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Demonstration of Energy Savings of Cool Roofs

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H. Akbari, and L. Rainer

Environmental Energy Technologies Division

June 1998

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Demonstration of Energy Savings of Cool Roofs

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Abstract

Dark roofs raise the summertime air-conditioning demand of buildings. For highly-absorptive roofs, the difference between the surface and ambient air temperatures can be as high as 90°F, while for highly-reflective roofs with similar insulative properties, the difference is only about 20°F. For this reason, "cool" roofs are effective in reducing cooling energy use. Several experiments on individual residential buildings in California and Florida show that coating roofs white reduces summertime average daily air-conditioning electricity use from 2 - 63%

This demonstration project was carried out to address some of the practical issues regarding the implementation of reflective roofs in a few commercial buildings. We monitored air-conditioning electricity use, roof surface temperature, plenum, indoor, and outdoor air temperatures, and other environmental variables in three buildings in California: two medical office buildings in Gilroy and Davis and a retail store in San Jose.

Coating the roofs of these buildings with a reflective coating increased the roof albedo from an average of 0.20 - 0.60. The roof surface temperature on hot sunny summer afternoons fell from 175°F - 120°F after the coating was applied. Summertime average daily air-conditioning electricity use was reduced by 18% (6.3 kWh/1000ft^2) in the Davis building, 13% (3.6 kWh/1000ft^2) in the Gilroy building, and 2% (0.4 kWh/1000ft^2) in the San Jose store.

In each building, a kiosk was installed to display information from the project in order to educate and inform the general public about the environmental and energy-saving benefits of cool roofs. They were designed to explain cool-roof coating theory and to display real-time measurements of weather conditions, roof surface temperature, and air-conditioning electricity use.

Executive Summary

The use of dark roofs affects cooling and heating energy use in buildings and the urban climate. At the building scale, dark roofs are heated by the summer sun and thus raise the summertime air-conditioning (a/c) demand. For highly-absorptive (low-albedo†) roofs the difference between the surface and ambient air temperatures may be as high as 90°F on a summer afternoon. While for less absorptive (high-albedo) surfaces with similar insulative properties, such as roofs covered with a white coating, the difference is only about 20°F (Berdahl and Bretz 1997). For this reason, "cool" roofs (which absorb little insolation‡) can be effective in reducing cooling energy use. Earlier studies have suggested that cool roofs incur no additional cost if color changes are incorporated into routine re-roofing and re-surfacing schedules (Bretz et al 1998 and Rosenfeld et al 1995).

There is a sizable body of measured data (primarily collected for residential sector) documenting energy-saving effects of cool roofs as shown in **Table EX.1**. Both measured data and simulations clearly demonstrate that increasing the albedo of roofs is an attractive (and cost-effective) way of reducing the net radiative heat gains through the roof and hence, reducing building cooling loads. To change the albedo, the rooftops of buildings may be painted with reflective coatings or covered with a new light-colored material. Since most roofs have regular maintenance schedules or need to be re-roofed or re-coated periodically, the change of the albedo should be done then. In that case, the cost would be limited to the incremental cost associated with the high-albedo material. In buildings and climates with significant air-conditioning use, increasing the albedo of roofs will reduce energy use and produce a stream of savings immediately.

Why this project?

The question then is why reflective roofs are not used as widely as expected. One can offer a few answers:

1. For building owners and managers, the primary function of a roof is to protect the building. Energy savings are perceived as a secondary issue. The cost associated with repair and maintenance of a leaky roof far exceeds the energy saved by changing the reflectivity of the roof.
2. For existing buildings, the compatibility of a reflective roofing material with the existing roof is important. Many types of building materials, such as tar roofing, are not well adapted to painting. Although such materials could be specially designed to have a higher albedo, this would be at a greater expense than painting. Additionally, to maintain a high albedo, roofs may need to be re-coated on a regular basis. The cost of a regular

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† When sunlight hits a surface, some of the energy is reflected (this fraction is called the albedo = a) and the rest is absorbed (1-a). Low-a surfaces become much hotter than high-a surfaces.

‡ INcoming SOLar radiATION.

maintenance program could be significant.

3. A third factor is the durability of the albedo of the material. As a reflective roofing material is weathered and collects dust, its reflectively and hence its capability to save air-conditioning energy decreases.
4. Building owners and architects like to have the choice as to what color to select for their rooftops. This is particularly a concern for sloped roofs.
5. Most existing data are documenting savings for homes. For flat-roof low-rise commercial buildings that offer significant savings potentials, energy-saving data are scarce.
6. Finally, the lack of information and incentives for building owners and roofing contractors can be an important factor.

This project was designed to address some of the questions regarding the implementation of reflective roofs in a few commercial buildings. The objective of this project was to work with developers, industry, businesses, and utilities to develop and carry out up to three demonstration cases, in commercial buildings, to show effectively the impact of cool materials on building cooling energy use.

There were three target audiences for this demonstration: technical staff, corporate facility managers, and the general public. The technical audience is interested in valid scientific observations which further our knowledge about white roof coatings and energy savings. To meet this audiences expectations the instrumentation used on these buildings was comprehensive, including monitoring of air-conditioning electricity use, temperature measurements throughout the ceiling, plenum, and rooftop layers, and a weather tower to measure solar radiation, wind speed, air temperature, and humidity at each site.

The corporate facility managers and engineering and maintenance staff of the individual buildings need to be educated about the performance of light-colored roofs. The buildings chosen for this study were selected partly because they were facilities belonging to large corporations with hundreds of buildings under their control. The hope here was to educate key corporate personnel about the value of white coatings, stimulating their use on other buildings and spreading the word by example. Since the facilities managers were paying for their own coatings, we hoped to demonstrate cost-effectiveness, ease of application, and durability.

To educate and inform the general public about the environmental and energy-saving benefits of cool roofs, the buildings were also chosen for the high volume of people passing through them each day. Information kiosks were located conspicuously in each of the buildings. These kiosks introduced the concept of cool roofing and its role in saving energy and reducing pollution. In addition to the kiosks in each building, pages on the World Wide Web were published with the results of the demonstrations for the cyber-public.

Results

In this project we monitored air-conditioning electricity use, plenum, indoor, and outdoor air temperatures, roof surface temperature, and other environmental variables in three buildings in California:† two medical office buildings in Gilroy and in Davis and a retail store in San Jose. The following is the summary of findings.

Reduction in roof surface temperatures

In the Davis building, coating the roof with a reflective coating increased the roof albedo from 0.24 - 0.60. The roof surface temperature on hot sunny summer afternoons before coating was applied reached 175°F but only 120°F after coating. In the Gilroy building, coating the roof increased the roof albedo from 0.25 - 0.60; the roof surface temperature was reduced from 170°F - 120°F. In the San Jose building, coating the roof increased albedo from 0.16 - 0.60 and the roof surface temperature decreased from 175°F - 120°F. **Figure EX.1** is an infra-red photograph of the edge of the roof coating at Gilroy at the time of application.

Air-conditioning electricity savings

Summertime standard-weekday average daily air-conditioning savings are highlighted in **Table EX.1**, where electricity use was reduced by 18% (6.3 kWh/1000ft^2) in the Davis medical office building, 13% (3.6 kWh/1000ft^2) in the Gilroy medical office building, and 2% (0.4 kWh/1000ft^2) in the San Jose retail store. The most savings were seen in the Davis building since of the three buildings its roof system was least resistant to heat transfer (i.e. primarily R-8 rigid insulation) and it had an unvented return plenum. The Gilroy building utilizes similar shell construction and internal load characteristics as in the Davis building, but with two significant differences: R-19 fiberglass ceiling insulation and large passive roof vents; experienced about 25% less relative savings than in the Davis building. The air-conditioning electricity use in the San Jose retail store is internal-load driven, and the roof system contributes relatively little to the whole-building load, and thus the savings were least in this building (even though Δa was higher than in the medical office buildings). It has a well-ventilated plenum, which efficiently exhausts to the outdoors any heat that is transferred through a radiant barrier attached under the roof.

Experience in having the roofs coated

There were many unexpected difficulties in getting the rooftops coated with high-reflectance coatings. In this project the cost of the coatings were paid by the facility itself, and the coatings were applied by roofing contractors instead of by project personnel. One of the difficulties was associated with selling the coating based on its cost-effectiveness. Based on the projected energy savings of these coatings alone (2 - 5¢/ft^2) a roof coating is not very cost-effective. If the

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† We also subcontracted the Florida Solar Energy Center to carry out a similar demonstration project in Florida. The results of that effort are reported separately in Parker et al 1997.

coating can be used to lengthen the life of the roof and avoid replacement costs, it becomes much more economically attractive. Other difficulties arose in working with facility managers and roofing contractors. Neither group has much experience with or knowledge of high-reflectance coatings, leading to a hesitance to adopt this new technology. These people are also extremely busy, so scheduling meetings and work can be challenging. A set of information to collect and guidelines for coating costs were developed to help streamline the process of coating rooftops.

Display kiosk

Display kiosks were designed to explain cool-roof coating theory and to display real-time measurements of weather conditions, roof surface temperature, and air-conditioning electricity use to visitors of the buildings. They were situated in the lobby or a central area of each building so patrons would have easy access to them and could then learn about the cool-roofing project underway. **Figure EX.2** is a photo of the display kiosk in operation in the San Jose building.

Table EX.1. Monitored summertime daily air-conditioning electricity savings from cool-roof research in single-story residential and commercial buildings in California and Florida.

location	building type	1000ft^2	roof system description			daily a/c savings	
			insulation	duct location	Δ albedo	kWh/1000ft^2	%
California							
Davis	medical office(a)	31.7	R-8	cond. space	0.36	6.3	18
Gilroy	"	23.8	R-19	plenum	0.35	3.6	13
San Jose	retail store(a)	32.9	rad. bar.	plenum	0.44	0.4	2
Sacramento	school(b)(c)	1.0	R-19	ceiling	0.60	4.4	46
Sacramento	residence(b)	1.8	R-11	crawl space	0.59	1.3	63
Florida							
Cocoa Beach	residence (d)	1.2	none	attic	0.53	12.7	43
Cocoa Beach	"	1.3	none	attic	0.39	10.8	26
Cocoa Beach	"	1.3	R-11	attic	0.52	7.9	25
Merritt Island	"	1.7	R-11	attic	0.44	6.8	20
West Florida	"	0.9	none	none	0.53	6.2	25
Miami	"	1.4	R-11	attic	0.30	5.9	15
Cape Canaveral	"	1.4	R-11	attic	n/a	5.4	22
Cocoa Beach	"	1.5	R-19	attic	0.42	2.9	13
Merritt Island	"	1.8	R-25	attic	0.51	2.2	11
Palm Bay	"	1.5	R-19	attic	0.44	2.1	10
Palm Bay	"	1.8	R-19	attic	0.42	0.5	2
Cocoa Beach	strip mall (e)	12.5	R-11	plenum	0.46	0.7	25

a This report.

b Akbari, H., et al. 1997. *Peak Power and Cooling Energy Savings of High-Albedo Roofs.* Energy and Buildings. vol. 25, no. 2, pp. 117-126.

c Two identical school bungalows.

d Parker, D., et al. 1998. *Measured and Simulated Performance of Reflective Roofing Systems in Residential Buildings.* ASHRAE Transactions, vol. 104, pt. 1.

e Parker, D., et al. 1997. *Demonstration of Cooling Savings of Light Colored Roof Surfacing in Florida Commercial Buildings: Retail Strip Mall.* Florida Solar Energy Center Report FSEC-CR-964-97.

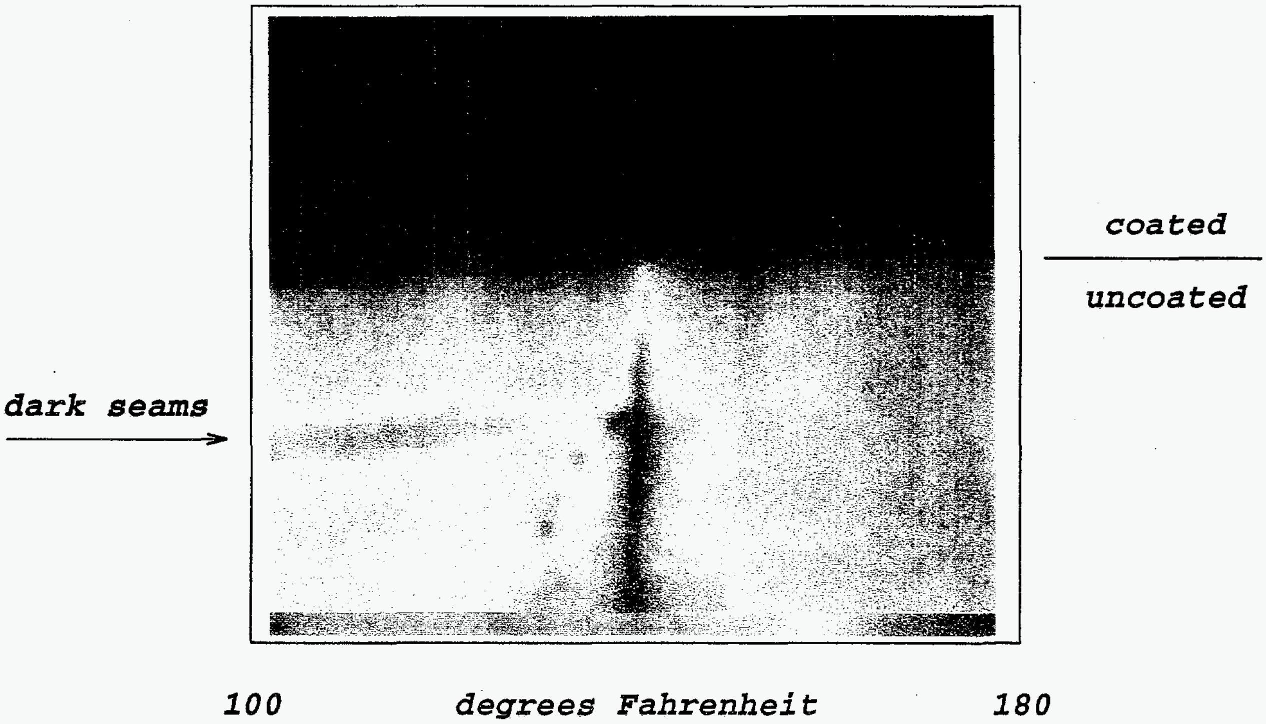

Figure EX.1. Infra-red photograph of roof-coating edge at Gilroy.

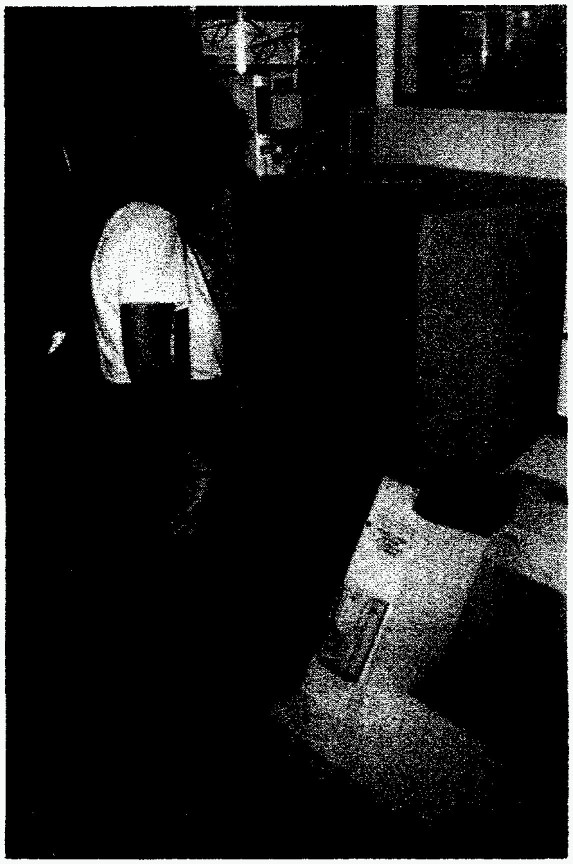

Figure EX.2. Kiosk in operation at the San Jose site.

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1.0 Introduction

1.1 Background

The use of dark roofs affects cooling and heating energy use in buildings and the urban climate. At the building scale, dark roofs are heated by the summer sun and thus raise the summertime air-conditioning (a/c) demand. For highly-absorptive (low-albedo[1]) roofs the difference between the surface and ambient air temperatures may be as high as 90°F on a summer afternoon. While for less absorptive (high-albedo) surfaces with similar insulative properties, such as roofs covered with a white coating, the difference is only about 20°F (Berdahl and Bretz 1997). For this reason, "cool" roofs (which absorb little insolation[2]) can be effective in reducing cooling energy use. Earlier studies have suggested that cool roofs incur no additional cost if color changes are incorporated into routine re-roofing and re-surfacing schedules (Bretz et al 1998 and Rosenfeld et al 1995).

There is a sizable body of measured data (primarily collected for residential sector) documenting energy-saving effects of cool roofs as shown in **Table 1.1**. In the summers of 1991 and 1992, Akbari et al (1997) monitored peak power and cooling-energy savings from high-albedo coatings at one house and two identical school bungalows in Sacramento, California. Applying a high-albedo coating to one house resulted in summertime average daily savings of 1.3 kWh/1000ft^2 (63% of base case use) and peak demand reductions of 0.33 kW/1000ft^2 (about 25% of base case demand). In the school bungalows[3], cooling energy was reduced by 4.4 kWh/1000ft^2 (46% of base case use) and peak demand by 0.6 kW/1000ft^2 (about 20% of base case demand).

Parker et al (1998) report monitored energy savings in eleven Florida homes after applying high-albedo coatings to their roofs. Daily air-conditioning energy use was reduced by 2 - 43%, with an average savings of 5.8 kWh/1000ft^2 (19% of low-albedo use). Peak demand between 5 and 6pm was reduced by 0.2 - 1.0 kW, with an average reduction of 0.4 kW (22% of low-albedo demand). In general, energy savings were inversely correlated with the level of ceiling insulation and duct system location: large savings in poorly insulated homes and those with duct systems in the attic space and smaller savings in well-insulated homes.

Parker et al (1997) have monitored seven retail stores with R-11 ceiling insulation within a strip mall in Florida before and after applying high-albedo coatings to the roof. Average daily summertime space cooling energy dropped 0.7 kWh/1000ft^2 (25%).

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[1] When sunlight hits a surface, some of the energy is reflected (this fraction is called the albedo = a) and the rest is absorbed (1-a). Low-a surfaces become much hotter than high-a surfaces.

[2] INcoming SOLar radiATION.

[3] Gartland et al (1996) report that DOE-2 simulations under-estimated the cooling-energy savings and peak power reductions by as much as twofold.

Table 1.1. Monitored summertime daily air-conditioning electricity savings from previous cool-roof research in single-story residential and commercial buildings in California and Florida.

location	building type	$1000ft^2$	roof system description			daily a/c savings	
			insulation	duct location	Δ albedo	$kWh/1000ft^2$	%
California							
Sacramento	school(a)(b)	1.0	R-19	ceiling	0.60	4.4	46
Sacramento	residence(a)	1.8	R-11	crawl space	0.59	1.3	63
Florida							
Cocoa Beach	residence (c)	1.2	none	attic	0.53	12.7	43
Cocoa Beach	"	1.3	none	attic	0.39	10.8	26
Cocoa Beach	"	1.3	R-11	attic	0.52	7.9	25
Merritt Island	"	1.7	R-11	attic	0.44	6.8	20
West Florida	"	0.9	none	none	0.53	6.2	25
Miami	"	1.4	R-11	attic	0.30	5.9	15
Cape Canaveral	"	1.4	R-11	attic	n/a	5.4	22
Cocoa Beach	"	1.5	R-19	attic	0.42	2.9	13
Merritt Island	"	1.8	R-25	attic	0.51	2.2	11
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Cocoa Beach	strip mall (d)	12.5	R-11	plenum	0.46	0.7	25

a Akbari, H., et al. 1997. *Peak Power and Cooling Energy Savings of High-Albedo Roofs.* Energy and Buildings. vol. 25, no. 2, pp. 117-126.

b Two identical school bungalows.

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d Parker, D., et al. 1997. *Demonstration of Cooling Savings of Light Colored Roof Surfacing in Florida Commercial Buildings: Retail Strip Mall.* Florida Solar Energy Center Report FSEC-CR-964-97.

A recent study has made quantitative estimates of annual cooling electricity and peak demand savings that would result from increasing the reflectivity of roofs (Konopacki et al 1997). The estimates of cooling electricity savings were adjusted for the increased wintertime heating energy use. The analysis was based on DOE-2.1E building energy use simulations. The study has specified 11 prototypical buildings: single-family residential (old and new), office (old and new), retail store (old and new), school (primary and secondary), health (hospital and nursing home), and grocery store. Building stock and weather data for 11 U.S. Metropolitan Statistical Areas (MSAs) were used: Atlanta, Chicago, Los Angeles, Dallas/Fort Worth, Houston, Miami/Fort Lauderdale, New Orleans, New York City, Philadelphia, Phoenix, and Washington DC/Baltimore. Sum totals for all 11 MSAs were: annual electricity savings of 2.6 terawatt hours (TWh) (200 kilowatt hours per $1000ft^2$ roof area of air-conditioned buildings) and net savings in annual energy bills of \$194M (\$15 per $1000ft^2$). Six building types accounted for over 90% of the annual electricity and net energy savings: old residences accounted for more than 55%, new residences about 15%, and four other building types (old/new offices and old/new retail stores) together about 25%. The study estimates that, nationally, light-colored roofing could produce savings of about 10 TWh/yr (about 3% of the national cooling electricity use in residential and commercial buildings) and a decrease in net annual energy bills for the rate-payers of \$750M.

Both measured data (of course mostly for residential sector) and simulations clearly demonstrate that increasing the albedo of roofs is an attractive (and cost-effective) way of reducing the net radiative heat gains through the roof and hence, reducing building cooling loads. To change the albedo, the rooftops of buildings may be painted with reflective coatings or covered with a new high-albedo material. Since most roofs have regular maintenance or need to be re-roofed or re-coated periodically, the change of the albedo should be done then. In that case, the cost would be limited to the incremental cost associated with the change in albedo. In buildings and climates with significant air-conditioning use, increasing the albedo of roofs will reduce air-conditioning energy use and produce a stream of savings immediately.

Why this project?

The question then is why reflective roofs are not used as widely as expected. One can offer a few answers:

1. For building owners and managers, the primary function of a roof is to protect the building. Energy savings consideration is perceived as a secondary issue. The cost associated with repair and maintenance of a leaky roof far exceeds the energy saved by changing the reflectivity of the roof.
2. For existing buildings, the compatibility of a reflective roofing material with the existing roof is important. Many types of building materials, such as tar roofing, are not well-adapted to painting. Although such materials could be specially designed to have a higher albedo, this would be at a greater expense than painting. Additionally, to maintain a high albedo, roofs may need to be re-coated on a regular basis. The cost of a regular maintenance program could be significant.

3. A third factor is the durability of albedo of the material. As a reflective roofing material is weathered and collects dust, its reflectivity and hence its capability to save air-conditioning energy decreases.
4. Most existing data are documenting savings for homes. For flat-roof low-rise commercial buildings that offer significant savings potentials, measured energy-saving data are scarce.
5. Finally, the lack of information and incentives for building owners and roofing contractors can be an important factor.

Aside from the above issues, Bretz et al (1998) discusses two other possible deterrent factors:

- A drastic increase in the overall albedo of many roofs in a city has the potential to create glare and visual discomfort if not kept to a reasonable level. Extreme glare could increase the danger of the incidence of traffic accidents. Fortunately, for flat roofs, the glare is not a major problem for those who are under the canopy of buildings. For sloped roofs, the problem of glare should be studied in detail before a full-scale implementation of this measure proceeds.
- Building owners and architects like to have the choice as to what color to select for their rooftops. This is particularly a concern for sloped roofs which are visible from ground level.

This project .was designed to address some of the questions regarding the implementation of reflective roofs in a few commercial buildings.

1.2 Project Objectives

The objective of this project was to work with developers, industry, businesses, and utilities to develop and carry out up to three demonstration cases, in commercial buildings, to show effectively the impact of cool materials on building air-conditioning energy use. The elements of the project included:

- Identifying target demonstration sites
- Negotiating with owners to encourage the use of cool materials
- Encouraging utilities to participate in and share cost of the demonstrations
- Designing, procuring, and installing monitoring systems for measurements
- Installing systems to showcase the demonstration sites
- Developing materials to increase public awareness for use of cool roofs.

1.3 Target Audience and Goals

There were three target audiences for this demonstration: technical staff, corporate facility managers, and the general public. The technical audience is interested in valid scientific observations which further our knowledge about white roof coatings and energy savings. To meet this audiences expectations the instrumentation used in these buildings was comprehensive, including monitoring of air-conditioning electricity use, temperature measurements throughout the ceiling, plenum, and rooftop layers, and a weather tower to measure solar radiation, wind speed, air temperature, and humidity at each site.

The corporate facility managers and engineering and maintenance staff of the buildings need to be educated about the performance of cool roofs. The buildings chosen for use in this study were selected partly because they were facilities belonging to large corporations with hundreds of buildings under their control. The hope here was to educate key corporate personnel about the value of white coatings, stimulating their use in other buildings and spreading the word by example. Since the facilities managers were paying for their own coatings, we hoped to demonstrate cost-effectiveness, ease of application, and durability.

To educate and inform the general public about the environmental and energy-saving benefits of cool roofs, the buildings were also chosen for the high volume of people passing through them every day. Information kiosks were located conspicuously in each of the buildings. These kiosks introduced the concept of white roofing and its role in saving energy and reducing pollution. The kiosks contained a personal computer with a touchscreen monitor for displaying current weather conditions, rooftop temperatures, and building air-conditioning energy use. By visiting the kiosks, the public could get direct exposure to the impact of roof albedo on roof temperature and building cooling energy use. The kiosks screens were placed on the World Wide Web for the cyber-public.

2.0 Methodology

2.1 Description of Buildings

Based on the project objectives and goals, three commercial buildings in Northern California were selected: Kaiser Permanente medical office buildings in Gilroy and Davis and a Longs Drug retail store in San Jose. All three buildings are single-story with flat/low-slope (less than 3°) roofs and use asphalt based capsheet[4] as their roofing material. The characteristics of these buildings with emphasis on the roof system are listed in **Table 2.1** and mechanical equipment schedules in **Table 2.2**. Details of these building are described below.

Davis

The Davis building is 31,700ft^2 with a hermetic reciprocating air-cooled chiller and a gas boiler. It has four variable-volume air-handling units with hot water reheat, which use a minimum of 20% outside air. Supply air ducts are located in the conditioned spaces. The roof is built-up with light-gray granules and had a solar reflectance of 24%. There is R-8 rigid insulation and an unvented return plenum located underneath. **Figures 2.1** and **2.2** are photographs of the Davis building (elevation and rooftop). The rooftop of the Davis building was given two coats of *Sunwhite*[5] elastomeric roof coating on April 12, 1997. The reflectance of this type of bright white coating product has a laboratory-measured value of 70% or higher on a smooth surface. The capsheet roof is fairly rough, which tends to absorb more sunlight and thus lower reflectances. The field-measured reflectance of the Davis post-coated rooftop was 60%.

Gilroy

One half of the Gilroy building was monitored as the other half was undergoing occupancy changes during the monitoring period. The monitored half of the building is 23,800ft^2 with seven roof-mounted packaged single-zone air conditioners. They are variable-air-volume units with gas heating. The roof is built-up with light-gray granules and had a solar reflectance of 25%. There is a ventilated plenum with supply ducts located underneath and R-19 fiberglass ceiling insulation over a dropped ceiling. **Figures 2.3** and **2.4** are photographs of the Gilroy building (elevation and rooftop). The rooftop of the Gilroy building was given two coats of *Sunwhite* elastomeric roof coating on August 5, 1996, and had a post-coating field-measured reflectance of 60%.

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[4] Capsheet roofing is similar to residential asphalt roofing tiles, with surface granules pressed into asphalt-saturated felt fibers, but capsheet roofing comes in large sections of about 4 feet by 10 feet.

[5] Asphalt Products Oil Corporation.

Table 2.1. Building descriptions.

	Davis	Gilroy	San Jose
type	Kaiser Permanente medical office single-story 31,700 ft^2	Kaiser Permanente medical office single-story 23,800 ft^2	Longs Drugs retail store single-story 32,900 ft^2
roof			
materials	built-up asphalt capsheet w/ light-gray granules R-8 rigid metal deck return plenum ceiling tiles	built-up asphalt capsheet w/ light-gray granules wood deck ventilated plenum R-19 fiberglass ceiling tiles	built-up asphalt capsheet w/ tan granules wood deck radiant barrier ventilated plenum ceiling tiles
age	5 years	10 years	5 years
pre-coating condition	25% granule loss and bubbling	50% granule loss and cracking	25% granule loss and cracking
solar reflectance (pre)	0.24	0.25	0.16
solar reflectance (post)	0.60	0.60	0.60
supply duct			
insulation	none	R-4.6	R-2
location	conditioned space	plenum	plenum
mechanical schedules	Table 2.2	Table 2.2	Table 2.2

Table 2.2. Mechanical equipment schedules.

System	Fans			Cooling				Fans & Cooling		Heating Input	
	cfm	kW	W/cfm	Capacity		Input	EER			kW	kBtu/hr
				kBtu/hr	tons	kW		kW	EER		
Davis: reciprocating air-cooled chiller w/ variable-air-volume, min-out-air ~20%, and hot water reheat: gas boiler											
AHU-1	17500	20	1.1								
AHU-2	8500	10	1.2								
AHU-3	7800	10	1.3								
AHU-4	9700	15	1.6								
CH-1				1157	96.4						
TOTAL	43500	55	1.3	1157	96.4			135.1	8.6		
Gilroy: packaged-single-zone w/ variable-air-volume and gas heating											
AC-1	2000	1.0	0.5	58	4.8			7.9	7.3		75
AC-2	2500	1.5	0.6	92	7.7			10.0	9.2		114
AC-3	1320	0.8	0.6	36	3.0			5.1	7.1		75
AC-4	5000	3.0	0.6	149	12.4			18.6	8.0		154
AC-5	5300	3.0	0.6	149	12.4			18.6	8.0		154
AC-6	3000	1.5	0.5	92	7.7			10.0	9.2		114
AC-7	5200	3.0	0.6	149	12.4			18.6	8.0		154
TOTAL	24320	13.8	0.6	725	60.4			88.8	8.2		840
San Jose: packaged-single-zone w/ constant-air-volume, electric reheat, and two-staged compressor: heat pump											
AH-1	27300	20	0.7								
CU-1				350	29.2	50	7.0				
CU-2				350	29.2	50	7.0				
DH-1										40(2)	
DH-2										2	
DH-3										3	
TOTAL	27300	20	0.7	700	58.3	100	7.0	120	5.8	85	
HP-1					5						

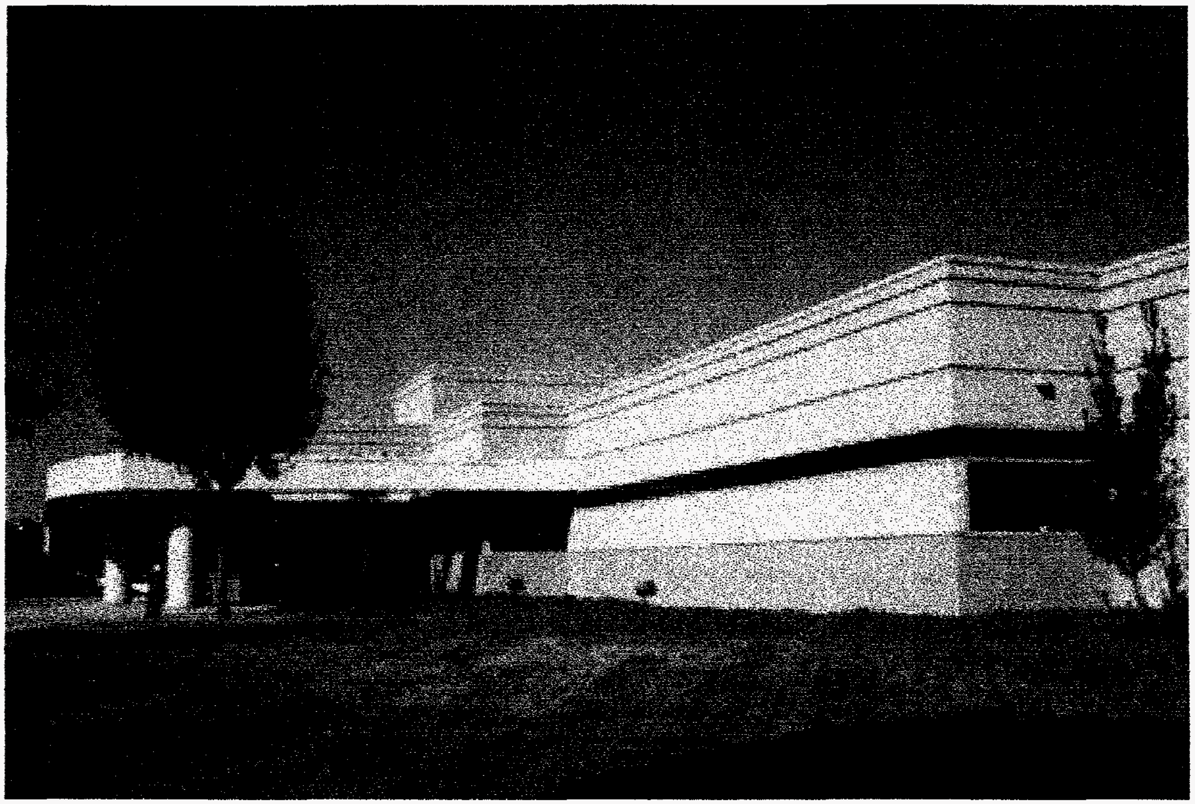


Figure 2.1. Kaiser Permanente Medical Office Building in Davis, California.

Figure 2.2 Rooftop of the Kaiser Permanente Medical Office Building in Davis, California, light gray capsheet with solar reflectance of 0.24.

Figure 2.3 Kaiser Permanente Medical Office Building in Gilroy, California.

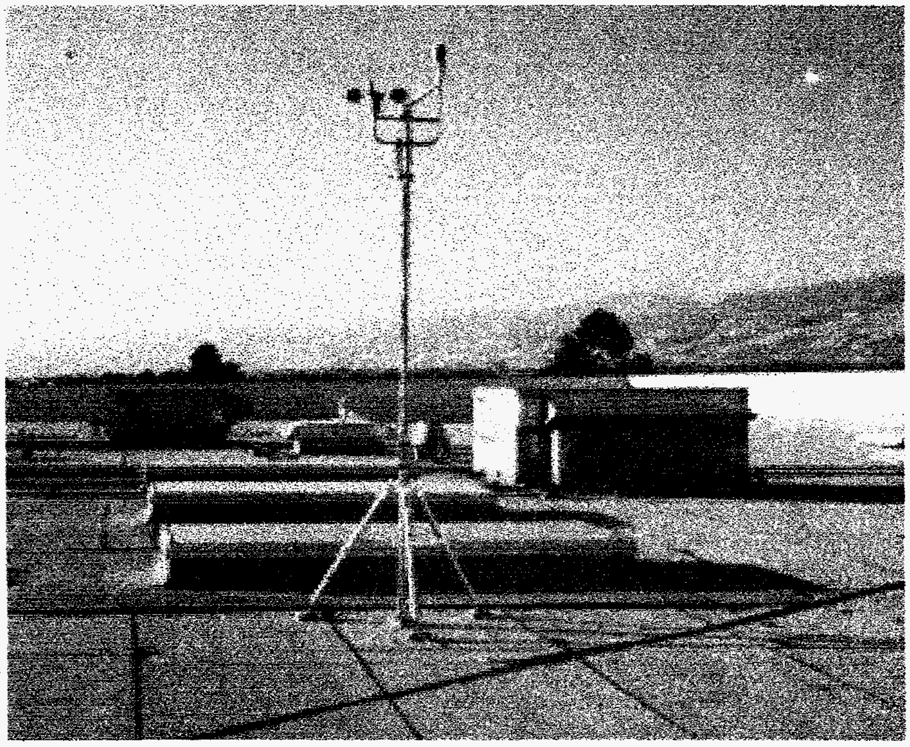


Figure 2.4 Rooftop of Kaiser Permanente Medical Office Building in Gilroy, California, light gray capsheet with solar reflectance of 0.25.

San Jose

The San Jose building is 33,000ft^2 with a constant-volume roof-mounted packaged single-zone air conditioner, where a sales area accounts for 26,000ft^2 and an unconditioned mezzanine for 7,000ft^2. It operates with a two-staged compressor and electric reheat. There is a five-ton heat pump servicing the pharmacy. The roof is built-up with tan granules and had a solar reflectance of 16%. There is a radiant barrier and a well-ventilated plenum with supply ducts located underneath. There is a dropped ceiling in place above the sales zone of "loose" construction. It provides a low-resistive path for evacuation of air from the sales space to the plenum above, which is then exhausted outdoors. **Figures 2.5** and **2.6** are photographs of the San Jose building (elevation and rooftop). The rooftop of the San Jose building was given two coats of *Sunwhite* elastomeric roof coating on March 24, 1997, and had a post-coating field-measured reflectance of 60%.

2.2 Instrumentation and Data Acquisition Systems

Instruments measured the weather conditions on the roof of each building, total and air-conditioning electricity use, heat flux through the roof, and temperatures inside the buildings and throughout the roof layers. The weather variables were all measured on a ten foot weather tower located at the approximate center of each rooftop. Multiple sets of roof/plenum measurements were made on each building, with the roof surface, roof underside, plenum, and inside temperatures stacked at the same locations. The inside temperatures were not always aligned with the roof and plenum locations due to difficulties accessing the correct inside locations. **Figures 2.7 - 2.9** are roof plans of each building and identify where the instrumentation was located on the roof. **Table 2.3** lists the parameters monitored at each building. **Figures 2.10 - 2.13** are photographs of a weather tower, roof surface temperature sensor, an air conditioner power panel, and a data logger.

Instrumentation was wired into a data logger, which was in turn hooked up to an IBM clone personal computer with an internal modem hooked to a phone line. The PC has ProComm Plus for Windows software operating in the background. Every 15 minutes the data logger sends data to the PC. The ProComm Plus software sends these data to two files: an archive file and a file containing all data collected for the previous 168 hours (weekly file). ProComm Plus also maintains a bulletin board in the background, which allows the archive file to be downloaded remotely by calling into the PC. A detailed list of the instrumentation and equipment used, including its manufacturer and cost, is in **Appendix A**.

The PC is in a kiosk located in a central area of the building. The PC has a touch screen monitor with Quattro Pro for Windows software running in the foreground to display the data collected at the site. In response to a building occupant touching a button on the screen, Quattro Pro will display the preferred page of information about the project. These pages contain plots of real-time weather, temperature, and energy use data, as well as more general information about the project and white roof coatings. To keep the plots up to date, Quattro Pro imports the latest weekly file whenever more than 15 minutes have elapsed since the last screen touch.

Figure 2.5 Longs Drug Store in San Jose, California.

Figure 2.6 Rooftop of Long's Drug Store in San Jose California, tan capsheet with 0.16 solar reflectance.

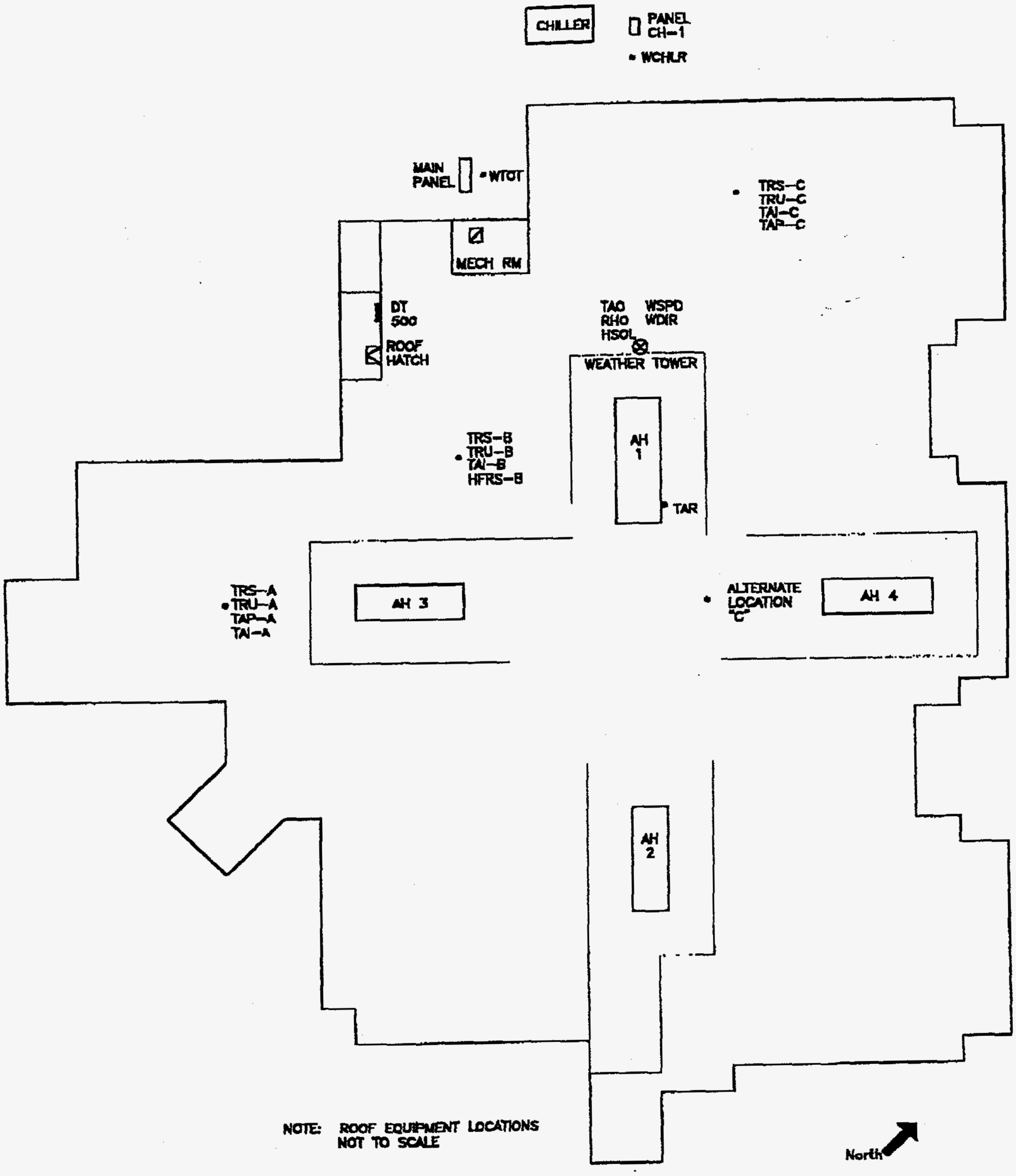
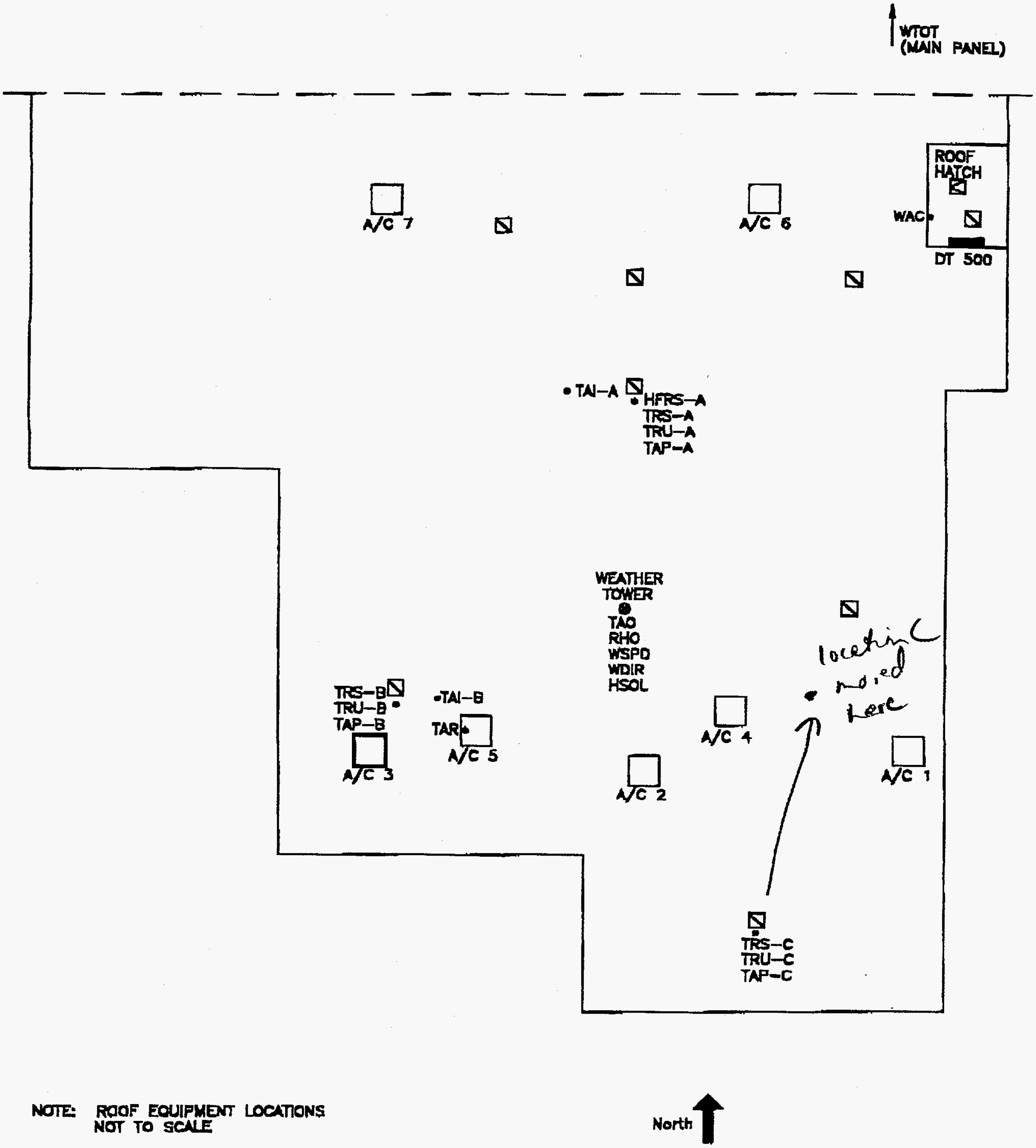


Figure 2.7. Davis roof plan.



NOTE: ROOF EQUIPMENT LOCATIONS
NOT TO SCALE

Figure 2.8. Gilroy roof plan.

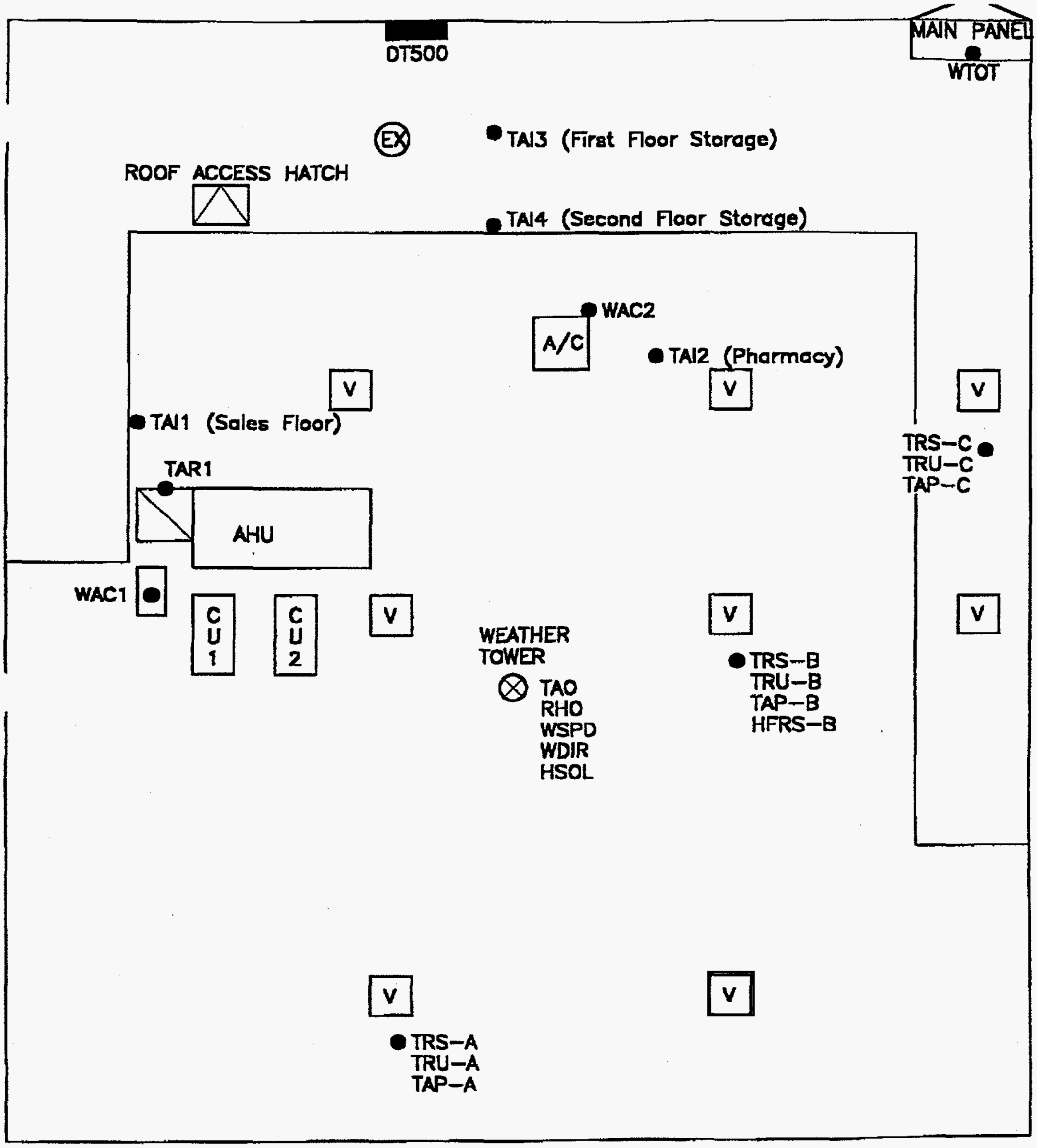


Figure 2.9. San Jose roof plan.

In addition to the parameters measured by the data logging system, the rooftop solar reflectance was measured before and after the rooftops were coated. These measurements were made using an Eppley pyranometer and ASTM Standard 1918-97 (ASTM 1998).

Table 2.3. Parameters measured at each building and instrumentation used.

parameter	number	instrumentation
Weather		
wind speed	1	3 cup anemometer
wind direction	1	wind vane
outdoor temperature	1	platinum RTD in gill radiation shield
outdoor relative humidity	1	capacitive humidity sensor in gill radiation shield
horizontal solar radiation	1	silicon photodiode pyranometer
Energy		
whole-building electricity use	1	power transducer / current transformer
cooling electricity use	1	power transducer / current transformer
roof surface heat flux	1	thermopile thermal flux transducer
Temperature		
roof surface	3	platinum RTD
roof underside	3	platinum RTD
plenum air	2 - Davis 3 - Gilroy 3 - San Jose	LM34 semiconductor
inside air	3 - Davis 2 - Gilroy 4 - San Jose	LM34 semiconductor
return air	1	LM34 semiconductor

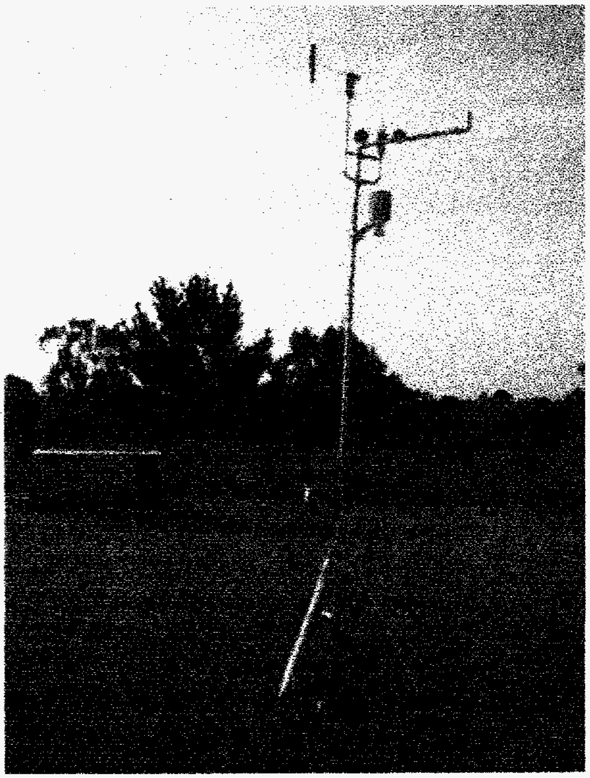


Figure 2.10. Weather tower.

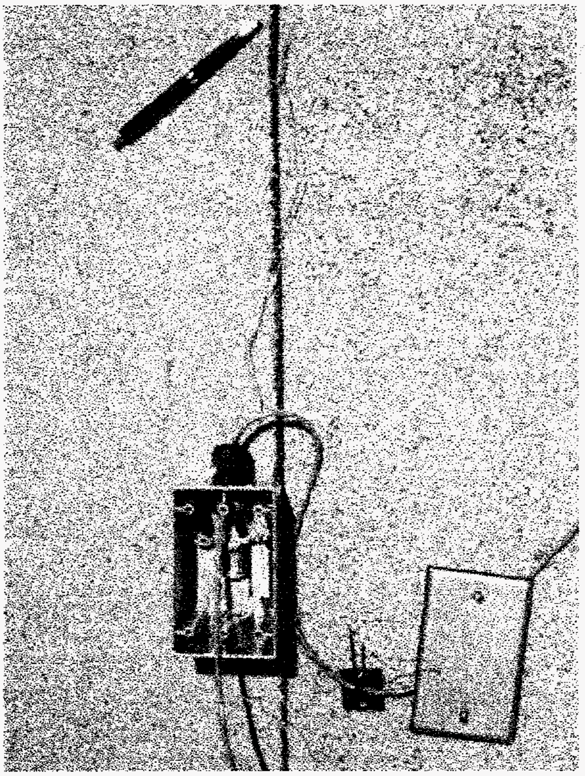


Figure 2.11. Roof surface temperature sensor.

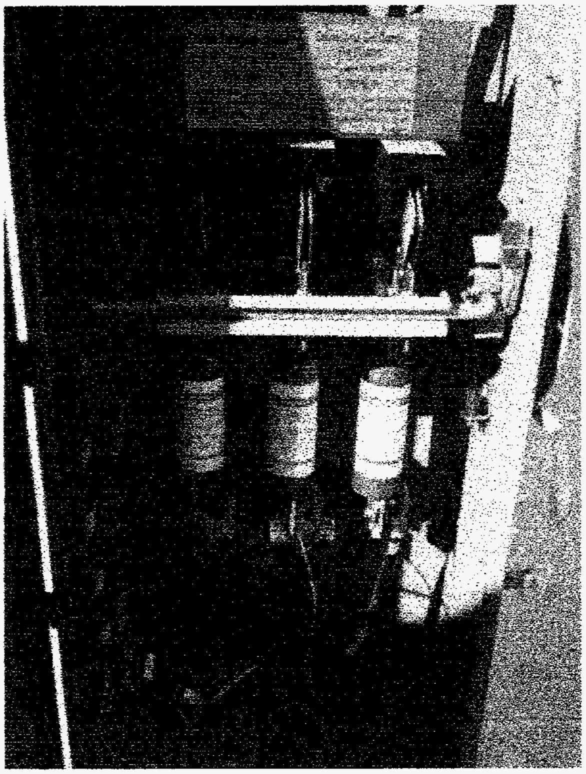


Figure 2.12. Chiller panel.

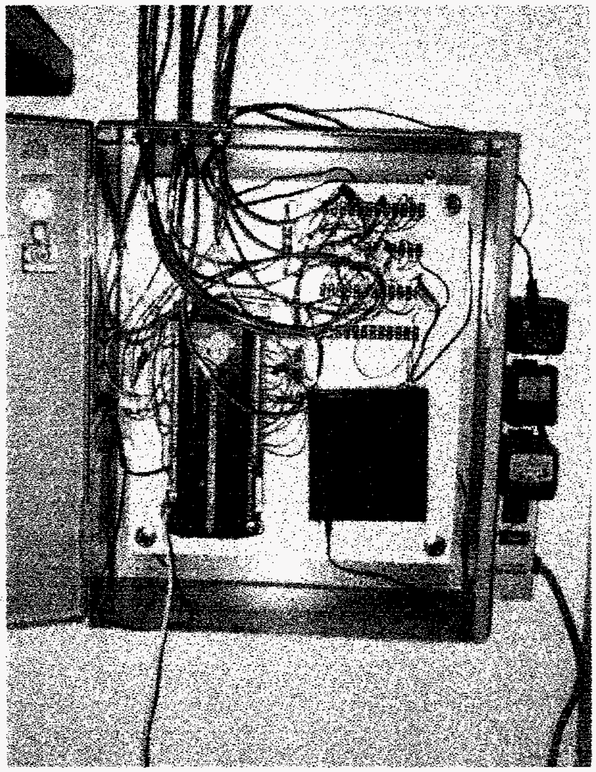


Figure 2.13. Data logger.

2.3 Data Collection

Data was collected on 15-minute intervals beginning June 1, 1996 and ending September 30, 1997. These data were plotted weekly for inspection. As an example, San Jose data for the week of August 18 - 24, 1997, is plotted in **Figure 2.14**. Questionable or missing data, holidays, and days with abnormal operation were identified in this manner. Also visible was the weekday versus weekend variation in air-conditioning electricity use. Davis and Gilroy typically were not operating during the weekends and holidays, whereas San Jose was operating on weekends but not on holidays.

Before the analysis could begin the final data base was prepared. Days with questionable or missing data were identified and removed from the domain, since only complete days were to be used. Holidays and weekends were not included in the data base. At this point the data were considered "validated" and consisted of only "standard weekdays".

2.4 Data Analysis Technique

The flow diagram in **Figure 2.15** illustrates the data analysis technique. The first step in the analysis was to convert the validated 15-minute data into hourly data by summing the a/c and total electricity use and averaging the remainder of the variables. From these data average daily profiles were derived for a/c electricity use, outdoor and indoor air temperatures, and the temperatures through the roof layers by month and for both pre- and post-coating periods. Also, scatter plots showing the dependence of a/c electricity use on outdoor air temperature were created.

Second, we converted the hourly data into daily data by summing the a/c electricity use and averaging the outdoor air temperature. At this point, multi-variate regressions performed on the summertime data, with daily a/c electricity use as the dependent variable and average daily outdoor air temperature as the independent variable, generated a single slope and eight y-intercepts (one for each month) or a single slope and two intercepts (one for the pre-coating period and one for the post). The decision to use daily average outdoor air temperature as the regressor variable is defended in **Appendix C**.

The third and final step was to normalize the monitored average daily a/c electricity use for temperature based on the slope found from the regressions in order to make constant temperature month-to-month and pre-period-to-post-period comparisons possible.

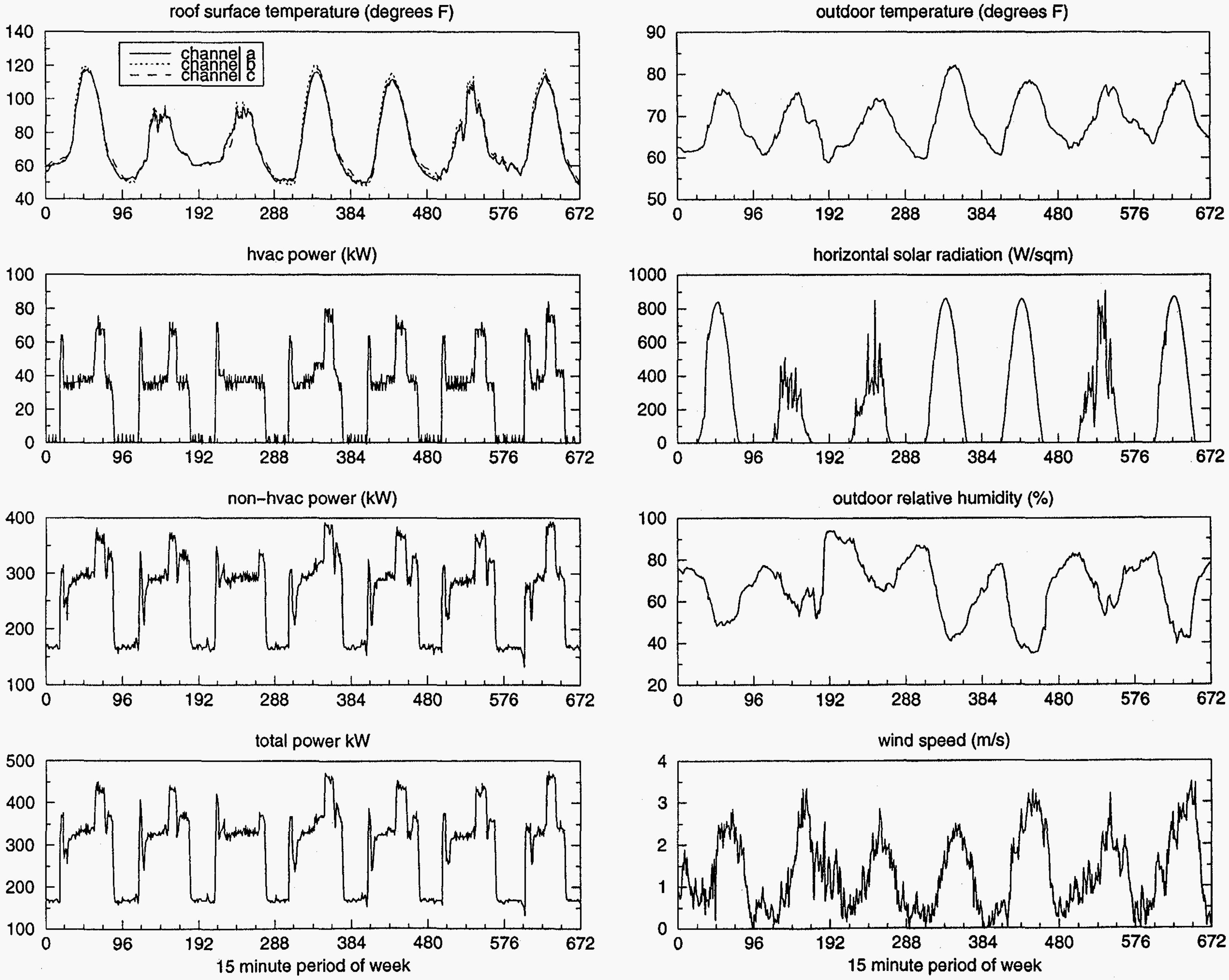


Figure 2.14. San Jose monitored 15 minute data for the week of August 18 - 24, 1997.

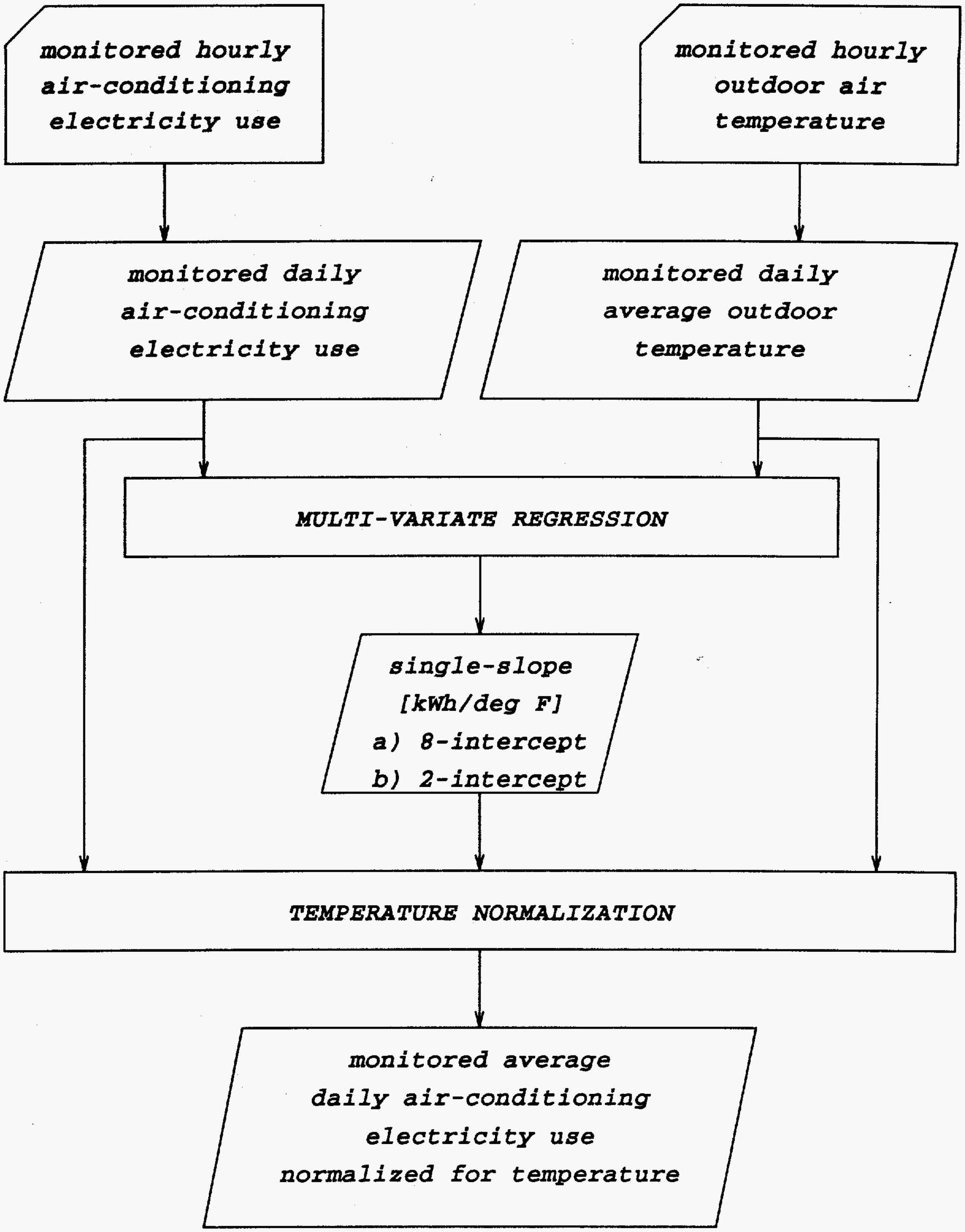


Figure 2.15. Data analysis flow diagram.

3.0 Data Analysis and Results

3.1 Data Summary

Figures 3.1a and **3.1b** display the monitored data averaged on one-hour intervals collected at the Davis building during June 1, 1996 - September 30, 1997. The same data for the Gilroy and San Jose buildings are shown in **Figures 3.2a, 3.2b, 3.3a,** and **3.3b**. Data collection at the Gilroy building did not begin until June 12, 1996, and the San Jose site was not monitored during March 5 - 24, 1997. These data clearly show the strong seasonal and daily dependency of some of the monitored data such as the air-conditioning electricity use and ambient air and roof surface temperatures. In the Davis building, the pre-coating roof surface temperature on hot sunny summer afternoons reached 175°F but only 120°F after coating, in Gilroy it was reduced from 170°F to 120°F, and in San Jose the reduction was 175°F - 120°F. The air-conditioning electricity use data in the Davis and Gilroy buildings show the difference between the weekday and weekend schedules in the building operation.

A summary of the monitored cooling electricity use (monthly total and daily average) and the daily average outdoor air temperature is shown in **Table 3.1** by month. Also, the number of standard weekdays with validated data are identified in the table. Holidays, weekends, and weekdays with questionable or missing data were excluded from the analysis with the remainder defined as "standard weekday". The database used in the analysis contained only standard weekdays for the summer months of June, July, August, and September, 1996 and 1997.

3.2 Comparison of Weather at the Three Sites

A comparison of 1996 and 1997 summer season degree-days at all three sites revealed that Davis was the most cooling intensive and the least heating intensive and Gilroy was the most heating intensive. Davis had a total of 2429 cooling degree-days[6] during the 1996 and 1997 summer seasons, compared to 1402 for Gilroy and 1403 for San Jose, and a total of 381 heating degree-days[7] compared to 863 and 522 for Gilroy and San Jose, respectively. **Table 3.2** shows cooling and heating degree-days for the 1996 and 1997 summer seasons of June - September and for the twelve month period of June 1996 - May 1997. Davis being the northern most site had the lowest maximum insolation measurement, which was 987W/m^2, compared to 1021W/m^2 and 1017W/m^2 for Gilroy and San Jose, respectively. The min/max hourly outdoor air temperatures were 28/107°F, 28/104°F, and 29/99°F for Davis, Gilroy, and San Jose, respectively.

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[6] cooling degree-days were calculated at a base temperature of 65°F

[7] heating degree-days were calculated at a base temperature of 65°F

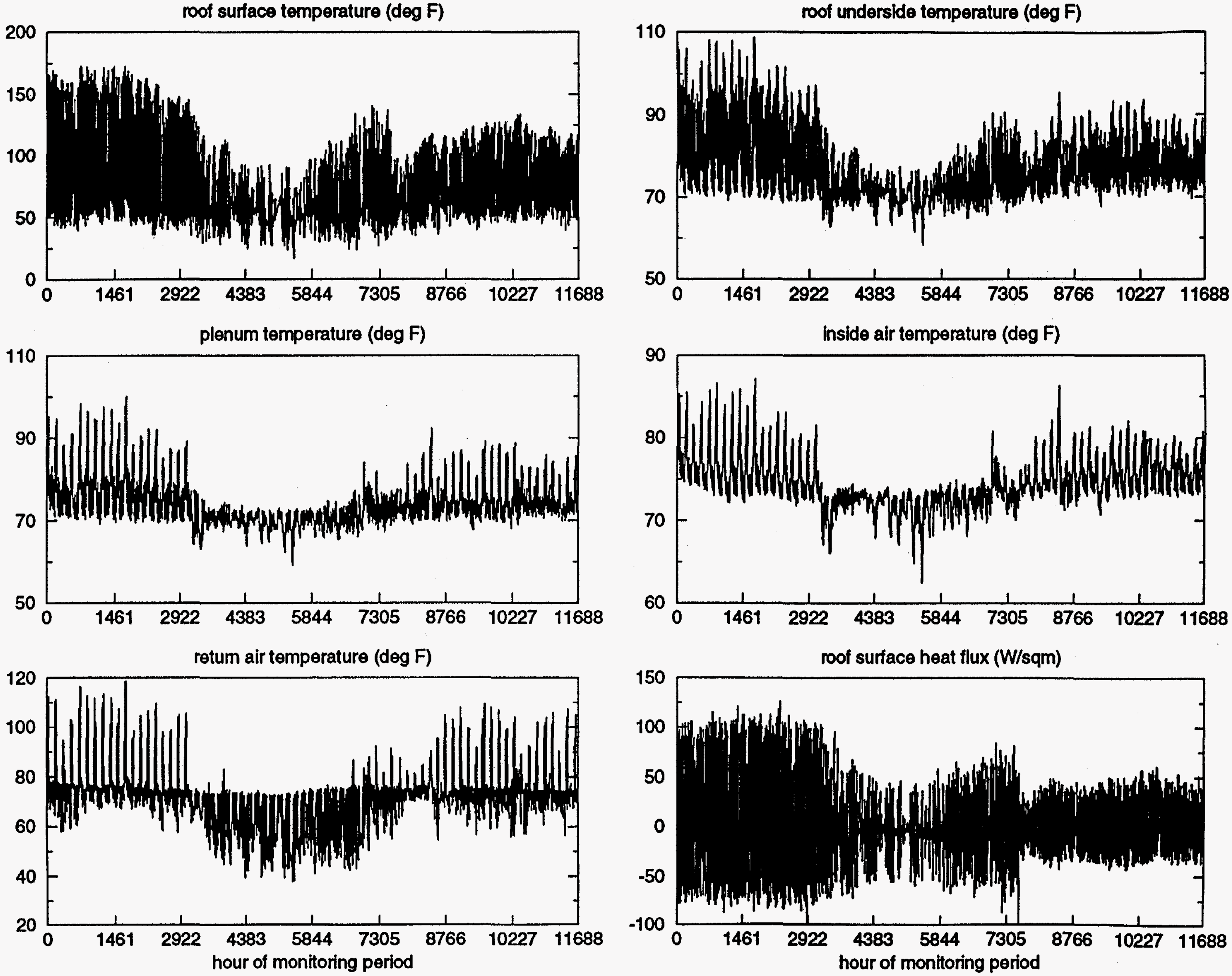


Figure 3.1. Davis monitored hourly data from June 1996 - September 1997.

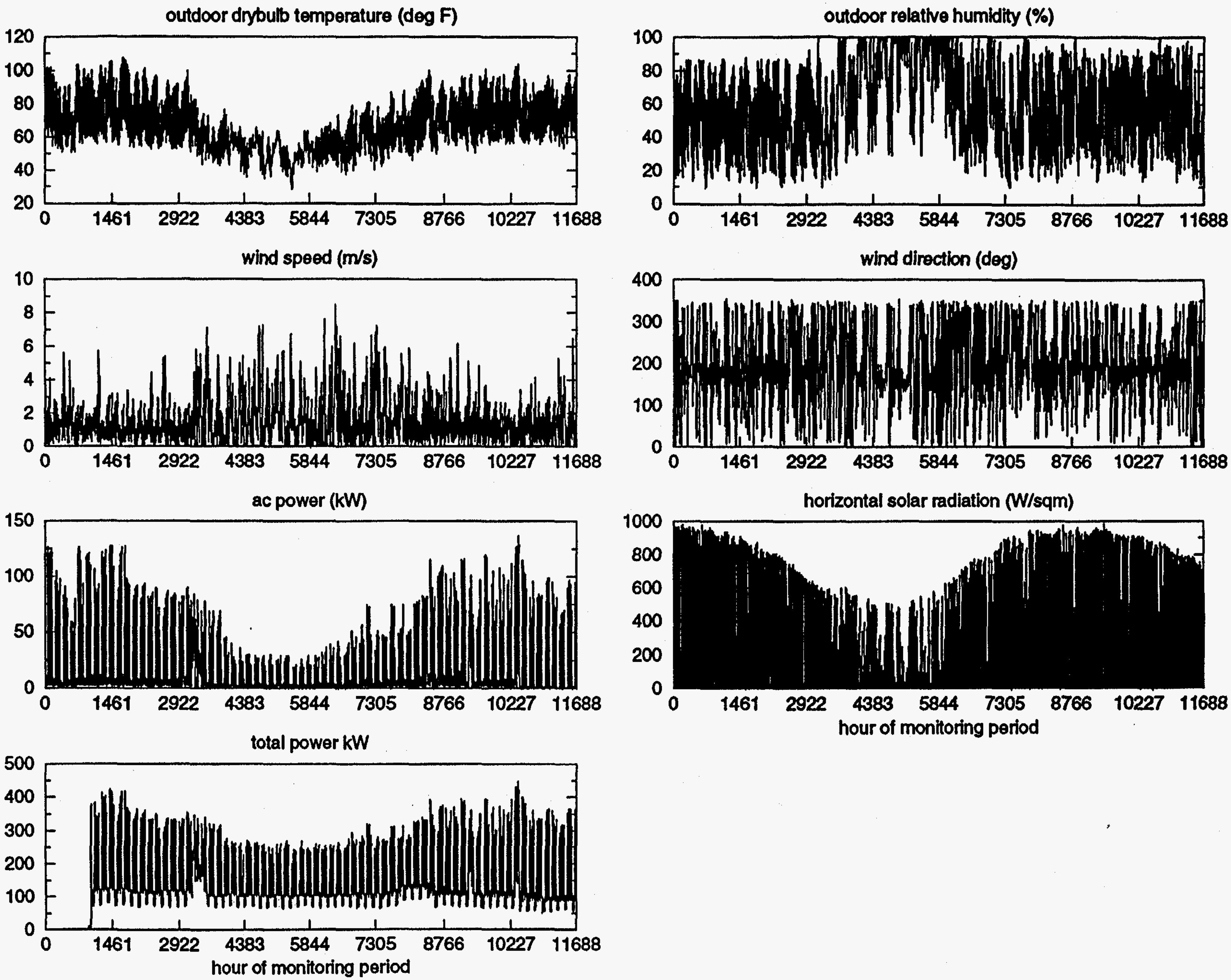


Figure 3.1(cont). Davis monitored hourly data from June 1996 - September 1997.

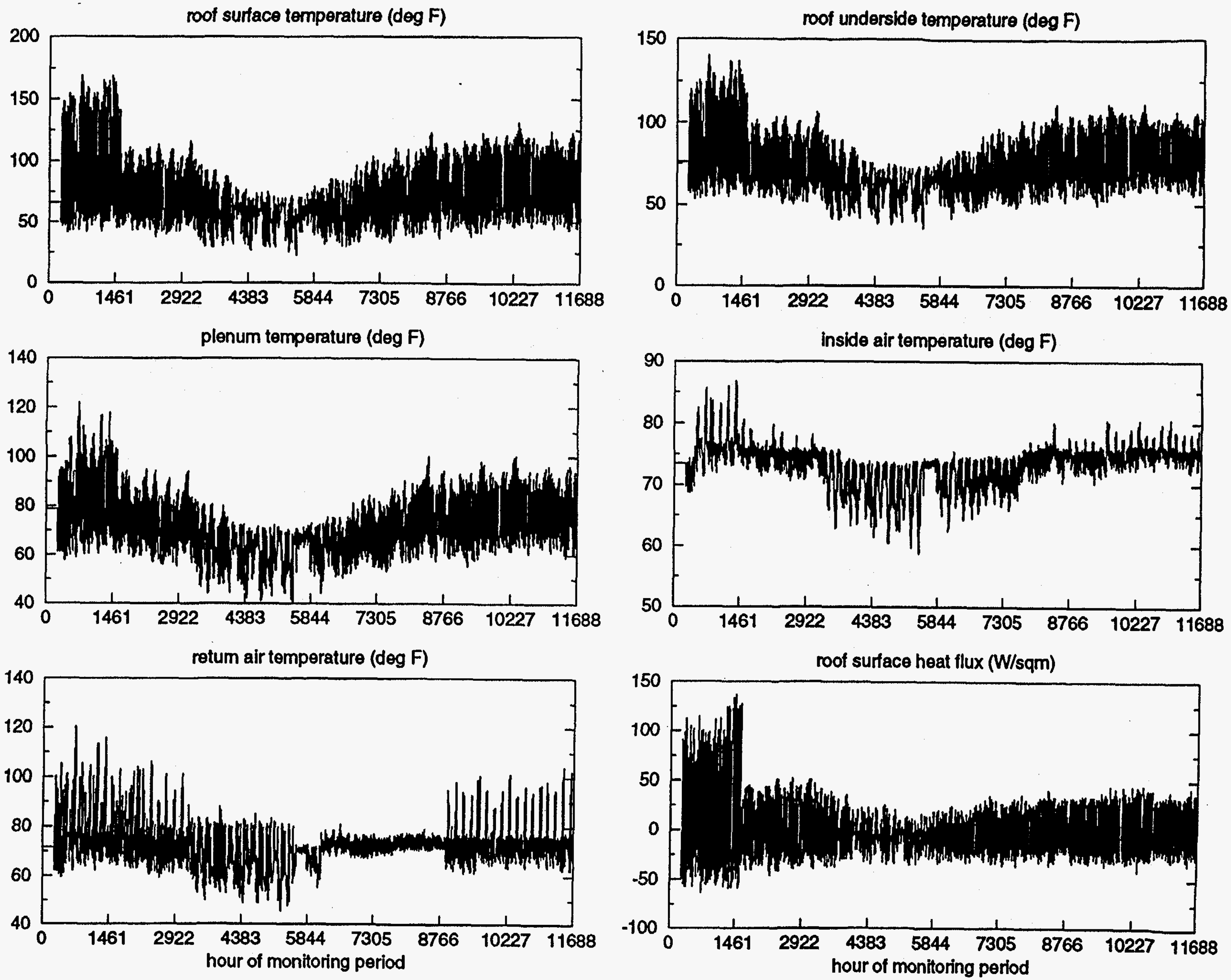


Figure 3.2. Gilroy monitored hourly data from June 1996 - September 1997.

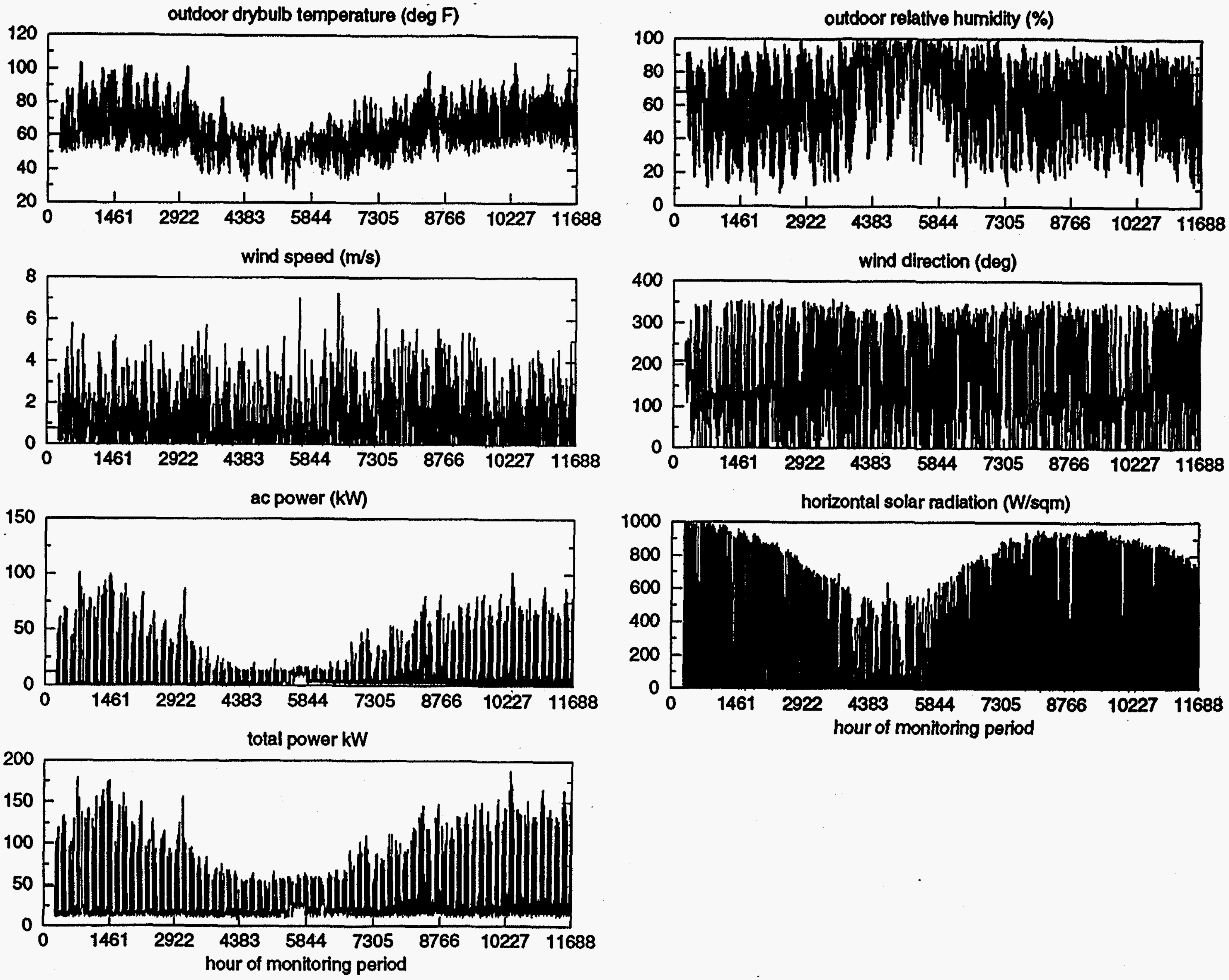


Figure 3.2(cont). Gilroy monitored hourly data from June 1996 - September 1997.

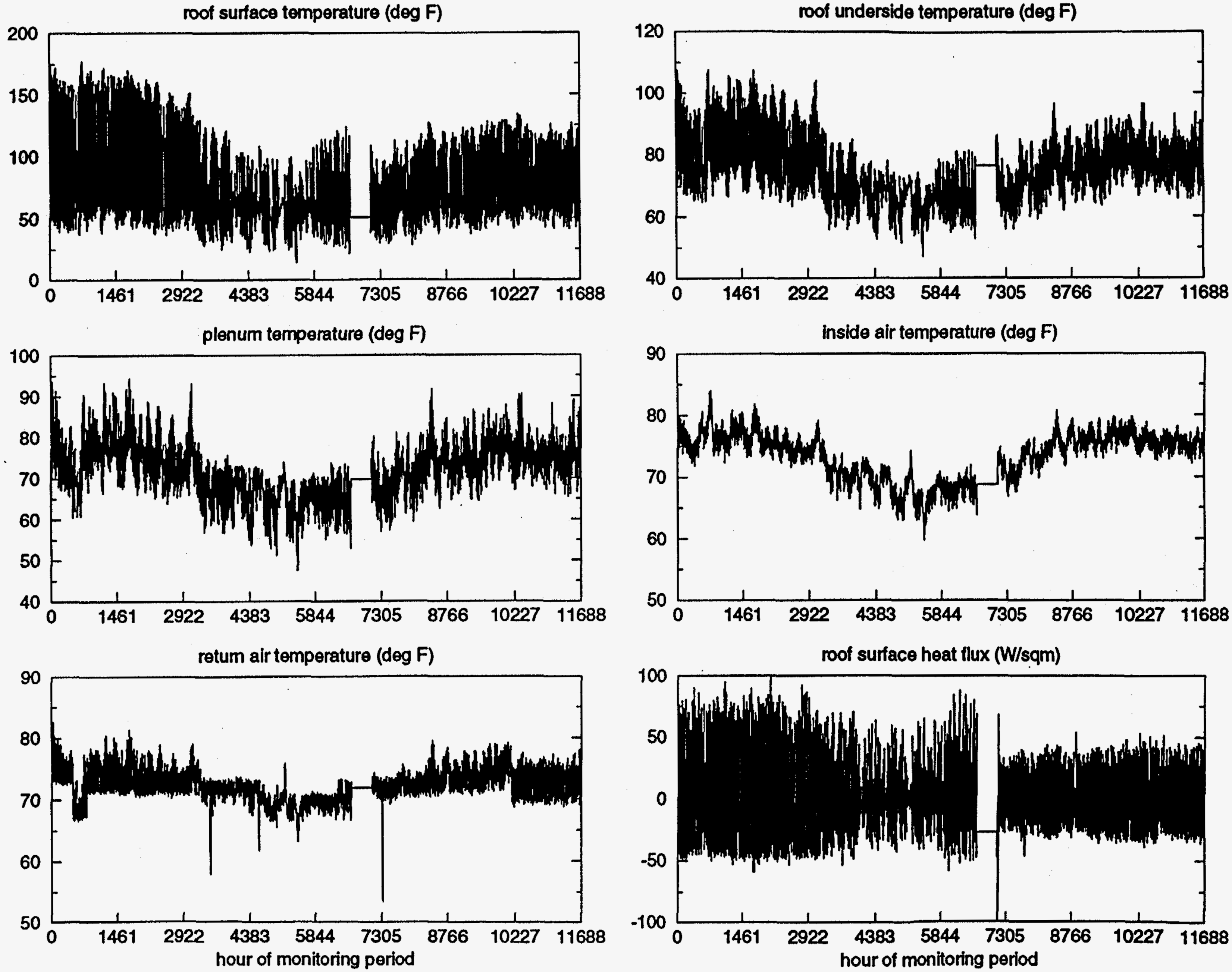


Figure 3.3. San Jose monitored hourly data from June 1996 - September 1997.

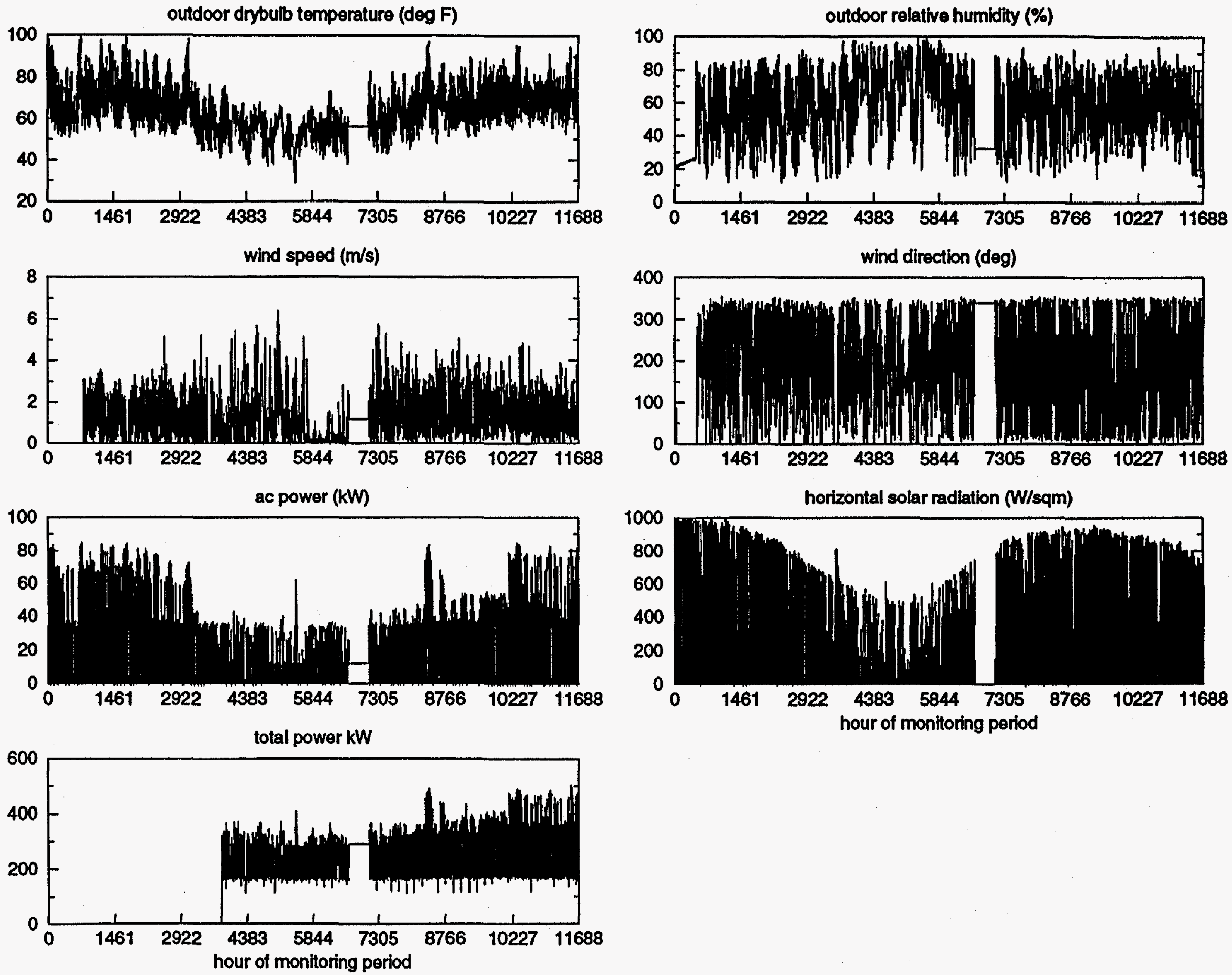


Figure 3.3(cont). San Jose monitored hourly data from June 1996 - September 1997.

Table 3.1. Monitored monthly total and average daily air-conditioning electricity use, average daily outdoor air temperature, and number of standard weekdays.

month	Davis				Gilroy				San Jose			
	total	average daily		n	total	average daily		n	total	average daily		n
	a/c [MWh]	a/c [kWh]	T_{out} [°F]		a/c [MWh]	a/c [kWh]	T_{out} [°F]		a/c [MWh]	a/c [kWh]	T_{out} [°F]	
1996												
June	20.1	1006	72	20	6.6	511	63	13	12.9	645	66	20
July	29.0	1320	76	22	17.0	774	69	22	17.9	814	71	22
August	25.7	1168	75	22	11.5	606	70	19	17.0	772	70	22
September	17.1	853	69	20	7.7	385	63	20	12.1	605	65	20
October	17.7	768	63	23	8.0	349	61	23	12.6	546	62	23
November	7.8	389	56	20	4.3	213	55	20	6.7	336	56	20
December	4.5	237	50	19	4.0	210	52	19	5.7	300	54	19
1997												
January	4.3	215	48	20	5.3	242	50	22	6.3	285	51	22
February	5.7	302	53	19	4.4	234	52	19	5.7	302	53	19
March	9.3	463	59	20	6.5	309	57	21	6.8	325	56	21
April	12.2	555	62	22	7.8	354	60	22	9.0	408	60	22
May	20.8	992	71	21	12.6	599	68	21	13.6	646	67	21
June	20.8	991	72	21	11.9	565	66	21	13.0	618	66	21
July	19.7	895	74	22	12.8	641	68	20	16.2	736	69	22
August	21.5	1026	74	21	15.0	715	70	21	16.8	798	70	21
September	15.7	750	74	21	14.9	709	71	21	16.1	766	70	21

Table 3.2. Cooling and heating degree-days for the 1996 and 1997 summer seasons of June - September and for the twelve month period of June 1996 - May 1997.

cdd = cooling degree-days at 65°F and hdd = heating degree-days at 65°F

location	summer 1996		summer 1997		June 1996 - May 1997	
	cdd	hdd	cdd	hdd	cdd	hdd
Davis	1281	218	1148	163	1814	2485
Gilroy	676	518	726	345	1094	2929
San Jose	751	309	652	213	1068	2472

3.3 Temperatures and Heat Flux Through the Roof System

Pre- and post-coating monitored hourly data

Figures 3.4abc show pre- and post-coating monitored hourly data for the period when the coating was applied. There are noticeable drops in roof surface temperature and heat flux at the time the roofs were coated at all three sites. At the Gilroy site there is also a noticeable decrease in the roof underside and plenum temperatures because the major resistive component (R-19 fiberglass ceiling insulation) is located beneath the plenum.

The roof of the building at Davis was coated on April 12, 1997; the maximum roof surface temperature dropped from 140°F - 100°F immediately after the light-colored coating was applied. At Gilroy the roof was coated on August 5, 1996, which resulted in a drop in the maximum roof surface temperature from 160°F - 100°F. In San Jose the roof was coated on March 24, 1997, and the maximum roof surface temperature dropped from 130°F - 85°F.

The impact of the coatings on reducing roof surface temperature can be observed by inspecting the infra-red photographs of the roof. **Figure 3.5** is an infra-red photograph of the edge of the roof coating at Gilroy at the time of application. The roof surface temperature ranges from 100°F (blue--areas coated by the reflective coating) - 160°F (yellow--uncoated areas) with seam temperatures reaching 180°F (red--uncoated areas).

Figure 3.4 also shows the underside roof and plenum temperatures, the heat flux through the roof, and cooling electricity use. As expected, the impact of roof coating was less pronounced on the temperatures of layers below the roof surface. But in all the buildings the reduction in temperatures in all layers and reductions in heat flux can be observed.

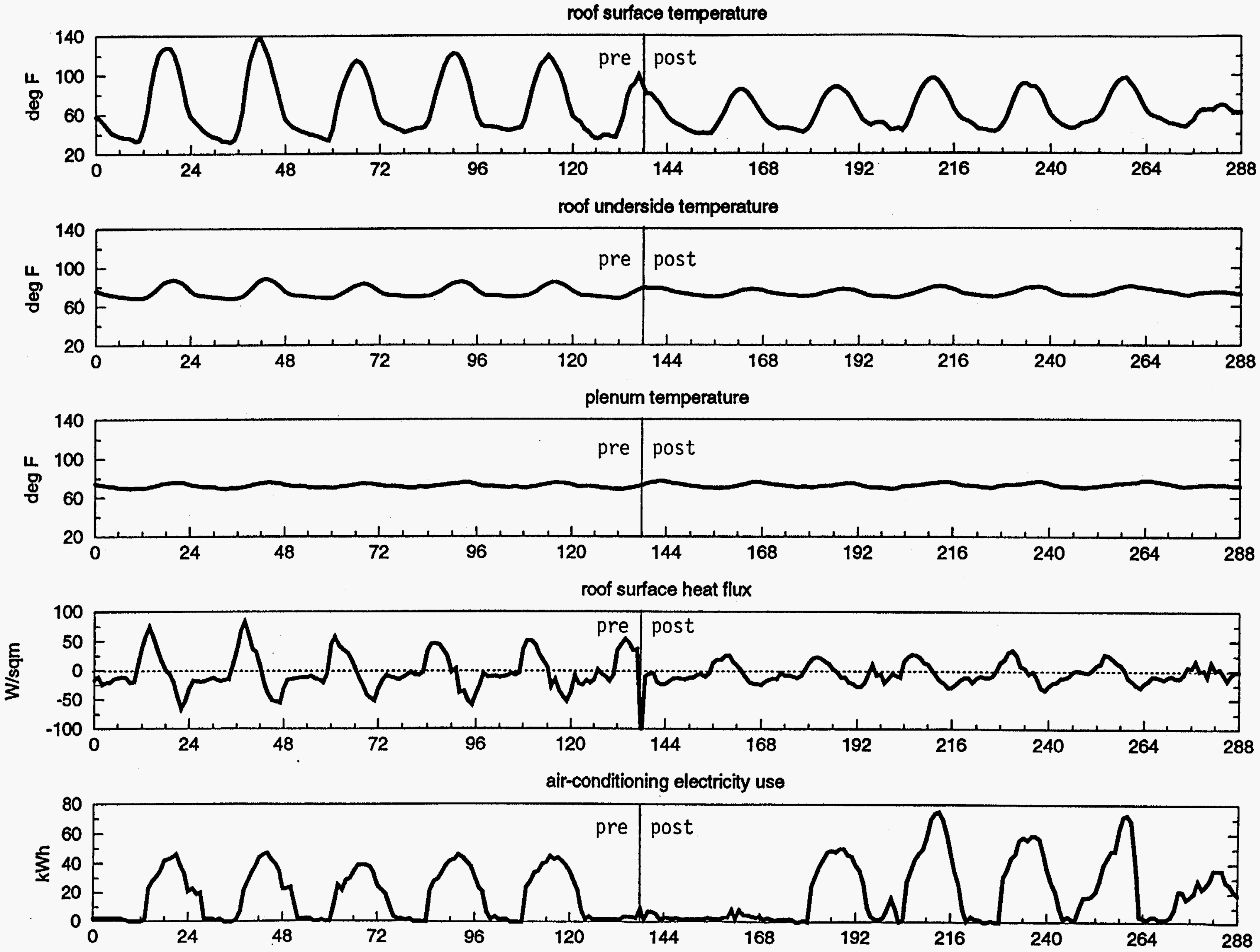


Figure 3.4a. Davis monitored hourly data from April 7 - 18, 1997.

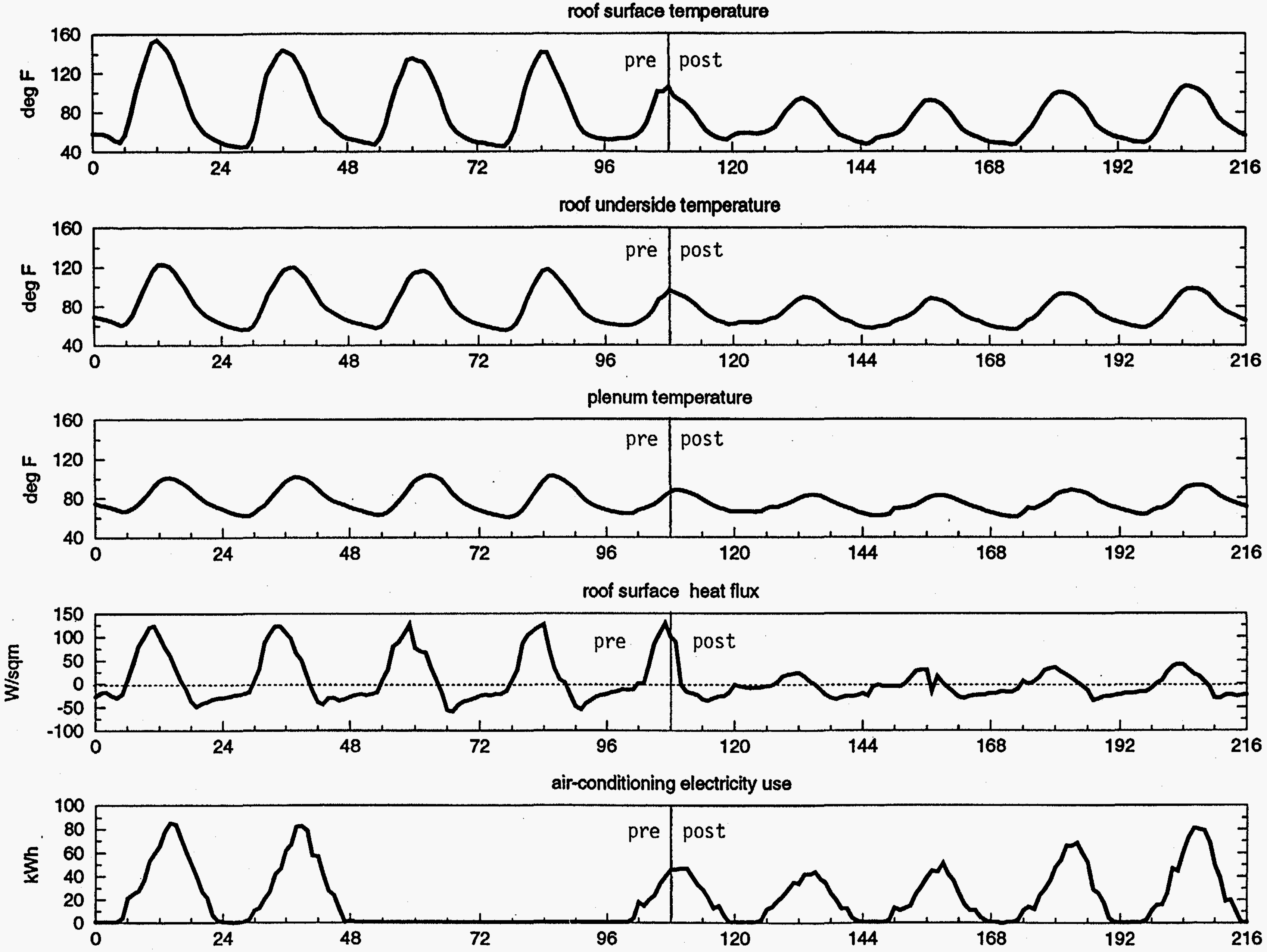


Figure 3.4b. Gilroy monitored hourly data from August 1 - 9, 1996.

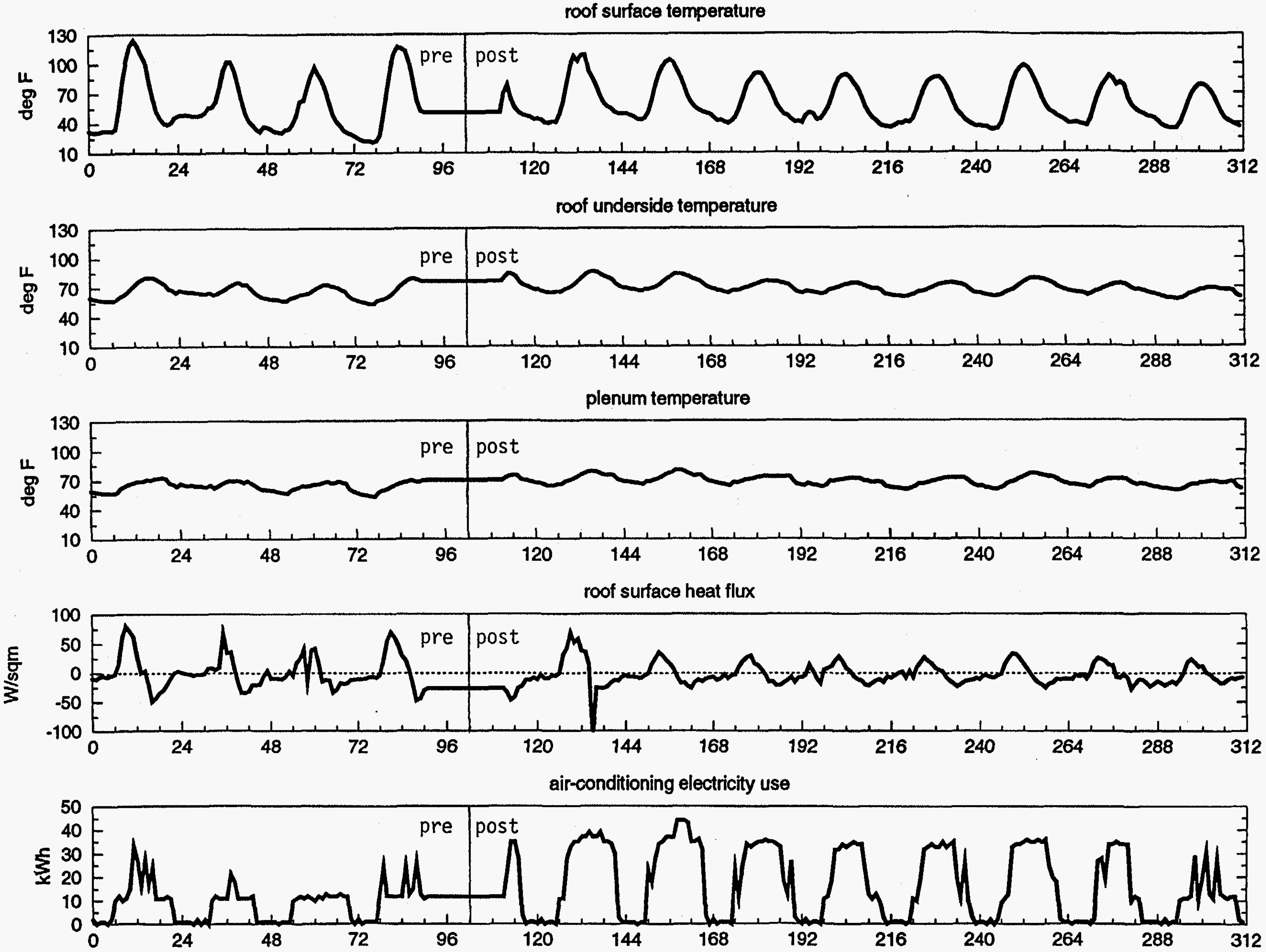


Figure 3.4c. San Jose monitored hourly data from March 1 - 4 and 23 - 31, 1997.

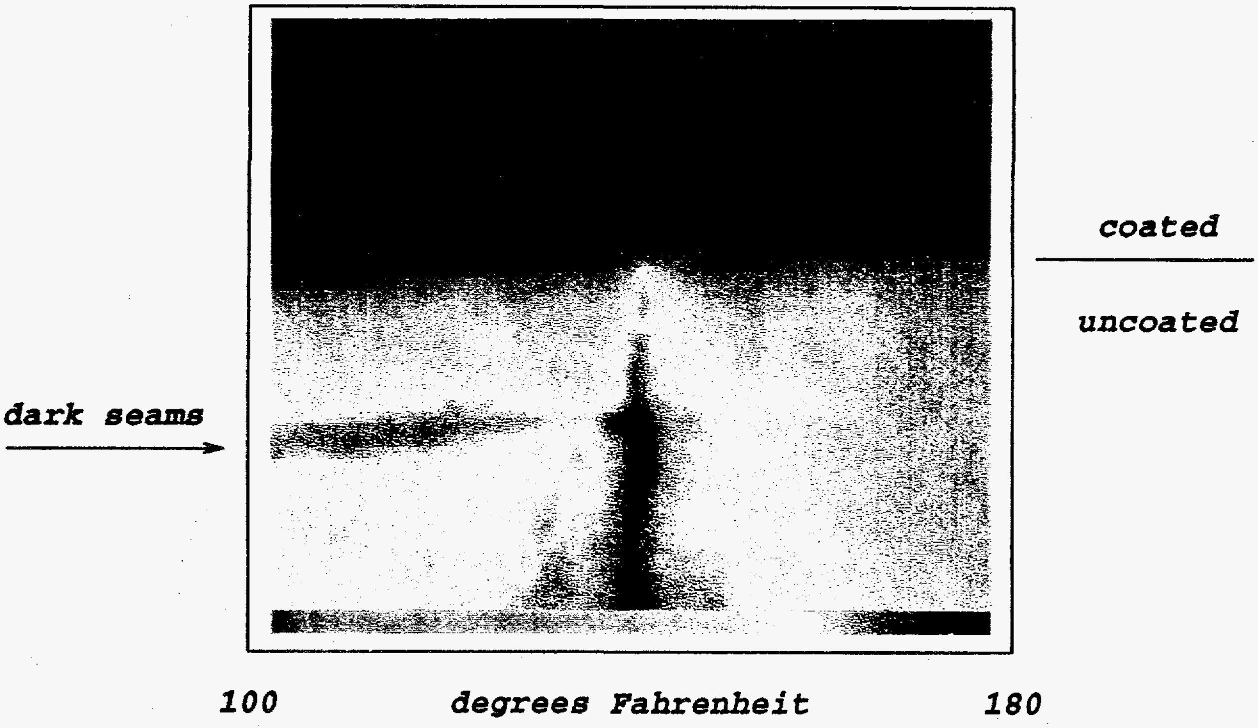


Figure 3.5. ***Infra-red photograph of roof-coating edge at Gilroy.***

Figures 3.6abc show representative hourly data for 1) a summer pre-coating hot day, 2) a summer post-coating hot day, and 3) a winter pre-coating day. In Davis, the pre-coated roof surface temperature peaked at about 175°F on July 1, 1996. On a comparable day with similar insolation and outdoor air temperature profiles (July 8, 1997), the post-coated roof surface temperature peaked at about 120°F. The outdoor temperature peaked at just under 105°F both of these days, therefore the temperature difference between the roof surface and the outdoor air decreased from 70°F - 15°F. The heat flux was essentially cut in half and the air-conditioning demand was noticeably affected. From 8am - 4pm the demand profile decreased substantially from pre- to post-coating conditions.

At the Gilroy site, the pre-coated roof surface temperature peaked at 170°F on July 29, 1996. On a comparable day (July 3, 1997) the post-coated roof surface temperature peaked at 120°F. The outdoor air temperature peaked at about 95°F both of these days, therefore the temperature difference between the roof surface and the outdoor air decreased from 75°F - 25°F. The heat flux decreased by a factor of three and the air-conditioning demand was noticeably affected. From 7am - 4pm the demand profile decreased substantially from pre- to post-coating conditions.

For the San Jose building, the pre-coated roof surface temperature peaked at 165°F on August 9, 1996. On a comparable day (August 5, 1997) the post-coated roof surface temperature peaked at 135°F. (On other comparable days the post-coated roof surface temperature peaks at 120°F). The outdoor temperature peaked at about 95°F both of these days, therefore the temperature difference between the roof surface and the outdoor air decreased from 70°F - 40°F. The heat flux decreased by 50%. But the air-conditioning demand was not noticeably affected. This is probably due to a well-ventilated plenum installed over the ceiling in this building.

The reduction in surface temperature had a net effect in reducing the a/c electricity use (this is discussed further in later sections). However, as an example, **Figure 3.7** depicts a scatterplot of monitored daily air-conditioning electricity use versus daily average outdoor air temperature for Gilroy in August 1996. Note that the three pre-coating days (August 1, 2, and 5, 1996) demonstrated a higher a/c demand for a given daily average outdoor temperature than the post-coating days.

Average daily roof layer temperature profiles

Figures 3.8abc show the average daily roof layer temperature profiles for summer standard weekdays at all three sites by month and for each coating period (pre and post). Temperature measurements were taken on the roof exterior surface, roof underside, in the plenum, and in the conditioned spaces (indoor air).

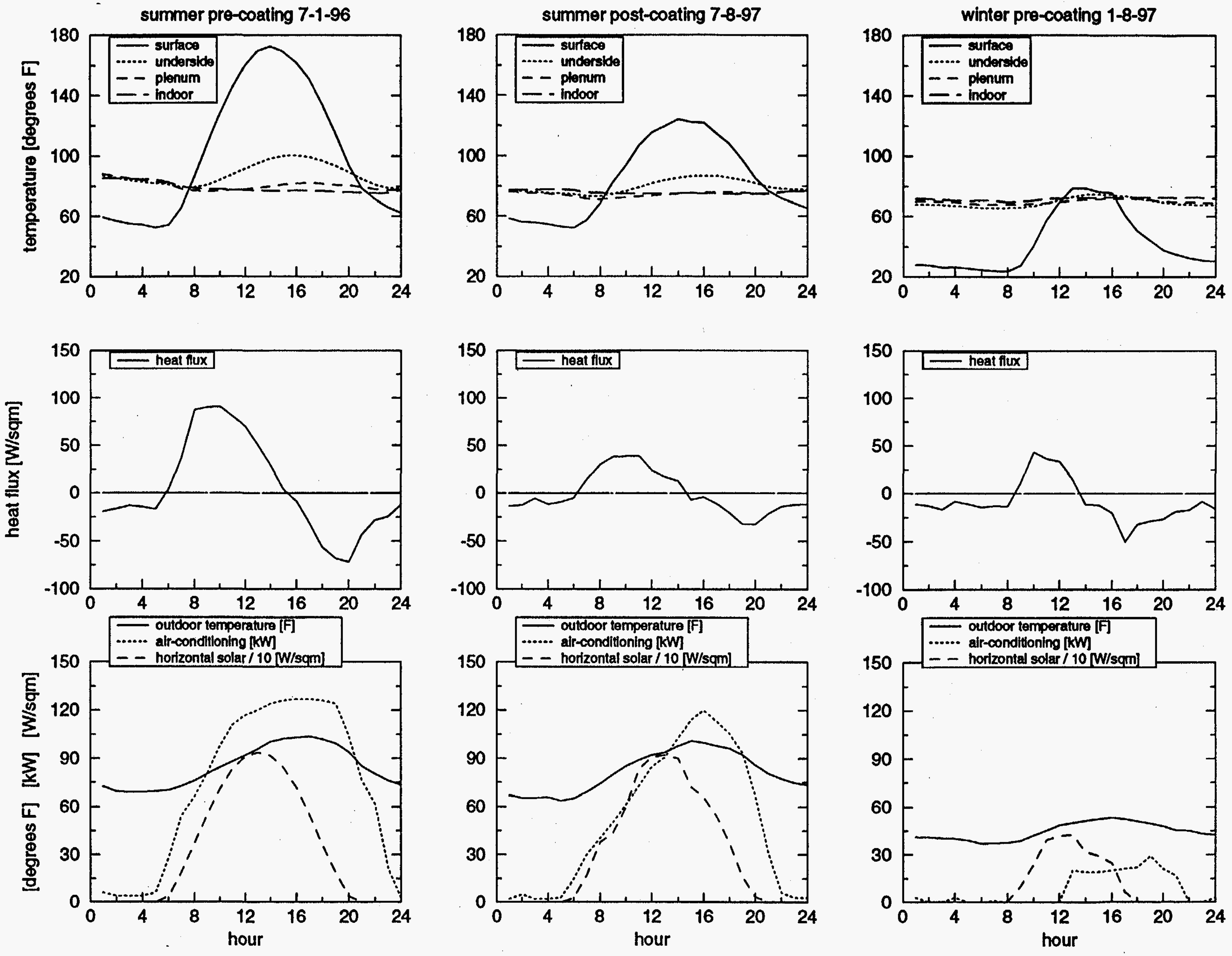


Figure 3.6a. Davis monitored hourly data for July 1, 1996, July 8, 1997, and January 8, 1997.

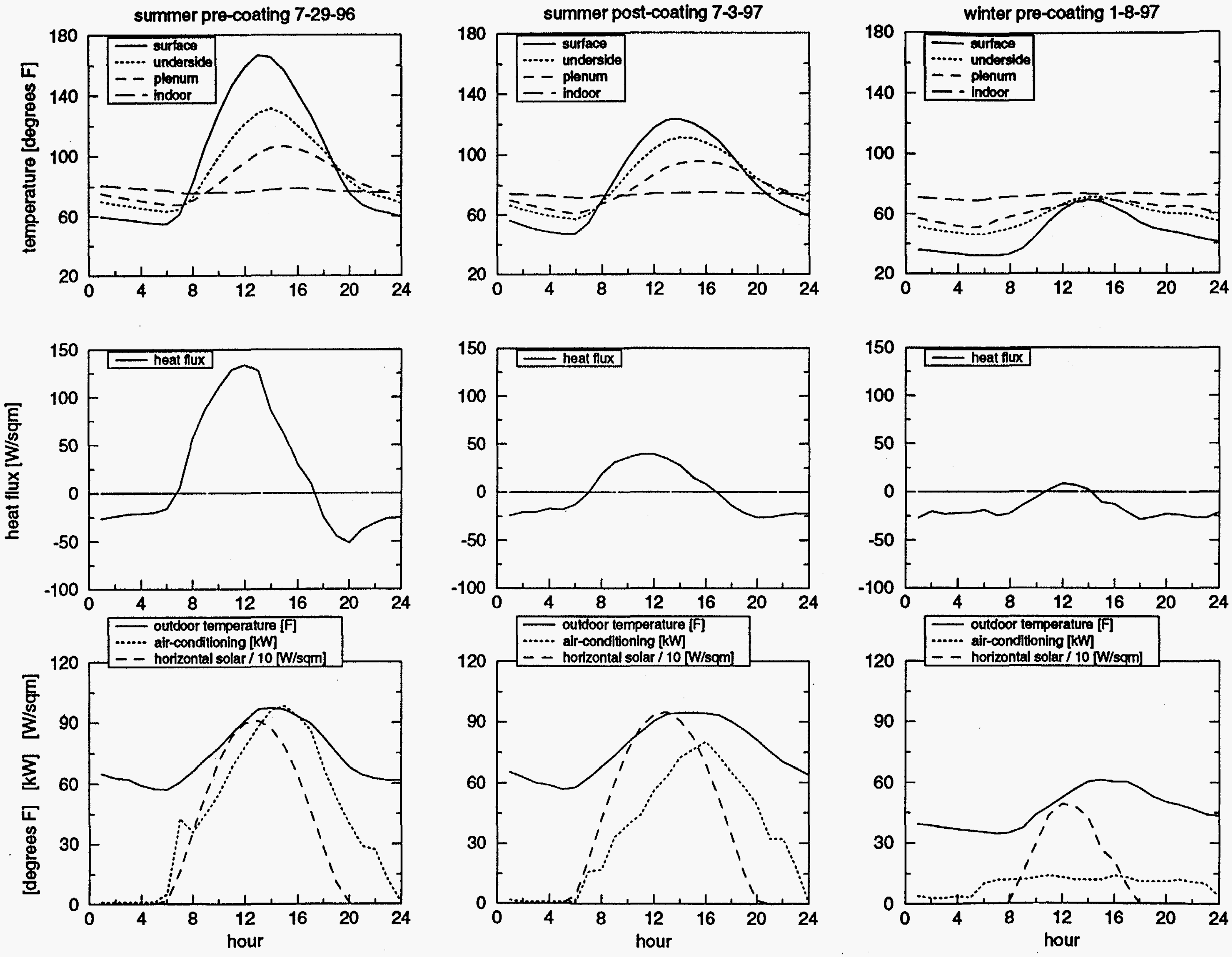


Figure 3.6b. Gilroy monitored hourly data for July 29, 1996, July 3, 1997, and January 8, 1997.

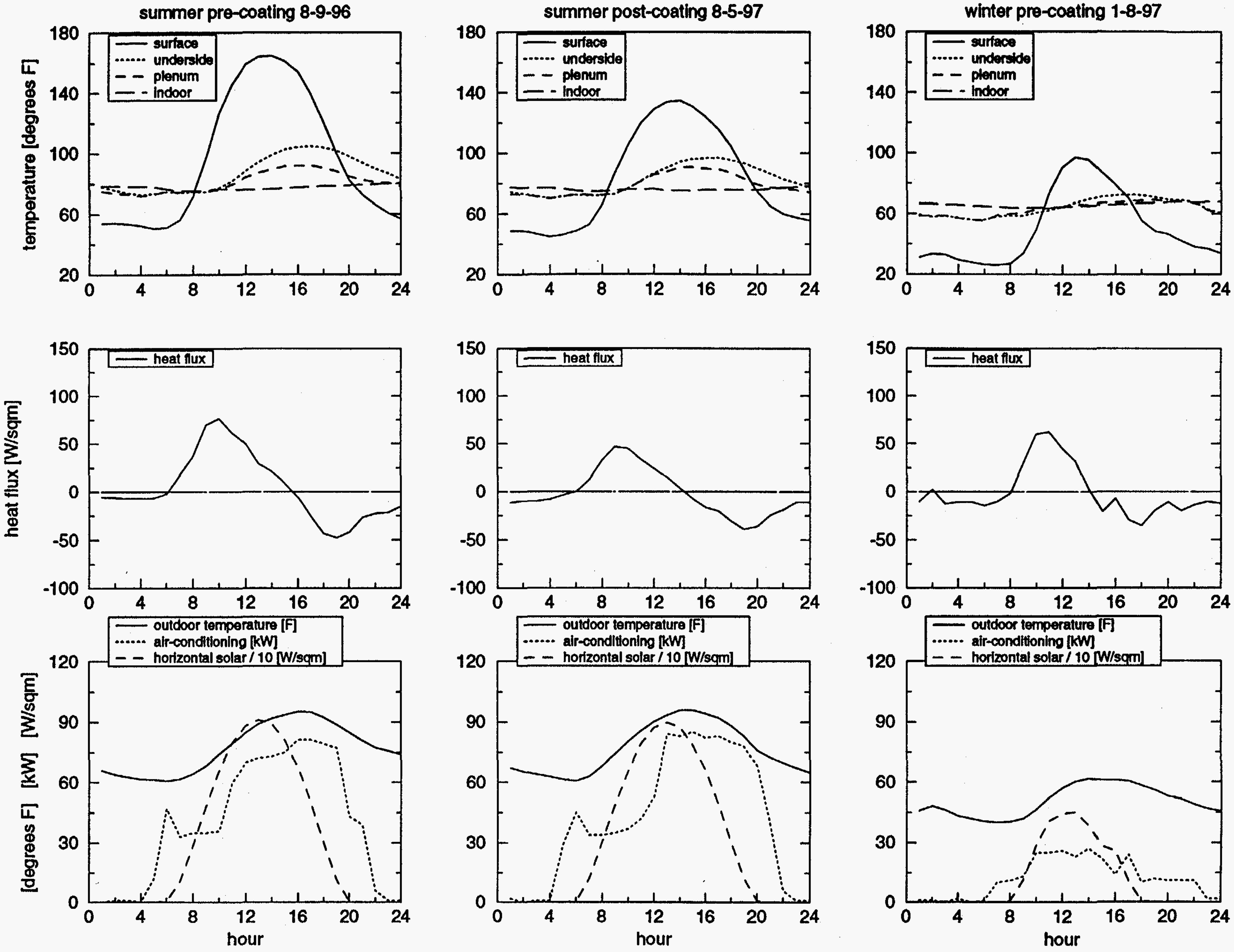


Figure 3.6c. San Jose monitored hourly data for August 9, 1996, August 5, 1997, and January 9, 1997.

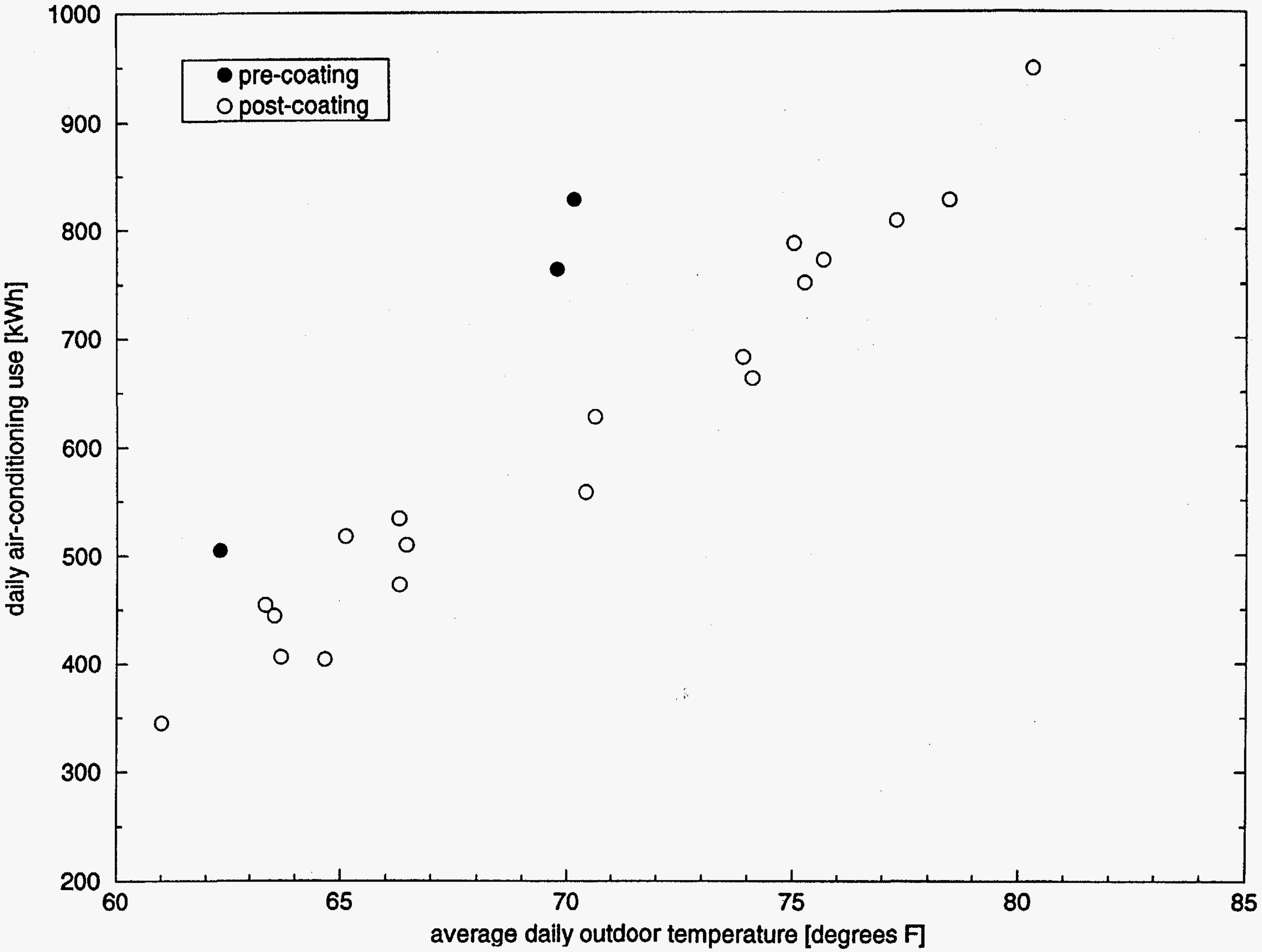
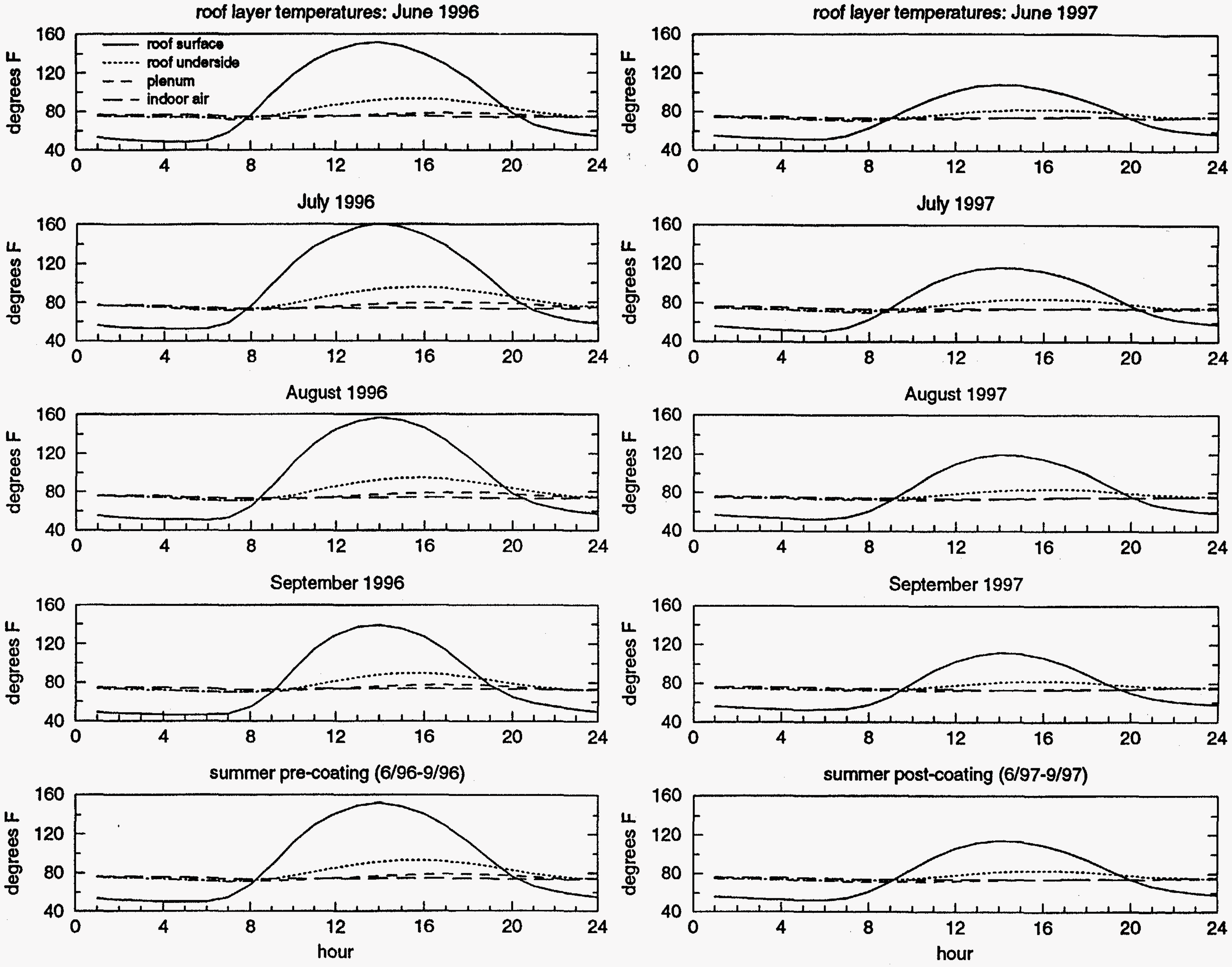


Figure 3.7. Gilroy monitored daily air-conditioning electricity use vs daily average outdoor air temperature for August, 1996.



roof layer temperatures: June 1996

roof layer temperatures: June 1997

July 1996

July 1997

August 1996

August 1997

September 1996

September 1997

summer pre-coating (6/96-9/96)

summer post-coating (6/97-9/97)

Figure 3.8a. Davis average daily roof layer temperature profiles for standard weekdays.

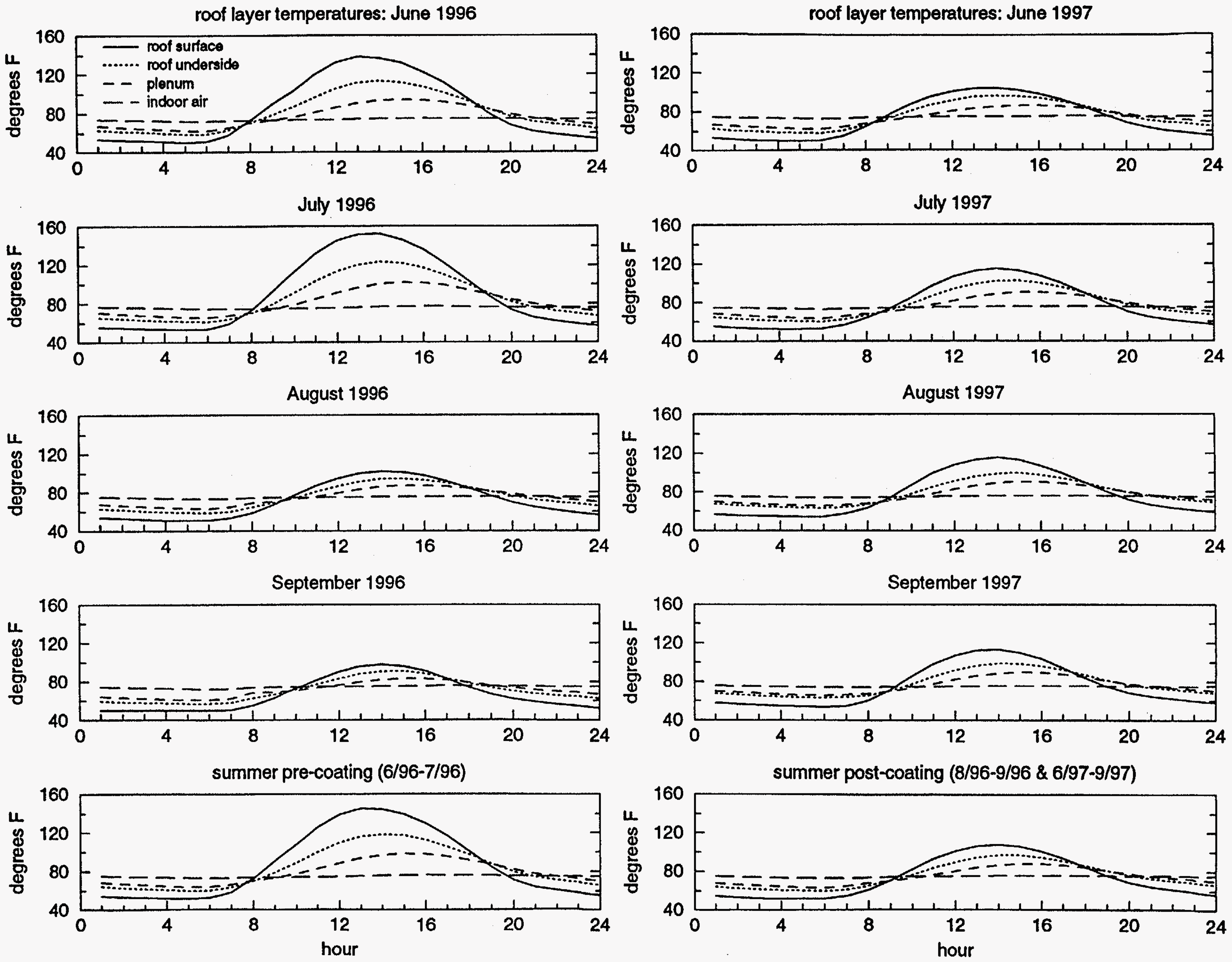


Figure 3.8b. Gilroy average daily roof layer temperature profiles for standard weekdays.

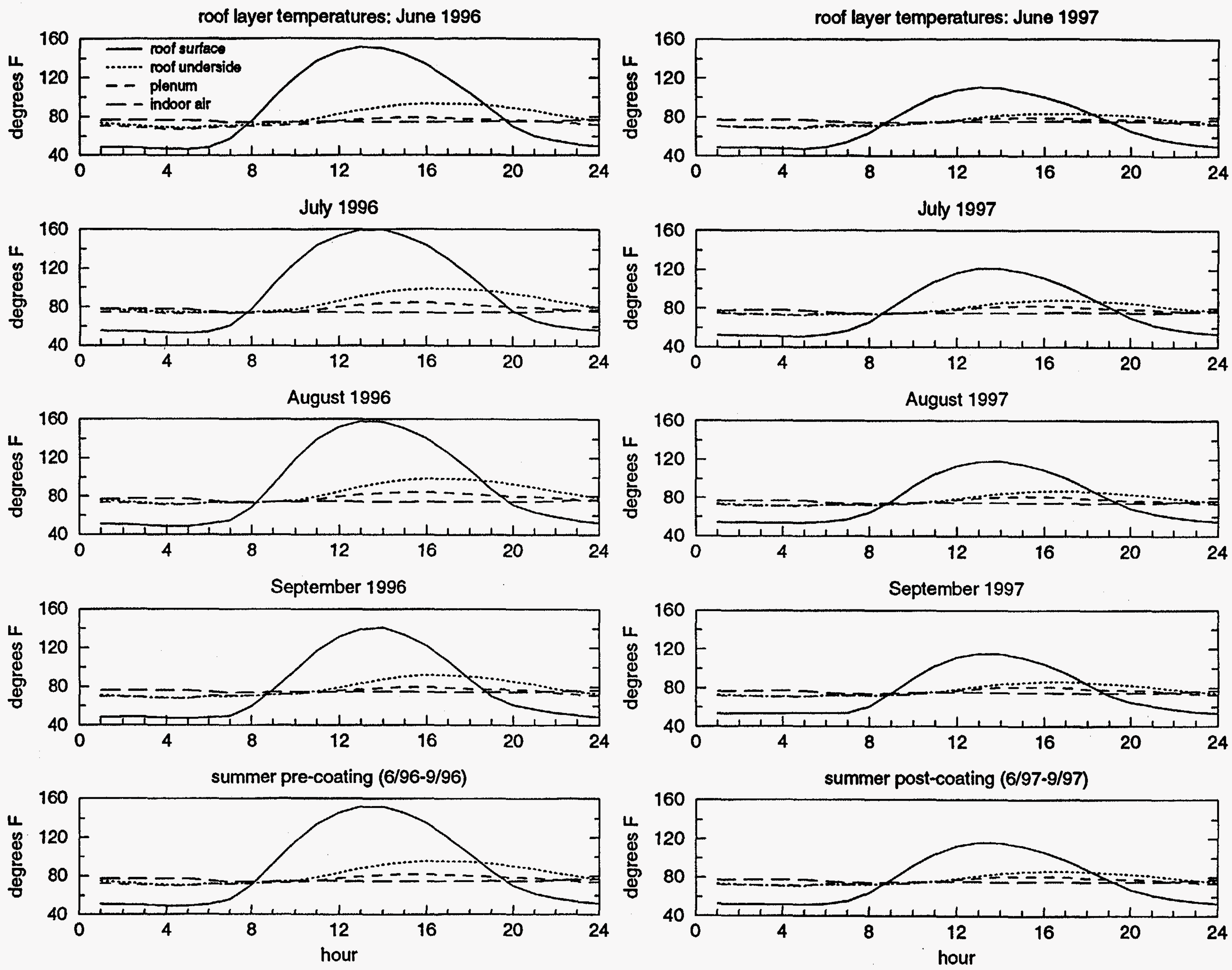


Figure 3.8c. San Jose average daily roof layer temperature profiles for standard weekdays.

In Davis the pre-coating average peak roof surface temperature was 152°F where the post-coating was 114°F, a difference of 38°F. The average peak roof underside temperature decreased 10°F (93°F - 83°F), the average peak plenum air temperature decreased 4°F (79°F - 75°F), and the average indoor air temperature remained stable at 74°F during operating hours.

In Gilroy the pre-coating average peak roof surface temperature was 145°F where the post-coating was 108°F, a difference of 37°F. The average peak roof underside temperature decreased 21°F (118°F - 97°F), the average peak plenum air temperature decreased 10°F (98°F - 88°F), and the average indoor air temperature remained stable at 75°F during operating hours.

In San Jose the pre-coating average peak roof surface temperature was 152°F where the post-coating was 116°F, a difference of 36°F. The average peak roof underside temperature decreased 10°F (96°F - 86°F), the average peak plenum air temperature decreased 1°F (82°F - 81°F), and the average indoor air temperature remained stable at 75°F during operating hours.

3.4 Impact of "Cool" Coatings on Air-Conditioning Electricity Use

The effect of cool-roof coatings on air-conditioning electricity use was examined during the summer months of June, July, August, and September for 1996 and 1997. The pre-coating period for Davis and San Jose were those summer months in 1996, and the post-coating were those in 1997. Because the Gilroy roof was coated in August 1996, August and September 1996 were grouped into the post-coating period.

Average daily air-conditioning electricity use and outdoor air temperature profiles

Figures 3.9abc show average daily air-conditioning electricity use and outdoor air temperature profiles for summer standard weekdays at all three sites by month and for each coating period (pre and post). **Appendix B** contains air-conditioning electricity use profiles for all months monitored. These figures provide an overview of the daily air-conditioning energy use in relation to outdoor air temperature in these buildings, as well as some relevant information regarding the schedules of operation.

In the Davis building, the average air-conditioning electricity use profiles in June 1996 and 1997 differ only during the late evening hours. The average outdoor air temperature profiles are also very close throughout the entire day. In July there was a significant reduction in air-conditioning electricity use during each hour of operation, with the outdoor temperature less in July 1997 than in 1996. Thus, there is a strong indication that the cool roof influenced a/c electricity use. The average air-conditioning use profiles for August and September differ significantly only in the early morning and late evening hours. In August 1996 the outdoor temperature is higher during peak operating hours than 1997 and the reverse is true for September. From examining the average daily profiles of air-conditioning electricity use and outdoor temperature, it can be concluded that further analysis is necessary to understand the effect of the light-colored roof on a/c electricity savings.

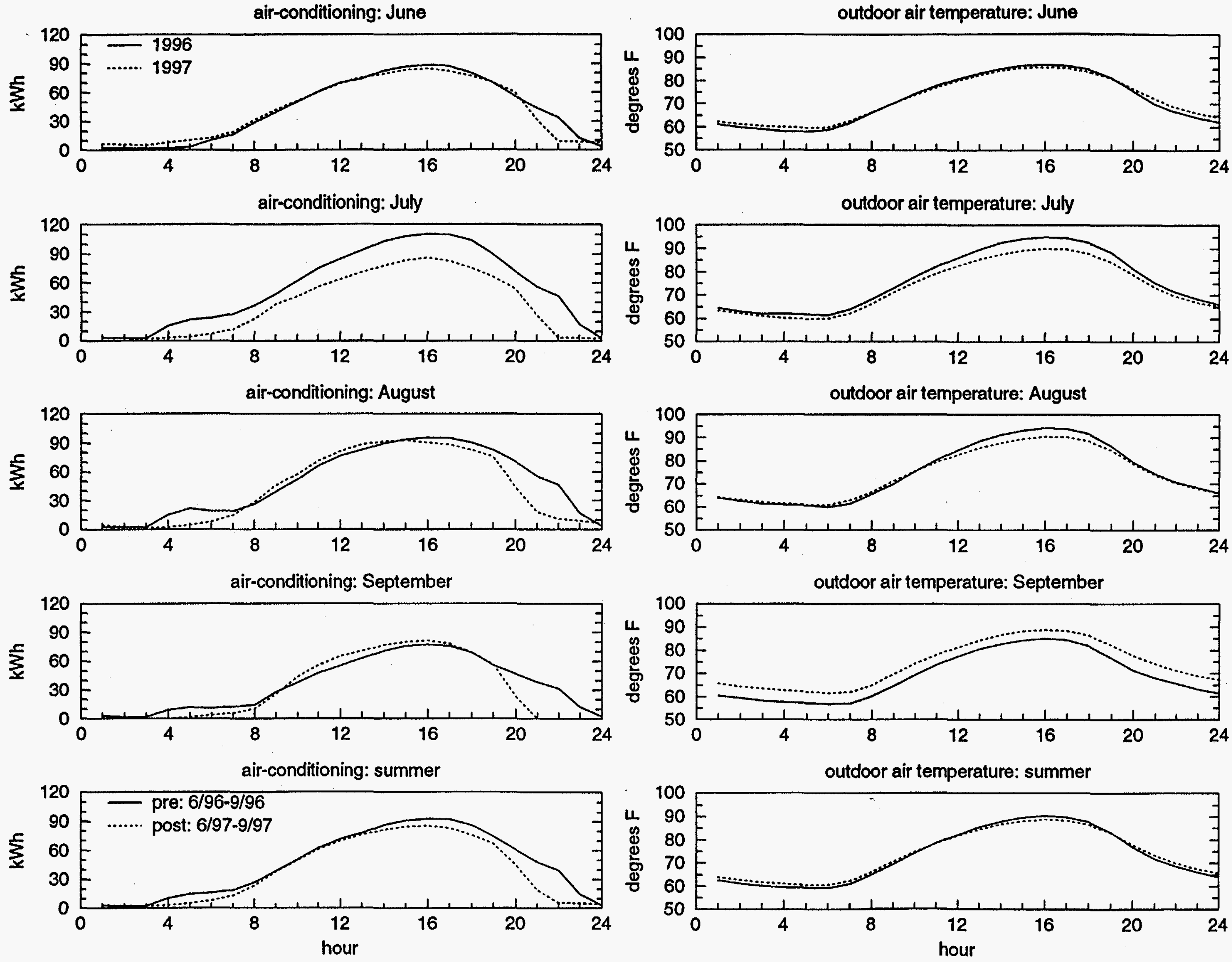


Figure 3.9a. Davis average daily air-conditioning electricity use and outdoor air temperature profiles for standard weekdays.

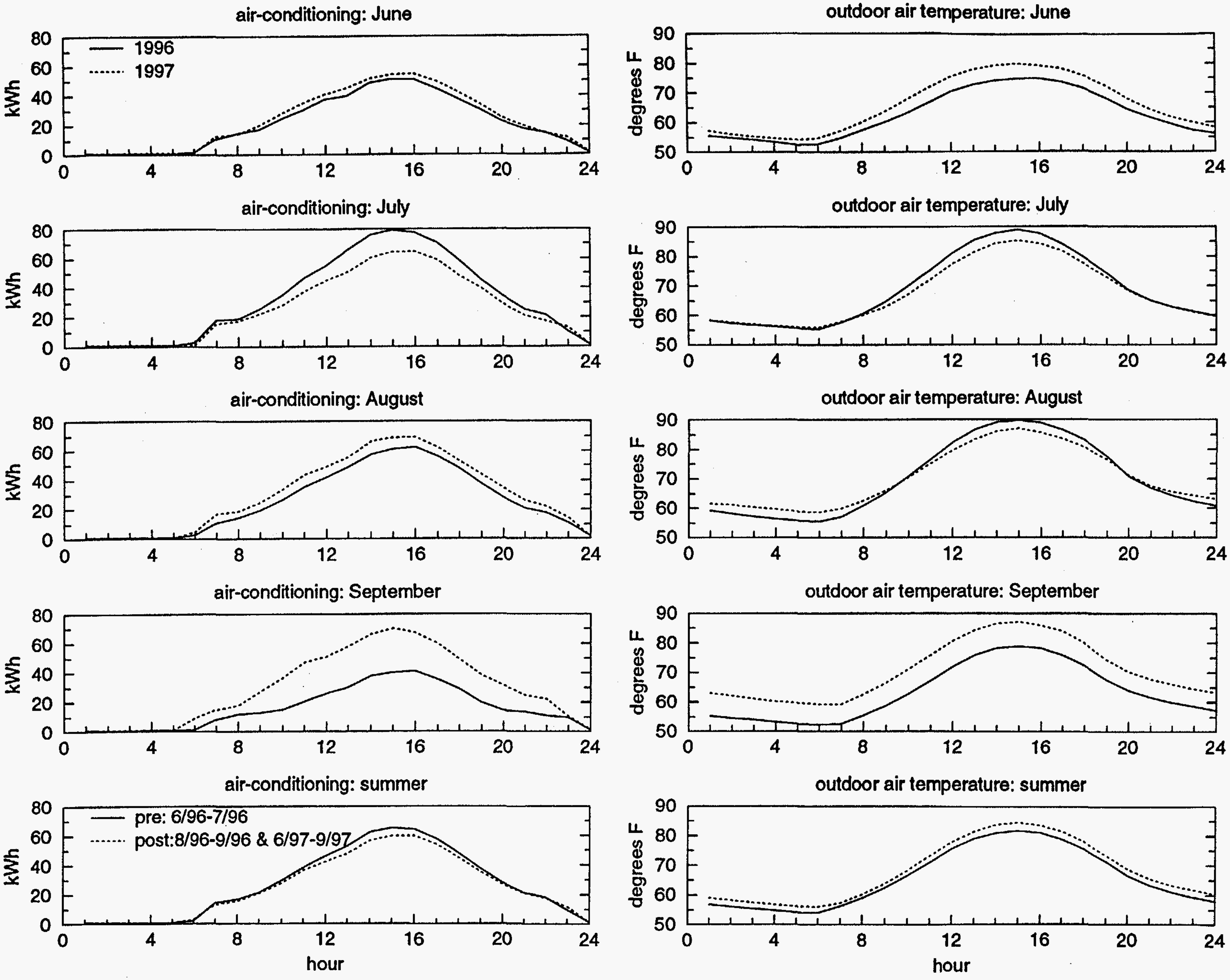


Figure 3.9b. Gilroy average daily air-conditioning electricity use and outdoor air temperature profiles for standard weekdays.

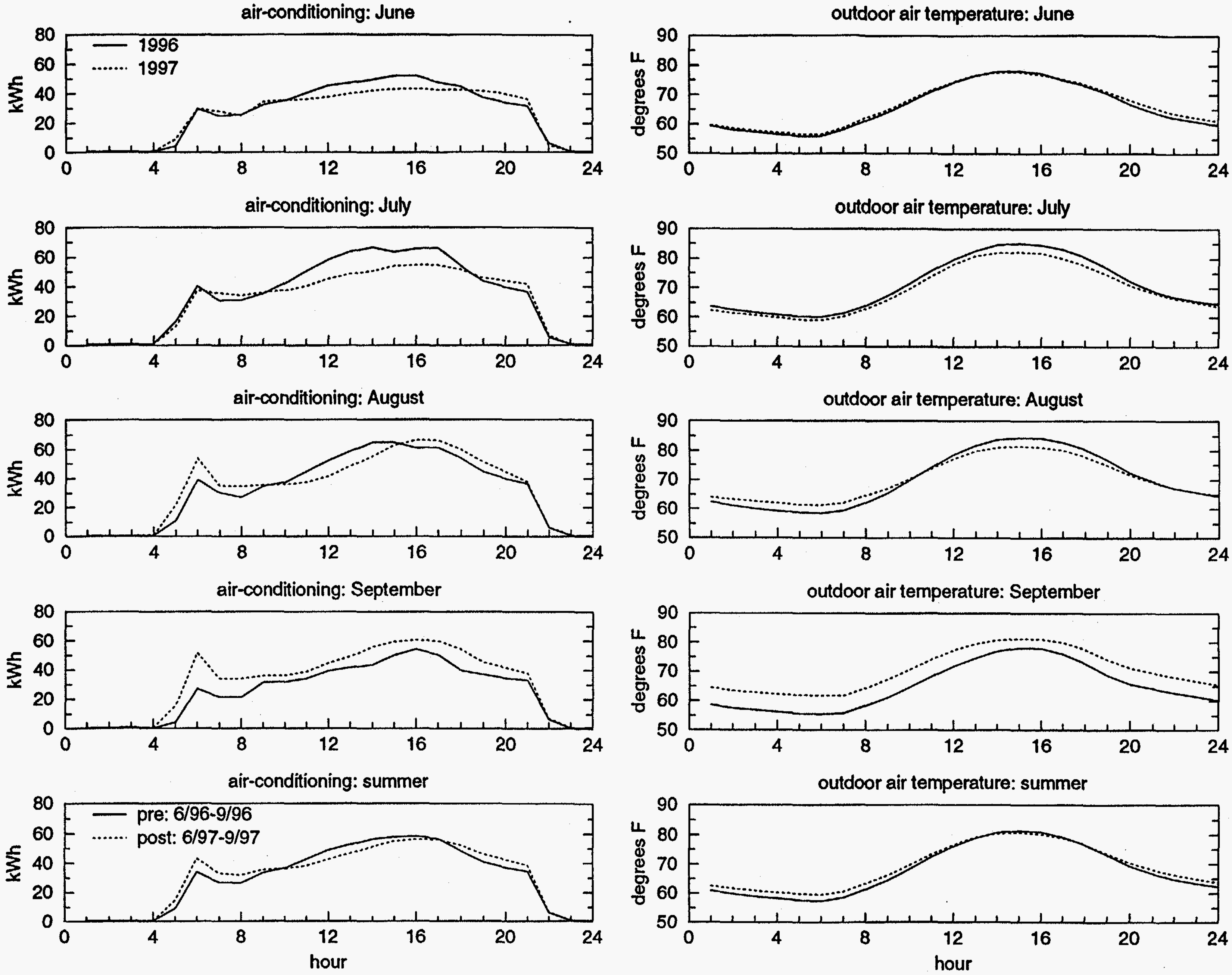


Figure 3.9c. San Jose average daily air-conditioning electricity use and outdoor air temperature profiles for standard weekdays.

In the Gilroy building, the average hourly data for June show a slight increase in a/c use and in outdoor temperature from 1996 to 1997. In July the a/c demand decreases as does the outdoor air temperature. In the San Jose building, June and July peak hour (12noon - 5pm) a/c demand was reduced from 1996 to 1997. Both the a/c use and outdoor air temperature were higher in September of 1997.

Daily air-conditioning electricity use versus daily average outdoor air temperature scatter plots

Scatter plots were prepared to show the dependence of daily a/c electricity use on outdoor air temperature and to isolate clusters of data for each summer month and coating period. **Appendix B** contains scatter plots for all months monitored. **Figure 3.10a**. shows monitored daily air-conditioning electricity use versus daily average outdoor air temperature for summer standard weekdays for Davis. In the months of July and September two groups of data are easily identifiable, pre- and post-coating a/c electricity use, with the pre-coating cluster shifted higher than the post-coating cluster in both. However, June and August do not have distinct pre- and post-coating data clusters. Based on this figure we postulated that all eight slopes (one for each month) were approximately equal and only the y-intercepts would differ significantly. This would be the foundation for the next step in data analysis. Summertime monthly scatter plots for Gilroy and San Jose are presented in **Figures 3.10bc**. Scatter plots with the data grouped into pre- and post-coating periods are presented in **Figure 3.11** for Davis, Gilroy, and San Jose.

Statistical analysis of air-conditioning electricity use

Our methodology focused on the statistical analysis of daily a/c electricity use as a function of daily average outdoor air temperature. Through a series of single-variable regressions with the following independent variables: daily average outdoor air temperature, daytime (8am - 7pm) average outdoor air temperature, daily peak outdoor air temperature, daily average outdoor air enthalpy, and daytime average outdoor air enthalpy, it was determined that the daily average outdoor air temperature provided the best correlation with daily a/c electricity use. The effect of clouds on daily a/c electricity use was examined as well. We concluded the daily average outdoor air temperature captures the variations in cloud cover and outdoor air moisture that influence the cooling loads on these buildings; therefore, it was selected as a representative climatological indicator. For further discussion, scatter plots, and regression results of this investigation see **Appendix C**.

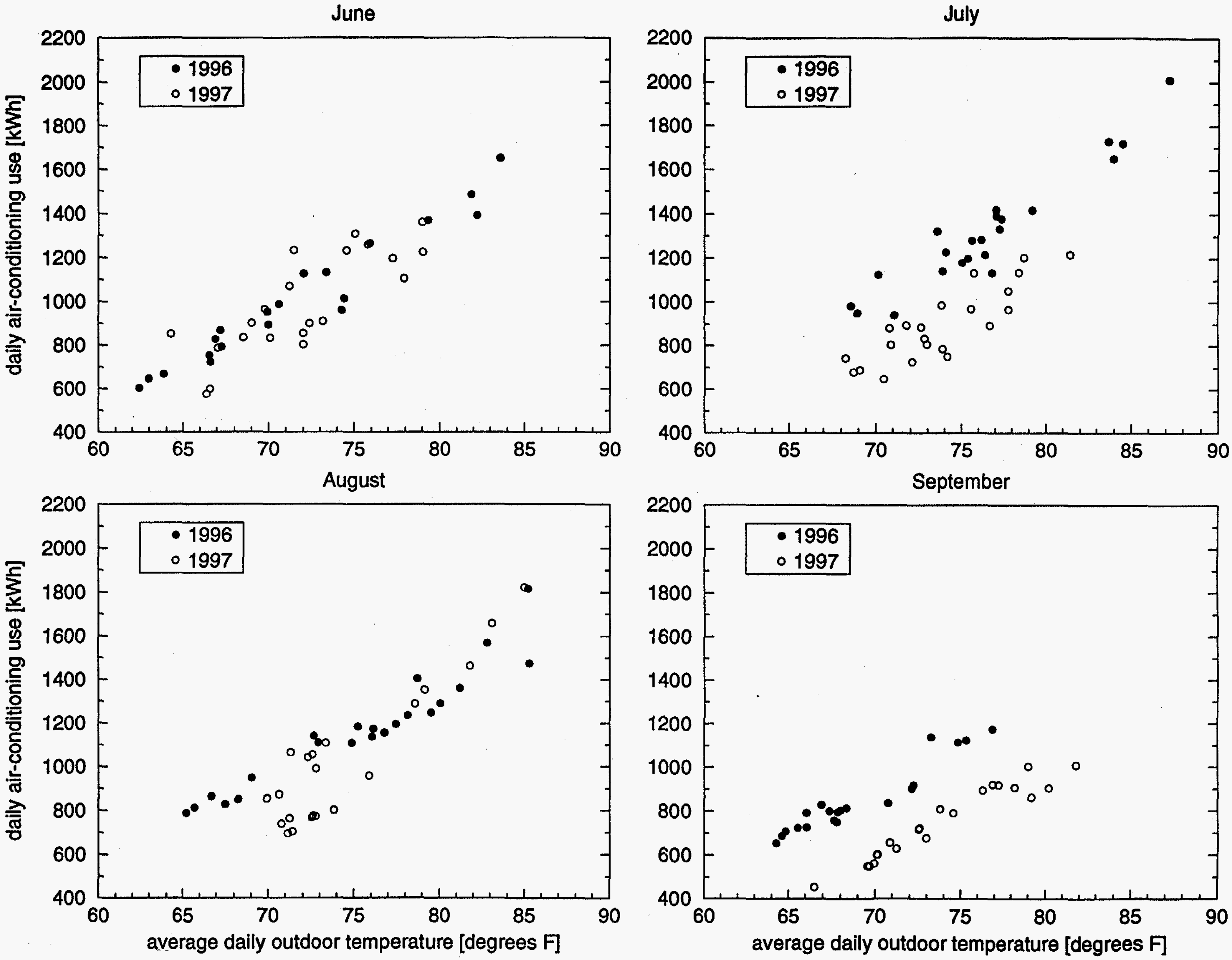


Figure 3.10a. Davis monitored daily air-conditioning electricity use vs daily average outdoor air temperature for standard weekdays.

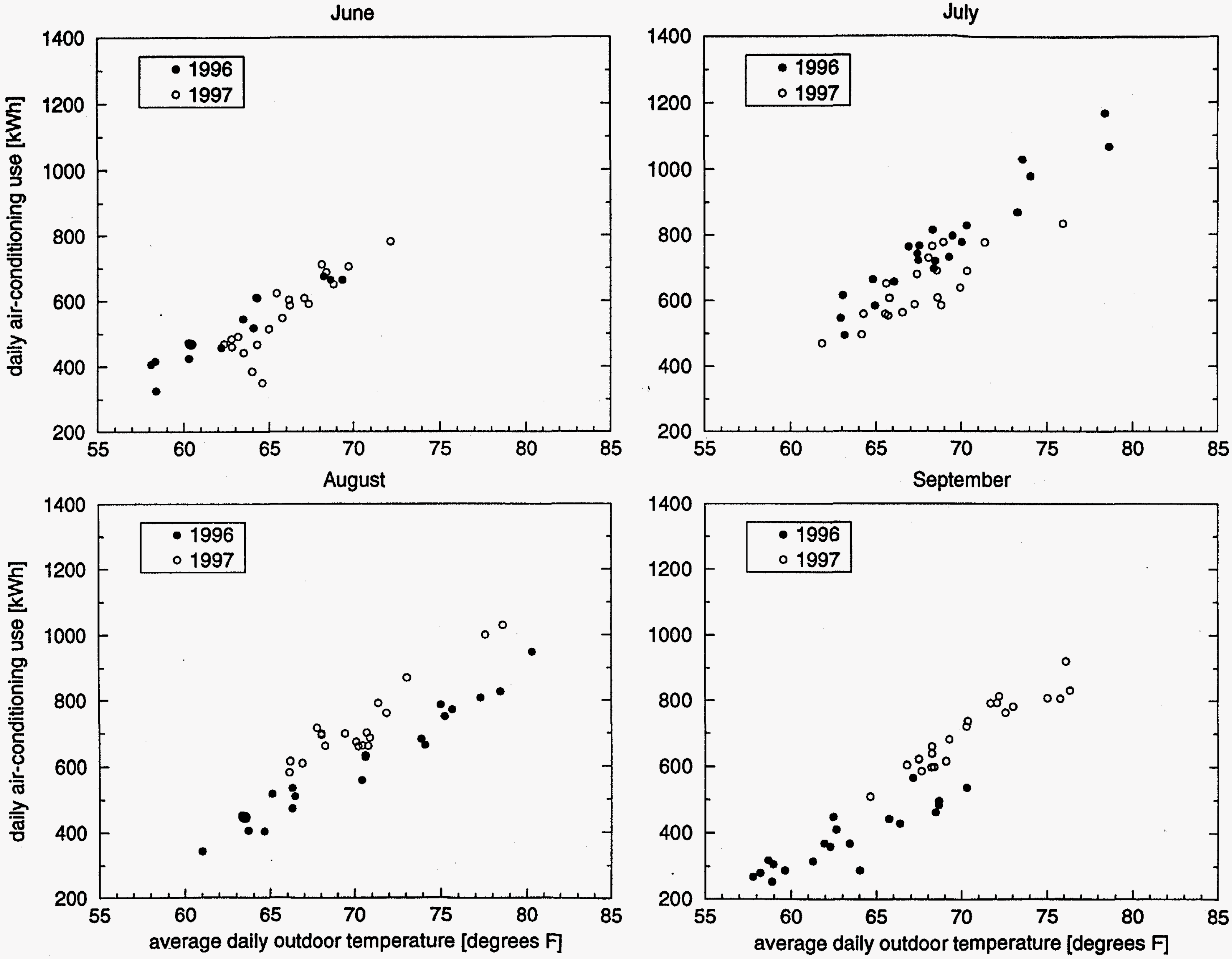


Figure 3.10b. Gilroy monitored daily air-conditioning electricity use vs daily average outdoor air temperature for standard weekdays.

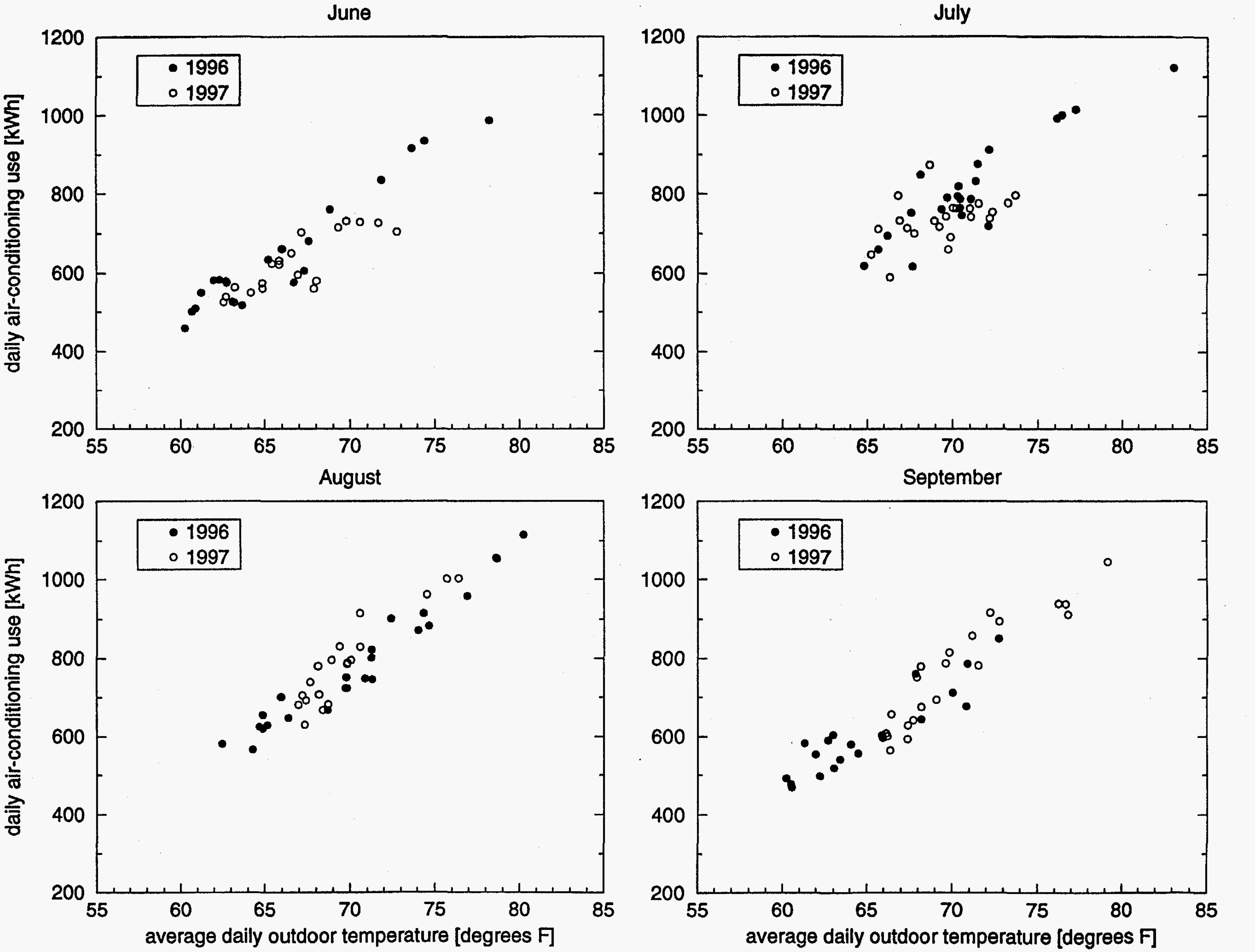


Figure 3.10c. San Jose monitored daily air-conditioning electricity use vs daily average outdoor air temperature for standard weekdays.

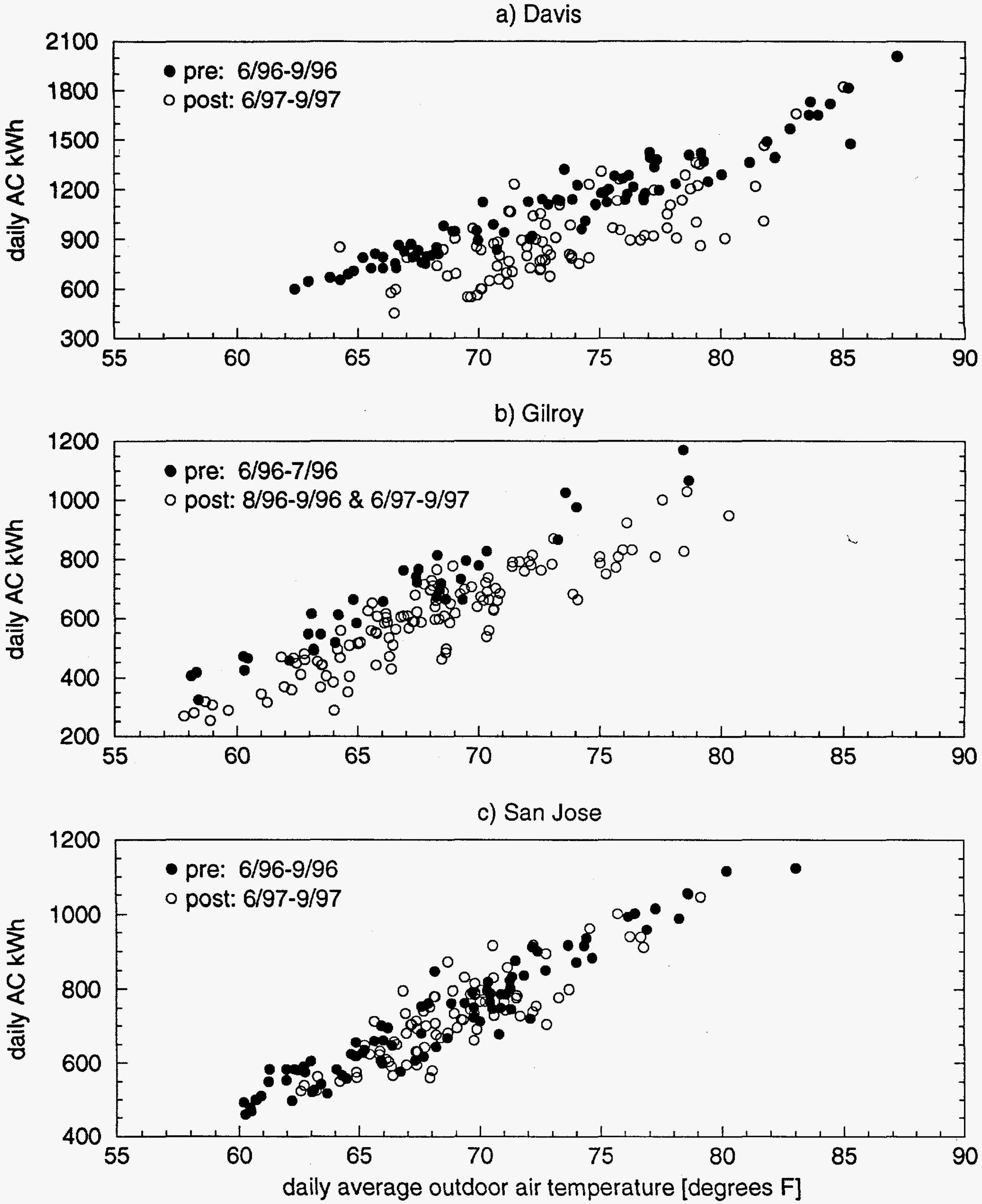


Figure 3.11. Summertime daily a/c electricity use vs. daily average outdoor air temperature.

The statistical analysis was performed in two steps. First, we used a single-variate regression model with the daily a/c electricity use regressed against the daily average outdoor air temperature for each month. The equation used was of the form

$$kWh_{a/c} = C_0(i) + C_1(i)T \qquad [1]$$

where,

$kWh_{a/c}$ = daily a/c electricity use during the month of i
T = daily average outdoor air temperature during the month of i.

The analysis of variance and parameter estimates from these regressions are shown in **Table B.1**. Most months from each site do have similar slopes and high R^2. This confirms the theory that the temperature dependency of the a/c electricity use (C_1) should be fairly constant during all summer months and for both pre- and post-retrofit conditions.

In the second step of the analysis, we utilized a multi-variate model and repeated the regressions for each building assuming a single slope for all months and one for pre- and post-retrofit data with:

a: 8 intercepts (one for each summer month)

b: 2 intercepts (one for the pre- and one for the post-retrofit period).

The model used was of the form

$$kWh_{a/c} = \sum_{j=1}^{j=m} C_0(j)\delta_{ij} + C_1 (T - T_{mean}) \qquad [2]$$

where,

δ_{ij} = 1 for $i = j$ and = 0 for $i \neq j$, $m = 8$ for monthly and $m = 2$ for seasonal regressions,
T_{mean} = daily average outdoor temperature of both summer seasons.

Parameter estimates and standard errors are displayed in **Table 3.3** for both 8-intercept and 2-intercepts multi-variate models and the analysis of variance in **Table B.2**. Note that the slopes (C_1) are close, but not equal, to the mean slope in the single-variate regressions.

By examining the y-intercepts (C_0) in Table 3.3, Davis shows, month by month, the pre-coating months with a higher a/c demand than the post-coating months and the same is true for Gilroy. In San Jose the 1996 months of June and July had higher a/c demand than the respective months in 1997, however the opposite was true for August and September. The month of July 1996 had the greatest demand in Davis and Gilroy and was a very close second to August 1997 in San Jose. We used (C_1) of the single-slope model to normalize the monitored a/c use for variation in the outdoor air temperature in the next step.

Table 3.3. Parameter estimates and standard errors from multi-variate regressions of daily air-conditioning electricity use versus daily average outdoor temperature for summer standard weekdays.

$$kWh_{a/c} = \sum_{j=1}^{j=m} C_0(j)\delta_{ij} + C_1\,(T - T_{mean})$$

$C_0(j)$ [kWh/day]					
8-intercept model			2-intercept model		
period	estimate	error (%)	period	estimate	error (%)
Davis					
June 1996	1089	22(2)	pre	1102	15(1)
July	1178	22(2)			
August	1083	21(2)			
September	1052	23(2)			
June 1997	1053	22(2)	post	907	15(2)
July	875	21(2)			
August	980	22(2)			
September	724	22(3)			
Gilroy					
June 1996	658	15(2)	pre	711	11(2)
July	737	11(1)			
August	535	12(2)	post	595	6(1)
September	517	12(2)			
June 1997	614	11(2)			
July	643	11(2)			
August	636	11(2)			
September	622	12(3)			
San Jose					
June 1996	722	12(2)	pre	727	6(1)
July	747	11(1)			
August	729	11(2)			
September	707	12(2)			
June 1997	678	11(2)	post	715	6(1)
July	713	11(2)			
August	754	11(1)			
September	717	11(2)			
C_1 [kWh/day °F]					
Davis	45.6	1.6(4)		46.6	2.0(4)
Gilroy	29.8	1.1(4)		33.1	1.1(3)
San Jose	28.2	1.0(4)		29.9	0.9(3)

Estimated savings in air-conditioning electricity use

The monitored average daily a/c electricity use for the post-retrofit period were normalized for differences in the daily average outdoor air temperature between the pre- and post-retrofit periods as shown in equation 3.

$$kWh_{a/c,1997norm} = kWh_{a/c,1997mon} + C_1 \ (T_{1996} - T_{1997}) \qquad [3]$$

where,

$kWh_{a/c,1997norm}$ = normalized daily a/c electricity use for month (period) in 1997
$kWh_{a/c,1997mon}$ = monitored daily a/c electricity use for month (period) in 1997
C_1 = coefficient from equation 2
T = daily average outdoor temperature for month (period).

The upper portion of **Table 3.4** shows the monthly monitored a/c electricity use for 1996 and 1997, and the 1997 a/c electricity use data normalized for the temperature difference between 1996 and 1997. The slopes from the 8-intercept multi-variate regression model were used to normalize the 1997 a/c electricity use. The table also lists the estimated savings in a/c electricity use for each month. When comparing 1996 to 1997 month-by-month the Davis building experiences a/c electricity savings each month ranging from 3 - 39%. The month-by-month comparison for Gilroy is limited to June and July and show savings of 9 and 12% respectively. In San Jose the month-by-month comparison shows some savings during June and July (7 and 4%) and a similarly small deficit in August and September (-3 and -2%). The uncertainty associated with these estimates are ± the standard error in the intercept (C_0) estimated at T_{mean}.

The lower portion of **Table 3.4** shows the summertime monitored a/c electricity use for pre- and post-retrofit conditions, and the post a/c electricity use data normalized for the temperature difference between pre- and post-periods. The slopes from the 2-intercept multi-variate regression model were used to normalize the post-retrofit a/c electricity use. In the Gilroy building, the pre-coating monitoring period consisted of the months June and July 1996, as the roof was coated early in August of that year. We extrapolated the a/c electricity use in the post-coating months of August and September 1996 to estimate pre-coating use and obtain the value 675 kWh in column A of the table.

Summertime standard-weekday average daily air-conditioning savings were 18% (198 kWh/day) in the Davis medical office building, 13% (86 kWh/day) in the Gilroy medical office building, and 2% (13 kWh/day) in the San Jose retail store. The most savings were seen in the Davis building since of the three buildings its roof system was least resistant to heat transfer (i.e. primarily R-8 rigid insulation) and it had an unvented return plenum. The Gilroy building utilizes similar shell construction and internal load characteristics as in the Davis building, but with two significant differences: R-19 fiberglass ceiling insulation and large passive roof vents; experienced about 25% less relative savings than in the Davis building.

Table 3.4. Monitored and outdoor temperature normalized average daily air-conditioning electricity use and estimated savings for summer standard weekdays by month and for the entire season.

uncertainty is ± the standard error in the intercept (C_0) estimated at T_{mean}

month	monitored a/c [kWh/day]		normalized 1997 a/c [kWh/day] for 1996 T_{out}	estimated a/c savings	
	1996	1997		Δ kWh/day	%
	A	B	$C=B+m(T_A-T_B)$	D=A-C	E=(D/A)*100
Davis					
June	1006	991	973 ± 22	33 ± 22	3 ± 2
July	1320	895	1018 ± 22	302 ± 22	23 ± 2
August	1168	1026	1063 ± 22	105 ± 22	9 ± 2
September	853	750	522 ± 22	331 ± 22	39 ± 3
Gilroy[a]					
June	511	565	467 ± 13	44 ± 13	9 ± 3
July	774	641	680 ± 11	94 ± 11	12 ± 1
San Jose					
June	645	618	601 ± 12	44 ± 12	7 ± 2
July	814	736	781 ± 11	33 ± 11	4 ± 1
August	772	798	795 ± 11	-23 ± 11	-3 ± 1
September	605	766	617 ± 11	-12 ± 11	-2 ± 2
summer	monitored a/c [kWh/day]		normalized post a/c [kWh/day] for pre T_{out}	estimated a/c savings	
	pre	post		Δ kWh/day	%
Davis	1094	915	896 ± 15	198 ± 15	18 ± 1
Gilroy	675[b]	658	589 ± 7	86 ± 7	13 ± 1
San Jose	713	730	700 ± 6	13 ± 6	2 ± 1

[a] The roof was coated August 5, 1996; therefore, a direct month-to-month comparison for August and September could not be made.

[b] The pre-coating monitoring period consisted of the months June and July 1996. We extrapolated the a/c electricity use in the post-coating months of August and September 1996 to estimate pre-coating use and obtain the value 675 kWh in column A of the table.

The air-conditioning electricity use in the San Jose retail store is internal-load driven, and the roof system contributes relatively little to the whole-building load, and thus the savings were least in this building (even though Δa was higher than in the medical office buildings). It has a well-ventilated plenum, which efficiently exhausts to the outdoors any heat that is transferred through a radiant barrier attached under the roof.

4.0 Cost and Implementation Issues Regarding Roof Coatings

In this demonstration project the facilities were responsible for coating their own buildings. Previous projects at LBNL have paid for the cost of coatings and the project analysis teams actually coated the buildings themselves (Akbari et al 1997). Getting facilities to contract and pay for their own coatings has been a beneficial learning experience for understanding the barriers to reflective roof coating adoption.

Lessons learned

Facility managers are generally extremely busy. The three managers involved in these projects are responsible for operation of literally hundreds of buildings throughout California. Getting their time and attention can be difficult. But three major factors have delayed this process - the heavy workload of the facility managers, the unfamiliarity of facility managers and contractors with reflective coating materials and their application, and the contractors difficulties in scheduling the coating around weather and other commitments.

All three of the facility managers solicited a bid for the roofing coating from their usual roof contractors. One of these bids was within the anticipated range (the bid was actually lower than it should have been due to a mistake made by the roofing contractor) and this manager arranged to have the building coated immediately. Two of these bids were much higher than expected, which surprised the managers. The managers then required time to re-focus their attention and arrange for new coating bids, which delayed the coating process.

A productive way to work with facility managers is to get as much information as possible about regional roofing contractors before talking to them. Information to collect is listed in **Table 4.1**. If the managers preferred contractors seem inexperienced or overpriced, recommend another contractor who can do the coating work. To save the facility managers time, it is also helpful for project personnel to meet with roofing contractors to collect bids.

Facilities managers tend to think white coatings make a lot of sense. However, they have probably never used one before and need to be convinced of their cost-effectiveness. Even though high-reflectance roofs do save energy costs (an estimated 2 - 5¢/ft^2 per year in the areas east and south of the Bay Area) these energy savings alone are very small compared to the operating budget of the facility manager, and on its own will generally have a fairly long payback period. Roof coatings can be made much more cost-effective if they can extend the longevity of a roof system. An estimate of the payback period needs to be accompanied by a life-cycle cost analysis of the roofing system, including the avoided cost of replacing the entire roof.

Roofing contractors are not very familiar with high-reflectance coating materials. They frequently assume that highly reflective, low-energy use roof materials include aluminum fiber coatings. They do not, aluminum coatings have high reflectance but low emittance, i.e. they retain more heat collected from the sun than a high-reflectance, high-emittance material, and typically heat to temperatures comparable to conventional dark surfaces. These contractors also tend to be wary of new technology. They must generally maintain all the roofs they install, so untested products are not popular. Especially unpopular are products touted as being able to reduce the need for reroofing, a major part of a roofing contractors livelihood.

Table 4.1. Information to collect from roofing contractors in reference to high-reflectance roof coating jobs.

Materials costs and issues
Coating materials used - elastomeric or cementitious
Coating material rated reflectance/albedo
Coating cost per gallon
Coating coverage - number of coats
Guaranteed coating life
Comparative cost of completely reroofing
Labor costs and issues
Labor cost per hour
Estimated coverage per hour
Time and cost of preparatory work
Union or non-union contractor
Charges for weekend work
Contractor quality issues
Experience & references from coating jobs
Contractor attitude towards coatings
Contractor preferences of facilities managers

Roof coating bids

A contractor who is willing to install roof coatings may not have much experience. The one contractor who bid on, and subsequently coated, the roof of the Gilroy building ended up under-bidding. The bid was made for one coat of material at 35¢/ft^2. The coating product called for two coats of material, which should have cost about 47¢/ft^2. The contractor ended up having to pay for the extra 12¢/ft^2.

The anticipated cost of coating the rooftops was found by obtaining quotes over the phone from roofing contractors. These turned out to be much lower than the bids given from site visits. According to phone calls made to numerous contractors, the price of coating initially quoted was 20 - 30¢/ft^2, including labor and pre-washing of the surface. This value turned out to be off by a factor of two or more, depending on the contractor.

Typical roof coating bids in the San Francisco Bay Area and the Sacramento Valley are evaluated in **Table 4.2**. This table compares a high-priced bid for coating with the expected lower bid, listing some general guidelines obtained from various roofing contractors.

Table 4.2. Cost estimates for coating the roof of a 30,000 ft^2 building.

	Contractor Quote	Our Estimate
Materials		
gallons of material	825	600 [a]
cost per gallon	\$18.30 [b]	\$11.00 [c]
cost of materials	\$15,100	\$6600
Labor		
hours of labor	150 [d]	-
roof area ft^2	30,000 + parapet area	30,000
labor cost per hour	\$50	-
labor cost per 100 ft^2	-	\$25 [e]
weekend labor	\$1300	\$0
cost of labor	\$8800	\$7500
Total	\$23,900	\$14,100
Total per ft^2	\$0.80	\$0.47

[a] Typical coating thickness for elastomeric materials is 2 gallons per 100ft^2.

[b] Price seems high.

[c] Price per gallon of a typical elastomeric coating.

[d] Typically 200ft^2 coated per hour.

[e] A typical labor cost per 100ft^2 for applying coatings.

Cost savings

Cost savings were estimated to be 6¢ per ft^2 per year for Davis, 4¢ per ft^2 per year for Gilroy, and under 1¢ per ft^2 per year for San Jose. At an application cost of 47¢ per ft^2 the simple payback for Davis is 8 years and 12 for Gilroy. These estimates are based on 10¢ per kWh and 100 days of standard-weekday summertime operation.

5.0 Display Kiosks

Display kiosks were designed to explain cool-roof coating theory and to display real-time measurements of weather conditions, roof surface temperature, and air-conditioning electricity use to visitors of the buildings. They were situated in the lobby or a central area of each building so patrons would have easy access to them and could then learn about the cool-roofing project underway. A display kiosk is a personal computer seated in a locked cabinet. The computer monitor has touchscreen capabilities and is seen through a window in the cabinet. A visitor only needs to touch the screen to access any one of sixteen panels. These panels are presented in **Appendix D** and are briefly described below.

1. Welcome to the Cool Roof Demonstration Project Kiosk
2. Keep a Roof Cool with Highly Reflective Materials
3. White Coatings
4. Infrared Photo of the Roof at the Edge of a White Coating
5. Energy from the Sun
6. Building Measurements
7. Current Weather Conditions
8. Current Roof Surface Temperature
9. White Roof Energy Savings
10. Roof Temperature Over the Last Week
11. Air-Conditioning Energy Use Over the Last Week
12. Outdoor Temperature and Humidity Over the Last Week
13. Sunshine Over the Last Week
14. Wind Speed and Direction Over the Last Week
15. For More Information
16. Our Sponsors

The kiosk runs a spreadsheet program on the personal computer, which reads data from the data logger. The spreadsheet program creates plots of the collected data for several of the panels. The plots of air-conditioning electricity use were derived from an early set of regressions and are not the regressions utilized in our analysis described in this report. The kiosks were used most often to check the outside weather conditions. There has not been a count of the number of people that have viewed the kiosks, but patrons have been seen using them whenever project personnel visited the buildings. **Figure 5.1** is a photo of the display kiosk in operation in the San Jose building. The kiosks screens were placed on the World Wide Web for the cyber-public.

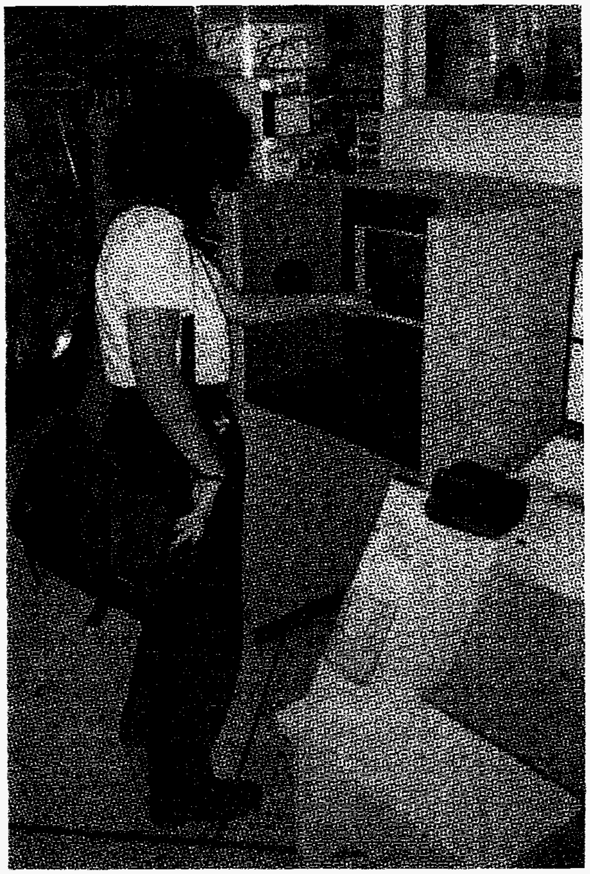


Figure 5.1. Kiosk in operation at the San Jose site.

6.0 Conclusions

In this project we monitored air-conditioning electricity use, plenum, indoor, and outdoor air temperatures, roof surface temperature, and other environmental variables in three buildings in California: two medical office buildings in Gilroy and in Davis and a retail store in San Jose. The following is the summary of findings.

Reduction in roof surface temperatures

In the Davis building, coating the roof with a reflective coating increased the roof albedo from 0.24 - 0.60. The roof surface temperature on hot sunny summer afternoons before coating was applied reached 175°F but only 120°F after coating. In the Gilroy building, coating the roof increased the roof albedo from 0.25 - 0.60; the roof surface temperature was reduced from 170°F - 120°F. In the San Jose building, coating the roof increased albedo from 0.16 - 0.60 and the roof surface temperature decreased from 175°F - 120°F.

Air-conditioning electricity savings

Summertime standard-weekday average daily air-conditioning savings are highlighted in **Table 6.1**, where electricity use was reduced by 18% (6.3 kWh/1000ft^2) in the Davis medical office building, 13% (3.6 kWh/1000ft^2) in the Gilroy medical office building, and 2% (0.4 kWh/1000ft^2) in the San Jose retail store. The most savings were seen in the Davis building since of the three buildings its roof system was least resistant to heat transfer (i.e. primarily R-8 rigid insulation) and it had an unvented return plenum. The Gilroy building utilizes similar shell construction and internal load characteristics as in the Davis building, but with two significant differences: R-19 fiberglass ceiling insulation and large passive roof vents; experienced about 25% less relative savings than in the Davis building. The air-conditioning electricity use in the San Jose retail store is internal-load driven, and the roof system contributes relatively little to the whole-building load, and thus the savings were least in this building (even though Δa was higher than in the medical office buildings). It has a well-ventilated plenum, which efficiently exhausts to the outdoors any heat that is transferred through a radiant barrier attached under the roof.

Table 6.1. Monitored summertime average daily air-conditioning electricity savings in three Northern California commercial buildings.

building	ft^2	roof system description			daily a/c savings		
		insulation	duct location	Δ albedo	kWh	kWh/1000ft^2	%
Davis	31700	R-8	cond. space	0.36	198	6.3	18
Gilroy	23800	R-19	plenum	0.35	86	3.6	13
San Jose	32900	rad. bar.	plenum	0.44	13	0.4	2

Experience in having the roofs coated

There were many unexpected difficulties in getting the rooftops coated with high-reflectance coatings. In this project the cost of the coatings were paid by the facility itself, and the coatings were applied by roofing contractors instead of by project personnel. One of the difficulties was associated with selling the coating based on its cost-effectiveness. Based on the projected energy savings of these coatings alone (2 - 5¢/ft^2) a roof coating is not very cost-effective. If the coating can be used to lengthen the life of the roof and avoid replacement costs, it becomes much more economically attractive. Other difficulties arose in working with facility managers and roofing contractors. Neither group has much experience with or knowledge of high-reflectance coatings, leading to a hesitance to adopt this new technology. These people are also extremely busy, so scheduling meetings and work can be challenging. A set of information to collect and guidelines for coating costs were developed to help streamline the process of coating rooftops.

Display kiosk

Display kiosks were designed to explain cool-roof coating theory and to display real-time measurements of weather conditions, roof surface temperature, and air-conditioning electricity use to visitors of the buildings. They were situated in the lobby or a central area of each building so patrons would have easy access to them and could then learn about the cool-roofing project underway.

References

Akbari, H., Bretz, S., Kurn, D., and Hanford, J. 1997. "Peak Power and Cooling Energy Savings of High-Albedo Roofs". *Energy and Buildings* 25:117-126. Lawrence Berkeley National Laboratory Report LBL-34411. Berkeley, CA.

ASTM Standard E1918-97. 1998 (in press). Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field. Philadelphia, PA.

Berdahl, P. and Bretz, S. 1997. "Preliminary Survey of the Solar Reflectance of Cool Roofing Materials". *Energy and Buildings* 25:149-158. Lawrence Berkeley National Laboratory Report LBL-36020. Berkeley, CA.

Bretz, S., Akbari, H., and Rosenfeld, A. 1998. "Practical Issues for Using Solar-Reflective Materials to Mitigate Urban Heat Islands". *Atmospheric Environment* 32:95-101. Lawrence Berkeley National Laboratory Report LBL-38170. Berkeley, CA.

Gartland, L., Konopacki, S., and Akbari, H. 1996. "Modeling the Effects of Reflective Roofing". *In Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings* 4:117. Pacific Grove, CA. Lawrence Berkeley National Laboratory Report LBL-38580. Berkeley, CA.

Konopacki, S., Akbari, H., Pomerantz, M., Gabersek, S., and Gartland, L. 1997. "Cooling Energy Savings Potential of Light-Colored Roofs for Residential and Commercial Buildings in 11 U.S. Metropolitan Areas". Lawrence Berkeley National Laboratory Report LBNL-39433. Berkeley, CA.

Parker, D., Huang, J., Konopacki, S., Gartland, L., Sherwin, J., and Gu, L. 1998. "Measured and Simulated Performance of Reflective Roofing Systems in Residential Buildings". *In ASHRAE Transactions* vol. 104, pt. 1. Atlanta, GA.

Parker, D., Sonne, J., and Sherwin, J. 1997. "Demonstration of Cooling Savings of Light Colored Roof Surfacing in Florida Commercial Buildings: Retail Strip Mall". Florida Solar Energy Center Report FSEC-CR-964-97. Cocoa, Fl.

Rosenfeld, A., Akbari, H., Bretz, S., Fishman, B., Kurn, D., Sailor, D., and Taha, H. 1995. "Mitigation of Urban Heat Islands: Materials, Utility Programs, Updates". *Energy and Buildings* 22:255-265. Lawrence Berkeley National Laboratory Report LBL-36587. Berkeley, CA.

Appendix A - Instrumentation and Equipment Specifications

Item	Description	Use	Manufacturer	Unit price	# Purchased	Cost
Personal Computer	486X-133 Mhz	Kiosk data processing	Oak Tree computers	$1013.00	3	3039.00
Monitor with Touch Screen	Touch Screen EMB15	Kiosk monitor	SCT, Incorporated	$1095.00	3	3369.00
PCPlus for Windows Software	PCPlus 3.0 and CD ROM Upgrade	Kiosk data collection and processing	Datastorm	$208.95	1	$235.05
Power meter	kWh meter, 277 Volt	Power monitoring	Veris Industries, Inc	$267.53	6	$1605.18
Current transformer	Split core 2400 amp CT	Current monitoring - whole building	Veris Industries, Inc	$95.50	6	$573.00
Current Transformer	Split core 300 amp CT	Current monitoring - chillers	Veris Industries, Inc	$52.20	12	$626.40
Fuse Packs	H6901	use with power meters	Veris Industries, Inc	$29.75	6	$178.50
Data Logger	DataTaker 500	Data Logging	Data Electronics	$2575.00	3	$7725.00
NEMA 1 Enclosure	#A907	box to hold data logger	Grainger	$117.65	3	$352.95
RTD Thermal Ribbon	1-S65PDY24	measuring roof surface temperatures	Minco Products, Inc	$47.00	18	$846.00
Temperature Transmitter	16-TT111pd1AC	converts RTD readings for data logger	Minco Products, Inc	$52.65	18	$947.70
Temperature Sensor	TS1082 TCS	return air sensor	Burke Engineering Co.	$15.50	3	$46.50
Temperature Sensors	TS1080 TCS	room air sensors	Burke Engineering Co.	$11.48	9	$103.32
Temperature Sensors	TS1087 TCS AD592's	Plenum air sensors	Burke Engineering Co.	$8.42	8	$67.36
Pyranometer & Mounting Fixture	LI-200SZ	solar insolation	Li-Cor	$198.00	3	$594.00
Anemometer	TV-110-L320	measure wind speed	Texas Electronics, Inc	$285.00	3	$855.00
Wind Vane	TD-106	measure wind direction	Texas Electronics, Inc	$415.00	3	$1245.00
Thermal Flux Transducer	ITI Model B	measure roof surface heat flux	ITI Company	$240.00	3	$720.00
Temperature & Relative Humidity Probe&Shield	41372LF & 41002P	measure rel. humidity & outdoor temperature	R.M. Young Company	$778.00	3	$1860.00
Wire	1, 2 and 3 pair wire, shielded	Wire to bring readings to data logger	Sacramento Electric Supply Co.	$110.57/1K ft $152.00/1K ft $305.05/1K ft	2500 ft 1 pair 500 ft 2 pair 2000 ft 3 pair	$962.53
Hardware, Electrical, Shipping						$1532.09
Photos						$45.91
Kiosks		Encloses PC's & displays their screens	donated by PG&E, modified by Parkmead	$500	3	$1500.00
TOTAL						$29029.69

Appendix B - Air-Conditioning Electricity Use Analysis

Visuals were developed to aid in the month-to-month analysis of a/c electricity use. **Figures B.1ab,2ab,3ab** show average daily air-conditioning electricity use profiles for standard weekdays by month (June 1996 - September 1997) at Davis, Gilroy, and San Jose, respectively. **Figures B.4ab,5ab,6ab** show monitored daily air-conditioning electricity use versus daily average outdoor air temperature for standard weekdays by month (June 1996 - September 1997) at Davis, Gilroy, and San Jose, respectively.

The statistical analysis was performed in two steps. First, we used a single-variate regression model with the daily a/c electricity use regressed against the daily average outdoor air temperature for each month. The equation used was of the form

$$\mathrm{kWh}_{a/c} = C_0(i) + C_1(i)T \qquad [1]$$

Analysis of variance and parameter estimates from the single-variate regressions of daily a/c electricity use versus daily average outdoor air temperature for the months of June 1996 - September 1997 are presented in **Table B.1**[8].

In the second step of the analysis, we utilized a multi-variate model and repeated the regressions for each building assuming a single slope for all months and one for pre- and post-retrofit data with:

a: 8 intercepts (one for each summer month)

b: 2 intercepts (one for the pre- and one for the post-retrofit period).

The model used was of the form

$$\mathrm{kWh}_{a/c} = \sum_{j=1}^{j=m} C_0(j)\delta_{ij} + C_1\,(T - T_{mean}) \qquad [2]$$

Analysis of variance from the multi-variate regressions of the summer season are presented in **Table B.2**.

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[8] (prob>f) significance probability, the probability of getting a greater F statistic than that observed if the hypothesis is true. (σ) an estimate of the standard deviation of the error term, it is calculated as the square root of the mean square error. (R^2) is a measure between 0 and 1 that indicates the portion of the total variation that is attributed to the fit rather than left to residual error.

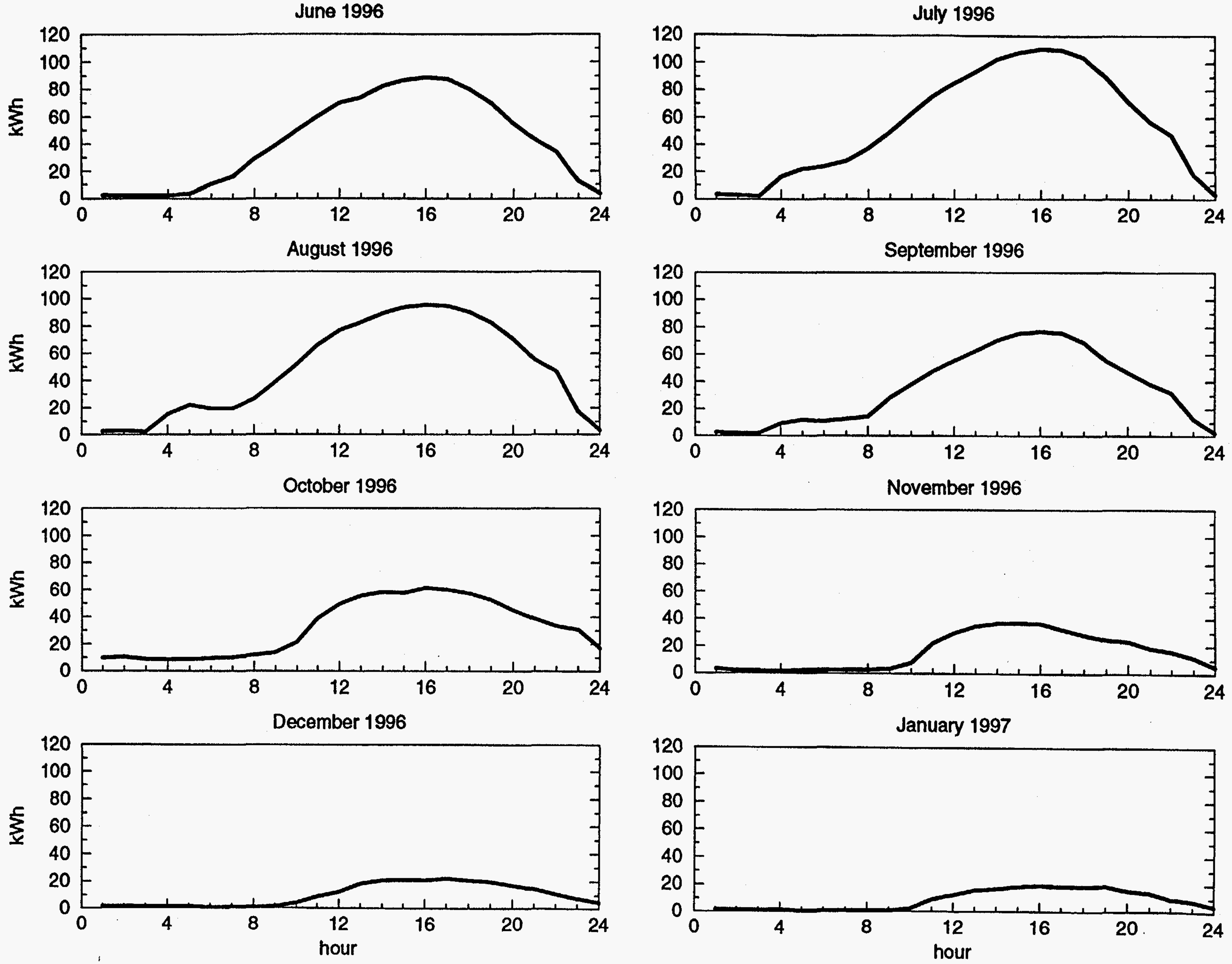


Figure B.1a. Davis average daily air-conditioning electricity use profiles for standard weekdays (6/96-1/97).

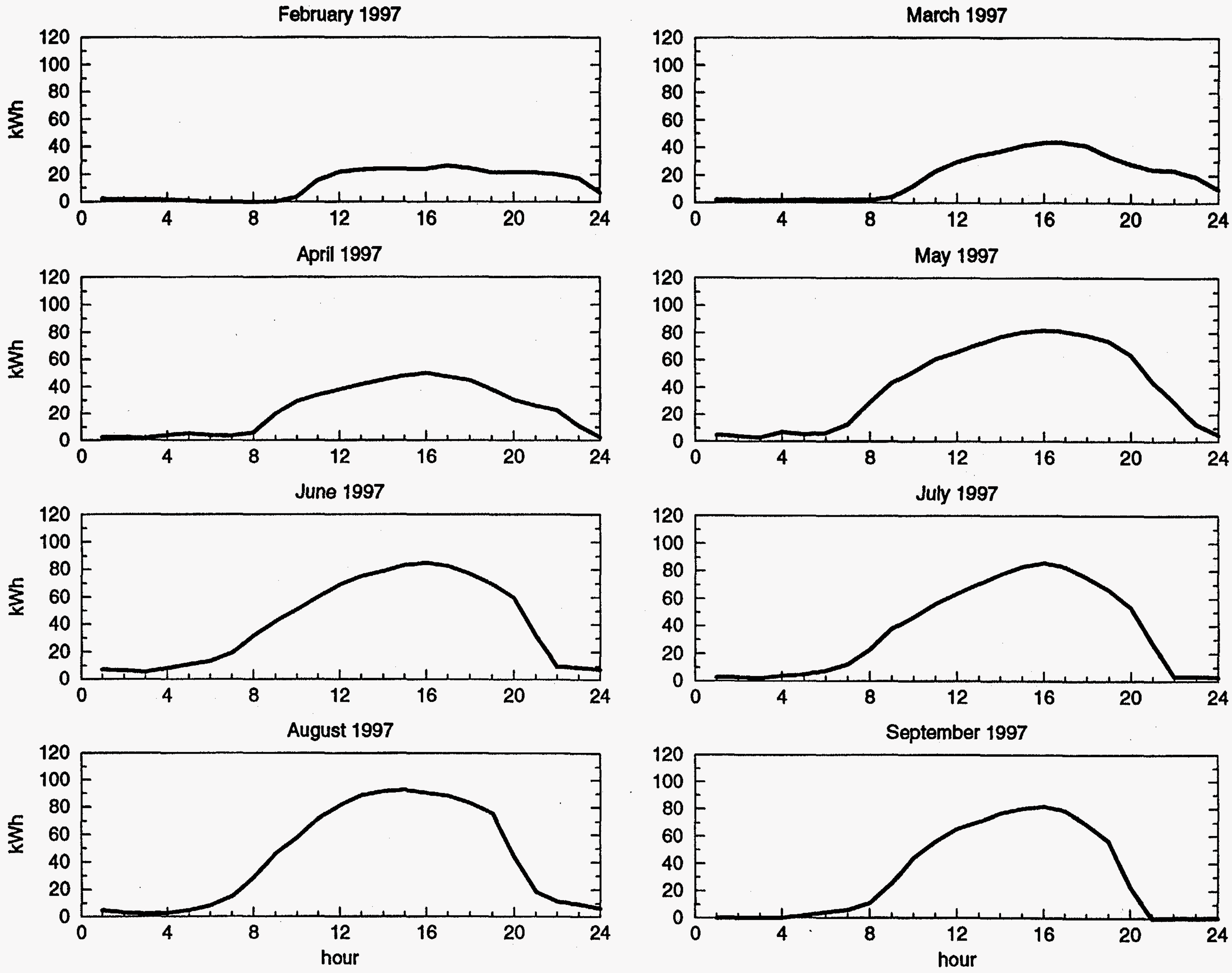


Figure B.1b. Davis average daily air-conditioning electricity use profiles for standard weekdays (2/97-9/97).

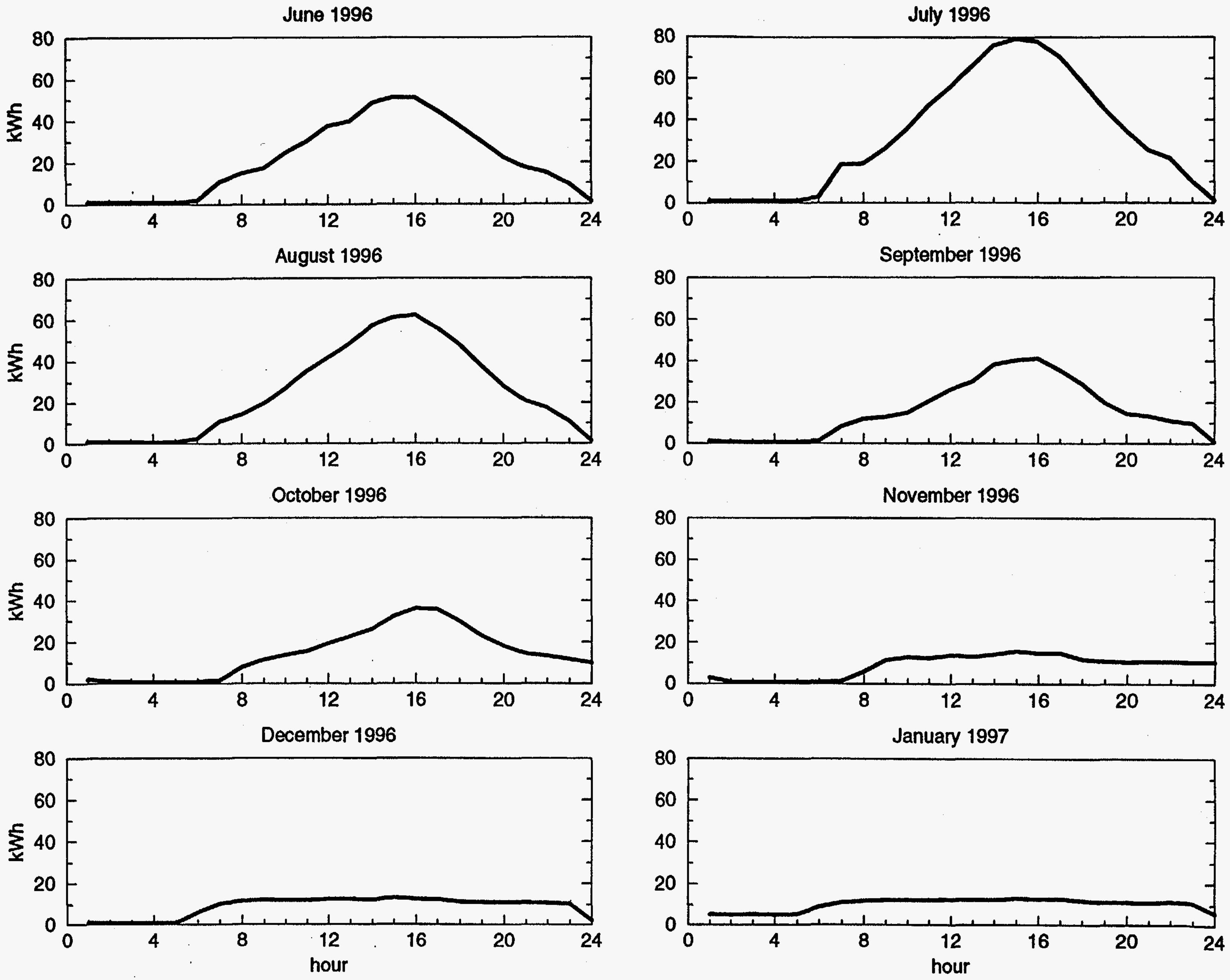


Figure B.2a. Gilroy average daily air-conditioning electricity use profiles for standard weekdays (6/96-1/97).

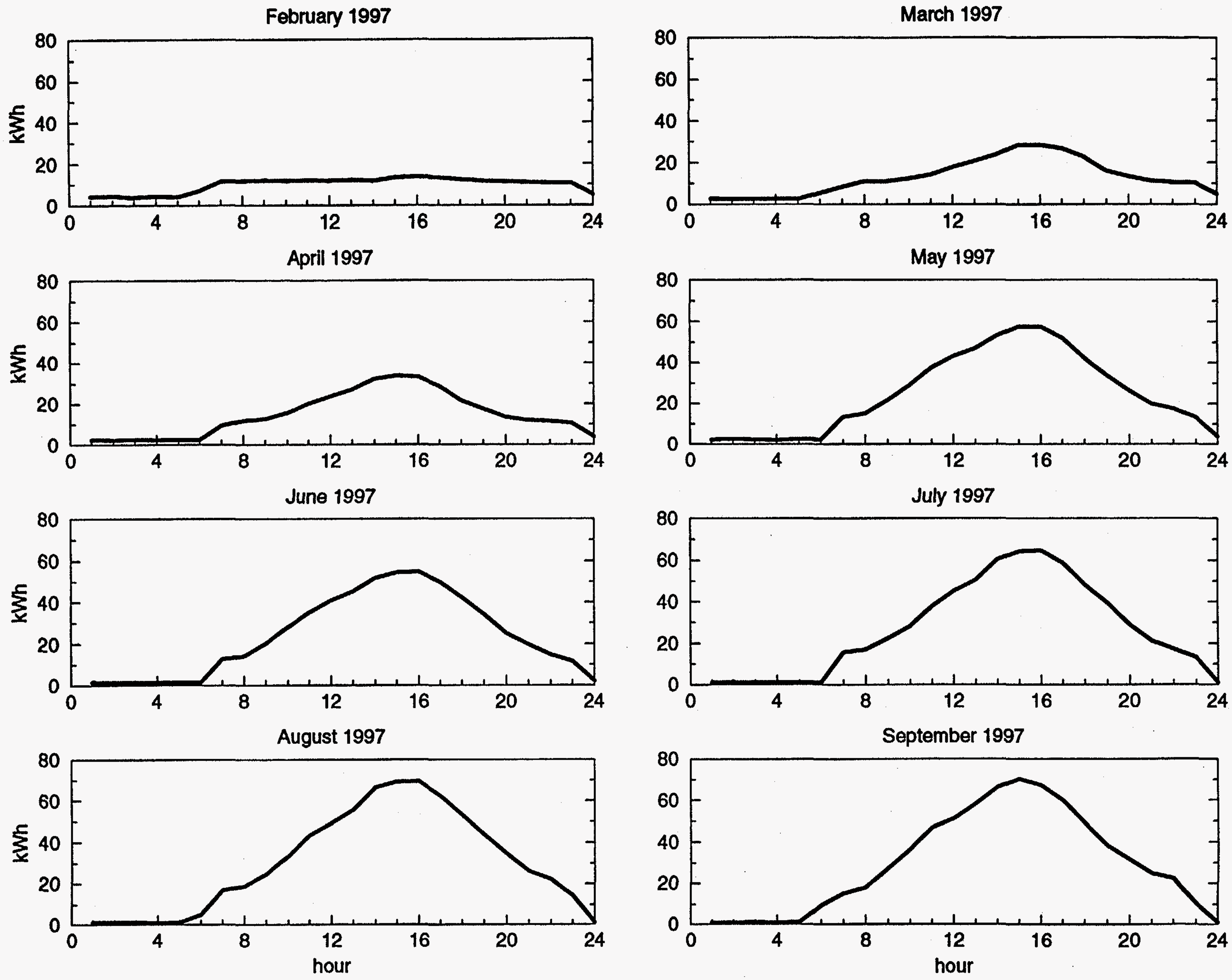


Figure B.2b. Gilroy average daily air-conditioning electricity use profiles for standard weekdays (2/97-9/97).

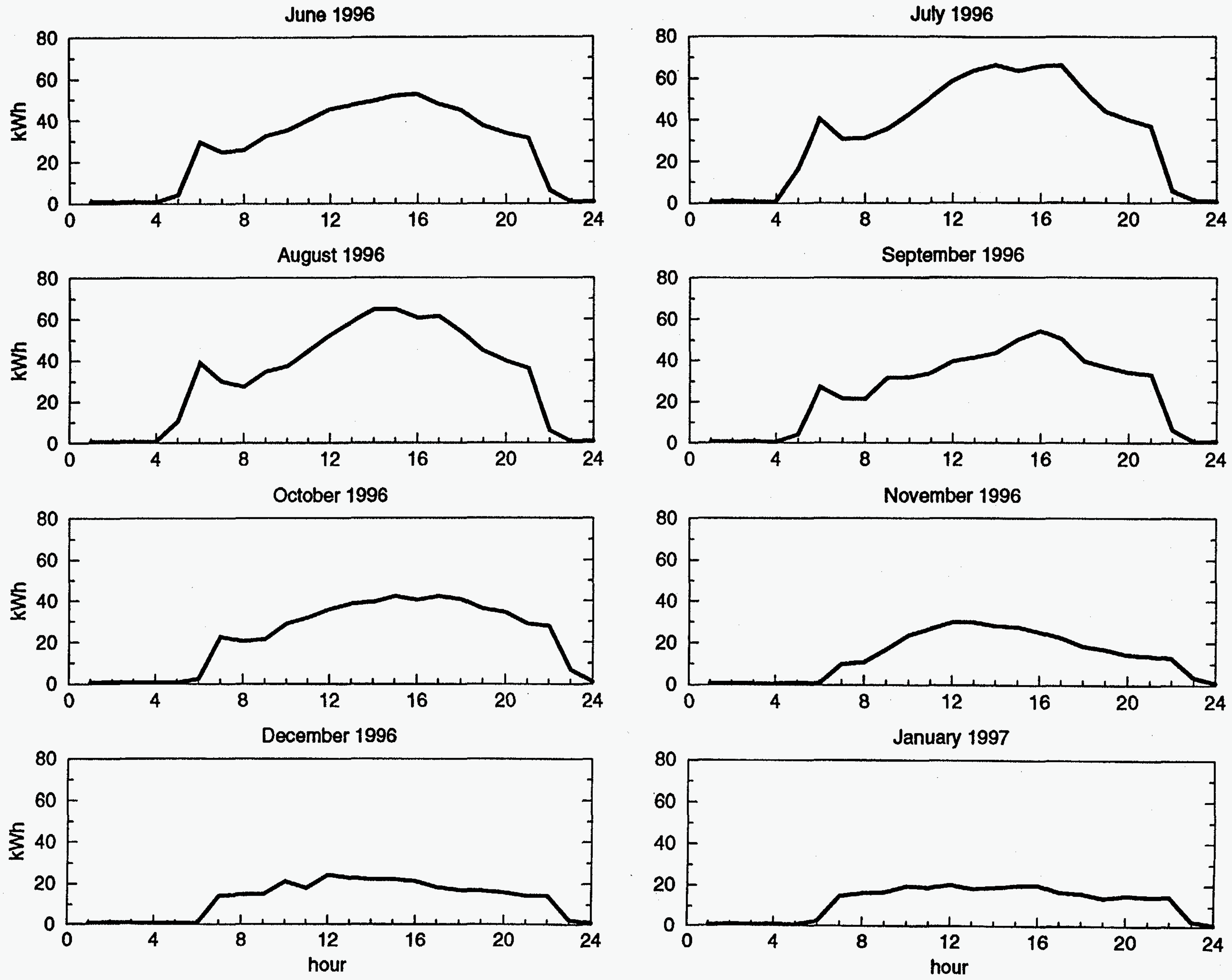
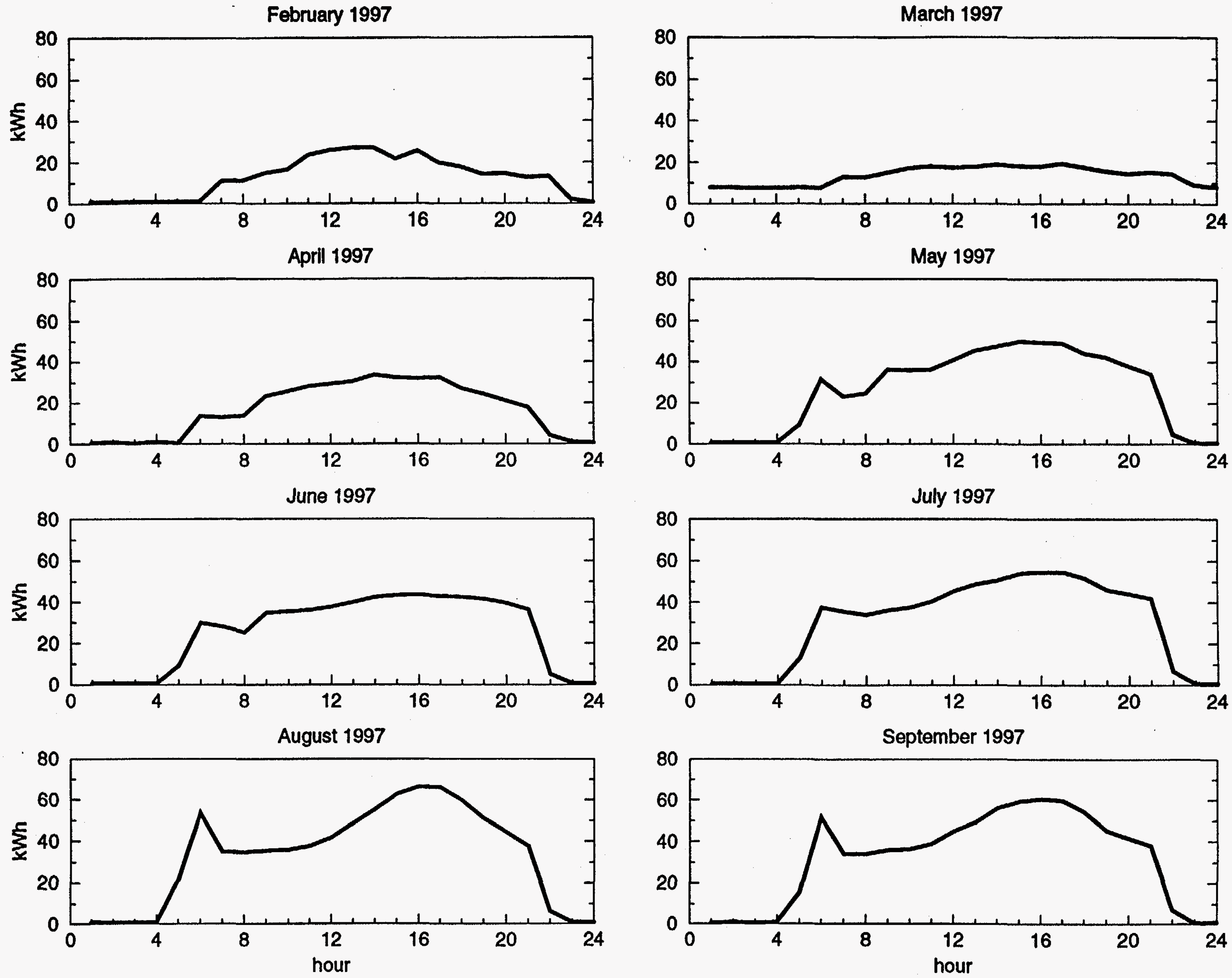


Figure B.3a. San Jose average daily air-conditioning electricity use profiles for standard weekdays (6/96-1/97).



February 1997

March 1997

April 1997

May 1997

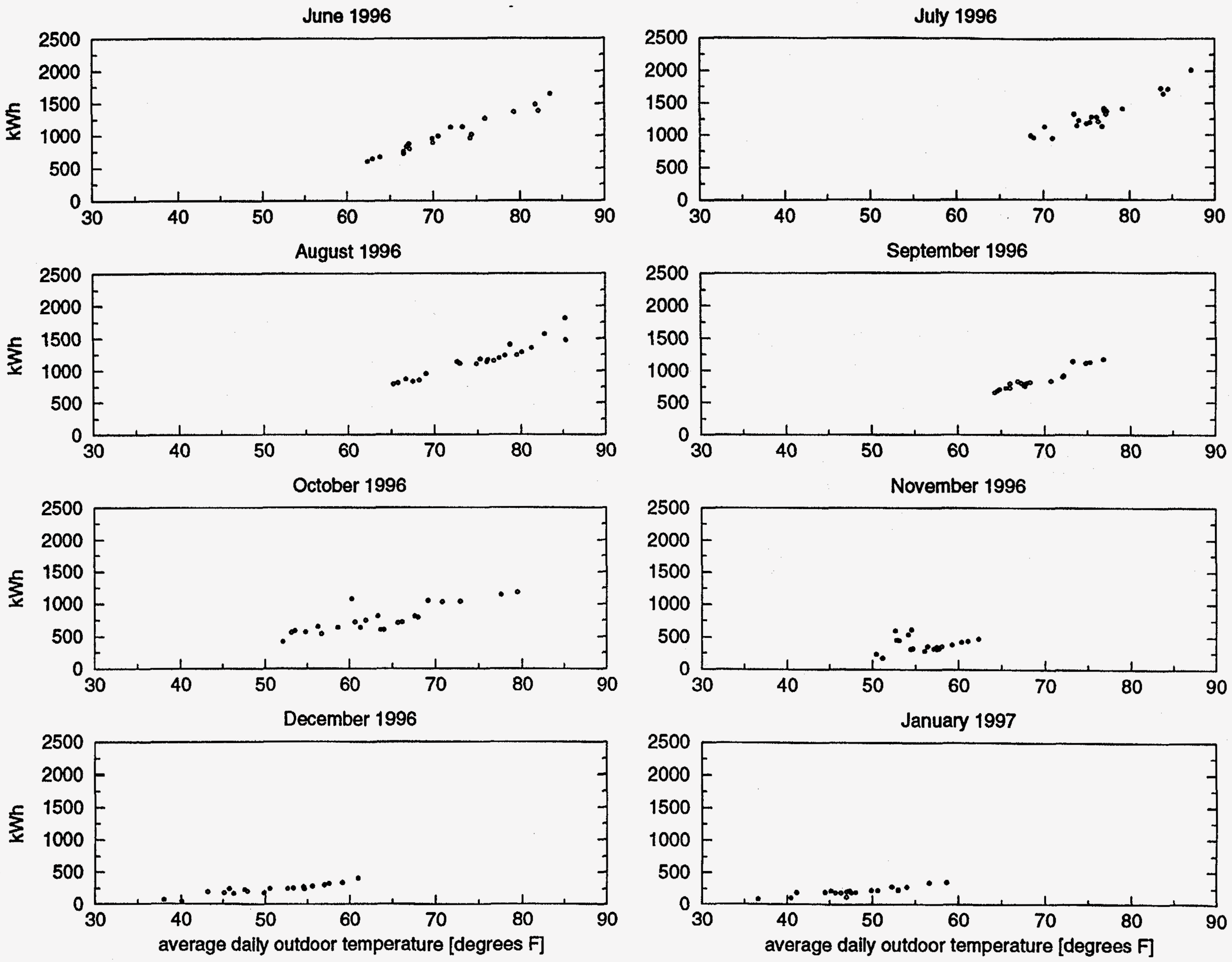
June 1997

July 1997

August 1997

September 1997

Figure B.3b. San Jose average daily air-conditioning electricity use profiles for standard weekdays (2/97-9/97).



June 1996

July 1996

August 1996

September 1996

October 1996

November 1996

December 1996

January 1997

Figure B.4a. Davis monitored daily air-conditioning electricity use vs daily average outdoor air temperature for standard weekdays (6/96-1/97).

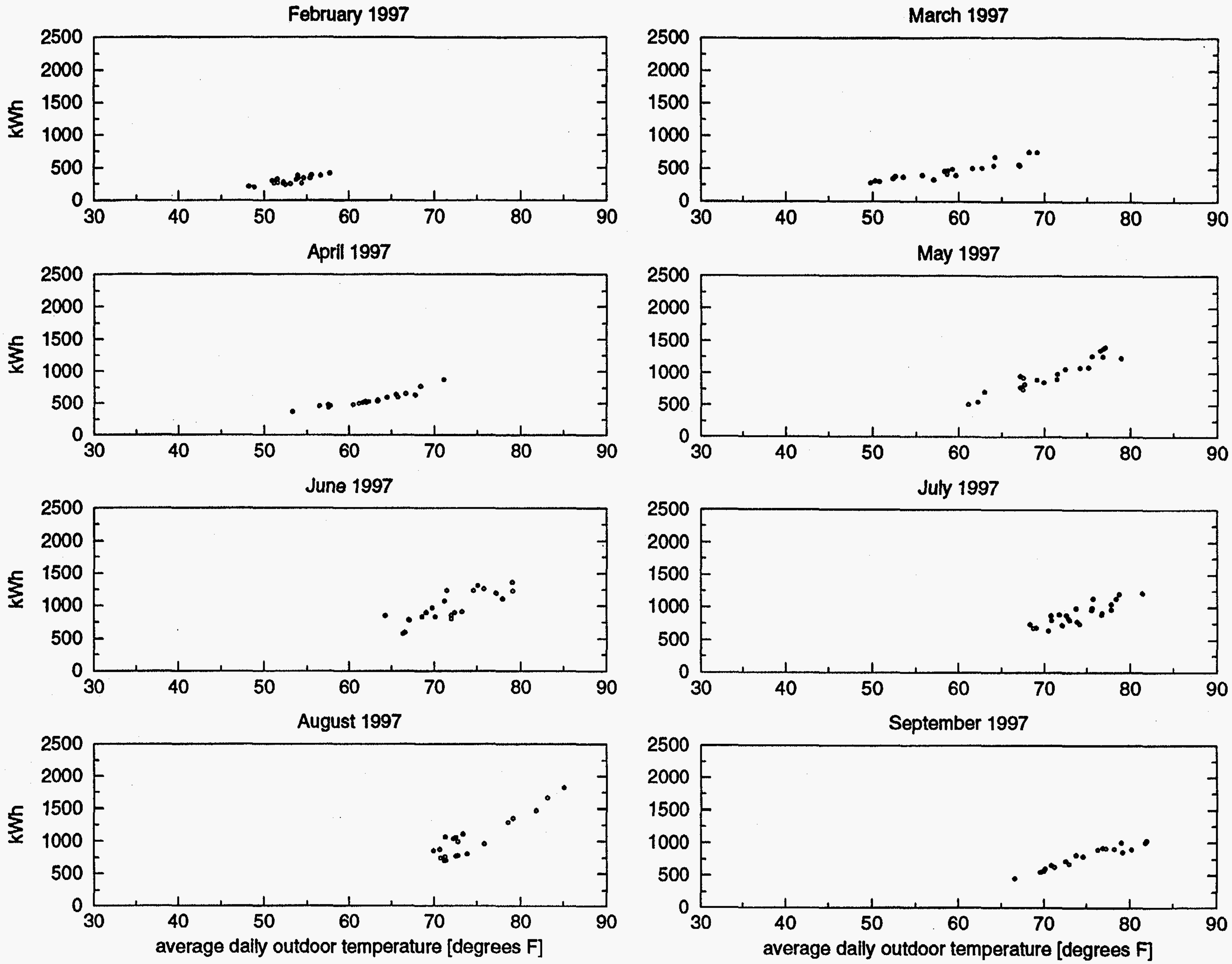


Figure B.4b. Davis monitored daily air-conditioning electricity use vs daily average outdoor air temperature for standard weekdays (2/97-9/97).

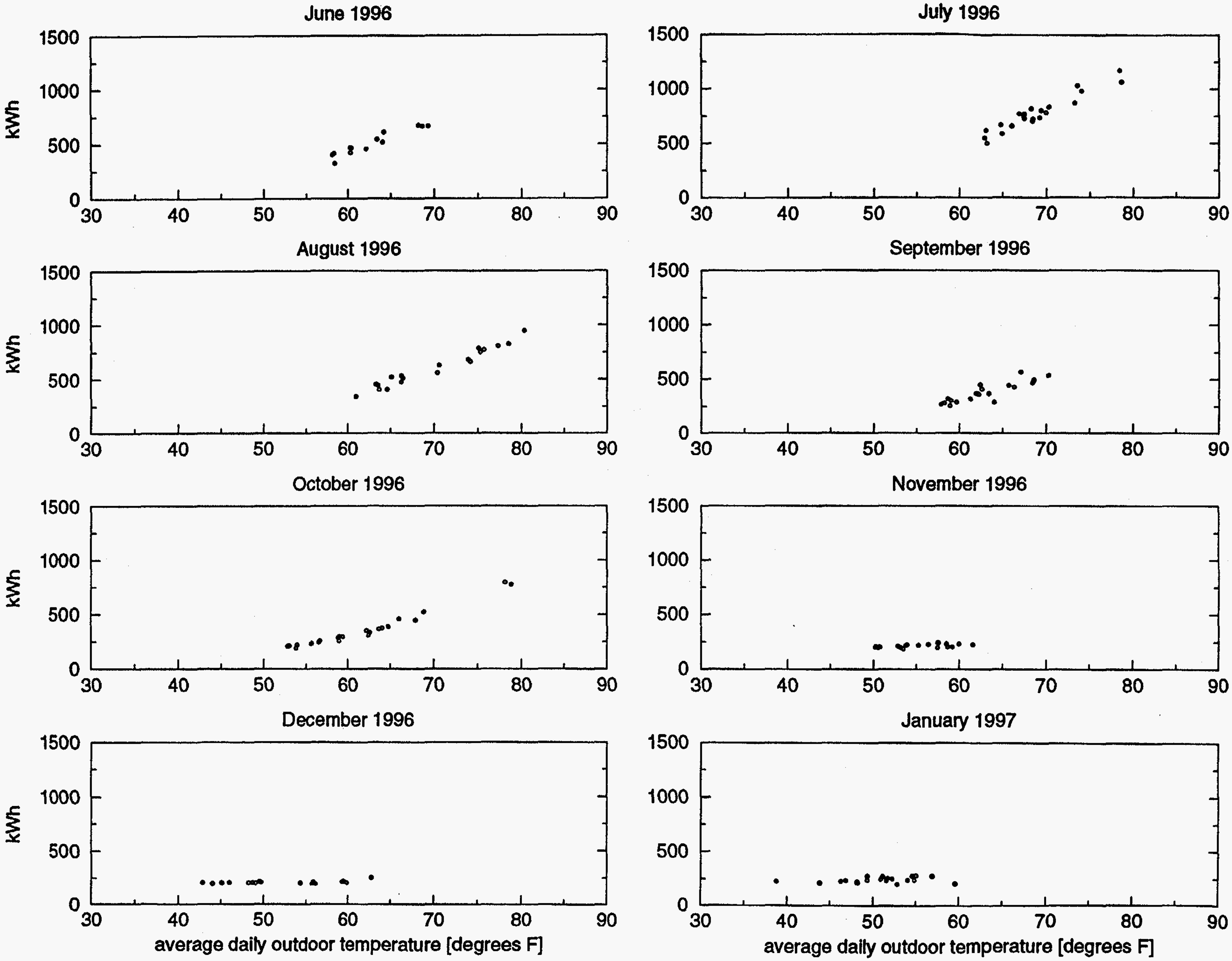


Figure B.5a. Gilroy monitored daily air-conditioning electricity use vs daily average outdoor air temperature for standard weekdays (6/96-1/97).

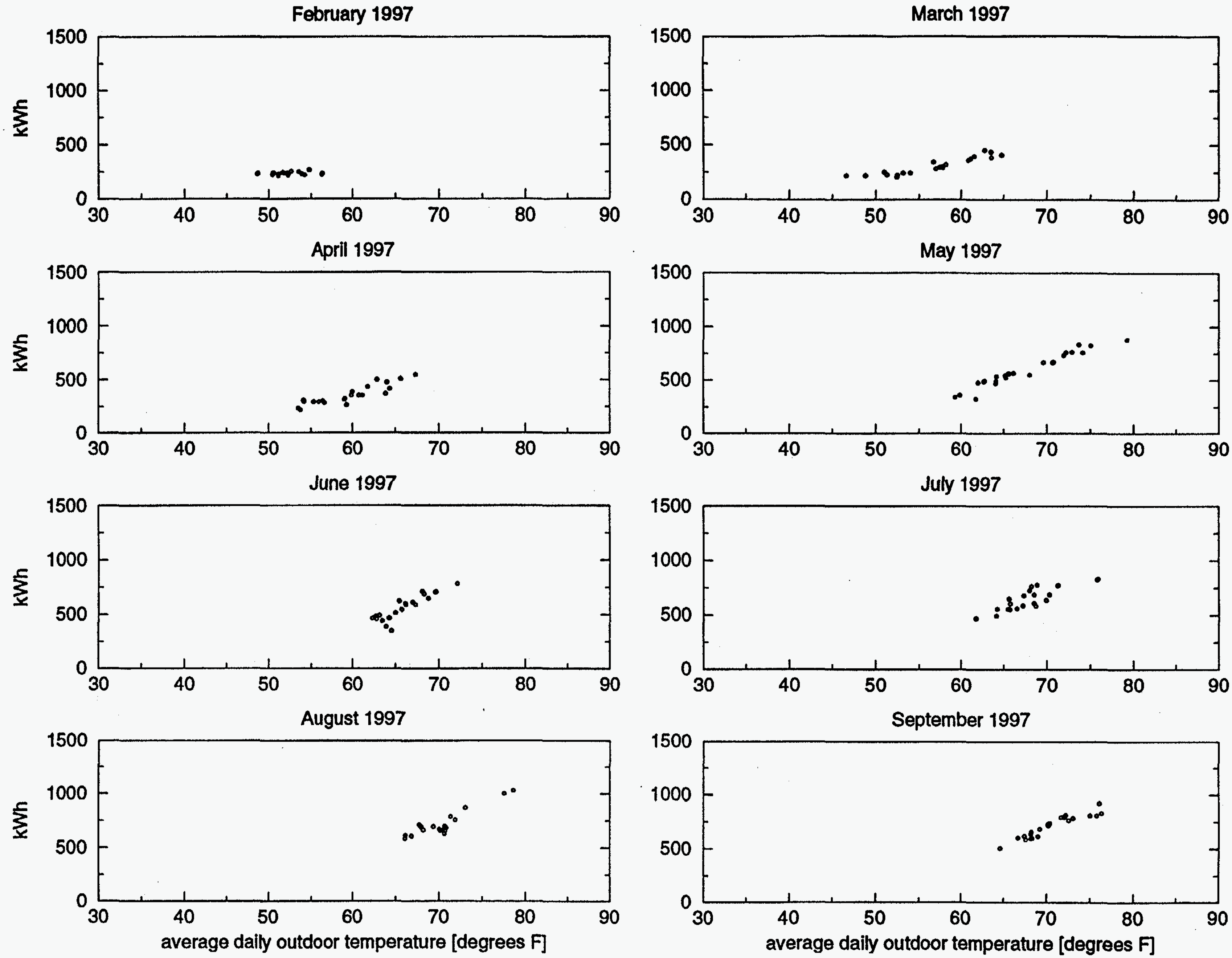


Figure B.5b. Gilroy monitored daily air-conditioning electricity use vs daily average outdoor air temperature for standard weekdays (2/97-9/97).

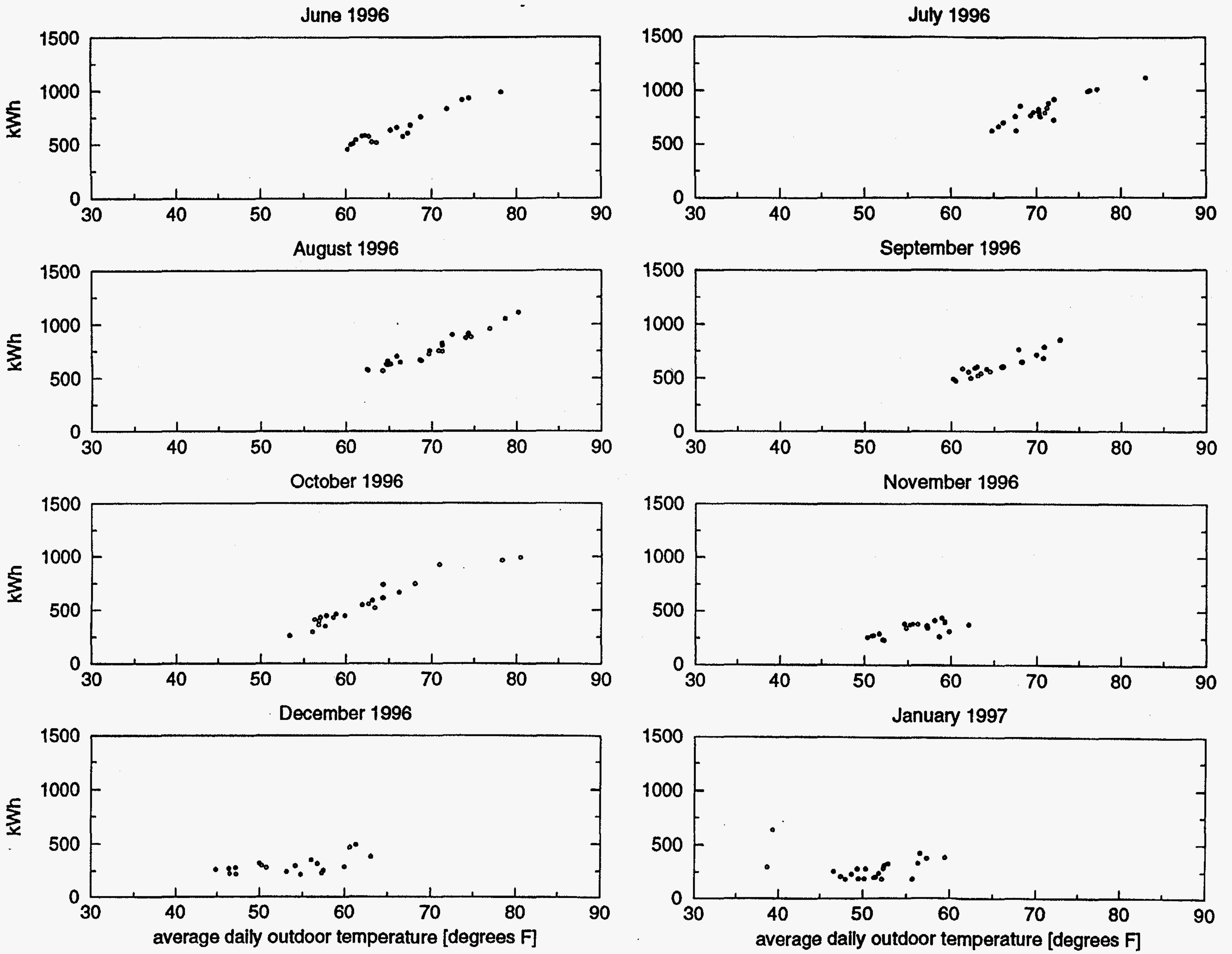


Figure B.6a. San Jose monitored daily air-conditioning electricity use vs daily average outdoor air temperature for standard weekdays (6/96-1/97).

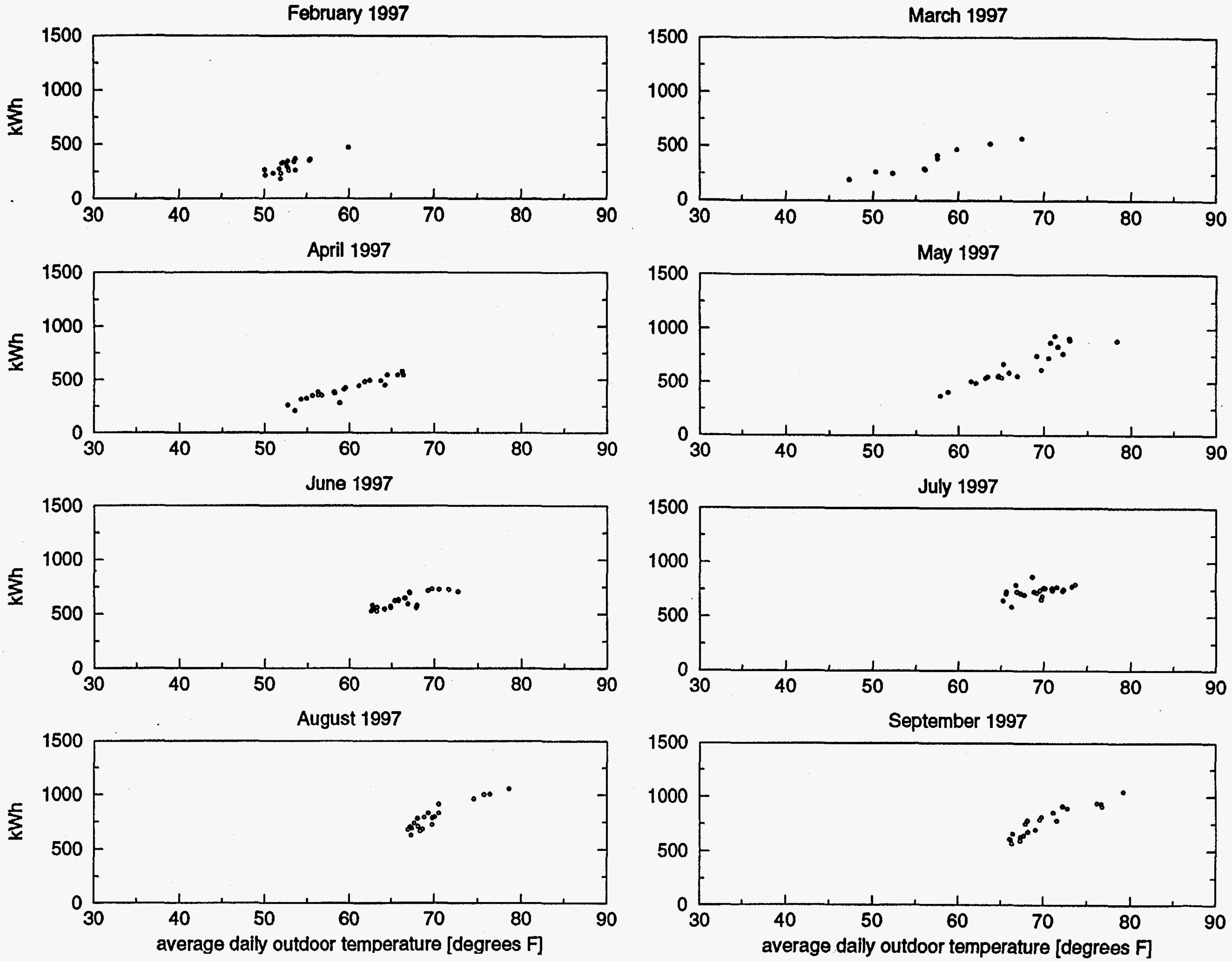


Figure B.6b. San Jose monitored daily air-conditioning electricity use vs daily average outdoor air temperature for standard weekdays (2/97-9/97).

Table B.1. Analysis of variance and parameter estimates from regressions of daily air-conditioning electricity use versus outdoor temperature by month for standard weekdays [Eq. 1].

month	analysis of variance				parameter estimates	
	n	prob>f	σ	R^2	C_0	C_1
Davis						
June 1996	20	0.0001	70.825	0.947	-2197.433	44.758
July	22	0.0001	87.351	0.898	-2614.524	51.426
August	22	0.0001	82.957	0.904	-1877.600	40.470
September	20	0.0001	49.560	0.909	-1900.810	39.887
October	23	0.0001	120.832	0.702	-768.616	24.245
November	20	0.6746	115.699	0.010	192.450	3.489
December	19	0.0001	34.608	0.847	-379.527	12.207
January 1997	20	0.0001	32.008	0.789	-316.885	11.033
February	19	0.0001	35.414	0.682	-784.730	20.481
March	20	0.0001	55.971	0.853	-820.426	21.873
April	22	0.0001	40.866	0.875	-995.971	24.832
May	21	0.0001	85.744	0.896	-2290.671	46.297
June	21	0.0001	138.675	0.655	-2128.790	43.309
July	22	0.0001	89.307	0.739	-2139.565	41.094
August	21	0.0001	131.428	0.842	-3946.246	66.821
September	21	0.0001	45.759	0.928	-2049.223	37.842
Gilroy						
June 1996	13	0.0001	36.001	0.907	-1182.292	26.979
July	22	0.0001	49.396	0.917	-1726.034	36.268
August	19	0.0001	35.730	0.960	-1368.470	28.176
September	20	0.0001	45.199	0.785	-954.795	21.174
October	23	0.0001	36.207	0.953	-1016.782	22.236
November	20	0.0343	13.943	0.226	101.844	2.026
December	19	0.0373	11.467	0.231	158.773	0.995
January 1997	22	0.1348	23.738	0.108	164.855	1.545
February	19	0.5912	13.880	0.017	181.277	1.008
March	21	0.0001	29.882	0.863	-486.424	14.002
April	22	0.0001	42.231	0.791	-802.570	19.437
May	21	0.0001	39.353	0.948	-1386.602	29.297
June	21	0.0001	55.068	0.791	-1994.346	38.742
July	20	0.0001	58.544	0.673	-1177.287	26.880
August	21	0.0001	55.165	0.794	-1615.853	33.138
September	21	0.0001	36.773	0.888	-1434.709	30.355
San Jose						
June 1996	20	0.0001	42.914	0.931	-1288.189	29.345
July	22	0.0001	53.597	0.839	-1205.187	28.441
August	22	0.0001	36.144	0.947	-1319.308	29.819
September	20	0.0001	43.955	0.836	-1017.446	24.970
October	23	0.0001	54.811	0.932	-1249.828	28.835
November	20	0.0010	48.311	0.460	-362.755	12.526
December	19	0.0066	63.215	0.360	-135.303	8.123
January 1997	22	0.6282	108.562	0.012	401.422	-2.286
February	19	0.0001	43.123	0.624	-1033.739	25.250
March	21	0.0001	42.352	0.807	-846.755	20.756
April	22	0.0001	37.561	0.869	-906.596	22.046
May	21	0.0001	67.324	0.844	-1345.382	29.743
June	21	0.0001	40.668	0.705	-725.139	20.206
July	22	0.0266	52.845	0.223	-57.469	11.432
August	21	0.0001	45.713	0.868	-1634.362	34.661
September	21	0.0001	54.047	0.857	-1530.058	32.649

Table B.2. Analysis of variance from multi-variate regressions of daily air-conditioning electricity use versus daily average outdoor temperature for summer standard weekdays [Eq. 2].

building	analysis of variance						T_{mean} °F
	n	mean	8-intercept		2-intercept		
			σ	R^2	σ	R^2	
Davis	169	1004	135	0.98	99	0.99	73.4
Gilroy	157	621	67	0.99	51	0.99	67.7
San Jose	169	721	53	0.99	50	0.99	68.6

σ An estimate of the standard deviation of the error term. It is calculated as the square root of the mean square error.

R^2 Is a measure between 0 and 1 that indicates the portion of the total variation that is attributed to the fit rather than left to residual error.

Appendix C - Statistical Analysis: Independent Variable Identification

Our methodology focused on the statistical analysis of daily air-conditioning (a/c) electricity use as a function of daily average outdoor air temperature. Through a series of single-variable regressions with the following independent variables: daily average outdoor air temperature, daytime (8am - 7pm) average outdoor air temperature, daily peak outdoor air temperature, daily average outdoor air enthalpy, and daytime average outdoor air enthalpy, it was determined that the daily average outdoor air temperature provided the best correlation with daily a/c electricity use. The effect of clouds on daily a/c electricity use was examined as well. We concluded the daily average outdoor air temperature captures the variations in cloud cover and outdoor air moisture that influence the cooling loads on these buildings; therefore, it was selected as a representative climatological indicator.

Scatter plots of pre- and post-retrofit daily a/c electricity use versus daily average, daytime average, and daily peak outdoor air temperature are displayed in **Figure C.1a**, and versus daily average and daytime average outdoor air enthalpy in **Figure C.1b**. These plots provide the visual evidence that the daily average outdoor air temperature gives the best correlation with daily a/c electricity use. Analysis of variance, parameter estimates, and standard errors from regressions of daily a/c electricity use versus each of these independent variables are shown in **Table C.1**. By examination of the table[9], high R^2, low σ, and low relative error in the parameter estimates are the statistical evidence that the daily average outdoor air temperature is the best choice.

Scatter plots of pre- and post-retrofit daily a/c electricity use versus daily average, daytime average, and daily peak outdoor air temperature with cloud cover indicated are displayed in **Figures C.2ab**. Four levels of cloud cover were defined from the hourly insolation data: no clouds, light (10% and less), medium (10 - 30%), and high (30% and greater). About 85% of the summer days were cloudless and only 2 - 3% were classified with high cloud cover, thus the insolation generally remained constant and was removed from the analysis. These plots reveal that days with cloud cover typically have a lower outdoor temperature when compared to the entire range of data, and days with high cover are near the bottom of the range. Typically, days with cloud cover do not exhibit lower a/c electricity use when compared to days without clouds and similar outdoor air temperatures.

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[9] (σ) an estimate of the standard deviation of the error term, it is calculated as the square root of the mean square error. (R^2) is a measure between 0 and 1 that indicates the portion of the total variation that is attributed to the fit rather than left to residual error.

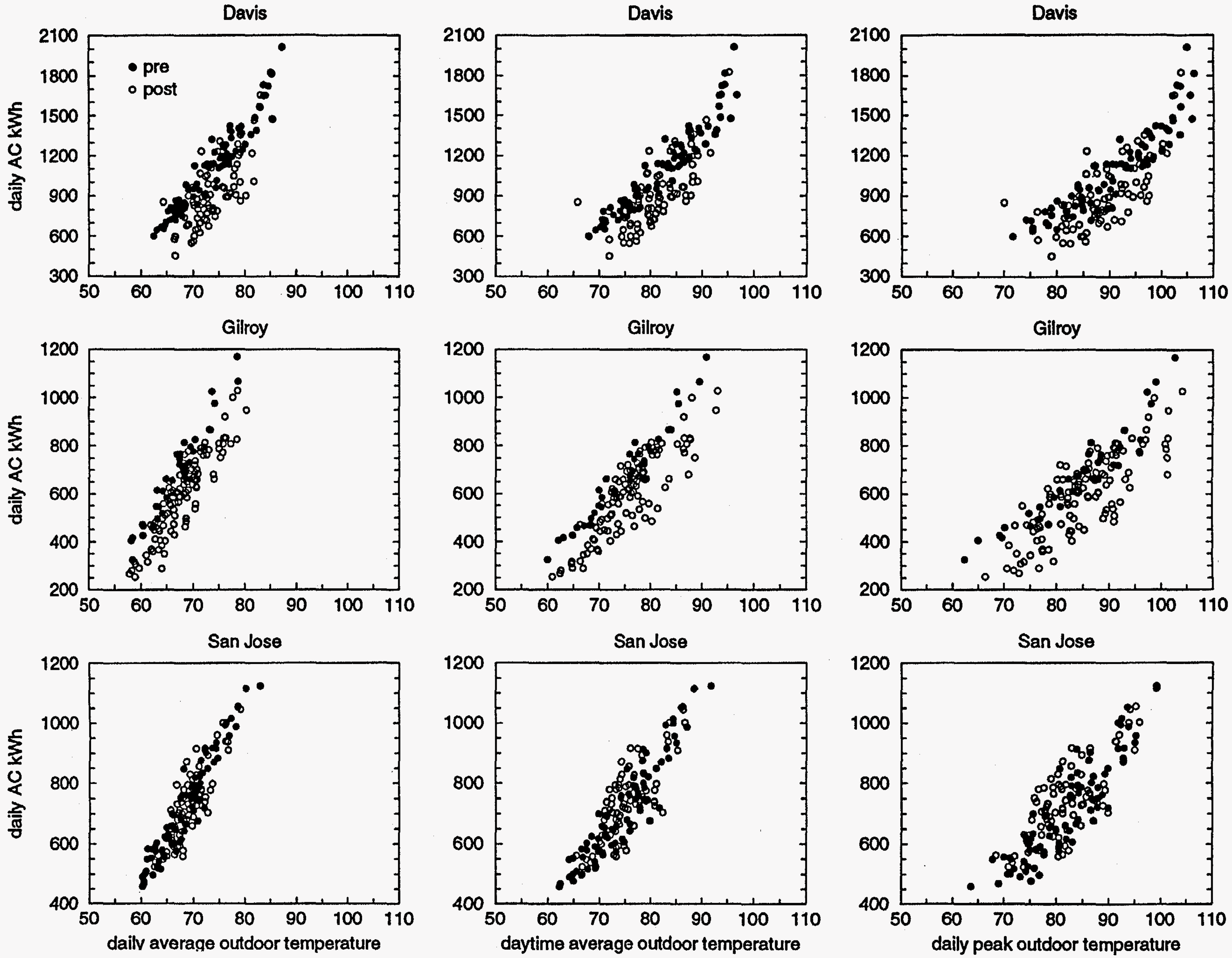


Figure C.1a. Summertime daily air-conditioning electricity use vs daily and daytime average and daily peak outdoor air temperature.

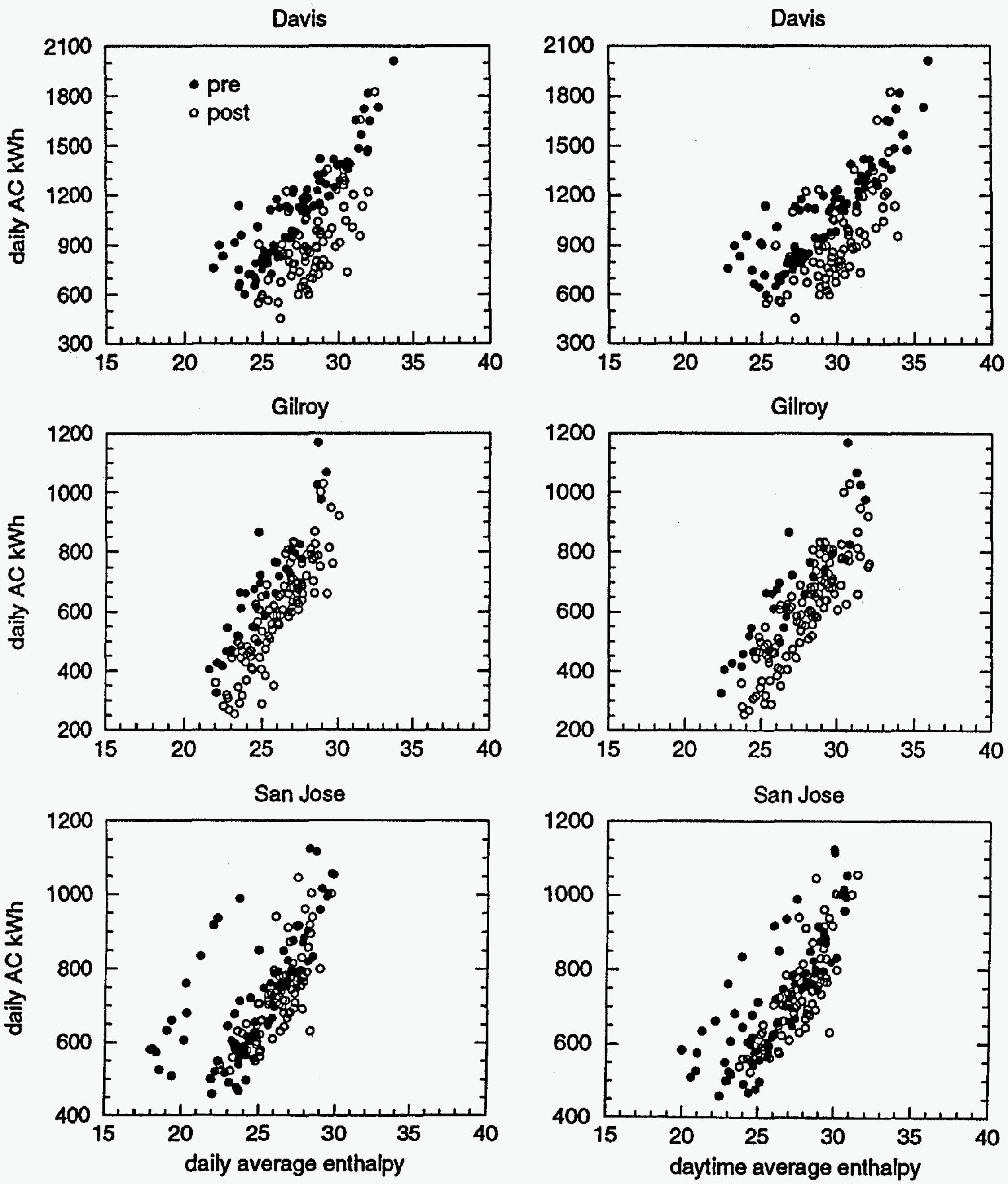


Figure C.1b. Summertime daily air-conditioning electricity use vs daily and daytime average outdoor air enthalpy.

Table C.1. Analysis of variance, parameter estimates, and standard errors from regressions of daily air-conditioning electricity use versus outdoor temperature and enthalpy for summer standard weekdays.

$kWh = C_0 + C_1 x$ *(where: x=t temperature and x=e enthalpy).*

period	x	analysis of variance				parameter estimates		standard error	
		n	mean	σ	R^2	C_0	C_1	C_0(%)	C_1(%)
Davis									
pre									
daily average	t	84	1094	89	0.92	-2385	47.5	117(5)	1.6(3)
daytime average	t			96	0.90	-2062	38.4	115(6)	1.4(4)
daily peak	t			123	0.84	-1789	31.7	140(8)	1.5(5)
daily average	e			126	0.83	-1660	101.3	138(8)	5.0(5)
daytime average	e			141	0.79	-1434	86.6	146(10)	5.0(6)
post									
daily average	t	85	915	169	0.55	-2357	44.5	327(14)	4.4(10)
daytime average	t			161	0.59	-2043	36.3	269(13)	3.3(9)
daily peak	t			172	0.54	-1594	28.1	257(16)	2.9(10)
daily average	e			189	0.44	-1725	93.3	331(19)	11.7(13)
daytime average	e			192	0.42	-1384	77.0	298(22)	10.0(13)
Gilroy									
pre									
daily average	t	35	676	53	0.93	-1756	36.5	117(7)	1.7(5)
daytime average	t			51	0.94	-1205	25.1	86(7)	1.1(4)
daily peak	t			67	0.89	-889	18.6	97(11)	1.1(6)
daily average	e			81	0.83	-1463	85.2	167(11)	6.6(8)
daytime average	e			88	0.80	-1118	66.3	155(14)	5.7(9)
post									
daily average	t	122	605	70	0.82	-1565	31.9	94(6)	1.4(4)
daytime average	t			78	0.77	-1107	22.6	86(8)	1.1(5)
daily peak	t			96	0.65	-846	17.0	97(11)	1.1(6)
daily average	e			81	0.76	-1410	77.2	105(7)	4.0(5)
daytime average	e			82	0.75	-1306	68.5	102(8)	3.7(5)
San Jose									
pre									
daily average	t	84	713	45	0.92	-1310	29.7	65(5)	1.0(3)
daytime average	t			58	0.87	-982	22.7	72(7)	1.0(4)
daily peak	t			71	0.81	-857	19.1	84(10)	1.0(5)
daily average	e			122	0.44	-200	37.1	115(57)	4.6(12)
daytime average	e			101	0.61	-494	46.2	106(21)	4.0(9)
post									
daily average	t	85	730	60	0.76	-1368	30.4	129(9)	1.9(6)
daytime average	t			74	0.64	-861	21.2	132(15)	1.8(8)
daily peak	t			80	0.58	-556	15.8	121(22)	1.5(9)
daily average	e			76	0.62	-840	59.7	137(16)	5.2(9)
daytime average	e			75	0.63	-821	56.3	131(16)	4.8(9)

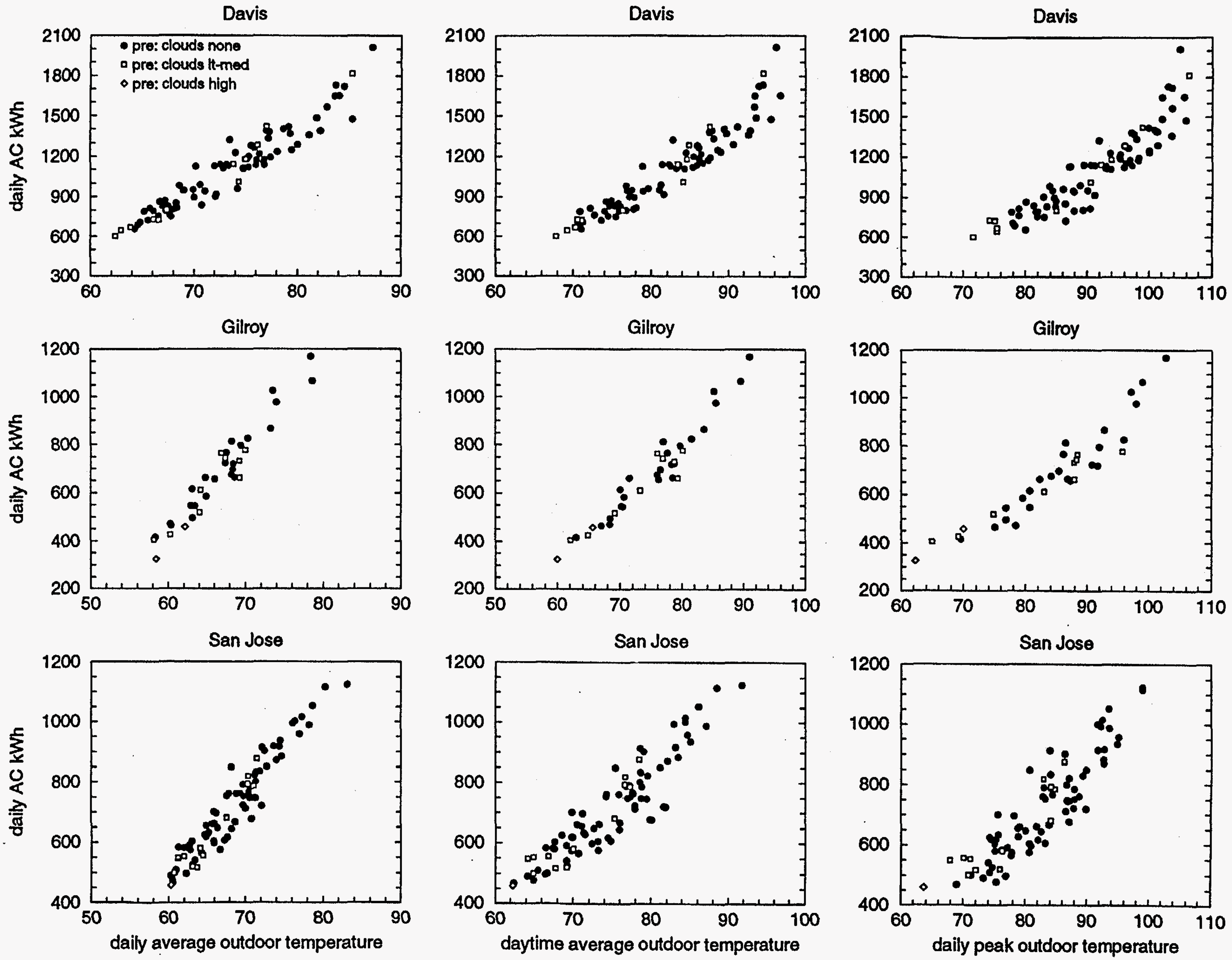


Figure C.2a. Summertime pre-coating daily air-conditioning electricity use vs daily and daytime average and daily peak outdoor air temperature with cloud cover identified.

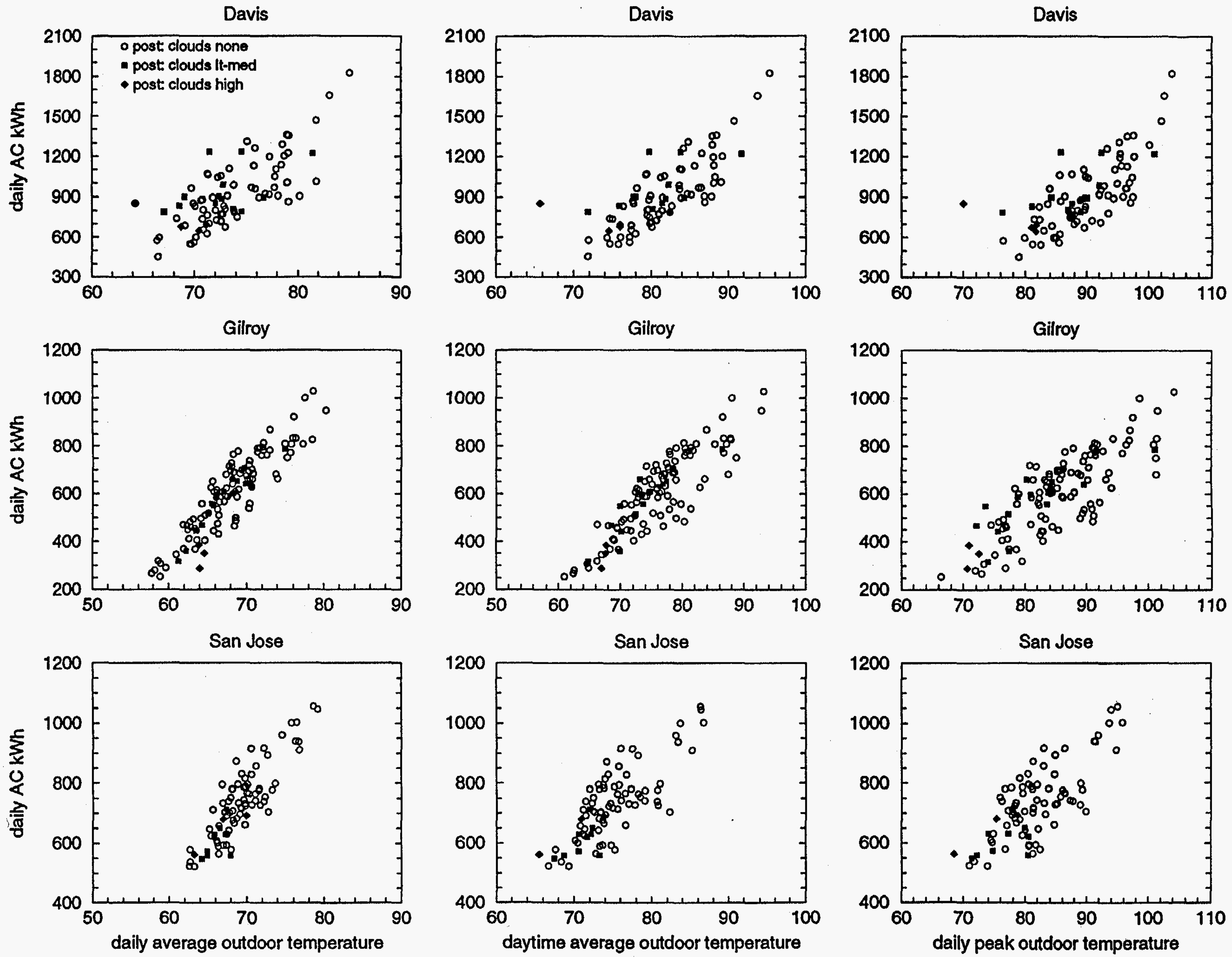
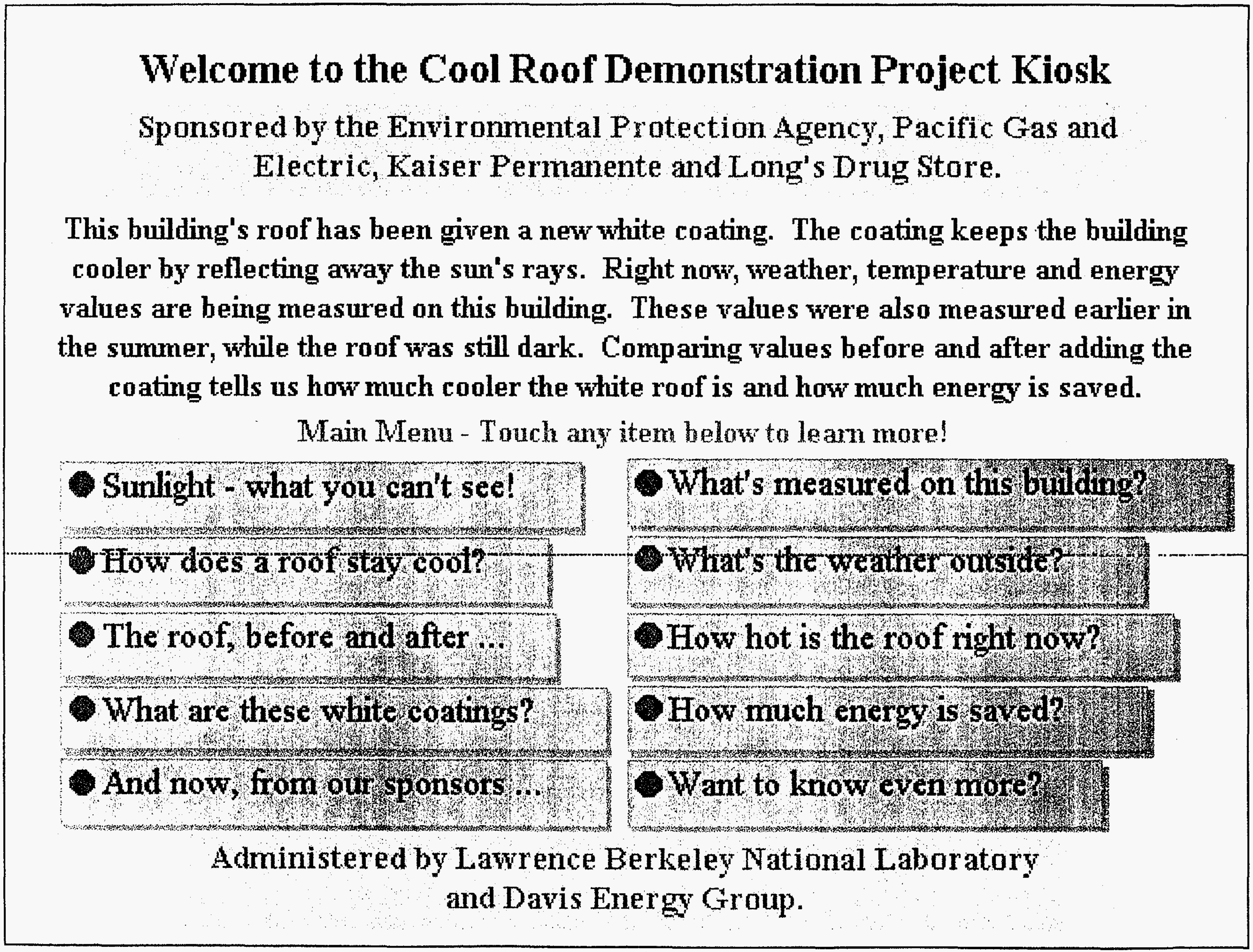


Figure C.2b. Summertime post-coating daily air-conditioning electricity use vs daily and daytime average and daily peak outdoor air temperature with cloud cover identified.

Appendix D - Display Kiosk Panels

Display kiosks were designed to explain cool-roof coating theory and to display real-time measurements of weather conditions, roof surface temperature, and air-conditioning electricity use to visitors of the buildings. Panels displayed on the kiosks are presented here and are briefly described below.

1. Welcome to the Cool Roof Demonstration Project Kiosk
2. Keep a Roof Cool with Highly Reflective Materials
3. White Coatings
4. Infrared Photo of the Roof at the Edge of a White Coating
5. Energy from the Sun
6. Building Measurements
7. Current Weather Conditions
8. Current Roof Surface Temperature
9. White Roof Energy Savings
10. Roof Temperature Over the Last Week
11. Air-Conditioning Energy Use Over the Last Week
12. Outdoor Temperature and Humidity Over the Last Week
13. Sunshine Over the Last Week
14. Wind Speed and Direction Over the Last Week
15. For More Information
16. Our Sponsors



Welcome to the Cool Roof Demonstration Project Kiosk

Sponsored by the Environmental Protection Agency, Pacific Gas and Electric, Kaiser Permanente and Long's Drug Store.

This building's roof has been given a new white coating. The coating keeps the building cooler by reflecting away the sun's rays. Right now, weather, temperature and energy values are being measured on this building. These values were also measured earlier in the summer, while the roof was still dark. Comparing values before and after adding the coating tells us how much cooler the white roof is and how much energy is saved.

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Administered by Lawrence Berkeley National Laboratory and Davis Energy Group.

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KEEP A ROOF COOL
WITH HIGHLY REFLECTIVE MATERIALS

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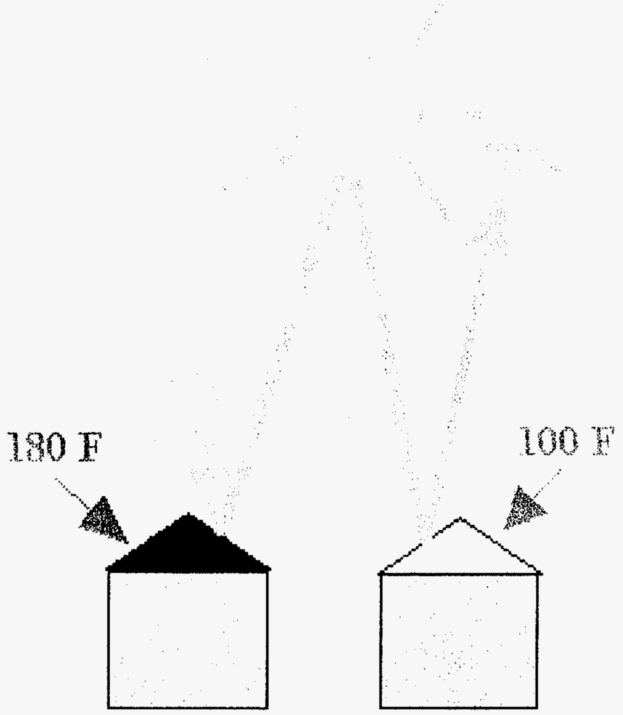

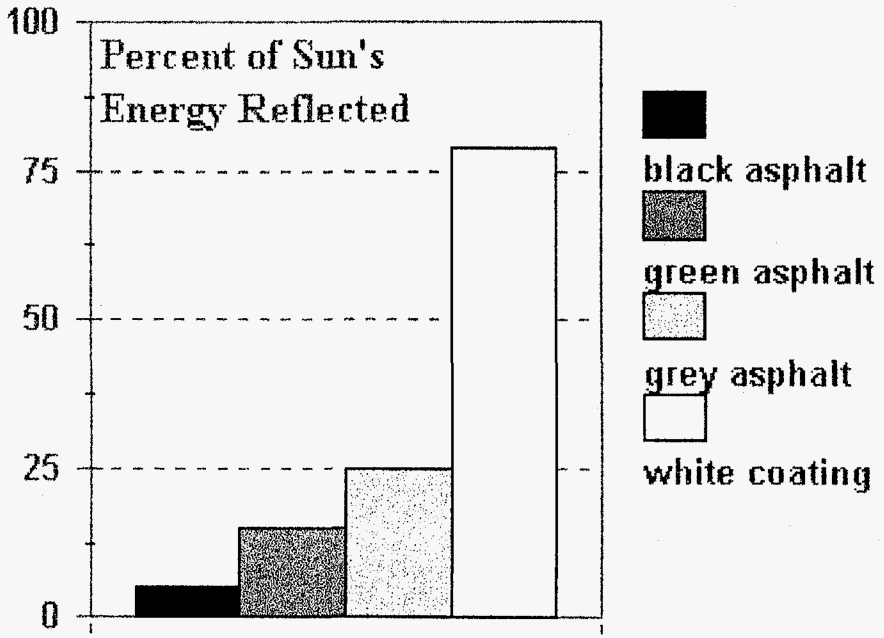

Highly reflective roofing materials bounce more of the sun's energy away and keep the roof cooler. A black asphalt roof reflects only 5% of the sun's energy. Lighter colored asphalts do better - green roofs have a 15% reflectance and light g grey roofs have 25% reflectance. But a w oating outdoes them all with a reflectance of more than 75%!

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WHITE COATINGS

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The white coating used to cover the roof is an acrylic based "elastomeric" membrane. Its reflective properties not only save cooling energy for the building, they also reduce degradation of the roofing materials below the coating. This theoretically means the roof will not have to be torn off and replaced, but simply recoated every 10 years or so. This potentially saves the expense of reroofing and keeps roofing materials out of landfills.

White coatings are recommended for flat commercial roofs, including metal, built-up, asphalt capsheet, modified bitumen or polyurethane foam roofs.

Acrylic coatings come in liquid form and can be sprayed or rolled onto a clean roof surface. It's important to apply them to leak-free surfaces, since these coatings don't fix roof leaks! Roof coatings are resistant to dirt, and stay fairly clean simply with the action of rainfall. In areas of low rainfall or high dirt or pollen, they may have to be cleaned every couple of years to get the highest energy savings.

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BEFORE AND AFTER THE ROOF COATING

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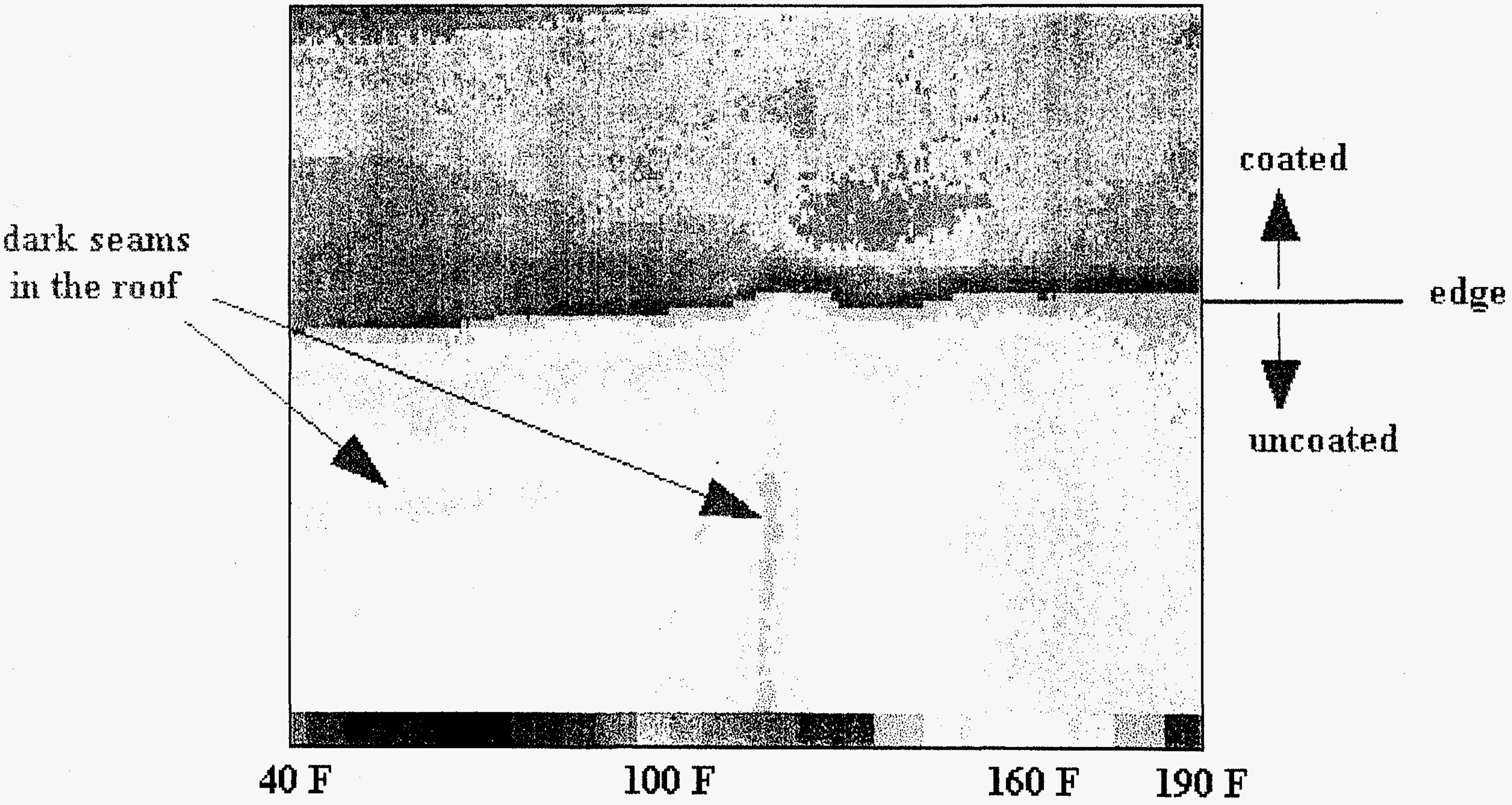
Infrared Photo of the Roof at the Edge of a White Coating



The white coating cools the roof by about 60 degrees during the sunniest summer weather! A cooler roof transfers less heat to the building, so it uses less energy for air conditioning.

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ENERGY FROM THE SUN

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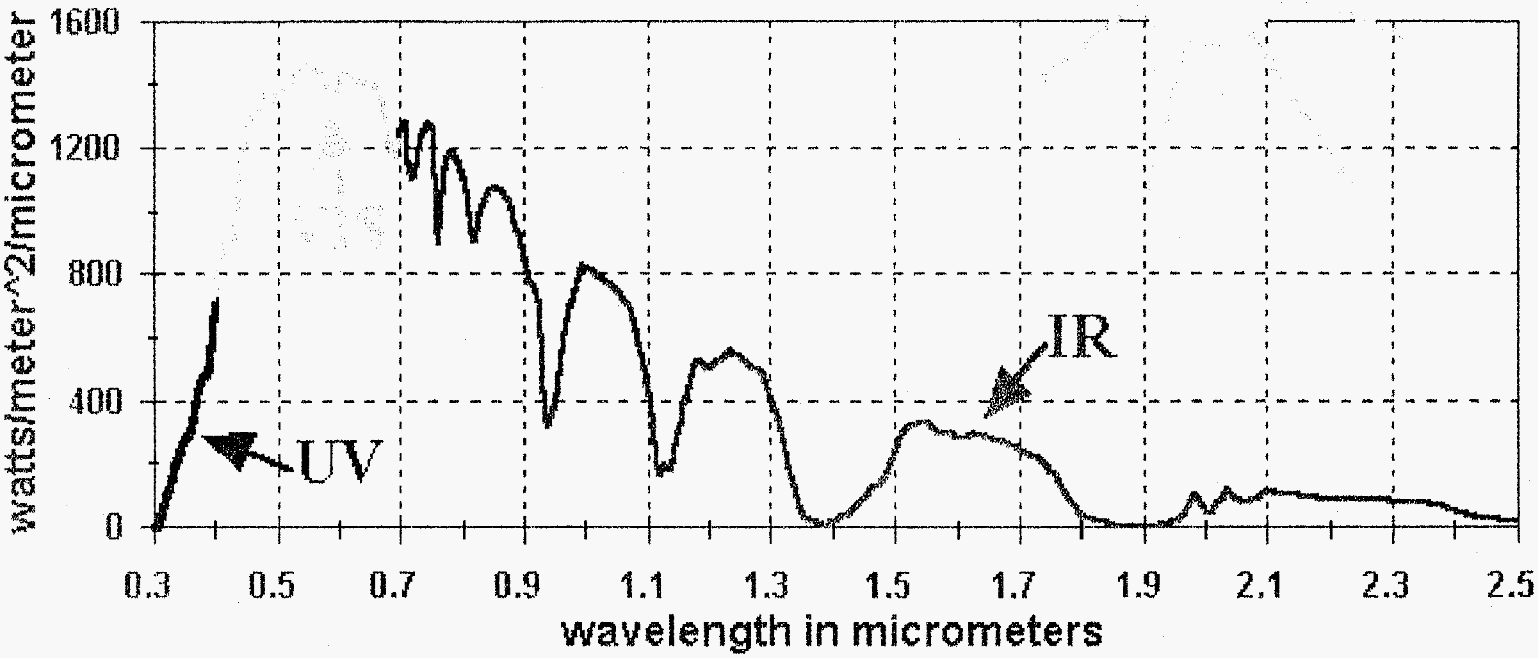
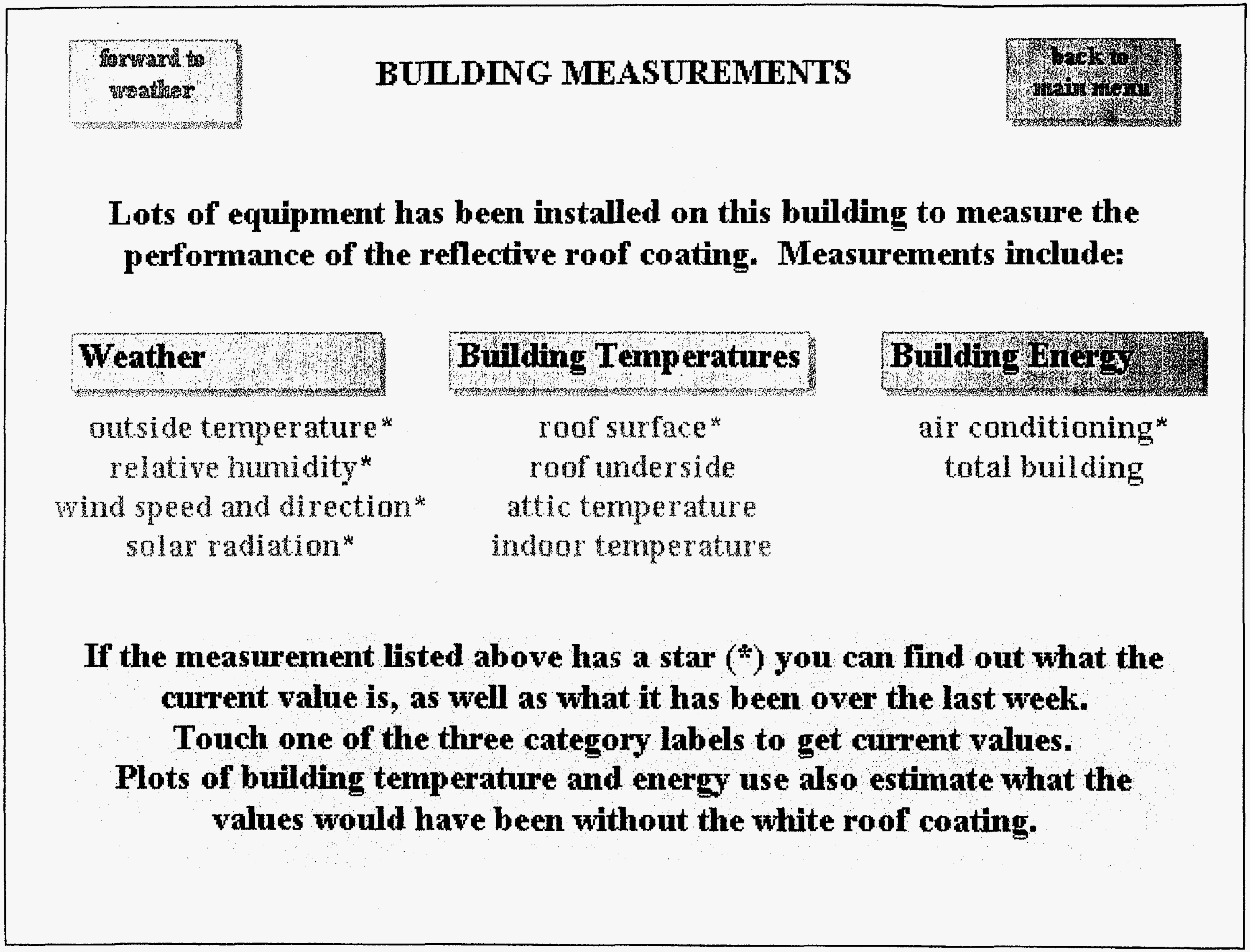


The energy from the sun is classified into three parts depending on its wavelength. Ultraviolet (UV) rays, the part of sunlight which causes sunburn, account for 20% of the sun's energy. [illegible] rays, 40% of the sun's energy, give us sunlight. The remaining 40% of the sun's energy comes from infrared (IR) rays, which we feel as heat.

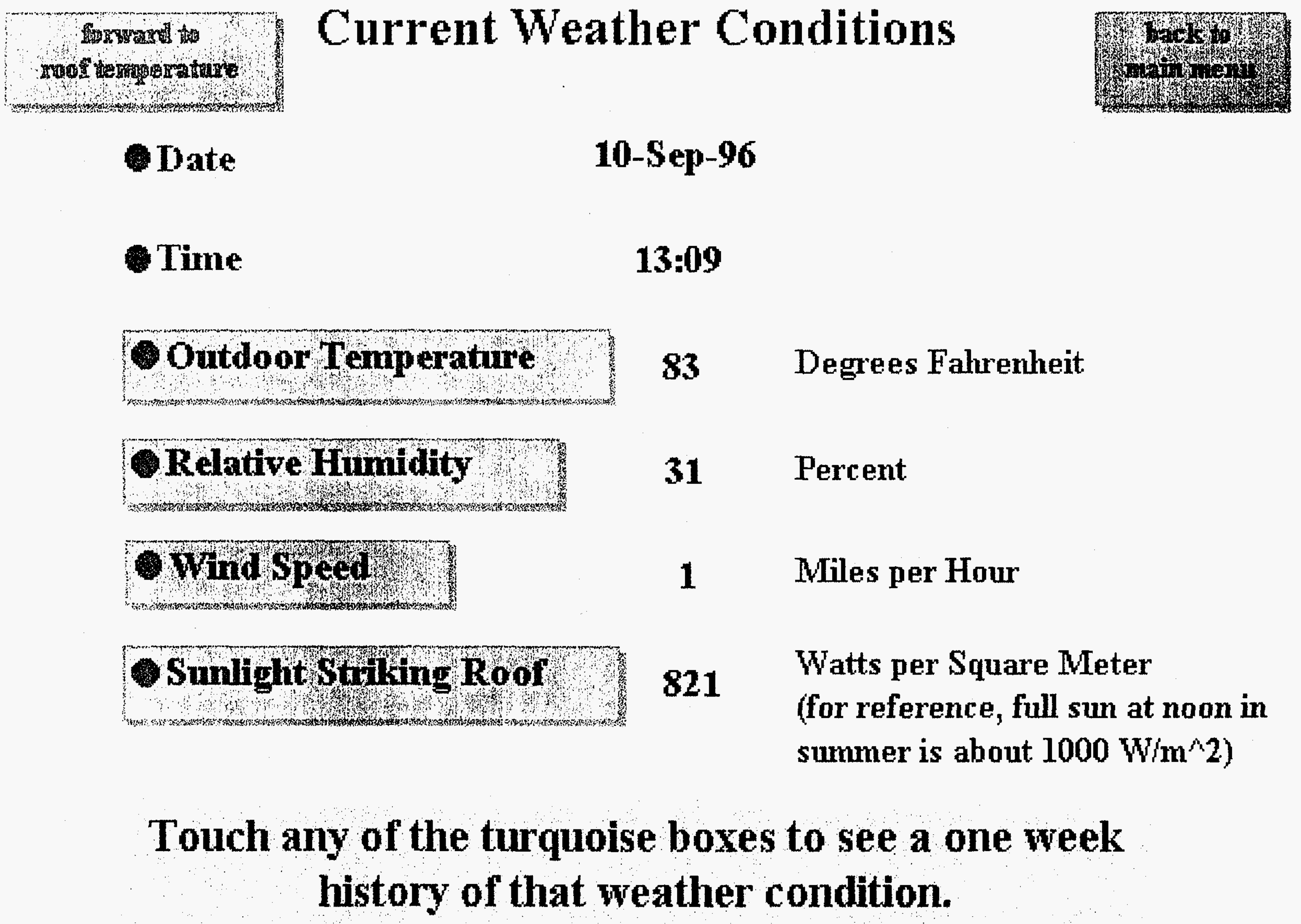


BUILDING MEASUREMENTS

Lots of equipment has been installed on this building to measure the performance of the reflective roof coating. Measurements include:

Weather	**Building Temperatures**	**Building Energy**
outside temperature*	roof surface*	air conditioning*
relative humidity*	roof underside	total building
wind speed and direction*	attic temperature	
solar radiation*	indoor temperature	

If the measurement listed above has a star (*) you can find out what the current value is, as well as what it has been over the last week.
Touch one of the three category labels to get current values.
Plots of building temperature and energy use also estimate what the values would have been without the white roof coating.



Current Weather Conditions

● Date	10-Sep-96	
● Time	13:09	
● **Outdoor Temperature**	83	Degrees Fahrenheit
● **Relative Humidity**	31	Percent
● **Wind Speed**	1	Miles per Hour
● **Sunlight Striking Roof**	821	Watts per Square Meter (for reference, full sun at noon in summer is about 1000 W/m^2)

Touch any of the turquoise boxes to see a one week history of that weather condition.

forward to A/C energy

Current Roof Surface Temperature

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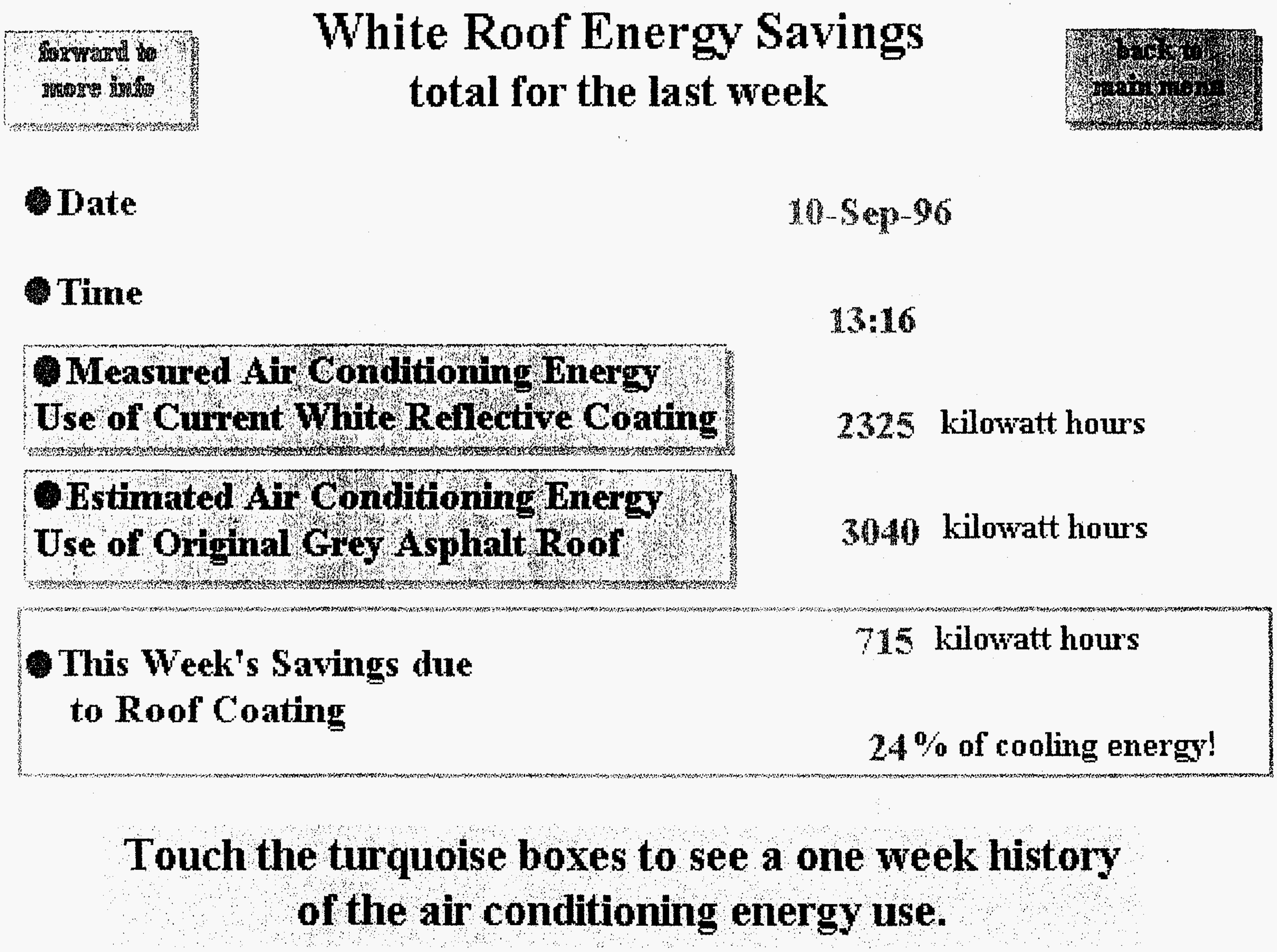
● Date	10-Sep-96	
● Time	13:16	
● White Roof Surface Temperature (current white reflective coating)	104	Degrees Fahrenheit
● Dark Roof Surface Temperature (original grey asphalt shingle)	137	Degrees Fahrenheit

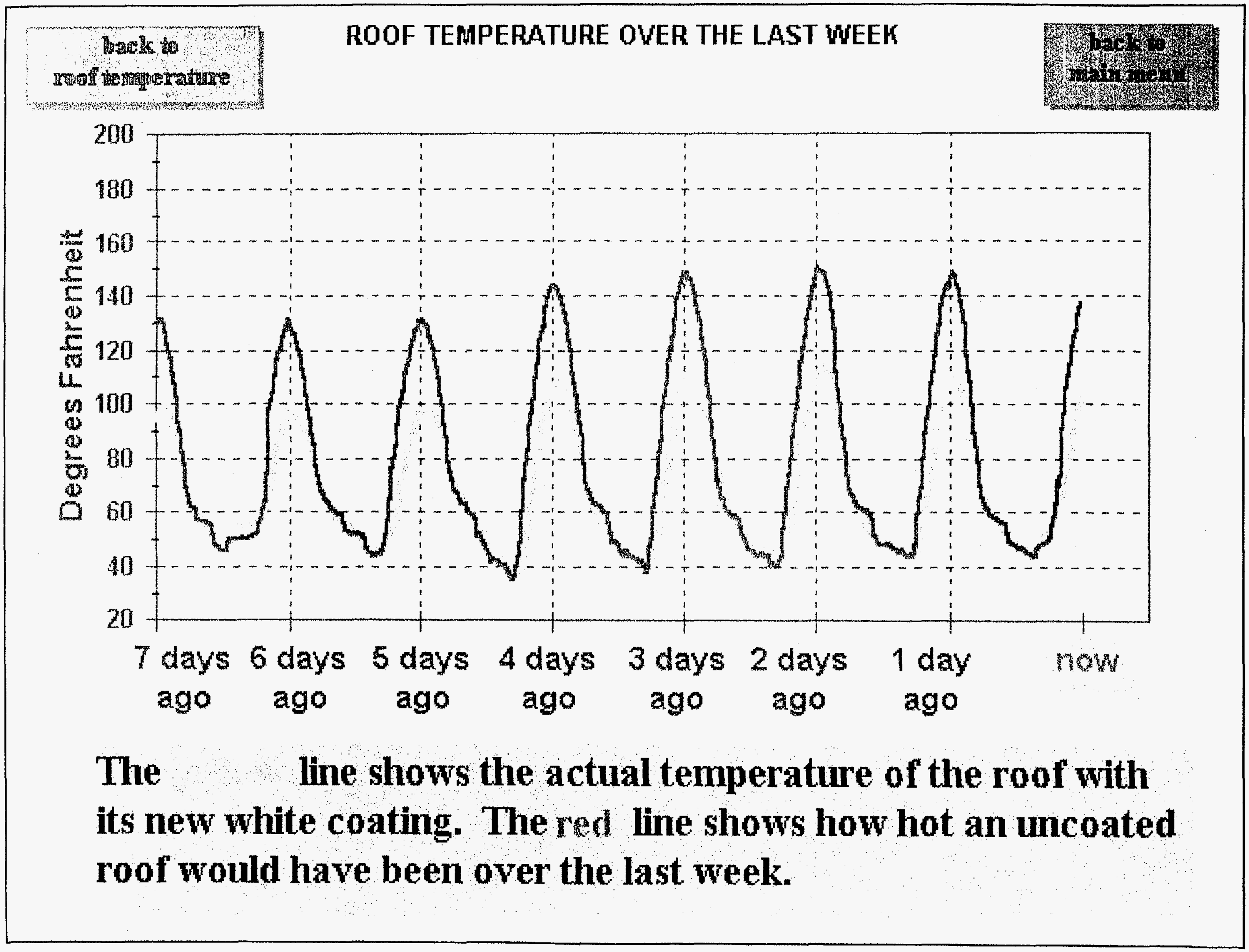
Touch the turquoise boxes to see a one week history of the roof surface temperature.



White Roof Energy Savings
total for the last week

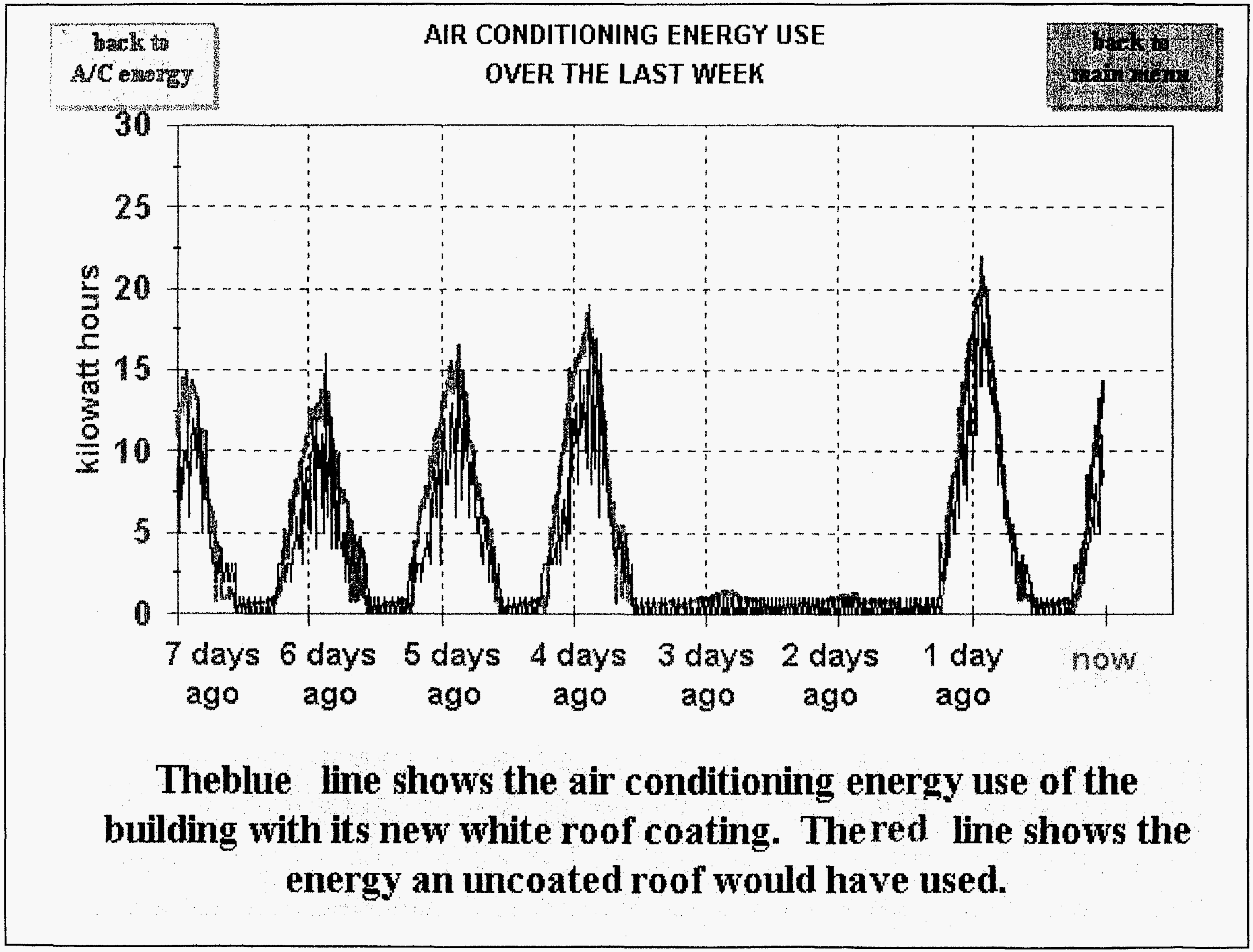
● Date	10-Sep-96
● Time	13:16
● Measured Air Conditioning Energy Use of Current White Reflective Coating	2325 kilowatt hours
● Estimated Air Conditioning Energy Use of Original Grey Asphalt Roof	3040 kilowatt hours
● This Week's Savings due to Roof Coating	715 kilowatt hours 24 % of cooling energy!

Touch the turquoise boxes to see a one week history of the air conditioning energy use.



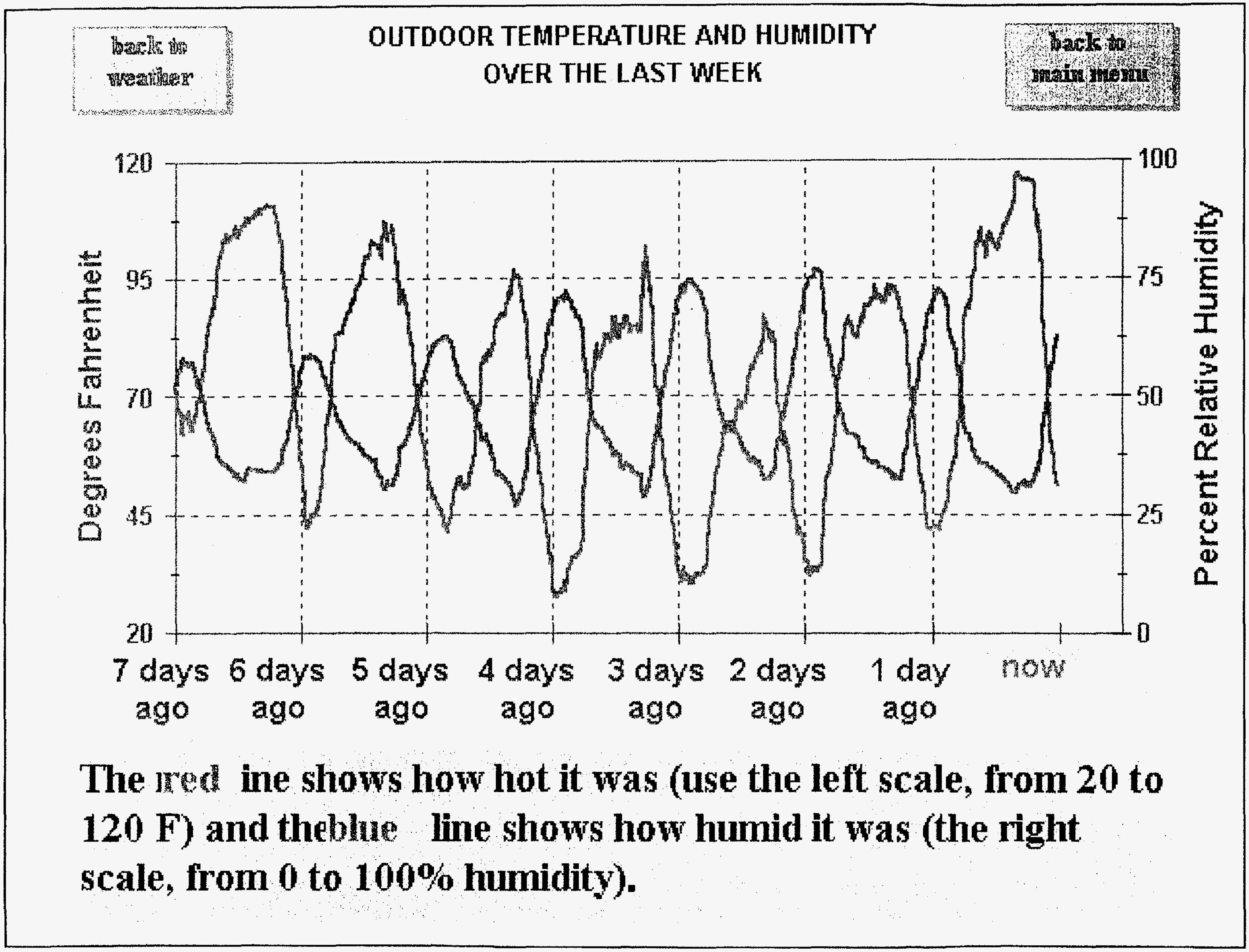
ROOF TEMPERATURE OVER THE LAST WEEK

The line shows the actual temperature of the roof with its new white coating. The red line shows how hot an uncoated roof would have been over the last week.



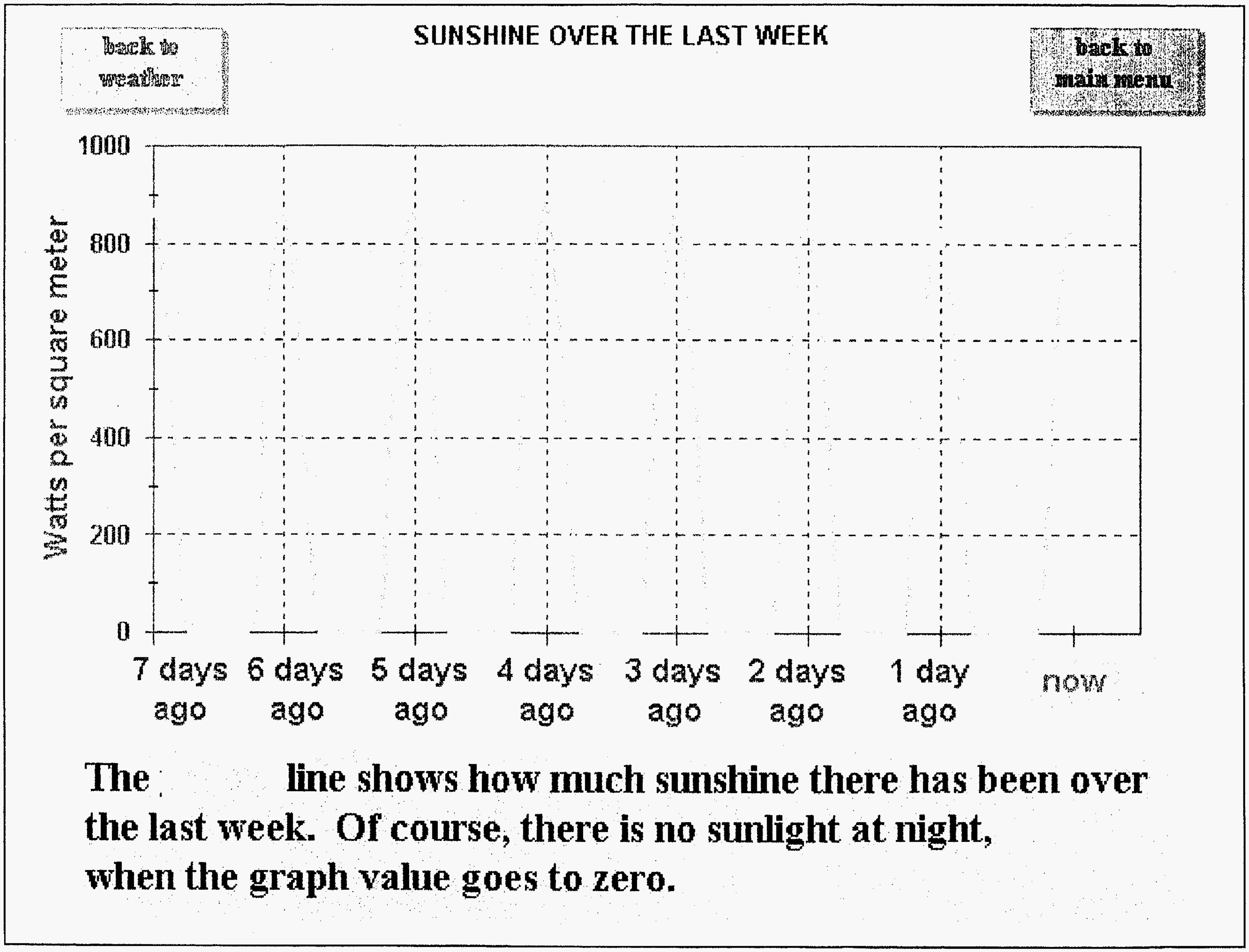
AIR CONDITIONING ENERGY USE
OVER THE LAST WEEK

Theblue line shows the air conditioning energy use of the building with its new white roof coating. Thered line shows the energy an uncoated roof would have used.



OUTDOOR TEMPERATURE AND HUMIDITY
OVER THE LAST WEEK

The red line shows how hot it was (use the left scale, from 20 to 120 F) and theblue line shows how humid it was (the right scale, from 0 to 100% humidity).



SUNSHINE OVER THE LAST WEEK

The line shows how much sunshine there has been over the last week. Of course, there is no sunlight at night, when the graph value goes to zero.

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WIND SPEED AND DIRECTION OVER THE LAST WEEK

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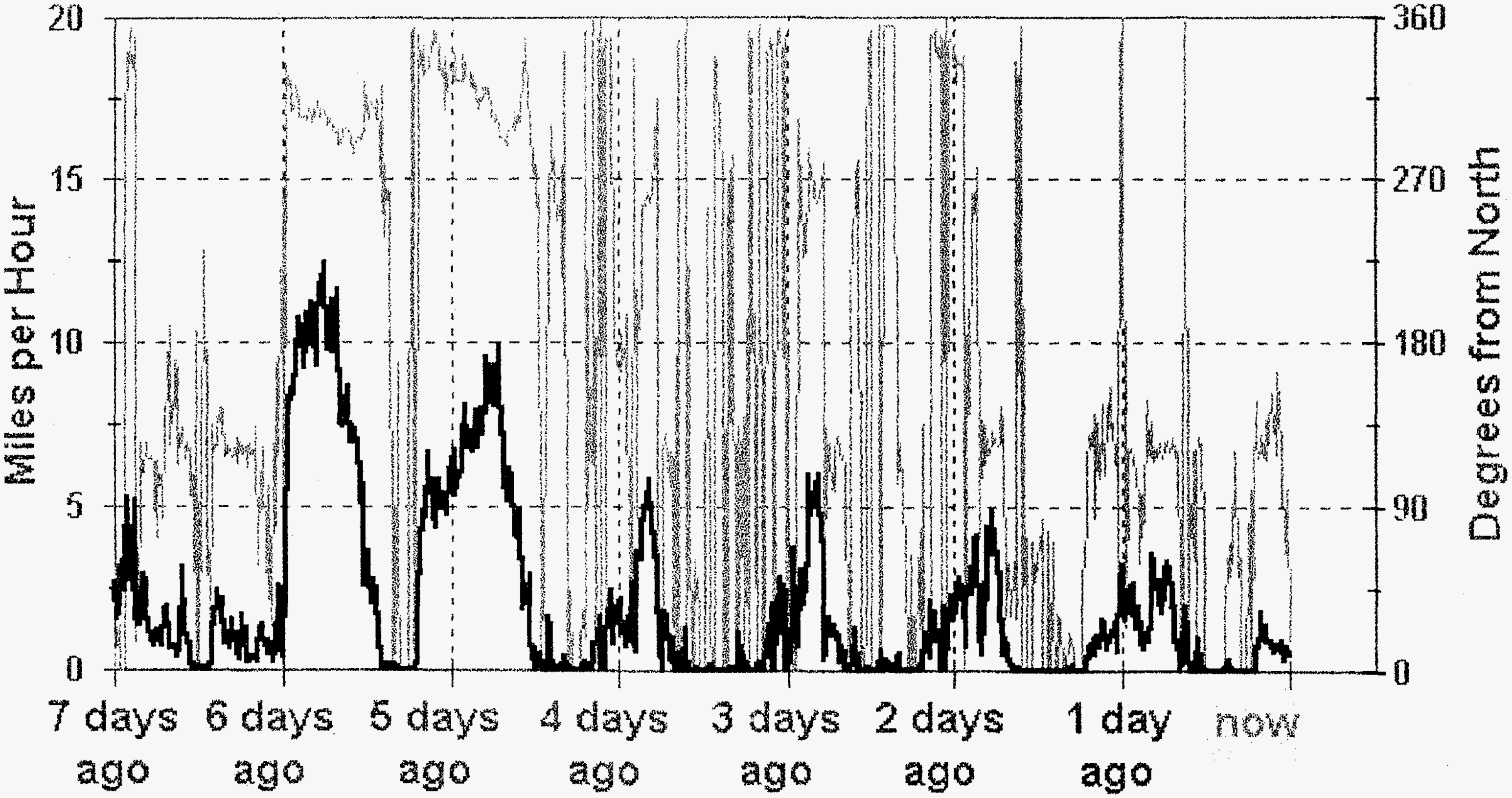

The lblue line shows how fast the wind blew (use the left scale, from 0 to 20 mph) and the green line shows where the wind came from (the right scale, 0 to 360 degrees from north).

FOR MORE INFORMATION

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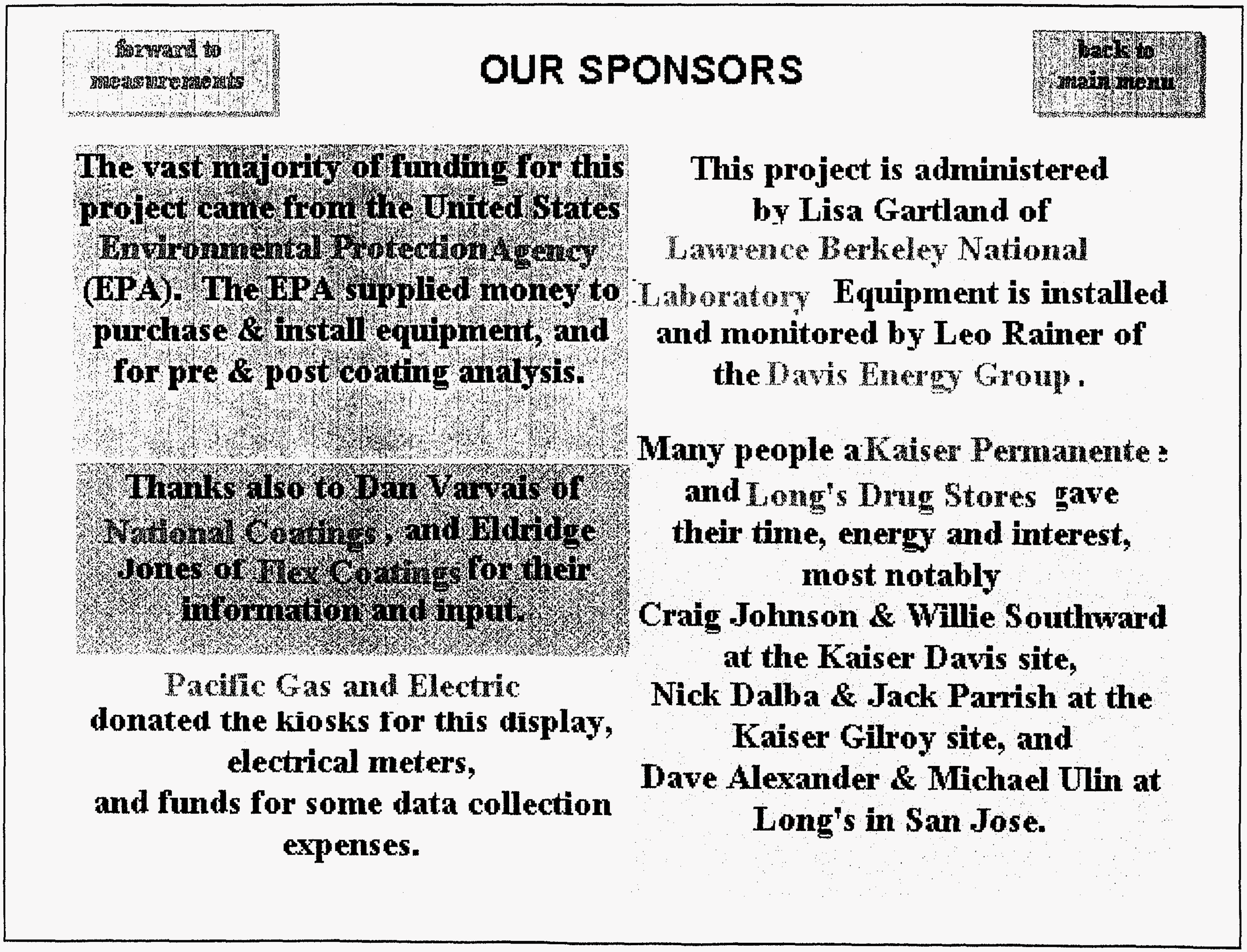
This project was administered by Dr. Lisa Gartland of the Heat Island Group at Lawrence Berkeley National Laboratory. The Heat Island Group performs interdisciplinary research on urban warming trends and how to reverse them.

Reflective surfaces are a very important solution to the warming trends occurring in our cities. They reduce building temperatures and cooling energy use, and they also help reduce summertime air temperatures and smog.

You can get more information about reflective roof coatings and the Heat Island Group's research by:

- linking up to our World Wide Web pages at http://eande.lbl.gov/EAP/BEA/HIP/himain.html.
- sending email to project administrator Lisa Gartland at lmgartland@lbl.gov, or
- phoning Lisa Gartland at (510) 486-7334.



OUR SPONSORS

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Thanks also to Dan Varvais of National Coatings, and Eldridge Jones of Flex Coatings for their information and input.

Pacific Gas and Electric
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This project is administered by Lisa Gartland of Lawrence Berkeley National Laboratory Equipment is installed and monitored by Leo Rainer of the Davis Energy Group.

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