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Final Report

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Durability of High-Albedo Roof Coatings and Implications for Cooling Energy Savings

ABSTRACT

Twenty-six spot albedo measurements of roofs were made using a calibrated pyranometer. The roofs were surfaced with either an acrylic elastomeric coating, a polymer coating with an acrylic base, or a cementitious coating. Some of the roofs' albedos were measured before and after washing to determine whether the albedo decrease was permanent.

Data indicated that most of the albedo degradation occurred within the first year, and even within the first two months. On one roof, 70% of one year's albedo degradation occurred in the first two months. After the first year, the degradation slowed, with data indicating small losses in albedo after the second year. Measurements of seasonal cooling energy savings by Akbari et al. (1993) included the effects of over two months of albedo degradation. We estimated ~20% loss in cooling-energy savings after the first year because of dirt accumulation.

For most of the roofs we cleaned, the albedo was restored to within 90% of its initial value. Although washing is effective at restoring albedo, the increase in energy savings is temporary and labor costs are significant in comparison to savings. By our calculations, it is not cost-effective to hire someone to clean a high-albedo roof only to achieve energy savings. Thus, it would be useful to develop and identify dirt-resistant high-albedo coatings.

A. INTRODUCTION

High-albedo[1] roof coatings can be used to reduce building air-conditioning use and, if widely implemented, might reduce summer urban temperatures. By lowering the absorption of solar energy, high-albedo coatings reduce building surface temperatures, and heat-transfer to the building interior. The lower surface temperatures also reduce the building's contribution to urban air temperature (Akbari et al., 1988). To maximize cooling energy savings, high-albedo roof coatings should 1) have high solar reflectance (both in the visible and near-infrared bands), 2) have high infrared emittance, and 3) maintain these properties for the service life of the coating.

This report addresses the albedo durability of solar-reflective roof coatings, as part of a joint project between Lawrence Berkeley Laboratory and Sacramento Municipal Utility District to assess the use of high-albedo building materials for cooling-energy savings. Information that was gathered on durability is reviewed and roof albedo measurements are presented, with implications of the results for cooling-energy savings.

A literature search produced little quantitative information on the albedo durability of roof coatings. Thus, field measurements were made to determine the effects of dirt collection and weathering on the albedo of highly reflective roof coatings. Several high-albedo coatings were chosen, and for each coating, several roofs that were surfaced with the coatings were selected. The albedo of each roof was measured with a pyranometer. Information, including age and substrate type and condition, was collected from the coating distributor.

B. BACKGROUND REVIEW

B.1. Definition of Albedo

In this report, we use the term "albedo" to refer to the integrated hemispherical reflectance within 0.28 and 2.8 micrometers (μm). As applied to a sloped roof, however, albedo is not a clearly defined parameter. Since a sloped roof receives some radiation that is reflected from surroundings and re-radiated by the ground, the spectral distribution of incoming radiation is different than that on a horizontal roof. The spectral distribution of radiation reaching the roof from surroundings can also be temporally variable. To estimate the albedo of sloped roofs in this

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[1] Albedo is the fraction of radiant energy reflected by a surface.

study, we measured the hemispherical incident radiation as measured on a plane parallel to the roof surface, as close to the peak of the roof as possible (to minimize the detection of outgoing radiation).

B.2. Techniques for Measuring Albedo

Albedo can be measured in the field or calculated from laboratory measurements. Typically, laboratory measurements include the use of a *spectrophotometer* with an integrating sphere. This device is capable of measuring the spectral characteristics of a material over the solar region of the electromagnetic spectrum, from approximately 0.3 to 2.5 μm. Spectral reflectance is measured in reference to a working standard, such as barium sulfate, that is highly reflecting and highly diffusing over the range of the solar spectrum. Apparent albedo is then calculated using a standard solar spectral irradiance distribution.

The advantage of albedo calculations based on laboratory measurements is that the laboratory measurements are more easily controlled than field measurements. Thus, it is easier to make comparisons between materials under similar environmental conditions. Such spectral reflectance data and infrared emittance data have been reported for a number of high-albedo roof coatings (Yarbrough and Anderson, 1993; Parker et al., 1993). Measurements indicated that coatings must be applied at a minimum critical thickness to obtain optimum solar reflectance (Yarbrough and Anderson, 1993). Of course, this minimum critical thickness depends on the coating. The implication is that a cost comparison of high-albedo coatings should be based on cost per unit thickness (governed by the percent solids by volume), rather than the usual cost per unit volume.

Field measurements of albedo typically involve the use of a *radiometer* for measuring the incident and reflected radiant flux. We use a high precision *pyranometer* that is sensitive to radiant energy in the 0.28 to 2.8 micrometer range. The pyranometer is mounted on a stand described in Taha et al. (1992). The stand LBL uses is designed to minimize the effects of the pyranometer's shadow and radiation reflected by surroundings. Uncertainties in the field measurements include the effect of the shadow of the pyranometer when it is facing down, error resulting from 1) radiation that is reflected by surroundings other than the surface in question, 2) solar incidence angle, and 3) nonuniformity of the surface. Albedo for selected surfaces is slightly higher at large solar zenith angles (low solar altitudes), but if the surface is spatially uniform and does not change over time, such as waves on the ocean, the sun angle effect appears to be small (Threlkeld, 1970). In contrast to the spectrophotometer, which measures the albedo of a small (~3cm^2) sample, the pyranometer measures reflected radiation from a large area. A ratio of 1/10 between the pyranometer's height and the diameter of a test area is required for a view factor of 95% or better from the roof to the inverted pyranometer. Still, the albedo measured cannot be assigned to the roof surface unless it fills the pyranometer's view (Taha et al., 1992). Since the roof substrate texture and environmental exposure can affect the albedo, these measurements cannot be used for a direct comparison of coating products on existing roofs.

Measurements of solar albedo should not be confused with reflectivity measurements, which are based on surface reflectance of visible radiation. Roof coating manufacturers may claim reflectances of over 90%, citing various test methods, such as ASTM D 1729 and ASTM E 97. Method ASTM D 1729, the "Standard Practice for Visual Evaluation of Color Differences of Opaque Materials," involves a visual comparison of a test sample and standard (ASTM, 1992a). Method ASTM E 97 was replaced in 1992 by Method E 1347, "Standard Test Method for Color and Color-Difference Measurement by Tristimulus (Filter) Colorimetry" (ASTM, 1992c). This method is for hemispherical or bi-directional reflectance, measured by a colorimeter.

B.3. Effects of Weathering

The performance of reflective roof coatings as an energy-efficiency measure is directly related to albedo. The temperature of a roof is approximately equal to the sol-air temperature, T_{sa}, defined as

$$T_{sa} = T_o + \frac{(1 - A_s)I_t - \varepsilon\delta R}{h_a}$$

where,

T_o = outdoor air temperature, °C

A_s = albedo

I_t = total solar radiation incident on the surface, W/m^2

ε = hemispherical emittance of the surface

δR = difference between thermal radiation incident on the surface and surroundings and that emitted by a blackbody at the outdoor air temperature, W/m^2

h_a = coefficient of heat transfer by long wave radiation and convection at the outer surface, $[W/m^2\ °C]$ (ASHRAE, 1989).

Changes in the emittance as weathering occurs are probably not significant, assuming the material has a high emittance initially. Albedo, however, is likely to decrease if the initial albedo is high, and increase if the initial albedo is low, because of surface accumulations and material degradation. Surface accumulations, such as dirt and microbial growth, may or may not be permanent, depending on their water solubility. Degradation, however, can modify the albedo permanently by inducing chemical change in the material. Insolation (particularly ultraviolet radiation), moisture (dew, rain, humidity), temperature (primarily the time-averaged temperature of the roof), and natural and anthropogenic pollutants (particularly aerosols and acid deposition) are the major elements that degrade roof coatings (Anderson, 1990).

B.3.A. Polymer Degradation

Photodegradation of polymers begins when ultraviolet (UV) photons with sufficient energy to break bonds strike absorbing groups (chromophores or impurities) in the polymer. Since

$$Q = h\,\nu$$

where,

Q = radiant energy, *joules*

h = Planck's constant, $6.625x10^{-34}$ *joule second*

ν = frequency, sec^{-1},

a wave train with a higher frequency carries more radiant energy. The absorption of light produces an excited state in the polymer, which will undergo bond cleavage to yield free radicals if the energy is not otherwise dissipated (Silberglitt and Le, 1990). A chain reaction between the free radicals and O_2 (oxidation) then leads to polymer degradation.

Because of absorption by oxygen and nitrogen in the upper atmosphere, and by ozone in the stratosphere, solar radiation that reaches the surface of the earth is greater than 0.29 μm in wavelength. The UV region, extending from 0.3 to 0.4 μm, is responsible for most of the photochemically induced degradation of coatings, due to the high energy of the photons. The energy in each quantum of solar UV is sufficient to exceed the dissociation energy of covalent bonds found in polymeric materials, as shown in **Table 1** (Sylvester, 1991).

Table 1. Energy Content of UV Light Compared to Bond Strengths in Organic Compounds
from Lappin, 1971

Wavelength (μm)	Energy kJ/ein†	Bond	Bond Energy kJ/mol
0.20	418	C-H	356-418
0.30	398	C-C	314-335
		C-O	314-335
0.35	339	C-Cl	293-335
0.40	297	C-N	251-272

† 1 Einstein (ein) = Avagadro's number of photons.

All organic and most inorganic pigments degrade in sunlight. Titanium dioxide, a pigment used in most white roof coatings, is thermodynamically stable but contributes to degradation of binders, since it is a strong UV absorber. As a UV absorber, it both protects the paint film, and also acts as a UV-activated oxidation catalyst (Braun, 1987).

In addition to photodegradation, moisture, temperature, and pollutants may damage coatings. For example, changes in temperature and humidity may cause cracking resulting from the expansion and contraction of coatings (Pappas, 1989).

B.3.B. Synergistic effects

The effects of moisture, temperature, and light can act together to increase the rate of deterioration of a roof surface. There are interrelationships between temperature and oxidative degradation, hydrolytic and oxidative degradation, and atmospheric pollutants and hydrolytic degradation. For example, studies of acrylic-melamine coatings show enhanced photo-oxidative degradation in high humidity and enhanced hydrolytic degradation with light exposure (Pappas, 1989). Elevated surface temperature of 10°F roughly doubles the oxidation rate of an organic material. On built-up roofs, water dissolves oxidized asphaltic compounds, thereby exposing fresh asphalt to sunlight and photo-oxidation (Griffin, 1982).

It is possible to formulate coatings to resist UV degradation, by adding stabilizers. In general, such coatings should be formulated with a minimum of resin components, which 1) absorb light of wavelengths over 0.29 μm 2) have readily abstractable hydrogen atoms or 3) are readily hydrolyzed. Abstraction of hydrogen from the polymer is a key process leading to photo-oxidative degradation. Pappas (1989) lists functional groups which promote the abstraction of H-atoms from adjacent carbon atoms, and groups which are subject to hydrolysis, in their order of importance. Groups less likely to hydrolyze are more likely to promote oxidation. The photo-oxidation process can be countered with 1) light absorbers to reduce light absorbed by the polymer or 2) quenchers to compete with bond cleavage of the excited-state polymers or anti-oxidants to reduce oxidative degradation (Pappas, 1989).

B.3.C. Assessment of Weathering Effects

For air-conditioning energy savings, the objective of exterior coatings is to reduce heat transfer into the building, or enhance night radiation. Measuring albedo is one method of determining the performance of a material as a solar reflector. Another method is to compare surface temperatures of different materials under controlled conditions.

B.3.C.1. Temperature Measurements

Under controlled conditions, Backenstow (1987) measured temperature under roofing systems of various ages, including a new black Ethylene Propylene Diene Terpolymer membrane

(EPDM), a four-year-old black EPDM, a new white EPDM, a two-year-old white EPDM, and a new, beige-colored EPDM that was found to approximate the solar reflectance of a very dirty or oxidized white roof. The difference in cooling-energy costs between a black and a white membrane on a 930 m^2 R-5 ft^2-h-°F/Btu roof was estimated at $4.56/day. About 26% of the savings would be lost if the roof were a very dirty white instead of new white.

Christian, Byerley and Carlson also measured surface temperatures to assess aging effects on white roof coatings on nine roof systems in two climates (Byerley, 1993). They found the aging effect to be most dominant in the first year, leveling out in subsequent years. They also found surprising durability differences for the same coatings applied on different substrates or roof membranes.

B.3.C.2. Albedo Measurements

The advantage of albedo measurements is that they are less sensitive to environmental conditions such as windspeed, air temperature and solar intensity. Thus, albedo measurements of a surface obtained on different days can be compared. Air conditioning savings from albedo modifications can be estimated using meteorological data, by either calculation or computer simulation.

The effects of one year equivalent solar exposure on the albedos of five white elastomeric coatings were measured by Anderson (1992). The samples were exposed to 12,709 MJ/m^2 (333 MJ/m^2 of UV radiation) between January and April, 1991. The exposure tests were conducted in accordance with the ASTM G90 test method. The samples were mounted vertically to prevent any exposure to moisture and to minimize the accumulation of atmospheric-borne dust and dirt. Hemispherical reflectance measurements in accordance with ASTM E903 performed before and after exposure indicated small (0-3%) changes in albedo. The original albedos of the samples were over 0.80. Griggs and Shipp (1988) investigated changes in albedo for black and white membranes over a 75-week period of outdoor exposure. Changes in solar reflectance were calculated from the energy balance at the roof membrane and from reflectometer measurements. In the first three months, the calculated albedo of the white membrane decreased from 0.8 to 0.7. Calculated albedo then decreased more gradually to 0.55 at the end of the 75-week period. The calculated albedo of the black membrane was more stable around 0.2. Reflectometer measurements indicated a more gradual aging effect for the white membrane, decreasing from 0.8 to 0.7 over the entire 75-week period. These measurements, however, were erratic and inconsistent, because the instrument was highly sensitive to outdoor measurement conditions.

B.3.D. Standard Measurement Techniques

There are various types of weathering effects. These effects can be evaluated individually by standard test methods, that are referenced in Appendix A, which contains a glossary of coating durability terms. All of these methods, however, rely on visual comparison with photographic reference standards. Such methods cannot be relied upon to provide information for energy conservation purposes because the eye is not capable of judging the reflected flux. Less than half of the incoming solar flux is in the visible region. Also, visual methods are imprecise.

At this time, there are no standards for measuring albedo degradation. The ability of coatings to retain high-albedo and high emittance has not been evaluated (Yarbrough and Anderson, 1993).

C. ALBEDO AND AGING MEASUREMENT METHODOLOGY

To enhance our understanding of albedo degradation of reflective roofs, we conducted field experimentation to determine the magnitude of the effect. We also used laboratory measurements to understand the spectral distribution of the reflected radiation from fresh samples. The following sections describe the methods we used, and the results, followed by a discussion of the implications for cooling-energy savings.

C.1. Experimental Approach

One way to assess the effects of natural weathering on high-albedo roof coatings would be to monitor the albedo of a particular roof for several years. The time limits of this project, however, necessitated a survey of different roofs with a variety of ages. It should be emphasized here that there is an inherent variability in albedo measurements between different roofs and that cross-roof comparisons are not always valid. Each roof has a unique albedo, depending on the roughness and condition of the substrate and the thickness of the coating. Similarly, the change in albedo over time will vary inconsistently between roofs depending on the climate, the slope of the roof, the roughness and condition of the substrate, atmospheric pollution, nearby sources of dirt and debris, and the dirt resistance of the roof coating. Nevertheless, our methodology allowed us to estimate the rate of albedo degradation.

In addition to roof measurements, we measured the albedo of small samples of the same coatings in the laboratory. These samples were provided by the coating distributors.

C.2. Selection of Roofs and Samples

A list of high-albedo roof coating distributors was obtained. All of these distributors, and several additional ones, were contacted and informed of the study. They were asked to identify horizontal or gently-sloped high-albedo roofs of various ages that could be measured. Of the ten distributors contacted, three offered their assistance by contacting residents, accompanying us to the roofs, and providing necessary equipment. The measurement sites were identified in Sacramento, Vallejo, Concord, and Stockton, California. The coatings for this study included:

Coating #1	A white polymer coating, with an acrylic base.
Coating #2	A white acrylic-based coating, with a widely used resin.
Coating #3	A white cementitious coating. A dry mixture of white cement, titanium dioxide, and resin binders is combined with water at the site.

Appendix B contains more information about these coatings.

Horizontal and sloped roofs were identified. The sloped roofs in this study are gently sloped, with less than 25% incline. Information on the dry samples, provided by distributors are given in **Table 2**.

Table 2. Roof Coating Samples for Hemispherical Spectral Reflectance Measurements

Coating Number	Dry Film Thickness*		Substrate Type	Equivalent Coverage	Cost
	mm	mils	(liters/m^2)	(\$/m^2)	
1	0.4	16	cardboard	0.7	6.3
2	1.0	39	rubber	1.9	13.8
3	0.6	25	mineral cap sheet	1.6	0.7

* For Coatings #1 and #2, thickness was measured and the amount needed to cover one m^2 was calculated from percent solids by volume. For Coating #3, thickness was estimated from the manufacturer's estimate of 0.73kg/m^2, assuming a density of 1105 kg/m^3. Density was estimated from the manufacturer's information on the coating's formulation.

C.3. Instrumentation

Albedos were measured on clear days between 11:00 am and 4:00 pm, using a pyranometer and stand. The analog output from the pyranometer was converted to digital output with a readout meter that has an accuracy of better than ±0.5% and a resolution of 1 W/m^2. The meter was scaled to the sensitivity of the pyranometer by the vendor laboratory (Taha et al., 1992). The pyranometer was tested against another pyranometer of the same model and found to have a consistent linear deviation that was independent of sun angle. Because albedo measurements involve ratios of two readings, the deviation is not expected to affect the results reported here.

Laboratory measurements of hemispherical spectral reflectance were made with a double beam spectrophotometer with integrating sphere. The integrating sphere is a 150 mm diameter sphere surfaced with reflectance material that gives the highest diffuse reflectance of any known material or coating over the UV-VIS-NIR region of the spectrum. The calculation of solar spectral reflectance was made according to ASTM Standard Test Method E903-82 (1992b), by weighting reflectance output by a standard solar irradiance. Solar data were obtained from Standard Terrestrial Solar Spectral Irradiance at Air Mass 1.5 for a 37° Tilted Surface (ASTM, 1992k).

D. RESULTS

D.1. Effect of Dirt Collection on the Albedo of a White Roof

To facilitate data analysis, roofs were separated into categories of smooth, medium, and rough substrates. A rough substrate can lower surface albedo because of geometrical effects (multiple reflections) and because it can accumulate dirt faster than horizontal surfaces. **Figure 1** shows the effect of two months to six years of dirt accumulation on the albedo of the roofs measured. Roof substrate types are described in the legend. Detailed descriptions of all the data and roofs in this study (including those that do not appear in the figure) are in Appendix C.

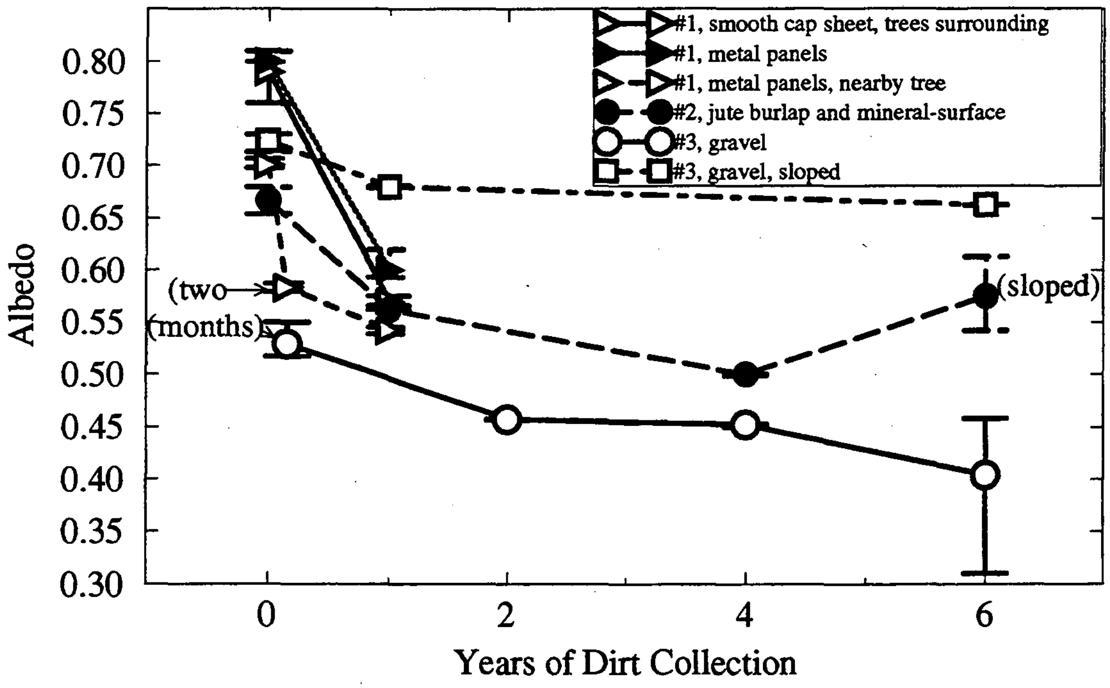

Figure 1. Albedo vs. exposure for 3 roof coatings, on different substrates. Years of dirt collection are either years since the roof was coated or years since the last thorough washing. Roofs are flat, except where noted.

The error bars in the figure show the range of albedos that were measured for each data point. All spot measurements were repeated several times. Measurements that were repeated within minutes varied by ±0.01, or within 2%. The largest variation between measurements of the same spot was 0.03, or 5% of the average albedo of that spot. The time that elapsed between these particular measurements was over an hour.

Spatial variability in albedo is different for each roof, but tends to increase with dirt accumulation. In one case, we recorded a variation in albedo of ±0.03 (6%), on a 23 m^2 (250 ft^2) mineral-surfaced roof that had been coated with Coating #2 six years earlier. A smaller spatial variation in albedo of ±0.01 (2%) was measured on a 170 m^2 (1800 ft^2) roof that had been surfaced with Coating #1 a year before.

In Figure 1, opaque right triangles and a solid line represent the albedos of a smooth roof with a 2% slope that was surfaced with Coating #1. The house was surrounded by trees that contributed to dirt build-up on the roof. The roof was measured days after it had been coated in 1991, and after a year of exposure in 1992. Then it was washed with a mop using soap and water to restore the albedo. In 1993, after a year of exposure, it was measured once more. The first year value on the graph represents an average of the 1992 and 1993 measurements.

Filled right triangles represent the albedos of a horizontal metal paneled roof, surfaced with Coating #1. The overlapping panels rose several centimeters in height at each edge of ~ 0.5 m panel. The texture of the roof may have affected the albedo measurements by blocking or scattering radiation.

Opaque right triangles with a dashed line represent the albedo of a roof similar and adjacent to the one just described. The building was washed after one year and the albedo was measured again after two months and after another year. Although after the second year the coating was two years old, it had only had a year of dirt accumulation because of the washing. The albedo measured in the second year was similar to the albedo measured after the first year.

Filled circles represent albedos of roofs with medium-rough substrates surfaced with Coating #2. For these roofs, no initial albedo was available so we used the average albedo of the roofs washed with a power-washer and soap. We assume that our estimated initial albedo is not more than 10% below that of a freshly coated roof. The roof substrates in this data set were jute burlap dipped in emulsion (data point 2), and mineral-surfaced cap sheet. The last measurement was taken on a 5% slope roof with a mineral-surfaced cap sheet, six years after it was coated.

Opaque circles in Figure 1 represent Coating #2 on horizontal roofs with gravel substrates.

The first value was taken on a roof two months after the coating was applied, and some fine dirt had settled on the surface. Given the drop in albedo in two months shown by the opaque triangles with a dashed line, we expect the initial albedo of this roof was higher. The other three values were taken on roofs that had been coated in different years but were all on the same building. The six year measurement is an average of two roofs, one of which ranged in albedo from 0.31 to 0.45 in different spots. These roofs were in poor condition when they were coated, which could affect albedo by decreasing durability. Also, heating, ventilating, and air-conditioning (HVAC) equipment on several roofs and poor drainage contributed to the dirt build-up.

Opaque squares represent albedos of gravel roofs surfaced with Coating #3. The initial value is an average of two roof measurements of horizontal roofs, but the other roofs had sloped portions. The decrease in albedo is most gradual for this combination of coating and roof type. It is unclear at this time whether the low dirt accumulation is because of the slope or properties of the coating.

The estimated decrease in albedo during one year averaged 20% and ranged from 0.04 (6%) for sloped gravel roofs with Coating #3 to 0.23 (28%) for a horizontal, metal paneled roof with Coating #1. The data indicate that most of the decrease in albedo occurs in the first year, possibly in the first two months. For the cementitious coating on gravel, after one year of weathering the albedo was reduced by an estimated 6%. After six years, it was 8%, indicating that approximately three fourths of the decrease could occur in the first year. Measurements on one roof two months and one year after washing indicate that 70% of the first year albedo decrease occurred in the first two months (Measurement Nos. 2 and 3 in Appendix C).

Beyond six years, the pattern of albedo degradation is unclear. One spot that we measured, 15 years after it had been coated with #3, had extensive microbial growth. The distributor informed us that in their service area such growth occurs after 10 years, at which point they offer a renewed warranty to the customer with recoating.

Although one would expect that horizontal roofs would see a larger decrease in albedo than sloped roofs, this cannot be confirmed by our data. The decrease in albedo is most gradual for the sloped roofs that are surfaced with Coating #3, but it is unclear whether this is due to the slope or the coating. It is worth noting, however, that Coating #3 was the least expensive coating we tested, and the price and performance are not always correlated.

D.2. Implications for Cooling Energy Use

Since three buildings in this study were also monitored for their cooling energy consumption for another study (Akbari et al., 1993), we estimated the impact of dirt accumulation on the cooling energy savings. For our calculations, we use a linear approximation of the relationship between cooling-energy savings and albedo. According to the sol-air equation mentioned in Section B.3, the linear assumption is good for the relationship between albedo and surface temperature, an indicator of heat transfer through the roof. Extending the linear assumption to cooling energy savings is adequate for our purposes here.

At one house with an R-11 ft^2-h-°F/Btu roof, measured cooling-energy savings from increasing roof albedo were 69% (2.2 kWh/day) (Akbari et al., 1993). The albedo of the original roof was 0.18. The energy savings were monitored over a summer period, at the beginning of which the albedo of the roof was measured at 0.73 ($\Delta A = 0.55$). The measured energy savings during the first summer includes the effect of dirt accumulation on the roof. By the start of the second summer, the albedo of the roof had dropped to 0.61 ($\Delta A = 0.43$). Thus, we estimate cooling energy savings would have dropped about 20% because of a change in albedo.

At another site, where two buildings were measured in parallel, a 40% cooling-energy savings (4.6 kWh/day) was measured from an increase in albedo from 0.08 to 0.7. Dirt accumulation was allowed to proceed during monitoring, at the end of which the albedo was 0.58. In the second year, the albedo had dropped to 0.53, roughly 20% lower than the first-year average of 0.64. Thus, we estimate cooling-energy savings for the second summer would have dropped by about 20% (to 32% cooling-energy savings).

D.3. Effectiveness of Washing

Roofs surfaced with Coating #1 and Coating #2 were washed, using several methods. Most roofs were washed with soap and water, using a mop. Two roofs were washed with a power-washer (Measurements 8 and 17 in Appendix C), but because we had no original albedo measurements for these roofs we cannot estimate the washing effectiveness. Other roofs were divided into sections that were washed differently, for comparison between washing methods. For the roofs that were measured successively in 1991, 1992, and 1993, we can calculate the albedo restoration as the percentage of the original value (**Table 3**). The Measurement Number is used for reference in the text and in Appendix C.

Table 3. Albedo Restoration of Smooth-Surface, Low-Slope Roofs Coated with Coating No. 1
Washed after one year of dirt accumulation.

Meas. No.	Substrate type	Age of Coating (years)	Albedo			Restoration (% of fresh albedo)
			Fresh	Dirty	Washed	
NA*	smooth cap sheet	1	0.79	0.59	0.64	81
21	smooth cap sheet	1	0.79	0.59	0.73	92
22	smooth cap sheet	2	0.79	0.61	0.76	96
2	metal panels	1	0.69	0.54	0.70	100

* All roofs but this one were washed with soap, mop and water. This roof was hosed off.

The increase in albedo resulting from washing a roof was dependent on many factors, but was generally significant. Simply hosing off the roof was not as effective as using a mop and soap. When a mop was used, the albedo was restored to within 90% of the original value, indicating that the loss of albedo is not permanent.

Estimating the effectiveness of washing on restoring albedo for the other roofs in the study is less precise, because the initial albedo of each roof is unknown. As a base for comparison, we used the albedo of a similar roof measured two months after coating, multiplied by a correction factor of 1.2. The correction factor was based on the decrease in albedo on another roof after two months of exposure (Measurement 3 in Appendix C). **Table 4** shows the estimated albedo restoration of these roofs. The measurements were made on rough roofs that were in poor condition prior to coating, which may have affected adherence of the coating, and exacerbated weathering. A few areas were stained by HVAC equipment located on the roof or by surrounding trees (Measurement Nos. 9 and 11 in Appendix C). With the method we used to clean the roofs, those with smooth surfaces were more easily cleaned than those with rough surfaces, which retained dirt.

Table 4. Estimated Albedo Restoration of Rough Surface Flat Roofs with Coating #2

These roofs were in poor condition prior to coating.

Meas. No.	Substrate Type	Age of Coating (years)	Albedo		Restoration* (% of fresh albedo)	Comments
			Dirty	Washed		
9	gravel	2	0.46	0.5	78	HVAC equipment; discolored
10	gravel	4	0.45	0.53	83	
11	gravel	6	0.40	0.52	81	poor drainage; discolored
12	gravel	6	0.45	0.53	83	HVAC equipment; discolored

* Albedo restoration through washing as percent of estimated original albedo of 0.64.

The data collected in this study for the buildings monitored in Akbari et al. (1993) were used to calculate the cost of conserved energy of washing a high-albedo roof. Our estimates are based on an annual cooling-energy use of 1000 kWh and the average change in albedo achieved through washing. Based on our experience, washing a 185 m^2 (2000 ft^2) would require four person-hours of work at an estimated cost of \$25/person-hour. With a cost of \$100 per roof, hiring someone to wash a roof by scrubbing with mop, soap and water, the cost-of-conserved energy (CCE) worked out to be ~ 70 cents/kWh. Hosing off a roof, which produced an increase in albedo of 0.05, resulted in a CCE of ~ 60 cents/kWh, for a one person-hour cost of \$25. Although savings would be dependent on the climate and house characteristics, our data showed that the savings from washing a roof are only gained for one season. Thus, it is unlikely that washing a high-albedo or hosing off a roof will be cost-effective for most buildings. If washing does take place, however, washing done shortly before the summer will maximize cooling energy savings. It would be useful to develop coatings that have dirt-resistance so that they do not require washing or hosing off, or coatings that are easier to clean with hosing only.

D.4. Spectral Albedo Measurements

Results from the spectrophotometer with integrating sphere for the small fresh samples described in Table 2 and titanium dioxide pigment, 0.2μm particle size, are shown in **Figure 2.** A standard solar spectral irradiance is shown in the background.

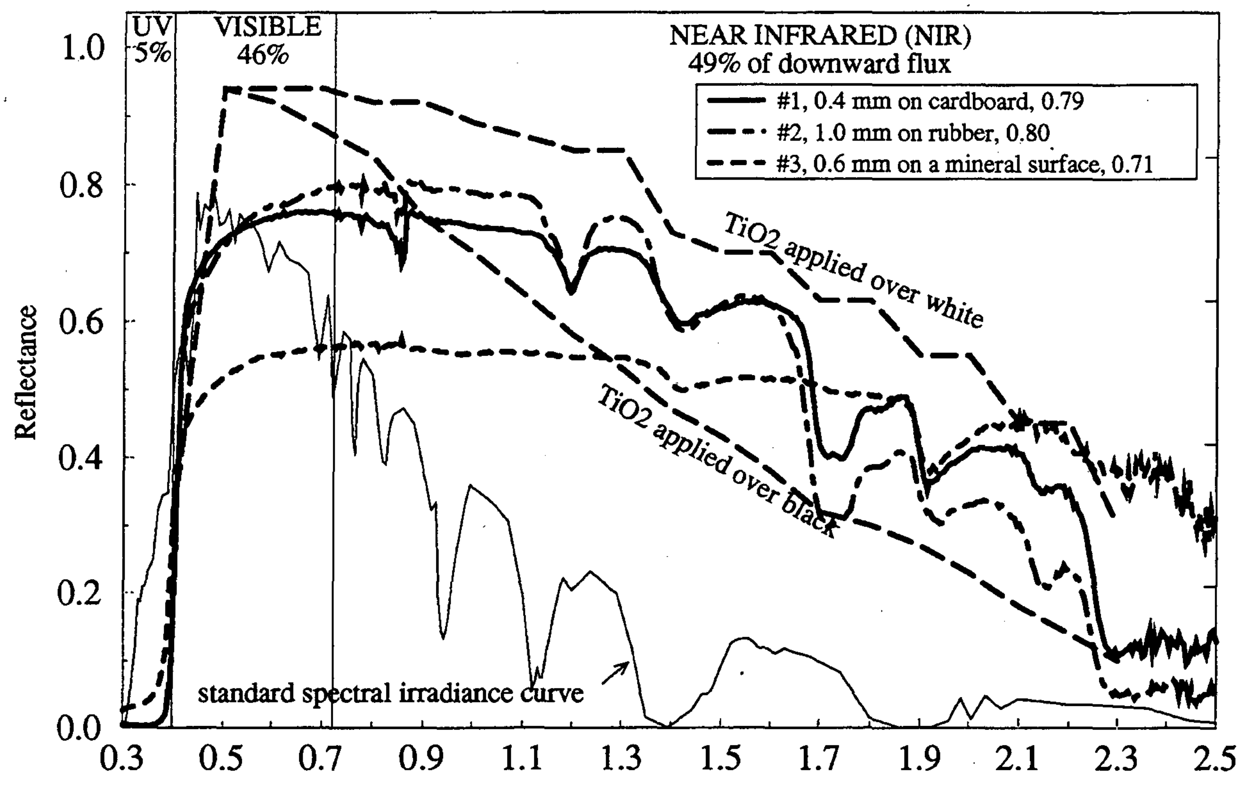

Figure 2. Spectral reflectance data for three roof coatings and titanium dioxide (Lewis, 1988) in the solar region of the spectrum. Also shown is a standard spectral irradiance curve for air mass 1.5. These data are useful for identifying absorption features of the coatings. Note that the coatings are applied at different thicknesses and to differing substrates. Apparent albedos appear inthe legend.

As with the rooftop measurements, the purpose of the spectral measurements is not to compare coating reflectances, because the samples vary in terms of thickness and substrate, as shown in Table 2. Coating #2 had a thickness of 1.0 mm and was therefore exhibiting maximum reflectance for that coating, 0.80 (Anderson, 1992). We suspect our samples of Coating #1 and Coating #3 are not exhibiting maximum reflectance. The sample of Coating #1 is slightly sub-standard thickness for roofs, while Coating #3 is below maximum reflectance because of the roughness of the mineral-surfaced substrate, and the thickness. The existing roofs surfaced with #3 measured in the field had thicker coats than this fresh sample.

All three coatings absorb in the UV region. This feature is common to titanium dioxide, a pigment that is used in many white roof coatings, including Coatings #2 and #3. Coating #3 does not have the same absorption features, as Coatings #1 and #2, although there is a small dip in reflectance at 1.4μm. Molecular groups containing hydrogen (e.g. OH^-) can cause absorption in the near infrared (Berdahl and Bretz, 1994). Commercial titanium dioxide pigments are often surface treated with aluminum hydroxide to improve various properties, such as dispersibility and durability (Lewis, 1988).

D.5. Future Research

The uncontrolled nature of this experiment makes it impossible to estimate the relative weatherability of various coatings. Further studies are necessary to link coating type and surface physical characteristics with albedo durability. Coating comparisons will require controlled conditions and long-term testing, so that all samples are exposed to the same weathering. It is possible that such comparisons will identify characteristics that promote dirt-resistance and high-albedo durability.

Before more albedo field studies are undertaken, measurement equipment need to be improved. With the present design, albedo measurements are time-consuming and require several participants. Because the pyranometer weighs 3.18 kg (7 lbs), the stand that holds it is unstable and unwieldy, especially for transport up and down ladders. We recommend that such measurements be done with either a lightweight pyranometer or albedometer. An albedometer has two sensors mounted back to back and thus increases the measurement speed. One commercially available albedometer weighs 0.85 kg (1.83 lb).

E. CONCLUSION

Our study has begun to address the aging characteristics of high-albedo roofs. The decrease in albedo depends on the coating itself, the texture of the surface, the slope of the roof and the nearby sources of dirt and debris. In general, the largest annual decrease in albedo, around 20%, can be expected to occur in the first year. This decrease, however, is already included in some of the reported cooling-energy saving measurements. After the second year, the incremental decrease in albedo can be small, lowering annual saving estimates by 20% of first year measured savings.

In most cases, washing the high-albedo coatings returned the albedo to within 90-100% of the estimated original value. Since dirt accumulation can occur in the first couple of months, the benefit from washing a roof is short term. Implications are that washing should be done shortly before summer, and that it is not cost-effective if one is concerned only with cooling-energy savings. The apparent differences between roof coatings found in this study indicate the need for quality testing and carefully controlled durability testing of high-albedo coatings that might be used for cooling-energy savings.

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APPENDIX A: Terms and Test Methods Related to Weathering

The American Society of Testing Materials (ASTM) is a not-for-profit organization that publishes the multi-volume *Annual Book of ASTM Standards.* ASTM provides "a forum for producers, users, ultimate consumers, and those having a general interest to meet on common ground and write standards for materials, products, systems and services."

The *Annual Book of Standards* includes classifications, guides, practices, specifications, terminology, and test methods. This Appendix refers to a number of ASTM test methods and includes terminology related to weathering, quoted from ASTM D 16: "Standard Terminology Relating to Paint, Varnish, Lacquer, and Related Products."

blistering resistance, the ability of a coating to resist the formation in the film of dome-shaped, liquid- or gas-filled projections resulting from local loss of adhesion and lifting of the film from the substrate or previously applied coating (ASTM, 1992b). Blistering can be evaluated in reference to photographic standards, as described by ASTM Standard D714 (1992c). Blistering and peeling can be related to the permeability of the coating: impermeable coatings on a porous substrate may prevent water vapor migration to the cold low vapor pressure air in winter, which may cause vapor to condense within the substrate, with resultant blistering or peeling (Sweet's Catalog File, 1990).

chalking resistance, the ability of a coating to resist the formation of a friable powder on the surface caused by the disintegration of the binding medium by degradative weather factors (ASTM, 1992b). Chalking can be evaluated according to ASTM D 4214 (1992i), by transferring the chalk to a fabric or fingertip and comparing to photographic reference standards. The degree of chalking will vary over any given area, and chalk will be removed by rain, snow, or moisture in any form. Although chalking leads to erosion, the rate of chalking as measured by the standard test methods, and the rate of erosion (as described below) may not be comparable because some pigment combinations tend to retain chalk on the surface while others exert a self-cleaning action by natural means. Atmospheric contamination and marine laden air can accelerate chalking (Sweet's Catalog File, 1990).

checking resistance, the ability of a coating to resist slight breaks in the film that do not penetrate to the previously applied coating or to the substrate (ASTM, 1992b). Checking can be evaluated with a standard test method using photographic reference standards (ASTM, 1992e).

cracking resistance, the ability of a coating to resist breaks of the film where the breaks extend through to the surface painted and the previously applied coating or the substrate is visible (ASTM, 1992b). Cracking can be evaluated according to ASTM Standard D661 (1992f), which involves comparison with photographic standards.

dirt resistance, the ability of a coating to resist soiling by foreign material, other than microorganisms, deposited on or embedded in the dried coating (ASTM, 1992b). There is a standard test method for evaluating the degree of surface disfigurement of paint films by microbial (fungal or algal) growth or soil and dirt accumulation. The procedure is to compare the surface with a photographic standards which rate disfigurement of paint films from 0 to 8, and to identify the prominent type (fungi, algae, or soil) (ASTM, 1992h). The quantity of dirt or microbial growth that accumulates on a surface may vary over the surface, depending on the location, nonuniformity of the substrate, film thickness, or other factors.

erosion resistance, the ability of a coating to withstand being worn away by chalking or by the abrasive action of water or windborne particles of grit. The degree of resistance is measured by the amount of the coating retained (ASTM, 1992b). Erosion can be evaluated through comparison with photographic reference standards, as described in ASTM Standard D662 (1992g). Erosion occurs as a result of chalking.

flaking resistance, the ability of a coating to resist the actual detachment of film fragments either from the previously applied coating or the substrate. Flaking is generally preceded by cracking, checking, or blistering and is the result of loss of adhesion. Also known as scaling resistance (ASTM, 1992b).

mildew (fungus) resistance, the ability of a coating to resist fungus growth that can cause discoloration and ultimate decomposition of a coating's binding medium (ASTM, 1992b). The standard method for evaluating microbial growth has been described previously (ASTM, 1992g). Some coatings contain chemical agents that inhibit the growth of mildew.

Other coating properties that affect albedo that were not defined in the ASTM document are:

cleanability or stain resistance, the ability of a coating to resist permanent damage to the surface caused by foreign material on the surface.

resistance to atmospheric discoloration, the ability of a coating to resist discoloration that may occur due to atmospheric contamination, such as caused by sulfur-containing gases. The resistance of a coating to atmospheric discoloration will depend on the chemical composition (Sweet's Catalog File, 1990).

APPENDIX B: Coating Information

Although LBL does not recommend any products, we publish here information obtained from the distributors of the roof coatings mentioned in this study.

Product: Enerchron

Description: Polymer roof coating with an acrylic base.

Specification: Appropriate for a wide variety of roofing substrates, with proper preparation. Also used on walls.

Installation: Enerchron is sprayed on by a qualified contractor. Dry in 30 minutes, cures in 7 days.

Distributor:
Helios Energy Products
P.O. Box 417218
Sacramento, CA 95841

Service Life: 10 year guarantee is provided. Guarantee may be extended to 20 years.

Manufacturer Claims:

- Energy savings.
- May be tinted to off-white or pastel.
- Fire retardant.
- Zero solvent product.

Material Cost:
Contractor: \$10/liter (\$38/gallon)
Retail: \$12/liter (\$45/gallon)
Percent Solids by Volume: 53%.
Coverage: For roofs, apply at 1-1.6 liters/m^2 (2.5-4 gal/ft^2) to a dry film thickness (DFT) of 0.4-0.6 mm (16-24 mils), and cost of \$12-19/m^2 (\$113-180/100 ft^2).

Product:	Flex White
Description:	Acrylic elastomeric roof coating with a Rohm and Haas resin.
Specification:	Appropriate for a wide variety of roofing substrates, with proper preparation. Another preparation available for use on walls.
Installation:	For a complete roofing system, a black emulsion is applied first, followed by polyester and the Flex White. Flex White is sprayed on by a qualified contractor. Dry in two-four hours, cures for up to 10 days.
Distributor:	Energy Products 300 Harris Ave, Suite E Sacramento, CA 95838 (916) 925-3065
Service Life:	5-30 year guarantee. A 10 year warranty is provided for most roofs. Up to 30 year warranties are available.
Manufacturer Claims:	• Energy savings. • Roofing system has a Class A fire rating. • Pollutant resistant.
Material Cost:	Retail: $7/liter ($26/gallon) Wholesale: 60% discount. Percent Solids by Volume: 50.8%. Coverage: For roofs, 1-1.5 liter/m^2 (2.5-3.7 gal/100ft^2), for a DFT of 0.5-0.7 mm (20-30 mils) at a cost of $7-11/m^2 ($65-96/100 ft^2).

Product: Heat Shield

Description: Cementitious coating containing white cement, titanium oxide, and resin binders.

Specification: Appropriate for gravel and mineral surface roofs.

Installation: Heat Shield is mixed with water at the site, and sprayed on by qualified contractors. Two coats may provide more reflectivity. Dry in six-eight hours.

Distributor:
Stockton Roofing Company
P.O. Box 1169
Stockton, CA 95201
(209) 466-5951

Service Life: 10 year guarantee. Guarantee may be extended to 20 years.

Manufacturer Claims:
- Energy savings.
- Inexpensive roof coating.
- Increases roof life.

Material Cost: \$20/110 kg. (50 lb.) sack. A sack of the dry mixture is mixed with 15 liters (4 gallons) at the site, and will cover 28 m^2 (300 ft^2) of a mineral-surface cap sheet, at a cost of \$1/m^2 (\$7/100 ft^2). More material is needed for gravel roofs, on which two coats are applied.

APPENDIX C: ALBEDO DATA

Table C-1 contains the data that were collected during this study. The Measurement No. is used to identify the measurement in the text. Some measurements were taken on the same roof in different years: Measurement Nos. 1 to 4; 5 and 6; and 21 and 22. These roofs were washed with mop, soap and water each year, so that there was never more than one year of dirt accumulation on them. Measurement Nos. 14 and 15, and 18 and 19 were taken on two parts of the same roof, where one part was flat and the other was sloped. Measurement Nos. 23 and 24 were taken on two parts of the roof: half that was newly coated and another half that had not been coated in 15 years. The first column in Table A-1 describes the texture of the roof surface, and the substrate type. Relevant information relating to the albedo measurement is listed in column four under "Comments." Years since last washing are listed as years since the roof was last coated or last washed with mop, soap and water.

Table C-1. Solar Albedos of Roof Coatings at Various Ages

Meas. No.	Substrate Type	Coating No.	Comments	Age of Coating (years)	Yrs. Since Last Washing	Albedo	
						Dirty	Clean
Horizontal Roofs							
1	rough (metal panels)	1	a tree was nearby	0	0	-	0.69
2				1	1	0.54	0.70
3				1.2	0.2	0.58	-
4				2	1	0.53	-
5	rough (metal panels)	1	adjacent to the above roof	0	0	-	0.80
6				1	1	0.57	-
7	rough (gravel)	2	dirt was visible on the surface	0.2	0.2	0.53	-
8	medium (jute and emulsion)	2	a power washer was used to clean the roof	1	1	0.56	0.65
9	rough (gravel)	2	roof was in poor condition before coating; staining from HVAC equipment located on the roof	2	2	0.46	0.50
10	rough (gravel)	2	roof was in poor condition before coating	4	4	0.45	0.53
11	rough (gravel and tar paper)	2	roof was in poor condition before coating; staining from HVAC equipment located on the roof	6	6	0.40	0.52
12	rough (gravel)	2	roof was in poor condition before coating	6	6	0.45	0.53
13	rough (gravel)	3		0	0	-	0.71
Sloped Roofs and Varied-Sloped Roofs							
14	smooth (3-ply built-up with aluminum coating)	1	flat part of the roof	1	1	0.62	-
15			sloped part of the roof	1	1	0.65	-
16	medium (corrugated aluminum)	1	incomplete coverage of substrate due to substandard coating thickness	3	3	0.62	0.68
17	medium-rough (mineral surface cap sheet)	2	a power washer was used to clean the roof	4	4	0.50	0.65
18	medium-rough (mineral surface cap sheet)	3	flat part of the roof	6	6	0.54	-
19	rough (gravel)	3	sloped part of the roof	6	6	0.66	-
20	smooth cap sheet	1	surrounding trees dropped debris on surface; some staining	0	0	-	0.79
21				1	1	0.59	0.73
22				2	1	0.61	0.76
23	rough (gravel)	3	half of the roof was newly coated	0	0	-	0.73
24	rough (gravel)	3	microbial growth on the other half	15	15	0.30	-
25	rough (gravel)	3		1	1	0.68	-
26	medium-rough (mineral surface cap sheet)	2	dirt caught at strip edges	6	6	0.57	0.67