing sales in 2012 by product area (Fredonia Group 2013a,b).

	Million squares [a]	Area fraction of high-slope roofing products (asphalt shingles + metal roofing + roofing tile)	Area fraction of all roofing products
Asphalt shingles	128.1	81%	57%
Metal roofing	20.4	13%	9%
Roofing tile	10.2	6%	5%
Bituminous low-slope roofing	33.5		15%
Elastomeric roofing	18.4		8%
Plastic roofing	11.3		5%
Other	3.7		2%
Total	225.6	100%	100%

[a] One roofing square covers 100 ft² of roof surface area.

Table 3. Residential roofing weight, lifespan, and cost (material + labor) by product type, adapted from Cuhaj (2009). [a]

Product	Weight (lb/square)	Lifespan (years)	Cost ($/square)	Annualized cost ($/square·year)
Asphalt (3-tab)	190 – 250	15 – 20	75 – 125	4 – 8
Asphalt (laminated)	240 – 340	20 – 30	125 – 200	4 – 10
Metal (coated steel)	80 – 150	30 – 50	250 – 450	5 – 15
Plastic Polymer	70 – 300	50+	400 – 650	7 – 13
Clay Tile	600 – 1,800	50+	800 – 1,000	13 – 20
Concrete Tile	550 – 1,000	50	300 – 500	5 – 10
Slate	800 – 1,000	75+	1,100 – 2,000	10 – 20
Wood (cedar)	200 – 350	15 – 25	350 – 450	14 – 30

[a] “Weight and cost are listed per square of roofing (100 square feet) and include both labor and materials. Actual price may vary depending on the particular product used, the complexity of the job, and labor costs in different parts of the country. The cost per year indicates the price of the labor and materials per square over the roof’s projected life.” (Cuhaj 2009).

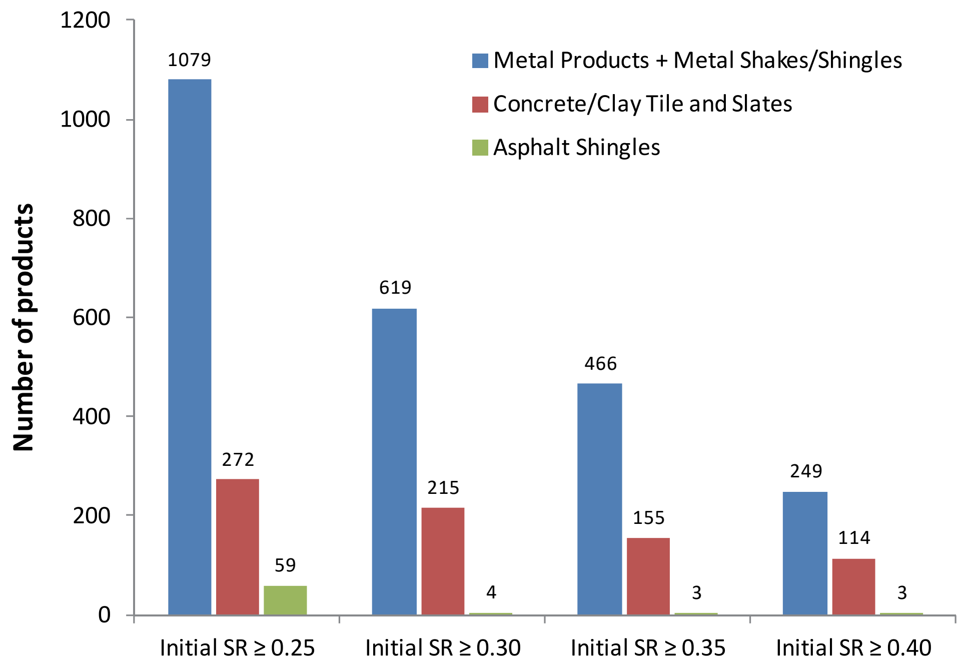


Figure 1. Numbers of metal, tile, and asphalt shingles products in the Rated Products Directory of the Cool Roof Rating Council (CRRC 2015) with initial solar reflectances of at least 0.25 (minimum to qualify for Energy Star label), 0.30, 0.35, or 0.40 (approximate goal of current project).

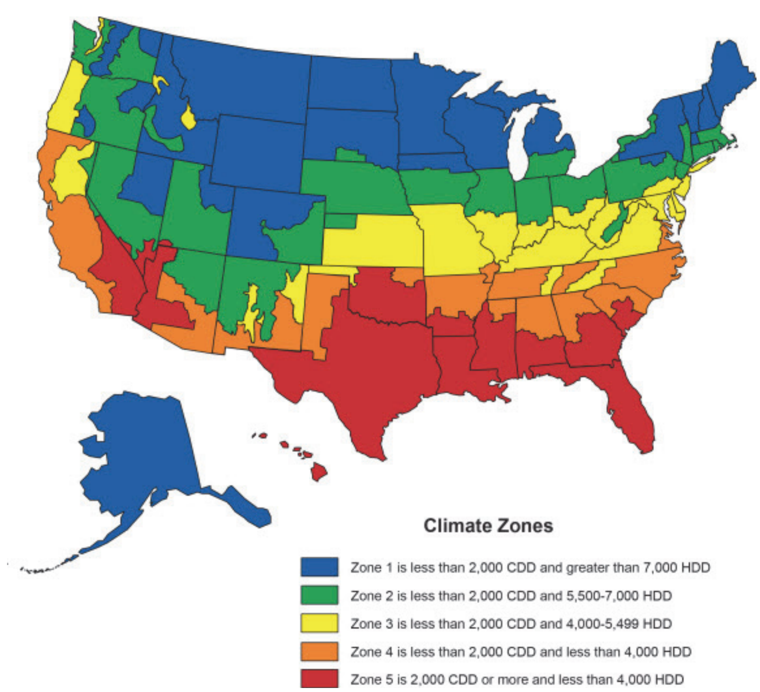


Figure 2. American Institute of Architects (AIA) climate zone map (US EIA 2015). Zones are defined by cooling degree days (CDD) and heating degree days (HDD). Base temperatures for CDD and HDD are not specified, but presumed to be 65 °F.

Shingles dominate the residential roofing market by offering lowest first cost, rather than, say, longest service life (Table 3). Therefore, we expect that consumers will not accept a large cost premium for high-performance cool shingles. The US Department of Energy's Prioritization Tool assumes that cool colored residential roofs will cost $0.43/ft² more than conventional residential roofs (Farese et al. 2012). In April 2014, we found that commercially available cool shingles cost up to $1.58/ft² (131%) more than comparable conventional shingles (Table 4).

Note that roofing product prices are expressed per unit area of roof surface covered, rather than per unit area of roofing material, because piecewise roofing products, such as shingles and tiles, can overlap. In the U.S. market, prices are usually reported either per square foot of roof surface area, or per roofing "square", where one square covers 100 ft² of roof surface.

1.3 Potential energy savings

Konopacki et al. (1997) calculated that increasing the albedo of asphalt shingle roof by 0.30 reduces the annual cooling energy use of a one-story, single-family home in a warm climate by 6 – 17%, depending on vintage (pre- or post-1980 construction). Since cool roof cooling energy savings scale with footprint area, while whole-building cooling energy use scales with floor area, fractional cool roof savings (cooling savings / whole-building cooling energy use) scale inversely with the number of floors. In the U.S., 96% of single-family homes have one or two stories, and the area-weighted average number of floors (average floor area / average footprint area) for this population of one and two story homes is 1.34 (Table 5). Scaling the single-story-home results of Konopacki et al. (1997) to this average number of floors in U.S. homes, we expect a cool roof on a U.S. single family home to save about 4 – 13% of residential annual cooling energy in a warm climate.

Table 4. Retail prices for comparable conventional and cool roofing shingles at a home improvement store in April 2014 (Lowes 2014).

Classification	Product	Initial SR [a]	Price per unit roof area ($/ft²)	Price premium per unit roof area ($/ft²)
Conventional	CertainTeed Landmark Burnt Sienna AR Laminate Shingle	NA	1.21	-
Cool	CertainTeed Landmark Solaris Max Def Burnt Sienna AR Laminate Shingle	0.26	2.79	1.58 [131%]

[a] CRRC (2015).

The American Institute of Architects (AIA) divides the U.S. into five climate zones (CZs) (Figure 2).[1] Air conditioned homes in the two warmest AIA climate zones (4 and 5) consume nearly 170 billion kWh/y of cooling site energy (Table 6). Upgrading 95% of these homes with high-performance cool colored roofs could reduce their annual source cooling energy use by about 130 TBTU, or 7.5%, agreeing well with the 4 – 13% whole-building cooling savings estimated above. The annual heating source energy penalty is just 8.5 TBTU, or 0.5% of the annual source cooling energy use (Table 7).

Table 5. Average floor areas, footprint areas, and roof areas of U.S. homes (US EIA 2013b).

Stories	Number of housing units (millions)	Fraction of total housing units	Average floor area [a] (ft^2)	Average footprint area [b] (ft^2)	Average roof area [c] (ft^2)
1	46.2	59%	1,934	1,934	2,095
2	29.6	38%	3,114	1,557	1,687
Other	2.8	4%			
Average for 1 and 2 story homes, weighted by number of housing units			2,395	1,787	1,936

[a] Reported as "average square footage per housing unit".

[b] Footprint area = floor area / number of stories.

[c] Calculated assuming a roof pitch of 5:12, yielding roof surface area / footprint area = 13/12.

Table 6. Residential air conditioning energy use by AIA climate zone, as reported in RECS 2005 (US EIA 2008). [a]

Zone	Annual site energy use (billion kWh)
1	7
2	40
3	52
4	48
5	120
4 + 5	168

[a] RECS 2005 was the last RECS to report air conditioning energy use by AIA climate zone.

1.4 Cool roofs versus attic insulation

Retrofitting a house with a cool roof typically saves more cooling energy than adding attic insulation because most homes route their HVAC ducts through the attic, above the attic-floor

[1] We use AIA climate zones because from 1997 to 2005, the U.S. Energy Information Administration's Residential Energy Consumption Survey (RECS) disaggregated U.S. residential energy consumption by AIA climate zone. Note that the five AIA climate zones (US EIA 2015) differ from the eight climate zones used by the American Society for Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and the International Energy Conservation Code (IECC) (PNNL 2013).

insulation. Heat flows from the roof to the conditioned space through the home's ceiling, and through the walls of the HVAC ducts in the attic. A cool roof reduces both ceiling and duct heat gain; attic-floor insulation reduces only ceiling heat gain. Ducts have much less insulation than ceilings (typically R-6 vs. R-19 in a stock home), and duct surface area is roughly 35% of ceiling area. This makes duct heat gain comparable to ceiling heat gain—and sometimes greater, because the duct air is colder than the room air.

Table 8 compares the benefits of (a) doubling attic insulation to RSI-6.6 (R-38) from RSI-3.3 (R-19) and/or (b) increasing roof albedo by 0.3. Starting with a typical stock home (RSI-3.3 attic insulation, warm roof), doubling attic insulation without installing a cool roof reduces the total (ceiling + duct) heat gain by 19%, while upgrading to a cool roof without adding insulation reduces the total heat gain by 33%. Combined, the two measures reduce total heat gain by 44%. Starting with a typical new home (RSI-6.6 attic insulation, warm roof), upgrading to a cool roof reduces the total (ceiling + duct) heat gain by 31%. In short, upgrading to a cool roof is much more effective than doubling attic insulation in reducing roof-induced heat gain. The cool roof upgrade can decrease this heat gain by over 30% in both stock and new homes.

1.5 Effect of rooftop photovoltaics on space available for residential cool roofs

We also note that despite their growing popularity, photovoltaic (PV) panels occupy a tiny fraction of residential roof space. The Solar Energy Industries Association forecast 6.5 GW of PVs installation in 2014 across the U.S., raising the national PV resource to 16.1 GW (SEIA 2014). At 100 W/m², that represents 65 million m² of new PV, and 161 million m² of cumulative PV. There are about 2.8 billion m² of residential roofs that could be made cool in AIA climate zones 4 & 5 (Levinson 2012). Thus, locating every one of these new PVs on a home in one of these two climate zones would reduce the available residential cool roof site area in CZs 4 and 5 by about 2%, while the entire national stock of PVs would occupy just 6% of this roof area. Actual use of CZ 4 and 5 residential roof space for PVs would be lower, because many U.S. PVs are installed on other buildings (nonresidential, and/or outside these two climate zones).

Table 7. Potential cool roof source energy savings for U.S. homes in AIA climate zones 4 and 5.

A	Cool roof annual cooling source energy savings [TBTU] [a]	133
B	Cool roof annual heating source energy penalty [TBTU] [a]	8.5
C	Cool roof annual net source energy savings [TBTU] [a]	124
D	RECS 2005 annual air conditioning source energy use [TBTU] [b]	1,777
E	Ratio of cool roof cooling source energy savings (A) to air conditioning source energy use (D)	7.5%

[a] Upon upgrading 95% of conditioned roof area to high-performance cool color (aged SR 0.35 – 0.40) from traditional dark color (aged SR 0.05 – 0.10) (Levinson 2012).

[b] RECS 2005 site energy use in AIA climate zones 4 and 5 (Table 6).

Table 8. Effects of doubling ceiling insulation (B vs. A), installing a cool roof (C vs. A), and applying both measures (D vs. A) on the rate of roof (ceiling + duct) heat gain to the conditioned space of a 30-year old home on a summer afternoon. [a]

	Case A: warm roof, 1X ceiling insulation	Case B: warm roof, 2X ceiling insulation	Case C: cool roof, 1X ceiling insulation	Case D: cool roof, 2X ceiling insulation
Ceiling insulation R_c [m² K/W]	3.3	6.6	3.3	6.6
Duct insulation R_d [m² K/W]	1	1	1	1
Attic air temperature T_a [°C]	50	50	40	40
Room air temperature T_i [°C]	25	25	25	25
Duct air temperature $T_d = T_i - 10$ [°C]	15	15	15	15
Ceiling area A_c [m²]	140	140	140	140
Duct area $A_d = 0.35 \times A_c$ [m²]	49	49	49	49
Ceiling heat gain rate $q_c = A_c (T_a - T_i) / R_c$ [W]	1,061	530	636	318
Duct heat gain rate $q_d = A_d (T_a - T_d) / R_d$ [W]	1,715	1,715	1,225	1,225
Total (ceiling + duct) heat gain rate $q_t = q_c + q_d$ [W]	2,776	2,245	1,861	1,543
Savings relative to Case A, $f_A = (1-q_t/q_{t,A})$	0%	19%	33%	44%
Savings relative to Case B, $f_B= (1-q_t/q_{t,B})$		0%	17%	31%
Savings relative to Case C, $f_C= (1-q_t/q_{t,C})$			0%	17%

[a] Assumptions: (a) base case A has warm roof, RSI-3.3 ceiling insulation, RSI-1 duct insulation, and ducts in attic; (b) duct surface area is 35% of ceiling area; (c) attic air temperature under warm roof is 50 °C; (d) switch to cool roof from warm roof lowers attic air temperature by 10 °C; (e) room is air conditioned to 25 °C; (f) duct air is 10 °C cooler than room air; and (g) ceiling and duct radiative heat gains are neglected for simplicity.

2 Prior cool shingle development

2.1 Activities at LBNL

In a two-phase study funded by the California Energy Commission [CEC] (Cool Colored Roofing Materials, 2002 – 2010), LBNL collaborated with the pigment, coating, and roofing industries to improve the solar reflectance of a variety of high-slope roofing materials, including metal, clay tile, concrete tile, and asphalt shingle (Akbari et al. 2006). Existing processes for making conventional and cool asphalt shingles are diagrammed in Figure 3, and detailed in Appendix A. The key to creating a dark shingle with enhanced albedo is to increase the near-infrared (NIR) reflectance, *N*, of its granule surface. As described in an earlier publication by the LBNL research team (Levinson et al. 2007),

> 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 0.5–2 mm in diameter. 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 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 5–10 µm), and (c) the weak to moderate NIR backscattering exhibited by most pigments.
>
> The simplest way to increase the NIR reflectance of individual granules is to use 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 UV radiation in sunlight. If 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 NIR-absorbing aggregate to produce an NIR-reflective granule. For example, a 5-µm thick coating of refractive index 1.5 that is pigmented with titanium dioxide rutile white can increase the NIR reflectance of a smooth, flat, dark-gray surface (N = 0.10) to 0.35. A 10-µm thick coating will increase NIR reflectance to 0.50; a 25-µm thick coating, to 0.65. 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.

In the first phase of the CEC-sponsored study (2002 – 2005), LBNL collaborated with ISP Minerals, a manufacturer of roofing granules, to improve granule reflectance (Levinson et al. 2007). Figure 4 illustrates the development of an inorganically pigmented cool black asphalt shingle. The granules on the reference shingle are pigmented with carbon black, a hot black. Prototype 1 replaces the carbon black by a cool inorganic black; Prototype 2 adds a thin white basecoat below the cool black topcoat. Prototype 3 increases the thickness of the white basecoat below the cool black topcoat. Compared to the reference shingle, the third prototype raised NIR reflectance by 0.25, and solar reflectance by 0.14.

In the second phase of the CEC-sponsored study (2006 – 2010), LBNL collaborated with Arkema, a coating manufacturer, to create prototype asphalt shingle roofing products in which granules are colored only *after* they are pressed into the asphalt (Levinson et al. 2010). This "shingle coating" process begins with shingles surfaced with dark, bare granules (solar reflectance S = 0.06). The shingle receives a bright white polymer basecoat, followed by a cool colored polymer topcoat. Trials yielded darkish red, green, and brown prototypes shingles with albedos of 0.24 – 0.29, as well as lighter colored shingles with albedos up to 0.62 (Figure 5).

2.2 Activities at CertainTeed

CertainTeed Corporation (Valley Forge, PA), a North American manufacturer of building materials with $3.2B in sales in 2011, has substantial experience in the technology, production, and marketing of conventional and cool shingles. In 2012, CertainTeed received an R&D 100 Award in the Energy Technology category for its Landmark Solaris Platinum solar reflective roofing shingles. As reported in the award announcement,

> A new coating process utilizes more of the solar spectrum to produce a solar reflectance of 40% (as compared to 5% on a black-shingled house). Granule base particles are suspended in a fluid medium to separate the individual particles. A coating is uniformly deposited on the surface of the base particles, fully covering the surface, and then cured. The coated particles are again suspended in a fluid medium and a color coating is applied and then cured. The first coating provides high solar reflectivity. The second color coating provides visible color while allowing the transmission of infrared radiation to the first coating where the solar heat is reflected, passing through the color coating to be released. (RDMag 2012)

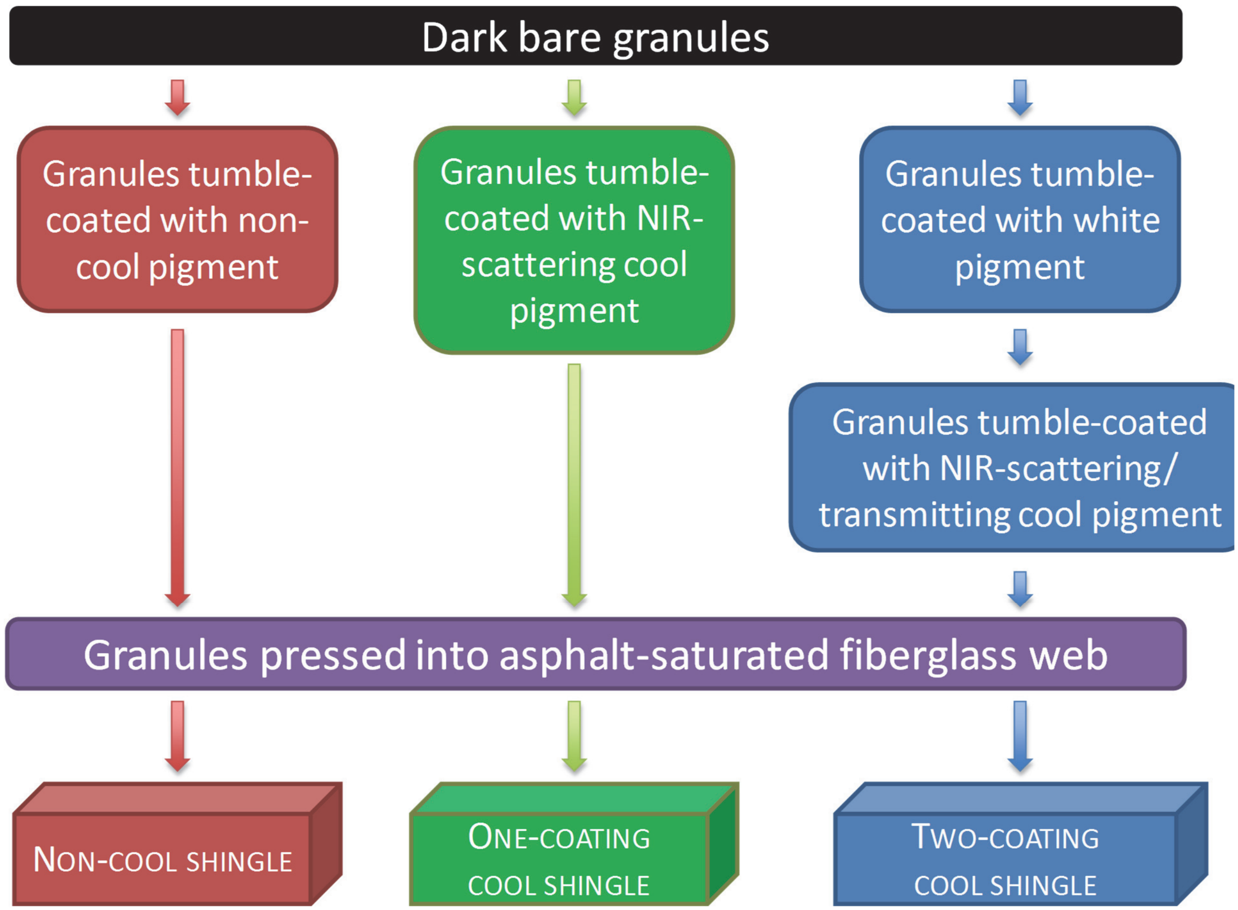


Figure 3. Existing processes for making fiberglass asphalt shingles.

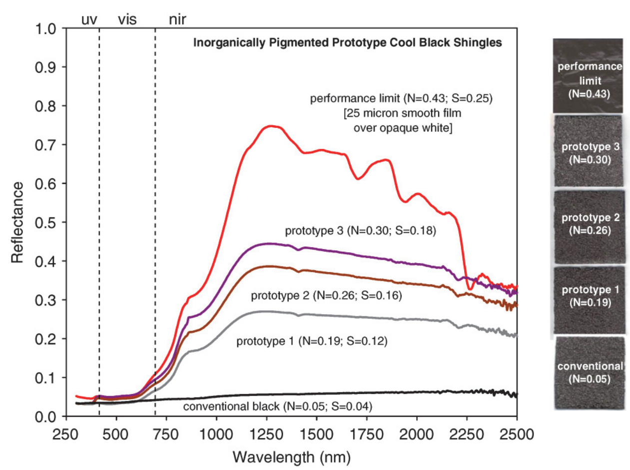


Figure 4. Solar spectral reflectance curves and images tracing development of an inorganically pigmented cool black asphalt shingle by Levinson et al. (2007). N, S = NIR, solar reflectances.

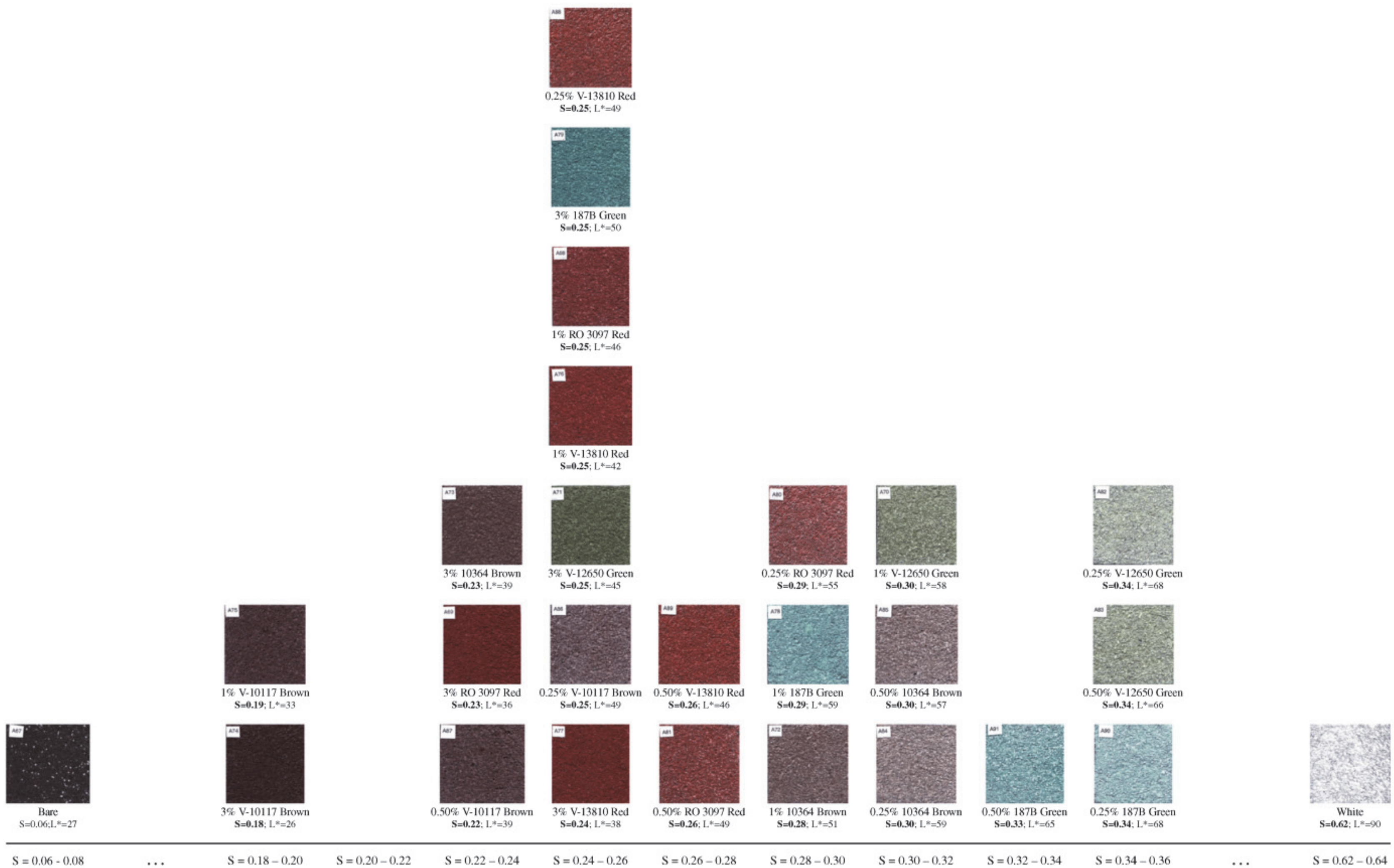


Figure 5. Surface-coated asphalt shingle prototypes prepared by Levinson et al. (2010), ordered by solar reflectance.

3 Overview of current project

Our project has two phases. Phase 1 (year 1) extends our prior cool shingle research, with the objective of developing prototype high-performance, low-cost cool shingles with an initial solar reflectance of at least 0.40, and a cost premium of \$0.50/ft² (\$50/square) or less. Assuming that a high-quality conventional shingle costs about \$1.20/ft² for material only and about \$5.00/ft² installed (Table 1), this premium would represent a 42% increase in material cost, and a 10% increase in total cost (material + labor + supplies + tools). Phase 2 (years 2 and 3) includes activities to refine the cool shingle prototypes, manufacture cool granules, and manufacture and market high-performance cool shingles.

In Phase 1, LBNL collaborated with CertainTeed to explore the three novel approaches to cool shingle fabrication diagrammed in Figure 6. Method A replaces dark bare granules by white bare granules to enhance the NIR reflectance attained with cool pigments. Method B applies a white basecoat and a cool-color topcoat to a shingle surfaced with dark bare granules. Method C applies a visually clear, NIR-reflecting surface treatment to a conventionally colored shingle.

LBNL also collaborated with Blue Planet, Ltd. (Los Gatos, CA), a start-up company that synthesizes bright-white calcium carbonate by bubbling into seawater CO_2 captured from industrial sources, such as fossil fuel power plants and cement plants (Service 2012). The carbon dioxide is converted to bicarbonate and the bicarbonate is combined with calcium, forming calcium carbonate in a solid mass that is indistinguishable from natural limestone. Because the

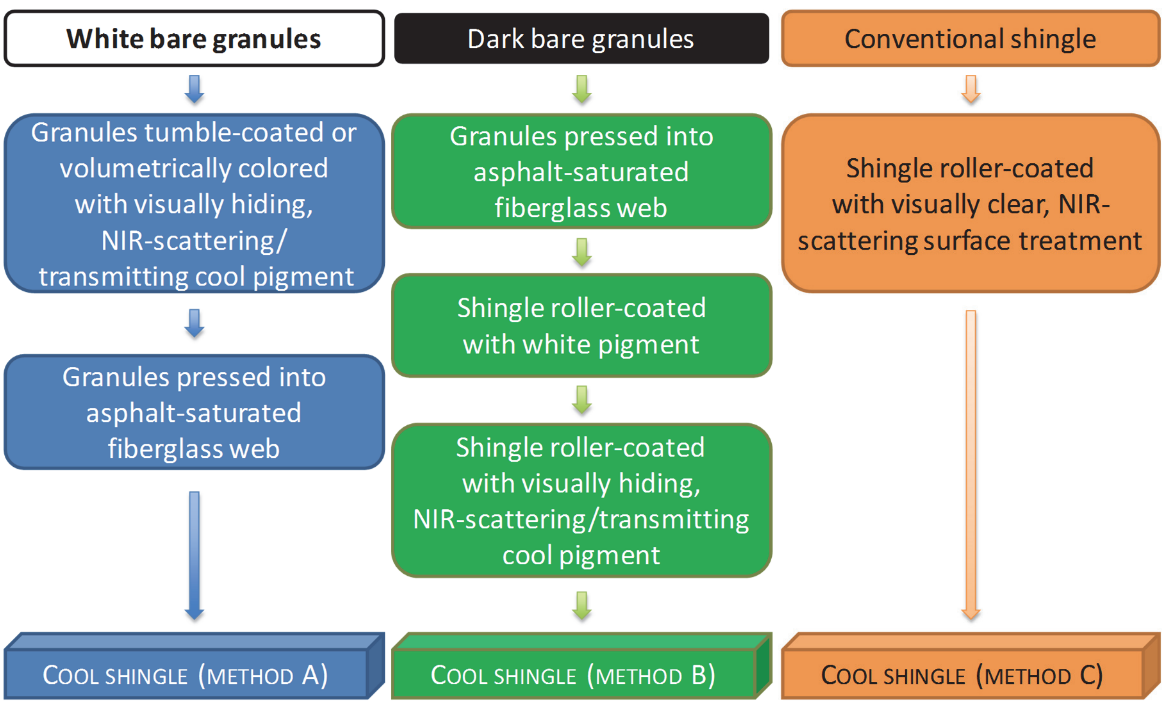


Figure 6. Three novel methods for making cool shingles: (A) coating white bare granules before they are pressed into the asphalt; (B) applying a white basecoat and cool color topcoat to shingle surfaced with dark bare granules; and (C) applying a visually clear, NIR-scattering surface treatment to a conventionally colored shingle.

process is conducted under physiological conditions, the calcium carbonate minerals produced have microstructure similar to those of the natural biominerals that form limestone (Pokroy et al. 2004). With the addition of cool pigments, this “synthetic limestone” (SL) can yield cool colored granules for use in Method A. Each tonne of synthetic limestone ($CaCO_3$) also sequesters 0.44 t of CO_2.

The Phase 1 work plan has three tasks:

Task 1. In support of Method A, create high-performance cool roofing granules by (i) identifying spectrally selective pigments that yield “cool-colored” surfaces with high NIR reflectance when applied to the surface or body of white granules, or over dark bare granules with a white basecoat (Section 4.1); and (ii) characterize the radiative properties of white bare granules, and white bare granules colored with spectrally selective pigments, with attention to their color, solar reflectance, NIR reflectance, and UV transmittance (Sections 4.2 and 4.3).

Task 2. In support of Method B, for which prototypes were previously created by Levinson et al. (2010), assess options for applying a two-layer surface coating (white basecoat, color topcoat) to bare-granule shingles in a factory production line (Section 5).

Task 3. In support of Method C, seek clear, NIR-reflecting surface treatments that can boost the albedo of conventional shingles with minimal effect on appearance (Section 6).

4 Task 1: Create high-performance cool roofing granules

4.1 Identifying spectrally selective pigments suited to bare white granules

Table 9 identifies 54 pigments in the LBNL Pigment Database (Levinson et al. 2005d) that attain an NIR reflectance at least 0.50 when applied in a thin (~ 25 μm) coating over a flat, bright-white substrate with NIR reflectance 0.88 and solar reflectance 0.85. This reflectance requirement is arbitrary, but ensures that NIR reflectance, which does not affect color, contributes at least 0.25 to the coating's solar reflectance.

The table includes both inorganic and organic pigments. Inorganic pigments are preferred in the traditional granule coating process (Figure 7), which bakes the granule's pigmented silicate coating at high temperatures (250 – 550°C) that may damage organic pigments. However, many organic pigments offer strong visible hiding and minimal NIR absorption, making them desirable as cool colorants. Organic pigments could be used to volumetrically color Blue Planet's bright-white synthetic limestone, which is formed at room temperature.

4.2 Characterizing radiative properties of white granules and white-granule faux shingles

LBNL characterized four specimens of bare white granules. Specimens A and B were prepared by crushing two different blocks of Blue Planet's white synthetic limestone, then sieving each to the #11 size distribution commonly used for roofing granules (Table 10). Specimen C is a #11 kaolin-based calcined clay granule acquired from a company that wishes to remain anonymous.

Following ASTM E903-12: Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres (ASTM 2012), we used a Perkin-Elmer Lambda 900 UV-vis-NIR spectrometer fitted with a 150 mm Labsphere integrating sphere to measure the solar spectral reflectances (250 – 2,500 nm @ 5 nm) of (a) the solid blocks from which Specimens A and B were derived; and (b) faux shingles (granules bound to aluminum panels with a dark adhesive) of Specimens A – C prepared by LBNL following the technique of Levinson et al. (2014). We measured the solar spectral transmittance of a monolayer of each specimen in a quartz holder. Broadband values of solar (300 – 2,500 nm), UV (300 – 400 nm), visible (400 – 700 nm), and NIR (700 – 2,500 nm) reflectance were calculated by averaging spectral reflectance weighted with an air mass 1 global horizontal (AM1GH) solar spectral irradiance (Levinson 2010; Levinson et al. 2010a,b).[2] AM1GH values of solar and NIR reflectance are designated *S* and *N*, respectively.

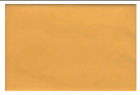
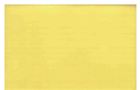
[2] Table X2.6 of ASTM Standard E903-12 (ASTM 2012) provides weighted ordinates for a solar spectral irradiance nearly identical to AM1GH.

Table 9. Cool pigments in the LBNL Pigment Database (Levinson et al. 2005d) selected for strong visible hiding and NIR-reflectance *N* ≥ 0.50 when applied over a bright white substrate. Images and reflectances shown for smooth thin films (about 25 µm) over a flat, opaque white substrate (*S* = 0.85, *N* = 0.88). [a] To the physical properties obtained from the database we have appended information about pigment cost and availability.

Code	Name	Image	S	N	Organic	Pigment make & Model [b]	Price ($/lb) [c]	Note from maker [d]
B12	Perylene Black		0.47	0.85	Yes	BASF Paliogen Black L0086 (PB 32)		
B13	Burnt Sienna		0.38	0.61	No	Calcined Natural Iron Oxide (PBr 7)		
B16	Iron Titanium Brown Spinel (i)		0.55	0.74	No	Shepherd Brown 156 (PBk 12)	5.10	No equiv-alent
B17	Iron Titanium Brown Spinel (ii)		0.41	0.61	No	Shepherd Brown 8 (PBk 12)	5.87	Sample Brown 10P858
B18	Iron Titanium Brown Spinel (iii)		0.48	0.68	No	Shepherd Golden Brown 19 (PBk 12)	5.06	Sample Brown 20C819
B19	Manganese Antimony Titanium Buff Rutile		0.40	0.65	No	Ferro Chestnut Brown V-10364 (PY 164)	7.15	
B20	Zinc Iron Chromite Brown Spinel (i)		0.30	0.50	No	Shepherd Brown 12 (PBr 33)		Discon-tinued
B21	Zinc Iron Chromite Brown Spinel (ii)		0.39	0.61	No	Shepherd Brown 157 (PBr 33)	6.12	OK to sample
U01	Cobalt Aluminate Blue Spinel (i)		0.45	0.64	No	Ferro Blue V−9250 (PB 28)	20.10	
U02	Cobalt Aluminate Blue Spinel (ii)		0.46	0.65	No	Shepherd Blue 385 (PB 28)	14.59	OK to sample
U03	Cobalt Aluminate Blue Spinel (iii)		0.53	0.71	No	Shepherd Blue 424 (PB 28)	12.01	OK to sample
U04	Cobalt Aluminum Blue		0.44	0.62	No	Shepherd Arctic Blue 3A (PB 28)	14.16	Sample Blue 385

U05	Cobalt Blue		0.42	0.62	No	Oxides of Cobalt and Aluminum (PB 28)		
U06	Cerulean Blue		0.47	0.68	No	Cobalt Chromite (PB 36)		
U07	Cobalt Chromite Blue		0.35	0.55	No	Shepherd Blue 190–A (PB 36)	18.11	Sample Blue 211
U08	Cobalt Chromite Blue–Green Spinel (i)		0.42	0.64	No	Ferro Blue V–9248 (PB 36)	26.75	
U09	Cobalt Chromite Blue–Green Spinel (ii)		0.48	0.70	No	Shepherd Blue 212 (PB 36)	18.75	Sample Blue 211
U11	French Ultra Marine Blue		0.33	0.52	No	Complex Silicate of Na and Al with S (PB 29)		
U12	Phthalo Blue (i)		0.39	0.63	Yes	Copper Phthalocyanine (PB 15)		
U13	Phthalo Blue (ii)		0.34	0.55	Yes	Toyo Lionel BF–28201 (PB 15)		
U14	Dioxazine Purple		0.47	0.82	Yes	Carbazole Dioxazine (PV 23 RS)		
G01	Chrome Green		0.32	0.50	No	Bayer GN–M Chrome Oxide Green (PG 17)		
G02	Chromium Oxide Green		0.35	0.57	No	Anhydrous Chromium Sesquioxide (PG 17)		
G03	Chromium Green-Black Modified		0.41	0.71	No	Ferro Camouflage Green V–12650	9.70	
G04	Cobalt Chromite Blue–Green Spinel (iii)		0.41	0.64	No	Shepherd Green 187B (PB 36)	12.91	OK to sample
G05	Cobalt Chromite Green Spinel (i)		0.39	0.64	No	Ferro Camouflage Green V–12600 (PG 26)	9.65	
G06	Cobalt Chromite Green Spinel (ii)		0.35	0.58	No	Shepherd Green 179 (PG 26)	8.49	Sample Green 410

G07	Cobalt Teal		0.54	0.73	No	Light Green Oxide (PG 50)		
R02	Red Iron Oxide (ii)		0.34	0.53	No	Elementis RO−3097 (PR 101)		
R03	Red Iron Oxide (iii)		0.42	0.67	No	Ferro Red V−13810 (PR 101)	4.25	
R04	Red Oxide		0.39	0.62	No	Synthetic Red Iron Oxide (PR 101)		
R05	Cadmium Orange		0.65	0.87	No	Cadmium Orange (PO 20)		
R06	Acra Burnt Orange		0.52	0.83	Yes	Quinacridone (PR 206)		
R07	Acra Red		0.59	0.85	Yes	Quinacridone Red Gamma (PR 209)		
R08	Monastral Red		0.57	0.86	Yes	Ciba Geigy Monastral NRT−742−D Scarlet (PV 19)		
R09	Naphthol Red Light		0.61	0.87	Yes	Naphthol AS−OL (PR 9)		
Y01	Yellow Oxide		0.51	0.70	No	Synthetic Hydrated Iron Oxide (PY 42)		
Y02	Cadmium Yellow Light		0.73	0.87	No	Cadmium Yellow (PY 35)		
Y03	Chrome Yellow		0.66	0.83	No	Dominion Color Krolor KY−781−D (PY 34)		
Y04	Chrome Antimony Titanium Buff Rutile (i)		0.61	0.82	No	Ferro Autumn Gold V−10415 (PBr 24)	6.30	
Y05	Chrome Antimony Titanium Buff Rutile (ii)		0.67	0.86	No	Ferro Bright Golden Yellow V−10411 (PBr 24)	6.25	
Y06	Chrome Antimony Titanium Buff Rutile (iii)		0.63	0.84	No	Shepherd Yellow 193 (PBr 24)	5.22	Sample Yellow 10C242

Y07	Chrome Titanate Yellow		0.59	0.80	No	Ishihara Tipaque TY−300 (PBr 24)		
Y08	Nickel Antimony Titanium Yellow Rutile (i)		0.78	0.87	No	Ferro Yellow V−9415 (PY 5)	7.90	
Y09	Nickel Antimony Titanium Yellow Rutile (ii)		0.71	0.85	No	Ferro Yellow V−9416 (PY 53)	11.15	
Y10	Nickel Antimony Titanium Yellow Rutile (iii)		0.72	0.81	No	Shepherd Yellow 195 (PY 53)	5.89	Sample Yellow 10C112
Y11	Nickel Titanate Yellow		0.69	0.77	No	Ishihara Tipaque TY−50 (PY 53)		
Y12	Primer		0.76	0.86	No	Strontium Chromate Yellow + Titanium Dioxide		
Y13	Yellow Medium Azo		0.72	0.87	Yes	Arylide Yellow 5GX (PY 74 LF)		
Y14	Yellow Orange Azo		0.69	0.87	Yes	Diarylide Yellow (PY 83 HR70)		
P10	Brass (Pearlescent)		0.72	0.85	No	Engelhard Exterior Mearlin 2329X Brass		
P11	Bright Bronze (Pearlescent)		0.53	0.71	No	Engelhard Exterior Mearlin 249X Bright Bronze		
P12	Bright Copper (Pearlescent)		0.47	0.67	No	Engelhard Exterior Mearlin 349X Bright Copper		
P14	Russet (Pearlescent)		0.46	0.68	No	Engelhard Exterior Mearlin 449X Russet		

[a] The global solar reflectances in this table are based on an air mass 1.5, rather than air mass 1, global horizontal solar irradiance, because that is how they were reported by Levinson et al. (2005d).
[b] Pigment manufacturer (make) is not shown if the pigmented coating was prepared from an artist paint.
[c] September 2013 list prices for 1,100 lb quantities (FOB Washington, PA) are reported for Ferro pigments. February 2015 list prices for 1,100 lb quantities (free shipping) are reported for Shepherd Color pigments.
[d] Remarks from Shepherd Color in February 2015. “OK to sample” means still made and sold; “discontinued” means no longer made or sold. If availability is limited, Shepherd has identified a similar pigment to sample, or stated “no equivalent”.

Table 10. Particle size distribution for #11 granules (3M 2009).

U.S. sieve number	Nominal opening (mm)	Mass fraction retained specification (%)	Typical (%)
8	2.36	0 – 0.1	NA
12	1.70	4 – 10	NA
16	1.18	NA	30 – 50
20	0.85	NA	20 – 40
30	0.60	NA	10 – 30
40	0.425	0 – 2	NA

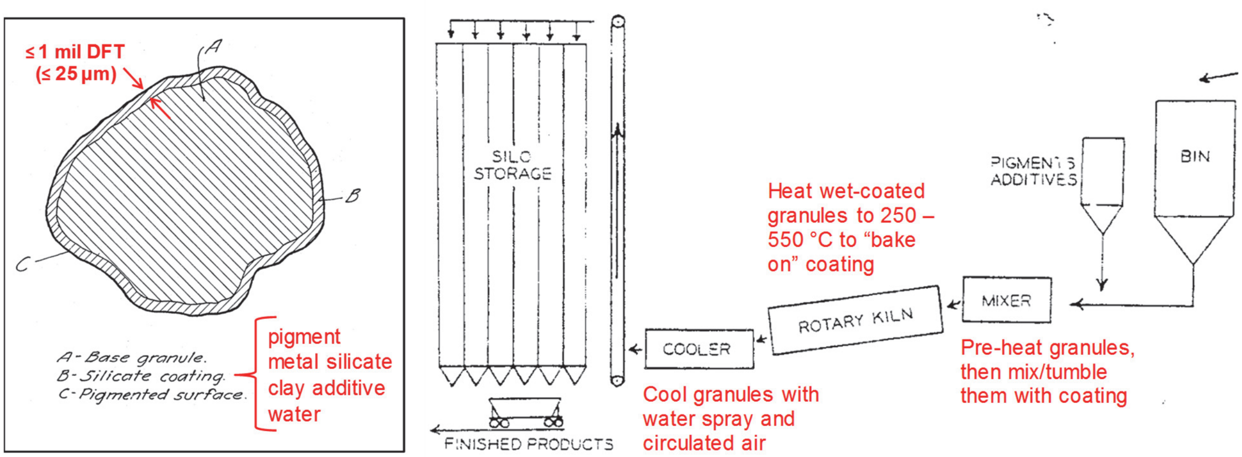


Figure 7. Schematic of traditional granule coating process (left box based on Lodge et al. 1961; remainder from Jewett et al. 1994).

While a roof's solar reflectance is most accurately estimated with a global (beam + diffuse) solar spectral irradiance, such as AM1GH, the solar reflectance metric reported by Cool Roof Rating Council in its rated products directory is based on a beam-only solar spectral irradiance. This irradiance, named E891BN (ASTM Standard E891 Beam Normal), can overestimate the solar reflectance of a selective cool colored surface by as much as 0.08, though more commonly by 0.02 – 0.06 (Levinson et al. 2010a,b). Therefore, we measured both AM1GH (realistic) and E891BN (rated) solar reflectances for the faux shingles. The latter is designated S_{E891BN}.

We also measured the AM1GH solar reflectance of opaquely thick piles of each granule specimen (A – D), obtained as the "G1" (AM1GH) output of a Devices & Services Solar Spectrum Reflectometer, version 6. Operation of this instrument follows ASTM C1549-09: Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer (ASTM 2009).

As expected, the faux shingles (S = 0.55 – 0.71) were less reflective than the opaque granule piles (S = 0.62 – 0.89), which in turn were less reflective than the solid blocks (S = 0.76 – 0.92) (Table

11; Figure 8; Figure 9). A shingle surfaced with white granules is less reflective than an opaque pile of these granules because light transmitted through the granule monolayer (solar transmittance 0.02 – 0.08) on the faux shingle is absorbed by dark asphalt or adhesive ($S \approx 0.05$). Meanwhile, an opaque pile of granules is less reflective than a flat, solid block of the same material because some of the light reflected from the pile's rough surface re-strikes the pile (Levinson et al. 2014).

The UV transmittance T_u of granule monolayers ranged from 0.02 to 0.07. While low UV transmittance is important to shield the asphalt from the sun, CertainTeed has not specified the maximum allowable value of this property.

The high solar reflectances of the faux shingles surfaced with white granules suggest they could be superficially or volumetrically colored with spectrally selective pigments to produce high-performance cool colored granules. We also note that without further pigmentation, these white granules could be used to produce high albedo roll roofing for low-slope applications, such as cool roofing for commercial buildings.

Table 11. AM1GH reflectances and transmittances of white granules and their sources.

	Specimen A	Specimen B	Specimen C
Source	Blue Planet	Blue Planet	[withheld]
Material description	calcium carbonate	calcium carbonate	kaolin-based calcined clay
Solar reflectance, source solid	0.76	0.92	not available
NIR reflectance, source solid	0.72	0.86	not available
Solar reflectance, opaque pile of #11 granules	0.62	0.89	0.76
Solar reflectance, faux shingle	0.55	0.71	0.65
NIR reflectance, faux shingle	0.53	0.67	0.68
Solar transmittance, granule monolayer	0.02	0.08	0.08
UV transmittance, granule monolayer	0.02	0.07	0.02

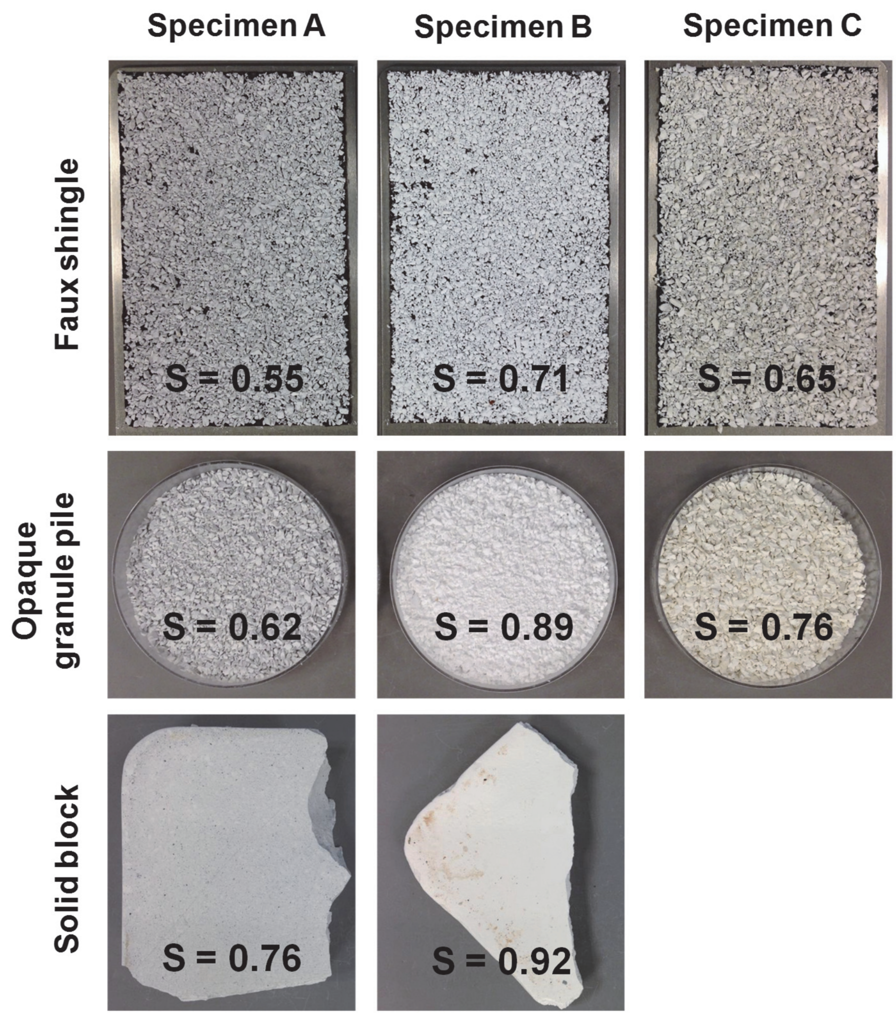


Figure 8. AM1GH solar reflectance (SR) of faux shingles (top row), opaque granule piles (middle row), and solid block sources (bottom) row associated with bright white granule specimens. We do not have a solid block source for specimen C.

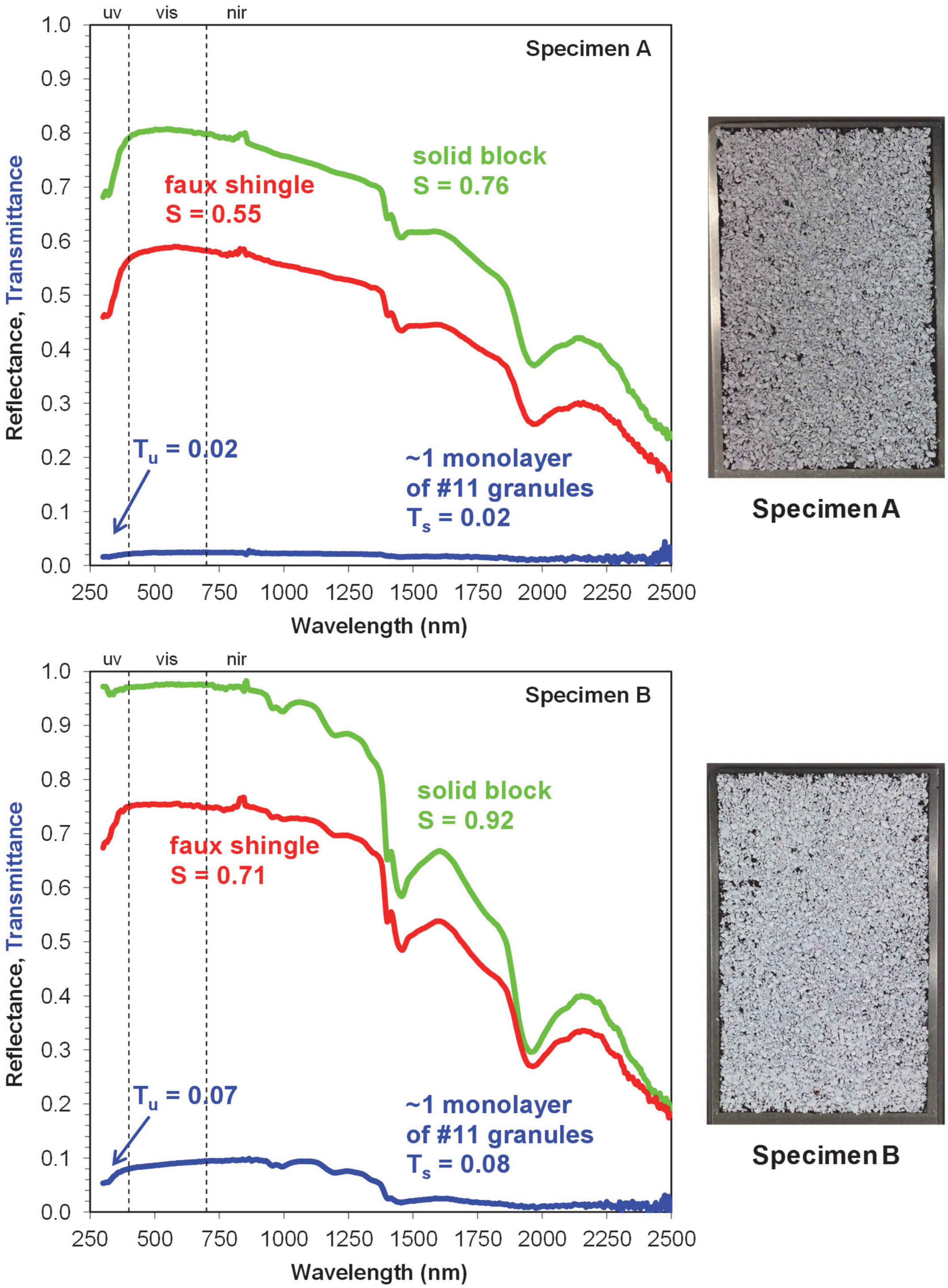
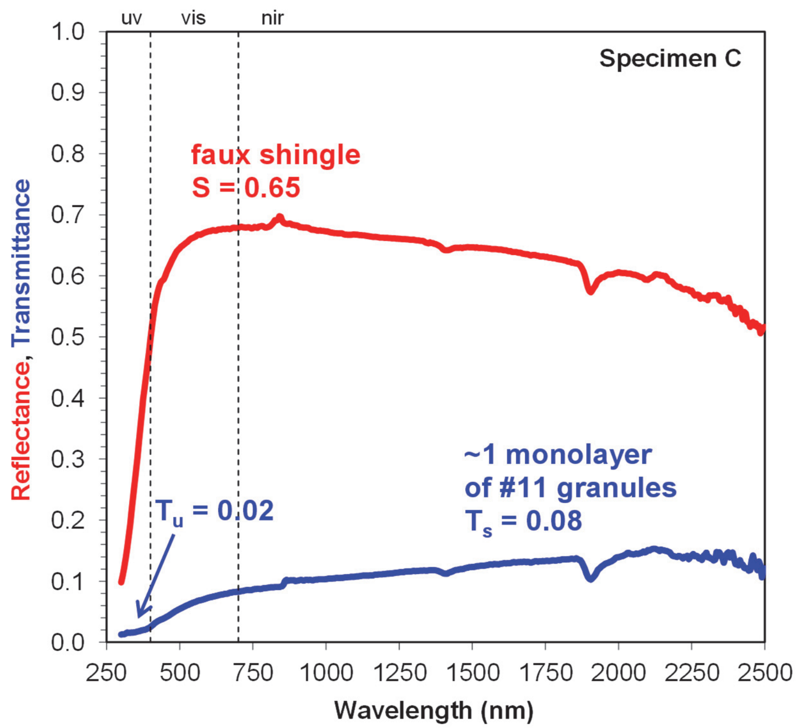


Figure 9. Solar spectral reflectances of faux shingles (granules affixed with dark adhesive to an aluminum panel), and solar spectral transmittances of granule monolayers, prepared from bright-white granules. Faux shingles are pictured at right.



Specimen C

Figure 9 (continued).

4.3 Characterizing radiative properties of cool-colored granules and cool-colored granule faux shingles (Method A)

To color the white granules, LBNL and Blue Planet selected several inorganic, spectrally selective pigments with strong visible absorptance and weak NIR absorptance. These included two reds, two greens, a brown, and a black (Table 12).

Blue Planet synthesized volumetrically colored red (Sakrete Red), green (Ferro Green V-12650), brown (Ferro Brown 10364), and black (Ferro Black 10202) discs (Table 13; Figure 10), and prepared faux shingles series BP-A from these four colored discs and an unpigmented disc.

Figure 11 shows the faux shingles (BP-A). Table 14 details their composition, reflectances, temperature elevations, and color coordinates. Temperature elevation is surface temperature minus outside air temperature, estimated under medium-wind speed conditions on a sunny summer afternoon following ASTM E1980-11: Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces (ASTM 2011).

The AM1GH solar reflectances of the colored faux shingles were 0.28 – 0.35 in series BP-A. Their E891BN solar reflectances were 0.31 – 0.39 in series BP-A—that is, up to 0.04 higher in series BP-A.

Table 12. Pigment cost for surface coloration of white granules and volumetric coloration of Blue Planet (BP) synthetic limestone. Also included for comparison is a conventional pigment (not cool). [a]

		Per mass of pigment ($/lb)	Per mass of colored granule ($/t)		Per area of roof ($/square)	
Pigment	Chemistry		Surface coloration	Volumetric coloration (BP)	Surface coloration	Volumetric coloration (BP)
Conventional pigment (not cool)	iron oxide	0.45	10	20	0.23	0.34
Sakrete Red [b]	iron oxide red	3.30	73	145	1.65	2.47
Ferro Red V-13810	iron oxide red	4.25	94	187	2.13	3.19
Ferro Green V-12650	modified chromium oxide green	9.70	214	427	4.85	7.28
Ferro Green 10241	chromium green-black hematite	10.85	239	478	5.43	8.14
Ferro Brown 10364	manganese antimony titanium buff rutile	7.15	157	315	3.58	5.36
Ferro Black 10202	proprietary	13.80	304	608	6.90	10.35
Cool pigment cost premium [c]		2.85 – 13.35	63 – 294	125 – 588	1.42 – 6.67	2.13 – 10.01

[a] Assumptions: pigment mass fraction (mass pigment / mass colored granule) = 1% for surface-colored white granules, 2% for BP granules; bulk density (g/cm^3) = 1.2 for surface-colored white granules, 0.9 for BP granules; colored granule application rate (lb/square) = 50 for surface-colored white granules, 38 for BP granules.

[b] A colorant for cement mixes (Sakrete 2015).

[c] Relative to use of conventional pigment.

Table 13. Pigment mass fraction (mass pigment/mass disc), solar reflectance, and lightness of synthetic limestone sources for Blue Planet faux shingles

Disc	Pigment	Pigment mass fraction	Solar reflectance[a]	Lightness[b]
BP-A-1	None	0%	0.88	95
BP-A-2	Sakrete Red	2.9%	0.47	54
BP-A-3	Ferro Green V-12650	6.9%	0.50	61
BP-A-4	Ferro Brown 10364	6.9%	0.48	59
BP-A-5	Ferro Black 10202	6.9%	0.42	58

[a] Air Mass 1 Global Horizontal (AM1GH).

[b] CIELAB lightness (L*) with D65 illuminant and 10° observer.

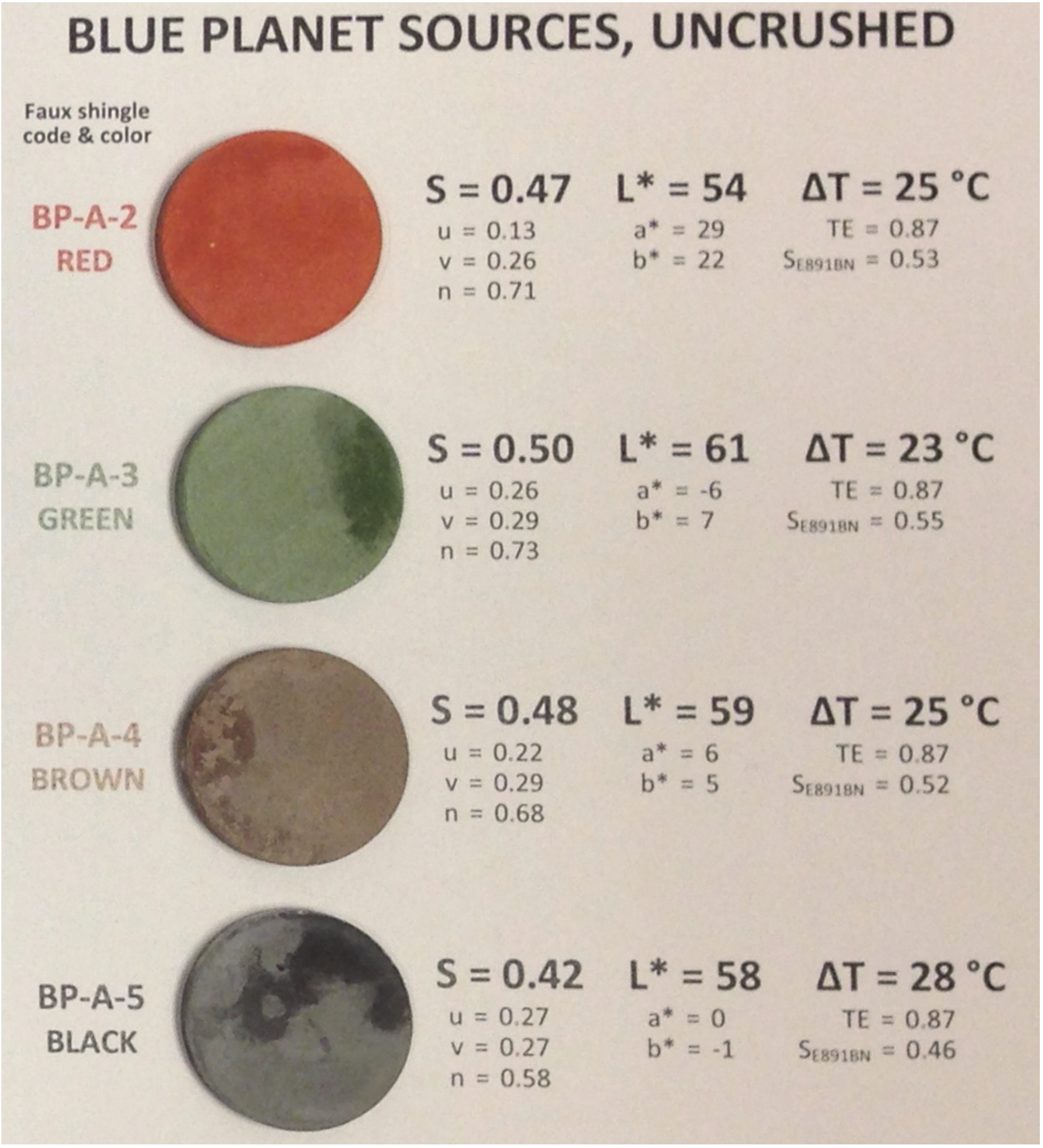


Figure 10. Appearance, radiative properties, and temperature elevation of colored synthetic limestone discs from which colored granules were prepared.

Table 14. Composition, reflectances, temperature elevations, and color coordinates of faux shingles.

Code	Description	S	U	V	N	S_{E891BN}	ΔT (°C)	L*	a*	b*
BP-A-1	bare BP synthetic limestone	0.65	0.54	0.65	0.66	0.65	16.0	85	1	2
BP-A-2	BP synthetic limestone colored with Sakrete Red	0.35	0.09	0.18	0.53	0.39	31.3	46	26	20
BP-A-3	BP synthetic limestone colored with Ferro Green V-12650	0.31	0.12	0.16	0.48	0.35	32.9	47	-5	8
BP-A-4	BP synthetic limestone colored with Ferro Brown 10364	0.28	0.08	0.13	0.44	0.31	34.6	41	7	6
BP-A-5	BP synthetic limestone colored with Ferro Black 10202	0.28	0.16	0.15	0.41	0.31	34.6	45	1	-1

Key: *S*, *U*, *V*, *N* = air mass 1 global horizontal (AM1GH) solar, ultraviolet, visible, and near-infrared reflectances; S_{E981BN} = solar reflectance metric used by the Cool Roof Rating Council; *ΔT* = surface temperature – outside air temperature, evaluated under ASTM E1980 conditions; L*, a*, b* = CIELAB color coordinates (lightness, green-magenta, blue-yellow) with D65 illuminant and 10° observer.

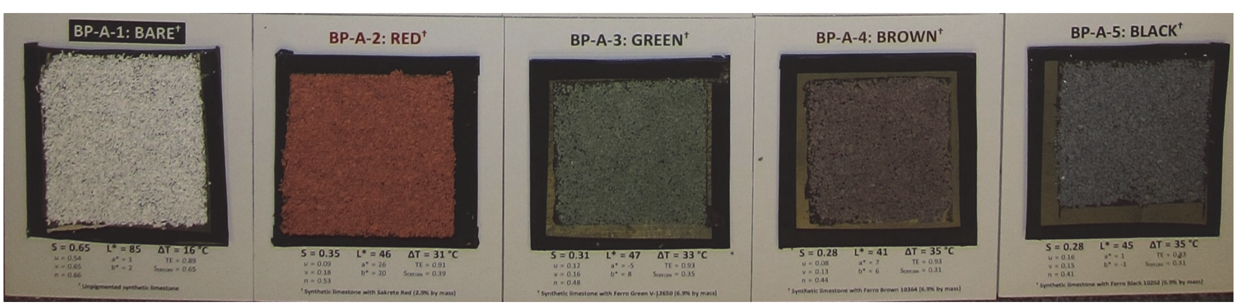


Figure 11. Faux shingles prepared with synthetic limestone granules, volumetrically colored with cool pigments (series BP-A).

Next, Blue Planet and LBNL evaluated the variation with pigment mass fraction (PMF; mass pigment per mass pigmented solid) of the reflectance and color of volumetrically pigmented discs of the Blue Planet synthetic limestone by preparing concentration ladders with an iron oxide red pigment (Figure 12) and a modified chromium oxide green pigment (Figure 13). The trends in Figure 14 suggest that a 2% PMF of this red pigment will yield a red disc with a solar reflectance of about 0.50, while a 2% PMF of this green pigment will produce a green disc with a solar reflectance of about 0.63. Reducing discs to granules, and applying the granules over a dark binder, lowers albedo by about 30% (Figure 15) and decreases lightness by about 20% (Figure 16).

We conclude that the pigment mass fractions in the BP-A series (3 – 7%) were substantially higher than necessary, and plan to reduce them to about 2% in the next round of BP prototypes. This is expected to increase the albedo and the lightness of the shingle, while saving pigment.

We also note that follow-up tests indicate that improved packing of the BP granules (to better hide the dark adhesive) could increase the albedo of a BP faux shingle by 0.05 – 0.10, depending on the granule albedo.

4.4 Cool shingle cost premiums (Method A)

In Method A, the only difference between a cool shingle and a conventional shingle is the nature and cost of the colored granules. The following cost premiums are relative to shingles surfaced with conventionally colored, non-cool rock granules, and are reported to only two significant figures.

Pigment only. The pigment-only cost premium for shingles surfaced with rock granules that have a white basecoat and a 1% PMF cool color topcoat would be 60 – 290 $/t colored granules, or 1.5 – 6.7 $/square roof. The pigment-only cost premium for shingles surfaced with synthetic limestone granules with 2% PMF cool pigment would be 130 – 590 $/t colored granules, or 2.1 – 10 $/square roof (Table 12).

Colored granules. The colored granule cost premium for white calcined clay granules with a 1% PMF cool color coating would be 1500 – 1700 $/t colored granules, or 31 – 36 $/square roof. The colored granule cost premium for white calcined clay granules volumetrically colored with 2% PMF cool pigment would be 1600 – 2000 $/t colored granules, or 32 – 42 $/square roof. Finally, the colored granule cost premium for white synthetic limestone granules volumetrically colored with 2% PMF cool pigment would be 53 – 530 $/t colored granules, or 0.16 – 8.2 $/square roof (Table 15). These colored-granule cost premiums are all within the project's target of $50/square ($0.50/ft^2) roof.

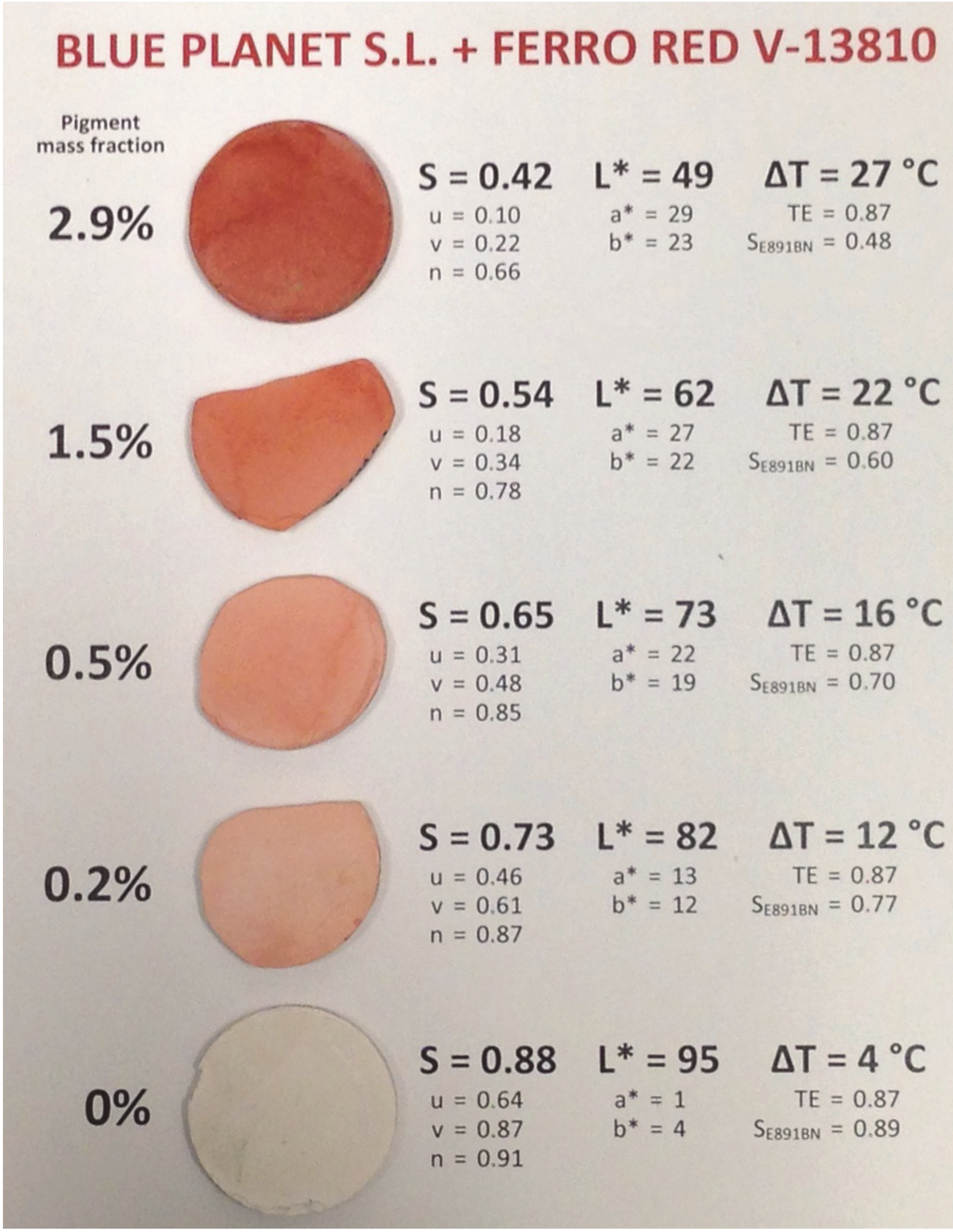


Figure 12. Red concentration ladder, showing variation with pigment mass fraction of the appearance, radiative properties, and temperature elevation of synthetic limestone colored with an inorganic cool red pigment.

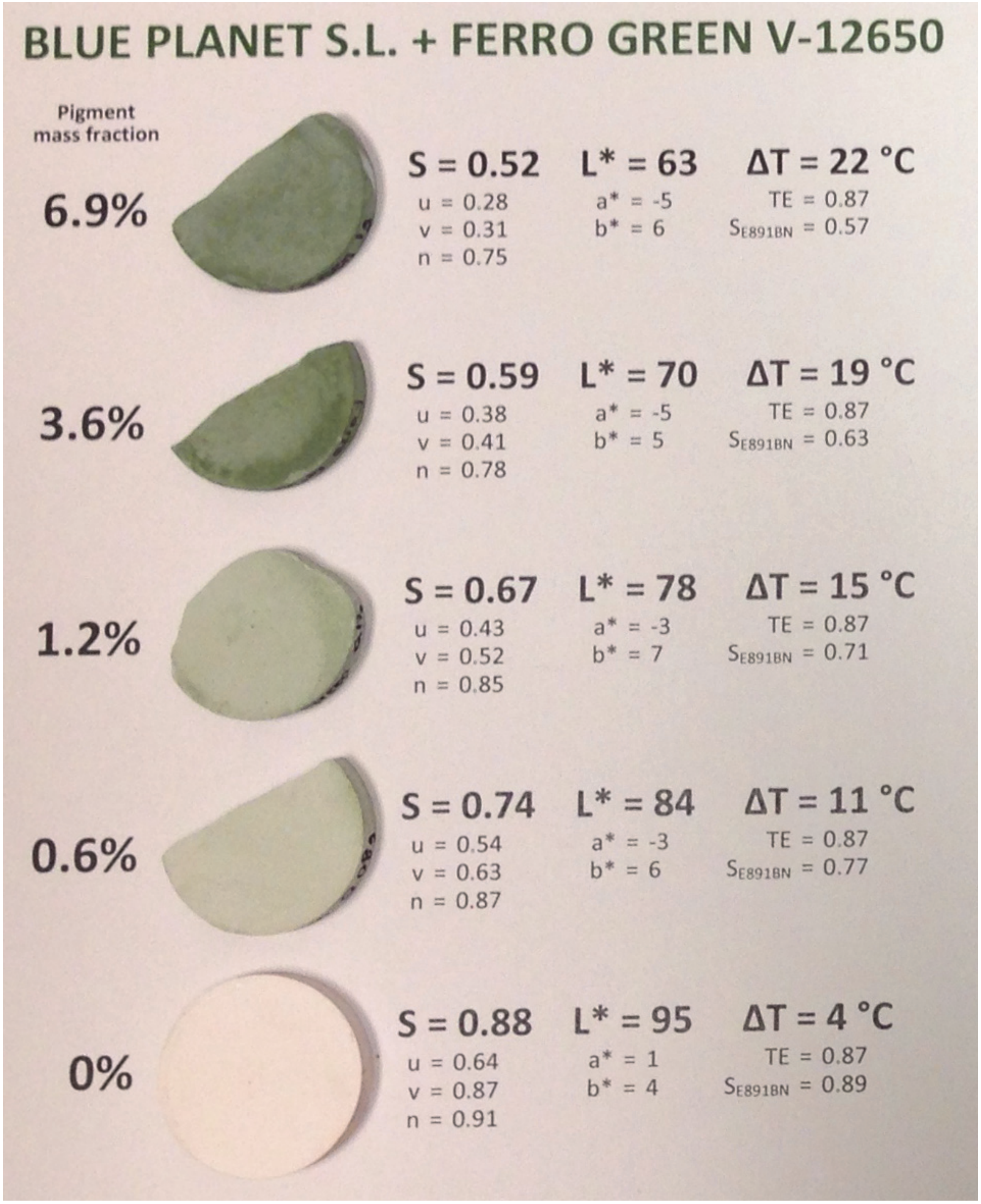


Figure 13. Green concentration ladder, showing variation with pigment mass fraction of the appearance, radiative properties, and temperature elevation of synthetic limestone colored with an inorganic cool green pigment.

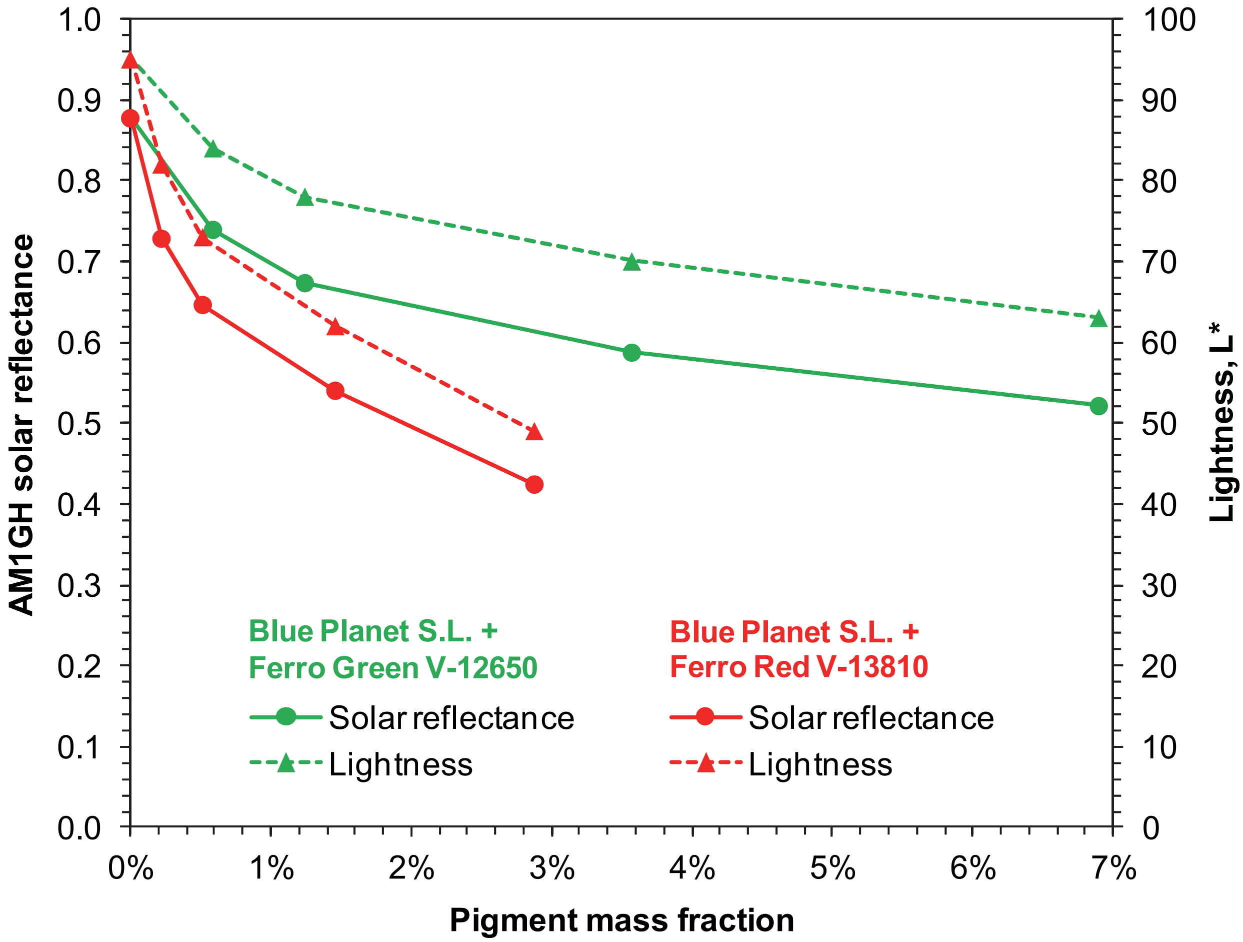


Figure 14. Variations with pigment mass fraction of the solar reflectance and lightness of the solid discs of synthetic limestone shown in Figure 12 and Figure 13.

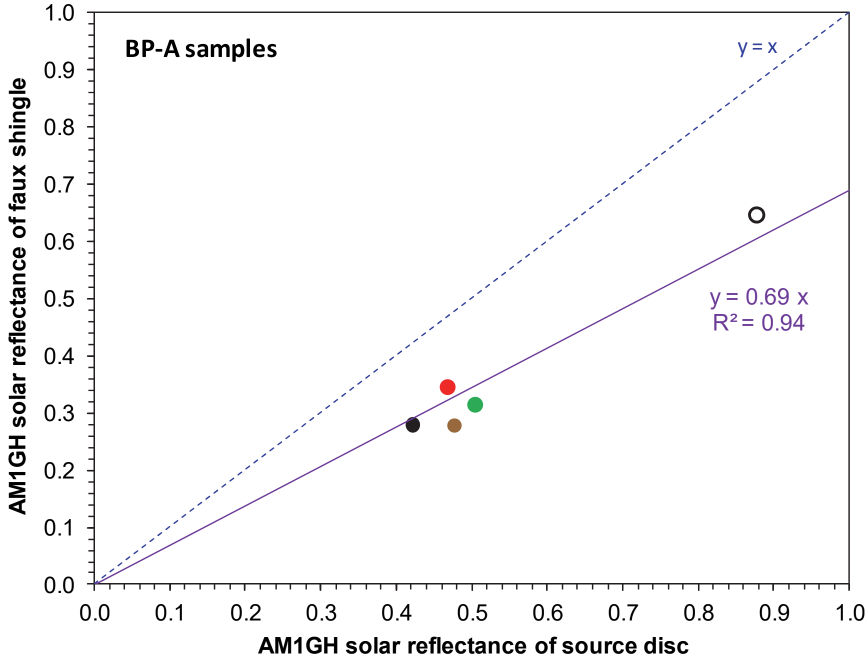


Figure 15. The albedo of a faux shingle surfaced with synthetic limestone granules (series BP-A) is about 30% lower than that of the solid disc from which the granules were crushed.

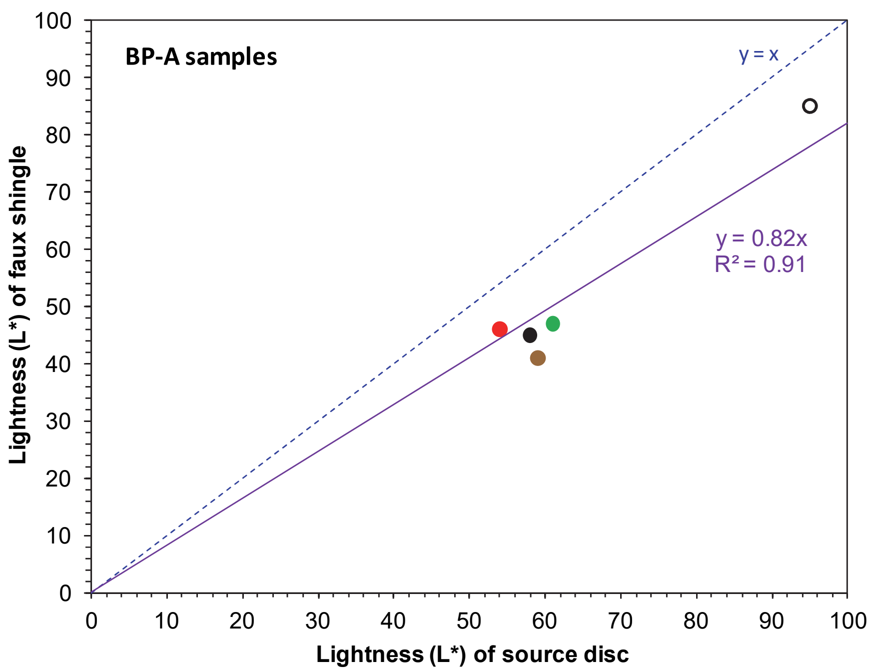


Figure 16. The lightness of a faux shingle surfaced with synthetic limestone granules (series BP-A) is about 20% lower than that of the solid disc from which the granules were crushed.

Table 15. Costs of conventional and cool granules. [a]

	Conventionally colored granules (dark rock granules with nonselective color coating)	White calcined clay granules with cool color coating	White calcined clay granules, volumetrically colored with cool pigment	White synthetic limestone granules, volumetrically colored with cool pigment
Pigment cost per unit mass of colored granules ($/t) [b]		73 – 304	145 – 608	145 – 608
Pigment cost per unit mass of uncolored granules ($/t)		74 – 307	148 – 620	148 – 620
Cost per unit mass of uncolored granules ($/t)		1,543 [c]	1,543 – 1,543	35 [d]
Cost per unit mass of colored granules ($/t)	130 [e]	1,617 – 1,850	1,691 – 2,164	183 – 655
Colored granule cost premium per unit mass ($/t)[f]		1,487 – 1,720	1,561 – 2,034	53 – 525
Cost of colored granules per unit roof area ($/square)	2.9	33.6 – 38.5	35.2 – 45.0	3.1 – 11.1
Colored granule cost premium per unit roof area ($/square) [f]		30.7 – 35.5	32.2 – 42.0	0.2 – 8.2

[a] Assumptions: when using cool pigments, pigment mass fraction = 1% for surface coloration, 2% for volumetric coloration; bulk granule density (g/cm³) = 1.2 for rock, 1.1 for calcined clay, 0.9 for synthetic limestone; colored granule application rate (lb/square) = 50 for rock, 46 for calcined clay, 38 for synthetic limestone.

[b] From Table 12.

[c] Based on estimate of $0.70/lb from supplier of Specimen C granules.

[d] Estimate from Blue Planet.

[e] Estimate from LBNL.

[f] Relative to conventionally colored granules.

5 Task 2: Assess options for applying opaque surface coatings to dark bare-granule shingles ("top coating")

Coating bare granules *after* they are pressed into the asphalt-coated fiberglass matt ("top coating") could conserve coating (binder and pigment) by coloring only the upper (exposed) surface of each granule. It might also be possible to apply a white basecoat and a cool color topcoat at consecutive stations within a production line, if the coating cures rapidly enough to avoid the need for a long distance between the two stations. Table 16 assesses several techniques for coloring bare-granule shingles: curtain coating, spray coating, and roller coating.

We investigated the process of roller coating. Roller coating has two stages: coating and drying. The team found two companies that design and manufacture industrial-scale coating and drying equipment: Black Bros. (Mendota, IL; http://blackbros.com) and ProTherm (Brandon, MN; http://pro-therm.com).

Black Bros., a manufacturer of roll coating equipment and systems, estimated that depositing a 3 – 7 mil wet film would require two coaters. They proposed applying and drying an initial layer before applying a final layer. A roller coater that can operate at 200 – 250 ft/min costs about $90,000. The desired line speed (500 ft/min) would be possible, but increase costs. Rolls, which are replaceable, have services lives that depend on the substrate roughness. If coating shingles, each roll ($300 – 400) could last 4-6 months. Black Bros. requested samples to run tests and provide a more accurate price estimate.

ProTherm, a manufacturer of electric infrared heaters for industrial process heating applications, requested 20 – 25 ft^2 of shingle samples to run tests and provide a more accurate estimate of the required heating system design and its cost.

We have not yet sent samples to either company.

Table 16. Strengths and limitations of coating processes that could be used to apply an opaque coating to a bare-granule shingle.

Process	Strengths	Limitations
Curtain coating	Easy to double production volume by increasing width of the web feeder to ≥ 2 m (6.6 ft).	Deposition is non-uniform at desired line speed of 2.5 m/s (500 ft/min).
Spray coating	Apply coating at variable angles for a more uniform application.	Low accuracy of the spray nozzles wastes coating. Messy, and expensive to maintain.
Roller coating	Works well for the proposed line speeds. Little pigment waste during application process.	The shingle's rough surface will decrease the lifetime of rollers, but the rollers are inexpensive.

6 Task 3: Assess clear, NIR-reflective surface coatings for conventional shingles

LBNL investigated surface treatments that could increase the albedo of conventional asphalt shingles without markedly changing their appearance.

6.1 Liquisol 4Ever

Mica flakes with chemically deposited titanium oxide (TiO_2) coatings have some promise as cost-effective pigments for solar reflective clear coatings. These coatings are sometimes called pearlescent because the whiter colors resemble pearls. One commercially available coating based on TiO_2-coated mica flakes is 4Ever Liquid Solar Control (LiquisolUSA 2015), an acrylic paint sold by LiquisolUSA (Tempe, AZ). The coating is intended for outdoor use on skylights. A dry free film about 50 µm thick exhibited very low absorptance in the visible (0.04) and NIR (0.02), and moderate reflectance in the visible (0.25) and NIR (0.34) (Figure 17). Applying a coating with a dry film thickness (DFT) of 50 µm to a dark shingle modestly increased its visible reflectance to 0.14 from 0.07, its NIR reflectance to 0.20 from 0.09, and its solar reflectance to 0.14 from 0.07. It also imparted a purple hue (Figure 18). This indicates that Liquisol 4Ever has limited utility as a clear, NIR-reflective coating.

6.2 Indium tin oxide (ITO)

Indium tin oxide (ITO) is an inorganic transparent conducting oxide with high reflectance in the NIR, suggested to us by a window coating researcher. We pigmented a clear acrylic binder with 1:1 and 1:20 pigment-to-binder mass ratios of ITO. At 1:1, the coating was solar opaque, and reflected 26% of sunlight. At 1:20, the coating transmitted 49% of visible light, and reflected 15% of sunlight. However, at each ratio its NIR reflectance was less than its visible reflectance (Figure 19). Thus, these samples of ITO were not cool.

6.3 Lanthanum hexaboride (LaB_6)

Lanthanum hexaboride (LaB_6) is an inorganic cool pigment suggested to us by a window coating researcher. We pigmented a clear acrylic binder with 1:1 and 1:20 pigment-to-binder mass ratios of LaB_6. At 1:1, the coating was dark, solar opaque, and reflected 16% of sunlight. At 1:20, the coating was equally dark, nearly opaque, and reflected 11% of sunlight (Figure 20). This suggests that these samples of LaB_6 were modestly selective, but unlikely to be useful as clear or opaque cool topcoats.

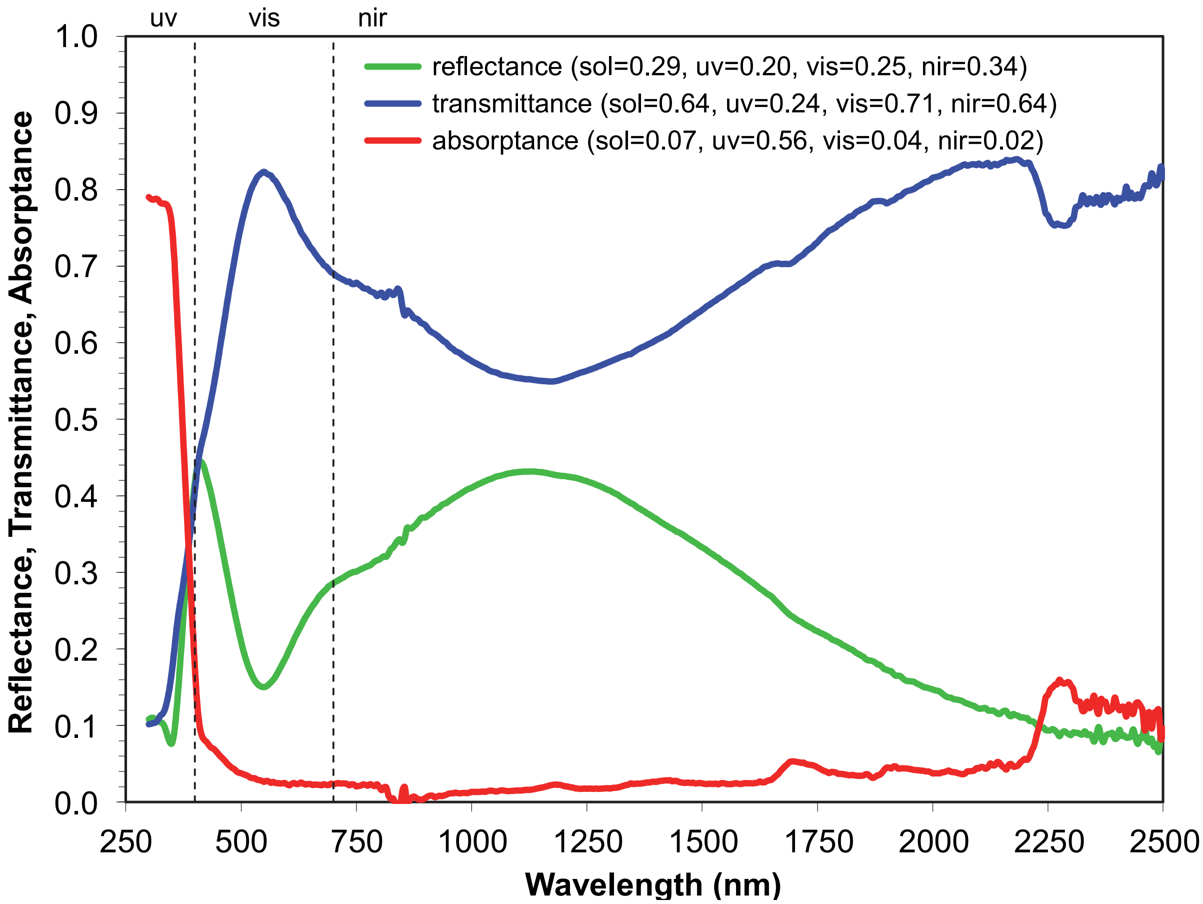


Figure 17. Spectral reflectance, transmittance, and absorptance of a free film of Liquisol 4Ever, about 50 μm thick.

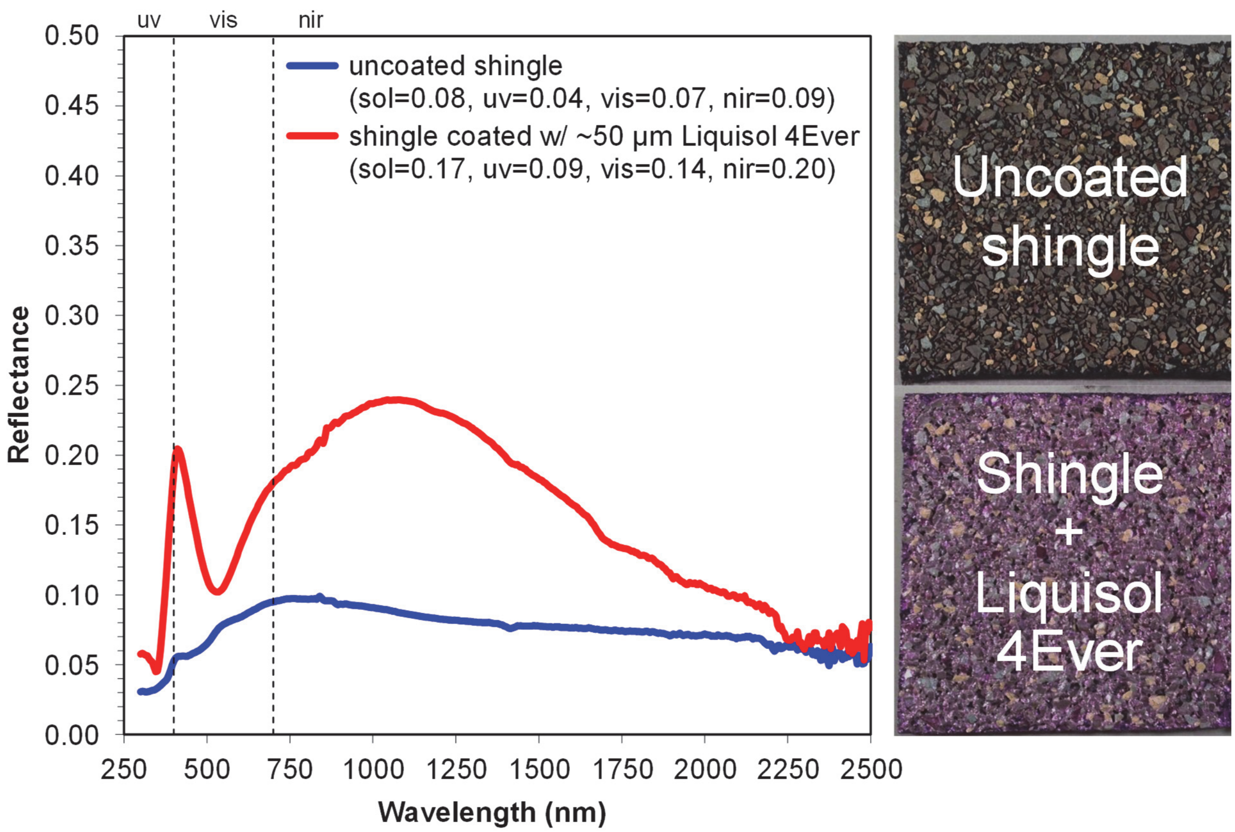
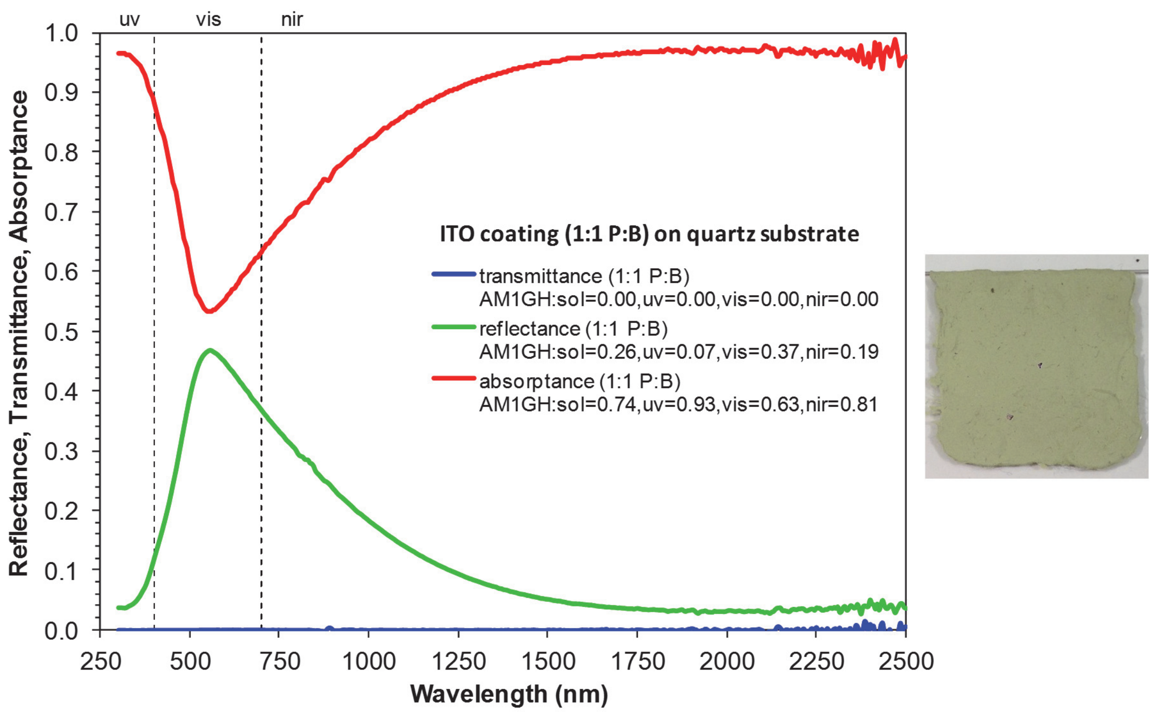
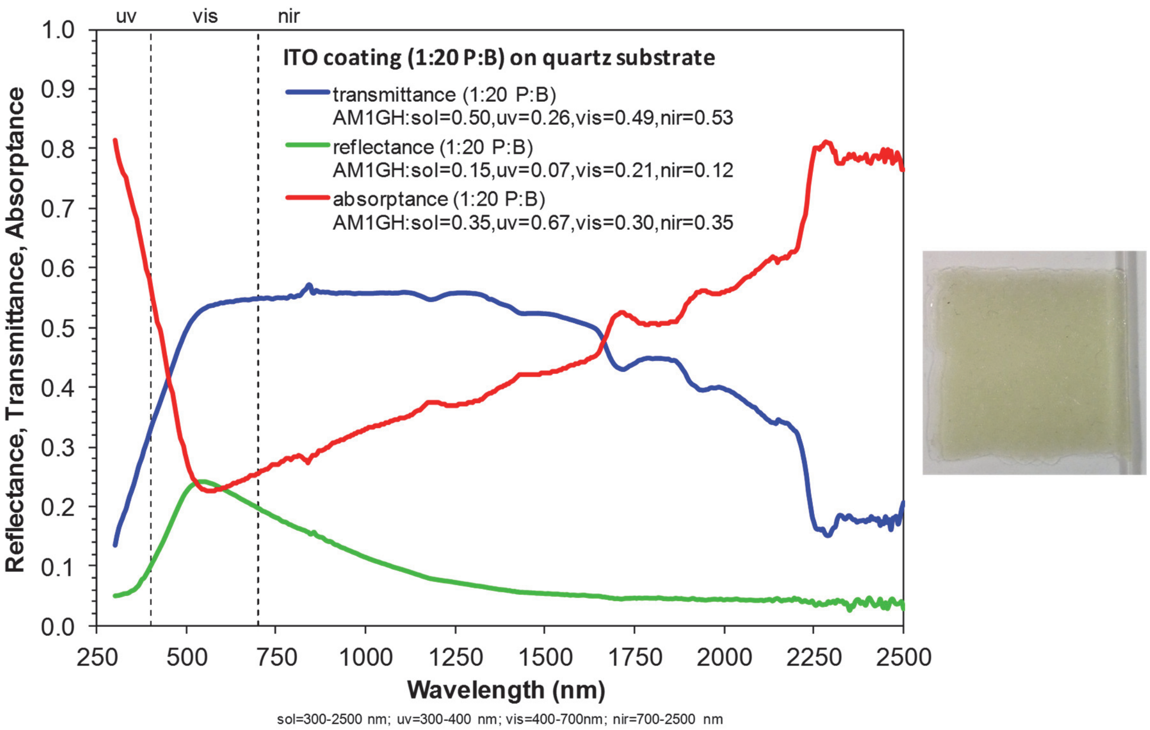


Figure 18. Solar spectral reflectance (left) and photographs (right) of an uncoated asphalt shingle, and of the same shingle coated with Liquisol 4Ever.



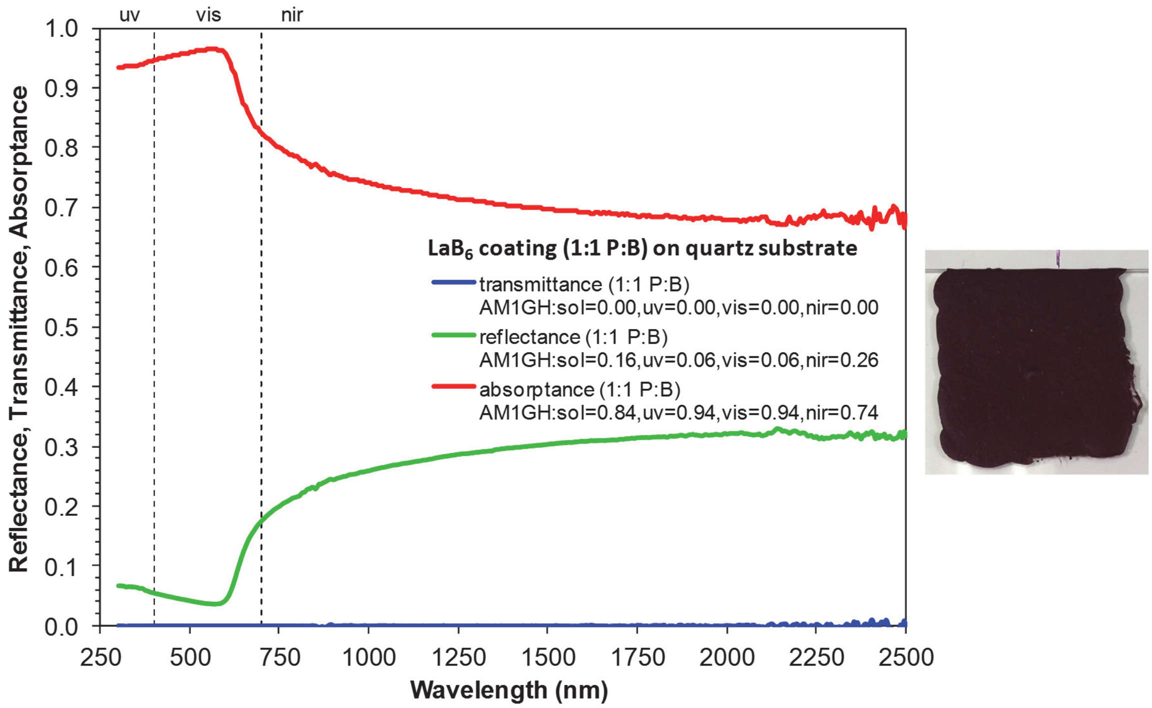
(a)



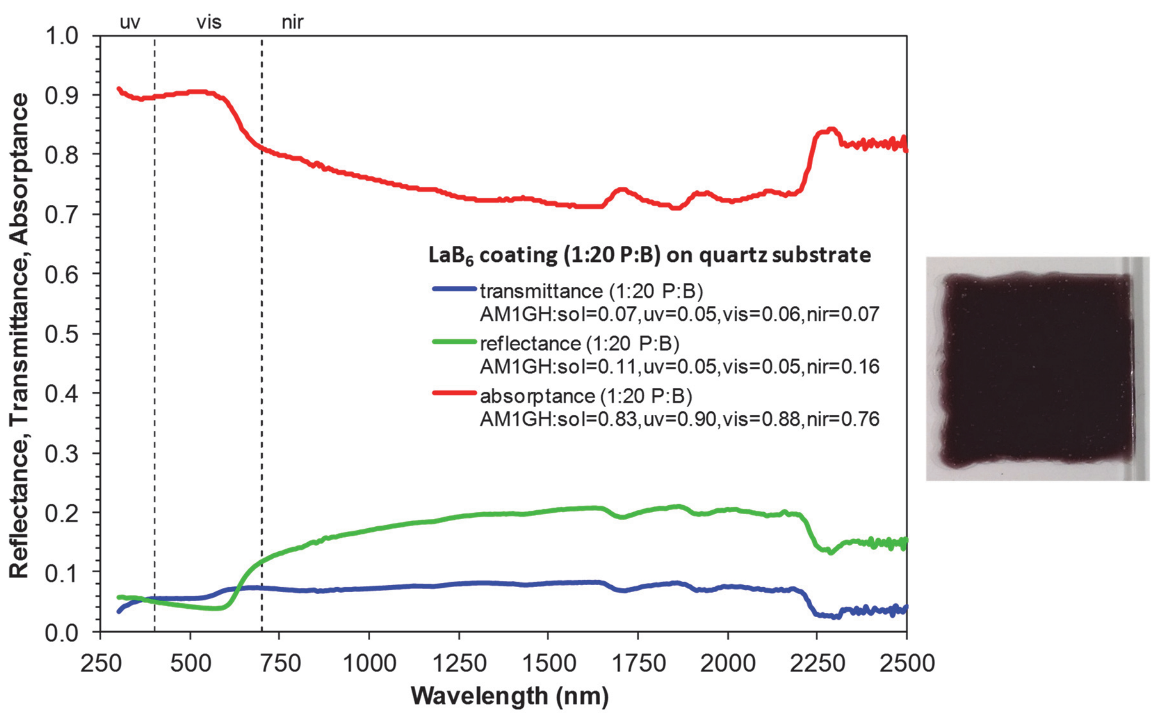
(b)

sol=300-2500 nm; uv=300-400 nm; vis=400-700nm; nir=700-2500 nm

Figure 19. Solar spectral reflectances and transmittances of quartz substrates with indium tin oxide (ITO)-pigmented acrylic coatings, shown for pigment to binder (P:B) mass ratios of (a) 1:1 and (b) 1:20. Images shown over white background.



(a)



(b)

Figure 20. Solar spectral reflectances and transmittances of quartz substrates with lanthanum hexaboride (LaB_6)-pigmented acrylic coatings, shown for pigment to binder (P:B) mass ratios of (a) 1:1 and (b) 1:20. Images shown over white background.

6.4 Further ideas

Other options were explored and are described here for completeness, and because they may become more feasible in the future. Our list includes technologies for making liquid crystal layers and near-infrared-reflective window coatings (Table 17).

- Liquid crystal filters prepared by the company Chelix (Chelix 2015) were considered. As spectrally selective filters they can have very high performance. In particular, cholesteric liquid crystals are very reflective to light with wavelength equal to the helical pitch. A first difficulty with this approach is that the liquid crystal molecules are organic and thus not likely to be highly durable. Also, high reflectivity is only attained for either left or right circular polarization, so at least two separate layers are required.
- Very thin metal layers (e.g., 10-nm layers of silver) can transmit visible light while reflecting the near-infrared component of sunlight. This technology is used in some window designs. Usually the spectral optical properties are enhanced with additional dielectric coatings; these additional coatings can also help seal the metal layer to inhibit corrosion. Often the window coatings have multiple layers deposited by sputtering (vacuum evaporation and spray pyrolysis are also used). However, this technology is thought to be currently too expensive for coating of roofing granules.
- Thin layers of certain semiconductors are electrically conducting yet optically transparent. They are used to make contacts for flat panel displays and photovoltaic cells. The electrical conductivity makes them reflective in the infrared spectral range and if the doping induced conductivity is sufficiently strong, the reflective region can be extended to wavelengths as short as the near infrared (700 – 2,500 nm). Indium tin oxide is an example (ITO, In_2O_3 doped with Sn). Such coatings on mica or glass flakes (if they were available) could likely serve as pigments that are transparent to visible light and reflective to near infrared. As discussed above in §6.2, we did verify that an indium tin oxide powder itself cannot provide the needed performance; the individual crystals need to be connected into a continuous film in order to provide the needed infrared reflectance.
- Yet another logical possibility is an electrically conductive wire mesh. [We sent a Record of Invention (ROI) on this topic to LBNL's Tech Transfer department in October of 2013, "Visually transparent near-infrared-reflective coatings using metal nanowires."] In this scheme, the holes in the mesh are large enough to allow visible photons to pass through, while the metal's electrical conductivity provides reflectivity for longer-wavelength photons (Figure 21). A clear polymer topcoat would be added to maintain high thermal emittance (Figure 22). While looking into this potential technology, we found a pocket of relevant recent research by investigators who want to replace ITO in flat panel displays by wire meshes in order to lower costs (indium is expensive) and to make flexible displays. This technology seems promising, but it is too immature for application to roofing granules in the near future.

Table 17. Status of techniques that could be used to apply an NIR-scattering clear coat to a colored-granule shingle.

Technique	Method of Deposition	Commercially Available?
Dielectric coating	Vacuum evaporation	Yes
Thin metal coating	Vacuum evaporation	No
Doped transparent semiconductors	Sputtering, sol-gel deposition	No
Liquid crystals	Chemical synthesis	Yes
Nanowire mesh	Coating with nanowire suspension	No

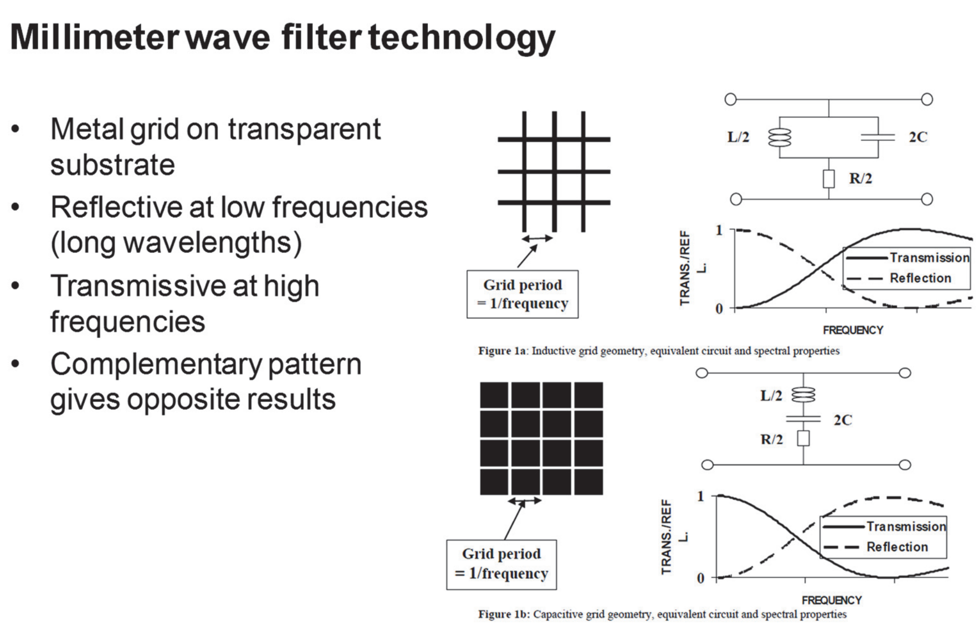


Figure 21. Millimeter wave filter technology on which the metal mesh concept is based (Ade et al. 2006).

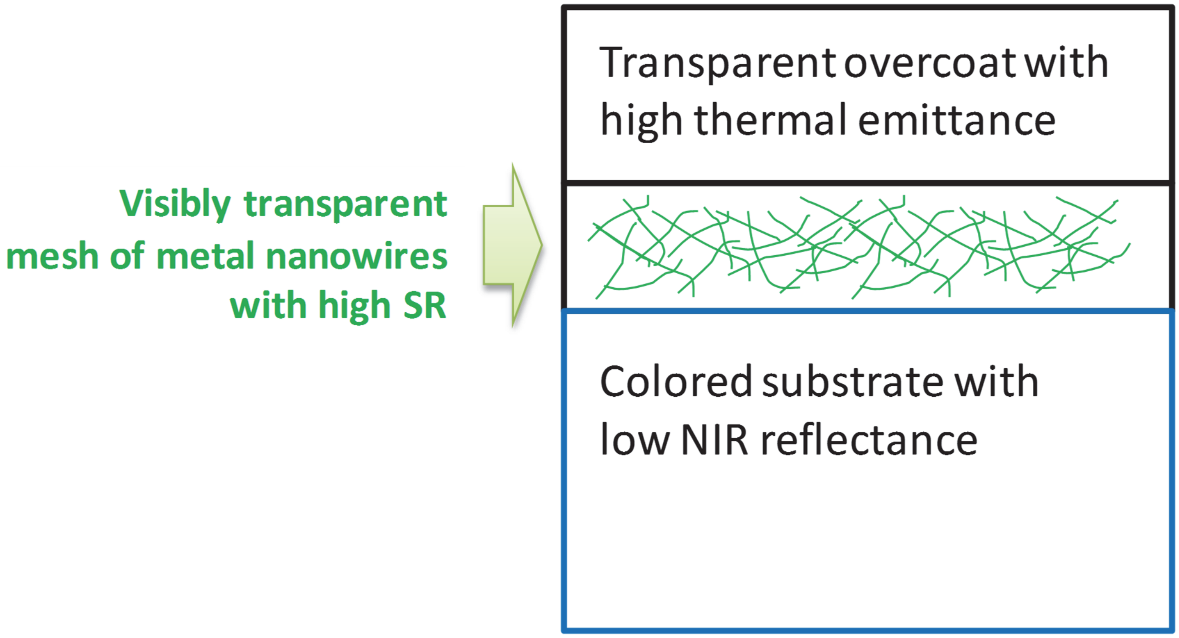


Figure 22. It may be possible to increase the solar reflectance of a non-cool surface without changing its appearance by applying a clear, NIR-reflecting mesh of metal nanowires. A clear polymer topcoat would be added to maintain high thermal emittance.

7 Discussion

7.1 Phase 1 results

Of the three paths toward high-reflectance, low-cost cool shingles explored in Phase 1 of this study, Method A—replacing dark bare granules with white bare granules to enhance the NIR reflectance attained with cool pigments—seems most promising. Faux shingles surfaced with the Phase 1 colored granule prototypes attained AM1GH (i.e., realistic) solar reflectances of up to 0.35 with volumetric coloration (series BP-A). Using the E891BN solar reflectance metric with which products are rated by the Cool Roof Rating Council raises these values as high as 0.39, bringing them just shy of our target initial SR of 0.40. Our concentration ladder study indicates that albedo can readily be increased by using less pigment. At planned pigment mass fractions of 1% for surface coloration and 2% for volumetric coloration, the cost premium for cool shingles would range from about zero to \$0.40/ft^2, depending on choice of granule material and pigment. This cost premium is well within our target limit of \$0.50/ft^2, and would represent less than a 10% increase in the installed cost of a shingle roof.

An unanticipated but welcome development was the combination of high albedo and rich color (rather than pastel) yielded by volumetrically pigmenting the synthetic limestone. We could try extending this approach to coloration of calcined clay granules.

Our study of Method B—applying a white basecoat and a cool-color topcoat to a shingle surfaced with dark bare granules—eliminated two techniques that did not work well with a high-speed shingle production line, and identified roller coating as the top-coating technique that appears best suited to coloring shingles in a high-speed factory line. If this approach is pursued, substantial further work will be needed to test specific combinations of roller coaters, driers, and production line configurations.

Our investigation of Method C—applying a visually clear, NIR-reflecting surface treatment to a conventionally colored shingle—did not yield any available coating systems that could substantially increase albedo without changing color. While a commercial coating based on TiO_2-coated mica flakes modestly boosted the NIR reflectance of a dark shingle to 0.20 from 0.09, it also turned the shingle purple. Two pigments recommended by a window coating researcher, indium tin oxide and lanthanum hexaboride, did not exhibit the desired spectral selectance. However, we did identify several other technologies worth revisiting as their performances improve or costs fall. We also developed and filed a record of invention for a novel scheme that involves a mesh of metal nanowires.

Based on the outcome of Phase 1, we recommend that Phase 2 focus on Method A.

7.2 Phase 2 plan

In Phase 2, we propose the following activities to refine the cool shingle prototypes, manufacture cool granules, and manufacture and market high-performance cool shingles. This second phrase would run for two years. The first year would address improving, testing, and finalizing high-performance cool granules; the second would address producing cool shingles surfaced with these granules.

Optimize granule albedo, color, and cost (first year of Phase 2)

1. Following Levinson et al. (2005b,c), calculate the Kubelka-Munk solar spectral backscattering and absorption coefficients of synthetic limestone and white calcined clay. Knowledge of these coefficients for both pigments and medium will let us predict the solar spectral reflectances of volumetrically pigmented synthetic limestone or calcined clay, guiding their coloration.
2. Evaluate pigments for both surface and volumetric coloration, possibly combined. (The cool pigment performance data in Table 9 characterize surface, but not volumetric, coloration.)
3. Seek inexpensive pigments (e.g., iron oxides) that may happen to be cool. The Sakrete red iron oxide identified in Phase 1 is a good example.
4. Seek additional sources of white granules, including other clay-based products, as well as natural white rock.
5. Explore coloring synthetic limestone with organic cool pigments. As noted in §4.1, such pigments can provide strong hiding and excellent selectance, and may be compatible with Blue Planet's room-temperature process used to synthesize limestone.
6. Assess from existing market research the best colors for cool granules.
7. Vary the limestone synthesis process to maximize NIR backscattering, thereby increasing NIR reflectance of granules. (The unpigmented synthetic limestone samples studied in Phase 1 —white granule Specimens A and B—transmit about 10% of NIR light to the substrate, where it is nearly entirely absorbed. Therefore, changing this transmission to reflectance could boost shingle albedo by as much as 0.05.)
8. Vary the limestone synthesis process to reduce visible backscattering. This could reduce the quantity of pigment needed to create dark colors.
9. Vary the limestone synthesis process to induce coloration by absorption within the visible spectrum. This could reduce or even avoid the need to add pigments.
10. Vary the limestone synthesis process to increase UV absorption and decrease UV backscattering. Whether this step is needed depends on (a) whether high UV reflectance is of concern for human health or atmospheric chemistry (smog production), and (b) the extent to which added pigments absorb UV.
11. Add small, colorless TiO_2 particles (< 100 nm) to granules to enhance their UV opacity.
12. While it is already clear that colored pigments can be physically mixed into the Blue Planet material (in a manner similar to adding pigment to paint), it may also be possible to dope the calcium carbonate chemically. For example, Fe_2O_3 (hematite) could be formed in-situ by addition of chemical precursors. Then the Fe^{3+} ion can impart a different color, due to a different chemical environment and very small particle size. Also, the scattering effect due to refractive index discontinuities between Fe_2O_3 and $CaCO_3$ (calcium carbonate) would be absent. Blue Planet has begun to explore this approach.
13. Re-examine coated glass and mica flakes as pigments, particularly as visibly transparent, NIR-reflective pigments. For non-transparent pigments, since Fe_2O_3 seems interesting, mica flakes coated with Fe_2O_3 might be good. Hematite absorbs the shortwave part of the visible but has a very high refractive index (3.0)—helpful for scattering NIR. For transparent NIR-

reflective pigments, the latest window coating technology should be examined. Cost may well exclude the use of coated flakes as pigment, but it is important to monitor developing window technology to see if it can be utilized for roofing granules.

14. Explore optimal size distribution of granules to maximize NIR reflectance and coverage fraction.
15. Guided by the above, make new cool granules that use volumetric and/or surface coloration of synthetic limestone and calcined clay. New granules should increase albedo and reduce pigment use, while maintaining acceptably dark color.

Verify radiative, mechanical, chemical, and biological durability of cool granules (first and second years of Phase 2)

1. Conduct outdoor (natural) and laboratory (accelerated) exposure of uncolored and colored granules to assess lightfastness, resistance to soiling, and changes to color and albedo.
2. Conduct mechanical tests to assess the strength of synthetic limestone and/or calcined clay granules.
3. Measure the resistance of synthetic limestone and/or calcined clay granules to (a) attack by acid rain, (b) water permeation, and (c) microbiological growth.

Manufacture cool granules and cool shingles (second year of Phase 2)

1. Develop a process (or processes) to manufacture cool granules, after the granules have been optimized for reflectance, cost, and color, and have been tested for radiative, mechanical, chemical, and biological durability.
2. Manufacture and market cool shingles surfaced with these cool granules.

8 Summary

As the least expensive category of high-slope roofing in the U.S., shingles are found on the roofs of about 80% of U.S. homes, and constitute about 80% (by product area) of the U.S. high-slope roofing market. Shingles are also among the least reflective high-slope roofing products, with few cool options on the market. This limits requirements for residential cool roofs in energy efficiency standards, as well as the actual use of residential cool roofs. The widespread use of cool roofs in the two warmest U.S. climate zones could reduce annual residential cooling energy use in these zones by over 7%, and would be substantially more effective than doubling the attic insulation in stock homes. Therefore, this project targets the development of high-performance cool shingles with initial solar reflectance at least 0.40 and a cost premium not exceeding $0.50/ft^2.

Phase 1 of the current study explored three approaches to improving cool shingles. Method A replaces dark bare granules by white bare granules to enhance the NIR reflectance attained with cool pigments. Method B applies a white basecoat and a cool-color topcoat to a shingle surfaced with dark bare granules. Method C applies a visually clear, NIR-reflecting surface treatment to a conventionally colored shingle. While our investigation of Method B identified roller coating as a promising top-coating technique, and our study of Method C developed a novel approach based on a nanowire mesh, Method A was most successful.

Method A yielded red, green, brown, and black faux shingles with AM1GH (realistic) solar reflectance up to 0.35 using volumetric coloration (series BP-A). Switching to the solar reflectance metric with which products are rated by the Cool Roof Rating Council raises these values as high as 0.39, just shy of our target initial SR of 0.40. These albedos can readily be increased by using less pigment. The expected cost premium for Method A faux shingles is less than our target limit of $0.50/ft^2, and would represent less than a 10% increase in the installed cost of a shingle roof. One combination of pigment and material that appears to offer especially high albedo and low cost is using inexpensive but cool (spectrally selective) iron oxide pigments to volumetrically color white limestone synthesized from sequestered carbon and seawater.

In Phase 2, we plan to refine the cool shingle prototypes, manufacture cool granules, and manufacture and market high-performance cool shingles.

References

Ade PAR, Pisano G, Tucker C, Weaver S. 2006. A review of metal mesh filters. Proc. SPIE 6275, Millimeter and Submillimeter Detectors and Instrumentation for Astronomy III, 62750U http://dx.doi.org/10.1117/12.673162 .

Akbari H, Berdahl P, Levinson R, Wiel S, Miller W, Desjarlais A. 2006. Cool-Color Roofing Material. California Energy Commission, PIER Building End-Use Energy Efficiency Program. CEC-500-2006-067. http://www.energy.ca.gov/2006publications/CEC-500-2006-067/CEC-500-2006-067-ALL.PDF .

Akbari H, Levinson R, Berdahl P. 2005a. Review of residential roofing materials, Part I: a review of methods for the manufacture of residential roofing materials. *Western Roofing Insulation and Siding*, Jan/Feb, 54-57. http://goo.gl/j2U52k

Akbari H, Levinson R, Berdahl P. 2005b. Review of residential roofing materials, Part II: a review of methods for the manufacture of residential roofing materials. *Western Roofing Insulation and Siding*, Mar/Apr, 52-58. http://goo.gl/3bCI4Z

ASTM. 2009. ASTM C1549-09: Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer. ASTM International, West Conshohocken, PA. https://compass.astm.org/Standards/HISTORICAL/C1549-09.htm

ASTM. 2011. ASTM E1980-11: Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/E1980-11 .

ASTM. 2012. ASTM E903-12: Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/E0903-12 .

CEC. 2012. 2013 Building Energy Efficiency Standards, Title 24, Part 6. California Energy Commission, Document CEC-400-2012-004-CMF. http://www.energy.ca.gov/title24

Chelix. 2015. Pigment technology. http://www.chelix.com/products_pigment.html .

CRRC. 2015. Rated Products Directory, Cool Roof Rating Council. Retrieved 2015-01-25 from http://coolroofs.org .

Cuhaj J. 2009. How to choose a roof for your home. *Today's Homeowner with Danny Lipford.* Retrieved 2015-01-25 from http://todayshomeowner.com/choosing-a-roof .

Farese O, Gelman R, Hendron R. 2012. A tool to prioritize energy efficiency investments. Technical Report NREL/TP-6A20-54799, National Renewable Energy Laboratory, Golden, CO. http://www.nrel.gov/docs/fy12osti/54799.pdf .

Freedonia Group. 2013a. U.S. roofing demand predicted to rise, driven by new construction. *Building Design + Construction*, September 20. http://www.bdcnetwork.com/us-roofing-demand-predicted-rise-driven-new-construction .

Freedonia Group. 2013b. Roofing—Demand and Sales Forecasts, Market Share, Market Size, Market Leaders. Industry Study 3082, September, 408 pages. http://www.freedoniagroup.com/Roofing.html

Homewyse. 2015. Retrieved on 2015-01-29 from http://homewyse.com .

Jewett CL, Collins RC, Weaver LW, McShea T. 1994. Roofing Granules. In *Industrial Minerals and Rocks (Nonmetallics other than Fuels)*. Senior Ed. Donald D. Carr, American Institute of Mining, Metallurgical, and Petroleum Engineers. Society for Mining, Metallurgy, and Exploration, Littleton, CO.

Konopacki S, Akbari H, Pomerantz M, Gabersek S, Gartland LM. 1997. Cooling energy savings potential of light-colored roofs for residential and commercial buildings in 11 US metropolitan areas. Technical Report LBNL-39433, Lawrence Berkeley National Lab, Berkeley, CA. http://dx.doi.org/10.2172/510556 .

Levinson R. 2010. AM1GH Solar Spectral Irradiance. http://coolcolors.lbl.gov/irradiance .

Levinson R. 2012. The case for cool roofs. http://heatisland.lbl.gov/publications/case-cool-roofs .

Levinson R, Akbari H. 2010. Potential benefits of cool roofs on commercial buildings: conserving energy, saving money, and reducing emission of greenhouse gases and air pollutants. *Energy Efficiency* 3 (1), 53-109.

Levinson R, Akbari H, Konopacki S, Bretz S. 2005a. Inclusion of cool roofs in nonresidential Title 24 prescriptive requirements. *Energy Policy* 33(2), 151–170.

Levinson R, Berdahl P, Akbari H. 2005b. Solar spectral optical properties of pigments, part I: Model for deriving scattering and absorption coefficients from transmittance and reflectance measurements, *Solar Energy Materials & Solar Cells* 89, 319-349.

Levinson R, Berdahl P, Akbari H. 2005c. Solar spectral optical properties of pigments, part II: Survey of common colorants, *Solar Energy Materials & Solar Cells* 89, 351-389.

Levinson R, Akbari H, Berdahl P. 2010a. Measuring solar reflectance—Part I: defining a metric that accurately predicts solar heat gain. *Solar Energy* 84, 1717-1744.

Levinson R, Akbari H, Berdahl P. 2010b. Measuring solar reflectance—Part II: review of practical methods. *Solar Energy* 84, 1745-1759.

Levinson R, Berdahl P, Akbari H. 2005c. Lawrence Berkeley National Laboratory Pigment Database. http://pigments.lbl.gov .

Levinson R, Akbari H, Berdahl P, Wood K, Skilton W, Petersheim J. 2010. A novel technique for the production of cool colored concrete tile and asphalt shingle roofing products. *Solar Energy Materials & Solar Cells* 94, 946–954.

Levinson R, Berdahl P, Abkari H, Miller W, Joedicke I, Reilly J, Suzuki Y, Vondran M. 2007. Methods of creating solar-reflective nonwhite surfaces and their application to residential roofing materials. *Solar Energy Materials & Solar Cells* 91, 304-314.

Levinson R, Chen S, Berdahl P, Rosado R, Medina LA. 2014. Reflectometer measurement of roofing aggregate albedo. *Solar Energy* 100, 159-171.

LiquisolUSA. 2015. Liquisol 4Ever Solar Control Paint. LiquisolUSA, Tempe, AZ. http://liquisolusa.com/4ever

Lodge JR et al. 1961. Colored Roofing Granules. U.S. Patent 2,981,636, April 25.

Lowes. 2014. Asphalt shingles prices for Concord, CA retrieved on 2014-04-20 from http://Lowes.com .

PNNL. 2013. Building America Top Innovations Hall Of Fame profile: building science-based climate maps. Publication PNNL-SA-90570, Pacific Northwest National Laboratory, Richland, WA. http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/4_3a_ba_innov_buildingscienceclimatemaps_011713.pdf

Pokroy B, Quintana JP, Caspi EN, Berner A, Zolotoyabko E. 2004. Anisotropic lattice distortions in biogenic aragonite. *Nat Mater* 3(12), 900–902.

RDMag. 2012. 2012 R&D 100 Winner: Layered coating, cool roof. *R&D Magazine*, August 15. http://www.rdmag.com/award-winners/2012/08/layered-coating-cool-roof .

Sakrete. 2015. Cement color additive. http://www.sakrete.com/products/detail.cfm/prod_alias/Cement-Colors

Service RF. 2012. ~~Save~~ pave the world. *Science* 337 (6095), 676-678.

SEIA. 2014. United States installs 1,354 MW of Solar in Q3 2014. News release, Solar Energy Industries Association, December 9. http://seia.org/news/united-states-installs-1354-mw-solar-q3-2014 .

3M. 2009. Wausau #11 grade roofing granule data sheet. 3M Industrial Mineral Products, Wausau, WI. http://tinyurl.com/qfnrh5f .

US EIA. 2008. 2005 Residential Energy Consumption Survey (RECS), Table AC2. U.S. Energy Information Administration. http://www.eia.gov/consumption/residential/data/2005/c&e/airconditioning/pdf/tableac2.pdf .

US EIA. 2013a. 2009 Residential Energy Consumption Survey (RECS), Table HC2.1. U.S. Energy Information Administration. http://www.eia.gov/consumption/residential/data/2009/xls/HC2.1%20Structural%20and%20Geographic%20by%20Housing%20Unit%20Type.xls .

US EIA. 2013b. 2009 Residential Energy Consumption Survey (RECS), Table HC10.14. U.S. Energy Information Administration. http://www.eia.gov/consumption/residential/data/2009/xls/HC10.14%20Average%20Square%20Footage%20of%20Single-Family%20Homes.xls) .

US EIA. 2015. American Institute of Architects (AIA) climate zone map, as supplied by the US Energy Information Administration. Retrieved 2015-01-25 from http://www.eia.gov/consumption/residential/reports/images/climatezone-lg.jpg .

US EPA. 2015. Energy Star Roof Products Key Product Criteria. US Environmental Protection Agency. http://www.energystar.gov/index.cfm?c=roof_prods.pr_crit_roof_products .

USGBC. 2009. Leadership in Energy & Environmental Design (LEED) 2009. US Green Building Council. http://www.usgbc.org/credits/new-construction/v2009 .

Appendix A

The following is excerpted from Akbari et al. (2005a,b), a two-part article by the LBNL research team that reviews methods for the manufacture of residential roofing materials. It aggregates the text specific to production of asphalt shingles.

Types of Asphalt Shingle

Asphalt is a dark-brown-to-black cementitious material, solid or semisolid, in which the predominant constituents are naturally-occurring or petroleum-derived bitumens. It is used as a weatherproofing agent. The term asphalt shingle is generically used for both fiberglass and organic shingles. There are two grades of asphalt shingles: (1) standard, a.k.a. 3-tab; and (2) dimensional. Asphalt shingles come in various colors.

Examples: Fiberglass shingles, commonly known as "asphalt shingles," consist of fiber mats that are coated with asphalt and then covered with granules. Granules, a.k.a. mineral granules or ceramic granules, are opaque naturally or synthetically colored aggregates commonly used to surface-cap sheets and shingles.

Organic shingles have a thick cellulose base that is saturated in soft asphalt. This saturation makes them heavier than fiberglass shingles, and less resistant to heat and humidity, but more durable in freezing conditions.

Manufacturing Methods — Shingles

Production of colored granules. Granules cover over 97% of the surface of a typical asphalt-soaked fiberglass shingle. Granules are applied to asphalt shingles for several reasons, including UV protection, coloration, ballasting, impact resistance, and fire resistance.

Granule manufacturing plants are typically sited near a quarry of suitable base rocks, including andesite, coal slag, diabase, metabasalt, nephaline syenite, quartzite, rhyodacite, rhyolite, and/or river gravel. The essential characteristics of the base rock include: opacity to ultraviolet light, to protect the asphalt from ultraviolet damage; chemical and physical inertness, to provide resistance to acid rain, leaching, freeze/thaw, wet/dry cycling, oxidation and rusting; low porosity, to improve physical strength, binding between coating and rock, and efficiency with which the pigment coating covers the surface; and resistance to high firing temperatures. Other necessary characteristics include moderate hardness, to remain intact during the granule coloring process; moderate density (to weight the shingle against wind lift); uniformity, and crush equidimensionality (to prevent directional embedment in the shingle manufacturing process, which changes shingle appearance).

In a roofing-granule manufacturing plant, rocks blasted from quarries are crushed in several stages to reduce the rock to granule-size aggregate (0.5 to 2 mm). In this process, the larger aggregates are recycled to the crushing system and the smaller debris is separated for other usage.

Once the granules are milled to the right size, they are transferred to the coloring plant. In the coloring plant, in a continuous process they are mixed with a semi-ceramic color coating. The coating is a mix of color pigments in a sodium silicate, hydrated kaolin clay, and water. The preheated granules are mixed and tumbled with coating sufficient to cover the surface. The wet coated granules are then transferred to a rotary kiln where they are gradually heated to 250-550°C (500-1,000°F). This dehydrates and polymerizes the coating, forming an insoluble pigmented ceramic layer. The granule is then gradually cooled in a rotary cooler by sprayed water and circulated air. Finally, the pigmented granules are coated with mineral oil to control dust and to improve asphalt adhesion. The mineral oil typically evaporates within a few months.

The pigments used for colored granules must have certain properties, including stability at high temperature, chemical inertness, ease of dispersion, color consistency, weather stability, non-toxicity, and low cost. Common pigments used in roofing granules include titanium dioxide (white), zinc ferrite (yellow), red iron oxides, carbon black, chrome oxide (green), and ultramarine (blue). Typically, 2.3-2.7 kg (5-6 lb.) of pigment per ton of granules are required to create a single-layer coating. Multiple coatings are needed to increase pigment loading. Some granule manufacturing plants have parallel coloring lines that can be used in series to apply multiple layers of coatings on granules. The granules (both colored and uncolored) are transported to shingle manufacturing companies by road and rail.

Production of shingles. Fiberglass asphalt shingles have three major components: fiberglass mat, asphalt (with additive fillers), and granules (colored and uncolored). In a typical plant, the fiberglass mat is fed into a roll coater that applies layers of stabilized coating asphalt to the top and bottom surfaces of the webbing sheet. Stabilized coating asphalt is harder and more viscous than straight asphalt, and has a higher softening point. The mineral stabilizer may consist of finely divided limestone, silica, slate dust, dolomite, or other minerals.

The "filled" or "stabilized" coating asphalt applied at the coater is produced in the mixer, which is usually positioned above the manufacturing line at the coater. Coating asphalt, typically at 200-270°C (400-520°F), is piped into the mixer, and the mineral stabilizer is added. To eliminate moisture problems and to help maintain the temperature above 180°C (360°F) for proper coating consistency in the mixer, the mineral stabilizer is dried and preheated before being fed into the mixer.

The weight of the finished product is controlled by the thickness of coating asphalt used. The coating rolls can be moved closer together to reduce the amount of coating applied to the substrate, or separated to increase it. Most modern plants are equipped with automatic scales or profile scanners that monitor the sheets during the manufacturing process and warn the operator when too much or too little coating is being applied.

Colored and uncolored granules are applied in a section of the manufacturing line that usually consists of a multi-compartmented granule hopper, two parting-agent hoppers, and two large press rollers. The hoppers are fed through flexible hoses from one or more machine bins above the line. These machine bins (sometimes called surge bins) provide temporary storage. The granule hopper drops colored granules from its various compartments onto the top surface of the moving sheet of coated web in the sequence necessary to produce the desired color pattern on the roofing.

Next, the sheet is cooled by passing it over watercooled rollers; water may also be sprayed directly onto the sheet to speed cooling. The final steps in the production of asphalt roofing shingles are cutting and packaging. After the shingles have been cut by machine they are moved by a roller conveyor to automatic packaging equipment. The packaged shingles are then stacked on pallets and transferred by forklift to storage areas or waiting trucks.

Methods to Produce Cool Roofing Materials — Shingles

The solar reflectance of a new shingle is dominated by the solar reflectance of its granules, since by design the surface of a shingle is well covered with granules. Hence, we focus on the production of cool granules. There are primarily two ways to increase the solar reflectance of the granules: manufacturing granules from highly reflective (e.g., white) rocks, and/or coating the granules with reflective pigments. The use of naturally white rock is limited by local availability of suitable inert rocks, which are often not found in large quarries. Hence, manufacturers usually color the granules.

Until recently, the way to produce granules with high solar reflectance has been to use titanium dioxide (TiO_2) rutile, a white pigment. Since a thin layer of TiO_2 is reflective but not opaque, multiple layers are needed to obtain the desired solar reflectance. This technique has been used to produce "super-white" (meaning truly white, rather than gray) granulated shingles with solar reflectances exceeding 0.5. Manufacturers have also tried to produce colored granules with high solar reflectance by using non-white pigments with high NIR reflectance. However, like TiO_2, cool colored pigments are also partly transparent to NIR light; thus, any NIR light not reflected by the cool pigment is transmitted to the (typically dark) granule underneath, where it can be absorbed. To increase the solar reflectance of colored granules with cool pigments, multiple color layers, a reflective undercoating, and/or reflective aggregate should be used. Obviously, each additional coating increases the cost of production.

A conventional black roof shingle has a reflectance of about 0.04. On the first try to increase the solar reflectance of the shingle, we replaced the standard black pigment on the granules with one that is NIR reflective. That increased the reflectance of the granule to 0.12. On the second try, we used a two-layered technique where we first applied a layer of TiO2 white base (increasing the solar reflectance of the base granule to 0.28) and then a layer of NIR-reflective black pigment. This increased the reflectance of the black granule to 0.16. On our third prototype, the base granule was coated in ultra-white (reflectance 0.44) and then with a NIR-reflective black pigment. This increased the solar reflectance to 0.18.

The application of pigmented coatings to roofing granules appears to be the critical process step. Several layers of silicate coatings can be involved, and may include not just one or more pigments, but the use of clay additives to control viscosity, biocides to prevent staining, and process chemistry controls to avoid unreacted dust on the product.

One way to reduce the cost is to produce cool colored granules via a two-step, two-layer process. In the first step, the granule is pre-coated with an inexpensive pigment that is highly reflective to NIR light. In the second step, the cool colored pigment is applied to the pre-coated granules.

Shingles tend to lose some granules as they age and weather, exposing asphalt-coated fiberglass and reducing solar reflectance. Substituting a reflective sealant for the black asphalt could slow this. While developing such a replacement for asphalt may be of long-term interest, we do not see an easy solution to this problem.

It should be noted that the reflectance of an asphalt shingle covered with granules will be less than that of the granule's coating, since some of the light reflected by each granule will strike a neighboring granule and be absorbed. These "multiple reflections" can reduce shingle reflectance by as much as 0.15.

Finally, the granule manufacturing and shingle manufacturing industries have designed their quality-control laboratories to test the visible color of their products. We anticipate that the industry will need to equip itself with additional instruments to test the solar reflectance and the NIR optical properties of their products. It is also envisioned that unified standards have to be developed to address issues related to manufacturing of cool colored granules and shingles.