Title
ADVANCED OPTICAL MATERIALS FOR DAYLIGHTING IN OFFICE BUILDINGS

Author
Johnson, R.

Publication Date
1985-12-01

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE
DIVISION

Presented at the 10th National Passive Solar
Conference, Raleigh, NC, October 15-19, 1985

ADVANCED OPTICAL MATERIALS FOR DAYLIGHTING IN OFFICE BUIDLINGS

R. Johnson, D. Connell,
S. Selkowitz, and D. Arasteh

December 1985

**APPLIED SCIENCE
DIVISION**

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-20080
EEB-W-85-12
W/DA-204

Presented at the 10th National Passive Solar Conference, Raleigh, NC, October 15-19, 1985, and published in the proceedings.

ADVANCED OPTICAL MATERIALS FOR DAYLIGHTING IN OFFICE BUILDINGS

R. Johnson, D. Connell, S. Selkowitz, and D. Arasteh

Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

December 1985

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

ADVANCED OPTICAL MATERIALS FOR DAYLIGHTING IN OFFICE BUILDINGS

R. Johnson, D. Connell, S. Selkowitz, and D. Arasteh

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

The use of daylighting to supplant electric light in office buildings offers substantial energy savings and peak electrical demand reductions. The benefits from electric lighting reductions can, however, be easily offset by increased cooling loads if solar gains are not controlled. The use of advanced glazing materials having optical switching properties can facilitate solar control and, with proper design, maximize energy and cost benefits. The potential net annual performance of these materials, based on simulation studies using DOE-2.1C, are discussed in this paper. Actively and passively controlled response functions are analyzed for the cooling-load-dominated climate of Lake Charles. The effects of advanced materials on net annual energy consumption, peak electrical demand, and chiller size are compared with those of conventional materials. The results demonstrate the importance of operable solar control to achieve energy-effective daylighting design. Advanced optical materials that provide the necessary level of control are shown to minimize peak electrical demand and electricity consumption.

Introduction

Daylighting in office buildings, now widely recognized as an important energy-conservation design strategy, requires careful architectural design and effective window management in order for maximum energy benefits to be realized. Prior studies have demonstrated potential energy benefits (1-4) while assuming that window shades, or equivalent conventional solar-control devices, are automatically managed to mitigate thermal gain caused by direct solar radiation. Building occupants occasionally manage window shades well, but occupant management of shades tends to be inconsistent and unreliable, making automatic controls desirable for good energy performance. Automatically controlled mechanical shading systems having electro-mechanical controls that assure proper management are available. They have been widely used in Europe for some time and their use in the U.S is increasing. New glazing materials with dynamic solar optical properties that can be changed to meet needs is another option now being researched. These optical switching materials can be selected to respond passively to a varying environmental force, such as solar radiation, or can be actively controlled according to environmental conditions and changing building requirements. In addition, the spectral selectivity of these materials can be designed to increase the ratio of visible light transmission to total solar transmission for improved energy performance relative to conventional glazing.

Methodology

To systematically study the effects of fenestration design on building energy performance, we developed a representative five-zone office building module for computer simulations. This module, described in detail in previous studies (1), consists of four perimeter zones, each 15 ft deep, surrounding a 100-ft square core zone. The ceiling and floor are modeled as adiabatic surfaces. The perimeter zones are separated from the core by adiabatic partition walls. Each of the zones has its own constant-volume, variable-temperature air supply system with economizer. Orientation effects in the perimeter zones are thus isolated for analysis. The four perimeter zones are served by a common plant to allow us to assess the net effects of fenestration on peak electrical demand and chiller size.

Using this basic building module with a window-to-wall ratio (WWR) of 0.3, two types of optical switching glazing materials and two types of conventional fenestration systems are assessed and performance results compared. We model hypothetical optical switching materials with linear response functions; actual optical switching materials' performance can be designed to approximate these characteristics (5,6). The five fenestration systems modeled are identified as follows:

PR - Passive response

Photochromic glass, responsive to solar radiation. Shading coefficient (SC) varies linearly from 0.8 to 0.2 as total solar radiation incident on the glass varies from 10 $\mathrm{Btu/ft^2 \cdot hr}$ to 100 $\mathrm{Btu/ft^2 \cdot hr}$. Visible transmittance (T_v) is equal to SC. There are no separate shades with the photochromic glass.

AC - Actively controlled

Electrochromic glass with T_v controlled to hold daylight levels to a maximum of 50 fc at the reference point in the room. Maximum T_v is 0.8 and $SC = T_v$. No operable shades.

HT - High transmission

Conventional high-transmission glazing system with SC = 0.8 and $T_v = 0.78$. No operable shades.

HTS - High transmission with shade

Conventional high-transmission glazing with SC = 0.8 and T_v = 0.78. A window shade is deployed when direct-beam solar transmission exceeds 20 Btu/ft^2 • hr. The window shade reduces solar gain by 40% and visible light transmittance by 65%.

LT - Low transmission

Conventional low-transmission glass with SC = 0.18 and T_v = 0.07. No operable shades.

For all cases the electric lighting power density is 1.7 W/ft^2 with design illuminance level of 50 fc. A continuous dimming system dims the electric lights in response to daylight to maintain 50 fc at a reference point 10 ft in from the window and 30 inches above the floor. The system dims linearly from 100% light output and 100% power to 0% light output at 10% power.

These fenestration configurations were simulated for the office-building module in Madison, WI, a heating-load-dominated climate, and Lake Charles, LA, a cooling-load-dominated climate, using the building-energy simulation program DOE-2.1C (7,8). This version of the program has an integral daylighting algorithm and a functional key word input that allows the variable optical properties of the glazing to be input in functional form.

Results

Energy Consumption

It has been well established that daylighting can provide net annual energy benefits, and that the magnitude of the benefits is a function of daylight levels in the space and the control of solar gain. In this study we have examined the effects of various solar-control strategies on net energy benefits from using daylighting. Our fenestration design alternatives involve three different control strategies: 1) maximize control of solar gain by using low-transmittance glass, 2) maximize daylighting by using high-transmittance glass, and 3) modulate daylight and solar gain using variable-transmittance advanced glazing. The critical issue in this study is the tradeoff between daylight illumination level and control of solar gain. In terms of annual energy use, solar gain is a more pronounced problem in cooling-load-dominated climates; for this reason we focus on results from Lake Charles. Many similar trends were observed in Madison but were generally of smaller magnitude, demonstrating the need for a considered balance between heating and cooling requirements.

In Figure 1 the daylight levels in a west zone over the course of a clear day are plotted. All of the fenestration configurations studied, with the exception of LT, provide high levels of daylight illumination. For the other fenestration configurations daylight provides all of the required illuminance during most hours of the day. With no shade management, HT provides daylight far in excess of requirements. With the simple shade management strategy for HTS, daylight levels exceed the set point much of the day. On an annual basis the three configurations HTS, HT, and AC all require the same small amount of electric lighting for most months, indicating maximum savings from daylight. Results for PR indicate that the material slightly overdarkens for daylighting purposes. The very low transmittance of LT is designed to maximize solar-gain control in order to allow large view apertures with minimum cooling penalty. However, even with 30 percent glass area the daylight levels fall far short of the required design illuminance. Even with the high intensity of solar radiation in the afternoon, the maximum daylight level at the control point is only about 35 fc with LT.

The effect of these strategies on electricity consumption for cooling is shown in Figure 2. As expected, cooling requirements are highest for those configurations having the least effective solar control. It is important to note, however, that the simple passive strategy of PR substantially outperforms the managed conventional shade, HTS. This is largely accounted for by the difference in the transmittance properties of the two systems. PR has a lower limit on SC, thus a higher degree of solar control, and T_v = SC throughout the operating range. The important issue, however, is performance reliability. The passive material, PR, consistently provides this performance without dependence on mechanically operated, either manual or automatic, physical shades and does not block the view out when deployed. In this study no attempt has been made to optimize the properties of PR so that further improvements in performance might be expected.

While solar control is maximized with LT, as seen in Figure 2, cooling load is low but not minimal. The minimum cooling load occurs with AC. The superior solar control with LT is obtained at the expense of daylight transmission and the resultant high use of electric lighting with LT imposes a significant total cooling load penalty. With AC, daylight transmittance is optimized, requiring minimal use of electric lighting and admitting no more solar radiation than necessary to provide design daylight levels. The cooling load with AC is lower because the electric lights are frequently at their minimum setting, because daylight has a high luminous efficacy (>100 lumens/W) and because of the improved spectral selectivity (T_v = SC) specified for AC, compared to the properties of LT where $T_v = 0.07$ and SC = 0.18.

The consequences of these lighting and cooling effects on net annual energy requirements are shown in Figure 3. Heating requirements are also included in these results, but their significance is essentially limited to December, January and February. For most of the rest of the year cooling is the dominant thermal issue. Considering the extreme months of June, July and August, one sees HT with the worst performance and AC with the best. With HT daylighting is making the maximum contribution to reducing electric lighting but the benefits are totally overwhelmed by the additional cooling requirements. Even with a managed shade (HTS), the solar-gain impact still overwhelms the daylighting benefits. On the other hand, AC has the same daylighting contribution but solar gains are controlled, cooling requirements minimized, and therefore energy benefits maximized.

During summer months HTS and LT perform about equally except for August and to a lesser extent September, when lower sun angles increase direct solar penetration. This slightly improves the daylighting contribution of LT while HTS already has maximum daylighting contribution. Compared to the rest of the year, August is an anomaly and HTS is typically the better performer because of daylighting.

The performance of PR, while not as good as that of AC, outperforms all of the conventional systems. Again this is significant because solar control is automatically provided at all times with a passive material. While the material itself would likely be more expensive than conventional glazing, the cost of separate shading devices and control systems would be eliminated. Materials with other switching property responses can be designed for even more "sympathetic" response to climate conditions, whether heating-dominated or cooling-dominated, and presumably provide even better performance.

The cooling and daylighting results in Madison have quite similar trends, showing very favorable performance with PR and AC, but because the annual requirements for cooling are much less and heating much greater, the differences in net annual energy requirements are less significant. In future work the control logic of AC will be modified to make improved use of solar gain in winter to offset heating loads and reduce net annual energy requirements.

Peak Electrical Demand

Peak electrical demand can be as important a cost consideration as annual electricity consumption in utility districts having high peak demand charges. Monthly peak electrical demand results shown in Figure 4 indicate that HT and LT consistently have the highest demand. With HT, although daylighting is maximized, solar gains are uncontrolled. With LT, solar gains are reduced to the point that daylighting levels are very low and electric lighting is required during peak demand periods.

Peak demand is minimized with AC. In this case daylighting savings are at a maximum and electric lighting at a minimum, while solar gains do not exceed levels associated with maintaining the required daylighting levels. The control strategy of AC, and to a lesser extent that of PR, reduce both electricity consumption and peak demand and could have attractive cost benefits in areas where both electricity rates and peak-demand charges are high.

Chiller Size

It is frequently assumed that daylighting design imposes added first cost in new building construction and cost recovery is assessed in terms of simple payback in operating savings. It is also often assumed that daylight will provide operating savings by reducing electric lighting and cooling requirements. As shown in this and other studies (1-4), the magnitude of operating savings is a function of both daylighting design and proper solar control. If solar gain is properly controlled, daylighting design will not only reduce lighting consumption but will also reduce cooling loads. With reduced cooling peaks, cooling equipment can be downsized, and the first-cost savings in chillers and associated HVAC equipment can be applied to offset the cost of daylighting controls and improved fenestration systems [4].

Optical switching materials offer the advantages of simple and reliable operating systems to achieve proper solar control. The electrochromic system, AC, assures maximum solar control consistent with maintaining design lighting levels with daylight. A comparison of required chiller sizes for the four perimeter zones of our module is shown in Table 1. Comparing a conventional glazing system with shading, HTS, to a high-performance optical switching glazing, AC, we find a reduction in chiller size of 0.806 x 10^{-3} tons/ft^{2} of floor area. If chiller and associated equipment cost $2000/ton, this is a first-cost savings of $1.61/ft^{2} floor area. For each 15 ft^{2} of floor area there are 3 ft^{2} of glazing area, so that chiller size reductions could provide about $8.00/ft^{2} of glazing area to offset fenestration costs. If we compare AC to LT, the chiller savings are not as large but will still contribute to the economic attractiveness of reduced operating costs.

Conclusions

Daylighting can substantially reduce electric lighting requirements, but in order to result in net energy benefits and to provide thermal and visual comfort, solar gains and glare must be controlled. Existing solar control options offer varying degrees of performance, usually involving compromises between effectiveness, complexity, and cost. A new generation of glazing materials with optical switching properties can overcome many of the drawbacks of existing materials.

We used the building-energy simulation program DOE-2.1C to examine the net annual energy performance of two switching materials, one passively actuated and the other actively controlled, to demonstrate the potential for these materials. While the switching responses selected for this study were not optimized, they nonetheless consistently outperformed conventional systems. Optical switching materials offer the advantage of dependable control and should reduce peak electric demand as well as overall energy consumption. The cost of these materials, which are still under study in research labs and are not presently commercially available in window sizes, is unknown. Cost can be expected to exceed that of conventional glass but not necessarily that of presently available fenestration systems incorporating automatically controlled mechanical shading devices. Positive control of daylight transmittance and solar gain can also result in substantial reductions in cooling equipment, with cost savings that may offset the added cost of the glazing and the daylighting control systems.

Our continuing research is examining and comparing more sophisticated glazing-control logic. Work in progress is focusing on refinements to optimize performance in heating-dominated and cooling-dominated climates. In the next year we expect to complement our simulation studies of operable sun-control systems with scale model photometric measurements and with field testing of the cooling load impacts of full-size systems in our Mobile Window Thermal Test (MoWiTT) Facility.

Acknowledgments

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

References

[1] "Glazing Energy Performance and Design Optimization with Daylighting", R.Johnson, R. Sullivan, S. Selkowitz, S. Nozaki, C. Conner, and D. Arasteh, Energy and Buildings, Vol. 6, pp. 305-317, Lausanne, 1984.

[2] "The Impact of Daylighting on Peak Electrical Demand," U.S. Choi, R. Johnson, and S. Selkowitz, Energy and Buildings, Vol. 6, pp. 387-399, Lausanne, 1984.

[3] "Energy Performance and Savings Potentials with Skylights", D. Arasteh, R. Johnson, S. Selkowitz, and R. Sullivan, ASHRAE Transactions, Vol. 91, Part 1, Atlanta, 1985.

[4] "Energy Reduction Implications with Fenestration", R. Johnson, D. Arasteh, and S. Selkowitz, Proceedings of CLIMA 2000, World Congress on Heating, Ventilating and Air-Conditioning, Vol. 2, pp. 363-368, Copenhagen, 1985.

[5] "Solar Optical Materials for Innovative Window Design," C.M. Lampert, Energy Research, Vol. 7, pp. 359-374, 1983.

[6] "Electrochromic Materials and Devices for Energy-Efficient Windows," C.M. Lampert, Solar Energy Materials, Vol. II, pp. 1-27, Amsterdam, 1984.

[7] DOE-2 Reference Manual, Version 2.1, LBL 8706, Rev.1, Lawrence Berkeley Laboratory and Los Alamos Scientific Laboratory, 1982.

[8] DOE-2 Supplement, Version 2.1C, LBL 8706 Rev. 1 Suppl., Lawrence Berkeley Laboratory, 1984.

TABLE 1

Chiller size as a function of fenestration system type
for a prototypical four-zone module. Floor area = 6000 ft^2.
Exterior wall area = 4800 ft^2. Window area = 1440 ft^2 (WWR = 0.3).
Installed lighting power density = 1.7 W/ft^2.

Fenestration Configuration		Chiller Size		HVAC System Cost		
		tons	10^{-3} tons/ft^2 floor	\$/ft^2 floor	\$/ft^2 glass	Savings/ft^2 glass relative to HTS
Passive Response	PR	13.1	2.18	4.37	18.19	3.20
Actively Controlled	PR	10.6	1.76	3.58	14.72	6.67
High Transmission	PR	16.5	2.57	5.50	22.92	<1.53>
High Transmission, Shade	HTS	15.4	2.57	5.13	21.39	0
Low Transmission	LT	12.1	2.01	4.03	16.80	4.58

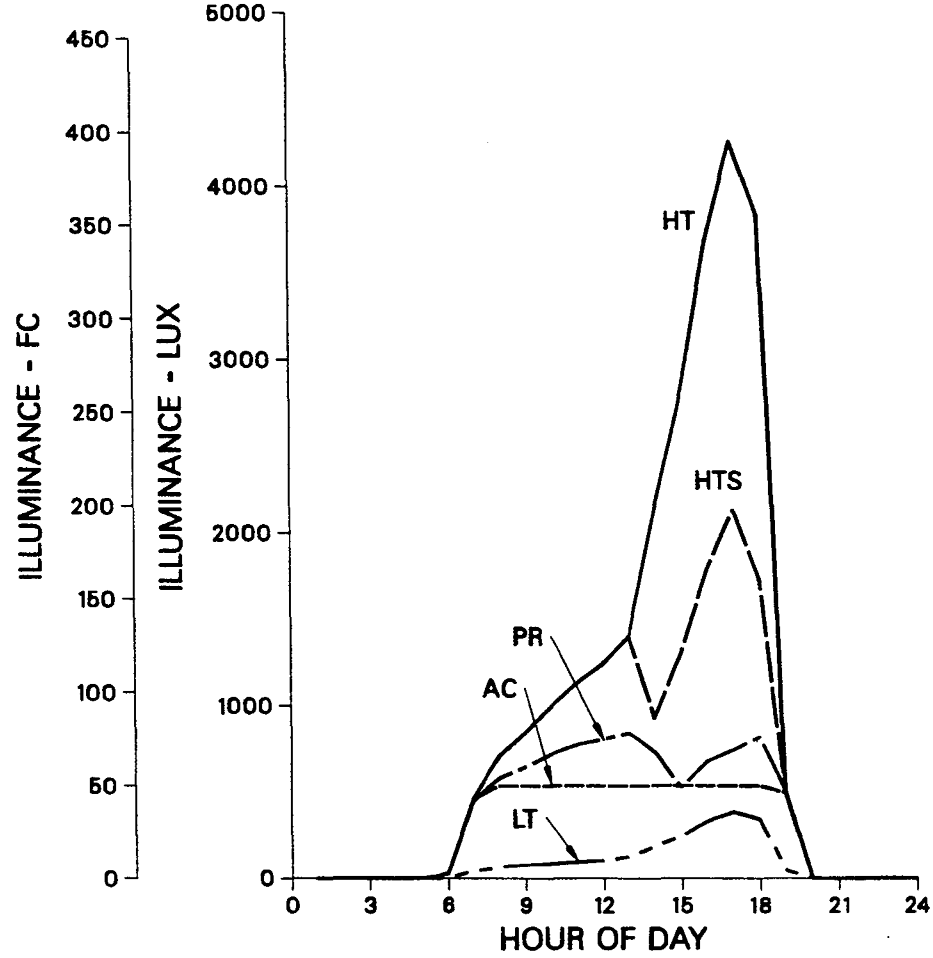

Fig. 1 Daylight illuminance level at reference point in west zone for a typical clear day in June with window-to-wall ratio of 0.3, Lake Charles, Louisiana.

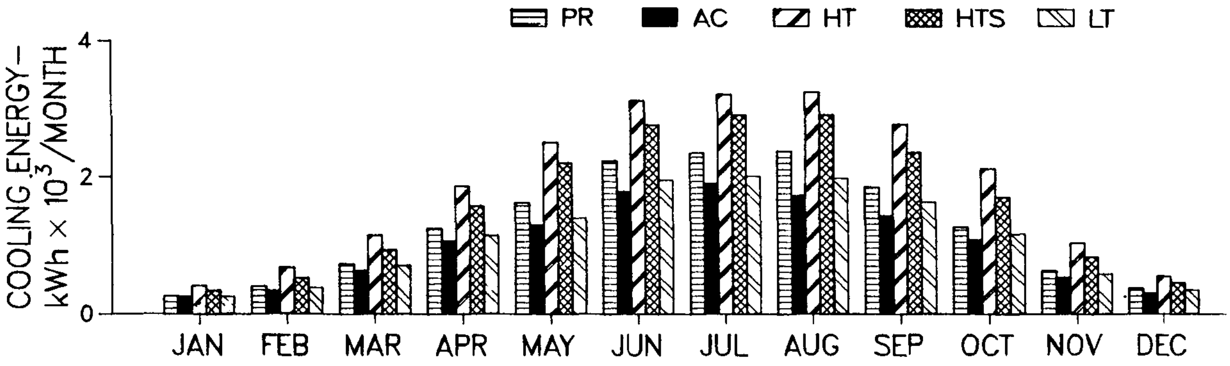

Fig. 2 Monthly energy consumption for cooling for the four-zone, 6000-ft^2 module, Lake Charles, Louisiana.

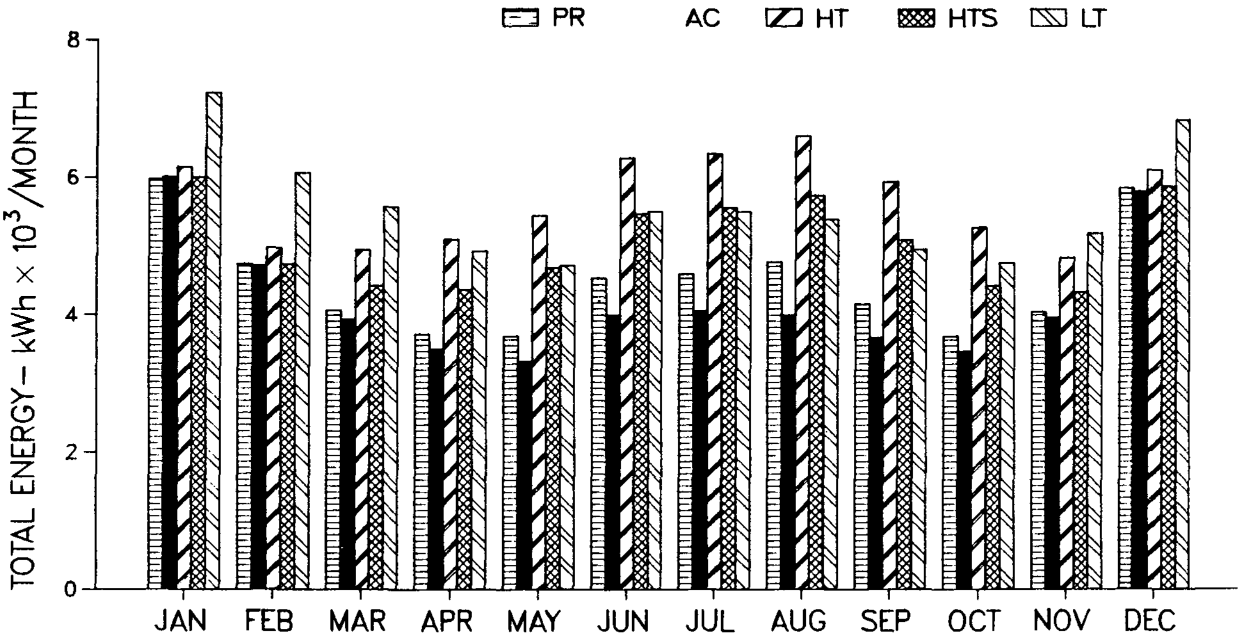

Fig. 3 Total monthly energy consumption for all end uses, 6,000-ft^2 module, Lake Charles, Louisiana.

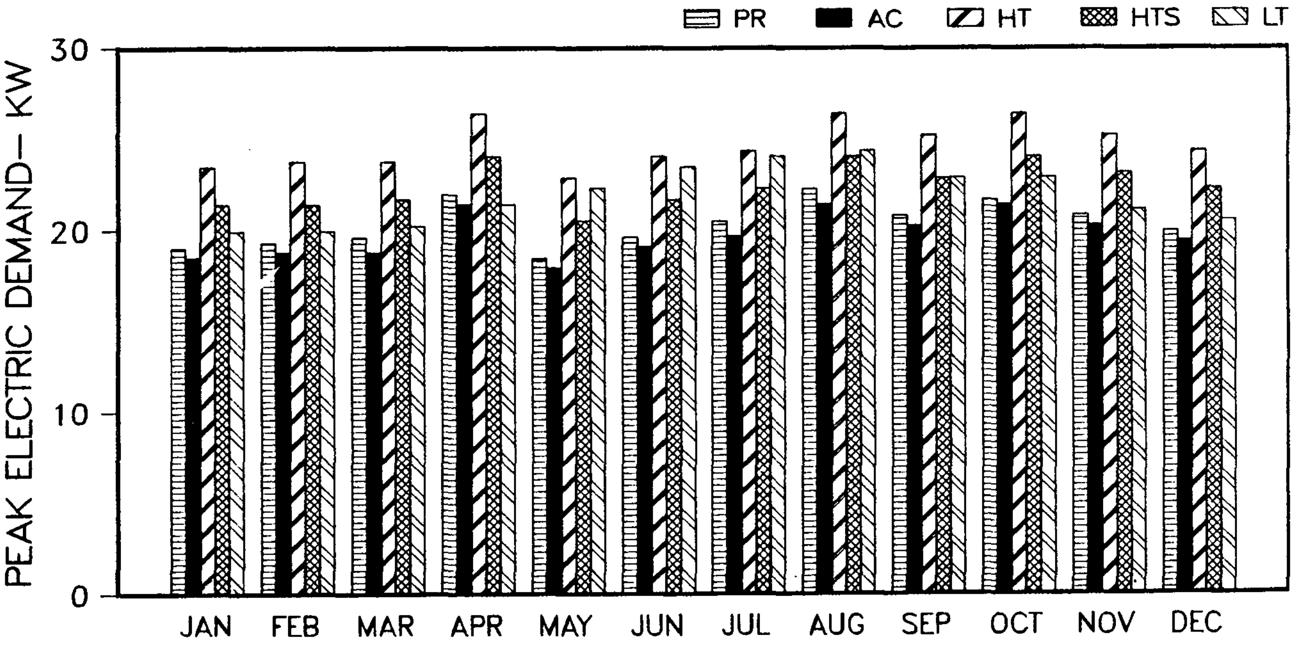

Fig. 4 Monthly peak electrical demand 6,000-ft^2 module, Lake Charles, Louisiana.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720