Daylighting with Integrated Envelope & Lighting Systems

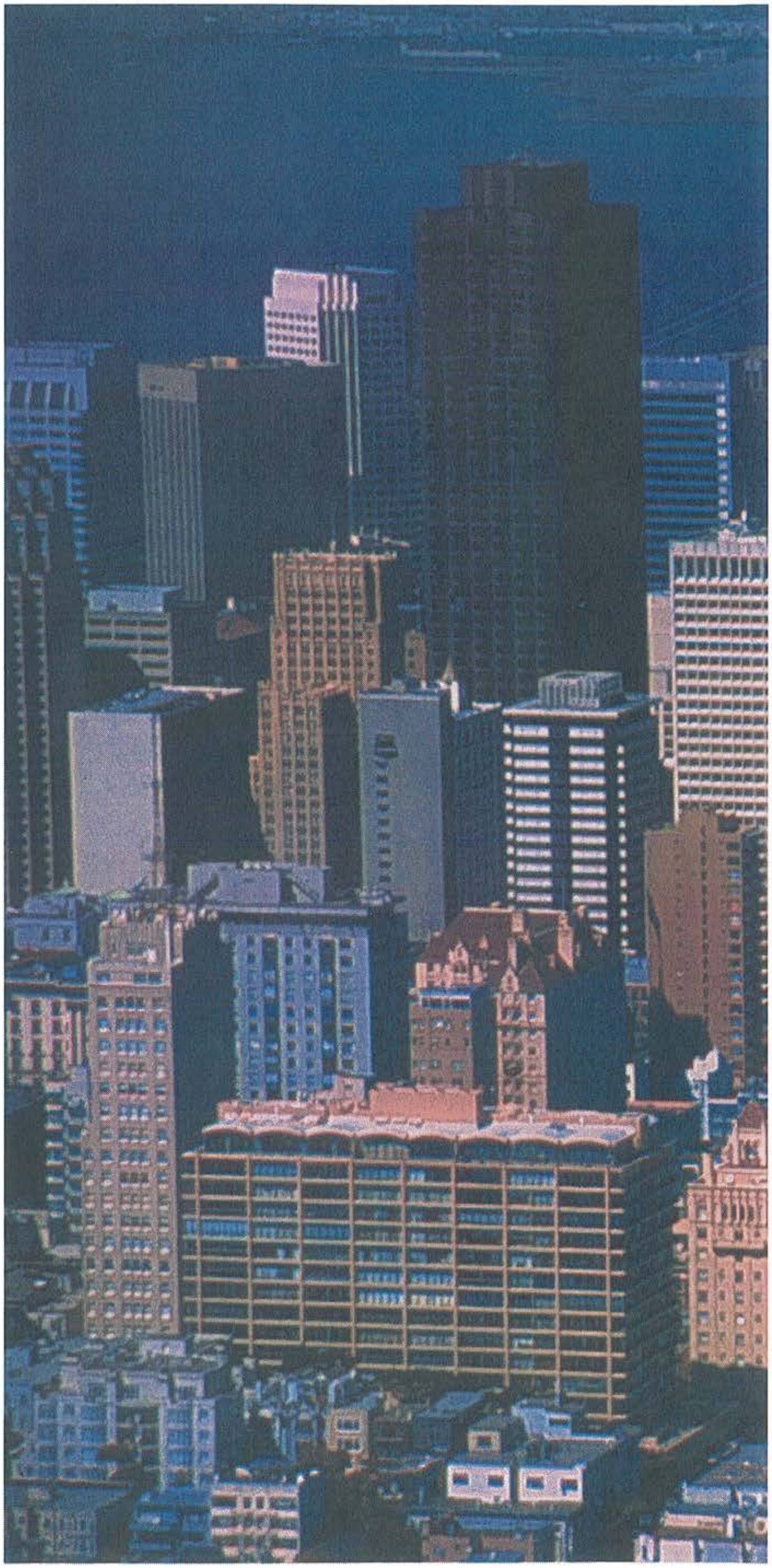
Architecture
The 1999 Awards for Architectural Research
Energy and Sustainable Design

December 1, 1998

Project Facts

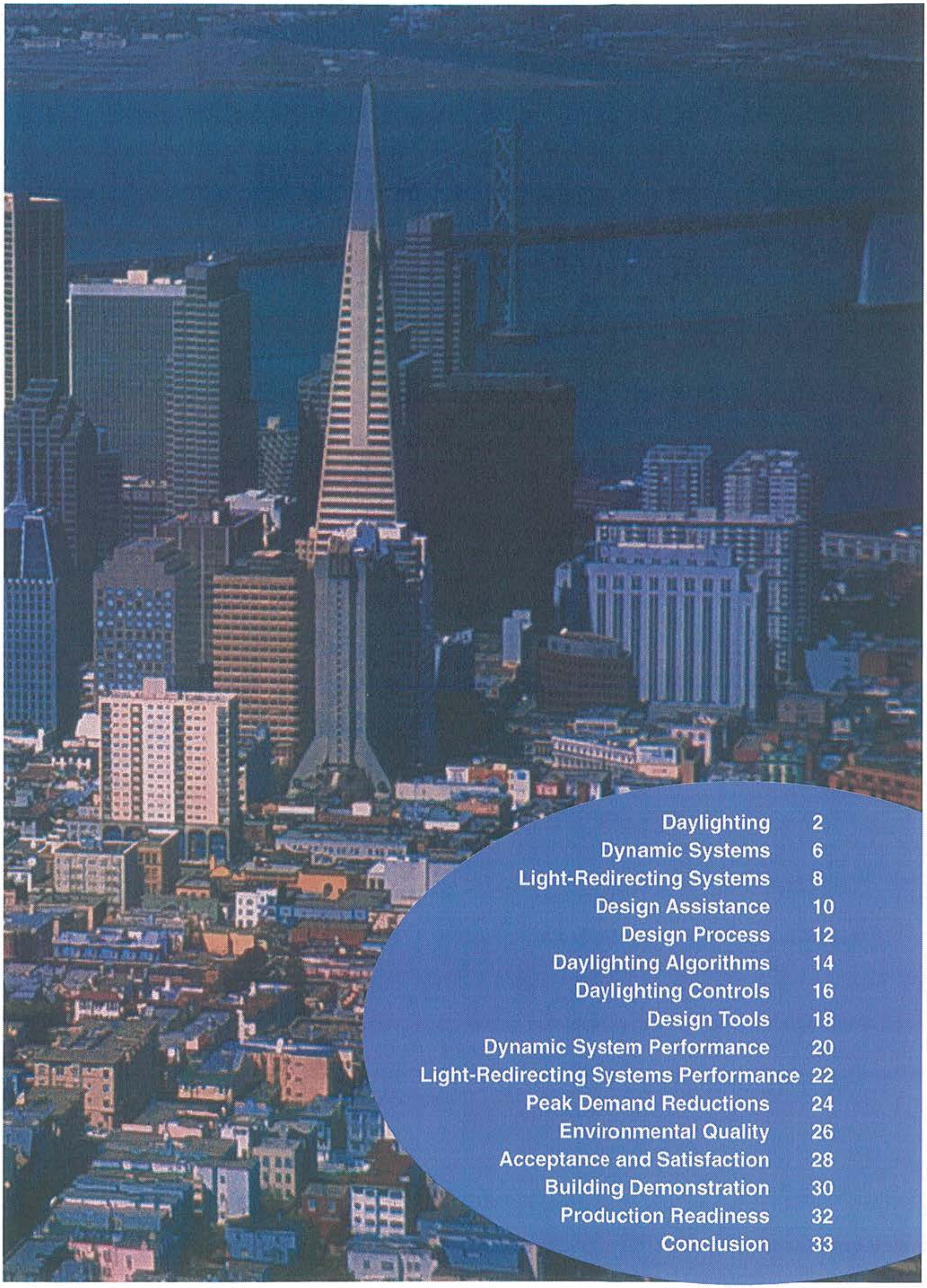
Daylighting systems in use world-wide rarely capture the energy-savings predicted by simulation tools and that we believe are achievable in real buildings. One of the primary reasons for this is that window and lighting systems are not designed and operated as an integrated system. Our efforts over the last five years have been targeted toward 1) development and testing of new technological solutions that involve a higher degree of systems integration than has been typical in the past, and 2) addressing current design and technological barriers that are often missed with component-oriented research. We summarize the results from this body of cross-disciplinary research and discuss its effects on the existing and future practice of daylighting in commercial buildings.

Project Title	Integrated Envelope and Lighting Systems
Research Category	Energy and Sustainable Design
Funding Source/ Client	California Institute for Energy Efficiency, Berkeley, California; U.S. Department of Energy, Pacific Gas and Electric, Southern California Edison, and the U.S. General Services Administration
Budget	$1.5 M
Start/ Finish Dates	1991-1997
Research Setting	Laboratory, Field Studies, Showcase Demonstrations
Form of Final Products	Reports, Design Guidelines, and Building Projects
Basis of Eligibility	Funded Research
Bibliographic References	See attached reference volume.



Electric lighting comprises 515,000,000 MWh or 20% of the nation's electricity consumption. Of this total, approximately 10-15% is used to light a building's perimeter zone where daylight is already present. For daytime-occupied commercial buildings, research projections show that total electricity and peak demand savings of 20-40% in lighting and its associated cooling energy can be achieved with the proper use of dimmable daylighting controls throughout the United States.

Even with the availability of more energy-efficient lamps, electronic ballasts, and alternative control systems, the potential for daylighting is substantial.



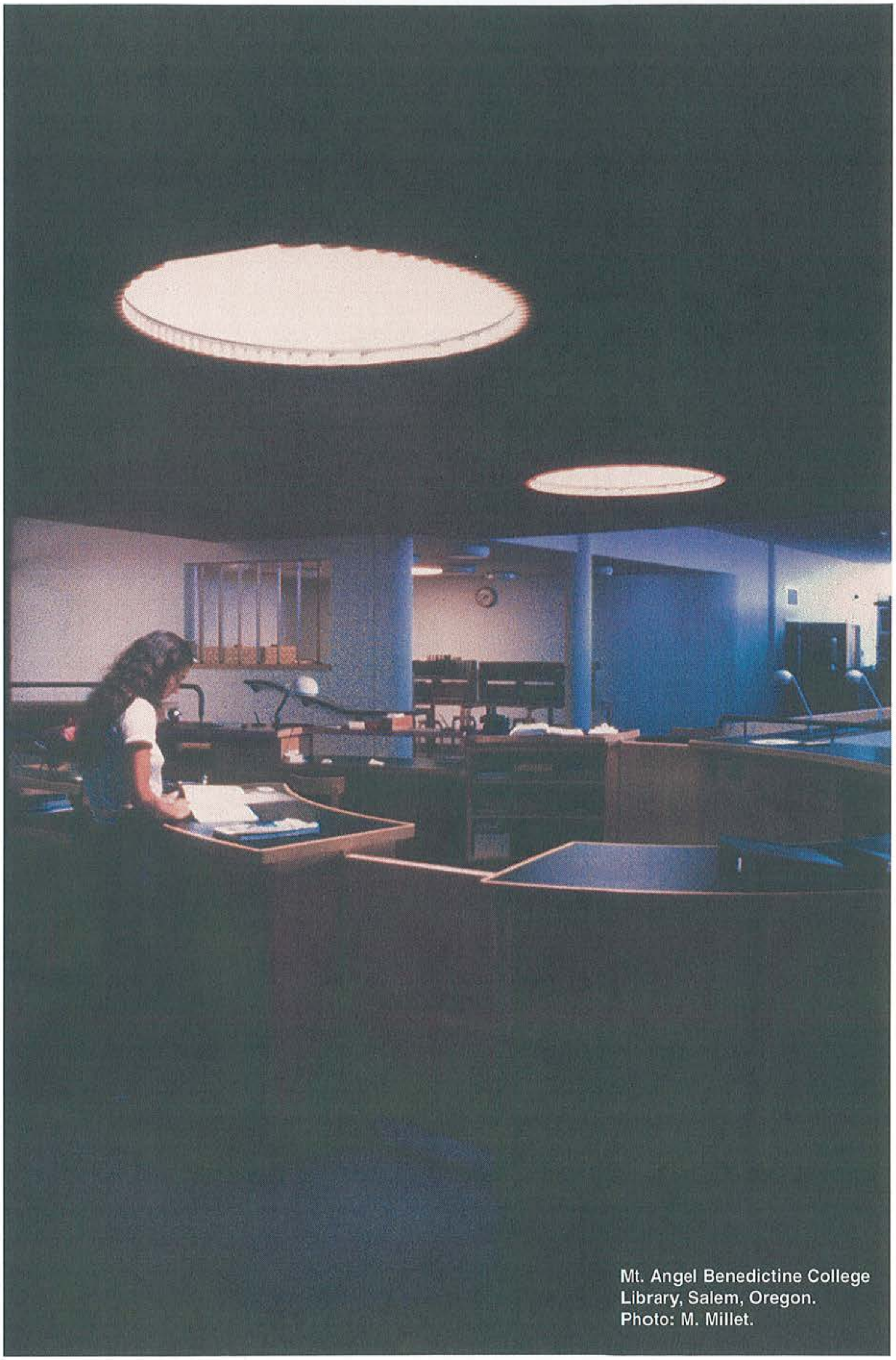
daylighting

In the realm of architecture, the artful use of "daylighting" requires imaginative and resourceful design capabilities, well demonstrated by Aalto, Kahn, and Le Corbusier.

Aalto, Kahn, and Le Corbusier

As an energy-efficiency strategy, daylighting plays a more utilitarian role by offsetting electric lighting with daylight.

Daylighting can be a sustainable and natural approach to energy efficiency and, when done well, can yield reliable and substantial reductions in both electricity consumption and peak demand throughout the perimeter zone of commercial buildings with the use of lighting controls and the careful specification of the window system. Economic benefits can be obtained such as reduced energy bills and lower capital or first costs due to reductions in space conditioning capacity. Other non-economic benefits can be attained such as greater occupant visual and thermal comfort (with possible productivity benefits), or greater design freedom to specify a larger window area.



Mt. Angel Benedictine College
Library, Salem, Oregon.
Photo: M. Millet.

the problem

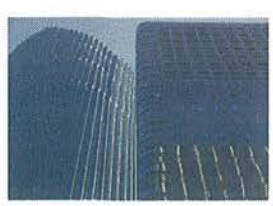
Despite the tremendous architectural interest and the large potential energy savings, the actual number of effectively daylit buildings that demonstrably save energy is very small. This is due to numerous design, implementation, and technological barriers:

1 A major barrier to the use of daylighting is technological. Daylighting is unique in that it requires designers to solve not only complex technical issues on a case-by-case basis, but also *qualitative* issues as well. There are a lack of good modular integrated building systems that perform well across energy-efficiency *and* qualitative criteria and can be easily used in most buildings. Concepts for innovative technologies need to be comprehensively tested to determine if they are truly viable and acceptable. Evaluation methods are not well established.

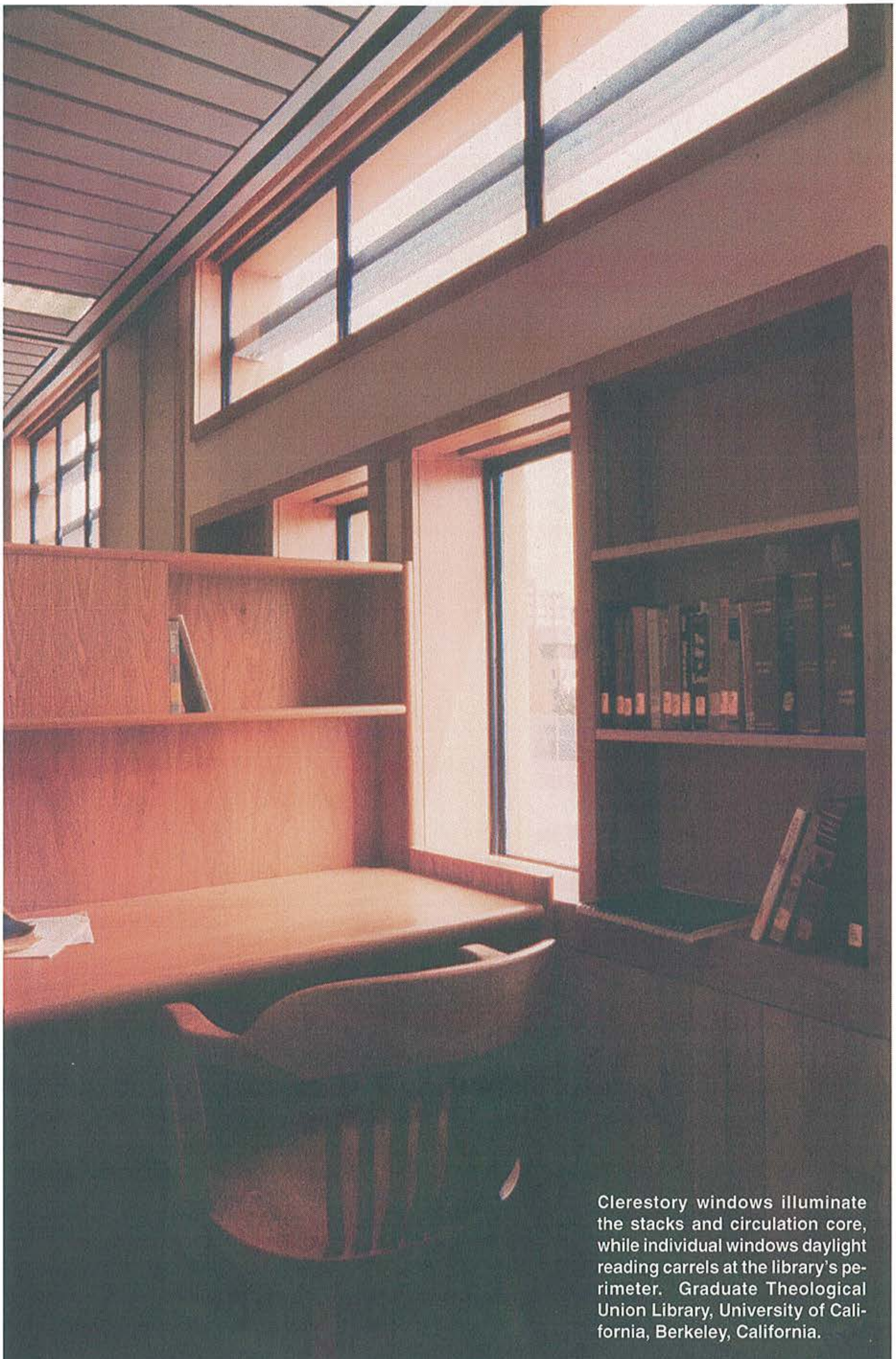
2 An integrated design *balances* the cooling load of the window against required daylight illuminance levels, thereby capturing both cooling and lighting energy savings without creating discomfort. A poor design imposes a substantial cooling load and creates glare. Achieving this balance requires careful and informed design and engineering.

3 Daylighting requires the participation and cooperation of multiple disciplines—architecture, lighting design, mechanical system design. Since the fenestration system is a predominant element that defines the exterior architectural "character" of a building, windows are often designed without considering the comfort of interior inhabitants. Energy-efficiency standards may encourage designers to substitute conventional components with new and better technologies, independent of whole building considerations. Even when the proper components are selected, poor design and commissioning practices often lead to unreliable performance and uncomfortable work environments.

view
connection to outdoors
ambiance
brightness
illumination
glare
light distribution
color rendition
privacy
direct sun
solar heat
conductive gains
fresh air
infiltration
egress
fire protection
security
facade character

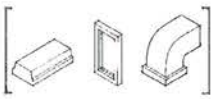


Design decisions for commercial building typically reflect bottom-line economics rather than environmental quality.

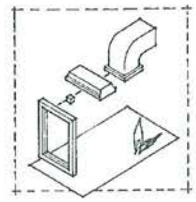


Clerestory windows illuminate the stacks and circulation core, while individual windows daylight reading carrels at the library's perimeter. Graduate Theological Union Library, University of California, Berkeley, California.

Integrated Envelope and Lighting Systems



Traditional approaches to creating energy-efficient buildings involve selecting from long lists of efficient components. By taking an integrated systems approach to combining disparate building envelope and lighting components, we can attain greater energy savings and improved occupant comfort compared to conventional energy-efficient design practice.



Windows +Lighting +Mechanical

This *integrated* systems approach was the basis for a multiyear project supported by the California Institute for Energy Efficiency with co-support from DOE, to develop and promote advanced building systems integrating high-performance envelope and lighting technologies. Since the illumination and cooling of commercial buildings accounts for the largest portion of electrical energy use and peak electrical demand, the promotion of such integrated systems can become a cost-effective, energy saving, demand-limiting option for both building owners and utilities. The research was structured to meet the following goals:

develop cost-effective, near-term technological solutions

target peak demand reductions of 15-40% in cooling-dominated climates

meet the full range of occupant requirements

promote an integrated whole-building approach (in lieu of a piecemeal approach) to daylighting design in commercial buildings

We addressed 1) *future* daylighting opportunities by developing reliable and high-performance integrated envelope/lighting prototypes that can be used in most commercial buildings, and 2) *current* daylighting opportunities by developing tools to promote integrated design and solve interdisciplinary technological problems that are often missed with typical component-oriented approaches.

Technological Solutions

Dynamic **envelope/lighting systems respond in real-time to temporal changes in sun and sky conditions in order to control daylight intensity and solar heat gains, and provide a more uniform, comfortable interior work environment.**

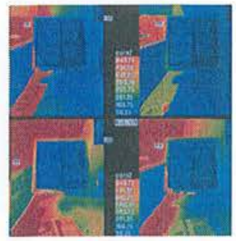
concept

sensors
hardware
software

performance evaluation

energy use
peak demand
control performance

environmental quality



acceptance &
satisfaction

implementation

production
readiness
industry input

Light-redirecting **envelope systems reflect daylight flux from the window or skylight aperture and distribute it more uniformly and at greater depths throughout the interior. Light-redirecting systems maximize the efficiency of daylight distribution so that solar heat gains are minimized for each element of electric light that is displaced.**

light shelves
light pipes
skylights

energy use
peak demand
illuminance
distribution

lighting quality
distribution
room luminance

full-scale
demonstration

Design Solutions

On-going provision of design assistance for numerous showcase building demonstrations provided a real-world basis for extended use of emerging technologies and the development of design tools. These improvements to the dysfunctional process for new and retrofit building design enable designers to take an integrated approach to daylighting design.

design assistance

showcase
demonstrations and
real-world buildings

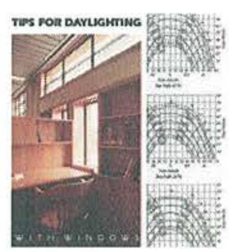
design process

new and retrofit
construction

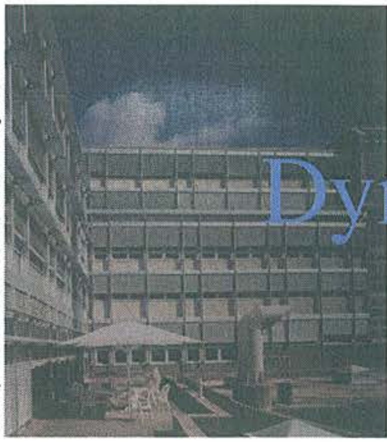
daylighting models

simulation tools;
daylighting control
commissioning tools

design tools

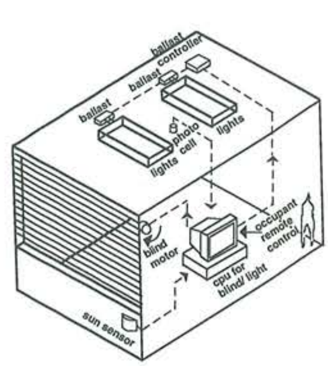


hands-on
"how-to" approach



European automated louver system

Dynamic Systems



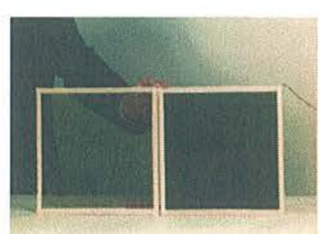
For commercial office buildings in moderate climates, choosing glazing materials to optimize energy use and electric demand may be viewed as a trade-off between lowering the solar heat gain coefficient to reduce cooling while maintaining the visual transmission of the glass to capture daylight savings. However, harnessing daylight in a building poses a significant technical challenge because of the great variability in daylight intensity. Achieving higher energy savings under these conditions requires looking beyond static systems to dynamic systems that respond to changing climatic or occupant conditions. By linking a dimmable electric lighting system with daylighting controls to a fenestration system that can automatically modify the transmission of daylight, we can get real-time control of the cooling and lighting energy balance while addressing glare and thermal comfort.

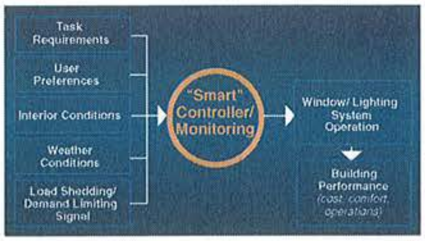
We investigated this dynamic systems concept using an automated blind system as a substitute for as yet unavailable electrochromic "switchable" glazings, working towards an occupant-responsive system that can be linked to the building HVAC system by a network of sensors and operated by intelligent energy management controls. The position of the blind system is coupled actively to variable external and internal conditions—the sun going behind a cloud or changing functional needs in a room, for example. The system accommodates occupant preferences for controlling view, glare, privacy, and task lighting levels when the space is occupied, and could switch to a minimum energy consumption mode whenever the occupant left the office.

Our performance evaluation can be found on page 20.

We developed new sensors and algorithms to implement integrated control cost-effectively.

"Smart" electrochromic glazings now under development offer the best long-term potential for dynamic control. The technology consists of a multilayered, thin-film device that changes from a clear to an increasingly dark, colored state when low-voltage current is applied. By employing electrochromic glazings in a curtain wall, we can dynamically alter daylight levels and visual privacy in the space and control thermal energy flows in the entire building envelope. Good progress is being made in R&D labs, but it will be several years before a specifiable product emerges from glass companies.

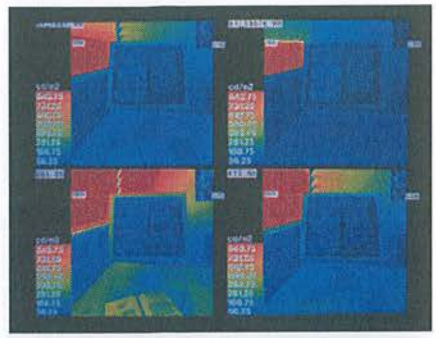




We used components that are available today, but we assembled, linked and operated them in an entirely new way. The resulting systems display a degree of flexibility that might best be called *adaptive* intelligence.

The control system is the hub about which this concept of adaptive intelligence revolves. There is an emerging effort to develop "intelligent" building systems to control start/stop times for optimal HVAC operation, monitor electrical and HVAC power consumption, and provide a diagnostic history of the zone interior environment. Little has been accomplished in developing control algorithms to optimize window and lighting operation in real-time with respect to energy and occupant comfort.

An optimum control system must be able to balance numerous energy and occupant parameters in real-time. Local task-based and room-based controls can be tied to whole building systems to facilitate powerful demand limiting capabilities in future buildings that use real-time pricing and distributed generation strategies.



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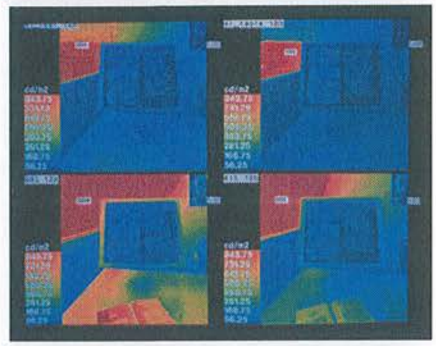

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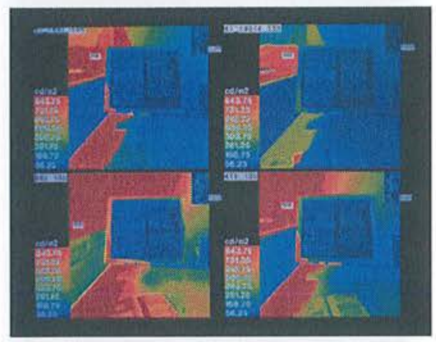

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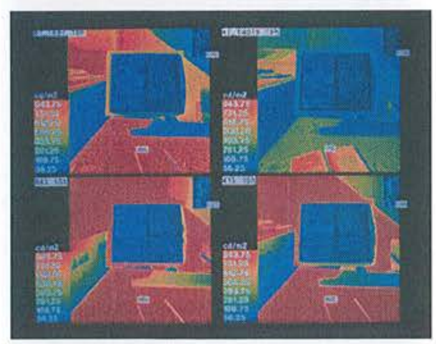

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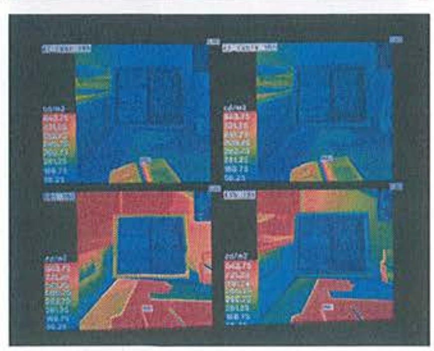
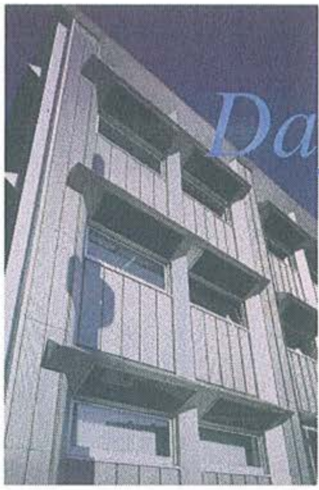


16:00

RADIANCE ray-tracing visualization software was used to model the lighting environment of a dynamic electrochromic glazing in a west-facing window. Falsecolor luminance maps show the magnitude of window glare and task-to-surround luminance levels of static and dynamic glazings.



Daylighting system on a European building

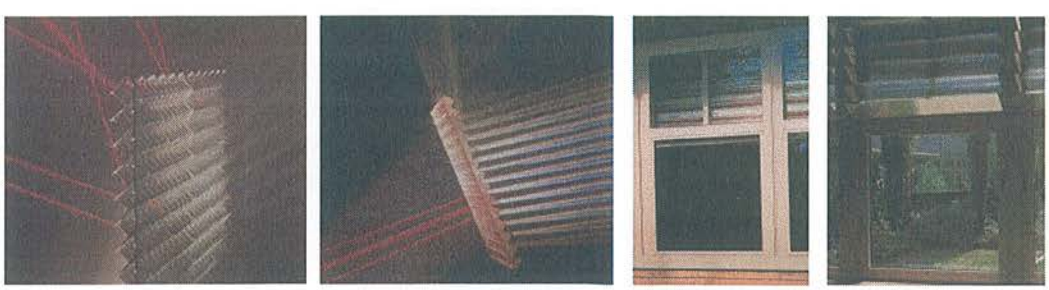
Daylight-redirecting systems

Conventional windows provide daylight in the outer 10 to 12 ft (3.0-3.7 m) of a perimeter space. New daylighting technologies can extend this daylit area by redirecting sunlight further from the glazing aperture, reducing electric lighting and cooling energy within a larger floor area. The challenge of successful daylighting design is to collect sunlight from a source that varies in both intensity and position and to distribute the luminous flux comfortably with minimal glare and thermal impacts.

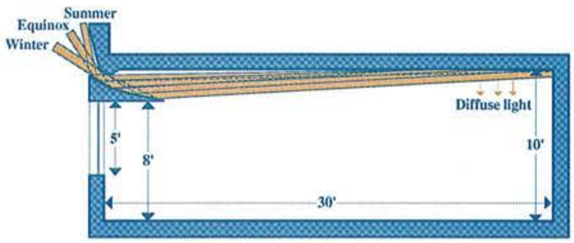
The basic light-redirecting systems we developed consists of a window wall divided into an upper daylighting and a lower view aperture. The lower view aperture incorporates spectrally selective glazing with a shading device to control glare, direct sun, heat gains, and view for those occupants adjacent to the window. The upper daylighting aperture incorporates a prototype light shelf or light pipe technology to redirect or transport direct sunlight to depths of 30 ft (9.1 m) from the window wall; supplemental daylight is contributed from the lower view window for the first 15 ft (4.6 m) from the window. We developed light shelves based on this window configuration, then light pipes and skylights based on variants of this configuration. All these daylighting technologies use a customized geometry developed from the solar path at a given latitude and unique reflective films to control the redirection and diffusion of the daylight.

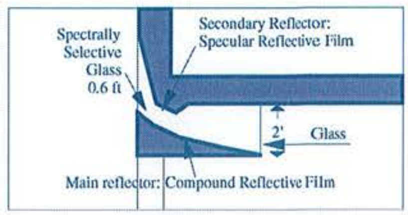
Our performance evaluation can be found on page 22.

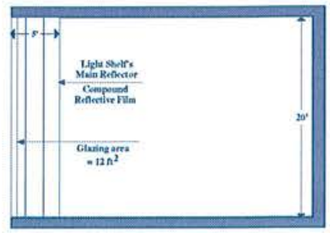
Commercially-available European prismatic and louver systems



cross section	detail of system	plan view (north →)

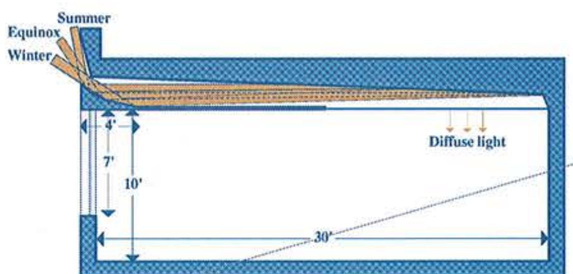


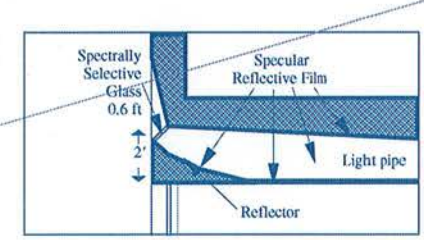


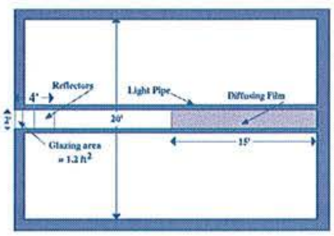


light shelves

Four light shelf designs were developed to fit within an articulated building facade. The reflector consists of segmented surfaces that, based on the window orientation and site latitude, redirects incoming sunlight to the ceiling plane deep within the space. The devices were designed to provide consistent illumination throughout the daily and seasonal range of solar position. Slimmer 1.5 ft (0.5 m) wide designs were created to minimize intrusion into the interior.

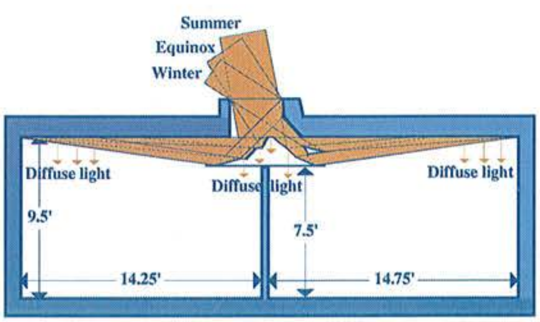


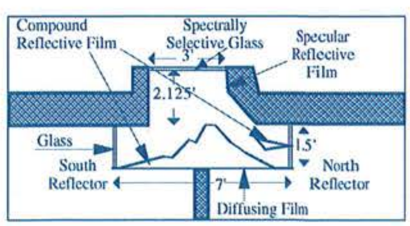


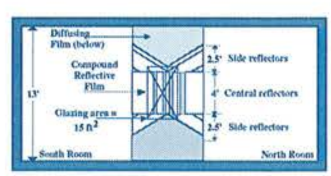


light pipes

Four light pipe designs were developed to fit within the plenum with its aperture set flush against the glazed spandrel of a flush or articulated facade. The light pipes were constrained to fit with other building subsystems within the ceiling plenum. Variants of the cross-section and reflector design improved illumination efficiency and distribution.







skylights

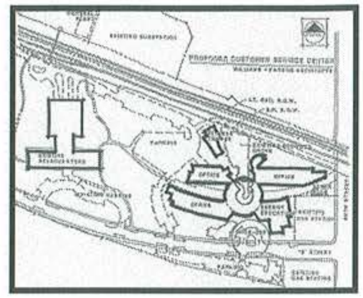
A skylight was designed to redirect sun to both the north and south sides of the skylight. A reflector array beneath a small skylight opening reflects diffuse light to the ceiling, as well as distributes diffuse light to the area directly below the reflector.

Design Assistance

This multi-year project provided a mechanism for investigating advanced daylighting technologies, strategies, commercial prototypes, and demonstrations in collaboration with designers, manufacturers, owners, and researchers.

Guidance was provided to industry to ensure that their market perspective was sufficiently broad—we found that many material or technology developers were solving problems from either a lighting or windows discipline and therefore had a limited approach. In general, we provided detailed analyses of product performance; e.g., holographic glazings, advanced skylights, angular-selective glazings, etc. In one case, we worked with a skylight manufacturer to develop and evaluate new skylighting systems, to be demonstrated in a new "green" department store. Our approach emphasized not only control of heat gains and light intensity but also improving the flux distribution for better visual quality. Retail sales were purported to be higher in the daylit area of the store. In another case, we advised developers of electrochromic windows to tune the material's solar-optical properties for visual comfort as well as energy-efficiency—a previously unexplored design criteria.

With designers, we dispensed quick assistance on demonstration projects (depending on their schedule) or conducted detailed analysis when we felt our involvement would advance the science and application of daylighting in the real-world. In most cases, we were able to influence the perspective of the developer or designer to encompass integration issues. For example, we contributed to the conceptual design of the Sacramento Municipal Utility District's New Customer Center, which was built using a broad array of daylighting strategies, including skylights, spectrally selective glazing, light shelves, exterior overhangs and fins for shading, atria, an "articulated" building form, integrated task and ambient lighting, and daylighting controls.



SMUD Customer Service Center

Palm Springs Chamber of Commerce

LADWP Canoga Park Service Center

Tahoe Forest Hospital

US Coast Guard, San Francisco

Wal-Mart, Kansas City, Kansas

Port Hueneme, California

New Tucson Courthouse

Sacramento Post Office

Oakland Federal Building

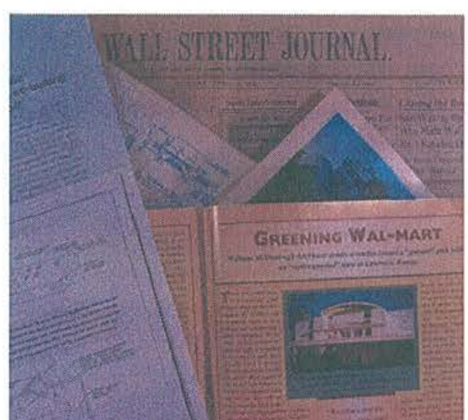
New Las Vegas Courthouse

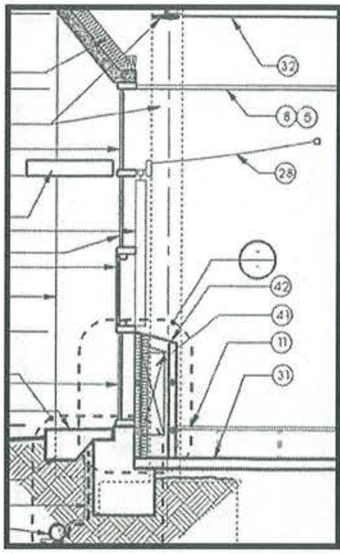
Carson City Courthouse

California Automobile Association, Antioch

California Museum of Science and Industry, USC

Jack Davis Building, Victoria, British Columbia





We contributed to the integrated daylighting design of the Sacramento Municipal Utility District's New Customer Center.

Design Process

While there were less tangible products resulting from the design assistance and demonstration activities of this research, we better understood the *process* of achieving integration in the real-world. We found today's process of designing the envelope *and* lighting system for most new and retrofit construction to be dysfunctional.

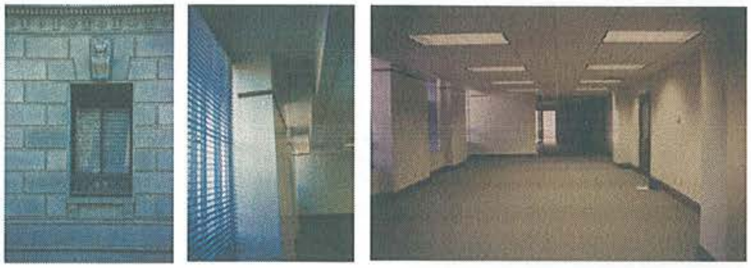
To achieve success in this work:

a) the concept of an integrated approach must be introduced at the start of new projects when design solutions such as building orientation, articulated floor plans, or exterior shading systems can still be considered. For retrofit projects, a proactive systems approach must be taken when upgrading building components for energy-efficiency in order to achieve cost-effective solutions that improve workplace comfort.

b) final design choices must incorporate value for human factors and amenity.

Design decisions based on bottom-line first cost may ultimately cost *more* because of the large cost of altering or modifying the building envelope once a foreseeable problem is identified after occupants move in. If not altered, occupants and building owners will have to contend with the design solution, since envelope systems last at least 15 to 20 years.

A 1.2 Mft^2 office building erected in Oakland in 1987 is a typical example. The design team considered advanced low-E glazing, but ultimately selected monolithic single-pane lightly-tinted glass, presumably on the basis of first cost. After occupancy, the facility manager has had to address the constant complaints of heat and glare from building occupants. Heat-absorbing window film would increase the thermal discomfort of those situated near the window, while reflective window film was unacceptable on the grounds of aesthetics. The added installed cost for the films of $3-5/$ft^2$-glass or $400K for the building could not be justified on the basis of energy-efficiency alone. Expensive window coverings ($2/$ft^2$-glass) have been purchased by individual tenants. No long-term solution has been reached.



An earlier retrofit of this Sacramento building resulted in a truncated window header, reduced daylighting, and a lighting circuit layout that will not accommodate the future use of daylighting controls. The building owners then tried to build a cost-effective, energy-efficiency case for replacing the single-pane clear glass windows.

typical retrofit construction

T12s replaced with
T8s & electronic ballasts
(3-5 year payback)

HVAC upgrades
CFC phase-out
(7-8 year payback)

occupancy lighting controls
incorrect circuit layout
for daylighting
(6-7 year payback)

window and exterior facade
upgrades
(weatherstripping and glass
replacement)
and daylighting controls
(10-20 year payback)

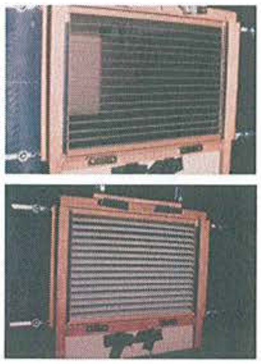
average design solution
continued discomfort and
poor lighting quality

With retrofit applications, the process is dysfunctional primarily because facility managers are not as well informed, having less resources than an A/E team. Economic and process barriers frustrated even the most well-intentioned facility manager. The *order* of retrofits is based on system breakdowns or approved alterations (lobby upgrades, energy-efficiency, etc.). Mechanical and lighting systems are usually replaced first, since they are not as long-lasting and energy-efficiency upgrades of such components (VFDs, T8 lamps) usually require less total capital and have a shorter payback than envelope systems. Often, advanced windows cannot be implemented as a retrofit because the energy-efficiency cost-benefits of recently upgraded lighting and mechanical systems (downsized capacity) cannot be folded in.

We encountered several such situations. In Sacramento, a previously naturally-ventilated 1932 office building was upgraded with a new mechanical system. The ceiling height was reduced by 3 ft (1 m) to accommodate new ventilation ducts, blocking daylight from the upper third of the window. The entire building was upgraded with new finishes (window shades, painting, etc.). New light fixtures were installed with multi-level switching. Two years after this complete renovation, the building managers turned to the upgrade of the exterior of the building, including replacement of the single-pane, clear glass windows but found their cost-effective energy-efficiency options limited.

If an integrated perspective had been taken initially, the facility manager may have been able to a) reduce the capacity of the chiller and possibly the depth of the air distribution ducts, b) design the layout of the lighting zones to accommodate future installation of daylighting controls (parallel to the window wall, not perpendicular!), and c) design the window-to-ceiling detail to admit more daylight and reduce the visual contrast in brightness between the interior and window. Retrofits must not be conducted piecemeal as events come about, rather with a proactive perspective of what is to come. We conveyed this approach in a document on spectrally-selective glazings to federal energy managers. Institutional changes in policy or design approach could also affect the way retrofits are conducted in businesses that manage a large number of facilities.

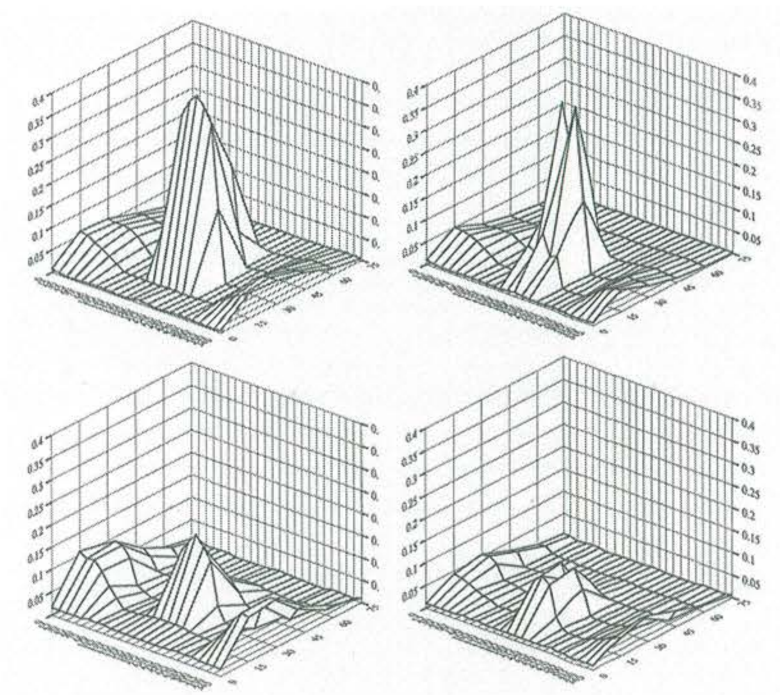
Daylighting algorithms



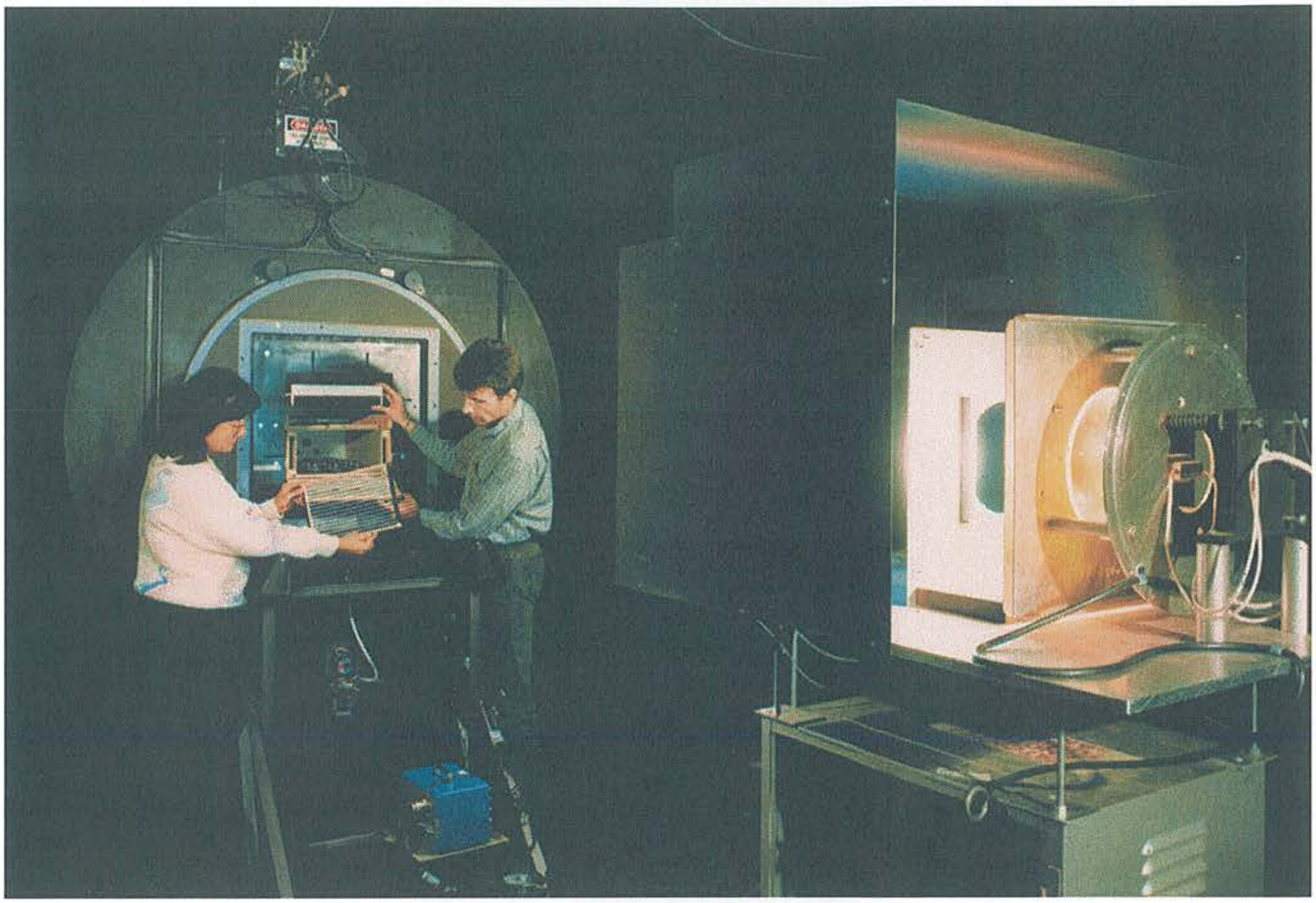
Venetian blinds scatter daylight in a complex, unpredictable manner.

The tools for describing the performance of daylighting systems are limited, in part because there is currently little research activity within industry and the business community to advance the science of daylighting with "advanced" window systems, such as automated blinds or holographic glazings.

A new approach was devised that combined experimental measurements with simulation tools to produce an accurate characterization of interior illuminance levels. This method is combined with an energy simulation engine such as DOE-2 to produce estimates of annual energy usage. The work provided a basis for more flexible daylight modeling tools that can ultimately be used by conventional engineering consultants.



Bi-directional daylight coefficients are used to characterize complex window systems.



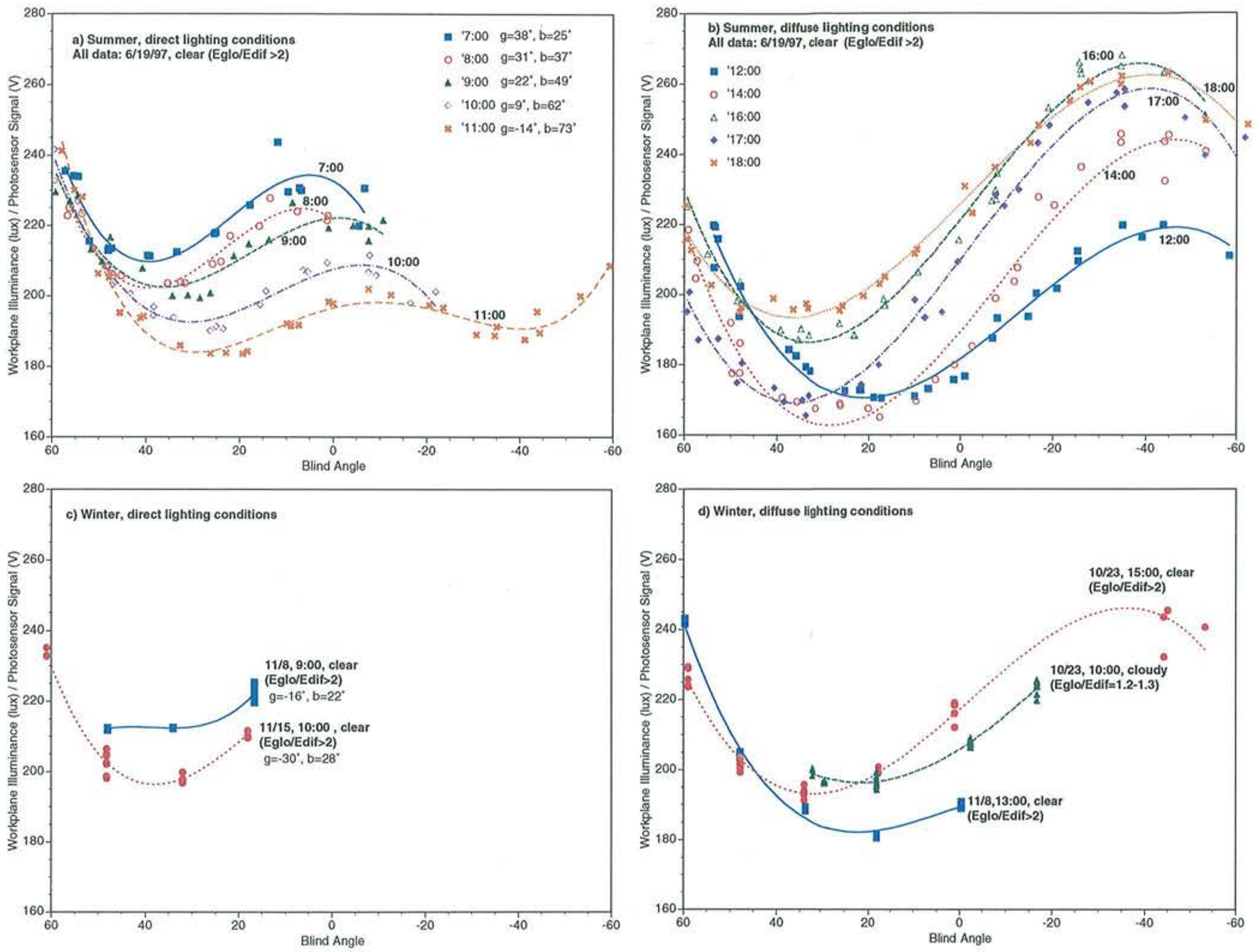
A physical model of an office space with a venetian blind (left) is rotated relative to a fixed sun source (right). The resultant daylight coefficients can be used to predict interior illuminance levels for any sun and sky condition.

Daylighting Controls

Daylighting controls in the U.S. have fundamental design flaws that simplify installation and reduce cost but decrease reliability. This unreliable performance is a significant barrier to its widespread and satisfactory use in buildings. Daylight from sidelight windows produces an illuminance pattern that changes with time of day and season, while fluorescent top lighting produces a predictable pattern. The simple control system is unable to adjust for these differences in lighting patterns so interior illuminance levels are often too low. To avoid occupant complaints, facility managers will decrease the sensitivity of photoelectric sensors so that the electric lighting is dimmed very conservatively, but this adjustment can severely undermine the energy-efficiency of the system.

Technological solution: The performance of closed-loop proportional control systems can be improved substantially at no added cost by using existing information from the control system to separate the electric lighting illumination contribution from the daylight contribution. This solution was tested at full-scale for over a year and was found to perform very well. Monitored workplane illuminance levels did not fall below 90% of the design level for 90% of the year, and when it did, the discrepancy occurred only an average of 13 minutes per day within a 12-hour day. Market adoption of our refinements will need a solid commitment from U.S. manufacturers to redesign their systems.

Commissioning solution: Past daylighting controls research has been devoted to control improvements such as photosensor design and placement to reduce the occurrence of insufficient illuminance. Taken from a cross-disciplinary approach, we have characterized how *windows* affect the performance of the daylighting control system. This work enabled us to add to the fairly sparse guidelines given to installers on how and when to commission daylighting control systems. Guidelines were developed on how to position the venetian blinds, whether to commission with or without direct sun, and whether to commission with the sun in or out of the plane of the window. Further research is required to determine whether the characterization is truly generalizable to other daylighting control systems and interior spaces, since this work builds on case-specific monitored data taken in a full-scale testbed facility.

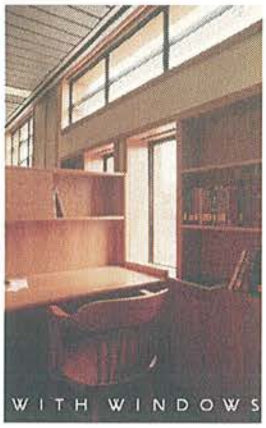


Variation in daylight correlation coefficient as blind angle is varied for a) summer direct lighting conditions, b) summer diffuse lighting conditions, c) winter direct lighting conditions, d) winter diffuse lighting conditions

The "gain" of a typical closed-loop proportional system varies with the spatial distribution of daylight in a space. This critical parameter is set *once* upon the daylighting control system's installation then left to control the lighting for all electric and daylighting conditions within the space over the entire year. Occupants will complain and even sabotage the system if the lights are too dim—a result of improper commissioning. We show above how this gain parameter varies with venetian blind angle and solar condition.

Design tools

TIPS FOR DAYLIGHTING



A concise "how-to" document was produced to enable designers to implement key window and lighting integration design concepts. The eleven-section document was designed with rules-of-thumb and short calculations to quickly determine if daylighting is a viable strategy, with additional pointers to more detailed tools and resources.

The tool targets the work style of the majority of architects who conduct business within the context of tight fees, insufficient resources, and multiple design considerations. More importantly, it reminds designers of the far-reaching effects of merely specifying the style of a window—from the capacity of the mechanical system and comfort of the occupants to its impact on the environment. Since the design of windows with daylight involves knowing how to balance solar heat gains against the admission of useful light, this tool informs designers of this complex balance point and enables them to assess design trade-offs sensibly within these energy-efficiency boundaries (e.g., larger glazing area with acceptable comfort is possible with spectrally selective glass). The document can be read or downloaded from the World Wide Web and has also been distributed to participating utilities, universities, and international research institutions.

TOOLS & RESOURCES

- **Manufacturer Technical Literature and Product Representatives** are free sources of information and assistance. Begin with section 08810 in Sweets Catalog to identify product choices and suppliers. Many of the brochures in this section contain useful general information on glazing in addition to product-specific data. Most manufacturers will readily supply samples (typically 12" by 12" or smaller) and copies of their Sweets brochures. Some manufacturers will also perform energy calculations for you.
- **National Fenestration Rating Council** compiles a directory of window products with associated thermal, solar, and optical properties. While the emphasis is on residential applications, much of the information is useful for commercial buildings. NFRC data and window labels provide a consistent and accurate way to compare product properties (similar to refriger
- **Scale Model.** A model studied outdoors can be a and evaluate daylight levels and direct sun control. for information on measuring daylight in a model, equipment (light meters). If light levels are not sa different visible transmittance or adjust window s model-building instructions given in ENVELOPE actual glazing material (get a sample from the ma color and transmittance of the glazing. Take the r

Daylight Feasibility

SECTION 2 Tips for Daylighting with Windows

OBJECTIVE

Determine how much day ... you can use in various areas of your building.

- Because daylight is not used simp connection, ventilation, egress), one can capitalize on it to incre
- Determine how much daylight

KEY IDEAS

- **Windows must see the light of** windows will not see much sky.
- **Glazing must transmit light.** A daylight in all but very sunny c
- **Install daylight-activated co** Automated lighting controls i scheduling, etc.) and benefi
- **Design daylight for the task** lighting environment, tailo
- **Assess daylight feasibility** views, ground reflectanc and cost-effectiveness o

PROVISC

- A low-rise building addressed in these g

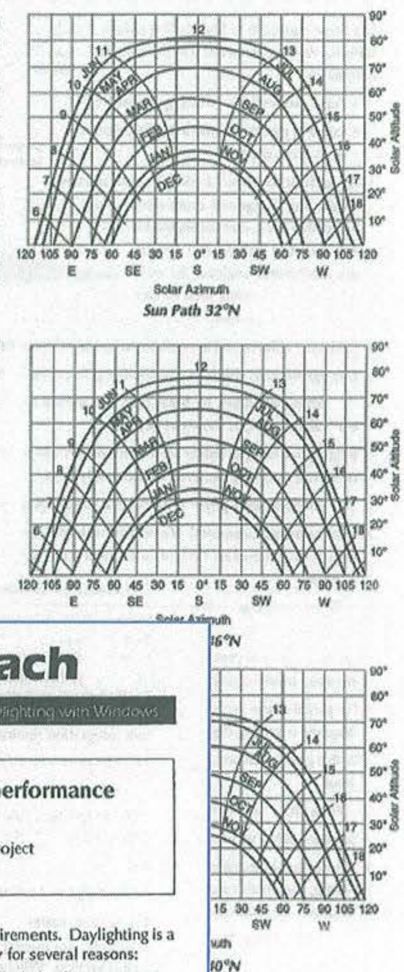
h Diagrams

find solar altitude time, to help in

m with latitude for Southern 140° for North-

curves corre- r of interest. titude from muth from tion at that

esign and



The Integrated Approach

SECTION 1 Tips for Daylighting with Windows

OBJECTIVE

Work as a team towards the shared goal of a high-performance daylighted building.

- Share decisions and information across the entire design team from project conception through occupancy.

What is the Integrated Approach?

These Guidelines provide a concise reference for a design approach that emphasizes teamwork. A high performance, cost-effective, comfortably daylighted building requires the design team to practice integration:

- Adopt a holistic design approach, where the building is viewed as a whole and not just a collection of parts. Common practice often fails to address the critical interactions between the building facade (which admits heat and light) and the electric lighting system, resulting in an uncomfortable and inefficient building that is expensive and difficult to retrofit.
- Share appropriate decisions across disciplines.
- Regularly evaluate decisions for any building-wide ramifications.

What is a high-performance building?

One that

- Meets design objectives.
- Maximizes occupant comfort and productivity.
- Minimizes occupant complaints and tenant turnover.
- Maximizes building value to the owner.
- Yields a lifetime of energy efficiency and lower operating costs.

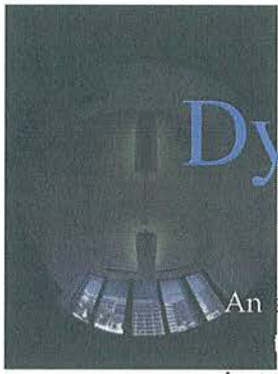
Why pursue daylighting?

Daylighting is the use of light from the sun and sky to complement or replace electric light. Appropriate fenestration and lighting controls are used to modulate daylight admittance and to reduce electric lighting, while meeting the occupants' lighting quality and quantity requirements. Daylighting is a beneficial design strategy for several reasons:

- Pleasant, comfortable daylighted spaces may increase occupant and owner satisfaction and may decrease absenteeism. Productive workers are a valuable business asset.
- Comfortable, pleasant, daylighted spaces may lease at better-than-average rates.
- Comfortable, pleasant spaces typically have lower tenant turnover rates.
- Lighting and its associated cooling energy use constitute 30 to 40% of a commercial building's total energy use. Daylighting is the most cost-effective strategy for targeting these uses. Both annual operating and mechanical system first costs can be substantially reduced.
- The Uniform Building Code, BOCA, and State Energy Codes regulate the "proper" use of windows in buildings.
- Energy-efficient buildings generally provide higher returns on developer investment and yield higher cash flows.
- Smart decisions up front save retrofit dollars later.
- Energy-efficient, daylighted buildings reduce adverse environmental impacts by reducing the use and need for power generating plants and their polluting by-products.
- Daylight contributes to a more sustainable design approach.

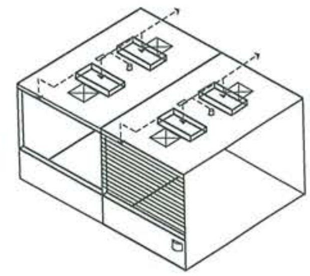
How do these guidelines work?

Quick tips, tools, and procedures are supplied here to point designers toward appropriate decisions and to help the design team stay focused on integration. Information is restricted to daylighting issues; broader building concerns are left to the designers.



Dynamic system performance

An automated venetian blind system coupled to a dimming lighting system was designed, built and tested for use in typical office spaces. Venetian blinds, widely used in U.S. commercial buildings, can control thermal loads and daylighting intensity by varying slat angle. The system was designed to balance cooling loads and daylight admission in real-time by preventing direct sun penetration, actively managing daylight and electric light to provide 50 fc (500 lux) on the workplane, and permitting view whenever possible.

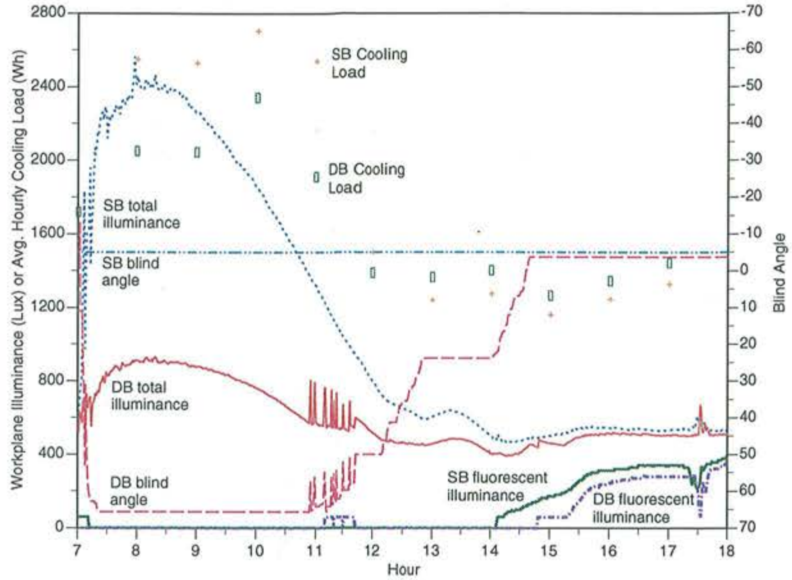


Side-by-side tests were conducted in full-scale under real sun and sky conditions for a 14-month period.

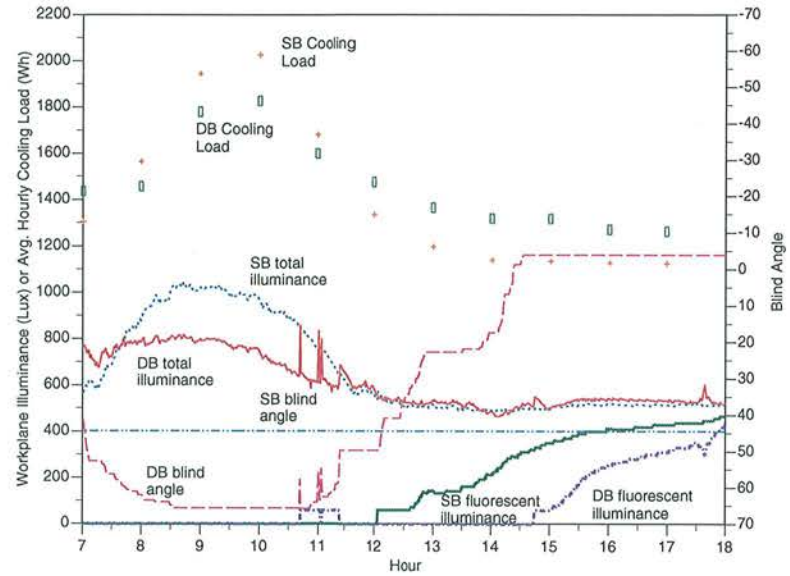
The system was built from readily-available components, which might be interchanged later with more advanced technologies. The work permitted testing of basic research premises at full-scale, enabling us to examine the validity of advanced material concepts (such as those for electrochromic glazings) that cannot be tested until large prototypes can be built.

Energy, control status, and illuminance data were collected for over a year in both reduced-scale and full-scale field test facilities. Occupant response studies were also conducted. Hourly DOE-2 building energy simulations predicted that 16-26% annual energy savings and peak demand reductions could be obtained with the automated venetian blind I lighting system compared to an advanced spectrally-selective window system in Los Angeles for all window exposures except north. Monitored daily lighting energy savings averaged 35% in winter and ranged from 40-75% in summer, when compared to a similar static partly closed blind system with the same daylighting control system. If compared to a non-daylighted space, daily lighting energy savings ranged from 22-86%. Summer daily cooling load reductions were measured to be 5-25%, while peak cooling load reductions were even larger. The control system met all design objectives over widely varying conditions to within 10% for 90% of the 14-month monitoring period in full-scale.

Performance of the dynamic blind system (DB) compared to a static horizontal blind (SB) system. Note the uncontrolled daylight levels of the horizontal blind of 2400 lux, which results in higher daily cooling of 21% and peak cooling loads of 13%. Daily lighting energy reductions were 21%. These data are for a southeast-facing window in Oakland on a clear day in August. Both rooms have the same daylighting control system.



Performance of the dynamic blind system compared to a static 45° blind system. Here, the daily cooling load and peak cooling load reductions were more modest, 4% and 8%, respectively, compared to this partly-closed blind; but daily lighting energy savings were 46%. These two examples show that irrespective of whether the static blind is horizontal or partly closed, the dynamic system wins in the reduction of total energy and peak demand.



Monitored Daily Lighting Electricity, Cooling Load, and Peak Cooling Load Reductions

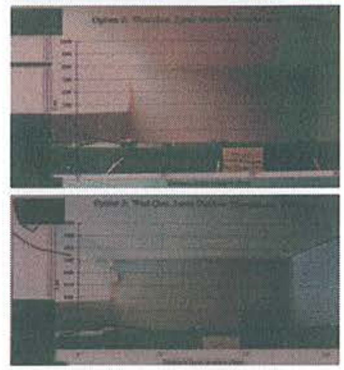
Static Blind Angle	Season	No. of Days	Lighting Electricity	No. of Days	Cooling Load	No. of Days	Peak Cooling Load
45°	Spring	9	27 ± 5%	4	15 ± 7%	8	11 ± 6%
	Summer	8	52 ± 9%	8	6 ± 6%	8	6 ± 8%
	Autumn	18	37 ± 12%	13	7 ± 3%	16	8 ± 5%
	Winter	4	19 ± 4%	0	—	4	15 ± 11%
15°	Spring	12	14 ± 8%	7	28 ± 16%	11	22 ± 6%
	Summer	14	22 ± 17%	12	13 ± 5%	13	13 ± 10%
	Autumn	3	7 ± 2%	3	22 ± 11%	3	21 ± 6%
	Winter	4	1 ± 1%	0	—	1	28 ± 0%
0°	Spring	13	-1 ± 4%	10	32 ± 16%	11	25 ± 8%
	Summer	11	-14 ± 19%	11	17 ± 6%	11	24 ± 7%
	Autumn	6	11 ± 10%	5	17 ± 10%	6	18 ± 11%
	Winter	5	-1 ± 3%	0	—	3	32 ± 3%

Base case static blind angle defined as downward angle from horizontal, occupant view of ground. Static settings (0° and 15°) may allow direct sunlight to penetrate the room.

Daylighting system performance

Distributing admitted daylight flux poses a critical technical problem. Spreading daylight evenly to attain a functional and comfortable lighting environment for a wide range of sun positions and sky types requires ingenuity.

We designed prototype lightshelves, lightpipes, and skylights to 1) extend the daylighted area of the perimeter zone of buildings from approximately 15 ft to 30 ft (5 to 10 m), and 2) to provide more brightness in the back of typical spaces without the associated high light levels near the windows. While the research was devoted to solving the optics problem of redirection with a variable sun source without introducing direct sun or creating glare, we also restricted the window aperture size to minimize solar heat gains. Prototypes were developed, simulated and tested in scale-model rooms, both outdoors and within indoor simulators. Both light-redirecting systems were designed without moving parts to reduce costs and maintenance. A full-scale demonstration of the skylight design at the Palm Springs Chamber of Commerce (discussed later) enabled us to solve critical fabrication issues and to evaluate the final daylit environment.

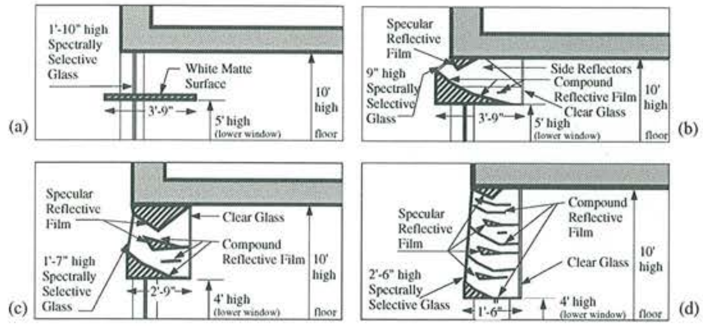


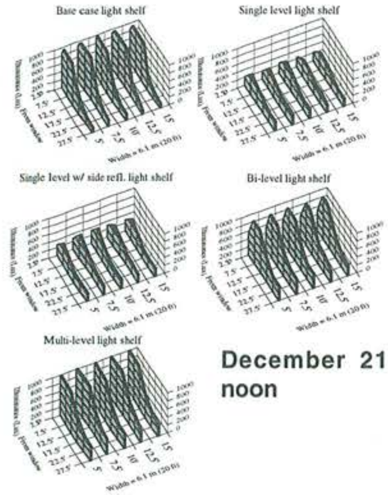
A

B

The light-redirectinglight shelf (B) illuminates ceiling and upper wall surfaces, creating a brighter quality space for the same workplane illuminance level.

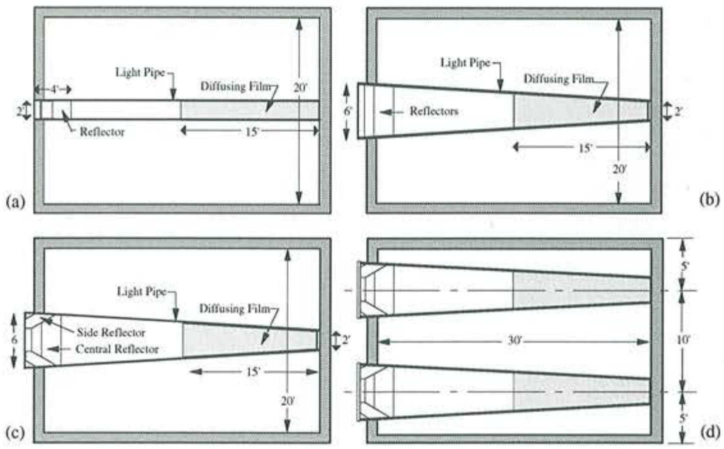
Our reduced-scale testing revealed the potential for substantial energy savings with improved lighting quality. Hourly DOE-2 simulations predicted annual energy savings of 10-20% with improved lighting quality compared to a clear glazed window (no interior shades) with daylighting controls. Performance was best for sun azimuth angles that were within ±45° of the window's outward surface normal, but a side reflector geometry improved performance for more obtuse surface solar azimuth angles. Although their benefit is greatest in sunny climates, we believe these systems show enough promise to pursue further development and testing activities.

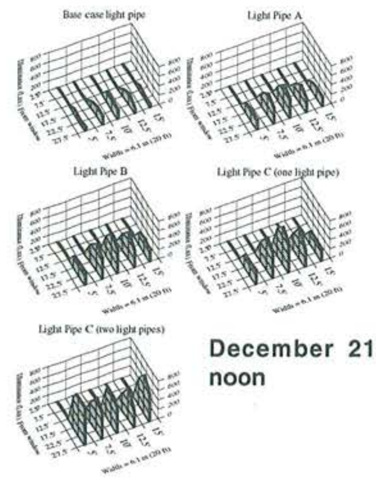




December 21 noon

2





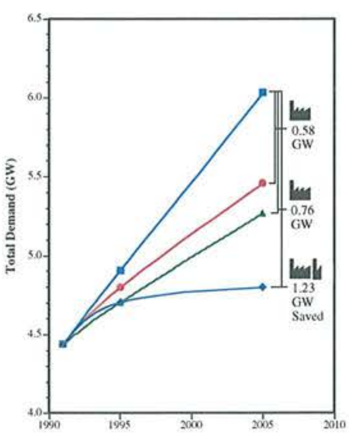
December 21 noon

Annual Lighting and Total Electricity Use (kWh/ft^2·floor·yr) with lower window

South Los Angeles	Dayltg Zones	Total Elec. (kWh/ ft^2·yr)	Lighting Elec. (kWh/ ft^2·yr)	%Δ Total Elec. Clear Glass, 0-15' Dayltg Zone	%Δ Ltg. Elec. Clear Glass, 0-15' Dayltg Zone
Base Case					
Clear Glass, 7' h	None	16.47	4.21		
Clear Glass, 7' h	0-15'	14.47	2.68	0%	0%
Clear Glass, 7' h	0-30'	12.72	1.36	12%	49%
Light Shelves					
Base case	0-30'	13.09	1.79	10%	33%
Single level	0-30'	11.88	1.89	18%	29%
Single level, side refl.	0-30'	11.92	1.92	18%	28%
Bi-level	0-30'	11.72	1.91	19%	29%
Multi-level	0-30'	13.03	2.06	10%	23%
Light Pipes					
Base case	0-30'	13.22	1.70	9%	36%
Light Pipe A	0-30'	13.20	1.53	9%	43%
Light Pipe B	0-30'	13.80	1.50	5%	44%
1-Light Pipe C	0-30'	13.80	1.50	5%	44%
2-Light Pipes C	0-30'	14.66	1.50	-1%	44%

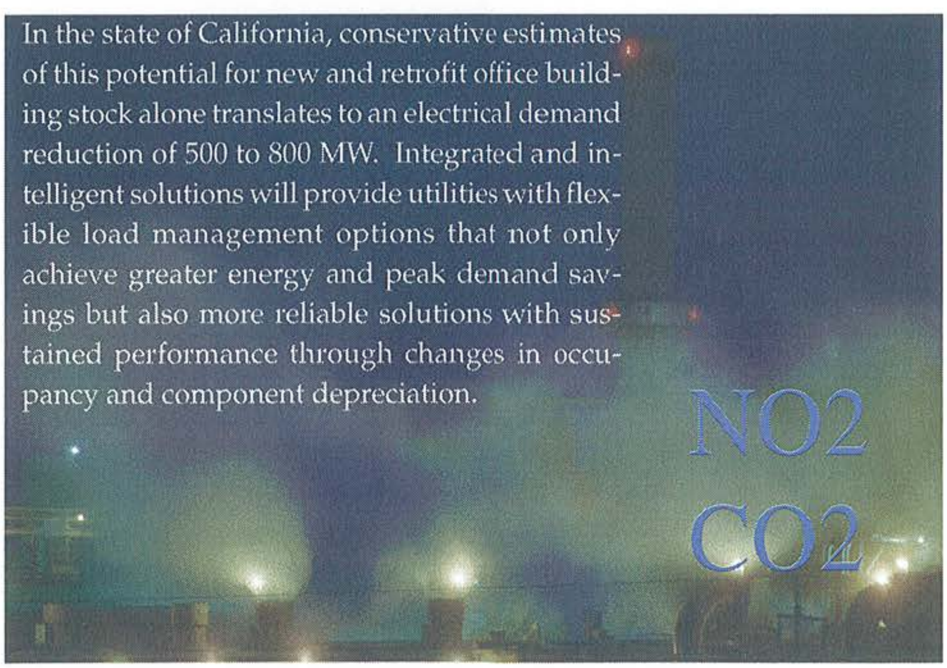
Peak Demand Reductions

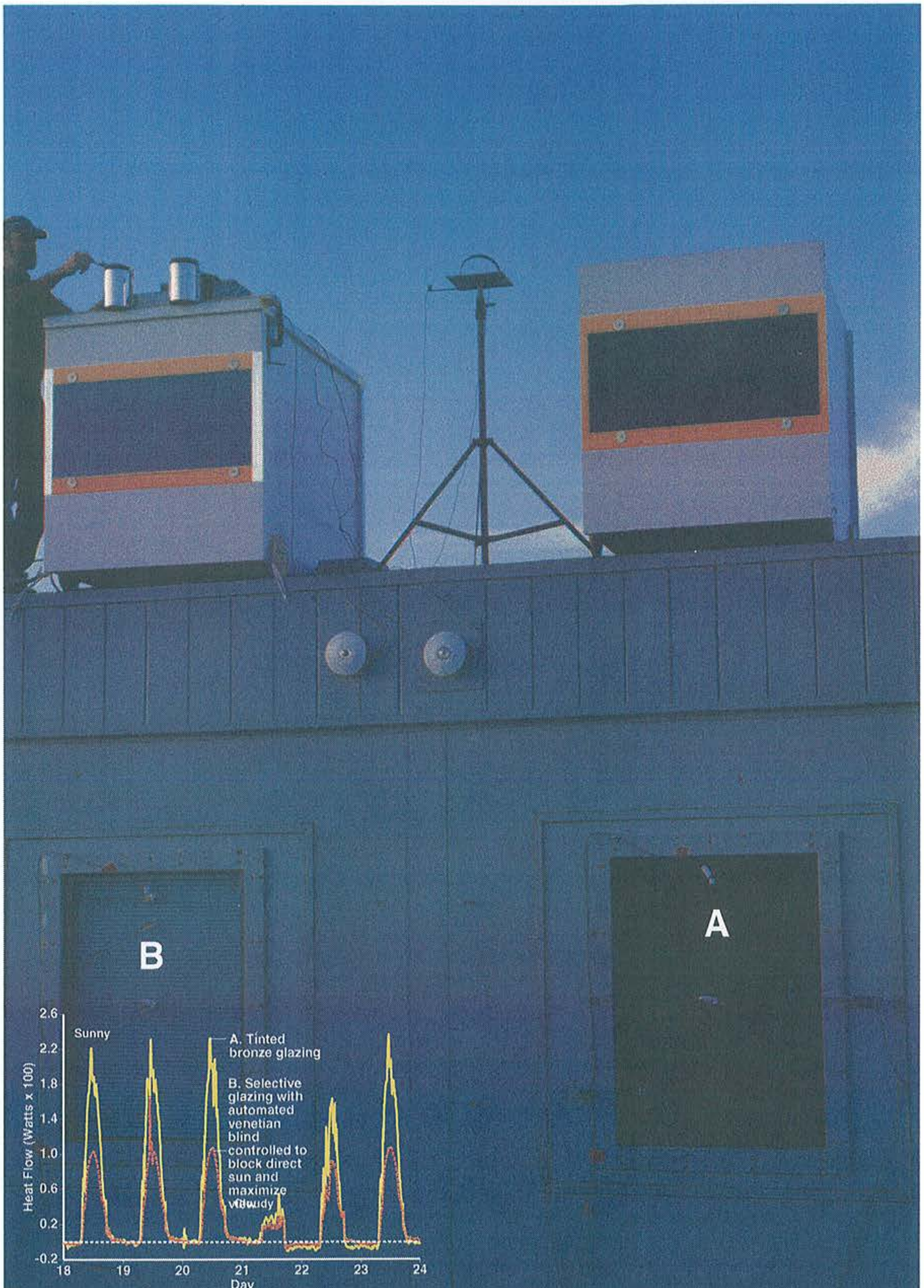
When daylight availability and summer outdoor temperatures are high, daylighting can substantially reduce peak electric loads due to cooling and lighting. This will result in monthly savings in demand charges, but it also reduces pressure on the utility to add new generating capacity (e.g. hydroelectric, nuclear, etc.). In the case of a retrofit of an existing building, it provides new available capacity for other needs. Some utilities are still willing to "purchase" these "negawatts" with upfront rebates that help offset the building owner's first cost. Conceptually, the glazing system becomes an energy source (relative to a conventional alternative) and the utility makes an investment in this "energy system" as if it were a new power plant. These payments can range from $0.50 to $5.00 per square foot of glazing. As the electric utility industry is restructured state by state, distributed generation options and real time pricing will provide additional incentives to manage electric demand carefully.



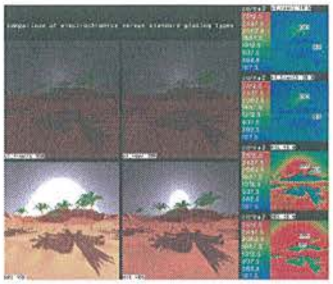
Projected demand reductions with integrated envelope and lighting systems adopted for all new construction and partial retrofit construction compared to business-as-usual practice.

In the state of California, conservative estimates of this potential for new and retrofit office building stock alone translates to an electrical demand reduction of 500 to 800 MW. Integrated and intelligent solutions will provide utilities with flexible load management options that not only achieve greater energy and peak demand savings but also more reliable solutions with sustained performance through changes in occupancy and component depreciation.





Results from a dual-chamber calorimeter test for a clear day indicate that the automatically-controlled interior blind coupled with a selective glazing (B) was more than twice as effective at reducing solar heat gain as a commonly-used non-operable system, single-pane tinted bronze glazing (A), while providing approximately the same level of useful daylight. The large differences in the heat flow between the two windows were driven principally by the admittance of direct sun into the base case chamber.



Environmental Quality

There have been unsubstantiated claims that daylighting benefits the health, satisfaction, and even productivity of humans. Both daylighting prototypes were designed to improve comfort as well as increase energy-efficiency. With this research, we began the process of quantifying the qualitative benefits of dynamic and light-redirecting window/lighting systems using simulation tools, reduced-scale field tests, and full-scale demonstrations. Some of our arguments for quality improvements compared to conventional systems were made based on meeting well-known design constraints, thresholds set by experimental field data (e.g., glare or thermal comfort indices), or industry guidelines (e.g., IES RP-1 for visual comfort). These methods only partially describe the fitness of a design solution to meet qualitative criteria because a) daylighting is constantly changing with solar position and sky conditions and b) one's complete experience of the daylit environment cannot always be reduced to "measurable" terms. Indeed, we found our understanding and evaluation methods of human factors most enriched by our full-scale demonstrations.

For example, we demonstrated light-redirecting concepts at the Palm Springs Chamber of Commerce and took simple lighting spot measurements on site to confirm that design criteria were met. Direct experience with the daylit space was ultimately more compelling. Occupants spoke of the visual interest, the unique connection to the outdoors conveyed by the passive skylight system, and the bright or soft mood created by the color and intensity of daylight. A lighting designer, however, was not pleased with the system saying that the bright patches of daylight on the ceiling contradicted (electric) lighting standards which require shielding of bright luminous sources.

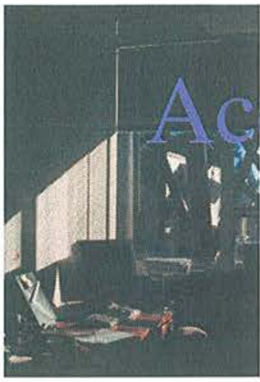
This raises the issue of the extent to which standards set for electric lighting quality can be applied to daylight. Prior studies suggest that occupants are more tolerant of glare from windows because the lighting source is accompanied by a view. For dynamic window l lighting systems, will users find the improved control in daylight intensity "unnatural" and less desirable despite its benefits in controlling glare? Would the provision of user-operated controls cause the dynamic system to be more acceptable? Long-term human factors studies with a sufficient sample size are necessary to better understand the basic underlying concepts of occupant response to daylighting systems. In addition, full-scale demonstrations play an important part in assessing the market acceptance of new technological solutions.

The basic functional goal of incorporating window and lighting systems in commercial buildings is to give occupants an adequate level of daylight or electric lighting to perform visual tasks productively. Occupant surveys reveal some of the shortcomings of conventional design practice and broaden the definition of an acceptable office environment. In a study of office workers in the Pacific Northwest region, slightly more than 40% of the occupants said the sunlight in their offices was too bright at least some of the time, and 60% of the occupants said the window was a primary source of glare and interfered with their work. Yet more than 50% of the occupants in several Tokyo high-rise office buildings preferred to have seats nearer the window, citing the brightness, outside view, wide visual range, and open feeling as advantages.

base case diffusing skylight distribution versus the light-redirecting skylight

"I like the feeling of sunlight... To me, the light gives me the feeling of my home environment because I have patches of light at home. I like this interplay of natural light. What I like most about the skylight is that it doesn't seem artificial. I feel like I'm outdoors but under the canopy of a tree."

"I like to trace the angles and think about how the sun angles are caught by the angles of the reflectors. I find the complexity pleasant. I like looking at how the light is reflected—it's fantastic. I don't understand the physics of it but I'm amazed at how the light is diverted to the ceiling and walls and how the angles are working with the sun..."



Acceptance & Satisfaction

By far the largest economic factor in commercial buildings is the cost of employee time. All other first costs and operating costs are but a tiny fraction of this cost—a person whose annual salary and benefits total $60,000 and who occupies a 120 ft^2 office costs $500 per square foot of space per year. Design solutions that improve productivity by even a small amount are thus highly cost-effective. While there is little hard data that shows a direct relationship between energy-efficient daylighting designs and productivity, there is anecdotal evidence that views of the outdoors, connections to the outside, and a glare-free and thermally comfortable environment all contribute to a more satisfied worker—who is likely to be more productive than an unhappy, uncomfortable worker.

We evaluated the occupants' acceptance and satisfaction of their work environment in a limited full-scale test with the automated blind I lighting system. A small number of occupants performed a limited set of visual tasks. These occupants reported that they were generally satisfied with the performance of the automated system. Although their satisfaction increased when they were given more control over the system, they also reported more dissatisfaction with specific problems with glare. They also indicated a desire for lighting levels above those typically provided (500 lux).

The incremental cost of the automated venetian blind/ lighting system should be approximately $3-5/$ft^2$-glazing for the motor, computer chip, power source, sensors, installation, commissioning, and maintenance. Considering energy and peak demand savings alone, we estimate that the technology has a simple payback of about ten years for the Los Angeles climate (at $0.09/kWh). An assigned value for qualitative benefits would make this system more economical. Few technologies have such an immediate impact on the quality of the inhabited environment and the comfort of its occupants. Aside from energy-efficient qualities, window and lighting technologies can change the mood of the interior, the comfort of occupants sitting beside it, and the character of the building. Demonstrating value for the amenity these systems deliver could increase market viability. As an example, the market growth popularity of low-E window glazing may have been partly due to its improvement in thermal comfort, not simply to its increased energy-efficiency. Correlating increases in worker satisfaction and productivity would build an even stronger economic argument but will require a significant R&D investment.

Survey Findings (N=14)

A: Strongly Disagree (%)
B: Disagree (%)
C: Neither Agree Nor Disagree (%)
D: Agree (%)
E: Strongly Agree (%)
F: N/A (%)

	A	B	C	D	E	F
Overall lighting comfortable?						
Automatic	0	29	14	57	0	0
Semi-control	0	21	0	71	7	0
Manual-control	0	7	7	64	21	0
Lighting uncomfortably bright for tasks?						
Automatic	43	50	7	0	0	0
Semi-control	21	71	7	0	0	0
Manual-control	29	71	0	0	0	0
Lighting uncomfortably dim for tasks?						
Automatic	21	21	29	29	0	0
Semi-control	7	71	14	7	0	0
Manual-control	14	79	7	0	0	0
Lighting poorly distributed?						
Automatic	21	36	7	36	0	0
Semi-control	21	57	7	14	0	0
Manual-control	21	64	7	7	0	0
Lighting caused deep shadows?						
Automatic	21	50	29	0	0	0
Semi-control	21	57	14	7	0	0
Manual-control	29	71	0	0	0	0
Reflections from light fixtures hindered work?						
Automatic	36	43	7	0	0	14
Semi-control	36	50	14	0	0	0
Manual-control	21	64	7	0	0	7
Lighting fixtures too bright?						
Automatic	29	50	7	0	0	14
Semi-control	36	57	0	0	0	7
Manual-control	14	64	0	14	0	7
Glare from ceiling lights bothersome?						
Automatic	29	43	7	0	0	21
Semi-control	43	43	7	0	0	7
Manual-control	14	71	0	7	0	7
Glare from windows bothersome?						
Automatic	21	71	7	0	0	0
Semi-control	36	57	7	0	0	0
Manual-control	8	69	8	15	0	0
Preferred more daylight for tasks?						
Automatic	0	21	7	64	7	0
Semi-control	0	29	21	43	7	0
Manual-control	14	29	29	21	7	0
Amount of daylight sufficient for work without additional electric lighting?						
Automatic	0	50	14	21	14	0
Semi-control	0	43	7	21	29	0
Manual-control	0	21	29	29	21	0
Dimming of lights bothersome?						
Automatic	7	21	21	21	0	29
Semi-control	7	43	21	7	7	14
Manual-control	14	29	21	0	0	36
Preferred more artificial lighting for tasks?						
Automatic	14	29	29	29	0	0
Semi-control	7	43	21	29	0	0
Manual-control	21	36	43	0	0	0
Lights being turned on and off not bothersome						
Automatic	0	21	21	29	7	21
Semi-control	0	14	29	36	7	14
Manual-control	0	7	14	29	7	43
Sound from the movement of the blinds bothersome						
Automatic	0	64	21	14	0	0
Semi-control	7	36	29	21	0	7
Manual-control	7	57	21	14	0	0
Intermittent opening and closing of the blinds bothersome						
Automatic	7	64	7	7	0	14
Semi-control	7	29	50	0	0	14
Manual-control	7	29	29	7	0	29
By controlling the blinds, able to satisfactorily adjust the amount of light for work.						
Automatic	0	7	7	7	0	79
Semi-control	7	21	7	29	14	21
Manual-control	0	7	0	57	21	14

Building Demonstration

A full-scale demonstration of a light-redirecting skylight was conducted in the Palm Springs Chamber of Commerce. Because cooling loads are a major problem in this climate and sunlight is almost always available, we designed a solution around a small skylight that admits and redirects direct sunlight to the ceiling of two separate interior rooms. The geometry of the internal skylight reflector was designed to provide daylight under all seasonal solar conditions, without allowing direct sunlight penetration to the task areas. The optical materials (reflectors and diffusers) were selected to provide good optical efficiency throughout the year. Initial surveys of the occupants indicated that they enjoyed the variability intrinsic in such a system and that it met their lighting needs well even during the winter.

Significant time and resources by all parties went into determining how the manufacturer's products could be used properly for the final construction. No single party had the ability to design, engineer, and construct the skylight systems. For example, to facilitate construction of the lightwell, the architect envisioned a process to laminate the specular film to some lightweight substrate material that the contractor could cut at the job site, place on an inclined ceiling plane, and fasten easily. The film is very thin (0.0025") and requires careful lamination onto a smooth non-porous substrate. Before the construction bids were awarded, we discussed the idea of cutting the substrate (masonite or acrylic) to the final job site conditions, placing the pieces to verify fit, laminating the film to the substrate, then screwing the panels into place. We later learned that the lamination required special mechanical equipment, the cutting could not be accomplished using typical job site tools, the substrate had to be aluminum to accommodate differences in coefficient of expansion, and that one could not drill or cut the panels after the film has been applied.

To obtain a mass-marketable product that can be installed easily in the field, close cooperation by the manufacturer(s) will be essential. For this project, the manufacturer contributed substantial staff time and resources by furnishing product specifications, samples, cost data, and design assistance. The manufacturer remains interested in collaborating on projects at a level where a mass-manufactured product could be realized.

A great deal of effort was expended by the contractor, manufacturer, architect, and ourselves to build the first full-scale installation of this light-redirecting skylight system. Tolerances were difficult to meet in this non-ideal work setting, especially with the sawzall approach of the contractor. This may have contributed to the slightly off optics of the final system. We expect that a manufactured solution will greatly improve the accuracy and ease of installing the final end-product.

Production Readiness

We progressed toward market adoption by developing, building and testing prototype systems using numerical simulation tools and field tests, by working with industry and manufacturing partners, and by demonstrating the technologies in full-scale commercial buildings. This provided a broad, highly defensible record of documented performance.

Prototypes were developed in cooperation with industry partners to speed commercialization and to work out market barriers to full-scale adoption. Industry partners in glazing, window systems, shading systems, controls hardware and lighting were solicited to participate. Feedback through trade associations, conferences and industry associations helped to identify potential obstacles such as difficulties with cross-disciplinary design, operation and maintenance concerns and manufacturing processes.

Because these systems cross traditional component boundaries, marketing and commercializing integrated products pose unique challenges; i.e., will it be sold by a windows or lighting systems manufacturer? Perhaps the best solution would be to define a new sub-industry where envelope and lighting systems could be tailored and assembled for individual clients by "system integrators."

Issues surrounding intelligent building systems—such as control-system protocol, control linkages from the zone level to whole building scale and hardware-to-software heuristics—are being addressed by the research, engineering and manufacturing communities. Skepticism abounds when actively-controlled systems are proposed, primarily due to poor building operation and maintenance practices in the United States. The light-redirecting systems provide static solutions, but for the large variability in exterior and interior building conditions, dynamic systems promise optimum solutions on a real-time basis throughout the year.

Conclusion

Daylighting strategies can provide large reductions in lighting and cooling-related energy use, as well as improved amenity, satisfaction, and perhaps occupant performance. But the successful adoption of daylighting in the marketplace requires an integrated approach to the design, specification, and implementation of envelope and lighting technologies. Through this research project, we believe we were able to take a small but important first step to change how architects, facility managers, and industry perceive the notion of daylighting commercial buildings by supplying design tools, credible energy performance data, demonstrations of future daylighting concepts, and commissioning protocols that address key window *and* lighting interactions. Clearly, the simple conceptual solution of manually switching off the lights when sufficient daylight is available from an unmanaged window in a naturally lit space doesn't work. We have developed systems that save energy consistently and reliably while delivering amenity, satisfaction, comfort, and health to its occupants through sensitive control of daylight intensity and distribution.

Despite the technical and organizational obstacles to the comprehensive integration of building envelope, lighting, and HVAC systems, these dynamic facade and light-redirecting concepts hold considerable power to stimulate the architectural imagination. It suggests a fundamentally different approach to optimizing the energy performance of buildings with new fenestration technologies while also improving the quality of the indoor environment, and displaying in a very tangible way the ever changing relationship between the products of human ingenuity, the local environment, and the imperative for sustainable design solutions.