Skylights and LightPipes: an Evaluation of the Daylighting Systems at Two ACT² Commercial Buildings

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As part of the ACT² project, sponsored by a major northern California utility, two occupied single-story commercial buildings were equipped with similar yet different daylighting systems in an effort to reduce electric lighting loads and provide a better workspace.

The daylighting system, at a newly constructed 15,000 sq.ft. office building in Antioch, California, incorporates skylights with louvers, perforated blinds on the windows, and dimming ballasts which control T8 fluorescent fixtures. At the 7,500 sq.ft. retrofitted office building in Auburn, California, the building required a different kind of ''skylight'' to provide daylighting. Due to the 10 foot attic space on the single-story building, a lightpipe-type of skylight was installed. The lightpipe incorporates a long cylinder with a reflective internal surface to direct available sunlight into the workspace through a white diffuser. Forty-seven lightpipes were installed. In addition, T8 fluorescent fixtures were controlled by dimming ballasts and light level controls.

A more thorough analysis of annual energy savings due to daylighting was done at the Antioch building. The daylighting controls reduce annual lighting energy consumption by 32%, with savings ranging from 14% in December to 45% in June. Without controls, the average lighting power at mid-day is 0.56 W/ft^2. With controls, mid-day lighting power drops to 0.37 W/ft^2 in the winter and 0.20 W/ft^2 in summer. Initial analysis of the Auburn building showed only 11% savings on a clear summer day and 3% on a cloudy spring day. Further testing at the Auburn building concluded that the dimming control system had not been calibrated properly and that placement of the photosensors in the light wells improved system response and increased energy savings. Occupant reaction to the daylighting system at both sites was largely favorable. Monitoring of the Auburn site will continue in 1996, with further evaluation following.

INTRODUCTION

The use of daylight in an office building has been reported to enhance the indoor environment for workers; boosting morale, lowering absenteeism, and increasing productivity (Romm and Browing, 1994). Daylight, along with a properly designed and commissioned electric lighting system, can also be an effective energy management tool. One of the goals in designing for daylighting is to provide a diffuse ambient light in the interior through the use of wall windows and overhead skylights with minimal direct sunlight entering the building. An interior that is designed to maintain an adequate ambient light level through daylighting has great potential for energy savings via reduced electric light use (Benton, 1989). A typical office building uses fluorescent lamp fixtures to provide light to the interior. The development of dimming controls in recent years has created an opportunity for energy savings in office buildings. Controls can be set to adjust the electric light output based on the daylight available in order to maintain adequate light levels in the interior. Continuous dimming electronic ballasts for fluorescent lamps allow the electric light output to adjust in small steps with minimal distraction to occupants. Some control systems will simply shut off the electric lighting once an preset interior light level is attained through the daylight contribution. The perceived advantage of installing an automatic lighting control system over manual control (i.e. occupant switches on/off when there is enough light) is that one would have greater confidence in achieving projected energy savings.

The Advanced Customer Technology Test (ACT²) for Maximum Energy Efficiency is a demonstration project of the Pacific Gas & Electric (PG&E) Research and Development Department (Brohard 1992). It is a project to design, implement and measure integrated packages of technologies which are optimized for maximum energy efficiency at selected customer facilities in the utility's service territory. As part of the project, daylighting design was incorporated in two office buildings. One, a 15,000 sq.ft. newly constructed office building located in Antioch, California, adopted a daylighting design which incorporates skylights with louvers, perforated blinds on the windows, and dimming ballasts which control T8 fluorescent fixtures (Figure 1). At the 7,500 sq.ft. retrofitted office building in Auburn, California, the design required a different kind of ''skylight'' to provide

Figure 1. *Antioch Office Building—Interior Daylighting—Entrance*

Figure 2. *Auburn Lightpipe skylight for daylighting*

daylighting. Due to the 10 foot attic space on the single-story building, a lightpipe-type of skylight was installed (Figure 2). In addition, T8 fluorescent fixtures were controlled by dimming ballasts and light level controls. Building and system descriptions are listed in Table 1.

The intent of this paper is to evaluate the energy savings due to daylighting achieved at two occupied office buildings. Due to the differences in project status at each site, the Antioch building will have a more detailed analysis while the Auburn building is presented here as a preliminary assessment prior to final analysis. Details on the design process, commissioning, productivity gains and cost are omitted in this presentation. These additional issues are being reviewed and will be considered for publication at a later date.

Design Considerations

Antioch

The original ‘‘basecase’’ design of this new construction office building did not include daylighting because the company had previously found that skylights allowed too much light and heat into their video display terminal (VDT) intensive environment (PG&E,1995). The resulting design incorporates natural daylight from overhead skylights and perimeter windows as the primary lighting source. The skylights would be supplemented by a high-efficiency, daylight sensitive lighting system using T-8 fluorescent fixtures with dimmable electronic ballasts.

The daylighting system at the Antioch building includes several features targeting energy efficiency, cost-effectiveness, and light quality:

- Ceiling height in the center of the building is vaulted to 15 feet, with the perimeter ceiling remaining at the base case design’s 10 feet. A higher ceiling allows uniform daylighting distribution over workstations from 29 triple-pane, acrylic, low-glare prismatic skylights spaced approximately 20 feet apart. Skylight wells are splayed at 45-degree angles to provide optimal light quality and distribution. Skylights and ceilings also enhance the architectural character of the building and its feeling of internal spaciousness.

__Table 1.__ Building and System Description

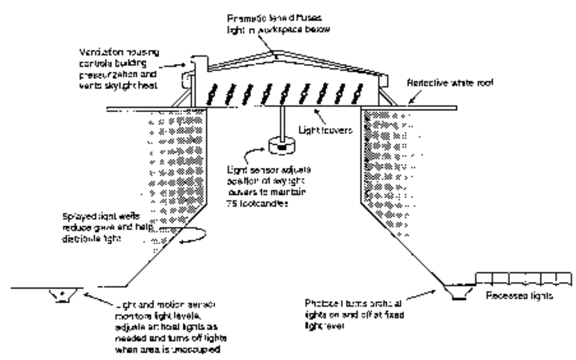
	Antioch Office Building	Auburn Office Building
Building type	Office	Office
sq. ft. of building	15,000	7,500
sq.ft. of daylit dimming area	~14,000	5,700
Skylight Type	Triple-glazed, clear acrylic prismatic Skylight, w/ automated louvers. *SunOptics Model 800B*	Light pipe, circular pipe, w/clear roof dome and white ceiling diffuser. *The SunPipe Co*.
skylight size & quantity	(27) 4.5′ × 3.5′-open areas (2) 4.5′ × 1.75′-back wall (2) 2′ × 8′-restrooms	(47) 13″ diameter pipes with 10 ft. extension between roof and ceiling.
Total sq.ft. of skylights	473	43.3
% daylit area	3%	0.75%
Fluorescent Fixture	4 ft., 2-lamp T8s w/parabolic reflectors	4 ft., 2-lamp T8s w/parabolic reflectors
Electronic Dimming Ballast	*Advance Mark VII*	*Lutron Hi-Lume*
Ballast Dimming Range [% Light Output]	20–100	1–100
Lighting Controller	*Sunoptics LCM* 3000 —skylight louvers *Sensor Switch* —occupancy —dimming photosensors —on/off photosensor	*Lutron Microwatt-LC* —occupancy sensor —dimming photosensor

- Louvers installed at the top of skylight wells (Figure 3) are controlled by photocells. These daylight-sensitive controls open and close louvers to continuously modulate the amount of light entering the building and maintain task illumination at glare-free levels.

- Barometric exhaust vents in each skylight provide building pressurization control and exhaust solar heat from skylight wells to reduce heat gain throughout the building.

- Low U-value, spectrally selective windows reduce thermal energy transfer and maintain comfortable environmental and visual conditions. Fixed-pitch perforated window blinds provide glare control. Perimeter workstations are illuminated primarily from windows and secondarily from skylights.

__Figure 3.__ Antioch Louvered Skylight System



Daylighting is supplemented by a high-efficiency lighting system incorporating heat-rejecting fixtures (32 watts, 2-lamp) with specular reflectors, parabolic louvers and T-8 fluorescent lamps with dimmable electronic ballasts. Compact fluorescent lamps provide downlighting in some areas with non-dimming ballasts. In perimeter areas, recessed light fixtures are spaced eight feet apart. In open office areas, recess light fixtures are evenly spaced relative to the skylight wells. Pendant-mounted, single-lamp fluorescent luminaires (indirect) are also used along the perimeter of the vaulted ceiling area to reduce shadows.

The lighting design criteria for this building follows published Illuminating Engineering Society (IES) standards for VDT office environments. The target interior illumination levels are summarized in Table 2.

All regularly occupied building areas use illuminance-sensing, continuous-dimming controls to respond to available daylight and maintain interior light levels at the Illuminating Engineering Society (IES) recommended levels. These combination light and motion sensors also activate the lighting system when a space is occupied. A second photocell turns off the lights when daylighting levels exceed 60 fc and on again when light levels fall below 30 fc. Workstations are equipped with tasklights to enhance lighting levels. Commissioning of all lighting and daylighting controls was done with satisfactory results

Auburn

Inspired by the initial results at the Antioch building, which revealed the potential to reduce dependence on electric lighting and lower heat gain due to daylighting measures, designers considered daylighting for the Auburn building. However, in the existing Auburn office building, the building's high ceilings, which are suspended 10 feet from the roof, precluded the use of conventional skylights, forcing the project team to find an alternative method for delivering natural light to the interior.

In the open office areas (Figure 4), to reduce fluorescent lighting needs and overcome the inability to use conventional skylights, the project team installed an innovative skylight pipe system. These pipes provide daylighting through a design developed by The SunPipe Company (Energy Design Update, 1995). The pipes use a cylindrical sheet metal tube with highly reflective inner walls to deliver natural light downward from the roof to diffusers at ceiling level. Each unit includes a clear top dome and collar, exterior flashing, pipe sections as necessary for the vertical drop, a white bottom diffuser, and a light well with flat white interior and open bottom fitted for the T-bar grid (see Figure 5 and Figure 6). The light well was designed to avoid creating

Figure 4. *Auburn Floorplan*

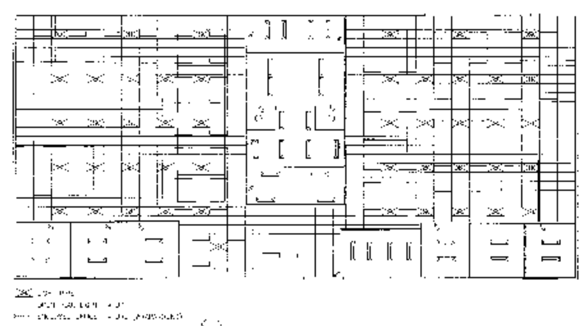
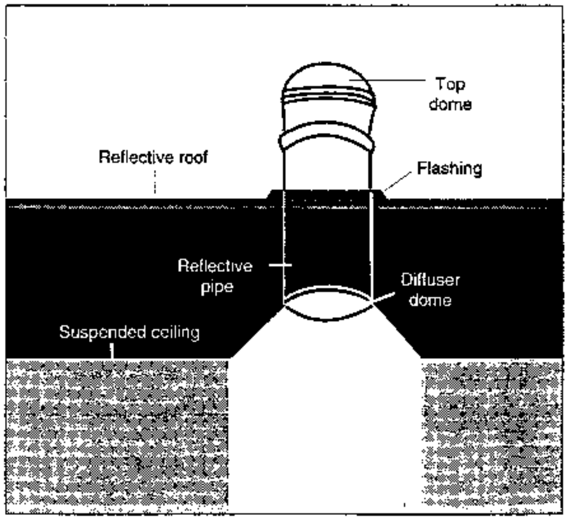


Table 2. *Lighting Design Criteria at the Antioch Building*

Area Descriptions	Target Avg. Illuminance (fc)	IES Category	IES Category Description
General Office Area	30 (75 max)	D	reading tasks (RP-24 standard for VDT office environments)
Work Stations w/task lights	50	—	IES RP-24 standard
Corridors/lobby/circulation	15	C	office lobbies, lounges & reception areas
Restrooms and Lunch room	15	C	toilets and wash rooms
Storage Rooms	30	D	active small items w/storage rooms

Figure 5. *Auburn Skylight Pipe System*



Natural light enters the skylight pipe system through the top dome and is delivered downward from the roof through a sheet metal tube with highly reflective inner walls to diffusers at ceiling level.

Figure 6. *Auburn Interior View*

intense light point sources in the ceiling that would create glare on VDTs (computer monitors).

Daylighting in the open office area allowed the project to reduce dependence on fluorescent lighting. The original fixtures, containing four T-12 fluorescent lamps with solid core magnetic ballasts, were replaced with fixtures containing two T-8 fluorescent lamps with dimmable electronic ballasts. The two lamps are stacked one on top of the other to reduce glare on VDTs. The initial design provided inadequate lighting levels at task height and had to be modified. Two more rows of fixtures were installed which then resulted in too much light. Fortunately, with the dimming feature of the electronic ballasts, the lamps were then set to the desired light level (70% light output w/o daylighting). Illuminance sensors continuously dim the lamps further in response to available daylight. Target lighting levels in the general work area were 50 fc average. Both buildings were commissioned to insure design light levels and proper operation of the daylighting systems.

Methodology

General

As part of the project, both office buildings were extensively monitored. Electric and gas loads were monitored separately and environmental conditions (temperature & relative humidity) were recorded in 15-minute time steps starting in 1994 and continuing through 1996. A rooftop weather station located at each building monitored and recorded wind and solar data in 15 minute intervals. Direct normal insolation was estimated using a multipyranometer (MPA) reconstruction algorithm developed from ACT^2 data. Details of the MPA reconstruction algorithm and it’s accuracy will be published later this year. After one year of post-retrofit operation, an impact evaluation was to be conducted at each site. Measured data (Nov. ’94 to Oct.’95 for Antioch analysis) is converted to hourly intervals and used to calibrate or tune a DOE2 computer model of the building (details of the calibration can be found in a separate report available later this year), then the model is run with Typical Meteorological Year (TMY) weather data for final comparison of the before and after situation of the whole building.

The intention of this paper is to focus only on the daylighting systems as energy management measures. Energy savings are calculated through comparison of measured lighting load data. Impacts on the HVAC loads are not discussed here, though these effects will be reported in the final Energy Efficiency Measure Impact Analysis for each site, due to be completed later this year. Solar insolation (Global Horizontal) measurements indicate the availability of sunlight, i.e. whether it is a clear or cloudy day. Unfortunately, no interior light level meters were mounted as part of the long term data collection scheme, though some short-term monitoring was done.

Antioch Daylighting Savings Methodology

Lighting energy and demand savings are estimated with DOE2.1E's daylighting simulation (DOE2.1E v.110 used for this analysis). The model employs the program's switchable glazing feature to approximate the performance of the automatic skylight louvers. The switchable glazing function varies the visible light transmittance, shading coefficient and U-value of the skylight to control illumination in the space. The simulated louvers start to close when available illumination exceeds 70 fc. The electric lighting in the model is controlled with continuous dimming to reduce the light output from 100% to 20% and power input from 100% to 40% as the daylight increases. When the daylight illumination exceeds 60 fc, the electric lighting shuts off. These daylighting parameters are based on system specifications, and are tuned so that simulation results match measured electricity consumption.

Savings are determined by running the simulation with and without daylighting controls. In the basecase, daylighting is turned off, and the electric lights follow a typical office schedule: 8:00 AM to 6:00 PM at 90% power and off hours at an average of 20% power. This schedule matches the measured lighting consumption profile. The same ON/OFF schedule is used for both cases, the only difference is that the daylighting function is disabled for the base case. Total installed lighting power is about 10.3 kW, which is equal to 0.66 Watts/ft^2. Eighty-six percent of the building's interior lighting power is under daylight control.

Auburn Daylighting Savings Methodology

Analysis using the computer model and measured data will occur later in 1996 during the impact evaluation process. Daily percent energy savings was calculated for one clear (July 6, 1995) and one cloudy day (April 28, 1995) by subtracting the dimming power profile from the full-load condition, between the hours of 7 a.m. and 5 p.m. It was thought that these two days represented two extremes in daylight availability. This information alone is not enough to project annual energy savings and is presented here only to illustrate the operation on clear and cloudy days. In addition, short-term light level and electric light monitoring was done to help diagnose a sensor placement problem.

Table 3. *Modeled Skylight Characteristics*

Louver Position	Shading Coefficient	Visible Light Transmittance	U-value (Btu/hr-ft^2-°F)
Full Open	0.68	0.64	0.55
Full Closed	0.22	0.04	0.35

No official occupant survey had been completed at the time of this writing, though some anecdotal feedback is included in the results section.

Results

Antioch

Seasonal average weekday electric lighting profiles are presented in Figure 7, where a baseline ''no-daylighting'' profile is compared to both measured and modeled daylighting data. These results are presented in both kW and Watts per ft^2 formats. Monthly interior lighting (kWh/month and kWh/ft^2/month) energy consumption are presented in Figure 8, again comparing the No-daylighting situation to both measured and modeled daylighting data.

Table 4 shows the percent of lighting energy savings due to daylighting on an hourly basis throughout the year, with

Figure 7. *Average Lighting Power [kW] and Power Density [W/ft^2]*
[——Measured – – – Sim, Day1 ------ Sim, No Day1.]

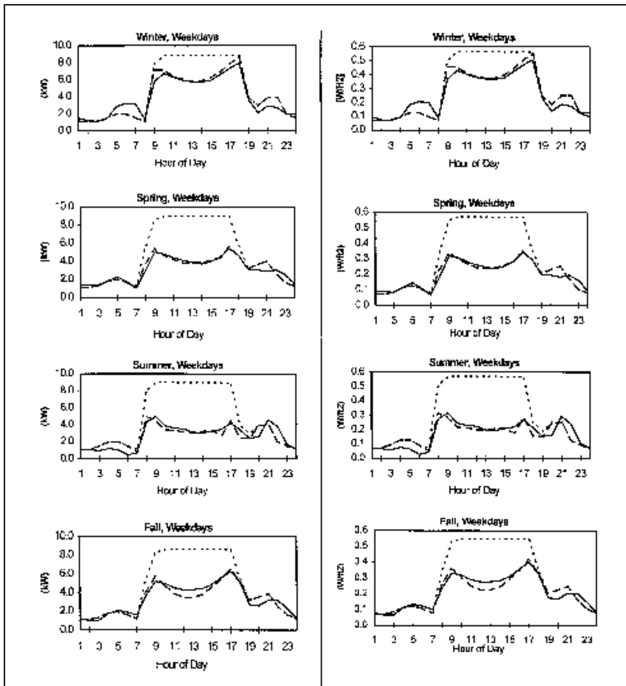
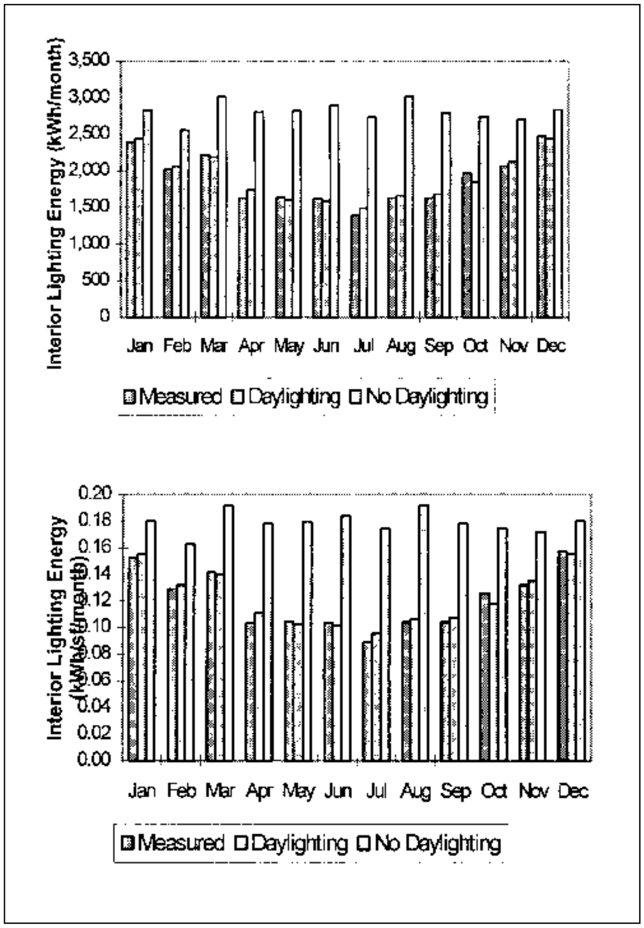


Figure 8. Monthly Interior Lighting (Antioch)



savings up to 70% savings occurring. Consistent savings of above 60% during the summertime afternoon hours illustrate how the daylighting design works very well at reducing demand (kW) during the utilities' peak period. This can translate into additional cost savings for the customer by reducing expensive onpeak demand charges. The data comes from the LS-I Report of DOE2.

The daylighting controls reduce annual lighting energy consumption by 32%, with savings ranging from 14% in December to 45% in June. Without controls, the average lighting power at mid-day is 0.56 W/ft^2. With controls, mid-day lighting power drops to 0.37 W/ft^2 in the winter and 0.20 W/ft^2 in summer.

Auburn

The commissioning process was unable to identify a problem with the daylighting system. Follow-up analysis of the system at Auburn (Figure 9) indicated a problem in the lighting control system. Only an 11% daytime energy savings was seen on a clear summer day and only 3% on a cloudy spring day. The occupants were satisfied at this point with the overall lighting quality of the interior, but it was disappointing to find that this expensive control system wasn't operating as advertised. Rather than starting the practice of pointing fingers and passing the buck, some additional tests were conducted with the illuminance sensors placed inside the light well with a direct view of the light pipe diffuser. The theory was that the illuminance sensor was not ''seeing'' the daylight contribution when it was placed on the ceiling plane facing the general direction of the light well, but not directly in view of the light pipe diffuser. Short-term data loggers were placed in a zone with a temporarily relocated illuminance sensor (inside the light well, see Figure 10) to record light levels and electric light dimming for a two-week period in February 1996. Data analysis at the time of this writing indicates that the system is dimming more noticeably. Several complaints were registered shortly after the relocation of the sensor. The complaints coincided with rapid changes in cloud cover, which caused the dimming system to reduce the electric lights to a minimum level. Some adjusting of the controller and a change in direction of the illuminance sensor (while remaining in the light well) was done to try to find a happy medium. If this proves satisfactory, the remainder of the illuminance sensors (there are four total) are to be relocated inside the nearest light well. Data will continue to be recorded via the long-term dataloggers and a more complete analysis, similar to Antioch, will be done later in the year.

An interesting issue arose during the installation of the light pipes. Two of the twenty employees complained that the lighting intensity from nearby light pipes was giving them headaches and causing eye strain. Unfortunately, there were no light level readings recorded at the time, as it would have been interesting to try to quantify the level of daylight that was causing these complaints. The solution, agreed upon by the design team, was to cover the light pipes nearest the 2 employees' workstations with a sunscreen fabric material (see Figure 11). This managed to dampen the daylight intensity to the satisfaction of the 2 employees. The manufacturer (Miller, 1996) also notes that flat diffuser disks are available to insert above the ceiling diffuser dome, that will provide the same effect as the sunscreen material mounted externally.

Also, some leakage of water inside the pipes were reported. There are several possible reasons for this happening. The installers used a different gasket material than prescribed for the clear roof dome. One dome blew off during a storm, which then allowed the pipe to fill with rain water. Further follow-up on the gasket material and attachment technique is underway.

SUMMARY

The application of daylighting to achieve significant energy savings in commercial office buildings can be a challenging

Table 4. *Percent Lighting Energy Savings Due to Daylighting*

	Hour of Day																								ALL
MONTH	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	HRs
JAN	0	0	0	0	0	0	0	0	8	17	25	30	31	29	25	16	9	0	0	0	0	0	0	0	14
FEB	0	0	0	0	0	0	0	2	12	21	29	35	40	40	35	29	19	4	0	0	0	0	0	0	19
MAR	0	0	0	0	0	0	1	13	25	33	43	49	47	51	44	34	29	13	0	0	0	0	0	0	27
APR	0	0	0	0	0	0	10	30	37	54	57	60	60	58	59	55	39	26	4	0	0	0	0	0	38
MAY	0	0	0	0	0	3	23	38	52	58	60	64	66	63	60	65	46	31	14	0	0	0	0	0	43
JUN	0	0	0	0	0	6	27	37	55	59	62	65	64	63	62	67	49	37	21	2	0	0	0	0	45
JUL	0	0	0	0	0	4	27	39	52	62	63	65	66	64	63	70	53	41	23	2	0	0	0	0	45
AUG	0	0	0	0	0	1	19	37	43	64	63	65	66	64	64	70	49	36	13	0	0	0	0	0	44
SEP	0	0	0	0	0	0	7	30	38	55	63	66	67	65	64	48	38	21	1	0	0	0	0	0	40
OCT	0	0	0	0	0	0	1	20	33	42	58	65	66	62	42	36	26	3	0	0	0	0	0	0	32
NOV	0	0	0	0	0	0	0	5	23	36	42	46	44	39	32	24	8	0	0	0	0	0	0	0	21
DEC	0	0	0	0	0	0	0	0	7	18	26	28	29	31	27	19	6	0	0	0	0	0	0	0	14
ANNUAL	0	0	0	0	0	1	9	30	33	43	50	53	54	53	48	45	31	13	6	0	0	0	0	0	32

task. The two case studies presented here illustrate two different designs and the potential for energy savings. Occupant reaction to the daylighting system at both sites has been largely favorable.

Antioch

Despite some concern about the complexity of the louvered skylight, the system has performed well. The daylighting controls reduce annual lighting energy consumption by 32%, with savings ranging from 14% in December to 45% in June. Without controls, the average lighting power at mid-day is 0.56 W/ft^2. With controls, mid-day lighting power drops to 0.37 W/ft^2 in the winter and 0.20 W/ft^2 in summer. DOE2 output reports energy savings due to lighting reduction and considers the 24-hour use of electric lighting as the reference case, thereby reducing the ‘‘percent’’ savings figure. Peak demand savings of above 60% were recorded. Overall, a very successful application of daylighting using skylights and lighting controls to achieve noteworthy energy savings.

Auburn

Light pipe skylights show promise in retrofit, as well as new construction, applications as a cost-effective and versatile daylighting energy saving measure. The quality of the lighting, though not adequately reported here in this paper, has been favorably received by the occupants at the Auburn building. The failure of the commissioning process to identify and correct problems with the control system indicates a need to have better defined design protocols and a commissioning team that understands the system. (ACT^2 1995) Follow-up analysis indicated some problems with the lighting control system and sensor placement. Sensor relocation and subsequent monitoring have indicated that there is promise for this system after all. Final judgment will wait until a more thorough analysis is completed at the end of 1996.

ACKNOWLEDGMENTS

This study was made possible through funding by Pacific Gas and Electric, Research and Development Department, as part of the ACT^2 project. Thanks to Erik Kolderup of Eley Associates for providing the DOE2 computer simulation analysis.

ENDNOTES

1. To inquire about additional information and available reports regarding the ACT^2 project, call (510) 866-5555 or write to: ACT^2 Project, Pacific Gas & Electric, 2303 Camino Ramon, Suite 200, San Ramon, CA 94583.

Figure 9. *Clear and Cloudy Day Operation at the Auburn Office Building*

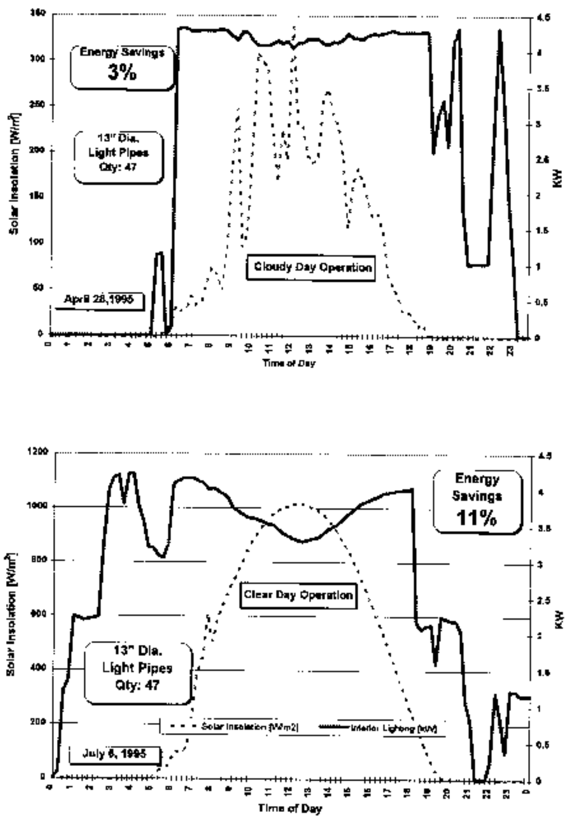


Figure 10. *Auburn—Lightwell interior with repositioned photosensor*

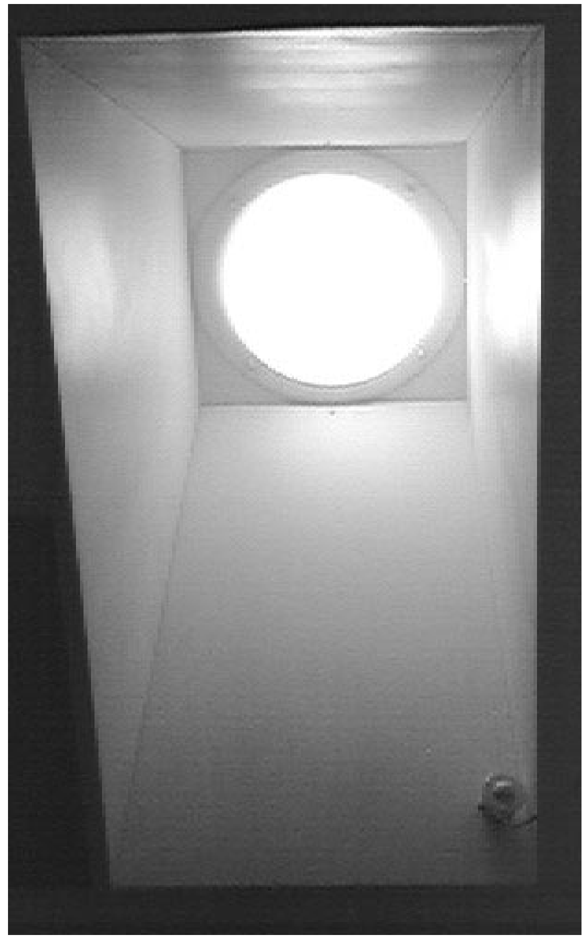
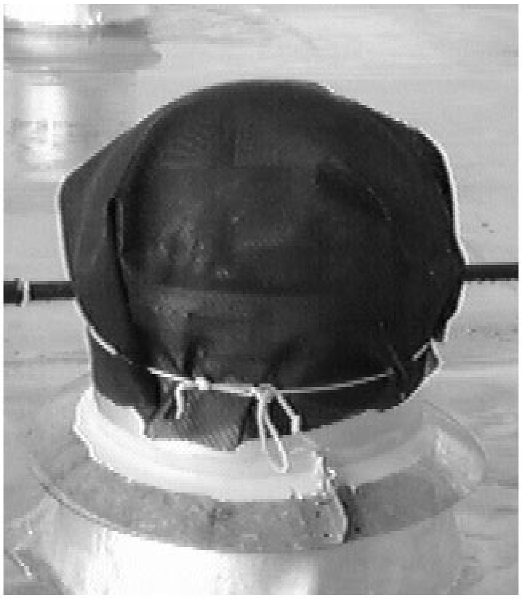


Figure 11. *Auburn—Suncreen Retrofit*



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