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Mitigation of Urban Heat Islands: Materials, Utility Programs, Updates†

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Abstract

Elevated temperatures in urban "heat islands" result in high cooling energy use and may enhance the formation of urban smog. Urban shade trees and light-colored surfaces can lower the air temperature of a heat island and reduce cooling energy use. Light-colored surfaces stay cool because they typically have a high "albedo" and reflect solar radiation that would otherwise heat the surface.

The albedo of a city may be increased gradually if high-albedo surfaces are chosen to replace darker materials at the time of routine maintenance. Most paints and roofing materials are available in light colors at no additional cost. Pavement albedo may be increased by using concrete or by using white aggregate in asphalt pavement and rolling on top an inexpensive layer of chippings, shells or sand. Light-colored surfaces may last longer than conventional dark surfaces because they reflect damaging radiation, stay cooler, and suffer less thermal expansion and contraction.

Using white surfaces to increase the albedo of a city may be a lucrative way to conserve energy and reduce pollution. Utilities could promote high-albedo surfaces

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to earn profits and reduce the demand for peak power. Suggested programs include paint labeling, marketing, and incentives for using light-colored materials for buildings and roads.

We present three recent measurements: the air-conditioning savings on a test house in Sacramento, on two houses in Florida, and some air temperature measurements at White Sands, New Mexico. In addition, we discuss the results of some meteorological simulations performed for Los Angeles, CA, that validate the measured data from White Sands.

1. Introduction

On a summer day, the average temperature in a typical American city is about 5°F hotter than the surrounding rural area. Dark surfaces that heat up as they absorb solar radiation, and the reduced vegetation, contribute to what is termed the "urban heat island." Akbari et al. (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 larger indirect cost of pollution. Elevated temperatures enhance the formation of smog and urban ozone, the pollutant that most often exceeds the National Ambient Air Quality Standards.

Trees and light-colored surfaces are inexpensive and effective ways to mitigate urban heat islands. Light-colored 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. Lower surface temperatures reduce the city's cooling energy use by directly reducing the heat gain through a building's envelope (direct effect) and by lowering the air temperature (indirect effect).

2. Heat Island Effects

Summer urban heat islands with temperatures 5-8°F higher than surrounding areas are found throughout the U.S. In large cities like Los Angeles, summer monthly average temperatures are increasing faster than 1°F per decade (**Figure 1**). This warming raises peak cooling demand 1.5% (Los Angeles) to 3.0% (Atlanta) for each 1°F rise. On a hot afternoon, U.S. heat islands raise air conditioning demand by about 10 GW (gigawatt), worth several million dollars per hour, and integrating to several billion dollars annually (Akbari et al. 1990; Competitek 1992).

Heat islands have several effects on urban air quality. The power needed to compensate for heat islands requires significant additional generating capacity, which contributes to urban air pollution. This contribution may be significant, since peak power is often supplied by the most polluting power plants. Further, elevated temperatures associated with heat islands accelerate the formation of smog. **Figure 2** shows that the probability of smog increases by 2% to 4% per °F. Below 70°F there are almost never smog "episodes" in Los Angeles, but starting at about 73°F, smog episodes begin and exceed 50% by 90°F. We estimate crudely that reducing daily highs by 7°F (i.e., just by eliminating the heat island, but we could do better than that) will eliminate an astounding 2/3 of the smog episodes (Akbari et al. 1990). As discussed later in this paper, we have started meteorological and smog modeling to refine this crude estimate.

3. Trees and White Surfaces

Shade trees and high-albedo surfaces are 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). Light-colored surfaces should be even more effective than trees at cooling cities, and cost less if color changes are incorporated into routine maintenance schedules. Also, the results from light-colored surfaces are immediate, while it may be ten or more years before a tree is large enough to produce significant energy savings. Akbari et al. (1989) discusses the relative benefit/cost of white surfaces vs. trees.

High-albedo materials on major urban surfaces such as roofs, streets, sidewalks and parking lots, will be cooler than the conventional dark materials. **Figure 3** demonstrates the relationship between albedo and surface temperature of various materials.

The effects of light-colored surfaces include "direct" energy savings and "indirect" effects on climate. Direct effects refer to the energy savings of an individual building achieved by changing the albedo of its roof. If albedo is altered on a larger, community scale so that the ambient temperature decreases, the energy savings of buildings in the area are indirect effects of albedo modification. Indirect savings are achieved because in a cooler environment, it requires less energy to cool a building.

Computer simulation fit to a real house in Sacramento has shown that applying a white coating to the roof and adding three shade trees will reduce the cooling electricity use by nearly 50% (**Figure 4**). Additional savings can be achieved by using high-albedo materials on major urban surfaces.

4. Costs

Increasing the albedo of a city may be very inexpensive, if the change is made at the time of routine maintenance. Buildings are typically repainted every 10 years, and white paint may be used for no additional cost. Similarly, many roof types, including single-ply membrane and built-up roofing, are available in white for no additional cost. For pavement, light-colored pavement could be installed at the time of resurfacing. "Whitetopping" (resurfacing an asphalt pavement with concrete) produces a light-colored pavement that has low maintenance costs and a long service life. Another option for light-colored pavement is a "hot-rolled" asphalt pavement using white aggregate. This paving method, popular in Great Britain, involves rolling chippings into the top surface of the pavement. If white chippings are locally available, a light-colored pavement is produced at no additional cost. White chippings can also be used in a "chip seal" surface treatment.

It appears that most light-colored surfaces are equivalent in cost to conventional dark surfaces and last longer because they are less susceptible to the damaging effects of solar radiation and large temperature swings.[19] While no quantitative data have been found to support this hypothesis, it is common knowledge among roofing professionals that white asphalt shingles last longer than dark asphalt shingles. Since "white" asphalt shingles are in fact quite dark (75% absorptive, see Fig. 3) when compared to white paint, it would seem that small improvements in albedo can significantly effect service life.

5. Labeling and Incentives for Cool Surfaces

We estimate that heat island reduction savings of several billion dollars annually could be realized through utility-sponsored demand-side management (DSM) programs that promote the whitening and greening of cities. Assuming these utilities are permitted to retain 10% of program savings, they could earn about $100-$300 million/year (Rosenfeld et al. 1992).

5a. Labels

Some utilities have already expressed interest in incentives, but incentives for what? The problem is that we want **cool** surfaces, and Fig. 3 immediately shows that there is little correlation between "cool" and "light-colored." An incentive for the "white" asphalt shingle at 175°F, or galvanized steel at 170°, would not only be counterproductive, but would miss the opportunity of making a huge new market for cool light shingle, cool-surfaced galvanized steel, and smart paints and surfaces (pleasant light colors, which stay cool because they are very reflective in the near-infrared). Thus, labeling is an essential first step.

Labels can be designed after we hold workshops for the paint/pigment industry, the roofing industry, and the pavement industry. These labels will probably carry the following information:

1. Surface temperature on a clear day under the midsummer sun in, say, Arizona.
2. Surface temperature under standard fire conditions (to allow better protection of roofs and walls from external fires).
3. Service life (to give credit for the fact that cool roofs and roads last longer than surfaces exposed to diurnal thermal shock and ultraviolet radiation).

5b. Incentives

Implementation programs for white surfaces should be designed to emphasize roof types that cover the largest area in a city. Rough estimates based on the percentage share of California's roofing market for each roof type (**Table 1**) suggest that programs in California should concentrate on the modified bitumen and fiberglass asphalt shingle roofs for homes and on built-up roofing and modified bitumen roofing for commercial applications. Built-up roofing can be installed with a white reflective coating for no additional cost, while adding a coating to modified bitumen may include a very small incremental cost, as mentioned above. Since coating asphalt shingles is an additional expense not included in installation and voids the warranty for the roof, it will be necessary to induce shingle manufacturers to make high-albedo shingles.

Another barrier to implementation of cool surfaces is the lack of measurements of the indirect effects of large-scale albedo modification. Lawrence Berkeley Laboratory is seeking innovative developers to build half of the houses in a development conventionally and half with light-colored roofs and roads. Researchers will then demonstrate the reduction in air temperature and savings in air conditioning.

Residential		Commercial	
Type	**%**	**Type**	**%**
Modified bitumen	22.2	Built-up roofing	25.4
Fiberglass asphalt shingle	15.8	Modified bitumen	7.2
Built-up roofing	6.4	Asphalt shingles	4.4
Wood shingles/shakes	1.6	EPDM	4.4
Organic asphalt shingle	1.6	PVC	2.0
Metal	2.6	Metal	1.8
Cement tiles	1.0	Tile	0.6
Single ply	1.0	Polyurethane foam	0.5
Clay tiles	0.3	Hypalon	0.4
Slate	0.1	Other single-plies	0.4
--	--	Liquid-applied	0.3
Total	52.6	**Total**	47.4

Table 1. Areas of Roof Types in California. Rough estimates, based on data on California's roofing market (in dollars) from National Roofing Contractors Association (1990) and estimates of cost/area from Means (1990), as compiled in Bretz et al., 1992.

5c. Incentives vs. Standards

Because of the 30-50% savings in a/c bills, incentive programs for light surfaces and vegetation should work well but slowly (because roofs last 30 years and shade trees grow slowly). Cool, shaded roads and parking lots are more of a tragedy/challenge of the commons, and may require standards. In either case, international labels will make a market for environmentally benign and profitable new surfaces.

New Developments

In the preceding sections, we gave an overview of the causes and impacts of heat islands and mitigation methods. In this section, we summarize some new developments in heat island studies. In particular, we briefly discuss the measured cooling energy savings in two experiments (Sacramento and Florida studies), the indirect cooling effects of high-albedo surfaces measured at White Sands, NM, and some new simulation efforts performed for Los Angeles which validate our measured data in White Sands.

6a. Direct Cooling in Sacramento

In summers of 1991 and 1992, we conducted experiments to measure the impact of white roofs and shade trees on the cooling energy use of a few buildings in Sacramento. For most sites, we collected data on air-conditioning electricity use, indoor and outdoor dry bulb temperature and humidity, surface temperature of roof and ceiling, inside and outside wall temperatures, solar gain, and wind speed and direction.

To measure the impact of **shade trees**, we conducted a "flip-flop" experiment, divided into three periods, using two houses. In the first period, we monitored the cooling energy use of both houses in order to establish a base case relationship (see **Figure 5**). In the second and third periods, eight large and eight small shade trees were placed at one of the sites for a period of four weeks and then were moved to the other site. The cooling energy use of the site without trees indicates what the cooling energy use of the shaded site would have been were the trees not there. Figure 5 shows savings of 35% from the median a/c load. Seasonal analysis is underway.

To measure the impact of **high-albedo roofs** and walls, we monitored cooling energy use of a house and two school bungalows. The albedo of the house roof before modification was 0.18. A coat of high-albedo paint achieved 0.77. A year later, the albedo of the dirty roof was 0.59, but washing it with soap and water returned the albedo to 0.73.

Daily cooling-energy use in kWh per day are plotted against the daily average drybulb outdoor temperature in **Figure 6**. The squares represent the cooling-energy use for the period that the roof was dark (albedo 0.18). The circles represent 1992 data, when the albedo was measured at 0.73. The daily average outdoor temperature that causes the air-conditioning unit to come on has shifted upward by 2°C. Note that many circles fall at 0 kWh. The lines on Figure 6 are regression fits up to 25°C. Past this point, it is difficult to compare pre-modification and post-modification data because there are no pre-modification data with comparable environmental variables. The seasonal cooling energy savings at this site are estimated to be 40% (330 kWh/yr), but savings during the long, very hot days of summer are only about 30% (2.9 kWh/day).

Energy savings of 40% were also measured for the school.

6b. Direct Cooling in Florida

In 1991 and 1992, Parker et al. (1993) of the Florida Solar Energy Center (FSEC) conducted experiments and measured the impact of reflective roof coatings on air conditioning energy use in three homes in central Florida: one with a well-insulated R-25 attic; a concrete-block-wall house with R-11 ceiling insulation; and a concrete-block-wall flat roof house with no insulation. The roof albedo of these houses were modified to 0.73 from initial values of 0.20-0.22. The measured air conditioning energy savings were 10%, 25%, and 43%, respectively. The reported utility-coincident peak demand between 5 and 6 p.m. are 28% and 38% for R-11 house and flat roof house, respectively. **Figure 7** shows the roof air space temperature and the air conditioning energy use before and after the application of reflective coating on the R-11 house for July 28 to August 3, 1992. This study has concluded that reflective coatings are particularly appropriate for existing Florida homes in which the roof structure makes it difficult to retrofit insulation.

7. Islands of "Coolth"--White Cities and White Sands

Figure 1 suggests that if we restored Los Angeles to 1930's conditions of vegetation and road color we might remove the heat island, except for about 1°F from cars and the conversion of electricity to heat. We believe that we could do much better based on the two points on Fig. 3 labeled "Hypothetical White City," with a solar absorptivity of 50%, and labeled "Average City," with an absorptivity of 80%, i.e., a difference of 30%.

Our group is just beginning to study air temperature at the White Sands National Monument, which is a light-colored strip several miles wide, inside the White Sands Missile Range in southern New Mexico. The white sand is gypsum, which has the doubly interesting properties of being quite white (the dunes have an albedo of 0.65, so an absorptivity of 0.35), and being very alkaline, so that even between the dunes the vegetation is sparse. Near the middle of the Monument, the average absorptivity is about 0.4. The surrounding desert, at the same altitude of about 2000 ft., is vegetated with yellow-green bushes with an albedo of about 0.2 to 0.4, so an absorptivity of about 0.6 to 0.8. Hence, the absorptivity difference between the monument and the desert is about **0.4**, or comparable with the conceivable improvement in the albedo of large fractions of a city like Los Angeles (but not dense high-rise downtown areas, like parts of Manhattan).

As shown in **Figure 7.1**, the summer high temperatures in the vegetated desert are typically 105°F. **Although the data are very preliminary, we find it encouraging that the light-colored monument runs about 10°F cooler.** We chose to quote monthly highs for the summer months, because these are just the sort of conditions under which urban heat islands are the worst.

The data of Fig. 8 suggest the following relationship for the depression of summer peak temperature by a city-sized, high-albedo area:

$$\frac{\Delta T}{\Delta a} = \frac{10°F = 5.5K}{0.4} = 14\,\frac{K}{a} \qquad (1)$$

where ΔT is the change in temperature (measured in Kelvins, K, where 1 K = 1°C) and Δa is the change in albedo. We are encouraged that meteorological modeling of raising the albedo of the Los Angeles Basin produced similar results:

$$\frac{\Delta T}{\Delta a} = \frac{5.4°F = 3K}{0.16} = 19\,\frac{K}{a} \qquad (2)$$

(See Section 8).

Since we estimate that of the present 7°F summer heat island in Los Angeles, 3-4°F comes from dark roads and roofs, it then looks easy to reverse that 3-4°F, and we could actually aim for another 5-7°F of cooling. Figure 2 shows the potential gain in power and smog from cooling in Los Angeles 10°F below the present summer conditions: about 2 GW of peak power (worth $500,000/hour) and a 20% reduction in the probability of a smog episode.

Now that we have introduced the concept of a 10°F drop in temperature for a 35% increase in whiteness we can also address the alternative Hypothetical Green City of Fig. 3, which is 0.1 darker but has enough trees to cool by evapotranspiration (ET) and shading. We estimate that ET and shade will cool the city by 2-3°F, which will just about offset the 3-4°F from the increased absorptivity, still leaving us with a potentially nicely cooled city.

8. Meteorological Modeling of Albedo in Los Angeles

In another study, we use a three-dimensional mesoscale meteorological model to study the impacts of proposed surface modifications in the Los Angeles Basin (Sailor and Kessler 1993). The grid for these simulations covers the entire Los Angeles basin extending 325 km east-west and 200 km north-south. Each of the 2600 surface grid cells is 5 km on a side. A land-use data base was used to determine the breakdown of land-use in each grid cell.

In developing the high albedo modification scenario, 394 grid cells were identified as "developed areas" suitable for modification. In evaluating the level of potential albedo increase we assumed that typical "developed areas" are more than half covered with impermeable surfaces, and that existing technology could increase the albedo of any individual impermeable surface by 0.30 to 0.50. It is therefore reasonable that the albedo of an entire city could be increased by 0.15 to 0.25. **Figure 8a** illustrates the locations of albedo modification investigated in this study. The average albedo increase in each of the 394 modified grid cells for this study was 0.16. Note that an albedo increase of 0.16 does not imply a brilliant white city; instead it corresponds to a Los Angeles which is the color of weathered concrete. If, however, white cities become popular (as currently in Arizona) we could perhaps raise albedo by as much as 0.4.

Figure 8b shows the temperature changes resulting from the albedo modification with respect to the base case simulations for 9 a.m. As shown in **Figure 8c**, at noon the peak impact has moved slightly inland, now centered over downtown Los Angeles with a cooling magnitude of 2°C. The peak impact occurs in the early afternoon. **Figure 8d** illustrates that this impact exceeds 3°C at 3 p.m. We have conducted similar simulations under various initial conditions, all of which indicate a peak summertime temperature impact ranging from 2 to 4°C. If we chose ΔT = 3°C = 3K for Δa = 0.16, we can write Eq.(2) above and find encouraging agreement with Eq.(1) for White Sands.

9. Conclusion

Using white surfaces to increase the albedo of urban heat islands may be an easy way to conserve energy, save money and reduce pollution. Experiments have shown 20-40% direct savings by increasing the albedo of a single building, and computer simulation indicates that the indirect effects of wide-scale albedo changes will nearly double the direct savings.

Utility-sponsored DSM programs to promote white surfaces and trees could earn about $100 million/year. For residential buildings, asphalt shingle and modified bitumen roofing should be targeted, and built-up roofing and modified bitumen are important in commercial applications. In most cases, the albedo of these roofs may be changed at no additional cost, at the time of required maintenance. Labeling programs are needed to identify the best materials for increasing albedo, and incentives are needed to encourage the installation of light-colored pavement.

Acknowledgment

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Competitek/E-Source 1992. *State of the Art: Space Cooling and Air Handling*. Table 1.5A estimates U.S. peak a/c (including air handling) as 210 GW, and 1990 sales of 420 BkWh (equivalent to 210 GW for 2000 hours). To estimate the hourly cost of 210 GW, we note that the marginal cost of peak power is 20-50¢/kWh. Thus PG&E quotes 33¢ (San Francisco Chronicle 5-12-93, Bus. Sect, p. Z-6). The 210 GW would then cost marginally about $70 M/hour, and our estimate of 10 GW (5% of 210 GW) from heat islands would cost several million dollars per hour. To convert from hourly to annual marginal cost, we assume that this very expensive electricity is used for about 1000 hours/year. Competitek has changed its name to E-Source, Boulder CO, 80302 (303) 440-8500.

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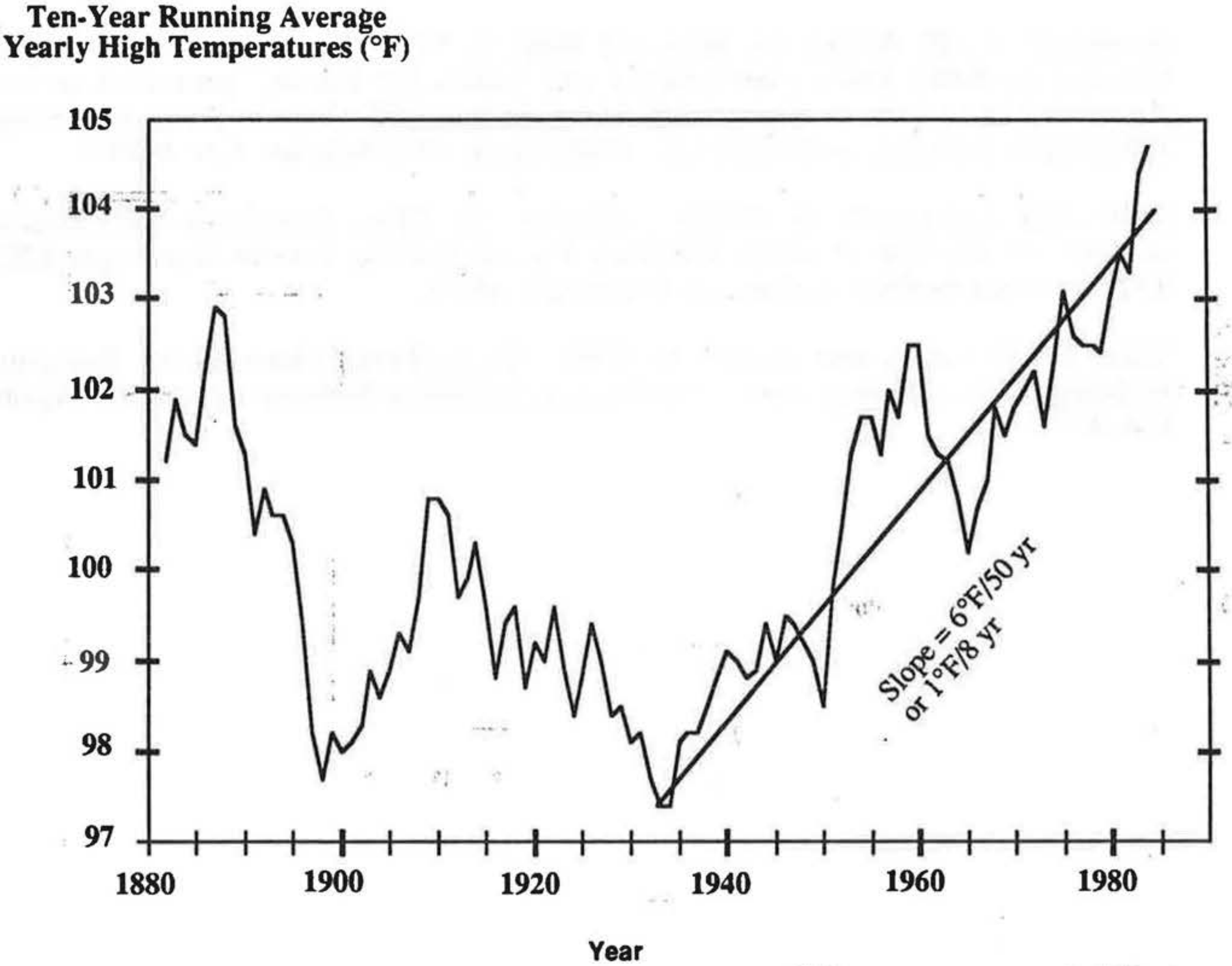

Figure 1. Ten-Year Running Average Yearly High Temperatures in Los Angeles, CA (1882-1984). With increasing irrigation and orchards, Los Angeles cooled 4 °F/yr until the 1930s. Then, as asphalt replaced trees, Los Angeles has warmed 7 °F (1°F/8 years). The ten-year running average is calculated as the average temperature of the previous 4 years, the current year, and the next 5 years.

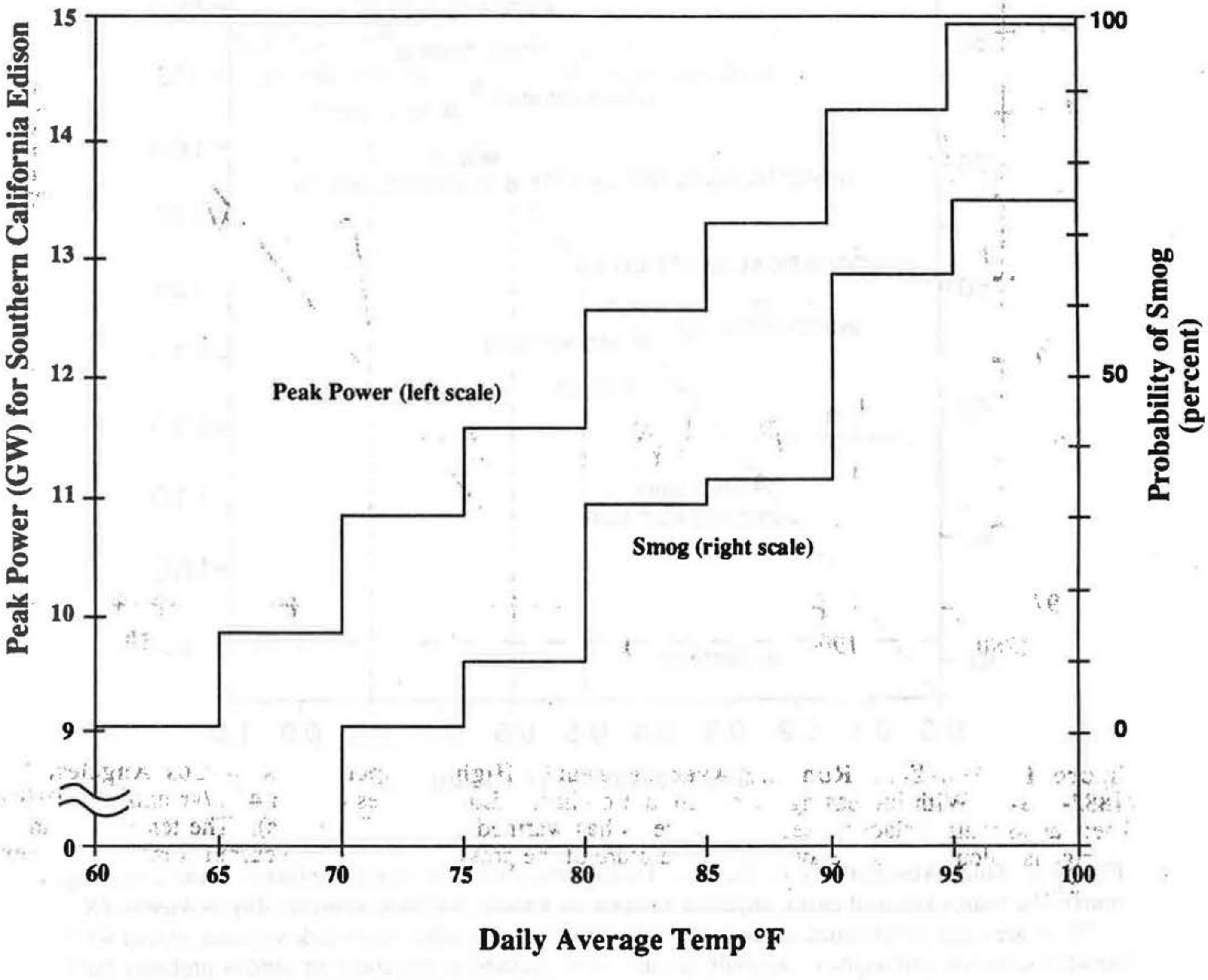

Figure 2. Ozone Level and Peak Power in Los Angeles, CA. Below 70°F there are almost never smog "episodes" in Los Angeles, i.e. the ozone level stays below the National Ambient Air Quality Standard (NAAQS) of 12 pphm. Starting at about 73°F, smog episodes begin and exceed 50% by 90°F. In Los Angeles, summer temperatures average 78°F. If the 7°F heat island were eliminated, the average temperature would drop to 71°F and smog incidents would greatly decrease. The probability of smog is derived from a scatter plot of ozone concentration vs. daily maximum T (Figure 6 of Akbari, H., Rosenfeld, A., and Taha, H. 1990. "Summer Heat Islands, Urban Trees, and White Surfaces," Proceedings of American Society of Heating, Refrigeration, and Air Conditioning Engineers, Atlanta, GA (February); also LBL-28308).

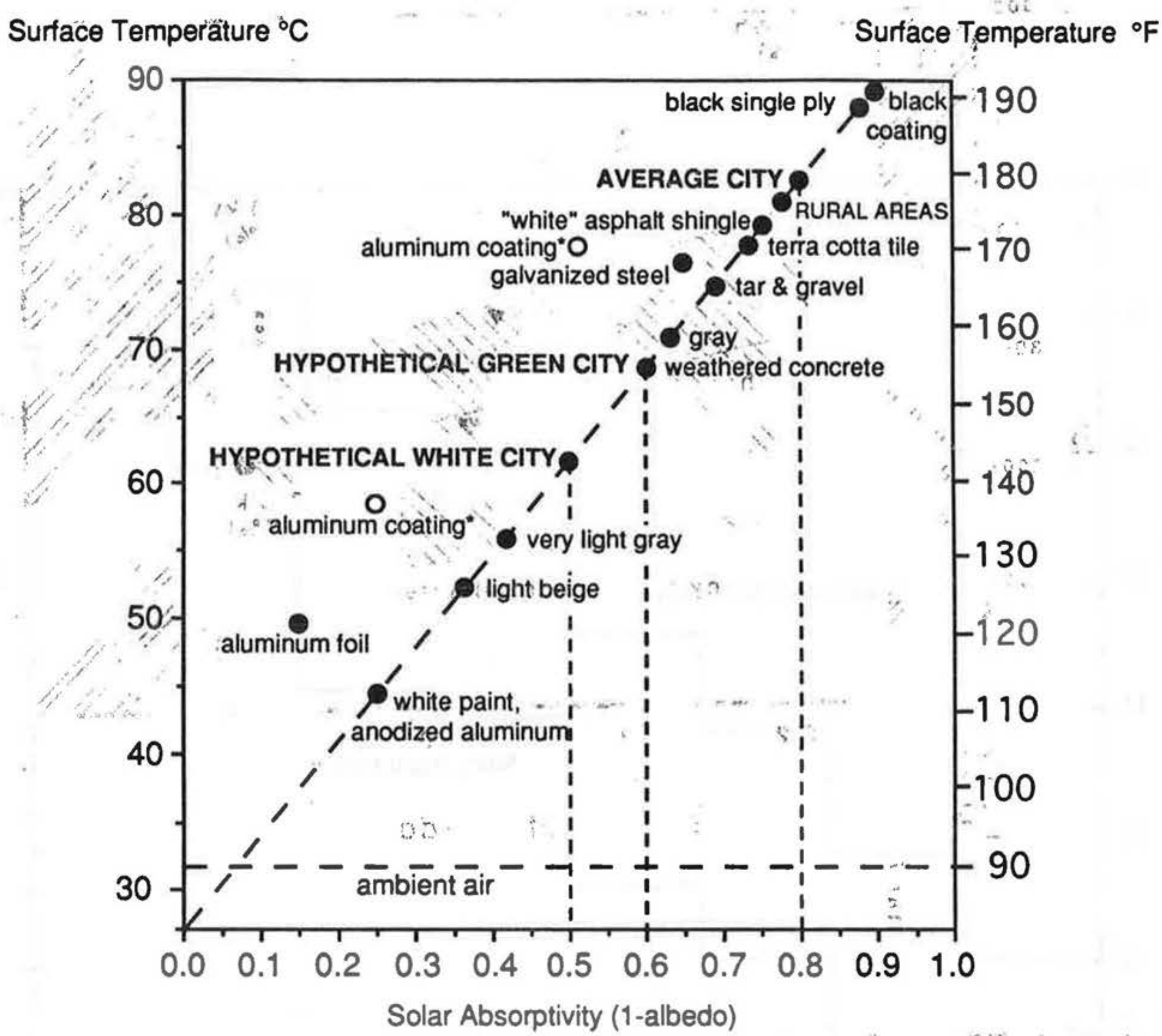

Figure 3. Solar Absorptivity vs. Surface Temperature of Horizontal Surfaces: Paints, roofing materials, roadways, and cities, adjusted to noon on a clear, windless summer day in Austin TX. There are large temperature spreads of about 70°F between white and black surfaces, and of 40°F between concrete 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.

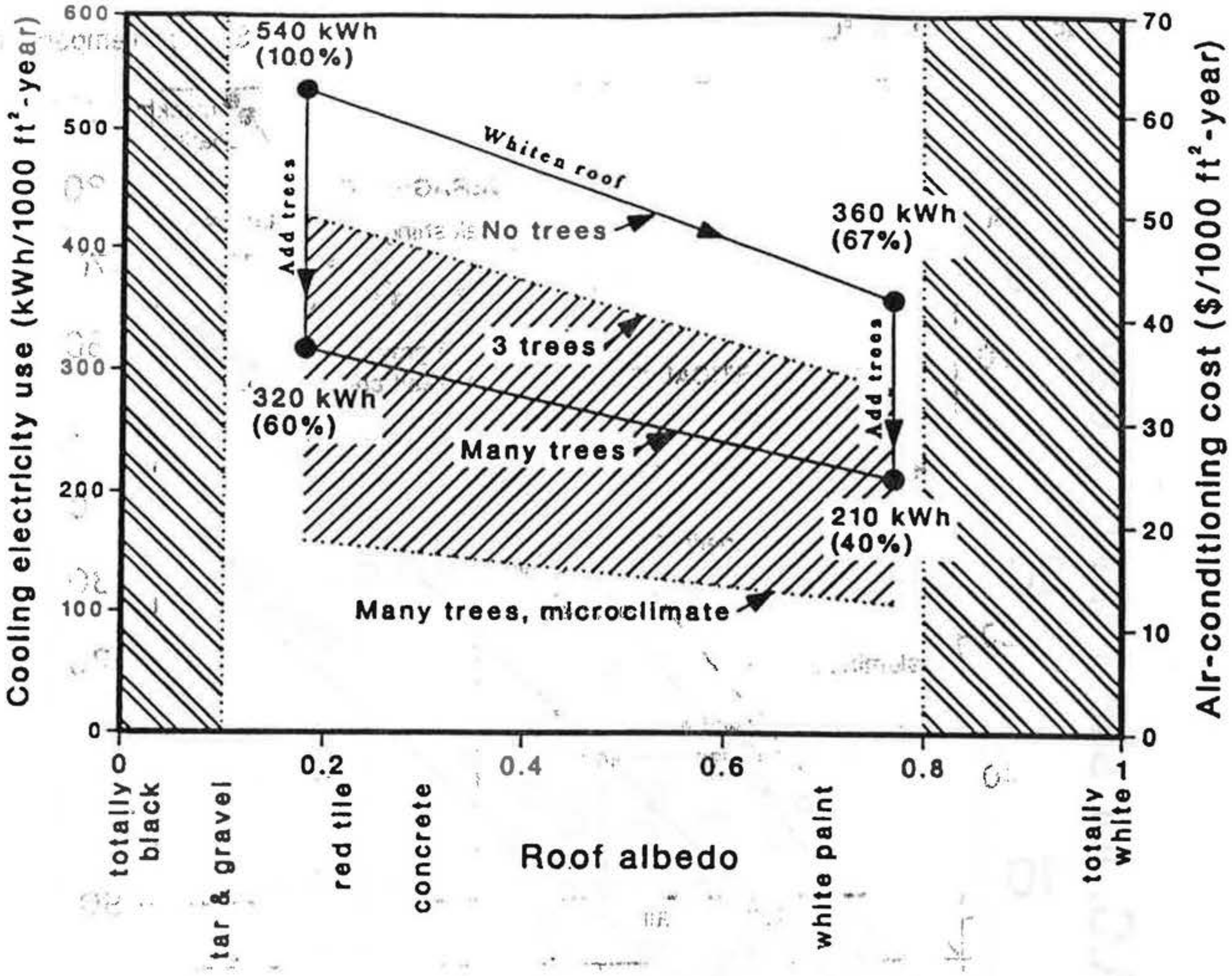

Figure 4. Effect of Roof Albedo and Tree Shading on Cooling Energy Use for a 1960s House in Sacramento. The lower solid line labeled "Many trees" is a fit to a real, well-shaded house, but using airport weather data (no local cooling by the trees). The cross-hatched area represents a range of savings from trees. At the top we estimate the a/c use by the same house with just 3 treees and no cooling of the microclimate. At the bottom we eatimate the microclimate effect of dense treees. (Building conditions and simulation assumptions: Floor area 1700 ft^2, 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).

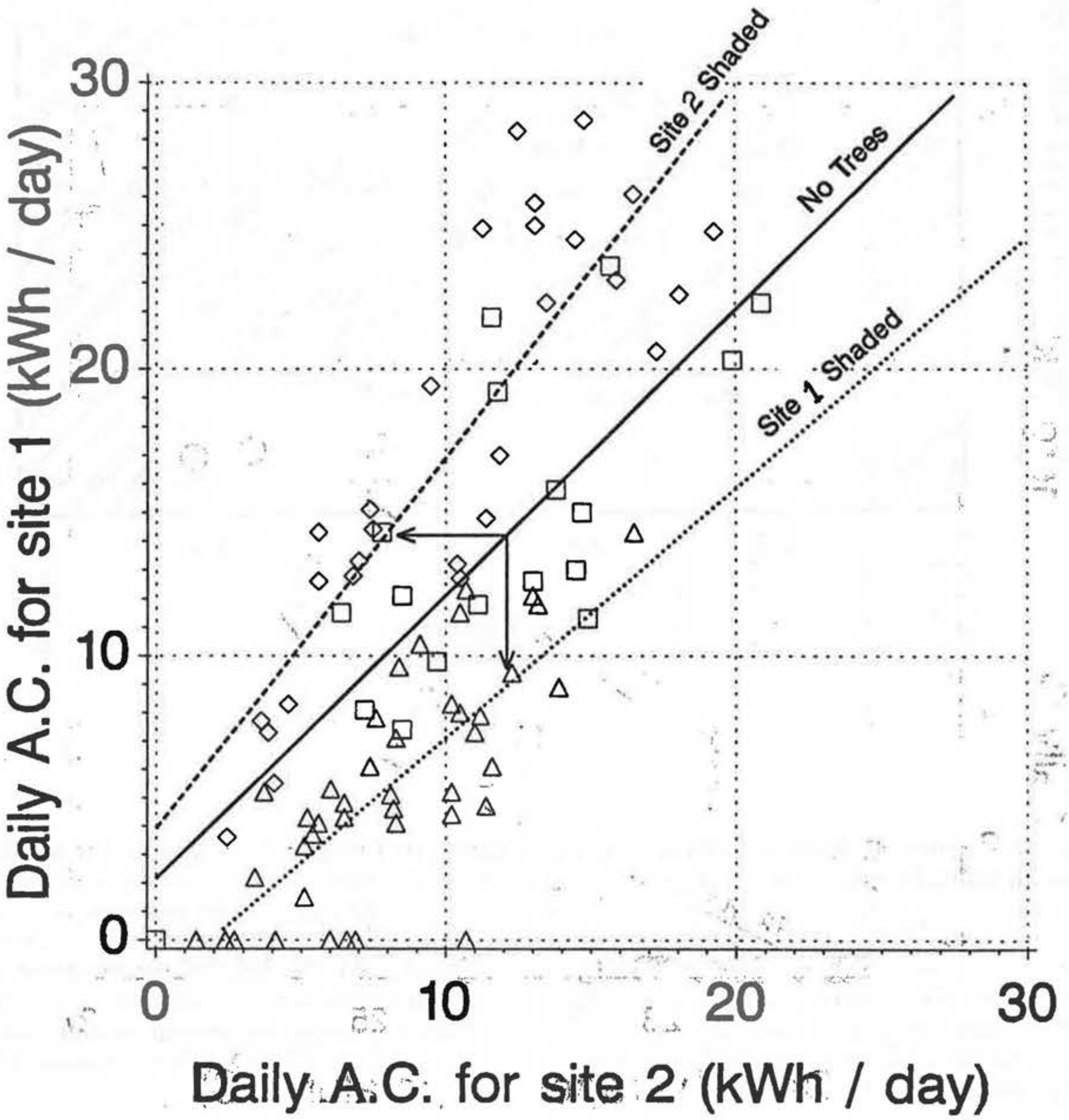

Figure 5. Impact of 8 Large and 8 Small Shade Trees on 2 Houses in Sacramento. Squares and their solid regression line represent 19 July base case days with no trees. Diamonds show the next 20 August days with Site 2 shaded. These data and their regression move **left** about 35%. Triangles show 39 September/October days with the shading moved to Site 1. These data move **down**, again by about 35%. Shading saves about 4 kWh/day.

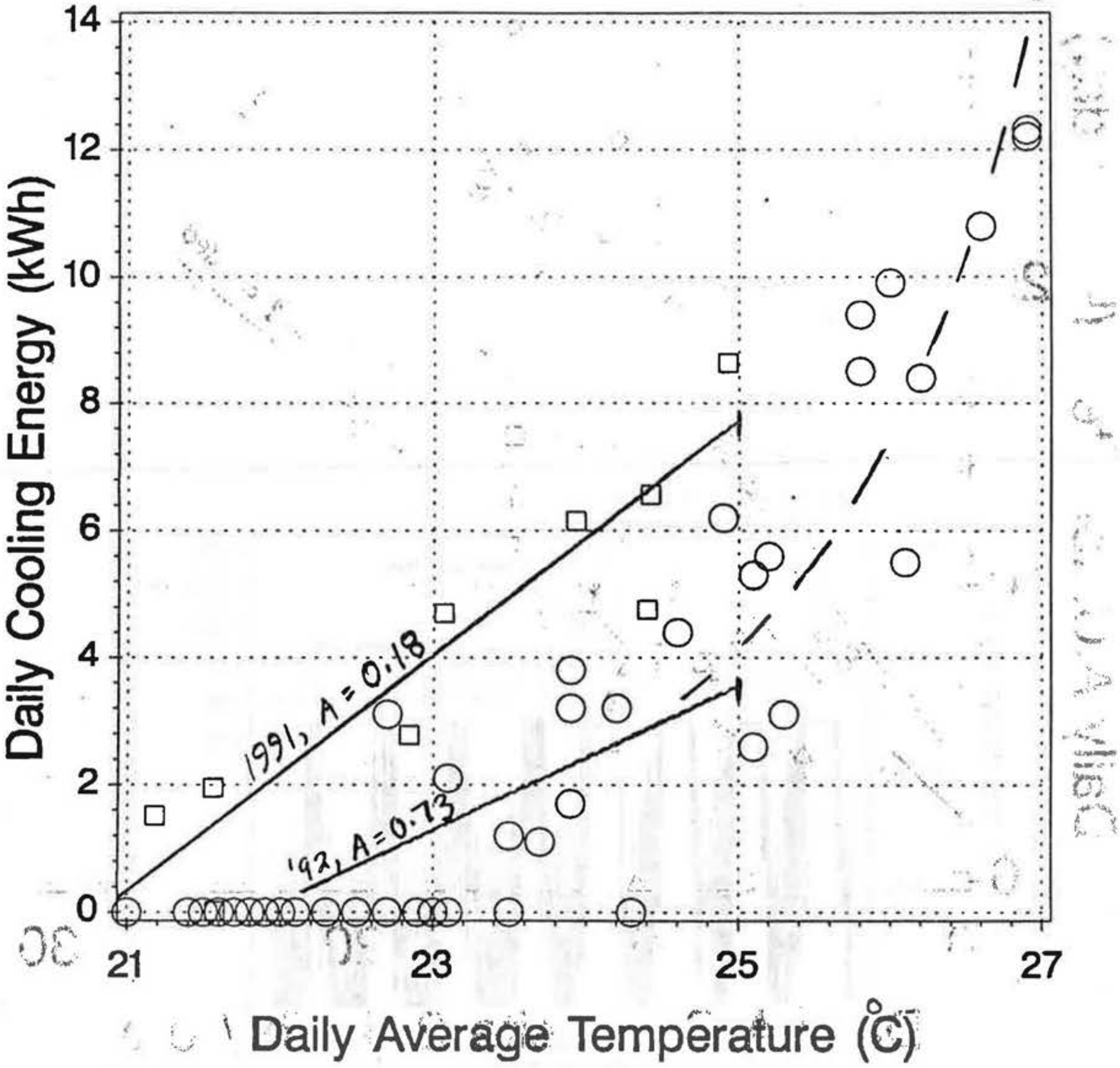

Figure 6. Daily Cooling-Energy Use at Site 2 Versus Daily Average Outdoor Temperature. The squares represent 1991, pre-modification conditions, with a roof albedo of 0.18. The circles, many of them at 0.0 kWh, represent the post-modification period, with an albedo of 0.73.

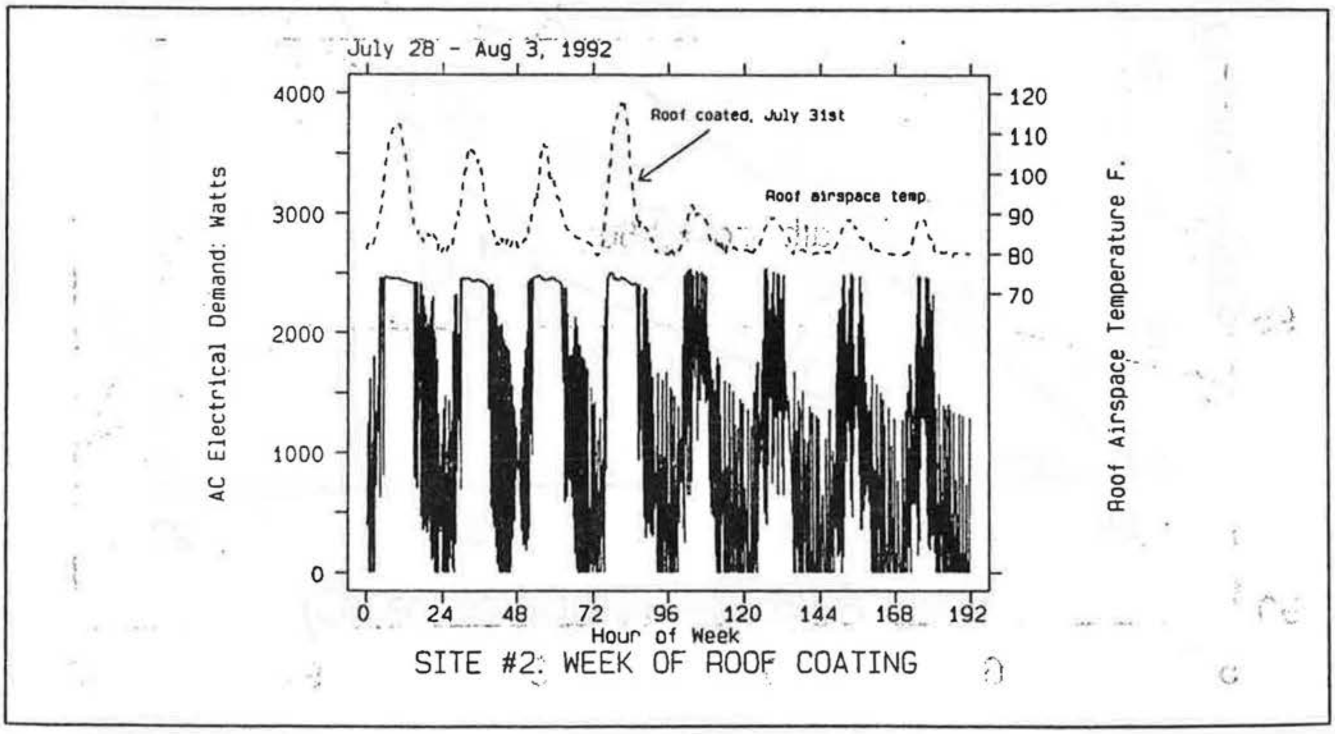

Figure 7. Roof Air Space Temperature and 15-minute Air Conditioning Consumption at Site 2 from July 28th to August 3rd, 1992. The roof was treated with a reflective roof coating on July 31st. Both roof temperatures and cooling energy consumption were substantially reduced. Air conditioning electricity use was decreased by 43% over periods with similar weather conditions (Parker et al., 1993).

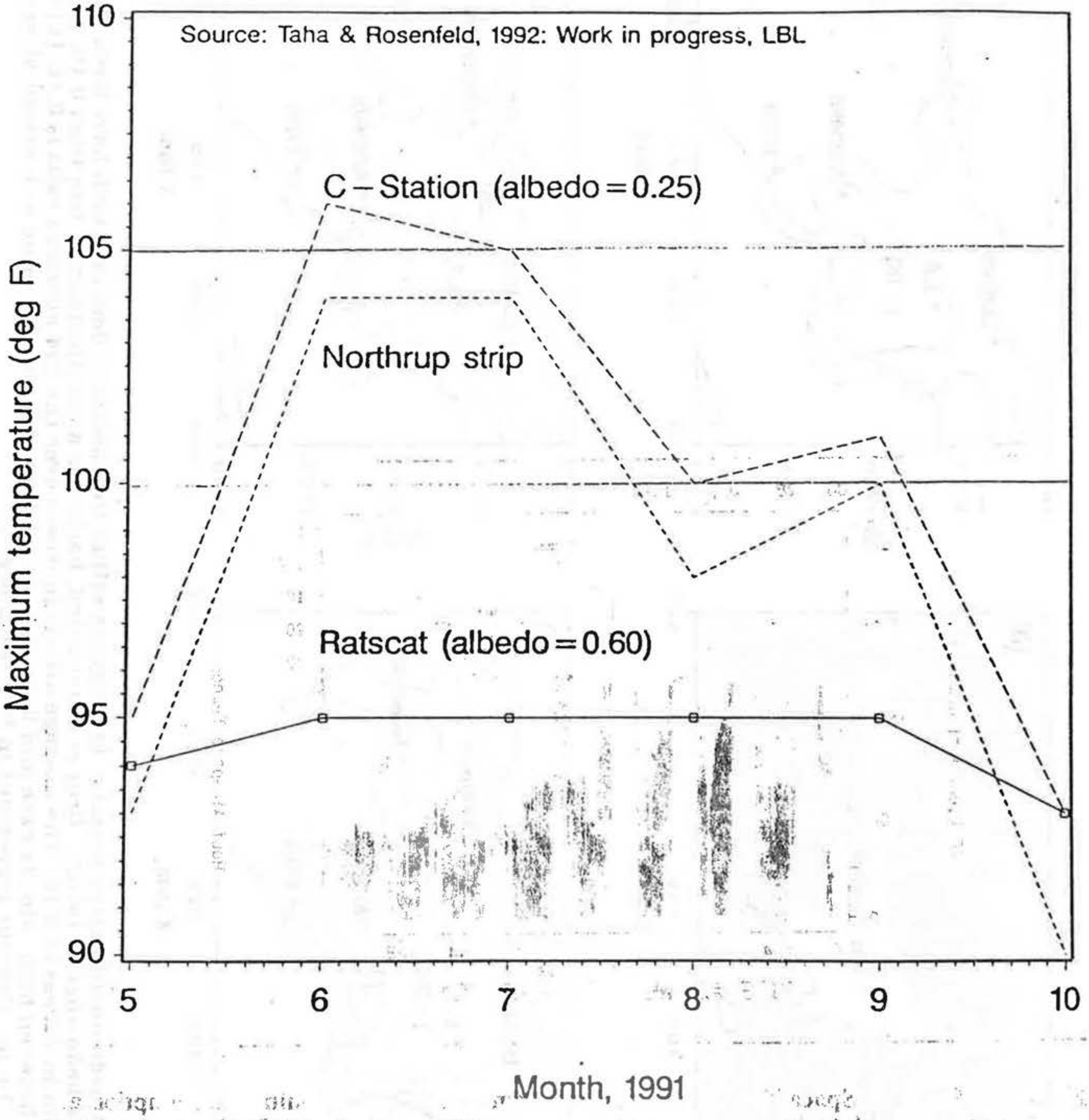

Figure 7-1: 1991 Monthly Maximum Temperatures, White Sands Missile Range, New Mexico. Ratscat weather station is at the edge of the white gypsum area; Northrup and C-Station measure the surrounding temperatures, but Northrup is closer to the fringe of the white, and should be cooler than C-Station.

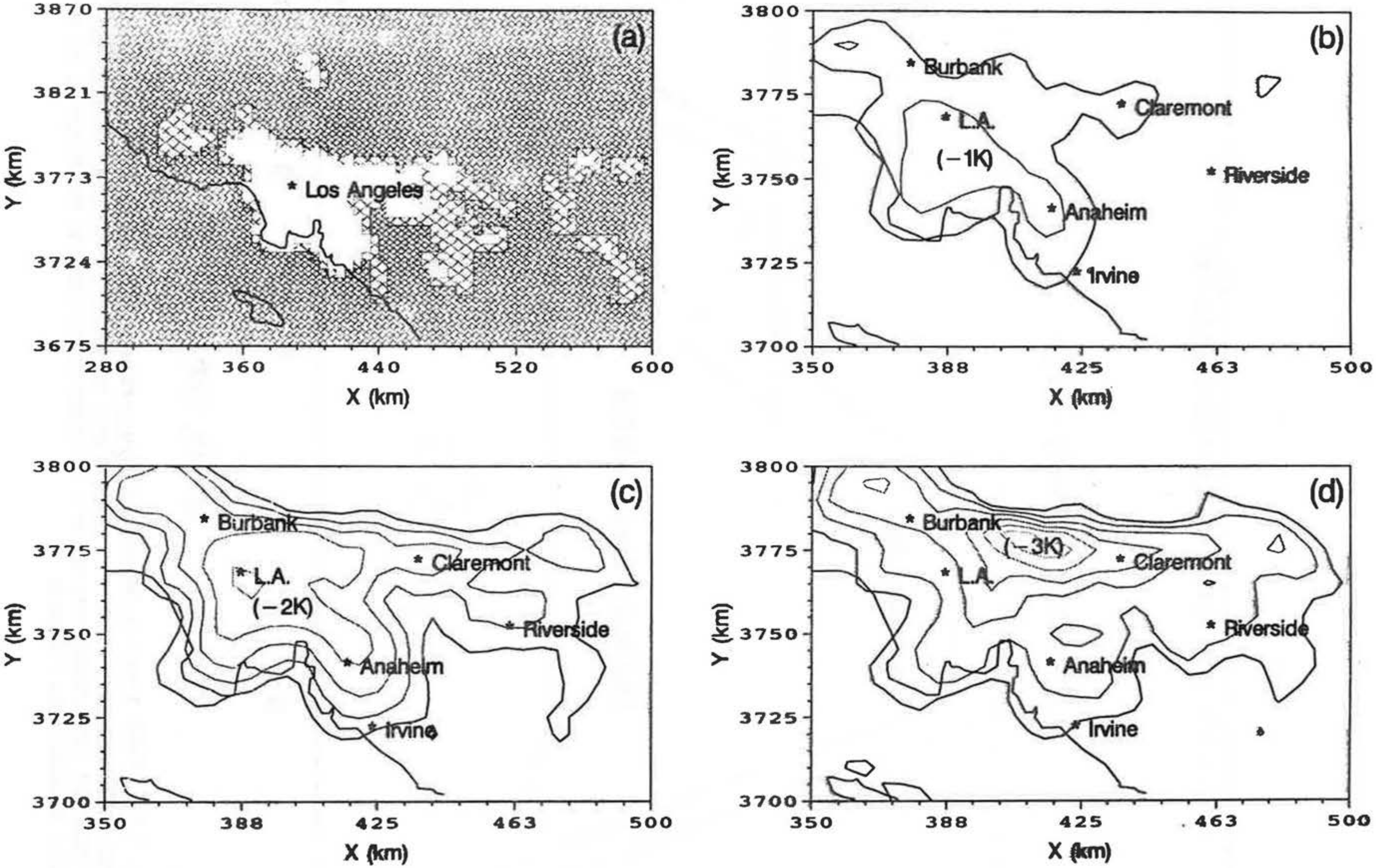

Figure 8: Albedo modification results: (a) Regions within the modeling domain which have been identified for simulated albedo augmentation. Grey is unmodified, hashed is a modification of less than 0.10, and white is a modification in excess of 0.10. The average albedo increase over the 394 modified cells is 0.16; (b) temperature difference between high-albedo case and base case simulation at 9 a.m. (c) same as b except at noon; (d) same as b except at 3 p.m. Contour increment in b-d is 0.5 deg. C.