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IMPLEMENTATION OF SOLAR-REFLECTIVE SURFACES: MATERIALS AND UTILITY PROGRAMS

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Abstract

This report focuses on implementation issues for using solar-reflective surfaces to cool urban heat islands, with specific examples for Sacramento, California. Advantages of solar-reflective surfaces for reducing energy use are: 1) they are cost-effective if albedo is increased during routine maintenance; 2) the energy savings coincide with peak demand for power; 3) there are positive effects on environmental quality; and 4) the white materials have a long service life. Important considerations when choosing materials for mitigating heat islands are identified as albedo, emissivity, durability, cost, pollution and appearance.

We estimate that there is a potential for increasing urban albedo in Sacramento by approximately an additional 18%. Of residential roofs, we estimate that asphalt shingle and modified bitumen cover the largest area, and that built-up roofing and modified bitumen cover the largest area of commercial buildings. For all of these roof types, albedo may be increased at the time of re-roofing without any additional cost. When a roof is repaired, a solar-reflective roof coating may be applied to significantly increase albedo and extend the life of the roof. Although a coating may be cost-effective if applied to a new roof following installation or to an older roof following repair, it is not cost-effective if the coating is applied only to save energy.

Solar-reflective pavement may be cost-effective if the albedo change is included in the routine resurfacing schedule. Cost-effective options for producing light-colored pavement may include: 1) asphalt concrete, if white aggregate is locally available; 2) concrete overlays; and 3) newly developed white binders and aggregate. Another option for a white pavement surface may be hot-rolled asphalt, with white chippings. We find that there are methods of changing the albedo of all major urban surfaces (streets, parking lots, flat roofs, and sloped roofs) at the time of resurfacing or reroofing for less than the avoided cost of electricity.

Programs to promote solar-reflective surfaces should be designed with regard to the perspectives of groups involved, including consumers, building and roofing contractors, utilities and local or state governments. Legislation might include a labeling program for paints and roof materials, and albedo specifications for new pavement surfaces. Utilities could promote solar-reflective surfaces through advertisement, educational programs and cost-sharing of road resurfacing.

Introduction

Most cities are "urban heat islands," with summer daily average temperatures 5°F to 8°F hotter than outlying rural areas. The elevated temperatures of the heat island increase energy use, the peak demand for power and have a negative impact on environmental quality.

Several factors contribute to create a heat island, including the installation of dark surfaces, such as roofs and pavement, that absorb solar radiation. When solar radiation is incident on a surface, the radiation will either be reflected, transmitted or absorbed. If it is absorbed, the surface temperature of the material increases and heat is then transferred from the heated surface to the near-surface air.

The surfaces we are concerned with in this paper, including pavement and roofing materials, are opaque and therefore do not transmit solar radiation. Thus, all incident radiation is either absorbed or reflected by these surfaces. Albedo is the ability of a surface to reflect solar radiation, including both visible and non-visible radiation. Sometimes, the terms "white" and "light-colored" may be used to describe high-albedo surfaces because such surfaces reflect most visible light and are typically high albedo. Yet because over half of the solar radiation that reaches the earth is non-visible, it is possible to have a high-albedo surface that is not visibly white.

Albedo is expressed on a scale from 0 to 1, so that a surface with an albedo of 0.8 reflects most of the incident solar radiation and has a relatively high albedo. The same opaque surface is absorbing 20% of the incident solar radiation, since for a given wavelength, 100% of the incoming radiation is either reflected or absorbed.

Since a high-albedo surface doesn't absorb much of the incident solar radiation, it stays cooler in the sun than a low-albedo surface. Since high-albedo surfaces stay cool in the sun, they may be used to mitigate urban heat islands. In addition to reducing energy consumption and the need for new power generation resources, there may be other benefits from solar-reflective surfaces such as reduced emissions of air pollutants (because of less power generation), fewer smog episodes and streets that are highly visible at night.

Urban albedo may be increased gradually, but inexpensively, if high-albedo surfaces are chosen to replace darker materials at the time of reroofing or repaving. Most roof types, including asphalt shingle and built-up roofing, are available with a white surface at no additional cost. Since building exteriors are repainted about every ten years, the albedo of these surfaces may be increased at no additional cost by using white paint. Pavement albedo may be increased by using concrete, by adding white aggregate to asphalt pavement, or by using newly-developed technologies. Most white surfaces are equivalent in initial cost to conventional dark surfaces, and may have lower annualized costs because of longer lifetimes. Since they reflect solar radiation, they suffer less radiation damage and less thermal expansion and contraction than dark surfaces.

Using white surfaces to increase urban albedo may be a lucrative way to conserve energy and reduce pollution. In some states, regulators allow a utility company to include investments in energy effieciency in the rate-base, thereby allowing the utility to benefit from promoting high-albedo surfaces. Local or state governments may choose to participate in high-albedo promotion to improve regional energy management. We intend this paper to serve as a non-technical guide for designing implementation programs for albedo modification, with particular application to Sacramento, California. Guidelines for choosing materials to increase the albedo of urban surfaces are presented, materials are compared in terms of cost and albedo, and the costs of conserved energy and energy efficiency supply curves are provided for various measures. An appendix summarizes information we gathered on high-albedo materials for urban surfaces.

We identify 1) single-family homes as the first target of a program to increase albedo and 2) built-up, modified bitumen and asphalt shingle roofing as the most popular roof types that can be modified with the strategies we propose. Suggested utility-sponsored programs include promotional programs aimed at consumers, builders, roofing contractors, and building design professionals, and investment in high-albedo pavement projects in co-operation with local governments. Government agencies may also promote cool communities in the public interest by labeling paints and roofing materials, and with incentives or standards to promote high-albedo surfaces.

Background

The following section is intended for readers who are not familiar with the use of shade trees and high-albedo surfaces to mitigate urban heat islands. It briefly describes the significance of urban heat islands and their impact on energy use and the quality of life in an urban area. This section describes how high-albedo surfaces may be used to mitigate urban heat island effects, advantages of high-albedo surfaces, and their potential as a heat island mitigation strategy.

Heat Island Mitigation Strategies

Akbari and others (1990) estimate that 5-10% of urban peak electric demand today is for additional air conditioning to compensate for heat islands, costing ratepayers over an additional $1 billion per year plus the indirect cost of pollution. It is worth noting that the additional power generated to compensate for heat islands on-peak is supplied by less efficient and typically more polluting power systems. In addition, elevated temperatures may enhance the formation of smog and urban ozone, the pollutant that most often exceeds the National Ambient Air Quality Standards (Akbari et al, 1990).

Trees and high-albedo surfaces may be the most inexpensive and effective ways to mitigate urban heat islands. Through direct shading and evapotranspiration, trees reduce summer cooling energy use in buildings at only about 1% of the capital cost of avoided power plants and air-conditioning equipment (Akbari et al, 1990). White surfaces may be even more effective than trees at cooling cities, and cost less if albedo changes are incorporated into routine maintenance schedules. Also, the results from high-albedo surfaces are immediate, while it may be 10 or more years before a tree is large enough to produce significant energy savings. Akbari and others (1988) discuss the relative benefits and costs of high-albedo surfaces, trees, and several energy efficiency measures.

White surfaces typically have a high "albedo," meaning that they reflect a large percentage of the sun's radiation. Because they are good reflectors, they stay cooler than absorbing surfaces. The effects of high-albedo surfaces include "direct" energy savings and "indirect" effects on climate. The term "direct" effects refers to the energy savings of an individual building achieved by changing the albedo of its exterior. Indirect effects of increasing albedo may result from reducing the air temperature. We predict that a high-albedo community will have lower surface temperatures than the average city and therefore lower air temperature. The lower air temperature, in turn, will reduce cooling-energy demand and increase general comfort within the city.

The direct effects of albedo modification have been estimated with measured data and with computer simulation by various researchers. At the Lawrence Berkeley Laboratory (LBL), researchers have used a computer program to simulate energy consumption of a typical 1960s house in Sacramento, California and quantify the direct effects of an albedo modification. The simulation results are calibrated with actual measurements from test sites located in Sacramento. Beginning with a roof albedo of 0.2, which is roughly equivalent to a weathered dark-shingled roof, the result of increasing the albedo to 0.78 by coating the roof with Enerchron® coating reduced cooling energy consumption by 33% (**Figure 1**).

Although the indirect energy savings from albedo modification have not been measured directly, Martien and others (1989) used computer simulation to estimate the indirect energy savings for a prototypical building in Sacramento. Their results suggest that there is roughly a 3% savings in cooling energy per building for each 0.01 increment in urban albedo. While these savings may be exaggerated because the model is one-dimensional and does not include the influx of warm air from other areas, direct measurements from a monitored experiment in the future will provide more data.

Taha and others (1988) estimate that increasing the albedo of Sacramento from current albedo conditions of approximately 0.25 to 0.40 may reduce the maximum urban temperatures by about 5°F, reducing peak cooling demand for an individual house by as much as 40%. The same modification may result in a 5-10% savings of the system-wide electric utility load.

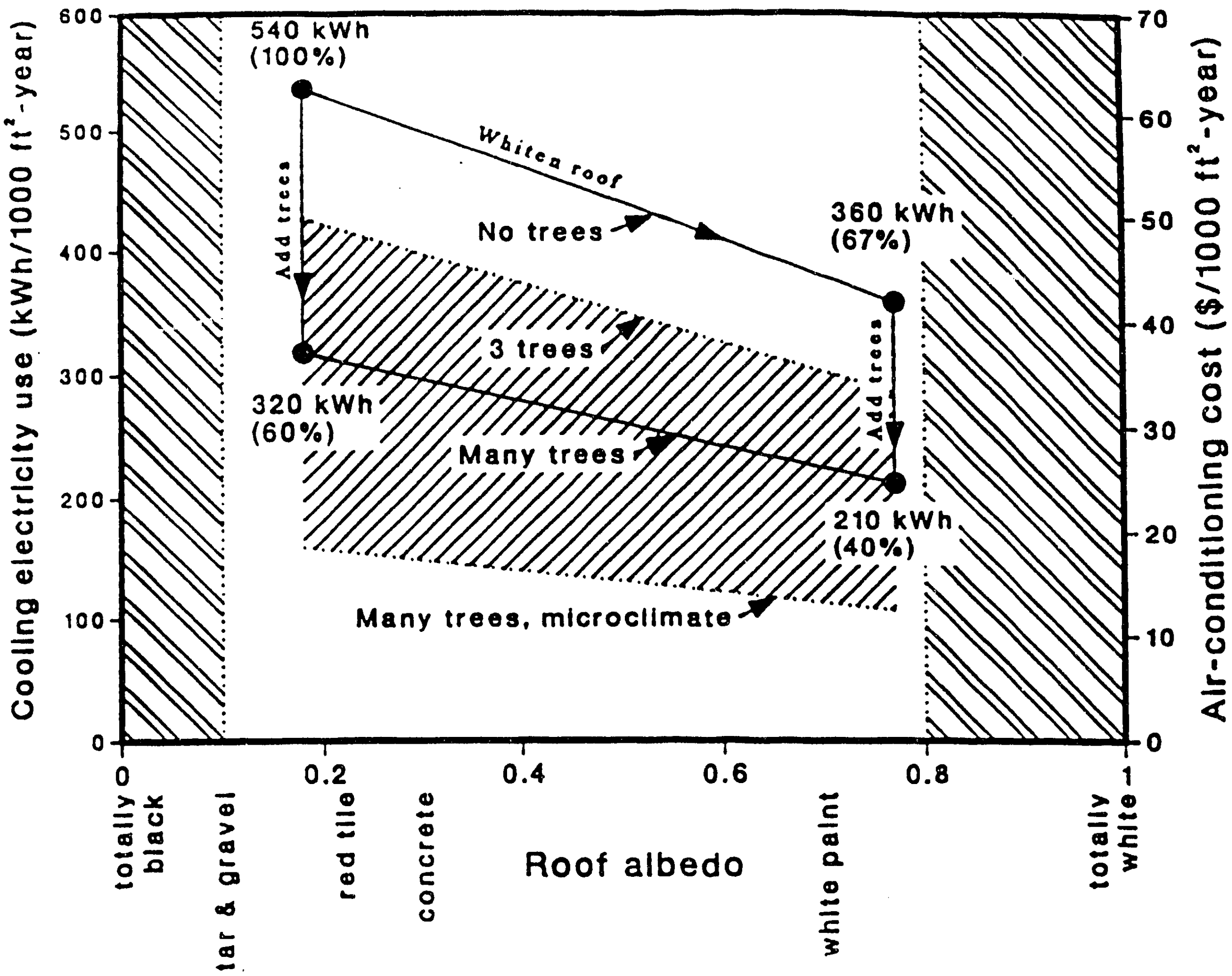

Figure 1. Effect of Roof Albedo and Tree Shading on Cooling Energy Use for a 1960s House in Sacramento. The lower solid line labelled 'Many Trees' is fit to a real, well shaded house, but using airport weather data (no local cooling by the trees). The cross-hatched area represents a range of savings from trees: At the top we estimate the air-conditioning use by the same house with just 3 trees, and no cooling of the microclimate. At the bottom we estimate the microclimate effect of dense trees. (Building conditions and simulation assumptions: Floor area 1700 square feet, one story; R11 roof, R7 walls, R0 floor, double glazing; Thermostat setpoint 80°F; Cooling SEER 12.6; Average residential electric rate for California $0.115/kWh. *Source: CEC Energy Watch*, Vol. 14, No. 5, June 1992).

There are several papers addressing the use of high-albedo surfaces to cool urban areas. Martien and others (1989) combine estimates of energy savings from albedo modification with typical roofing and paving cost estimates to predict costs of conserved energy achieved through a number of measures aimed at increasing surface albedos. Taha and others (1992) examine high-albedo materials for buildings and urban surfaces and their impact on the surface temperature heat island. Akbari and others (1991) present the preliminary results of a project to determine the impact of shade trees and high-albedo roofs on air-conditioning electricity of several buildings in Sacramento. And an overview mitigating heat islands with high-albedo surfaces is presented in Chapter 3 of Akbari and others (1992). This paper is a review of the above studies and provides updated cost data, information on materials and strategies for implementation.

Advantages of High-Albedo Surfaces

Before the widespread use of electricity, buildings in hot climates were often designed with the intention of minimizing solar gain. White surfaces have long been used throughout the Mediterranean region to provide comfort without high energy costs. In the United States, air conditioning was adopted for residences after World War II, transforming both the demographics of the country and individual building designs. Today, the significance of the environmental costs of energy consumption are apparent and methods of reducing energy use are attractive. Encouraging high-albedo surfaces in urban areas may be an easy and inexpensive means of achieving this goal.

From the utility company's perspective, high-albedo surfaces are ideal means of saving energy in areas with high cooling loads, because the energy savings match the utility's load curve. While it is relatively easy for the utility to provide power during much of the day, it is the peak hours, when the largest amount of power is demanded, that concern utility planners. In many parts of the country, peak hours occur during the summer in the middle of the day, when air conditioning is used to provide thermal comfort within buildings that are often highly absorptive of solar radiation. Minimizing the solar gain with high-albedo surfaces reduces the peak demand for power and lowers all of the social costs associated with providing the power.

Environmental costs associated with the generation of power from fossil fuels include destruction of land from mining, water pollution and the emissions of air pollutants that may affect human health, form acid rain, or contribute to global climate change. These costs, borne by society as a whole, are termed 'externalities,' because they are usually not included in the cost of power or fuel. There are several reasons why the environmental externalities of power used to supply peak demand may be particularly high. First, a utility dispatches resources economically, so that the least fuel efficient and typically most polluting resources are used only when needed to meet peak demand. Second, when power plants are running at maximum load in order to supply enough power to meet peak demand, they generate more nitrogen oxides per unit energy output than when they are operating at a fraction of their full power. Energy efficiency cuts environmental costs by reducing air emissions, including acid rain precursors, smog precursors, and carbon dioxide. The environmental benefits of reducing peak demand are clear.

Managing the heat island with high-albedo surfaces may also reduce the severity of urban smog episodes, although at this time it is impossible to quantify the effect of high-albedo surfaces would have on urban smog. Ozone, which is a major component of smog, is formed by many complex photochemical reactions, some of which are affected by temperature. By lowering air temperature, high-albedo surfaces may reduce below the present level the emissions of volatile organic compounds (VOCs) from vegetation and from cars. VOCs are harmful when they combine with nitrogen oxides in the presence of sunlight to form ozone. Urban ozone levels are also dependent on wind conditions, which also may be affected by a widespread presence of high-albedo surfaces.

High-albedo surfaces have advantages in addition to energy savings and environmental benefits. Because they absorb less radiation, high-albedo surfaces experience less thermal expansion and contraction and may last longer than other surfaces, thereby lowering replacement and repair costs. If a high-albedo surface reflects damaging ultra-violet radiation there could be significant benefits in terms of lifetime. Another advantage of high-albedo urban surfaces is the night-time visibility of white pavement that increases safety and reduces street lighting expenses.

Potential for Altering Urban Albedo

Studies of the composition of surfaces in Sacramento suggest that the potential for altering urban albedos is significant. We estimate that Sacramento is composed of about 28% rooftop, 16% streets, and 14% other impervious surfaces such as parking lots, sidewalks, school yards and driveways (**Table 1**). Table 1 shows our estimates of the composition of Sacramento and similar estimates from a much earlier study.

The estimates shown in Table 1 were made with the help of data and aerial photographs analyzed at Lawrence Berkeley Laboratory (Orvis, 1992). These data described the percentage of Sacramento occupied by a variety of land-use categories (i.e. low, medium and high-density residential). By locating representative samples of the land-use categories on aerial photographs, we were able to estimate the proportion of each category occupied by light and dark roof, light and dark pavement, and vegetation. Together, these estimates were used to obtain estimates of the make-up of Sacramento. Based on these percentages, as shown in Table 1, we estimate that it is possible to modify the urban albedo of Sacramento by about 18% (**Table 2**). This estimate is comparable to an estimate by Martien and others (1989) of ~15%, based on the Myrup and Morgan (1972) data.

TABLE 1. ESTIMATES OF THE URBAN FABRIC FOR SACRAMENTO, CALIFORNIA

SURFACE	AREA					
	Myrup and Morgan (1972)			Lawrence Berkeley Laboratory (1992)		
	Residential (46% of Total) %	Commercial/ Industrial (25% of Total) %	Total[a] %	Residential (58% of Total) %	Commercial/ Industrial (32% of Total) %	Total[a] %
Rooftop:	23	43	22	33	27	28
light				4	17	8
dark				29	10	20
Impervious Street	22	15	17	16	19	16
Impervious Other[b]	22	42	22	7	30	14
light				6	1	4
dark				1	29	10
Green[c]	33	~ 0	39	44	24	43
Total	100	100	100	100	100	100

a) Includes schools, parks, open space and freeways as well as residential and commercial/industrial areas.

b) Includes parking lots, driveways, sidewalks, etc.

c) In LBL study, includes tree canopy.

TABLE 2. POTENTIAL FOR MODIFYING URBAN ALBEDO

using Table 1, Column 6.

SURFACE		AREA (% OF TOTAL)	Δ ALBEDO	TOTAL Δ ALBEDO
Streets		16	0.30	0.048
Roof	(dark)	20	0.50	0.1
	(light)	8	0	0
Impervious Other	(dark)	10	0.30	0.03
	(light)	4	0	0
TOTAL		*	*	**~ 0.18**

Selection of High-Albedo Materials

This section is intended for readers interested in selecting high-albedo materials, either as part of a utility or governement promotional program, or for individuals who are in a position to affect urban albedo. It will provide information on high-albedo options for roofs, walls and pavements. The appendix to this paper includes information we have gathered on high-albedo materials but should not be considered an exhaustive list of the products that are available.

Increasing the albedo of cities is a cost-effective way to conserve electricity if albedo is increased as part of routine resurfacing or recoating. When flat roofs and walls are painted or resurfaced (typically every 10 years), high-albedo paint may be used at the same cost as a dark-color paint. When built-up roofs are replaced, a white surfacing may be used. Roof repair may include the application of a flexible high-albedo coating that, in addition to increasing albedo will extend the life of the roof. Asphalt roads and parking lots may be resurfaced as needed, but with a white aggregate and a thin topcoat of white chippings or shells, or with a concrete overlay.

There are a number of factors that determine how appropriate a given material is for managing urban heat islands. These factors are presented here and some are given further attention later in the paper.

(1) *Albedo.* Since surface temperature will increase as solar energy is absorbed, a high-albedo is preferred for heat island mitigation. The solar spectrum includes visible light as well as non-visible, longer-wavelength radiation. While the color of a material indicates its reflectance of visible radiation, one cannot tell by sight whether the material is reflective in the non-visible part of the solar spectrum. For this reason, two surfaces that appear to be the same color *may* have different albedos. Also, although a light-colored surface is usually more reflective of solar radiation dark-colored surfaces, there may be specialty surfaces that are highly reflective of non-visible radiation. **Table 3** lists the typical albedo of various urban surfaces.

(2) *Emissivity.* Emissivity is defined as the ratio of the energy radiated by an object at a given temperature to the energy emitted by a perfect radiator, or blackbody, at the same temperature. Like albedo, emissivity is measured from 0 to 1.

For opaque materials, radiation that is not reflected is absorbed, and will be emitted from a surface according to its temperature and emissivity. Since none of the surfaces considered here are completely reflective, they will absorb some solar radiation (shortwave). Shortwave radiation absorbed by a surface is emitted as longwave radiation, or heat. Materials with high emissivities are good emitters of longwave or heat energy, and readily release the energy that has been absorbed as shortwave radiation. The best solar-reflecting materials stay cool because they have a high albedo and a high emissivity. The most important point here is that emissivity and albedo together affect the surface temperature of a material. We have found that the surface temperature of a metal roof will be higher than that of a white-painted roof with similar albedo

TABLE 3†. ALBEDO[a] OF TYPICAL URBAN MATERIALS AND AREAS

Sources: Baker (1980), Oke (1983), Courville (1989).

SURFACE	ALBEDO
Streets	
Asphalt (fresh 0.05, aged 0.20)	0.05-0.2
Walls	
Concrete	0.10-0.35
Brick/Stone	0.20-0.40
Roofs	
Smooth-surface asphalt (weathered)	0.07
Tar and gravel	0.08-0.18
Tile	0.10-0.35
Slate	0.10
Thatch	0.15-0.20
Corrugated iron	0.10-0.16
Highly Reflective Roof After Weathering	0.6-0.7
Paints	
White, whitewash	0.50-0.90
Red, brown, green	0.20-0.35
Black	0.02-0.15
Urban areas[b]	
Range	0.10-0.27
Average	0.15

a) Albedo is the fraction of solar radiation reflected by a surface.

b) Based on mid-latitude cities in snow-free conditions.

† *Source:* Martien and others (1989).

but higher emissivity (**Figure 2**). In general, most materials have a high emissivity (are good radiators), with the exception of metallic surfaces and specialty coatings. **Table 4** lists albedo and emissivity of various materials.

Figure 2 demonstrates how the surface temperatures of various horizontal surfaces are related to solar absorptivity and emissivity. Aluminum foil and galvanized steel have higher surface temperatures than might be expected from albedo alone because they have low emissivities. Also shown in Figure 2 is a hypothetical light-roofed "green city," with high-albedo surfaces and trees. The green city has a cooler average surface temperature than most rural areas, which are

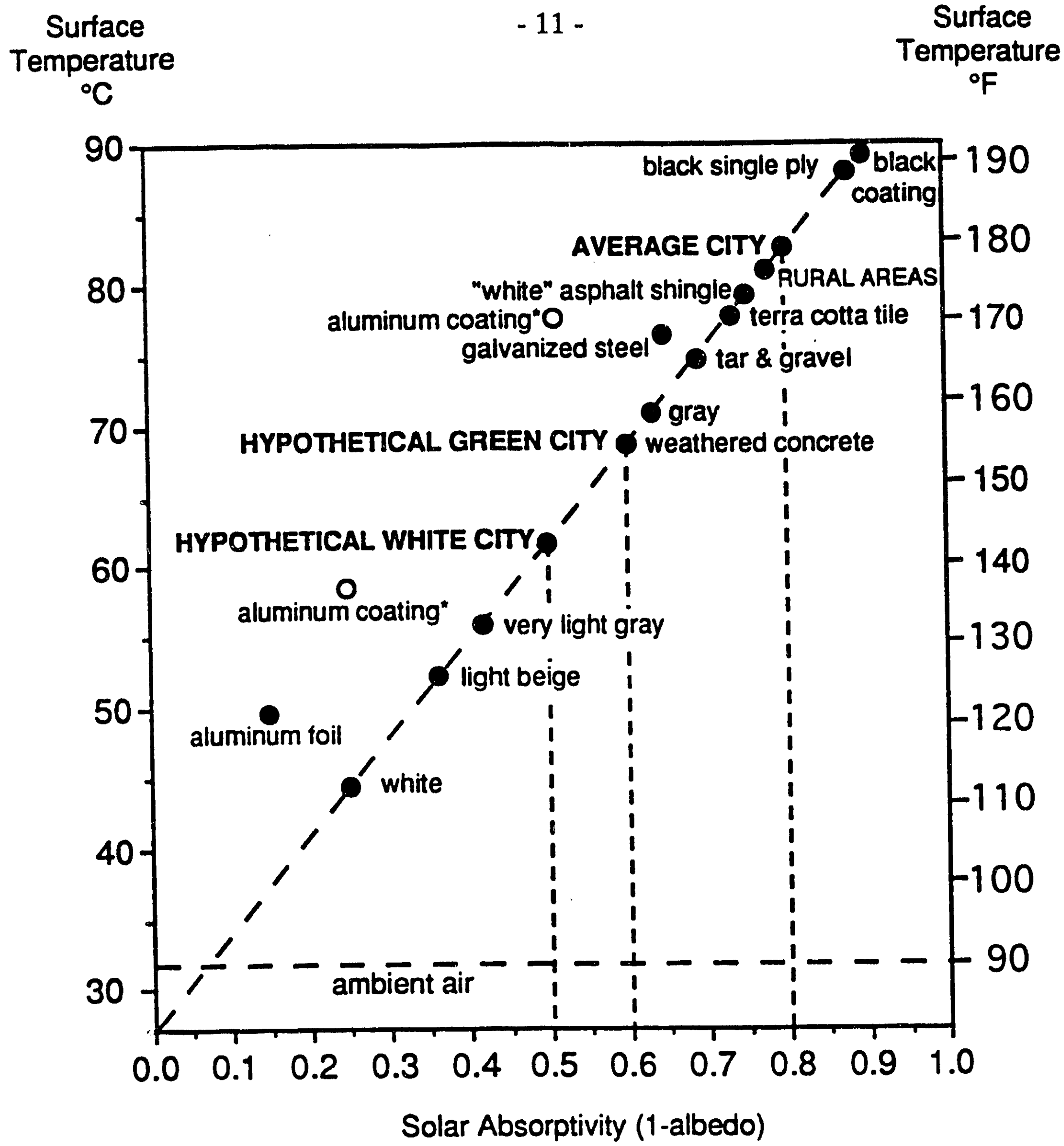

Figure 2. Solar Absorptivity vs. Surface Temperature of Horizontal Surfaces: Paints, roofing materials, roadways, and cities, adjusted to noon on a clear, windless summer day in Austin TX.

There are large temperature spreads of about 70°F between white and black surfaces, and of 40°F between concrete and asphalt. Asphalt surfaced with crushed oyster shells or sand is probably 60°F cooler than the traditional black version. There is also a large temperature spread between aluminum (or white) and galvanized steel. Both metals run hotter than paint because they radiate heat poorly (have a low "emissivity"); in addition, galvanized steel has a high absorptivity.

As surface temperatures change, so does air temperature, but much less sensitively. Nevertheless the average city's surface temperature is hotter than its rural surroundings, and thus the air is warmed. The figure shows a hypothetical light-roofed "green city" with surface temperatures 20°F-25°F cooler than either an average city or surrounding rural areas because of the combination of white roofs, light streets and parking lots, and urban vegetation. In the hypothetical "white city," there is less existing urban vegetation (such as in Phoenix where scarce water means fewer lawns), and the surface temperature is further reduced.

* We know that the absorptivity of aluminum coating ranges from 0.2 to 0.5. In one test, aluminum coating reached 172°F.

Source: Taha, Sailor, and Akbari, 1992 (LBL-31721), Fig. 6. and Table 11.

TABLE 4†. ALBEDO AND EMISSIVITY FOR SELECTED SURFACES[a].
Based on data from Edwards (1981) and Wechsler and Glaser (1966).

Material	Albedo	Emissivity
Concrete	0.3	0.94
Red brick	0.3	0.90
Building brick	-	0.45
Concrete tiles	-	0.63
Wood (freshly planed)	0.4	0.90
White paper[b]	0.75	0.95
Tar paper	0.05	0.93
White plaster[b]	0.93	0.91
Bright galvanized iron	0.35	0.13
Bright aluminum foil	0.85	0.04
White pigment[b]	0.85	0.96
Grey pigment	0.03	0.87
Green pigment[b]	0.73	0.95
White paint on Aluminum	0.80	0.91
Black paint on Aluminum	0.04	0.88
Aluminum paint	0.80	0.27-0.67
Gravel	0.72	0.28
Sand	0.24	0.76

a) Note that emissivity is a characteristic of the surface for long wave radiation whereas albedo covers the entire solar spectrum.

b) These are examples of good albedo and emissivity combinations.

† *Source:* Martien and others (1989).

presently cooler than the average city.

(3) *Durability.* It is obviously undesirable to have a product that has the right optical properties but degrades soon after it is applied. In addition, weathering or soiling of a material may affect both albedo and emissivity, requiring that the amount these properties change over time be considered when choosing a material to mitigate heat islands. Some materials will be more resistant to soiling than others, and some will be washable. Researchers at LBL are planning to collect data on how the albedos of various white roofing materials and paints change over time.

(4) *Cost.* Not simply the initial cost but also the life-cycle cost of the material should be considered.

(5) *Pollution.* Since emissions of volatile organic compounds (VOCs) from paints and coatings is an air pollution issue, efforts should be made to choose materials with low VOC content. VOCs combine with nitrogen oxides in sunlight to form urban ozone or smog, so attention to VOC content is needed in areas where ambient ozone or nitrogen oxide levels exceed National or State Ambient Air Quality Standards.

(6) *Appearance.* If a surface is highly visible, consideration of its appearance will be important. Care should be taken to prevent glare from surfaces that are highly visible.

Weathering and Soiling of High-Albedo Materials

The albedo of a surface will change over time due to weathering and soiling. Weathering may cause the albedo of a dark-colored roof to increase with age. For white roofs, albedo typically decreases with time, especially if the roof is flat and thereby more susceptible to dirt pick-up than a sloped roof. Depending on the amount of soiling that occurs, it may be cost-effective to include periodic washing of high-albedo roofs in a normal roof maintenance program.

White roads are prone to a decrease in albedo because of oil drippings and scuff marks, but the albedo of dark asphalt increases as the road wears and oxidation occurs. Quantitative data on the effect of weathering on both roof and pavement albedo are needed.

The durability of a high-albedo coating will depend on environmental conditions, the substrate it is used on, and the finish. The presence of aerosols, including salt and industrial chemicals, in the air may require a special coating. A permeable coating, such as an acrylic, is advisable for stone and concrete, since they may contain moisture; water that builds up beneath the film of an impermeable coating could cause blistering. Some solvent-based paints are water-permeable and allow the passage of moisture through the finish, therefore reducing the occurrence of blistering. These paints can be applied in more extreme conditions than normal acrylics. An elastomeric coating may be useful for roofs because it can stretch and accommodate cracks.

A paint's finish--either matt, gloss or smooth textured--is determined by the fineness of aggregates added to the paint, which affects the thickness of the film created and therefore the durability. Gloss and smooth finishes contain fine aggregates and should last for 10 years, while a matt finish is thicker and should last only half as long. Eventually, both acrylic and solvent-based paints will wash out or wear away, whereas cryltane polyurethane coatings, costing about 75% more, are virtually permanent. Cryltane is highly resistant to grit impact and ultraviolet or gas attack, but is too thin to bridge the cracks that are common on wall surfaces (Whitehead, 1991).

Roofing Materials

There are several reasons for designating roofs as the primary target for a program to increase urban albedo. To begin with, during much of the time that cooling energy is needed in

California, a roof is a more important sun receiver than a wall. Secondly, a high-albedo roof does not create the problems of glare that vertical walls may present. Lastly, based on our estimate that Sacramento is about 28% roofed area, increasing the albedos of these roofs may have a large effect on overall urban albedo.

In order to consider the options for increasing roof albedo, it is useful to have a basic understanding of the various roof types. Roofing, the barrier that serves to protect the substrate from the elements, may be a continuous membrane or individual overlapping units. Continuous roofing membranes are generally used on flat or gently sloping roofs, while overlapping units are always installed with a slope (otherwise they cannot shed water). Continuous roofing includes: 1) built-up membranes--alternating layers of bitumen and felt that are usually covered with a surfacing such as gravel, mineral granules or reflective paint; 2) liquid-applied membranes--roll-on or spray-on flexible coatings; 3) single-ply membranes--sheets of modified bitumen or of polymeric materials. Preformed panels and overlapping units include shakes, shingles, tiles, and panels that are mechanically attached to the substrate (*1991 Sweet's Catalog File*, 1990).

Sloped Roofs

Most steep roofs (slopes greater than one in three) are shingled with asphalt, wood shake or concrete tile shingles. For a residential roof with a pitch greater than 3.5 inches per foot, asphalt shingles have the lowest initial cost (*1991 Sweet's Catalog File, 1990). Although white asphalt shingles are an improvement over dark asphalt shingles, they do not have a high albedo.* In preliminary tests, we found the albedo of a white asphalt shingle to be 0.22, compared to 0.05 for a black asphalt shingle. If the primary goal is a high-albedo roof, it is more effective to either choose a different roof type than asphalt shingle, or to coat the asphalt shingles with a white roof coating (with an albedo of ~ 0.75). Applying a coating immediately after installing the shingles should not add significantly to the cost of the work, but will void the warranty that is offered by the shingle manufacturer. Other options for a high-albedo roof include white concrete tiles and asphalt roll roofing with a topcoat of white paint.

If a shingled roof is not in need of replacement, the shingles may be painted to increase the albedo and extend the life of the roof. There does not seem to be a consensus among contractors whether or not it is advisable to paint shingles on steep roofs. The *1991 Sweet's Catalog File* (1990), however, indicates that painting shingles, shakes and tiles is a common practice. For asphalt shingles, it is important to use a coating that can expand and contract with the shingles and that has a low volatile organic content. The Appendix lists some products that are currently available.

Table 5 presents options and estimated costs for increasing the albedo of a sloped roof, as compared to a base case installation of a dark asphalt shingle roof. The costs associated with the techniques in Table 5 are highly variable, and will depend on the slope and detail of the roof, and the markup of the contractor. They do not include the cost of removing an old roof, which may be necessary if a shake roof is installed (because of weight limits). The estimates in Table 5 are for 1991 costs in the Sacramento area and include subcontractor's overhead and profit: bare material plus 10%; bare labor cost plus overhead and profit; and the bare equipment cost plus 10%. A general contractor hiring a subcontractor might add another 20% to the costs in the table.

Annualized costs, displayed on the bottom row of Table 5, represent one attempt to compare the costs of different measures. These estimates are sensitive to two assumptions: the 7% discount rate that is used and the expected life of the material shown in the row above.

Note that we have estimated that a roll asphalt roof with white reflective paint will last longer than a dark roll asphalt roof, since it will be protected from ultra-violet degradation and experience less thermal expansion and contraction from solar heat gain. A dark roll asphalt roof, not included in Table 5, typically has about a 20 year lifetime.

We also note that discount rates imply a great deal about the time value of money for a consumer and that different individuals have different discount rates. The use of a 7% discount rate does not suggest that we believe a 7% discount rate to be the most appropriate way to evaluate the cost of a measure but that it is one way to estimate the cost-effectiveness of the measure. Under these assumptions, both the white asphalt shingle roof and the roll asphalt with reflective paint are cost-effective alternatives to the base case dark asphalt shingle roof.

Flat and Gently-Sloped Roofs

Table 6 compares the costs and albedos for roofing materials used on flat and gently sloping roofs (slopes less than one in three). Replacing a roof with a high-albedo material costs essentially the same as reroofing with a low-albedo roof. Each of the white roofs in Table 6 has an annualized cost that is competitive to the base case dark built-up roof. For built-up roofing, surfacings are commonly used to protect the black bitumen or asphalt of the roofing membrane from solar radiation and extend the life of the roof. Surfacings include an aggregate coating, a layer of roofing gravel, or a reflective paint. Selecting a white surfacing increases the albedo and cooling-energy savings without increasing the cost. White gravel, for example, costs no more than dark gravel. Among surfacings, white reflective paint has the highest initial albedo. A single-ply white polymer roofing membrane is also a cost-effective reroofing option and has a very high albedo.

Increasing the albedo of a roof before replacement is necessary can be accomplished by painting or by replacing the surfacing. White roof coatings may be applied to most roof types to protect the membrane from weathering and to reduce solar gain. Although painting or resurfacing a roof for energy savings alone is not cost-effective, it may be combined with roof maintenance to extend the lifetime of the roof.

TABLE 5†. COMPARATIVE COSTS ESTIMATES FOR SLOPED ROOFS[a]

Roof material	Reroofing Applications						Retrofit
	Asphalt shingles (dark)	Asphalt shingles (white)	Red cedar shingles (untreated)	Concrete tile	White concrete tile	Roll asphalt, with reflective paint	White acrylic roof paint (2 coats)
Bare material cost per square meter[b]	$4.8	$4.8	$10.2	$5.0	$11.4	--	$2.0
Bare labor cost per square meter[b]	$4.6	$4.6	$8.2	$15.4	$15.4	--	$2.8
(steep roof)	($7.0)	($7.0)	($12.4)	--	--	--	($3.7)
Bare total cost per square meter[b]	$9.5	9.5	$18.4	$20.4	$26.7	$11.0	$4.8
(steep roof)	($11.8)	($11.8)	($22.6)	--	--	--	($5.7)
Subcontracter total fee per square meter[b]	$12.4	$12.4	$22.8	$26.9	$34.8	$14.3	$6.0
(steep roof)	($15.3)	($15.3)	($27.9)	--	--	--	($7.1)
Albedo (estimated new)[c] (%)	5-10	20-25	30	35-40	70-80	80-90	80-90
Albedo (estimated weathered[c]) (%)	10-15	15-20	20-25	25-30	60-70	60-70	60-70
Expected life (years)[d]	20	20	15-20	50	50	25	5-10
Annualized cost per square meter[e]	**$1.17**	**$1.17**	**$2.37**	**$1.95**	**$2.52**	**$1.35**	**$1.06**
(steep roof)	**($1.44)**	**($1.44)**	**($2.90)**	**--**	**--**	**--**	**($1.25)**

†Based on data from Martien et al., (1989), with updated cost, albedo and lifetime estimates.

(a) *Assumptions:* Estimates are in 1991 dollars, include materials, equipment and labor costs only and are adjusted for the Sacramento area. They do not include the cost of removing an existing roof, which is necessary if the new roof is heavy, as may be the case with wood shake and concrete tiles.

(b) *Cost estimate sources:* White paint: Kiley and Moselle (1989). Other jobs: Means (1990).

(c) *Albedo source:* Martien et al. (1989). We emphasize that the weathering estimates are highly variable and uncertain. We expect that the albedo change will depend on climate, air quality, etc.

(d) *Sources for expected life:* Roll asphalt with reflective roof paint: we estimate that the lifetime of the roof is related to the stress of thermal expansion and contraction resulting from solar heat gain, which is reduced if the roof has a high albedo. Consequently, we estimate the white roof to last slightly longer than low-albedo roofs. White paint: discussions with roofing contractors. Other roofs: *1991 Sweet's Catalog File* (1990).

(e) *Annualized cost.* The real interest rate is assumed to be 7%.

TABLE 6†. COMPARATIVE COSTS ESTIMATES FOR FLAT ROOFS[a]

Roof material	Reroofing Applications					Retrofit
	Built-up asphalt with dark gravel	Built-up asphalt with reflective paint	Built-up asphalt with white gravel	Modified bitumen with white gravel	Single-ply white polymer roofing	White acrylic roof paint (2 coats)
Bare material cost per square meter[b]	$3.6	$3.6	$3.6	$5.6	$6.8	$2
Bare labor cost per square meter[b]	$7.5	$7.5	$7.5	$3.3	$3.1	$2.0
Bare total cost per square meter[b]	$11.1	$11.1	$11.1	$8.9	$9.9	$4.0
Subcontracter total fee per square meter[b]	$14.0	$14.0	$14.0	$11.3	$12.4	$5.2
Albedo (estimated new)[c] (%)	5-10	70-80	50-60	50-60	70-80	70-80
Albedo (estimated weathered)[c] (%)	15-20	60-70	40-50	40-50	60-70	60-70
Expected life (years)[d]	20	20	20	20	20	5-10
Annualized cost per square meter[e]	**$1.32**	**$1.32**	**$1.32**	**$1.07**	**$1.17**	**$0.91**

†Based on data from Martien et al., (1989), with updated cost, albedo and lifetime estimates.

(a) *Assumptions:* Cost estimates are in 1991 dollars and, except roof painting, are adjusted for the Sacramento area according to Means (1990) area modification. Estimates include materials, equipment and labor costs only. They do not include the cost of removing an existing roof. A general contractor might add a 20% markup to the subcontractor's fee.

(b) Cost estimates are rough and should be used only for comparison, not as absolute figures. *Sources:* White paint: Kiley and Moseile (1989); Others: Means (1990)

(c) *Albedo sources:* White polymer roofing: Labs (1990). White gravel: Baker (1980) Others: Martien et al. (1989). We emphasize that the weathering estimates are highly variable and uncertain. We expect that the albedo change will depend on climate, air quality, etc.

(d) *Sources for expected life:* Paint: discussions with roofing contractors. Others: *1991 Sweet's Catalog File* (1990).

(e) *Annualized cost.* The real interest rate is assumed to be 7%.

Although roof coatings are available with aluminum particles for reflection, a top coat of white paint would probably be more effective at keeping a roof cool because it has lower emissivity. Most roof paints and coatings are available in white and can be used on built-up and metal roofs to extend the useful life of the roof. Coatings are not recommended, however, on flat roofs if ponding water is a possibility, nor if moisture has penetrated the felts. If the existing roof is badly split or blistered, it makes more sense to replace the roof rather than to repair, since repair will only forestall the problem (Herbert III, 1989).

Coatings for Roofs and Walls

Modifying the albedo of a wall is very straightforward, since it may be lightened with a standard white or light-colored paint. The cost of changing the albedo of a building is zero, if the change is made at the time of routine repainting, which is generally done about every 10 years (more often for commercial buildings). Similarly, roof albedo may be increased with a white coating following repair or reroofing.

Coatings must be chosen to match the substrate and the environmental conditions, and must be applied correctly. Coatings with high volatile organic content should not be applied on asphalt, since they may leach asphalt to the surface, thereby reducing the albedo of the roof. Similarly, any incompatibility between substrate and coating will reduce adhesion and accelerate deterioration. Incompatibility may arise due to: 1) incompatible preservatives in wood; 2) incompatible primers and topcoats: the solvent in the topcoat may act as a paint remover on the primer; 3) applying a relatively hard topcoat over a relatively soft primer or undercoat; 4) applying a water-based coating over a surface which it does not wet; e.g., a water-based coating over a glossy solvent-based coating; and 5) poor surface preparation, including oil, chemicals or moisture on the surface or moisture in the substrate. Coatings that deteriorate because of substrate defects or any of the situations described above may no longer be recoatable and may need to be removed at considerable expense (*1991 Sweet's Catalog File*, 1990). For these reasons, it is essential that the person doing the labor understands the characteristics of both coating and substrate. The Appendix list a number of high-albedo coatings and suppliers.

Since solar radiation includes ultraviolet (UV), visible, and longer wavelength light, the best paints to reduce solar gain are highly reflective of visible *and* non-visible radiation. Most of the standard coatings available are not very reflective of non-visible radiation. Since the primary objections to white roofs may be based on their appearance, it is useful to note that high-albedo paints includes those that are not as reflective as white paint in the visible range, but more reflective of non-visible solar radiation. Because there has not been a market for paints to increase urban albedo, the best solar-reflecting paints may not be widely available yet.

Solar-reflective coatings that have been developed have been formulated in either of two ways. In the first case, a highly reflective white undercoat is topped with a coat that can be colored with pigments transparent to solar radiation. The topcoat creates the desired visual color but does not absorb infrared radiation. There are three drawbacks to this approach: 1) producing a consistent film thickness to create a uniform visual appearance may be difficult outside a factory; 2) maintenance is a problem because the topcoat and undercoat must be applied at proper thicknesses to retain their optical properties and 3) the cost exceeds that of a single coat.

Another approach is to use pigments that are reflective in the near-infrared to produce a single coating, which is more practical for building applications. Such solar-reflective coatings have been formulated with a grey color for painting battleships. One coating designed for U.S. Navy ships is twice as reflective of non-visible solar radiation (720 to 2300 nm) as the older coating, but with similar reflectance in the visible region (Brady and Wake, 1992). Metal oxide pigments may be useful in creating solar-reflecting paints, because they are durable and reflective in the non-visible portion of the solar spectrum. Chromium oxide pigments, in particular, may be used to produce earth-toned paints with albedos higher than conventional earth tones (Kettanacker, 1992).

The Naval Civil Engineering Laboratory (NCEL) has developed thermochromic pigments that change color with temperature. The pigments would lighten under strong sunlight and get darker on cool, shady days. The laboratory is seeking American manufacturers to commercialize the pigments (DiChristina, 1992).

Triangle Coatings of San Leandro, California sells a paint that they claim is highly reflective of non-visible solar radiation. This "Hi-Reflectance" paint can be tinted to various colors, and so may provide an albedo that is higher than standard tinted paint. Similarly, Helios Energy Products claims that the Enerchron coating is reflective in the non-visible parts of the solar spectrum and may be tinted. Researchers at Lawrence Berkeley Laboratory are interested in testing these coatings, along with a number of other exterior paints, to determine the albedo. The study includes the use of a spectrophotometer with an integrating sphere to provide reflectance at each wavelength of light. With these data, we will be able to compare coatings and paints according to their optical properties.

Pavements

Paving includes installing new pavement, replacing old pavement, and resurfacing old pavement. For heat island mitigation, we are mostly concerned with pavement replacement or resurfacing, although albedo should still be considered when placing new pavement.

Until recently, when pavement had deteriorated there were two options. If the pavement was not too badly damaged, it would most likely be resurfaced with an asphalt overlay. If deterioration was significant, however, the pavement would probably be torn up and replaced with a new pavement. Now, there are intermediate concrete paving options that may be cost-effective: bonded concrete overlay as a resurfacing technique and unbonded full-depth concrete inlay as an option for new pavement (Renier, 1987). There also are some newly-developed colored paving technologies which may be competitive with asphalt and concrete. Pavement selection depends on a wide variety of factors, as discussed below.

Resurfacing

There are several options for changing the albedo of pavements at the time of resurfacing, a technique that is often used to extend the life of a street or parking area (see **Table 7**). Resurfacing options include an asphalt concrete overlay, chip or slurry seal, or a bonded concrete overlay ("whitetopping"). Chip and slurry seals protect the existing bituminous surface from air and water, improve a raveled surface, and provide a skid-resistant surface. They do not, however, increase the load-bearing capacity of the pavement, as an overlay does.

The use of white aggregate in the upper layer of asphalt concrete or in a chip seal will eventually produce a light-colored pavement. White aggregates that are appropriate for use in asphalt concrete pavement include high silica gravel, quartz, white stone, white marble, and some granite. With an asphalt overlay, the pavement is initially dark because of the dark binding material, but may be fairly light-colored within a year, if the aggregate is a light color. The albedo of asphalt pavement increases because of oxidation of the asphalt binder and exposure of the aggregate caused by wear and weathering. For a pavement that has a high albedo from the time of installation, white chippings, sand, or oyster shells might be embedded on the top layer. Chippings that are approved for chip seals and hot-rolled asphalt pavement may be used now, but sand and oyster shells may have to be tested to see how they perform under traffic. A particular concern is that a material might "polish" under tire wear, creating a slick surface.

A chip seal is surface treatment that may have immediate albedo benefits, since it results in an exposed aggregate surface. Often, however, the pavement surface is too damaged for a chip seal to be cost-effective, and an overlay is necessary.

A bonded concrete overlay, with a thickness of 3 to 4 inches, is an effective and relatively new repair for distressed asphalt pavements. The overlay is thick enough to increase the load-bearing capacity of the pavement but thin enough that the cost may be as low as the cost of another blacktop layer (MIRMCA, 1985). Concrete overlays are attractive because they don't require periodic seal coats and have low maintenance costs. While the curing time for concrete has been known to require several days of traffic diversions, it is now possible to reopen concrete overlays in 8-24 hours through the use of curing compounds (Renier, 1987).

Concrete pavements may perform better in areas that experience heavy truck traffic and have an added benefit of reducing truck fuel use. Results of a 1982 study published by the Federal Highway Administration show that trucks can save as much as 2 miles per gallon by driving on concrete instead of asphalt pavements, even when the pavement surfaces are similar in roughness. The savings occur because concrete is more rigid than asphalt pavement, which is slightly deformed by the weight of a truck. Since a truck always runs in a slight depression on asphalt pavements, more energy is needed to propel it (anon, 1990).

New flexible paving technologies include the replacement of asphalt with a high-albedo binding material to hold aggregate. According to a representative of the Asphalt Institute, the initial cost of such materials presently precludes their use on large surfaces (Shuler, 1991). Nevertheless, we found a 1985 article that describes two new binders that can be used for color pavement with costs similar to regular asphalt cements. After testing, one of the binders was chosen to pave a park in Korea in 1982 (Lee et. al, 1985). We predict that if demand for high-albedo pavement exists, the technologies that have been developed will be more popular.

Another new technology that may emerge for heat island mitigation is the formulation of a white slurry seal. Slurry seal, used for resurfacing pavement, is a combination of aggregate, asphalt emulsion, and fillers mixed together. Colored slurry seal has been produced, but only for limited applications. Producing a white slurry seal would require reformulation of the emulsifier and might initially increase the cost by 25% to 50% (Valley Slurry Seal, 1992).

TABLE 7†. COMPARATIVE COSTS ESTIMATES FOR RESURFACING PAVED SURFACES[a]

Paving material	Regular asphalt (~2.5 cm)	Asphalt with light aggregate (~2.5 cm)	Regular chip seal (~1.3 cm)	White chip seal (~1.3 cm)	Regular slurry seal (~1.0 cm)	White slurry seal (~1.0cm)
Cost per square meter[b]	$2.3	$2.6	$1.2	$1.5	$1.2	$1.7
Albedo (estimated new)[c] (%)	5-10	5-10	15-20	40-50	5-10	60-70
Albedo (estimated weathered)[c] (%)	15-20	30-40	15-20	30-40	15-20	40-50
Expected life (years)[d]	4	5	4	5	4	5
Annualized cost per square meter[e]	$0.68	$0.63	$0.35	$0.36	$0.35	$0.41

†Based on data from Martien and others (1989), with updated lifetimes.

a) *Assumptions:* Estimates for resurfacing an existing asphalt city street that is structurally in good condition.

b) *Cost estimates. Source:* Means (1989), Reese (1989), ISSA (1989), PCA (1989).

c) *Albedo. Sources:* Threkeld (1970), Oke (1987), Griggs and others (1989), Reagan and Acklam (1979). We emphasize that the weathering estimates are highly variable and uncertain. We expect that the albedo change will depend on climate, air quality, local soil types, etc.

d) *Expecte life. Source:* PCA [1989], American City and County [1986], Riverside Cement [1989].

e) *Annualized cost.* The real interest rate is assumed to be 7%.

The annualized costs displayed on the bottom row of Table 7 are extremely sensitive to the expected lifetime shown in the row above. These lifetimes are rough estimates based on typical pavement lifetimes and considerations of surface temperature variations. For example, the lifetime of a thin asphalt overlay may be three to five years. The annualized costs in Table 7 demonstrate that light asphalt pavement is cost-effective if it lasts a full five years and the dark asphalt lasts only four years. A difference in lifetimes might occur because the dark pavement experiences greater temperature extremes and thermal movement. Since a normal slurry seal surfacing may last three to five years, we estimate a lifetime of four years for regular slurry seal and five years for a white slurry seal surface. The white slurry seal also has a lower annualized cost than the base case dark asphalt overlay.

Repaving

For new construction, or when a paved surface needs replacing, either asphalt or concrete may be used. While the initial cost of concrete is usually assumed to be higher than that of asphalt, they may actually be close in initial cost when based on equivalent design. Nine inches of concrete has the same load-bearing capacity as 12 inches of asphalt pavement, according to AASHTO's Interim Design Guide. When these design guidelines are followed, data from Federal Highway Administration's *Price Trends for Federal-Aid Highway Construction* indicates that concrete contract prices were lower than asphalt contract prices in nine of twelve years studied (PCA, 1986). Concrete also has lower maintenance costs and an average service life about ten years longer than that of asphalt. This would suggest that concrete has a lower life-cycle cost, but a comparison is not straightforward.

A life-cycle cost analysis may have six governing factors: initial construction cost, service life, analysis period, maintenance costs, discount rate factor and salvage value. Any one element can swing the analysis in favor of either asphalt or concrete (PCA, 1986). The choice depends not only on cost, but also on on the purpose of the pavement, the local weather conditions, and the environment (Taha et al, 1992). For example, asphalt is typically easier to remove for access to underground utilities.

Probably the largest obstacles to using concrete on city streets are inexperience with whitetopping and an outdated belief that traffic will have to be diverted for several days to allow the concrete to cure. The National Research Council Transportation Research Board reports that concrete may be the most appropriate choice for low-volume urban roads, for which maintenance financing is often difficult to obtain (TRB, 1975).

Standard gray concrete can be made lighter in color by reducing the amount of iron present in the cement during the manufacturing process. The cost of white cement is two to three times the cost of normal cement. A more practical option for high-albedo concrete may be a white-pigmented liquid membrane, a commonly used curing agent on street projects (TRB, 1975). We do not know, at this time, how durable these membranes are, nor how long they may be expected to last. If the mix contains a white aggregate, concrete pavement may also remain white as it wears.

Another high-albedo paving option is asphalt with white aggregate, already mentioned as a surface treatment alternative. The cost will depend on the availability of white aggregate, but for a repaving project, the white aggregate would only be needed for the uppermost layer. As already described, the pavement would be initially dark and would lighten as the aggregate is exposed. In contrast, a hot-rolled asphalt pavement may be initially white if a topcoat of white chippings is used. This method, popular in Great Britain, uses rolled asphalt with about 30% stone content and chippings applied to the surface. Although the chippings demand an additional procedure, it has the advantage of limiting the use of high-quality paving stone (and in this case, white stone) to only the immediate surface (OECD, 1978).

Table 8 shows comparative costs of various paving options. The annualized cost estimates indicate that if a light-colored pavement lasts a few years longer than a dark pavement of equivalent design, it is a cost-effective option.

Although not exactly a high-albedo surface, "porous pavement" is an alternative to traditional pavements that may be helpful in managing heat islands, and has a higher albedo than dark asphalt. Designed for areas that have low traffic, such as some parking lots, porous pavement consists of a concrete grid overlain by a layer of grass and weeds, or with the grass growing within the grid spaces. A cooler environment is attained through the combination of evapotranspiration, a slightly higher albedo and lower heat capacity than asphalt. Porous pavement also allows precipitation to go into the ground, thereby reducing problems associated with urban runoff (Wann, 1990).

Other high-albedo paving technologies that require further experimentation are mixtures of asphalt concrete prepared using artificial lighteners and high-albedo coatings that are designed to resist weathering and wear. It is necessary to determine whether new materials are durable and that they do not interfere with tire traction.

Implementation Issues

This section is directed at readers who are in a position to design and implement promotional programs for high-albedo surfaces. It includes energy supply-curves for high-albedo surfaces and also a discussion of non-economic considerations for designing promotional programs.

Energy Supply Curves for High-Albedo Surfaces

Using predictions of energy use for Sacramento houses and the cost and albedo estimates of various building and paving technologies (Tables 5-8), we estimate the costs of conserved energy for various measures to increase the albedo of individual homes and of an entire urban

TABLE 8†. COMPARATIVE COSTS ESTIMATES FOR REPAVING[a]

Paving material	Asphalt (18 cm)	Whitetopping (13 cm)	Asphalt with light aggregate (18 cm)	Whitetopping with white cement (13 cm)
Cost per square meter[b]	$16.4	$16.4	$16.7	$18.9
Albedo (estimated new)[c] (%)	5-10	35-40	5-10	70-80
Albedo (estimated weathered)[c] (%)	15-20	25-30	30-40	40-60
Expected life (years)[d]	15	25	15	25
Annualized cost per square meter[e]	**$1.80**	**$1.41**	**$1.83**	**$1.62**

†Based on data from Martien and others (1989), with updated lifetime estimates.

a) *Assumptions:* Estimates for repaving an existing asphalt city street that is structurally in good condition.

b) *Cost estimates. Sources:* Means (1989), Reese (1989), ISSA (1989), PCA (1989).

c) *Albedo. Sources:* Threkeld (1970), Oke (1987), Griggs and others (1989), Reagan and Acklam (1979). We emphasize that the weathering estimates are highly variable and uncertain. We expect that the albedo change will depend on climate, air quality, local soil types, etc.

d) *Expected life. Source:* A 40 year study undertaken by the FHA and the Bureau of Public roads found an average service life of 25 years for concrete pavements and 15 years for asphalt pavements (PCA, 1986). We estimate that a high-albedo pavement will last longer than a dark pavement because it is subject to lower temperature extremes and less thermal movement.

e) Annualized cost: The real interest rate is assumed to be 7%.

area (**Tables 9-11**). For a given measure, such as replacing dark shingles with white shingles, we estimate the change in albedo that may be expected, as shown in Tables 5-8. Assuming equal wall and roof areas, we divide this number by two for an estimate of the change in albedo of the building. Then, assuming the surface proportions listed in Table 1, we estimate the community-scale change in albedo that would be achieved with a 50% implementation. We estimate direct energy savings using an estimate of a 0.4% decrease in annual cooling-energy use for an individual building for each 0.01 increment in albedo of the building and indirect energy savings of 3% for each 0.01 increment in the albedo of the surroundings. The estimated decrease in annual cooling energy use is based on computer simulation of altering albedo at the community scale in the range of 15 to 40% (Martien et al, 1989). It should be noted that the computer simulation may exaggerate the energy savings because it is a one-dimensional model, and does not include the effects of the influx of air from warmer areas. In monitored experiments, however, savings equivalent to a 0.7% decrease in energy use for each 0.01 increment in the albedo of the roof have been measured, indicating that the estimate we use for direct effects is conservative (Akbari et al, 1993). Other assumptions used in our cost calculations are that the house has a floor area of 150 square meters and an annual cooling-energy expenditure of 1250 kWh.

As mentioned, Tables 9, 10 and 11 list costs of conserved energy for direct and indirect savings as a result of increasing albedo. In comparison to other efficiency techniques, savings achieved through changes in albedo are extremely cost-effective, with many measures having negative or zero cost when implemented as part of routine maintenance. We have found that there are methods of changing the albedo of all major urban surfaces (streets, parking lots, flat roofs, and sloped roofs) at the time of resurfacing or reroofing for less than the avoided cost of electricity. Although residential electricity in Sacramento is sold at an average price of about 8.1 cents/kWh, air-conditioning power is mainly "on-peak," costing commercial users about 12.3 cents/kWh. Since albedo modification saves mostly on-peak power, the measures offer significant monetary savings to the utility. Also, these costs of conserved energy do not account for the air pollutants or social costs that would be avoided by reducing power generation.

Two examples of least-cost energy-supply curves for albedo modification are shown in **Figures 4a-b**. Figure 4a is a energy-supply curve for a flat roofed building, when streets are repaved with white cement concrete overlays. It predicts the overall percentage cooling-energy savings to the building will be over 40% at no cost. Savings from normal concrete would be only 3.9%, compared to 12.9% for white cement, but would still represent a net savings per kWh.

As an alternative to concrete overlays, Figure 4b shows the savings from resurfacing with asphalt with light aggregate. If streets were repaved rather than resurfaced, savings would be the same but would cost about 2.4 cents/kWh. Although Figure 4b shows a sloped-roofed house, the savings due to the roof measure are the same (31% of cooling-energy use at the time the measure is implemented).

Our estimates indicate that measures for recoating or replacing a surface only to increase the albedo for energy benefits are not cost-effective. Painting a roof that would not otherwise be painted costs over 40 cents per kWh, which is significantly greater than the cost of electricity. Other benefits of high-albedo coatings that extend the lifetime of the roof itself are not considered in this analysis. Therefore, it could be worthwhile for some owners who desire to add protection to the roof or who are interested in the thermal comfort of a building to invest the additional money in painting costs.

TABLE 9. COST EFFECTIVENESS OF DIRECT AND INDIRECT MEASURES FOR WALLS AND SLOPED ROOFS

Measure	Repaint walls white	Replace dark asphalt shingles w/ light	Replace dark asphalt shingles w/ roll roofing w/ reflective coating	Paint roof -- non-maintenance
Change in the albedo of a roof or wall (A)[a] (%)	30	15	50	50
Change in the albedo of a home[a] (%)	15	7.5	25	25
Change in the albedo of the community[a] (%)	--	2.1	7.0	7.0
Direct savings[b] (%)	6.0	3.0	10.0	10.0
Indirect savings[b] (%)	--	6.3	21.0	21.0
Total savings (%)	6.0	9.3	31.0	31.0
Total annual energy savings per house[c] (kWh/year)	75	116	388	388
Unit annualized cost[c] ($\$/m^2$/year)	0	0	0.18	1.06
Annualized cost per house[c] ($/year)	0	0	27	159
Cost of conserved energy[d] (cents/kWh)	**0**	**0**	**6.9**	**41**

a) We make a conservative estimate of the change in albedo of a wall or roof surface (A) when the measure on line 1 is implemented (refer to Table 5). For the percent change in the albedo of a building, we assume equal roof and wall areas ($A/2$). The percent change in the community albedo assumes the surface proportions presented in Table 1 and 50% implementation ($A * 0.28 * 0.50$).

b) Direct savings are estimated by assuming a 0.4% decrease in cooling for each 0.01 increase in the albedo of a building ($A/2 * 0.004/0.01$). Indirect savings are estimated by assuming a 3% decrease in cooling for each 0.01 increase in the community albedo ($A * 0.28 * 0.5 * 0.03/0.01$).

c) Savings expressed on a per house basis assume a yearly cooling energy use of 1250 kWh. Annualized costs, presented in Table 5 assume a 7% real interest rate. Annualized costs expressed on a per house basis assume a floor area of 150 square meters; wall area is roughly equivalent.

d) Cost of conserved energy (CCE) = (Annualized cost per home)/ (Total annual savings per home).

TABLE 10. COST EFFECTIVENESS OF DIRECT AND INDIRECT MEASURES FOR FLAT AND GENTLY SLOPED ROOFS

Measure	Replace dark built-up w/ an equivalent design using white gravel	Replace dark built-up w/ an equivalent design using white coating	Replace dark built-up w/ modified bitumen & white gravel	Replace dark built-up w/ single-ply white polymer roofing	Paint roof white non-maintenance
Change in the albedo of a roof (*A*)[a] (%)	30	50	30	50	50
Change in the albedo of a house[a] (%)	15	25	15	25	25
Change in the albedo of the community[a] (%)	4.2	7.0	4.2	7.0	7.0
Direct savings[b] (%)	6.0	10.0	6.0	10.0	10.0
Indirect savings[b] (%)	12.6	21.0	12.6	21.0	21
Total savings (%)	18.6	31.0	18.6	31.0	31.0
Total annual energy savings per building[c] (kWh/year)	233	388	233	388	388
Unit annualized cost[c] ($\$/m^2$/year)	0	0	-0.25	-0.15	0.91
Annualized cost per house[c] ($/year)	0	0	-37.5	-22.5	137
Cost of conserved energy[d] (cents/kWh)	**0**	**0**	**-3.7**	**-2.6**	**35**

a) We use a conservative estimate of the change in albedo of a roof (*A*) (refer to Table 6). Change in the albedo of a building assumes equal wall and roof area (*A*/2). The percent change in the albedo of the community assumes the surface proportions presented in Table 1 and 50% implementation ($A * 0.28 * 0.50$).

b) Direct savings are estimated by assuming a 0.4% decrease in cooling for each 0.01 increase in the albedo of a building ($A * 0.004/0.01$). Indirect savings are estimated by assum.ng a 3% decrease in cooling for each 0.01 increase in the albedo of the community ($A * 0.28 * 0.5 * 0.03/0.01$).

c) Savings expressed on a per house basis assume a yearly cooling energy use of 1250 kWh. Annualized costs, presented in Table 6 assume a 7% real interest rate. Annualized costs expressed on a per house basis assume a floor area of 150 square meters; wall area is roughly equivalent.

d) Cost of conserved energy (CCE) = (Annualized cost per home)/ (Total annual savings per home). For measures with negative costs, we use CCE = (Annualized cost per home) / (Total annual energy use minus savings).

TABLE 11. COST EFFECTIVENESS OF INDIRECT MEASURES FOR PAVED SURFACES

Measure	(Resurfacing) Replace dark asphalt using light aggregate	(Repaving) Whitetopping	(Repaving) Replace dark asphalt with light aggregate	(Repaving) Whitetopping with white cement
Change in the albedo of a pavement surface (*A*)[a] (%)	20	10	20	30
Change in the albedo of the community[a] (%)	2.6	1.3	2.6	3.9
Indirect savings[b] (%)	7.8	3.9	7.8	11.7
Annual indirect savings per house[c] (kWh/year)	98	49	98	146
Unit annualized cost[c] ($/m^2/year)	0.05	-0.39	0.03	-0.18
Annualized cost per house[c] ($/year)	7.5	-58.5	4.5	-27
Cost of conserved energy[d] (cents/kWh)	**7.6**	**-4.9**	**4.5**	**-2.4**

a) The percent change in albedo of a pavement surface (*A*) is from Tables 7 and 8. The percent change in the albedo of the community assumes the surface proportions presented in Table 1 and 50% implementation (*A* * [0.16 + 0.10] * 0.5).

b) Indirect savings are estimated by assuming a 3% decrease in cooling for each 0.01 increase in the albedo of the community (*A* * 0.26 * 0.5 * 0.03/0.01).

c) Savings expressed on a per building basis assume a yearly cooling energy use of 1250 kWh. Annualized costs, presented in Tables 7 and 8 assume a 7% real interest rate. Annualized costs expressed on a per house basis assume a floor area of 150 square meters; wall area is roughly equivalent (Unit Annualized Cost * 150 * 0.26/0.28 * 0.5).

d) Cost of conserved energy (CCE) = (Annualized cost per home)/ (Total annual savings per home).

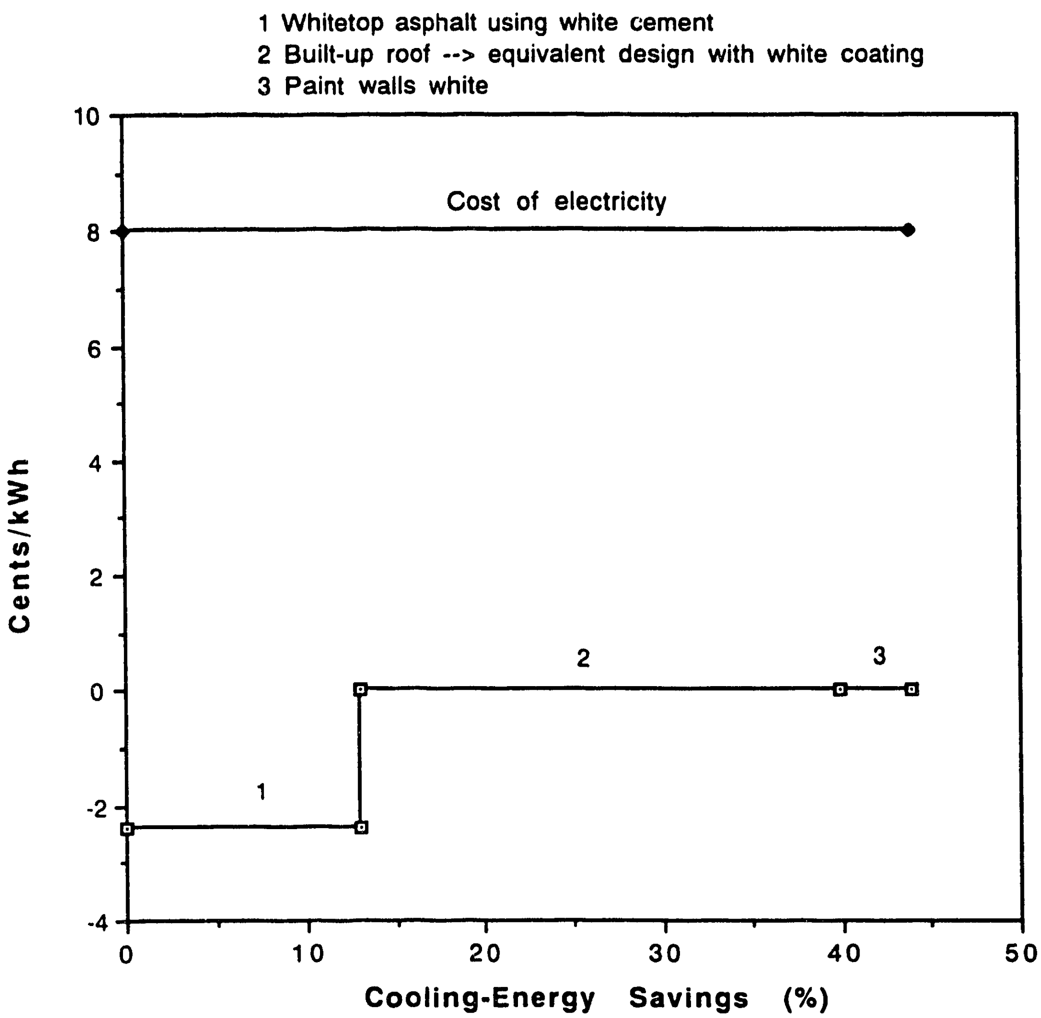

Figure 4a. Energy-supply curve for a flat-roofed house in Sacramento, California, based on savings estimates and urban surface proportions. Includes direct and indirect effects.

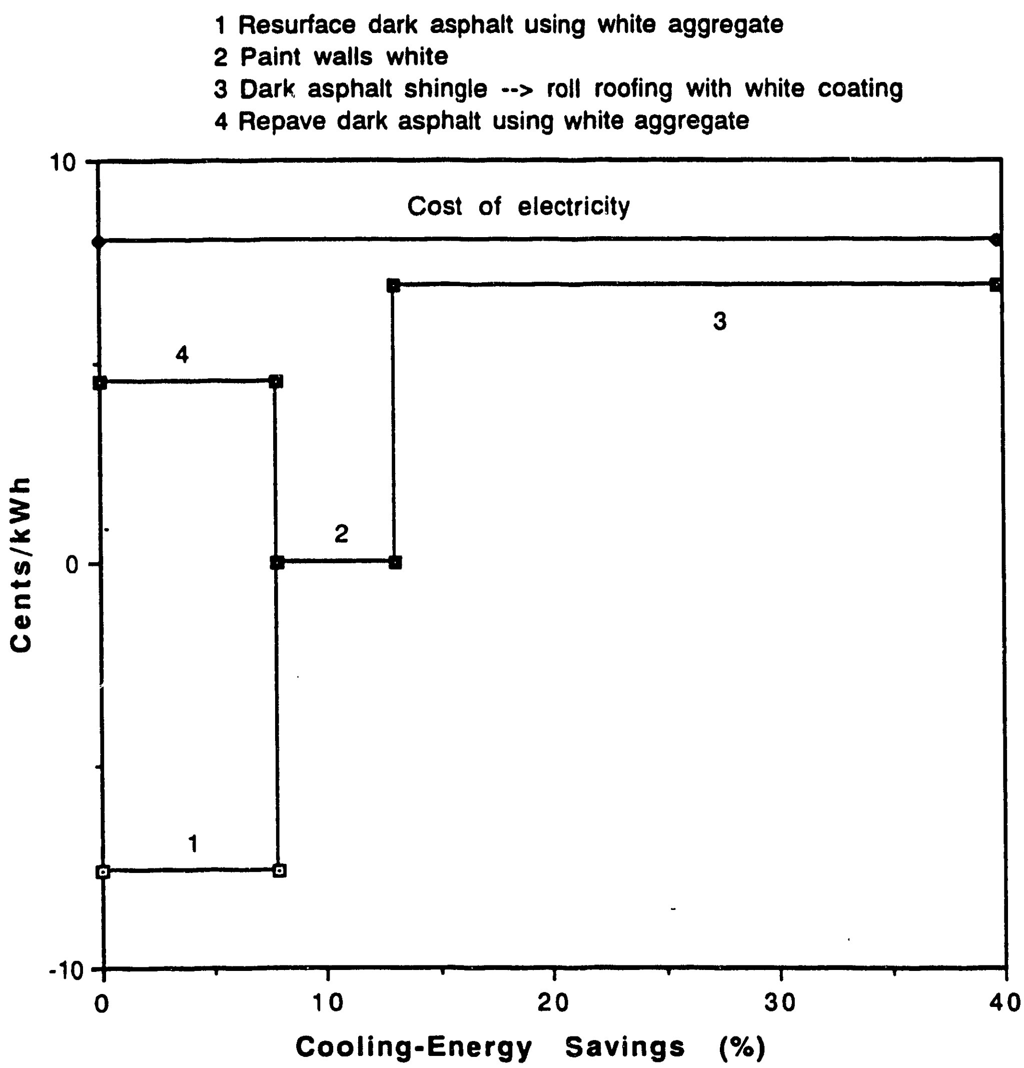

Figure 4b. Energy-supply curve for a sloped-roofed house in Sacramento, California, based on savings estimates an urban surface proportions. Includes direct and indirect effects.

Perspectives of Audiences and Implementing Groups

The selection of priorities for designing a promotional program for high-albedo surfaces, as well as the program itself should be based on an understanding of the motivations or interests of the implementing groups and audiences that will be involved. Implementing groups include the utilities and local or state governments. Audiences include consumers, roofing and building contractors, manufacturers of roofing products, paving contractors and public works departments, and energy service companies. Much of the information that follows is based on a study conducted by researchers at LBL on the promotion of Home Energy Rating Systems (HERS) throughout the U.S. A HERS is the rating and labeling of new and existing energy-efficient homes by local, state and federal government agencies, utility companies and other organizations (Vine et al, 1987). Since HERS and a high-albedo surfaces program involve similar audiences and implementing agencies, we are hopeful that a review of the successful aspects of various HERS promotion programs may improve the promotion efforts of an albedo program.

The Consumer's Perspective

Homeowners, landlords and building managers are the consumers for an effort to increase the albedo of buildings. Some building managers and landlords may be most concerned with costs and savings, comfort, and trustworthiness of the implementing group (Vine et al, 1987). In addition, interest in energy efficiency or concern for the environment may be a factor in forming the opinions of some individuals. A residential customer deciding whether to increase a home's albedo, may be most concerned with appearance and the thermal comfort that might be provided by a high-albedo exterior.

Extensive market research on consumers make decisions related to energy efficiency indicate that residential consumers may be separated into distinct groups, based on their values and concerns, as shown in **Table 12** (U.S. Congress,1992). Programs to promote high-albedo surfaces should have targeted to each of these groups.

While energy efficiency can be a successful promotional device for the resource conservers and value seekers, it is clearly important to emphasize the thermal comfort that will be provided by changing a building's exterior, since over 20% of the residential consumers studied were interested in comfort and convenience. For these homeowners, the monthly energy savings they might expect from choosing white over a darker color may seem very insignificant in comparison to the large investment that's being made to repaint or reroof. Thermal comfort will instead be a major factor in choosing a roof that will satisfy them for 20 or 30 years. Some consumers, especially low-income homeowners, may be concerned that energy efficiency and cost savings can only be achieved with reduced thermal comfort (Vine et al, 1987). Educational programs should stress that energy savings from high-albedo surfaces do not imply a loss of thermal comfort. In fact, many individuals prefer a room that is cool without the use of air conditioning.

TABLE 12†. MARKET SEGMENTATION OF RESIDENTIAL ENERGY USERS

Type	Description	Percent of market
Pleasure seekers	Interested in comfort convenience, and personal control	21.5
Appearance conscious	Most concerned with appearance	18.4
Lifestyle simplifiers	Less concerned with comfort; pursue simplicity, often rent or low income.	16.9
Resource conservers	Concerned with environment, will pursue conservation for its own sake	16.7
Hassle avoiders	Minimize hassle (time and effort) in making energy-related purchases, less concerned with cost	13.4
Value seekers	Most concerned with value, will invest time and effort in making decisions	13.1

†*Source*: National Analysts, et al, 1989.

Appearance is likely to be a major consideration for a number of homeowners or building managers contemplating exterior modification of their building. With the exception of a flat roof that is not visible from the street most white surfaces will raise concerns about glare and aesthetics.

Probably the best way to alleviate concern about glare is through visual demonstration, with actual demonstration homes, videos, or photographs. Consumers who worry about glare, are not usually thinking about themselves but about the effect on others, especially their neighbors. Promotional programs might want to emphasize how everyone benefits from the indirect effect of high-albedo roofs, lowering urban air temperature and making the neighborhood more comfortable. They can also point out that many Mediterranean and Mid-Eastern cities have mostly white surfaces, and we know of no reports of residents in these cities complaining about glare.

Glare from high-albedo roads may be a more significant problem than glare from walls. It is probable, however, that the albedos of the materials that are under consideration for streets are not high enough to create glare problems during the day. At night, white roads may have advantages, actually increasing safety by increasing road visibility and by reducing expenses for street lighting.

The aesthetics of high-albedo roofing materials is an issue that should also be mentioned. Some consumers have a preference for the traditional dark roof that provides a contrast to a colored wall surface. In fact, some homeowners associations do not allow white roofs within their boundaries, because of their somewhat unconventional appearance. Aesthetical concerns are often based on conventions, which may be different in different locations and depending on the individuals in the community. For example, in Louisiana, black roofs may be more popular than white roofs, while in Florida the opposite may be true. Conventions may also be dependent on other factors, such as the availability of materials. White roofs may be unpopular in one area because of a fungus that tends to grow on the shingles during humid weather, making the roof look dirty, while in another location people might use fungus-resistant asphalt shingles. Fungus-resistant shingles and coatings can reduce the association of unattractiveness with white roofs. Also, maintenance programs to clean soiled roofs may increase their acceptability. Promoting the value of high-albedo surfaces for energy efficiency and the value of energy savings for environmental quality may also affect peoples' beliefs about what is aesthetically beautiful. Pictures of attractive buildings that have white roofs, such as the Claremont Hotel shown in **Figure 5**, may also be useful in encouraging consumers who are unsure about the aesthetics of white roofs. Perhaps the most effective tool, however, would be a computer program that graphically depicts the appearance of a homeowner's house with a high-albedo roof.

Once there is a demand for high-albedo materials, manufacturers will likely sell high-albedo materials with no glare or high-albedo materials available in a variety of colors, which will be more attractive to the appearance conscious. Over 50% of solar radiation is not visible to the human eye. It is possible to create paints that are highly reflective in these regions but not reflective enough in the visible region to create unpleasant glare. These "solar reflective coatings" may be offered to consumers who are still apprehensive about glare. Similarly, tinted solar reflective coatings may be used by consumers who don't want a white roof or white building exterior for aesthetic reasons. These paints will probably have a lower albedo than a white paint but a higher albedo than other standard colored paints.

Lifestyle simplifiers may be difficult to reach with a high-albedo promotional program. Since this group often rents, it may be most effective to target their landlords with an incentive program. A utility might also offer reroofing assistance for low-income homeowners.

With the recent attention on the environment in the media and the threat of global climate change, some consumers will be encouraged to pick a white roof because of the air emissions that won't be released as a result of the energy that's saved. Indeed, the success of a number of "green" businesses has shown that resource conservers are willing to pay more for environmental products. Resource conservers would respond to an explanation of the significance of urban heat island effects for energy use and peak demand for power, and the links between power generation and the environment. Since this group is often already interested in energy efficiency, it may be worthwile to include information with other energy-efficient devices, such as compact flourescent lamps. It is also simple to reach resource conservers through environmental publications.

Hassle avoiders are a difficult group to reach, since reroofing and painting are typically hassles. The best approach is to try to reach those that need to reroof or repaint. One benefit of high-albedo materials that would be attractive to hassle avoiders is their long lifetime. A utility seeking to reach hassle avoiders might mention the problems caused by not attending to an aging roof and offer to choose a qualified contractor and quality roofing system for a homeowner.

Only about 13 percent of residential consumers are likely to be concerned about the monetary savings of a high-albedo roof, but those who are should be easily persuaded to choose a white roof. Assuming a consumer is already planning to repaint or reroof a building, choosing a white color does not usually increase the monetary cost of the work. It does, however, decrease the amount of money the consumer will spend on air-conditioning electricity use. In climate zones dominated by high cooling loads, cooling electricity savings should greatly outweigh any increase in heating costs. Even in areas that have cold winters, the impact of high albedo in winter is minimal due to reduced sunshine, rain, high winds, snow cover, and other variables. In a study of the effects of implementing energy measures, Rohm and Haas Company, a manufacturer of elastomeric roof coatings, found that a standard elastomeric coating over a built-up roof in Mississippi actually showed slight savings during the winter months. The average savings were 22% in the summer and 4% in the winter (Boutwell, Jr, et al, 1986). Promotional efforts should alleviate the consumer's fear that a white roof will significantly increase heating bills.

Some consumers may be interested in the magnitude of savings they can expect from changing the albedo of their building. Because vague information is typically inadequate for choosing a roofing system, programs should be as adaptable and as specific as possible. Unfortunately, providing the consumer with a specific estimate of savings is extremely difficult because of the number of variables involved, including the building's insulation (R-value), weather, occupant behavior, surface to volume ratio, location of the ducts within the building and building orientation. The utility might use a computer model, with inputs of R-value, dimensions, and color of the exterior of the house, to predict the expected savings based on the previous year's local weather data for customers that are interested, free of charge. Although uncertainties still exist, the consumer will be better prepared to make an investment decision, while the utility is likely to feel more comfortable with such an estimate than with a quote based on energy savings in a different situation.

For a consumer to follow the advice of a utility promoting a high-albedo modification, the utility has to be trusted. Often, however, consumers are suspicious about the seemingly contradictory objectives of a utility that promotes energy efficiency, since it makes money by selling energy. In order to alleviate suspicions about energy efficiency programs, it is helpful to use educational programs that not only promote high-albedo surfaces, but also explain the interest of the implementing authority in encouraging them. Offering guaranteed savings or lower utility rates to assure the consumer of an actual savings has the secondary consequence of reinforcing the trustworthiness of the utility (Vine et al, 1987).

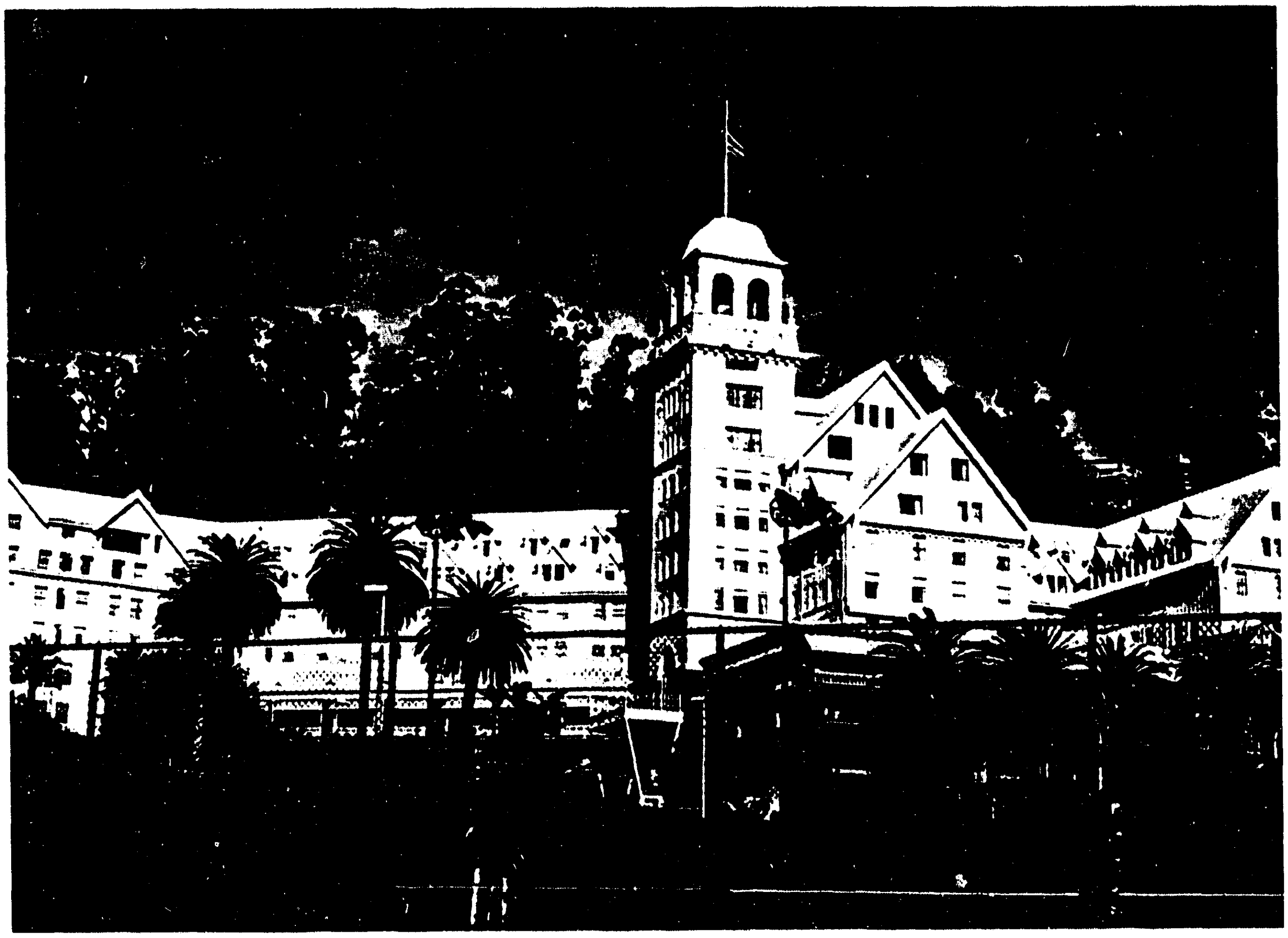

Figure 5. Claremont Hotel in Berkeley, California. An example of a beautiful building that has a white roof.

Building and Roofing Contractors' Perspectives

In general, the building industry is conservative and tradition-oriented (Vine et.al, 1987). Similarly, roofing contractors have a traditional practice constructing roofs that serve their purpose and promise customer satisfaction. Any innovation in the roofing or building industry is problematic and likely to be resisted.

Two criteria may determine the success of a program to promote high-albedo building surfaces. First, builders are often opposed to what they feel is an infringement on their rights to build as they chose. For this reason, mandatory programs are often resisted by builders, and should be avoided. Instead, efforts should be made to insure builders' cooperation in the program. Second, builders are concerned with the return on their investments, and therefore the effect of high-albedo surfaces on the marketability of the building or the workmanship (Vine et al, 1987). In most cases, high-albedo modifications will not require additional investment by a builder, but the consumer demand for the high-albedo home may be affected. For work that is done on the existing home, the roofing contractor will have to be confident in the materials and that the consumer will be satisfied.

Building and roofing contractors typically do not have a scientific background and do not share the energy efficient ideology embraced by those who may be promoting high-albedo surfaces. Many builders are likely to see any intervention in the building market by an outside party, whether utility or government agency, as an infringement on their rights. The introduction of a new practice threatens their sense of personal choice, sense of control and professionalism. If the innovation is successful they may fear the future of the industry becoming dependent on outside "experts" (Vine et al, 1987).

Resistance by building and roofing contractors to outside interference sheds light on the question of whether high-albedo surfaces should be voluntary or mandatory. Vine and others (1987) found that for HERS, whether the program was mandatory or voluntary, it would require builder cooperation, and most HERS authorities believe that the situation is better all around if the HERS remains voluntary. The same may be true for high-albedo surfaces, although there are some differences between the two programs. White surfaces do not require the builder to learn any new skills nor supply additional work, and so may encounter less resistance. On the other hand, this may make a well-marketed volunteer program all the more successful.

Vine and others (1987) found that the best approach to gaining builder cooperation was to use specifically targeted educational programs to convince builders that the utility had a legitimate reason for seeking to promote energy efficiency. Toward this end, the role of high-albedo surfaces in the utilities load management program and what that would mean in terms of decreasing the need for additional generating plant equipment would be explained to the builders and roofers. In contrast, educational programs explaining the general benefits of high-albedo roofs to all parties and stressing the social responsibility of the roofer or builder in providing energy-efficient buildings would probably not be successful. As described by Vine and others

(1987), builders feel as socially responsible as anyone else, but this type of program was not an effective behavior modifier and did not alleviate their fears over intrusion and coercion.

Because of their reservations, builders did not want to participate in a HERS unless it was economically attractive to them. There were, however, "building innovators" who formed a "critical nexus for change within the industry." Once these innovators had been convinced to build at higher energy efficiency levels, they had a competitive edge and other builders were forced to cooperate with HERS. In some programs, these builders were supported by extensive promotional effort on behalf of the utility companies (Vine et.al, 1987). In a similar manner, innovative roofing contractors may prove helpful in demonstrating high-albedo roofs to other roofers and to consumers. Other methods of appeasing builders that were used by utilities in promoting HERS included involving builders in the developmental stages of the program, free equipment sizing and design of air distribution systems and demonstration programs. Promotional programs should seek the support of trade associations, such as the National Roofing Contractors Association and the National Association of Home Builders, a group that has supported energy efficient building in the past.

A program should be supportive of builders and roofers, in their best interest, and of general benefit to the industry. The utility might offer support through cooperative advertising (paying a portion of the advertising costs for builders that promote high-albedo surfaces), and independent promotion of builders and roofers that are willing to cooperate.

Roofing contractors and builders, seeking a reasonable rate of return on their work, are sensitive to anything that affects the marketing of their product. Although the costs of high-albedo surfaces to the builder are typically zero and costs to the consumer are usually negative, the implementing agency will nevertheless need to stimulate consumer demand. If they are successful at increasing demand, high-albedo surfaces will be attractive to builders and roofers because they can help increase their profitability. This is especially true during an economic recession, when any marketing edge, such as "increased thermal comfort," is likely to be advantageous to the contractor.

Manufacturers and the Paving Industry

The perspectives of roofing material manufacturers and of the paving industry will be similar to that of the roofing contractor or builder. Many of the representatives of these industries will not appreciate outside intervention by a utility or government agency. Since they sell products that work and that may be warranted for a number of years, they will be extremely reluctant to experiment with new products. In many cases, high-albedo products will not be produced until there is a requirement or a demand for such products. Asphalt shingles, for example, can be made more reflective for a small cost increase, by increasing the amount of coating on the mineral granules that are on the surface of the shingle. Nevertheless, asphalt shingle manufacturers will not absorb the small cost increase unless they perceive a consumer demand for reflective shingles.

The Utility's Perspective

For some utilities, the promotion of high-albedo surfaces will further three organizational goals: profit, public good-will, and professionalism. A utility is concerned with profit to insure optimized returns to the shareholders, while public good-will legitimizes the utility's efforts in earning optimized profits and in supplying their service. A utility company is often concerned with professionalism, for public relations, to maintain its standing among other utility companies, and to satisfy the needs of its employees (Vine et.al, 1987).

Utilities have a large profit motive in promoting high-albedo surfaces, since the energy savings will make it easier for them to meet peak demand, reducing the need for new generating facilities. High-albedo surfaces are ideal for demand-side management because the energy savings are greatest at the time of peak demand, when they are most useful. Lowering demand will also reduce transmission and distribution losses for the utility. Some utilities are allowed by regulators to retain a portion of the savings achieved through energy efficiency investments and can increase profits with programs to encourage high-albedo surfaces. We estimate that savings from heat island mitigation strategies of $1 billion could be realized through utility-sponsored demand-side management (DSM) programs that promote high-albedo surfaces and shade trees. Assuming the utilities are permitted to retain 10% of program savings, they could earn about $100 million/year.

Another finding of the HERS study revealed that consumers appreciated the utility's efforts to reduce their energy consumption. In fact, HERS contributed to a feeling that the utility was caring, and concerned about the welfare of its customers. While public relations was not cited as a reason for starting HERS, once a program had been implemented it was often presented as the main reason why utility companies continued to support and expand existing HERS programs (Vine et al, 1987). A high-albedo surfaces promotional program could similarly improve a utility's public relations.

A program promoting high-albedo surfaces enhances a utility company's reputation by improving public relations through reducing customer energy bills and emissions of air pollutants and, in California, by acting in line with the request of the California Energy Commission (CEC). The CEC has asked California utilities to provide a significant portion of service through demand-side management programs, and to consider air quality in their investment decisions. Individuals gain status by working for a company with a good reputation and it contributes to their sense of well-being and self-esteem. The company also benefits from its professional reputation, by convincing its customers, employees and governmental regulatory agencies of its competency and efficiency (Vine et al, 1987).

State and Local Governments' Perspectives

State and local governments should promote high-albedo surfaces because of their interest in regional energy management and in controlling the amount of energy flowing into the state from outside its boundaries. The availability and price of energy is politically important because it affects the consumer directly. Indirectly, providing reliable and inexpensive energy may be important for the local economy and for attracting industry to the region. A state will be concerned with energy purchased from other states because such transactions represent a flow of money outside the states boundaries. Governments are also concerned with the need for new generating facilities within the state because of environmental problems and the effect on air quality (Vine et. al, 1987). For all of these reasons, the government will want to limit the growth of peak demand, and high-albedo surfaces are one way to achieve this goal.

A local or state government faced with the task of increasing urban albedo will have to choose between voluntary and mandatory measures, or some combination of both. Experience has shown that for builders, voluntary programs were more effective for promoting HERS for a number of reasons, some of which may be applied to an albedo program. In the HERS case, participating builders were required to invest money and learn new skills and were therefore likely to feel unfairly singled out by mandatory measures. In addition, the mandatory programs placed increased burden on the local governments' building inspectors in permit processing, inspections, and enforcement. A high-albedo measure would not generate as much government work as a HERS. The situation is also different for a high-albedo requirement because less is being asked of a builder, but it is nevertheless likely that a mandatory measure will be seen as unfair interference in their business. An albedo standard for roofing materials, coatings, and pavements is probably a more effective way to increase urban albedo.

Governmental Action

A first step that may hasten the adoption of high-albedo surfaces is distribution of a U.S. Environmental Protection Agency (EPA) guidebook on cooling communities with trees and high-albedo surfaces, aimed at city officials (Akbari et al, 1992). More data on the direct and indirect effects of albedo modification should be provided to city officials when it becomes available.

Since the albedo and emissivity of materials on the outside of a building can have such a large impact on the structure's energy consumption, this information should be readily available to the consumer. In particular, paints and roof surfaces should be labeled according to their expected performance. In areas that have high cooling requirements, the label should graphically indicate the likely surface temperature of the material under a noon day sun, compared to a black and a white surface. The rating would clearly have to reflect the performance of the product after several years of outdoor exposure, since there may be a number of products that have desirable optical properties but are not durable. Labels would be required by state government to encourage roofing product manufacturers to increase the albedo of their products. For example, asphalt shingle manufacturers are reluctant to improve their products unless they are motivated by a demand for high-albedo shingles. Such a rating system will not only aid people in choosing paints, but will also create a means of determining if an appropriate material has been used for incentive programs.

Minimum albedo standards for roofing and building products could be promoted with a reward for manufacturers that exceed the standard by a certain percentage. Products might be designated as as high-albedo, medium-albedo and low-albedo, giving the consumer a choice of colors. The products would be self-certified by the manufacturer according to standard testing procedure or tested for no charge by an independent agency. This agency would also perform random tests of the self-certified products to insure compliance. Those companies that exceed the standards would be commended and their performance publicized in trade magazines. Those that did not meet the standard or were caught using false certification would be similarly discredited (Klein, 1992).

Efforts to increase urban albedos would be aided by incorporating the energy use of a building into its market value. This would encourage high-albedo surfaces, since these surfaces would save energy and increase the value of the home. A statewide or nationwide home energy rating system (HERS) that is well marketed might accomplish this goal.

The cost of heating and cooling a building throughout it's lifetime adds to the total cost of constructing that building. For this reason and because of the heat island problem, it is critical that energy use and albedo be considered at the time a building is constructed. In California, Title-24 energy codes require that new construction meets specific energy standards, including some mandatory measures such as a certain minimum resistance value for the ceiling. Presently, methods of compliance include following a prescriptive package in designing the building, using a point system or computer simulation to evaluate the performance of the building. Albedo modification could be incorporated into the energy codes for the climate zones that have high cooling-energy requirements in the following ways: (1) a minimum albedo could be included as a measure in one or more of the prescriptive packages; (2) points could be given for high-albedo surface area in the point system; (3) the accepted computer simulation programs (such as CALRES) could be modified to include albedo values, or new programs could be devised; or (4) a minimum albedo could be one of the mandatory measures, although we note that this is not a preferred option because of the resistance that would be encountered. Legislation similar to Title 24 could be adopted in other states with provisions for increasing the albedo of new buildings. As mentioned earlier, older buildings should not be neglected in an albedo program because the direct energy savings are greatest for buildings with less insulation. High-albedo roofs for older buildings could be promoted through tax credits or promotional information. Alternatively, a minimum albedo standard for roofing products and coatings would insure that any building that is reroofed will also contribute to increasing urban albedo.

Efforts to promote high-albedo road surfaces should be aimed at public works departments and paving contractors. It may be effective to suggest that public works departments reconsider the relative benefits of concrete "whitetopping" over asphalt surface treatments. Legislation might be drafted that requires all new roads to meet a certain albedo standard, if such a standard is supported by public works departments and paving contractors. The albedo standard could be included in the specifications for streets. Specifications requiring white-pigmented curing compounds with a minimum reflectance value of 70 percent relative to magnesium oxide were adopted in Michigan in 1949, in an attempt to minimize temperature cracking in concrete pavements; these might be used as a model for an albedo standard (Rhodes, 1950).

Utility Programs

A governmental effort to label roof products and coatings should be accompanied by utility-sponsored promotion of the benefits of high-albedo surfaces, to stimulate consumer demand. Methods of promoting high-albedo surfaces include newspaper and magazine articles and special interest columns in real-estate supplements or home magazines (Vine et. al, 1987). These articals and special interest columns could be targeted according to the market segmentation of residential energy users, as shown in Table 13. Brochures on energy saving options might be included along with monthly power bills in the summer. Such publications could include information on the energy savings of albedo modification, benefits of high-albedo surfaces, and specific information about what would be involved in changing a building's albedo and who to contact. Another way to reach consumers would be to include information along with other energy saving equipment, such as fluorescent light bulbs and low-flow showerheads. Information could be included with these items as purchased, thereby reaching customers who are most receptive to energy saving ideas, or with complimentary equipment. Studies have shown that if a customer installs a free low-flow showerhead, the customer is likely to follow this action with other steps to conserve energy. There is a certain inertia to behavior that prevents people from taking action to save energy; once this is overcome, energy efficiency is likely to become a conscious goal and will be spread through natural channels of communication among neighbors, family, and friends.

It may be effective for utilities to design some educational programs to reach specific audiences. As an example, Pacific Gas and Electric's Pacific Energy Center in San Francisco serves as a resource for designers, developers, and homeowners to learn about energy efficiency in buildings. The Center includes a partial model of a house, pointing out the various energy-saving possibilities that have been included. Such visual displays could be very effective in promoting high-albedo surfaces for cooling energy savings to building designers. Similarly, visual displays could inform homeowners of the energy savings and additional benefits of increasing the albedo of their homes' exteriors.

Roofing contractors are an important audience for the utility, but efforts to reach them should be non-intrusive and sensitive to their perspective. Most contractors are only concerned with solar gain when installing roofs on large commercial buildings. In these cases they typically use an aluminum paint or coating to reduce solar gain. Such contractors may be unaware that a white paint is actually more reflective than aluminum and stays cooler because it has a higher emissivity (they may prefer aluminum paints because of proven durability).

Labelling of roof materials and paints can educate roofing contractors in a non-intrusive manner. Promoting the labels and attempting to raise the value of white roofs by explaining their benefits may be necessary. Roofers may discourage an energy-conscious customer from a white roof, because of concerns about appearance and the effects of soiling. Since white roofs are less conventional and more easily soiled, a contractor may think it is more likely to end up with a dissatisfied customer installing a white roof than if a dark roof is installed.

Along with informational programs, utilities sometimes offer incentives to promote energy efficiency. For immediate results, utilities could offer rebates to customers that choose to increase the albedo of their roof and reduced hook-up fees to new developments with high-albedo surfaces. One drawback to monetary incentives, however, is that they may not have a long-term effect on energy consumption. The consumer makes the energy-efficient choice to obtain the rebate, and does not learn the value of energy-conscious behavior. Also, the monetary incentives are not likely to persuade most residential consumers, since only about 13% appear to be value seekers. For these reasons, utilities may want to emphasize well-planned promotional and educational efforts over monetary incentives for the consumer.

Promoting high-albedo pavement requires consultation with public works departments in local governments. If utilities were to share some of the costs of high-albedo overlays for damaged pavements, residents would benefit from energy savings, cooler temperatures, and often under-funded street improvements. In addition, the utilities would be allowed to retain a percentage of the energy savings as profit.

Initial Focus for Increasing Albedo

We use information from computer simulation and from the roofing market to predict which surfaces may produce the greatest energy savings by an increase in albedo. Computer simulations have shown that direct energy savings resulting from albedo modification are much larger for a poorly-insulated home than those for a well-insulated home (Martien et al, 1989) and that direct energy savings will decrease with the size of the building (number of stories) in relation to the roof size. The first finding displays the importance of albedo modification for existing, old buildings, while the second shows its importance for small buildings. Hence, older residential buildings may represent a large potential for direct energy savings. Older residential buildings are also most likely candidates for weatherization, so that high-albedo reroofing should be combined with retrofits to add insulation. The City of Mesa, Arizona, included an albedo increase as part of a major retrofit of four buildings. By performing a number of energy improvements at the same time, they included a project which was not highly cost-effective but still energy efficient (Anon., 1992).

For indirect energy savings, we are interested in changing the albedo of large areas. **Table 13** lists estimates of the percentages of various roof types by area in California, which we have estimated together account for 28% of the area of Sacramento (Table 1). The data suggest that efforts should be aimed at asphalt shingle, modified bitumen and built-up roofs, since these occupy over 80% of the area of new roof cover. For residential roofing, modified bitumen and asphalt shingle have the largest influence on community albedo, while built-up roofing and modified bitumen are most prevalent in commercial areas.

Using white asphalt shingles in place of dark will moderately increase albedo without additional cost or a change in roof design. For a high albedo, other white roofing tiles may be used, or the shingles may be covered with a white coating. Modified bitumen and built-up roofing are easily lightened by choosing a high-albedo surfacing. Mineral granules, aggregates, and coatings are all available in white at no additional cost. Another option for replacing a built-up roof is to remove any gravel and cover it with a single-ply roof membrane, such as Ethylene Propylene Diene Monomer (EPDM). EPDMs are highly elastic, but tough, membranes that are relatively inexpensive and are available in white.

Small commercial buildings may be the best candidates for albedo modifications. One reason to focus on small buildings is that the energy savings are greatest for buildings with a large surface-to-volume ratio. Another reason is that residential consumers tend to be more concerned with appearance and more likely to be dissatisfied than building managers, who are not investing their own money. Homes do, however, represent over 50% of the total surface area of new roofs, and are also good candidates for albedo modifications.

Areas for Further Research

We identify a number of areas for further research, as follows:

- A large-scale experiment to monitor the indirect effects of albedo modification on air temperature is needed to convince regulators of the value of high-albedo surfaces. LBL is seeking innovative developers to build one half of a large development conventionally and one half with high-albedo roofs and roads. Researchers will then measure the reduction in air temperature and the energy savings.
- Albedo and emissivity of various products need to be quantified to produce data for a labeling program. Researchers at LBL and at the Florida Solar Energy Center are gathering some data, but much work remains to be done.

TABLE 13†. ESTIMATED AREA OF ROOF TYPES IN CALIFORNIA

Rough estimates, based on data on California's roofing market from National Roofing Contractor's Association and estimates of cost/area from R. S. Means (1990).

Commercial		Residential	
Type	%	Type	%
Built-up roofing	25	Modified bitumen	22
Modified bitumen	7	Fiberglass asphalt shingle	16
Asphalt shingles	4	Built-up roofing	6
EPDM	4	Wood shingles/shakes	2
PVC	2	Organic asphalt shingle	2
Metal	2	Metal	3
Tile	1	Cement tiles	1
Polyurethane foam	1	Single ply	1
Hypalon	<1	Clay tiles	<1
Other single-plies	<1	Slate	<1
Liquid-applied	<1	--	--
Total	47	Total	53

† Numbers may not add due to rounding.

- Computer modeling efforts may determine the optimal optical properties for exterior building surfaces for different climate zones in order to maximize energy savings in any given area.
- Data collection on the effects of weathering and soiling on the albedo of paints, roofing materials and pavements are needed.
- Data on the effect of color on lifetimes of outdoor materials would be useful for making accurate life-cycle cost estimates.
- The effect of heat island reduction on urban air quality should be established. This research should be based on actual measurements of the indirect effects of high-albedo surfaces on air temperature (first item above).
- More research is needed on the social science approach to implementations issues.

Conclusion

Using white surfaces to increase the albedo of a city is a technically simple way to conserve energy, save money and reduce pollution. Costs for increasing urban albedo are low when the changes are made as part of routine painting or resurfacing. Most roof types are available in white for no additional cost, and the same is true for paint; concrete overlays and asphalt pavements with white aggregate or a surface layer of white chippings may produce white pavement. High-albedo materials may have even lower annualized costs than the conventional dark surfaces.

Estimates of the area of new roofs in California and information from computer simulations suggest that small buildings should be the first target of an energy efficiency strategy to increase albedo. Older buildings will produce greater direct energy savings than newer buildings, since new buildings have more insulation. For residential buildings, asphalt shingle and modified bitumen roofing predominates, while for commercial buildings the most important roof types are built-up roofing and modified bitumen. Utility programs to promote high-albedo surfaces should be designed to focus on these roof types and on pavement. Legislation may help by setting albedo standards and requiring roof material and shingle labeling. Paint and shingle labeling are invaluable for informing consumers and increasing the demand for high-albedo products; advertisements, visual displays, and information packets are also needed. Specifications for minimum albedo for pavements and utility cost-sharing of high-albedo pavement will increase urban albedo and encourage developments in high-albedo paving technologies.

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APPENDIX : Light-colored Materials for Urban Heat Island Mitigation

Information that we were able to collect on white and light-colored materials for urban heat island mitigation are supplied on the following pages. Please note that the products listed are only those we were able to identify, and that we are not in the position of recommending products. Rough estimates are given for costs and service life and will vary depending on the application and the quality of installation. Cost estimates include bare materials, labor and equipment costs and a subcontractor's overhead and profit. Information was obtained through discussions with contractors and manufacturers and taken directly from product publications provided by the following companies: The Asphalt Institute, G.S. Roofing Products, National Coatings Corporation, MCI Quality Coatings, Helios Energy Products, Firestone Building Products, LifeTile Sales, Lehigh White Cement Company, Southwestern Paint, Kool Seal Inc., Davlin Coatings, Advanced Materials, Triangle Coatings, Thermo Materials, APOC, International Slurry Seal Association and Transmet Corporation. Other sources for the information that follows include:

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1991 Sweet's Catalog File, Vol 3: Products for Engineering and Retrofit: Mechanical, Electrical, Civil and Related Products Mc-Graw Hill Information Systems Company, New York, 1990.

Product:	**Reflective roof coatings and paints**
Description:	Flexible liquid coatings designed to protect asphalt components, to be tough and flexible in the winter cold and reflect solar radiation. Some will resist ponded water and chemicals in the industrial environment.
Specification:	May be applied to a variety of roof surfaces including modified bitumens, emulsion, cap-sheets, ply sheets, metal and more. Roof must be free of dirt and foreign matter. Rusted and new metal surfaces must be primed with a coating of asphalt emulsion and allowed to cure. Curing time for roof coatings is generally about 24 hours. Standard color is usually white, which provides the most reflectance.
Albedo:	White coatings have a high albedo of 0.7-0.9 when new and 0.6-0.7 after some weathering. Some are resistant to dirt pick-up.
Installation:	Brushed, rolled or sprayed on to the roof surface. Most may be applied with a minimum of training and supervision and without special equipment.
Availability:	There are a number of products available from contractors and manufacturers, including those listed in the cost section.
Service Range:	3-5 years (sometimes more, depending on the product).
Customer Benefits:	• May be used to improve an old roof. • May be applied by homeowner. • High albedo.
Cost:	Costs below are materials cost only, for a minimum coverage of 100 ft^2. Greater coverage may provide longer lifetime. When coverage was not specified by the supplier, we assumed 1.5 gallons for 100 ft^2 coverage. Product choice should not be made on cost alone, however, because there are significant variations in quality. For example, Enerchron has a high initial cost but is more resistant to soiling and may last longer than an elastomeric coating.

• **Astec 100 Ceramic Coating**, available through Insulating Coatings Corporation, Northern U.S. 1-800-223-8494, Southern U.S. 1-800-345-5306. A ceramic coating, with high-reflectivity in the non-visible part of the solar spectrum and high emissivity. ICC is the only Coatings Manufacturer licensed in the State of California as an Insulation Manufacturer.

• **Bulldog Topflex White Elastomeric-Emulsion Roof Coating**, made by Palmer Asphalt Company, (201) 339-0855.

• **Ceramicoat**, available from Jay Capers, Ltd., 1-800-736-7153. A borosilicate coating, with high-reflectivity in the non-visible part of the solar spectrum.

• **Enerchron**, available from Helios Energy Products, (916)332-5424 \$60/100 ft^2 (with labor \$108-\$150). Use on walls and roofs. Highly reflective of non-visible solar radiation. No primer needed. Low volatile organic content (important if applied on asphalt), waterproof and insulating. More durable than a typical elastomeric coating.

• **Firecade 2000**, available from Davlin Coatings (415)848-2863 \$26/100 ft^2. Fire resistant and reflective top coat. Not intended for waterproofing. Lab measurements of initial albedo indicate 88% albedo

• **Guardcote**, available from Advanced Materials, 1-800-822-8881 \$35 to \$52/100 ft^2 (price to contractor). Chemical resistant.

• **High Reflectance**, available from Triangle Coatings (510)895-8000 \$78/100 ft^2. Highly reflective in non-visible solar spectrum. May be tinted to produce desired color that has an albedo close to a normal white paint. While it has been used on roofs, it is sold as a specialty coating for parabolic dish recievers. The cost may decrease with a wider market for the product.

• **Insultec**, contact John Earle Loog at (619) 322-0084.

• **Kool-Kote Elastomeric Roof Coating**, available from Southwestern Paint & Varnish Company, (602) 795-0545. ~\$30/100 ft^2. Flexible coating that seals and waterproofs.

• **Kool Seal White Acrylic Roof Coating**, available from Kool Seal, Inc. 1-800-321-0572. ~ \$33/100 ft^2.

• **Premium Elastomeric White Roof Coating**, available from Henry Co. (213) 583-5000.

• **Solar Shield**, available from Thermo Materials, \$34/100 ft^2

• **Somay Products, Inc.**, make a number of white elastomeric and acrylic roof coatings. (305) 633-6333.

• **Sunwhite** (#252), available from APOC, (510) 548-4887. Cost for two coats: \$30/100 ft^2. Resists ponded water and chemicals.

Sources: 1991 Sweet's Catalog File, Vol. 3, 1990; Product information from manufacturers listed above.

Product:	**White portland cement**
Description:	A portland cement, with a lower iron oxide content than standard gray Portland cement.
Specification:	May be used in place of, or blended with gray cement for architectural precast concrete products, cast-in-place architectural concrete, architectural concrete masonry units, and white portland cement stucco.
Albedo:	White cement products have very high albedos.
Installation:	Same installation process as standard concrete.
Availability:	Available from Lehigh White Cement Company, 1980 Atlanta Avenue, Riverside, California 92507, (714)683-7796, 1-800-368-7557.
Service Range:	Data not available, but at least as long as standard Portland Cement products.
Customer Benefits	• Distinctive design possibilities. • Versatility.
Cost:	2-3 times the cost of gray Portland Cement.

Product: **Asphalt pavement with white aggregates and/or white top-coat.**

Description: Light-colored aggregates, such as granite or limestone, may be used in the upper layer of new asphalt pavements. A top-coat of chippings, sand, oyster shells could be used as surfacing.

Specification: For resurfacing or paving.

Albedo: Without a top-coat, pavement will be initially dark, with an estimated albedo of 0.05-0.1. The albedo will increase after some weathering and road wear exposes the white aggregates. We estimate a weathered albedo of 0.3-0.4. A top-coat of white chippings, sand, or oyster shells added during installation could produce a high albedo.

Installation: Aggregate and asphalt are heated and blended together in the appropriate proportions at a hot-mix plant. The mixture is then hauled to the site and spread on the prepared road-bed. Rollers are used to compress the mixture and achieve a specified density.

Availability: Trucking will be necessary if white aggregates are not locally available, and this will increase the cost.

Service Range: An average service life for dark asphalt pavement is 15 years, and an overlay may last 5 to 10 years. We have no information about the weathering of light-aggregate asphalt relative to dark asphalt. Since light-colored pavement will experience less thermal expansion and contraction caused by solar heat gain, it may last longer than dark pavement.

Customer Benefits:

- Asphalt may be easier to remove than concrete when underground service distribution lines need to be accessed.
- Asphalt has a relatively short setting time and may have a lower *initial* cost than concrete pavement.
- Light-colored pavement is more visible than dark pavement, and may reduce both accidents and street lighting expenses.

Cost: Costs include overhead and profit of the subcontractor. Cost of white aggregate below is a rough estimate based on multiplying materials cost by 1.5 to reflect the possibility that white aggregate may not be locally available.

Cost:	Surfacing roadway or large area using standard aggregate	$0.93/yd^2$
	Surfacing roadway or large area using white aggregate	$1.24/yd^2$
	Paving roadway or large area, wearing course, 1" thick	
	using dark aggregate	$2.15/yd^2$
	using white aggregate	$3.03/yd^2$

Sources: "Asphalt vs. Concrete," *American City and County*, July, 1986, p. 31; R.S. Means Company, *Means Building Construction Cost Data 1991*, Construction Consulting and Publishing, Kingston, MA, 1990.

Product: **Concrete pavement (whitetopping)**

Description: Whitetopping is a method of repaving worn asphalt city streets using concrete. Concrete may also be used also used for new pavements.

Specification: For city street paving, repaving, and surfacing.

Albedo: We estimate the albedo of standard concrete pavement at ~ 0.35-0.40 at installation and ~ 0.25-0.30 after aging. White aggregate could increase the albedo of weathered pavement, while application of a white-pigmented curing agent should increase initial albedo to ~ 0.7-0.8. Similarly, white cement concrete should have an albedo this high but is considerably more expensive than standard concrete.

Installation: Surface preparation may include sweeping and filling potholes with gravel. Concrete is placed from a ready-mix truck and followed by a paver to create a 3.5" layer. A white-pigmented curing compound may be sprayed on at the specified rate of one gallon per 200 square feet. The area may be opened to traffic in about 3 days.

Availability: Concrete is available from most paving contractors. White cement is available from Lehigh Cement Company, 1980 Atlanta Avenue, Riverside, California 92507, (714) 683-7796, 1-800-368-7557 and from Riverside Cement Company, (714) 861-6028, 1-800-442-4910 (CA only).

Service Range: 25 years is average. The pavement will last longer if the road is properly designed and the concrete is properly prepared.

Customer Benefits:
- Long-term cost comparable to or lower than that of asphalt pavement.
- Widely available.
- Low maintenance costs.
- Light-colored pavement is more visible than dark pavement, and may reduce both accidents and street lighting expense.

Cost: We do not have a cost estimate for whitetopping, an overlay that is only 3.5 inches deep. Instead, we give an estimate for a new standard concrete pavement, 6 inches thick, of $\$15/yd^2$. Cost is a rough estimate including labor, materials and equipment and a subcontractor's overhead and profit. The use of white aggregate may increase the pavement cost if it is not locally available.

Sources: "Whitetopping Demonstration Puts Asphalt Under Cover," *Concrete Construction*, August, 1988, p. 785; "Whitetopping an Asphalt Parking Area," *Concrete Construction*, May, 1985, p. 425; R.S. Means Company, 1990.

Product:	**Hot-rolled asphalt pavement with white chippings.**
Description:	It is a dense, gap-graded, sand-based mixture giving a durable, stable, mechanically strong, impervious material which contributes significantly to the strength of road structures. The material is tolerant of composition variations and laying conditions. As a wearing course material, rolled asphalt with about 30% stone content is used and a layer of chippings is applied to the surface.
Specification:	For resurfacing or paving.
Albedo:	We assume pavement color will be close to the color of the chippings, with an estimated albedo of 0.3-0.4.
Installation:	Chippings are rolled onto a hot layer of asphalt so that they are embedded.
Availability:	Trucking will be necessary if white aggregates are not locally available, and this will increase the cost.
Service Range:	We have no information about the service range of hot-rolled asphalt pavement. Hot-rolled asphalt is used in the United Kingdom as the wearing course for the maintenance of all major roads, and is used to a limited extent in Belgium, Spain, and Switzerland.
Customer Benefits:	• Asphalt is easier to remove than concrete when underground service distribution lines need to be accessed. • Applying chippings as a separate application reduces the need for high quality white stone. • Light-colored pavement is more visible than dark pavement, and may reduce both accidents and street lighting expense.
Cost:	We have no cost estimates for hot-rolled asphalt pavement.

Maintenance Techniques for Road Surfacings, Organisation for Economic Co-Operation and Development, Paris, 1978, p.60.

Paving

Product:	**White slurry seal pavement**
Description:	Aggregate, asphalt emulsion and fillers mixed together, used for paving and surface maintainance.
Specification:	For short-term resurfacing and paving.
Albedo:	A light-colored slurry seal could be developed for urban heat island mitigation. Colored slurry seal is made by reformulating the emulsifier. We estimate the albedo of a new white slurry seal might be ~ 0.7-0.8 and after some wear the albedo might be ~ 0.4-0.6.
Installation:	Mixing and spreading are accomplished in one operation, with the surface being reopened to travel within a few hours.
Availability:	Available from some paving contractors.
Service Range:	The service range for standard dark slurry seal surface treatment is 3 to 5 years. A white slurry seal might last longer because it would experience less thermal movement due to solar heat gain.
Customer Benefits:	• Highly cost-effective for some applications. • Swift installation. • Extends life of existing pavement by protecting it from oxidation and deterioration.
Cost:	$3.05/yd^2 for regular slurry seal. Reformulation of the emulsifier to make a white slurry seal might increase the cost by 25% or 50%.

Source: R.S. Means Company, 1990.

Product: **White asphalt roofing shingles**

Description: Small overlapping rectangular units installed on a pitched substrate to shed water.

Specification:
- Minimum slope 2 inches per foot.
- Suitable for new roofing or re-roofing.

Albedo: Initial measurements of a black asphalt shingle show an albedo of 0.05, and we estimate 0.10 to 0.15 for a weathered black shingle. A white asphalt shingle is a slight improvement, with an initial albedo measured at 0.22, and an weathered albedo estimated at 0.15-0.20. For a high albedo (around 0.7) shingles may be painted with an appropriate white coating that has a low volatile organic content. (Volatile organics may leach asphalt from the substrate and cause the paint to yellow). Note that applying the coating will void the warranty offered by the shingle manufacturer.

Installation: Shingles are laid overlapping and nailed to substrate in single or double courses.

Availability: Widely available from roofing contractors. Incentives for white roofs are needed to encourage development of a high-albedo asphalt shingle.

Service Range: Depends on the weight of the shingle, but generally about 20 years. Lifetime increases with the weight of the shingle. A high- albedo roof experiences less thermal expansion and contraction due to solar heat gain, and may last longer than a dark roof.

Customer Benefits: The most economical roofing choice for pitched roofs with slopes of 3.5 inches in 12 inches or more.

Cost: Cost is extremely variable depending on the slope of the roof, roof detail, and the weight of the shingles. Heavier shingles are more durable and cost more.

Standard strip shingles	
Inorganic, class A, 210-235 lb./100 ft^2, 3 bundles/100 ft^2	
for average slope	\$84/100 ft^2
for steep roof	\$110/100 ft^2
Organic, class C, 235-40 lb./100 ft^2, 3 bundles/100 ft^2	
for average slope	\$89/100 ft^2
for steep roof	\$118/100 ft^2
Standard, laminated multi-layered shingles	
Class A, 240-260 lb./100 ft^2, 3 bundles/100 ft^2	
for average slope	\$115/100 ft^2
for steep roof	\$148/100 ft^2

Class C, 260-300 lb./100 ft^2, 4 bundles/100 ft^2	
for average slope	\$115/100 ft^2
for steep roof	\$155/100 ft^2

Sources: *1991 Sweet's Catalog File*, Vol 3, McGraw Hill Information Systems Company, New York, 1990; R.S. Means Company, 1990.

Product: **Liquid-applied single-ply roofing membrane**

Description: Single coat--an elastic substance that will expand or contract with the substrate to which it is applied. Two coats--similar, except that the top coat is built-up of material with weathering characteristics that are superior to the those of the base coat.

Specification:

- Generally applied to flat or gently-sloped roofs.
- Suitable for new roofing, re-roofing, or waterproofing.
- May be applied to a variety of roof surfaces including modified bitumens, emulsion, cap-sheets, ply sheets, metal and more.
- Roof must be free of dirt and foreign matter.
- Rusted and new metal surfaces must be primed with a coating of asphalt emulsion and allowed to cure.
- Curing time for the roofing membrane is generally about 24 hours.
- Standard color is white, which provides the most reflectance.

Albedo: White roofing may have an albedo of 0.80 to 0.90.

Installation: Sprayed, rolled, or brushed on. If two coats are applied, each is a material of different properties. Most may be applied with a minimum of training and supervision and without special equipment.

Availability: Available from most roofing contractors. There are a number of products available, including:

- **Acryshield**, from National Coatings Corporation, 912 Pancho Road, Camarillo, California 93012, (805) 388-7112.
- **MCI Roof Coatings**, distributed by CONSPEC-BENJAMIN, INC, 5510-3 Phillips Highway, Jacksonville, Fla. 32207, (904) 731-3843
- **Enerchron** is distributed by Helios Energy Products, P.O. Box 417218, Sacramento, California 95841. (916)332-5424.

Service range: 5 to 10 years.

Customer Benefits:

- Ideal for re-roofing.
- High albedo.

Cost: Choice of membrane should not be made on cost alone, because there are significant variations in quality. Published data list materials and labor for Neoprene membrane, 1/8 inch thick at $258/100 square feet.

Sources: 1991 Sweet's Catalog File, Vol. 3, 1990; Firestone Roofing Products product information; R.S. Means Company, 1990; Helios Energy Systems.

Product: **Hot-applied built-up roofing membrane with white surfacing**

Description: Continuous roofing membrane of 3 to 5 alternating layers of hot bitumen and felt plies, with a bitumen top coat. Optional mineral aggregate is often used to protect the membrane.

Specification:
- For flat and low sloped roofs.
- Minimum slope of 1 in 48 recommended.
- Maximum slope of 1 in 6, when nailed.
- Appropriate for new roofing, re-roofing or waterproofing.

Albedo: Surfacing could be a white paint (albedo ~ 0.8), white mineral aggregate (albedo ~ 0.5), or a painted (albedo ~ 0.75) or mineral-surfaced (albedo ~ 0.3) cap sheet. A coating is not recommended where ponding water is a possibility. A white acrylic elastomeric mastic is useful as a high-albedo coating.

Installation: Felts are laid in shingle fashion or single course and bonded or spot anchored to the substrate.

Availability: Widely available from roofing contractors.

Service Range: 15 to 20 years A light-colored surfacing will reduce thermal expansion and contraction caused by solar heat gain and may extend the life of the roof.

Customer Benefits:
- Economical and reliable choice for gently-sloped roofs.
- Most roofing contractors have experience with built-up roofing.

Cost:

Asphalt flood coat with gravel/slag surfacing, not including insulation, flashing or wood nailers:	
asphalt base sheet, 4 plies #15 asphalt felt	
mopped	$130/100 ft^2
on nailable decks	$135/100 ft^2
Asphalt flood coat, smooth surface	
4 plies #15 asphalt felt	
mopped	$106/100 ft^2
on nailable decks	$111/100 ft^2
Coal tar pitch with gravel/slag surfacing	
4 plies #15 tarred felt, mopped	$149/100 ft^2

Product:	**Cold-applied built-up roofing membrane with white surfacing.**
Description:	Continuous roofing membrane of 2 or 3 alternating layers of cold bitumen and felt plies. May be surfaced with granules, aggregate or coating.
Specification:	• For flat and low sloped roofs. • Minimum slope of 1 in 48 recommended; slopes over 1 in 6 require nailing to substrate. • Appropriate for new roofing, re-roofing or waterproofing.
Albedo:	Surfacing could be a white coating (albedo ~ 0.8), white mineral aggregate (albedo ~ 0.5) or a white-coated (albedo ~ 0.8) or white-mineral-surfaced (albedo ~ 0.3) cap sheet. Mineral-granule-surfaced cap sheet is traditionally recommended but does not have a high albedo without paint. High-albedo coatings may be spray applied; primer may be required for proper adhesion. A coating is not recommended where ponding water is a possibility. A white acrylic elastomeric mastic is useful as a high-albedo coating.
Installation:	Felts are laid in shingle fashion or single course and bonded or spot anchored to the substrate. Mineral surfacing and colored coatings may be used on the surface.
Availability:	Widely available from roofing contractors.
Service Range:	10 to 15 years.
Customer Benefits:	Lower *initial* cost than for a hot-applied built-up roof.
Cost:	3 plies 25 lb. fiberglass base sheet, 2 coats #203 cold application cement, one coat #107 asphalt emulsion, and #120 aluminum coating — $122/100 ft^2
	1 ply 25 lb fiberglass base sheet, 2 plies #184 Rufon polyester fabric embedded in and top coated with #106 asphalt emulsion and #120 aluminum coating — $133/100 ft^2

Sources: 1991 Sweet's Catalog File, Vol. 3, 1990; R.S. Means Company, 1990.
Sources: 1991 Sweet's Catalog File, Vol. 3, 1990; R.S. Means Company, 1990.

Product:	**White cement concrete roof tiles**
Description:	Concrete roof tiles made with white cement designed for protection and beauty.
Specification:	Installed on pitched substrates to shed water rather than form a watertight barrier. Suitable for new roofing and re-roofing.
Albedo:	We estimate 0.7-0.8 new; 0.6-0.7 aged.
Installation	Tiles are nailed to the substrate.
Availability:	Manufactured by Riverside Cement Company, 714-861-6028, or 1-800-442-4910 (CA only). Available through distributors, including LifeTile Sales in Realto (714) 822-4407.
Service Range:	50 years.
Customer Benefits:	• Sound control. • Fire resistance. • Durable/long lifetime.
Cost:	Cost data are not available at this time, but initial cost is high.

Sources: Firestone Building Products Company product information; *1991 Sweet's Catalog File*, Vol. 3, 1990; R.S. Means Company, 1990.

Product: **White modified-bitumen roofing membrane**

Description: Single-ply, laminated, membrane made of modified bituminous material and layers of plastic or metallic film and surfacing and/or reinforcing. **APP** products are smooth-surface, modified-bitumen roofing membranes, consisting of an asphaltic waterproofing layer, modified with Atactic Polypropylene and reinforced with a polyester fabric. Firestone **SBS** products are granule-surface modified-bitumen roofing membranes, consisting of an asphaltic waterproofing layer, modified with Styrene-Butadiene-Styrene Rubber and reinforced with polyester fabric.

Specification: • Generally used on flat or gently-sloped roofs. • Suitable for new-roofing, reroofing, and waterproofing. • Firestone products are for commercial and industrial applications only. • Adequate drainage of the roof surface and a minimum slope of 1/4 inch per foot is recommended. • May be applied over metal, structural concrete, plywood, oriented strand board and waferboard, wood plank, precast gypsum and cementitious wood fiber, lightweight concrete and poured gypsum decks, smooth-surface or mineral-surfaced built-up roofs and coal-tar or gravel-surface built-up roofs. For some of these substrates, special treatment or a layer of insulation and base sheet may be necessary.

Albedo: Surfacing is usually granules or aggregate but may also be a white coating. A white-mineral-granule cap sheet will have an albedo of ~ 0.3, a white aggregate ~ 0.5 and a white reflective coating ~ 0.8.

Installation: The membranes are bonded to the substrate or loose laid and ballasted with aggregate. Joints are either heat sealed, or solvent or adhesive attached.

Availability: Available from manufacturers and contractors. **SBS** and **APP Granular** are manufactured by Firestone Building Products Company, 525 Congressional Boulevard, Carmel, IN 46032-5607. 1-800-428-4442.

Service Range: 10 to 20 years.

Customer Benefits: Low initial cost

Cost:

Modified-bitumen, 150 mils, 0.82 P.ft^2	
Loose-laid & ballasted with gravel (4 P.ft^2)	\$1.01/ft^2
Partially adhered with torch welding	\$1.30/ft^2
Fully adhered with torch welding	\$1.42/ft^2
Hot asphalt attachment	\$1.51/ft^2
APP/Granular, partially adhered with torch welding	\$.95/ft^2
SBS/Granular, partially adhered with torch welding	\$1.07/ft^2

Product: **White single-ply, preformed polymeric (elastomeric/plastomeric) roofing membrane**

Description: Precured sheets of elastic material joined by heat fusion or adhesion.

Specification: Generally used on flat or gently sloped roofs. Suitable for new roofing, re-roofing or waterproofing. **Ultraply® 78+** is available only for commercial and industrial use.

Albedo: Some single-ply membranes are available in white, such as the **Ultraply® 78+**, which we found to have an albedo of 0.88. Others, such as Ethylene Propylene Diene Terpolymer (EPDM) membrane may be covered with a white coating or paint, for which we estimate an albedo of ~ 0.8. before weathering. Alternatively, the surfacing may be a white gravel with an albedo of ~ 0.5.

Installation: The membrane is bonded to the substrate, spot anchored or laid loose and ballasted with aggregate.

Availability: Available from roofing contractors. We list here three manufacturers.

U.S. Intec, Inc. (1-800-62INTEC).

Stevens Roofing Systems, Hi-Tuff, (413)586-8750.

For commercial applications, Firestone markets **Ultraply® 78+** (Thermoplastic Alloy Membrane)--a reinforced white, mechanically attached thermoplastic roofing system utilizing heat-weldable seams, and an EPDM and acrylitop coating that is available in white. These products are available through roofing distributors and should be installed by independent roofing contractors approved by Firestone. For information contact Firestone Building Products Company, 1-800-428-4442.

Service range: 10-20 years.

Customer Benefits:
- Relatively inexpensive.
- Ideal for re-roofing.
- High albedo.

Cost:

Chlorinated polyethylene (CPE), 40 mils, 0.31 P.ft^2	
Partially adhered with mechanical fasteners	\$1.92/ft^2
Ethylene propylene diene monomer (EPDM), 45 mils, 0.28 P.ft^2	
Loose-laid & ballasted with stone (10 P.S.F)	\$0.90/ft^2
Partially adhered	\$1.12/ft^2
Fully adhered with adhesive	\$1.35/ft^2
Firestone EPDM,	

Partially adhered	$\$0.79/\text{ft}^2$
Acrylitop coating (materials only)	$\$.020/\text{ft}^2$
Ultraply® 78+, partially adhered	$\$1.10/\text{ft}^2$

Product:	**Transmet Aluminum Roofing Chips**
Description:	Reflective roofing chips that shield and protect the underlying waterproof membrane.
Specification:	May be used on new roofs or to extend the life of weathered roofs without moisture damage. Built-up roofing membranes and metal roofs may be recoated with an approved, compatible cold process asphalt and topped with a blown on surface of **Transmet Chips**.
Albedo:	According to the Transmet Corporation, the albedo is greater than 0.65. More reflective of ultraviolet and infrared radiation than white paint, but less reflective in the visible spectrum. Note that these chips have a low emissivity and are expected to be less effective at releasing heat than a non-metallic surface.
Installation:	May be applied on site by blowing on to asphalt layer or purchased pre-applied to roll goods such as modified bitumen and reinforced cap sheet.
Availability:	Many types of **Transmet Chip**-surfaced roll goods and cold process systems are available. Contact Transmet Corporation, (614) 276-5522.
Service range:	Maintain 96% of original reflectivity after 10 years of exposure, according to the manufacturer's accelerated aging studies.
Customer benefits:	• Extend roofing life of a dark roof by reducing temperature swings. • Because of low thermal emissivity properties, heat is retained in winter and at night, which may be an advantage in cold climates. • Light weight--1/10th the weight of granules and 1/100th the weight of gravel or stone. • Reflectivity values do not decline significantly with time.
Cost:	No cost data are available at this time.

Source: Transmet Corporation, (614) 276-5522.

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