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Technology Assessments of High Performance Envelope with Optimized Lighting, Solar Control, and Daylighting

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TECHNOLOGY ASSESSMENTS OF HIGH PERFORMANCE ENVELOPE WITH OPTIMIZED LIGHTING, SOLAR CONTROL, AND DAYLIGHTING

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ABBREVIATIONS AND ACRONYMS

BSDF	Bidirectional scattering distribution function
Btu	British thermal unit
cm	Centimeter
EU	European Union
FLEXLAB	Facility for Low Energy Experiments in Buildings
ft	Feet (unit of measure)
H	hour
HVAC	Heating, ventilation and air-conditioning
IEQ	Indoor environmental quality
IESNA	Illuminating Engineering Society of North America
LBNL	Lawrence Berkeley National Laboratory
LT	Local Time
m	Meters (unit of measure)
m/s	Meters per second
NFRC	National Fenestration Rating Council
PDT	Pacific daylight savings time
S	Seconds
SHGC	Solar heat gain coefficient
ST	Standard Time
TIR	Total internal reflection
TVIS	Visible transmittance
yr	year

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1. EXECUTIVE SUMMARY

Innovative, cost-effective, energy efficiency technologies and strategies for new and retrofit construction markets are essential for achieving near-term, broad market impacts.[1] This study focuses on innovative shading and daylighting technologies that have the potential to significantly curtail annual cooling and lighting electricity use and reduce summer peak electric demand, particularly in the hot, sunny, inland areas where there has been significant population growth.

The building industry is well aware that energy-efficiency potential does not always match actual, real world performance in the field due to a variety of mitigating factors. Third party verification of the energy savings potential of innovative technologies is important for market adoption. In the case of shading and daylighting technologies, new simulation tools have only recently been developed to improve modeling accuracy. Market acceptance is also heavily dependent on how well the technology balances comfort and indoor environmental quality (IEQ) requirements (e.g., view, brightness, etc.). PG&E commissioned this full-scale monitored study to better understand the impact of mitigating factors on performance so as to make more informed decisions when constructing program interventions that support technology adoption in the market.

PROJECT GOAL

The objective of this monitored field study was to identify near-term innovative façade technologies for solar control and daylighting with a goal of 20-40% energy use savings below Title 24 2013 in the 30-ft deep perimeter zone near vertical windows within cost and comfort constraints. The targeted market was new or existing commercial office buildings or buildings with similar patterns of use.

PROJECT DESCRIPTION

Daylight-redirecting technologies–

- Static daylight-redirecting films: Recent developments in material science and low-cost fabrication methods have led to commercialization of thin films with microscopic features that are designed to redirect beam sunlight up to the ceiling plane, more deeply from the window wall.
- Automated, motorized daylight-redirecting systems: These systems have even greater potential to reduce energy use due to an active real-time response to variable sun and sky conditions.

Both of these types of systems are installed in the upper clerestory portion of south-, east-, or west-facing windows with or without venetian blinds, depending on the product design, and when used in combination with dimmable lighting systems, reduce lighting energy use and peak demand and enhance the daylighting quality of the interior space.

[1] Energy-efficiency technologies and strategies are advocated by California Assembly Bills (AB) 32 and AB 758, and are essential to meeting zero net energy goals defined by the California Long Term Strategic Energy Efficiency Plan by 2030.

Exterior shading technologies –

Exterior shading has long been known to be more effective at reducing window heat gains than interior shades, but their use in the United States has been limited in part due to concerns of durability and maintenance.

- Static solar screen: A simple, micro-louvered solar screen, which has been on the market for years, can be an effective retrofit measure for a broad range of building types.
- Automated, motorized shading systems: An innovative operable roller shade has recently become commercially available that can withstand higher lateral loads from wind, enabling use on low- and mid-rise buildings.

These innovative shading and daylighting technologies were evaluated through a controlled field monitoring program in the Lawrence Berkeley National Laboratory's (LBNL) new Facility for Low Energy Experiments in Buildings (FLEXLAB) facility. The FLEXLAB facility consists of side-by-side, full-scale test rooms designed to emulate a 30 feet deep commercial office zone with open plan workstations. Four daylight-redirecting technologies and two exterior coplanar (parallel to the face of the façade) shading systems were evaluated over a six-month, solstice-to-solstice period. Monitored data related to energy use, comfort, and indoor environmental quality (IEQ) were used to conduct a comprehensive assessment. The results are intended to provide utilities with vital, third-party information needed to plan energy efficiency incentive offerings for these two classes of technologies in California.

PROJECT FINDINGS/RESULTS

Daylight-redirecting technologies

Monitored data demonstrated that annual lighting energy savings of 48-63% were achieved with the daylight-redirecting window technologies and daylight-responsive LED lighting (8 AM to 6 PM, daylight controls only, 30 ft deep perimeter zone). These savings were achieved compared to a reference case that had a conventional static venetian blind[2] and efficient, daylight-responsive T5 fluorescent lighting. The reference energy use intensity was 0.40 kWh/ft^2-yr. Average annual savings were 0.20 kWh/ft^2-yr in the 30 ft deep office space. Under clear sky conditions, average savings were 62%. Savings were due to increased interior daylight levels, increased efficiency of the LED source, and differences in power use over the dimming range of the lighting system.

Savings achieved with the daylight-redirecting technology and the *same* dimmable fluorescent lighting as the reference case were on average 8% and under clear sky conditions, average savings were 22%. These energy savings were due solely to the daylighting system.

Visual discomfort was within acceptable limits[3] if views were of the sidewall (parallel to the window) but was unacceptable during the period between the equinox and winter solstice if the occupant's field of

[2] The venetian blinds were lowered to fully cover the window and were set to a fixed slat angle that just blocked direct sunlight (three slat angles were used, corresponding to the summer, equinox, and winter seasons).

[3] Visual discomfort was considered to be within acceptable limits if the maximum daylight glare probability (DGP) index was below "just perceptible" levels (DGP=0.35) for 95% of the day and the average DGP for the remaining 5% of the day was below 0.38 ("perceptible glare") throughout the

view was both toward and near the window. Shades will be required with some of the systems. During sunny mid-day periods, particularly during the equinox to winter periods, the entire room cavity was brightly daylit, enhancing overall daylight quality in the space. Radiance simulations from a prior study (McNeil et al. 2013) pointed to greater energy and peak demand savings with less efficient electric lighting systems.

Exterior shading technologies

Daily cooling loads due to the window were reduced by 16-68% on sunny days (8 AM to 6 PM) when an exterior static metal mesh screen was used to control admission of direct sunlight compared to the same Title-24 2013 compliant, dual-pane, low-emittance window (SHGC=0.27, U-value=0.28 Btu/h-ft^2-°F) with an indoor venetian blind. Peak cooling demand due to the window was reduced by 19-62% (for non-coincident peak periods).

Daily lighting energy use was decreased by 16%, due to the net effect of both decreased daylight from the static exterior shade (which increased lighting energy use) and increased efficiency of the LED source and dimming profile (which decreased lighting energy use). (Savings are given for 8 AM to 6 PM, daylight controls only, 30 ft deep perimeter zone.) If the same fluorescent lighting system was used in the reference and test cases, lighting energy use was increased by 0.175 kWh/ft^2-yr (74%) due to decreased daylight admission from the static exterior shade.

An indoor shade may be required to control glare during sunny winter periods. On cloudy winter days, the space may be perceived as inadequately daylit (as defined by IEQ metrics described in Section 7.2.3) since the exterior shade reduces overall daylight admission. Views to the outdoors were filtered and non-distorted. Prior building energy simulations indicated total annual source energy savings for a 15-ft deep south-facing perimeter office zone in Oakland of 3.7-5.1 kWh/ft^2-yr (25-38%) with and without an indoor shade to control glare (Hoffmann et al. 2016).

The dynamic, automated exterior shading system offers the opportunity to better balance the trade-offs between solar control, daylight, glare, and view. On clear sunny days, daily cooling loads due to the window were reduced by 12-24% and peak summer cooling demand was reduced by 26%. Daily lighting energy savings were 33% if LEDs were used (net effect due to decreased daylight and increased LED source and dimming efficiency). Lighting was increased by 34%, however, if the same fluorescent lighting was used in both rooms due to decreased daylight admission from the dynamic exterior shade. Glare was well managed during the summer but unacceptable on sunny days during the winter period near the window if the view was looking at the window – when lowered, the 5% openness of the fabric roller shade inadequately blocked direct sun. Depending on the climate and layout of the interior space, a denser weave fabric or an indoor shade may need to be provided. The space may be perceived as having inadequate daylight during the winter. Views were more accessible with the automated shade.

PROJECT RECOMMENDATIONS

Daylight-redirecting technologies

The daylight-redirecting films are recommended for adoption with the proviso that the application be designed to mitigate glare, either through informed use of interior shades and/or space layout. Because there can be significant variation in savings depending on the application, we recommend that the daylight-redirecting technologies be modeled prior to final specification or that design guidelines be developed in order to achieve the best balance between daylight, glare, and solar control. Radiance tools

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six-month monitored period. DGP was determined from high dynamic range luminance data measured in the FLEXLAB facility. See Section 6.6.3.

have recently been developed (Lee et al., 2014) to assess such technologies but these tools are not yet turn-key. Human factors studies are also recommended to better understand the impact of glare / interior shade use on performance and to assign occupant satisfaction and possibly market-related value to a well daylit environment in perimeter zones.

The dynamic, automatically-controlled daylight-redirecting system did not provide significant energy savings above and beyond that of the static films and is therefore not able to justify its added cost and complexity based on energy savings alone. The dynamic system however may have the potential to improve its performance if designed and controlled more optimally.

Solar control technologies

Both the static and dynamic exterior shading systems are recommended for adoption, particularly for low- to medium-rise commercial applications in moderate to hot climates where the cost of delivering cooling to perimeter zones is significantly greater than that for lighting (e.g., VAV system with low-resolution zonal controls versus lighting system with occupancy controls in every office). Both of these solutions deliver the benefit of exterior shading at a relatively low cost. Guidelines will be needed to ensure proper application since performance of the exterior shades is tied to the properties of the existing window, climate, HVAC and lighting system details, and other site specifics. Dynamic shading provides owners with a demand side management option that can be integrated at the whole building/ microgrid/ grid level. Further product development and R&D will be required to improve and optimize commercial solutions and to better understand end user preferences and satisfaction with the controls.

1. INTRODUCTION

Innovative, cost-effective, energy efficiency technologies and strategies for new and retrofit construction markets are essential for achieving near-term, broad market impacts, as advocated by California Assembly Bills (AB) 32 and AB 758, and meeting the zero net energy goals defined by the California Long Term Strategic Energy Efficiency Plan by 2030. This study focuses on innovative shading and daylighting technologies that have the potential to significantly curtail annual cooling and lighting electricity use and reduce summer peak electric demand, particularly in the hot, sunny, inland areas where there has been significant population growth.

Exterior solar shading has significant technical potential to reduce envelope loads but broad market adoption has not occurred in the US, unlike the more progressive European Union with its milder climate. Shading that projects out from the face of the façade (called "non-coplanar" shading) such as overhangs and fins affect the architectural aesthetics of the exterior façade, require engineering to handle wind and seismic loading, and increase maintenance costs when it comes to washing the windows. Co-planar exterior shading (shading that is parallel to the face of the façade) presents somewhat less of an engineering challenge and is therefore potentially a more cost-effective candidate for retrofit applications – but less is known about available products and their performance.

Daylighting technologies are window or skylight technologies that introduce daylight into a space in a variety of ways that enable the electric lighting to be turned off. Since daylight availability is coincident with the utility peak demand period, these technologies are of particular relevance in California. Skylights have been widely promoted by recent revisions to the Title-24 code. Daylighting technologies for vertical windows have broader applicability but have historically gained less market traction due to unfamiliarity with the technologies and cost barriers; these technologies are investigated in this study.

The challenge with both types of technologies is a low adoption rate that is impeded not only by various market factors but also uncertainty in performance. California utilities can provide financial incentives to building owners and design teams to accelerate market adoption of promising energy-efficiency technologies. The decision as to *which* technology to include in utility rebate programs is dependent in part on the magnitude of energy and peak demand savings that can be garnered by the technology per unit installed cost. Utilities need to have concrete third-party measured evidence of energy savings and also a detailed understanding of the real-world mitigating factors that can impact the savings.

This study was designed to provide such empirical evidence for innovative shading and daylighting technologies through a controlled field monitoring program in the Lawrence Berkeley National Laboratory's (LBNL) new Facility for Low Energy Experiments in Buildings (FLEXLAB) facility. The FLEXLAB facility consists of side-by-side, full-scale test rooms designed to emulate a deep commercial office zone with open plan workstations. The window wall, lighting, and HVAC systems were designed to be reconfigurable so that multiple technologies could be evaluated over a designated test period. Four daylight-redirecting technologies and two exterior coplanar shading systems were evaluated over a six-month, solstice-to-solstice period. Monitored data related to energy use, comfort, and indoor environmental quality (IEQ) were used to conduct a comprehensive assessment. The results are intended to provide utilities with vital, third-party information needed to plan market transformation programs for these two classes of technologies in California.

2. BACKGROUND

2.1. DAYLIGHTING

Recent developments in material science and low-cost, roll-to-roll fabrication methods have led to commercial offerings of thin films with microscopic features that redirect daylight. Such solutions could potentially supplant macroscopic solutions such as light shelves and reflective louver systems. The films are designed to be installed on the inside surface of the upper clerestory portion of the window, similar to solar control films. Conceptually, sunlight is redirected by the film into the room and up towards the ceiling plane which in turn reflects light downward to desk surfaces, thereby increasing the overall quantity of daylight in the space with better distribution across wall and ceiling surfaces. Several manufacturers have recently introduced commercial products on the market, providing low cost, low maintenance alternatives to conventional daylighting systems.

Prior studies have also indicated that daylighting potential can be increased if the daylight-redirecting system is operable and automated. There are high-end applications of tracking heliostats that reflect beam sunlight into atria or to a light pipe installed in the ceiling plenum. On the more conventional side, several manufacturers offer indoor shading systems that automatically adjust the slat angle of a reflective blind in the clerestory portion of the window to redirect sunlight to the plane of the ceiling.

Both of the static film and sun-tracking daylight-redirecting systems are applicable to new and retrofit construction with south, east, or west-facing windows. The technologies are applicable to deep spaces with few vertical obstructions to the daylight (e.g., open plan offices with low-height partitions) and with clerestory windows that are continuous across the façade without significant shading from the exterior (e.g., setback from the façade). The technologies can alter the exterior appearance of the façade and so may require approval by the building owner prior to its application in a retrofit application.

2.2. 6SOLAR CONTROL USING EXTERIOR SHADING

Commercial product offerings for exterior coplanar shading include a variety of solutions: a) fixed or operable louvered systems (15-91 cm, 0.5-3 ft wide louvers) that can withstand the weather elements; b) lighter-weight, operable louver, venetian blind, or roller shade systems that are retracted when wind speeds exceed a specified level or when ice and snow accumulation are expected (e.g., seasonal retraction during the winter); c) thin, light-weight fixed solar screens held within a frame for low-rise applications; and d) metal mesh screens that can be rolled up into a header rail. Some of the more innovative systems are comprised of shading elements/slats whose geometry and surface reflectance properties have been engineered to address the challenges of delivering both solar control, daylight, and view. Each of these solutions have been used by the architectural/ engineering community in innovative ways to define the architectural character of the façade.

In California and within the context of this project, simple coplanar exterior shading systems are needed to deliver significant, reliable energy savings to a wide variety of new and

existing commercial buildings. Two types of systems have the potential to meet these criteria: a) flexible, operable shading elements such as roller shades or screens whose side edges are held in an innovative structural rail (e.g., "zipper" roller shade) so as to withstand higher lateral loads from wind, and b) a light-weight but rigid, framed metal solar screen that can be mounted on existing windows using a simple set of clips on the edge of the screen. Both solutions provide direct sun control with some diffusion of daylight to the interior. Views to the outdoors are filtered by the fabric or metal screen. The operable shade is suitable for high end applications, lending a clean look to the façade. The fixed metal solar screen is appropriate for punched window openings on low-rise buildings.

Both exterior shading systems reduce solar heat gains primarily by shading the exterior façade from direct sun. In the case of the metal solar screen, which is composed of horizontal slats, the cut-off angle of the slats blocks direct sunlight transmission to the indoors for moderate to high solar altitudes. For the automated roller shade, the shade height is adjustable so the owner can allow some direct sun into the space for increased daylighting and unobstructed views by specifying the desired depth of sunlight penetration into the room.

The exterior shades also reflect and/or absorb solar radiation, depending on the properties of the shade. Absorbed radiation is re-radiated to the interior if the existing window does not have a low-emittance (low-e) coating and/or is convected, depending on the air flow through and around the shade. Heat flow can also occur via conduction if the window frame in contact with the shade is not thermally broken.

The choice of operable versus fixed shading is typically defined by economic and amenity trade-offs; i.e., operable systems have a greater expense but they enable greater access to unobstructed views. In the European Union (EU), manually-operated coplanar shading is prevalent on both historic and modern commercial buildings as a low-cost alternative to air-conditioning. The shades are lowered during the summer for cooling and retracted in the winter for passive heating and unobstructed view. For cooling-dominated buildings in moderate to hot climates, solar shading is deployed year round.

In general, today's market context is more favorable towards actively-controlled, dynamic technologies. Demand side management is and has been of concern for utilities over the past three decades, but as the adoption of renewables increase in California, integrated, active building load management in energy-intensive perimeter zones can be a cost-effective hedge against the volatility produced by intermittent renewable resources. These technologies anticipate future markets that favor building-to-grid integration, tackling two of the largest electricity end uses that contribute to peak electric demand.

Performance is dictated by both the shade type and material (e.g., fabric weave, openness, thermal properties, color) and its operation. There have been significant advances in the development of building energy simulation tools that enable more accurate assessments of window heat gains, daylight, and comfort. Field measurements provide an opportunity to confirm findings from these tools.

3. EMERGING TECHNOLOGY/ PRODUCT

The specific technologies evaluated in this study were selected in consultation with the project advisory committee (see Acknowledgments). Using a web-based form, committee members were presented with descriptions and images of four general options for each

class of technology (daylighting and exterior shading). They were then asked to provide comments on each option, to rank the options, and then add comments on concerns and/or experiences with the options. LBNL then reviewed the responses and made the final selections in consultation with PG&E. Six technologies were evaluated in this study:

Daylighting-redirecting technologies

- Microscopic reflector window film (DL-L1)
- Microlouvered, see-through window film (DL-L2)
- Microprismatic window film (DL-P)
- Sunlight-tracking, automated mirrored blinds (DL-Dyn)

Exterior shading technologies

- Exterior, microlouvered, metal mesh screen (S-L)
- Exterior, automated roller shade with zipper side rails (S-Dyn)

3.1. INCUMBENT TECHNOLOGY

The California Title-24 2013 for non-residential buildings (CEC 2013) restricts the window area and properties of the window in the prescriptive approach by climate zone and window orientation. However, in California, most office environments have some sort of manually operated interior shade. Therefore, for this study, the incumbent technology is defined as a window with properties that meet the Title-24 2013 standards and has manually-operated interior shades such as roller shades or venetian blinds.

Manual operation of interior shading has not been systematically characterized in the U.S. Published studies indicate that the shades are typically adjusted to reduce discomfort and then often remain in this position for weeks or months on end (Inkarojrit 2005). In this study, the shade is assumed to be adjusted seasonally to block direct sun.

3.2. DAYLIGHT-REDIRECTING TECHNOLOGIES

Static Daylighting Films

The potential energy, comfort, and indoor environmental quality (IEQ) impacts associated with static daylight-redirecting systems compared to the incumbent technology are as follows:

- Lighting electricity use reductions in the primary, secondary and potentially tertiary daylit zones from the window (e.g., 10-40 ft from the window if the ceiling height is 9 ft);
- Peak lighting electricity use reductions on sunny days for south-facing orientations;
- Reduction in cooling energy use and increased heating energy use due to reduced electric lighting heat gains;
- Increase in cooling energy use or decrease in heating energy use due to the unshaded 2-ft high daylighting clerestory aperture (assuming that the window would have been shaded with an indoor shade or blind);
- Increased uniformity of daylight across the depth of the room;
- Increased daylight illuminance levels across the depth of the room;

- Increased variability of illuminance levels across a greater depth of the space due to the redirected sunlight;
- Increased visual comfort due to improved luminance distribution across the depth of the space;
- Possible glare due to reflections off of shiny surfaces on or near the ceiling plane (e.g., metallic fittings on light fixtures, fire sprinklers, etc.);
- Partial or complete obstruction of view through the clerestory portion of the window, depending on the optics of the system – the lower window, however, will remain the view window;
- Greater connection to the outdoors due to variations in indoor daylight that mimic the outdoor sky conditions;
- Health and productivity benefits due to increased daylight levels and variability of intensity.

Automated, Motorized Daylight-Redirecting Systems

The potential energy, comfort, and indoor environmental quality (IEQ) impacts associated with the automated motorized daylight-redirecting system compared to the incumbent technology are the same as the static system except:

- Increased cooling and/or lighting energy savings due to real-time control of solar and daylight admission;
- Increased visual and thermal comfort due to active response to real-time environmental conditions and occupant preferences;
- Increase in unobstructed view throughout the year compared to manually-operated interior shades.

3.3. EXTERIOR SHADING SYSTEMS

Static Exterior Shading

The potential energy, comfort, and indoor environmental quality (IEQ) impacts associated with the static exterior shading system compared to the incumbent technology are as follows:

- Reduction in window solar heat gains, particularly if the existing windows have a low-emittance coating (to reduce heat that is absorbed by the shade then radiated to the indoors)
- Reduction in annual cooling energy use with possible increase in heating energy use;
- Reduction in peak cooling energy use, particularly during sunny summer days;
- Potential to downsize HVAC equipment related to cooling;
- Decreased daylight illuminance across the depth of the space;
- Potential increase in annual lighting energy use in the primary daylit zone, particularly during overcast weather;
- Potential increase in peak lighting energy use, depending on the size of the window and design illuminance in the primary zone;

- Similar or increased visual and thermal comfort, assuming that the interior shades of the reference condition remains;
- Partially-obstructed view throughout the year.

Automated Exterior Shading

The potential energy, comfort, and indoor environmental quality (IEQ) impacts associated with the automated exterior shading system compared to the incumbent technology are the same as the static system except:

- Decrease in annual lighting energy use in the primary daylit zone because the automated shades are raised under cloudy conditions;
- Decrease in total peak energy use due to HVAC and lighting end uses, if shade is optimally controlled;
- Potential increase in visual and thermal comfort, depending on the control algorithm for the automated shade and whether the indoor shade is retained;
- Increase in unobstructed view throughout the year compared to manually-operated interior shades, assuming the interior shade is not retained.

4. Assessment Objectives

4.1. Main Objectives

The main objectives of this technology assessment were to:

- Demonstrate façade/ lighting office solutions that exceed the Title-24 2013 requirements and help to guide future code cycles and stretch code goals leading to meeting 2030 performance goals;
- Measure the reduction in cooling, heating, and lighting energy use, reduction in peak cooling load, and improvement in load shape resulting from the innovative technologies under real sun and sky conditions compared to the Title-24 2013 Standards;
- Demonstrate solutions that are 20-40% better than Title-24 2013 code compliant solutions;
- Demonstrate how emerging technology and design solutions translate into end use energy performance targets in terms of kWh/ft^2-yr savings;
- Demonstrate occupant comfort that is equal or better than baseline designs with associated energy savings.

4.2. Key Issues

In addition to a detailed examination of the overall performance of the technologies in a real world context, several key issues were addressed in this study:

- Daylight-redirecting technologies can potentially increase discomfort glare if the optics of the device or application of the technology is not optimal. Measures to mitigate glare, such as use of a shading device, can reduce the effectiveness of the daylighting technology. Simulation tools have only recently been developed that enable assessment of glare and daylight performance of optically-complex fenestration systems, so full-scale measurements enabled a more accurate evaluation of glare and daylight tradeoffs under real sun and sky conditions.
- Shading can reduce available daylight. The net energy use and peak demand impact of shading must therefore be considered both in terms of HVAC energy use reductions and increased lighting energy use. Shading can also reduce glare, but as a result, view can be obstructed. Innovative solutions successfully weigh these tradeoffs and provide solutions that are suited to a wide variety of situations. Full-scale field testing enabled simultaneous and accurate evaluation of these parameters at a high spatial and temporal resolution compared to demonstrations in occupied buildings.

5. Technology/ Product Evaluation

Full-scale field measurements were conducted in LBNL's new Facility for Low Energy Experiments in Buildings (FLEXLAB) facility. All tests were performed by LBNL staff who have extensive experience evaluating innovative daylighting and solar control technologies in both the full-scale, outdoor Advanced Windows Testbed and Mobile Window Thermal Test (MoWITT) facilities.

1) The FLEXLAB facility consists of side-by-side, full-scale test rooms situated at LBNL, Berkeley, California (latitude 37.87°N, 122.26°W). Details of the set-up are given in Section 6. Two adjacent, 20 ft wide by 30 ft deep, south-facing test rooms were fitted out to emulate a deep commercial office zone with open plan workstations. The reference Title-24 2013 compliant condition was set up in the west test room (Building 90, Room X3A). The test condition was set up in the east test room (Room X3B). Both test rooms were subject to nearly the same outdoor environmental conditions and monitored simultaneously so that measurements could be compared. The south-facing orientation enabled a thorough investigation of daylighting, HVAC, and comfort impacts over a broad range of incident solar angles.

In order to evaluate the annual performance of the technologies within a reasonable time frame, the technologies in the test rooms were evaluated over three test periods within a six-month, solstice-to-solstice term (Table 5.1). The three test periods were six weeks each, centered roughly around the summer solstice, equinox, and winter solstice. Each of the six technologies were evaluated for about one week within each six-week test period, varying by a few days depending on the weather and length of time it took to change out the previous system and install the new system. Tests were configured prior to 9 PM at night so that the thermal conditions had sufficient time to come to equilibrium before the following day's HVAC measurements. The periods between each six-week period were reserved for a separate PG&E evaluation of radiant cooling systems. All tests were conducted without occupants.

TABLE 5.1 TEST SCHEDULE

TEST PERIOD	SEQUENTIAL TEST OF:	START	END
1 Summer Solstice	4 daylighting, 2 shading systems	Jun 22	Aug 5
Unrelated PG&E Test		Aug 6*	Sep 20
2 Equinox	4 daylighting, 2 shading systems	Sep 21	Nov 8
Unrelated PG&E Test		Nov 9	Nov 22
3 Winter Solstice	4 daylighting, 2 shading systems	Nov 23	Jan 11

* Radiant ceiling tiles were installed August 6, 2015 and remained through January 11, 2016.

The FLEXLAB facility provided a unique setting to evaluate the daylighting potential of the innovative technologies in deep spaces – the test rooms were 20 ft wide and 30 ft deep. To enable a more stringent evaluation of glare, the open plan workstation partitions were set to a moderate height of 3.57 ft, emulating the more modern trends for furniture systems and workplace design that allow all occupants to have access to outdoor views.

For the assessment of solar heat gain control and HVAC measurements, the FLEXLAB facility was also designed to maximize incident solar radiation on the test room façades. Incident solar radiation was minimally unobstructed by trees and adjacent buildings. The ground immediately in front of the windows was a painted concrete apron with relatively uniform reflectance. On the interior, we attempted to minimize all differences between the two rooms so that performance differences could be isolated to the technologies under study. Finishes, layout, and equipment were selected to be typical of a conventional commercial office perimeter zone.

This was the first test conducted in these FLEXLAB test rooms and as such, the infrastructure for the test rooms was not fully developed and vetted. Considerable effort went into configuring the space, testing the HVAC system's operational modes to ensure that the systems were operating as intended, building and installing new instrumentation, and setting up and testing the data acquisition system. Lack of a mature test infrastructure had two impacts on the project:

(1) Thermal calibrations tests of the building envelope and HVAC systems were in progress prior to the PG&E tests in order to characterize the differences in construction and operations between the test rooms. The test rooms were constructed identically with significant envelope insulation to minimize differences in thermal response between test rooms. However, differences in exposure to the outdoor environment (e.g., between-room side wall versus side wall directly exposed to the outdoors) and operational differences in equipment introduced differences in room loads and thus HVAC energy use. A model to correct for these differences was being constructed but was not completed for this field study. Therefore, accuracy of between-room HVAC energy use savings with the same physical configuration is estimated to be about 10%.

(2) There were errors and glitches with the instrumentation and data acquisition and control systems, leading to erroneous data and improper HVAC operations. When these glitches occurred, the data were either corrected using independent measures or eliminated from the analysis.

6. Technical Approach/ Test Methods

6.1. Experimental Set-Up

6.1.1. Field Test Set-up

The two test rooms used in this study are at the east end of a row of test rooms that comprise part of LBNL's FLEXLAB facility (Figure 6.1). Each of these test rooms have interior dimensions of 20 by 30 by 9 ft and are oriented due south. The east-most test room which houses the test condition (Room X3B) has an east wall that is exposed to the outdoors and a west wall that is shared with the adjacent Title-24 reference condition (Room X3A). The west side wall of the reference test room is shared with a double-height test room. The roof of the two test rooms, which is a continuous planar surface between the two rooms X3A and X3B, is shaded by the double-height test rooms (which are 13 ft taller than the single-height test rooms) in the afternoon. The rear wall door opens to the outdoors. There is another door in the rear wall that opens to a small control room that houses the HVAC equipment and related electronics. Each test room is well insulated to minimize heat transfer between rooms.

FIGURE 6.1 OUTDOOR VIEW OF FLEXLAB TESTBED FACILITY WITH THE TWO TEST ROOMS THAT WERE USED FOR THIS STUDY ON THE RIGHT.

Each test room was constructed to be minimally compliant with the ASHRAE 90.1-2010 Standard on the south wall, roof, and floor but to be near thermally isolated from adjacent test rooms and the outdoor environment on the east, west, and intermediary wall between the two test rooms.

- Exterior walls consisted of 5/8-inch gypsum wallboard on interior over 6-inch metal studs at 16 inches on center with R-13 batt insulation between the studs, ½-inch plywood sheathing, R-3.8 rigid insulation, then cementitious wall board and metal sheathing on the exterior. Total R-value of the east, north, and south walls were 43, 48, and 13 h-°F-ft^2/Btu, respectively.
- The wall between test rooms consisted of a 8.25-inch thick structural insulated panel (SIP) (1/2-inch plywood over rigid insulation) with 4-inch rigid insulation on either side of the SIP then faced on both sides with 5/8-inch gypsum board. Total R-value of this wall was 62.
- The white roof was insulated with R-20 continuous insulation over glulam and plywood. Total R-value of the roof was 22.
- The floor was medium-weight, concrete slab on grade with a 6-inch topping slab over rigid insulation. Total R-value of the floor was 13.

Minimally compliant insulation levels for the Title-24 2013 code (R-13 walls, R-30 roof, R-19 floor) were nearly comparable to that constructed in the FLEXLAB. Since this analysis was focused on the difference in energy use between the test rooms due to the south-facing envelope and lighting systems, differences in insulation had minimal effect on the outcomes of this study.

Incident solar radiation on the south façade was nominally the same between the two test rooms. There was a one-story trailer (Building 90C) and Eucalyptus tree to the southeast of the test rooms (Figure 6.2). Figure 6.3 shows a fisheye photograph of these exterior surroundings when viewed from the center of each of the test room windows at a height of 4.5 ft above the floor of the test room. The sun path overlay indicates when the sun is obstructed by the tree and the differences in obstructions between the two test rooms. The ground in front of the windows consisted of a 10 ft deep apron of painted concrete (Rvis=0.21), then a 60 ft deep asphalt roadway.

The interior of the test rooms had a matte white painted finish on the walls, a 2x2 dropped acoustical tile ceiling, and a thin brown carpet and pad over the slab flooring. Visible reflectances, Rvis, of the indoor surfaces, were 0.85, 0.93, and 0.42 for the walls, ceiling, and floor, respectively. The space was furnished with open plan workstations with 3.57 ft high partitions (Rvis=0.61), birch wood desks (Rvis=0.79) and birch wood chairs. The layout of the furniture is shown in Figure 6.4.

A 700 W (1.17 W/ft^2) internal load emulating occupants and equipment was supplied with a convective electric resistance heater placed 15 ft from the window, 1.5 ft from the sidewall, and directed so that its airflow was toward the center of the room. The heater was operated from 9 AM to 6 PM local time.

Radiant ceiling tiles were installed between Test periods 1 and 2. The ceiling tiles were arrayed in a somewhat checkerboard pattern across the entire depth of the test room and occupied about 50% of the total area of the ceiling. Each 2x2 ft panel had a 0.5 inch copper pipe in thermal contact with the aluminum facing sheet and the panels were connected by push-on flexible hoses. The aluminum sheet was painted to match the existing surface reflectance of the existing acoustical tiles (which constituted the other 50% of the ceiling

area) so as not to affect the daylighting tests. When the Period 2 and 3 tests were conducted, the radiant tiles were non-operational and the water within the pipes was allowed to reach thermal equilibrium with the plenum return air. The tiles were unlikely to have any effect on the thermal measurements made for the solar control tests.

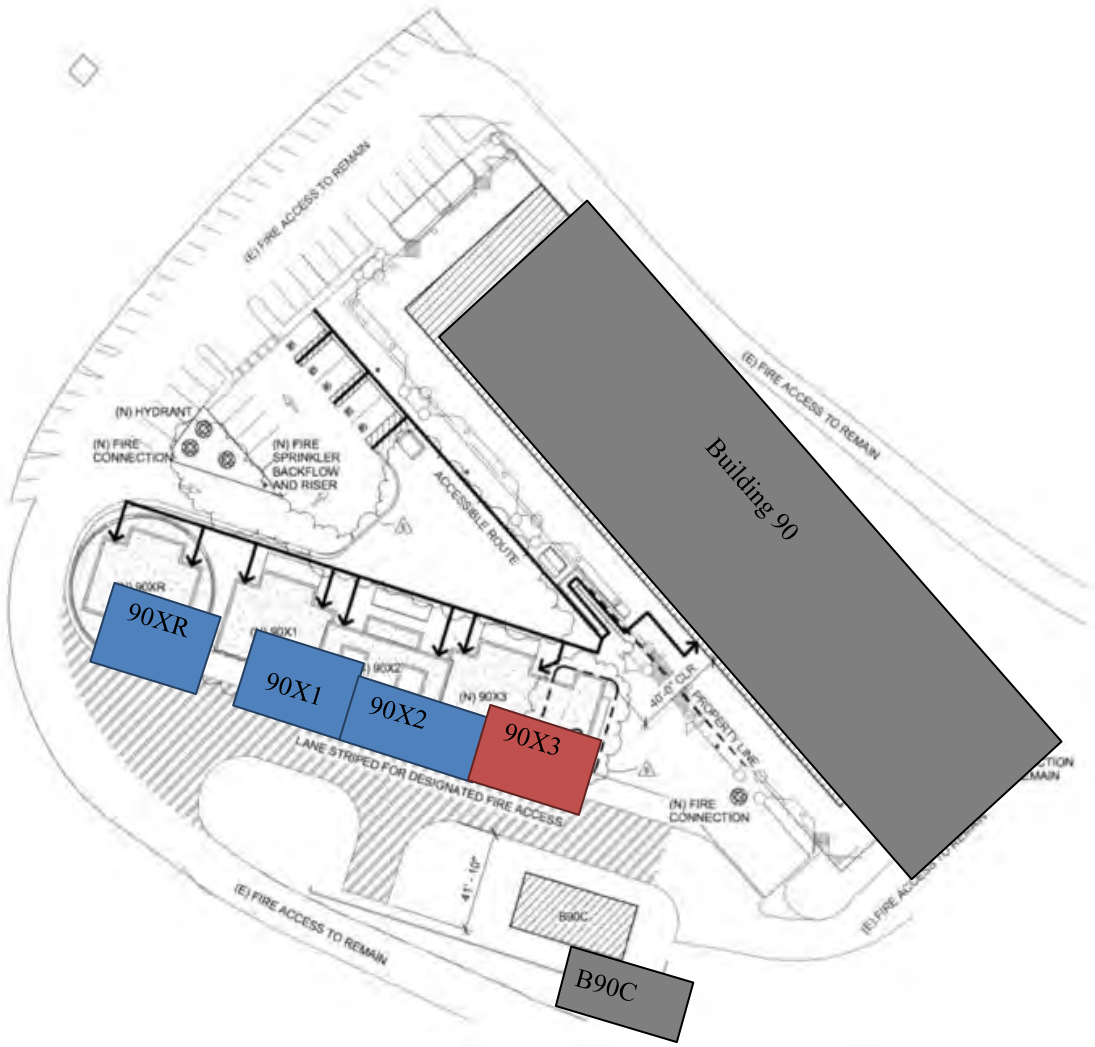

FIGURE 6.2 SITE PLAN OF FLEXLAB THE FLEXLAB TESTBED FACILITY WHERE TEST ROOMS 90X3 WERE USED FOR THIS STUDY. THE TEST ROOMS FACED DUE SOUTH.

FIGURE 6.3 EXTERIOR OBSTRUCTIONS AS VIEWED FROM THE TEST WINDOWS. FISHEYE PHOTOGRAPHS TAKEN AT GROUND LEVEL (UPPER ROW) AND AT MID-HEIGHT AT THE WINDOW WALL (LOWER ROW) OUTSIDE THE FACE OF TEST ROOMS A (LEFT) AND B (RIGHT).

FIGURE 6.4 PHOTOGRAPH OF THE REFERENCE TEST ROOM FROM THE BACK OF THE ROOM LOOKING TOWARD THE WINDOW (AUGUST 3, 2015, 2PM).

6.1.2. WINDOWS

The test and reference room windows were configured to be identical and were large in area in order to ensure that there was a sufficiently large HVAC load for a more accurate measurement. In each test room, the window wall was subdivided across the width into five separate areas and across the height into two separate areas for a total of ten panes. The total window-to-wall ratio (WWR) was 0.50, assuming a floor-to-floor height of 12 ft. Sill height was 3 ft above the floor. Depth of the glazing from the exterior face of the frame to the outdoor face of the glazing was 1.75 inches. The thermally-broken aluminum window frame had a total depth on the interior of 1.75 inches. The interior and exterior framing had a semi-matte finish with a surface reflectance of 0.83. Attached columns and beams projected out from the face of the façade, shading the edges of the window during periods when the sun was at oblique east and west angles.

ASHRAE 90.1-2010 compliant, dual-pane, low-emittance windows were originally installed in the test rooms: ¼-inch PPG Solarban-70XL (surface #2) annealed, ½-inch air gap, ¼-inch clear annealed insulating glass unit. Center-of-glass properties based on NFRC 100-2001 environmental design conditions were solar heat gain coefficient (SHGC) of 0.27, visible transmittance (Tvis) of 0.64, and U-value of 1.5 W/m^2-°C (0.28 Btu/h-ft^2-°F). Whole window properties were SHGC=0.24, Tvis=0.54, and U-value of 2.44 W/m^2-°C (0.43 Btu/h-ft^2-°F).

Title-24 2013 code requires a maximum U-value of 0.32 Btu/h-ft^2-°F, a maximum SHGC of 0.25, and a maximum total window-to-wall ratio of 0.20. Therefore, the properties of the windows were compliant with Title-24 2013 but the window area exceeded the permitted limits of the code to enable more accurate measurement of HVAC loads.

The test and reference conditions for the windows are described in Sections 6.2 and 6.3. When configured for daylighting, the daylight-redirecting systems were installed in the upper 2 ft clerestory portion of the window.

6.1.3. Lighting

In the reference room, the lighting system consisted of (6) 2x4 high-efficiency recessed troffers (HE Williams HETG-S) with (2) 28 W T5 fluorescent lamps per fixture (88 lumens/W). In the test room, the lighting system consisted of (6) 2x4 high-efficiency recessed troffers fixtures (HE Williams HETG-S) with an LED source (98 lumens/W, 80 color rendering index (CRI), color temperature of 3500K). Fixtures are shown in Figure 6.5.

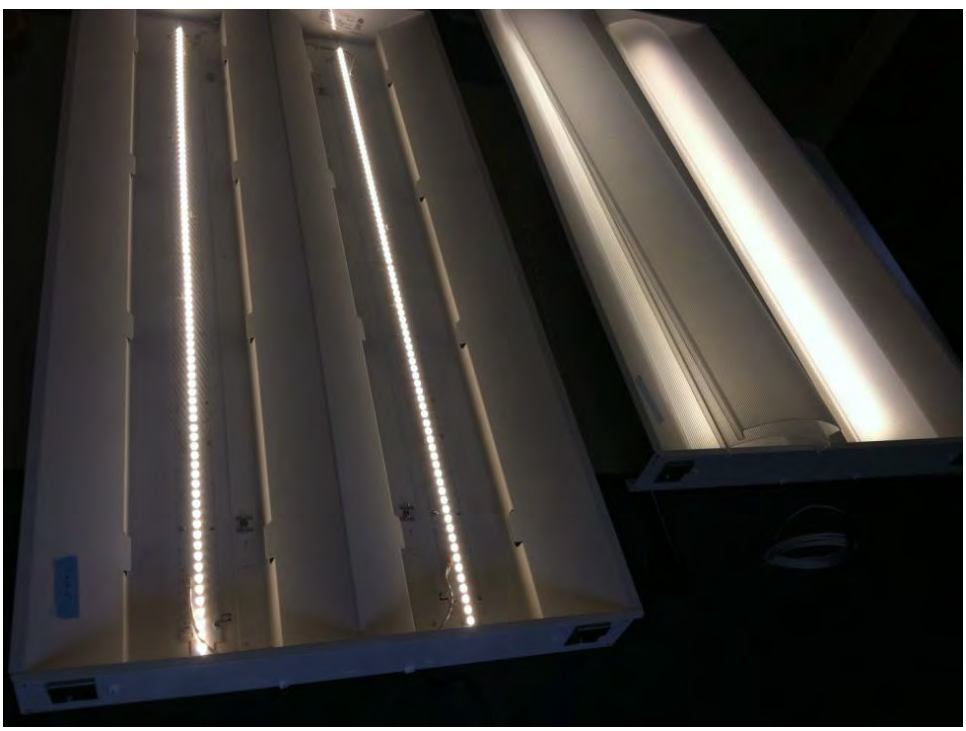

Figure 6.5 Photographs of LED (Left) and Fluorescent (Right) fixtures.

When tuned to produce a light level of 300 lux, the lighting power density in the reference and test rooms was 0.618 W/ft2 and 0.324 W/ft2 or 18% and 57% below Title-24 2013, respectively. Title-24 2013 allows an installed power density of 0.75 W/ft2 (not including the adjustment for occupancy sensors).

The fixtures in each room were continuously dimmable (0-10 V ballasts and drivers) and were outfitted with wireless networked lighting controls (Enlighted) consisting of fixture control units installed in the fixtures and wired to the dimmable ballasts and drivers, sensor units that included motion sensors (for occupancy detection), photosensors (for daylight dimming), and radio units for wireless communication with the controls network. The

controls system also included a wireless gateway to communicate with all 12 fixtures in the network and an energy management server hosting the lighting controls software and database. The lighting controls software was used to commission the schedule of operations, tune fixture power and output, set daylighting targets and sensor sensitivity, trend fixture operation, and troubleshoot operational issues.

PERIOD 1: SUMMER SOLSTICE

The fixtures were installed so that there were two fixtures per row and three rows or zones of fixtures from the front near the window to the rear of the room. In the reference room, the two zones of fixtures nearest the window were dimmed in response to daylight as required by the Title-24 2013 prescriptive code. In the test room, all three zones were dimmed in response to daylight. Occupancy control was not implemented so that energy savings could be isolated to daylighting.

The lighting was commissioned to continuously dim in response to daylight detected by the photosensor and maintain a minimum total workplane illuminance level of 300 lux. Six ceiling-mounted, shielded photosensors (Enlighted) were installed so that each fixture could be dimmed in proportion to available daylight. High-resolution controls are becoming more common. With the advanced lighting control system, the relationship between controller and photosensor is one-to-one. Each controller has its own photosensor plugged into it because the sensor is also the wireless bridge to the network. In a normal commercial setting, a controller could theoretically be wired to power and switch multiple fixtures and controlled by one photosensor, but we were unable to set up the lighting system in this manner because of FLEXLAB's unique plug-and-play approach to power the fixtures. The wiring of the FLEXLAB test rooms is such that the lighting circuits terminate in outlet boxes that the fixtures are plugged into and each lighting circuit is metered separately. The fixture controllers are installed inside the fixture, downstream from the AC plug that powers the fixture.

Due to this set up each fixture had its own controller and it was not possible to put the rows (pairs) of fixtures on one controller. The software also did not allow for multiple fixtures to be assigned to one photosensor. As a work-around, we co-located the photosensors for the pairs of fixtures in each row in the reference room so that the dimming level would be the same.

The photosensors were modified by LBNL in both rooms to restrict their field of view to a 60° cone so that the sensors could better track daylight levels on the workplane surface below. A small cylindrical shield was designed, fabricated, and installed to guard the photosensor from upward rays of daylight being redirected by the daylight-redirecting technology (see section6.3.1 Daylighting Technologies). For ease of installation, the shield was designed to follow the circular contours of and attach to the outside edge of the sensor housing. Note that the occupancy sensor was located in the center of the sensor housing and the photosensor was recessed in an open tube within a very small opening offset from the center of the sensor housing.

Problems with LBNL's illuminance sensors in this first period of measurement prevented continued use of the daylight responsive lighting controls in subsequent periods of measurement (see Section 6.6.1 Lighting Energy Use regarding methods used to correct for these errors). The system could likely have been made to work properly, but the tight test schedule in coordination with another field test prevented us from conducting the necessary testing and recalibrations needed to obtain an accurate response.

Impacts on the illuminance and lighting energy related outcomes of this study were negligible for the first test period, however results from this study reflect a virtual daylight dimming system (with a realistic dimming profile) instead of an actual dimming system as originally intended. This approach has an upside benefit of enabling energy savings to be attributed solely to the daylighting technology instead of combined with an actual dimmable lighting system which may or may not have been optimally configured and commissioned.

Periods 2 and 3: Equinox and Winter Solstice

Due to issues discussed above for test period 1, test periods 2 and 3's lighting system in both test rooms were set to a fixed light output level of 300 lux and lighting energy use was calculated based on available daylight. The method for this calculation is given in Section 6.6.1. There were no impacts of this approach on the measured outcomes – problems with the illuminance sensors were addressed prior to the start of test period 2.

6.1.4. HVAC

Each test room was conditioned with a dedicated air handler unit (AHU) that was operated at a constant volume continuously (24-h schedule) with no outside air. The AHU was located in the rear of the test room in a closet (with exterior insulation) that opened into the test room, although the variable frequency drive for the AHU was located outdoors. Chilled and hot water loops were placed in line with the air flow within the AHU. The AHU supplied air via ducts in the ceiling plenum at temperatures between 15-26°C. Air was returned to the AHU through the entire ceiling plenum creating a second thermal zone with a temperature nearly comparable to that of the occupied zone below. The proportional–integral–derivative controller (PID) controller maintained a cooling setpoint temperature of 21±0.5°C for all hours of the day. During the summer and equinox test periods, heating was not supplied so the indoor air temperature drifted lower during the night. During the equinox period, the temperature drifted no lower than 20.8°C. During the winter test period, heating was supplied so the indoor air temperature was maintained at 21±0.5°C (no deadband or nighttime setback) over the 24-h period.

Interior loads included heat from the windows, lighting, equipment, emulated "occupants", and AHU. The room load was met using the chilled and hot water loops with independent variable flow controls. The HVAC load measurement relied therefore on the accuracy of the flowmeter for the fluid (water), inlet and outlet fluid temperatures, and proper control of the air volume and temperature within the test room.

6.2. Reference Condition

The reference condition for the field tests was defined as the Title-24 2013 compliant window with an indoor venetian blind. The blind had 1-inch wide, matte-white (both top and bottom surfaces), curved aluminum slats (Rvis=0.88) that were fully lowered to cover the full height of the window and set to a fixed, slat angle for each period of testing. The slat angle was set to a cut-off angle that just blocked direct sun: 0°, 20°, and 58° for summer, equinox and summer periods, respectively. The overhead lighting was dimmed according to daylight availability in the primary (0-10 ft) and secondary zones (10-20 ft) as described in Sections 6.1.3 and 6.6.1.

6.3. TEST CONDITIONS

The test condition was defined as the same Title-24 2013 compliant window with the same window area (WWR=0.50) as the reference condition. The window was modified using two types of attachments: a) a daylight-redirecting technology attached to the upper 2 ft clerestory portion of the window with the same venetian blind as the reference room in the lower vision portion of the window, and b) an exterior shading technology attached to the outdoor face of the entire window with no interior venetian blind. The overhead lighting was dimmed using the same method as the reference condition.

6.3.1. DAYLIGHTING TECHNOLOGIES

DAYLIGHTING FILM 1 (DL-LIGHTSHELF1 OR DL-L1)

This 1-mm thick daylighting film (Lucent Optics' Daylighting Fabric™, Model P101504AS_CL) is made of an optically clear, UV-resistant, elastomeric thermoplastic material with embedded microscopic reflectors. The micro-reflectors are formed by a continuous array of parallel slits that are cut into the surface of the film (Figure 6.6). Each micro-slit has optical-quality surfaces that reflect light with high efficiency through total internal reflection (TIR). The micro-reflectors are encapsulated and protected from the environment by laminating the film to a rigid substrate or another flexible film. The width of each micro-slit is quite small allowing the film to maintain transparency of the core film at normal viewing angles.

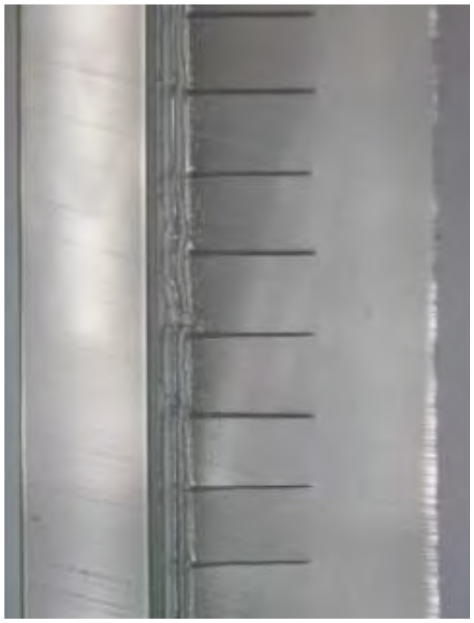

FIGURE 6.6. ENLARGED SECTION OF THE DL-L1 WINDOW FILM SHOWING THE MICRO-SLITS (IMAGE: LUCENT OPTICS, INC.).

The micro-reflectors redirect incident sunlight at angles that are approximately equal to the angle of incidence. Maximum redirection of total incident flux occurs for incident angles between 45-65°; about 80-100% of the incident light is redirected upwards for these incident angles. The fraction of light that is not redirected, is transmitted specularly downwards (like regular clear glass; i.e., without change from the incident direction). The

vendor's manufacturing technology enables one to adjust the spacing of the micro-slits to optimize the film for specific ranges of incidence angles (e.g., for different geographical locations, seasons or window orientation). The film can be transparent with a smooth finish for the clear view option or slightly diffusing with a matte surface finish for a privacy option. Diffusion spreads the outgoing light over a broader range of angles.

The film is designed to be installed on vertical windows at a height of 6-7 ft above the floor and can be used with indoor blinds to reduce glare. The film can be applied right side up, upside down, or facing outdoors or indoors and yield the same optical performance. Unlike the other two films that were tested, the film can be applied without an adhesive since it clings to the window surface. It can also be applied with wet lamination with permanent or removable pressure-sensitive adhesive. The film can be cleaned with a soft cloth or with a mild window cleaning solution.
Because test conditions were rotated every week, we could not adhere the DL-L1 film to the indoor face of the existing windows. Instead, DL-L1 panels (clear view option) were supplied by the vendor for FLEXLAB testing. Each panel was 1.96 ft high of varying widths (3.33 ft and 3.79 ft) to fit into the existing framed opening of the windows. The panels consisted of 3 mm thick acrylic with the DL-L1 film adhered to its surface. Each panel was installed so that its face was in contact with the inboard surface of the existing 1-inch thick, dual-pane window. The film was faced toward the indoors.

The lowest edge of the panel was 7 ft above the finished floor (Figure 6.7 and 6.8). The top edge of the panel was 2.5 inches below the 9 ft ceiling. The window framing projected 1.75 inches out from the outdoor face of the glazing, slightly shading the top edge of the window.

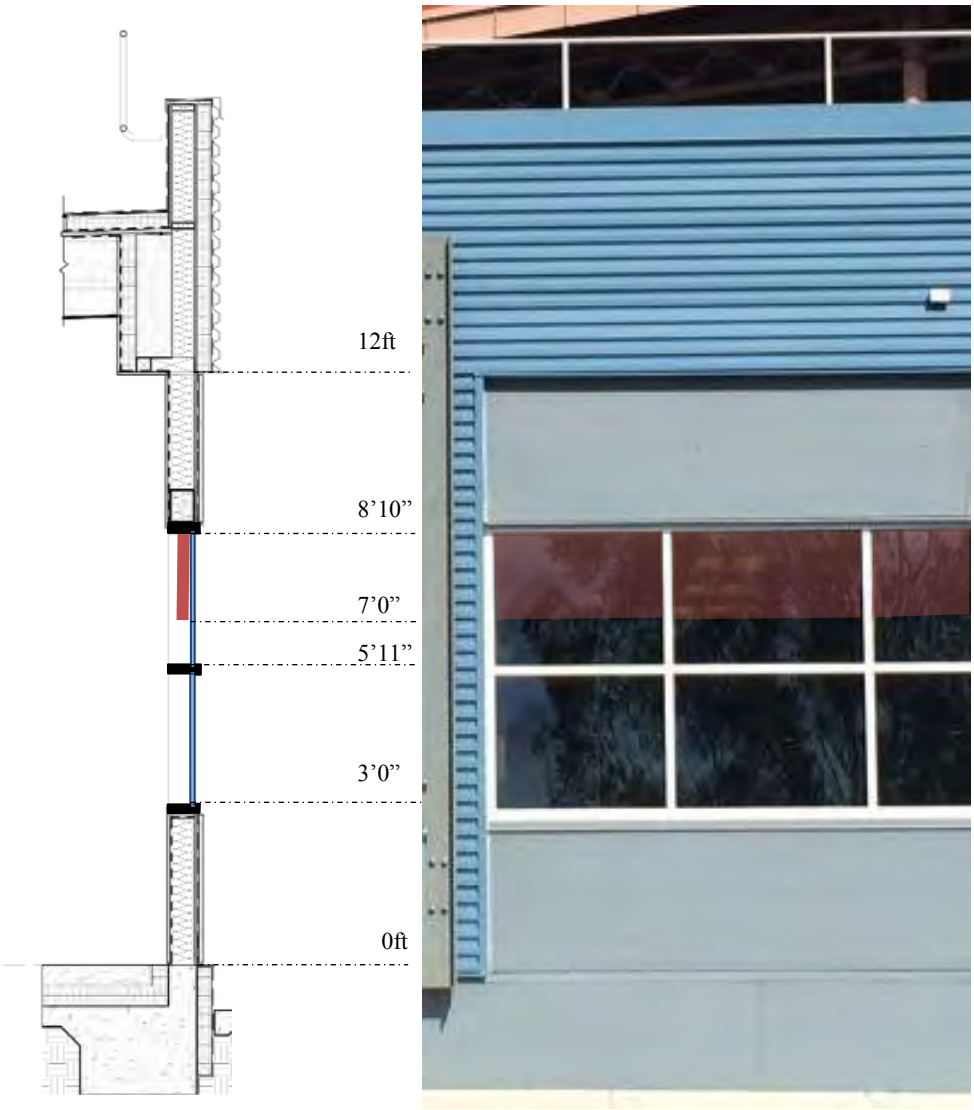

FIGURE 6.7 POSITION OF THE DAYLIGHT-REDIRECTING SYSTEM AT THE WINDOW WALL (AREA INDICATED IN RED).

FIGURE 6.8 ABOVE: PHOTOGRAPH FROM INSIDE THE TEST ROOM LOOKING OUT THROUGH THE DL-L1 FILM IN THE UPPER CLERESTORY PORTION OF THE WINDOW. BELOW, LEFT: CLOSE-UP OF THE MICROSTRUCTURE OF THE FILM; RIGHT: VIEW OF TREE THROUGH THE TRANSPARENT LOWER WINDOW WITH BLINDS AND DL-L1 FILM IN THE UPPER WINDOW.

In the window area below the DL-L1 panel, the same type of venetian blind used in the reference room was installed so that it hung from a beam that was mounted to the inside face of the existing window frame, 1.75 inches away from the inboard face of the window glass. This gap between the beam and window glass was left open so daylight filtered down

to the lower blind and vision window. The beam and header of the blind were positioned so that its top edge was at the same height as the lower edge of the DL-L1 panel; i.e., the blind did not block the daylight area of the DL-L1 panel. The venetian blind was fully lowered over the lower window and the slat angle was set seasonally to block direct sun as described for the reference condition (Section 6.2).

DAYLIGHTING FILM 2 (DL-LIGHTSHELF2 OR DL-L2)

This daylight-redirecting film (SerraGlaze) consists of a single 375 micron thick sheet of PMMA (polymethylmethacrylate) acrylic with micro-replicated prisms designed to create microscopic air pockets that act like light shelves set perpendicular to the faces of the sheet. The film is typically laminated to a pressure sensitive adhesive for mounting to the window (Figure 6.9). The light is reflected upwards through total internal reflection (TIR) when incident sunlight is at an angle that is greater than a critical angle of about 42°. At an incidence angle of around 55°, virtually all the light is redirected and none is specularly transmitted. For sun angles lower than the critical angle, a greater proportion of the light is transmitted downwards specularly with no change in direction.

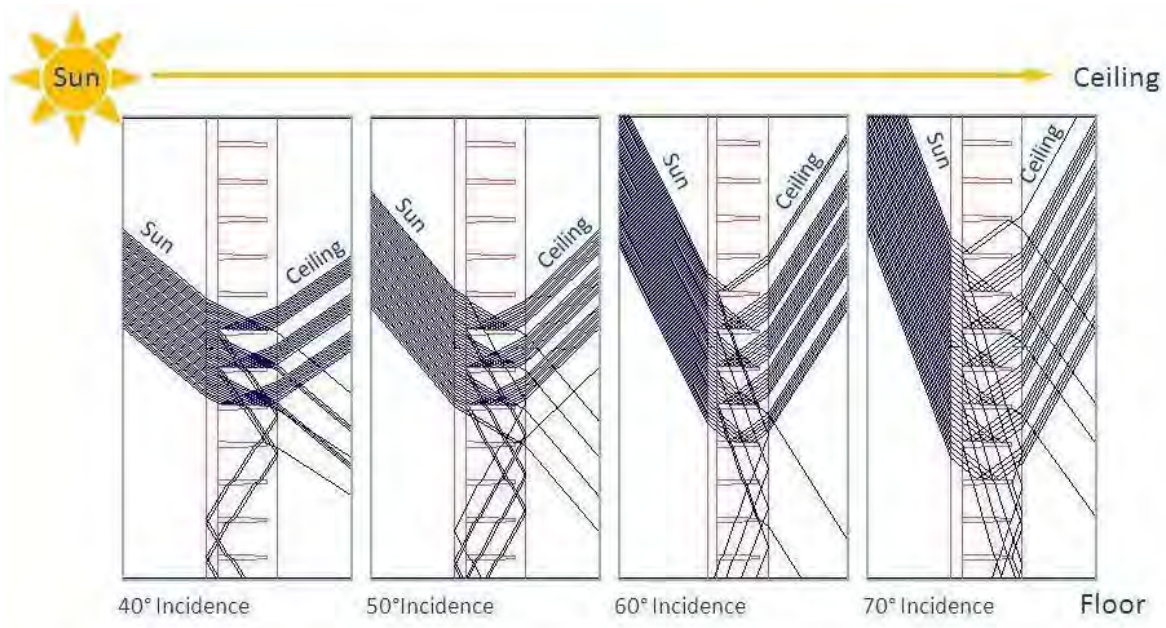

FIGURE 6.9 RAY-TRACING OF THE DL-L2 DAYLIGHT-REDIRECTING FILM (IMAGE: SERRAGLAZE)

Product literature indicates that the film enhances daylighting performance while permitting a nearly normal view to the outdoors. The film is applied to the interior surface of new or existing windows above eye level. Depending on the sun elevation, most or all of the daylight is redirected by the film to the ceiling that then serves to broadly diffuse daylight within the space. The higher the ceiling and greater the installed vertical height of the film, the deeper the daylight penetration into the space. The film is cleaned using conventional glass cleaning products and a soft cloth.

Similar to the DL-L1 film, the DL-L2 film was applied to a 3 mm thick acrylic panel and placed up against the face of the existing upper clerestory window with a venetian blind in the lower window. In a permanent application, the film would be applied directly to the

interior surface of the window. According to the manufacturer, depending on sun angle, Fresnel reflection losses in the test environment (with the additional acrylic panel) would reduce the visible light transmission by 8% or more and reduced total energy savings similarly.

Daylighting film P (DL-Prism, or DL-P)

This thin daylighting film (3M DRF 885-4A-3) consisted of an orderly array of microscopic linear protrusions on a clear film substrate and coated with a pressure sensitive adhesive (PSA) on the backside to enable application to the window. Each protrusion can be described as a prism where sunlight from an incident range of 5-80° is redirected via refraction and total internal reflection. The microprismatic film is combined with a diffusing film to form a single layer that can then be adhered to the indoor surface of existing windows as a retrofit measure or installed as a replacement insulating glass unit in the clerestory portion of the window wall. Sunlight is redirected by refraction to the ceiling plane, which then reflects daylight down to the workplane. Outdoor views are obscured by the film, similar to views through translucent glazing.

Similar to the DL-L1 film, the DL-P film was applied to a 3 mm thick acrylic panel and placed up against the face of the existing upper clerestory window with a venetian blind in the lower window.

Automated dynamic daylight-redirecting blind (DL-Dynamic or DL-Dyn)

This system consisted of an automated daylight-redirecting venetian blind in the upper clerestory window and an automated roller shade in the lower vision window. Both shades were controlled using a single integrated control system with distributed logic (MechoSystems; SolarTrac 50 and Infinity software modules). The upper and lower shading systems are described in more detail in the following sections.

Upper automated daylight-redirecting blind

The upper blinds had concave up, mirrored slats that were tilted automatically on a time-step basis (every 1 min if required) to reflect sunlight to the ceiling at a distance of 20-25 ft from the window. Each slat was 2.125-inches wide with a 1.5 mil metallized polyester film adhered to the upper surface of the slat using an acrylic pressure-sensitive adhesive. The lower surface of each slat had a light gray matte finish. Slats were spaced vertically apart by 2 inches.

The slat angle was determined by the position of the sun. The slats were positioned to one of four possible tilt angles: 0°, 8°, 16°, 24°, and 38° from the horizontal plane and tilted toward the indoors (Figure 6.10 Slat angles for the automated daylight-redirecting blind (DL-Dyn). Left is outdoors, right is indoors. Slats are actually curved, not flat.. The control system set the slat angle irrespective of whether the sun was or was not obscured by clouds. At night, the blinds were fully raised. Slat angle and the raise and lower functions were controlled by adjusting the string ladders that support the slats. The string ladders were adjusted using an encoded tubular motor in the head box of each of the three blinds spanning the width of the test room. Each 3-inch high head box was mounted inboard of the window frame at the ceiling plane.

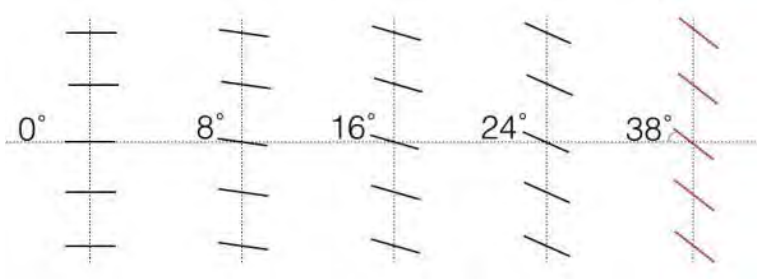

FIGURE 6.10 SLAT ANGLES FOR THE AUTOMATED DAYLIGHT-REDIRECTING BLIND (DL-DYN). LEFT IS OUTDOORS, RIGHT IS INDOORS. SLATS ARE ACTUALLY CURVED, NOT FLAT.

Lower automated roller shade

Similar to the DL-L1 system, the 3-inch high head box for the lower roller shade was mounted so as not to obstruct the upper vision portion of the window wall. The shade fabric was nickel gray in color, with its darker side facing indoors and higher reflectance lighter side facing to the outdoors (MechoSystems shade fabric 6210, 2% openness factor). A single motor was coupled to the three shade bands so that all shades were adjusted to the same height across the window wall. The motorized roller shade was programmed to move to 5 equal preset heights.

The lower shade was automated to limit the depth of sunlight penetration at floor level to 3 ft from the window when it was sunny outdoors (MechoSystems, SolarTrac-50), as determined by an outdoor radiometer mounted on the roof of the test room. If it was not sunny, then the shade was fully raised. The system did not control the shades for glare or brightness.

The four daylight-redirecting technologies are shown in Figure 6.11.

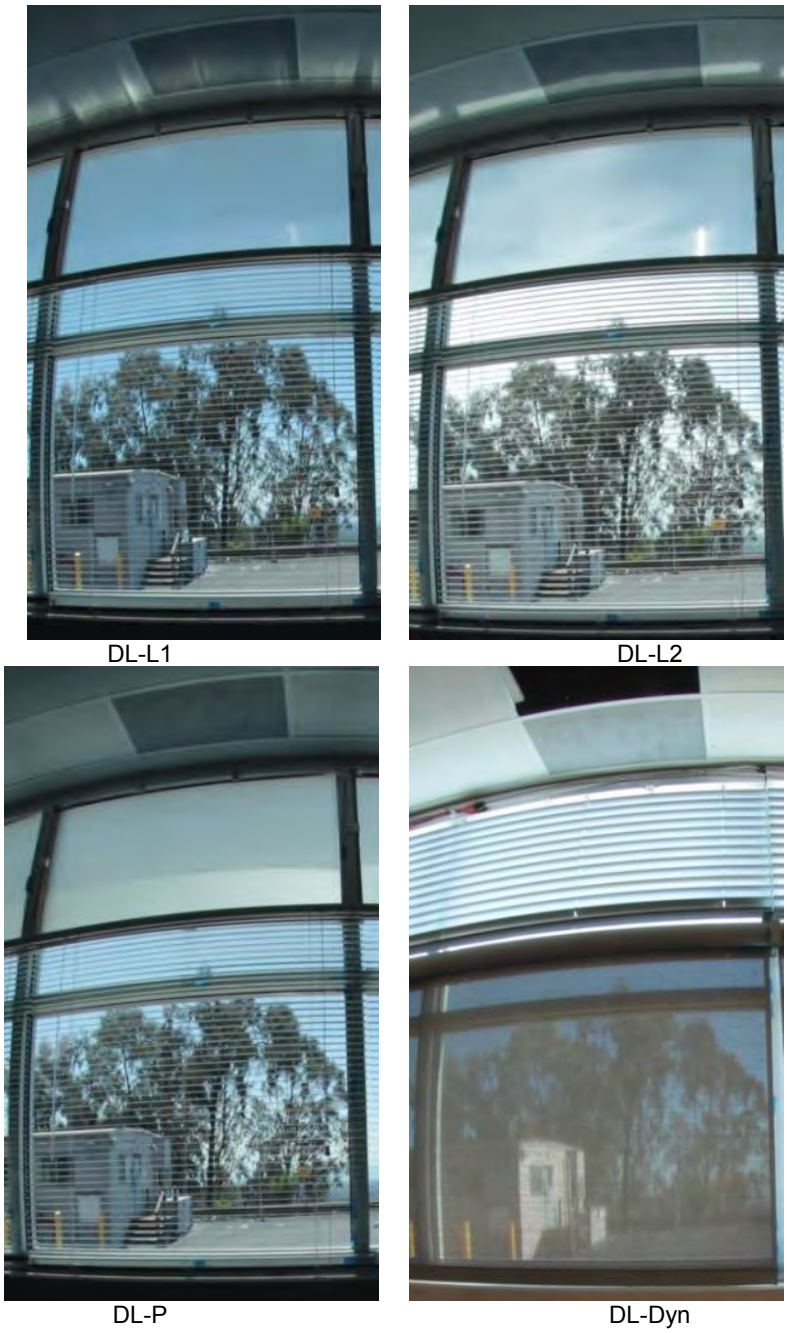

FIGURE 6.11 PHOTOGRAPHS OF THE FOUR DAYLIGHT-REDIRECTING SYSTEMS. DL-L1 AND DL-L2 HAVE A SEE-THROUGH VIEW THROUGH THEIR FILM. DL-P HAS AN OBSCURED VIEW SINCE THE MATERIAL IS TRANSLUCENT. THESE THREE SYSTEMS HAVE A VENETIAN BLIND IN THE LOWER WINDOW. THE DL-DYN HAS A PARTIAL VIEW THROUGH THE UPPER CLERESTORY AREA, DEPENDING ON SLAT ANGLE, AND A FILTERED VIEW THROUGH THE ROLLER SHADE FABRIC IN THE LOWER WINDOW.

6.3.2. SHADING TECHNOLOGIES

STATIC EXTERIOR MICRO-LOUVERED SCREEN (S-LOUVER OR S-L)

The static metal solar screen fabric (Smartlouvre Technology Ltd, MicroLouvre) consisted of 1.25 mm wide, 0.22 mm thick, flat bronze with a matte black finish, horizontal slats held in place vertically with stainless steel lacer wiring. The slats were inclined at an angle of 17° (lower edge towards the outdoors). The slats block direct sun with a cut off angle of 40°. The edges of the fabric are held in place with a EPDM gasket within a light-weight, 0.5-inch deep aluminum frame on the outside of the window. The screens weigh about 2 kg/m^2 (0.41 lb/ft^2) and being 80% open, has low wind resistance. The fabric can be used on a fixed or sliding frame or hinged to allow for cleaning. It can also be operable so that it can be rolled up into a head box. The static screen was evaluated in this study.

Each screen was sized to match the width of each of the windows. The height of the screens was sized to match the size of windows for a planned reconfiguration of the window wall so the edges of the screen in this study blocked a portion of the upper clerestory window (Figures Figure 6.12 and Figure 6.13).

The distance between the inside face of the screen and the outdoor face of the window glazing was 2.125 inches. The 0.5-inch wide face of the solar screen frame was in full contact with the face of the thermally-broken window frame. Each panel was held in place using a small L-shaped metal clip over the edge of the frame.

FIGURE 6.12 PHOTOGRAPH OF THE EXTERIOR SHADING S-L SYSTEM FROM THE OUTDOORS

FIGURE 6.13 PHOTOGRAPH OF THE EXTERIOR SHADING S-L SYSTEM FROM THE OUTDOORS.

AUTOMATED DYNAMIC EXTERIOR ROLLER SHADE WITH SIDE RAILS (S-DYNAMIC OR S-DYN)

The automated exterior roller shade (FlexShade Zip™, Draper, Inc.) consisted of (2) 90.875 by 80.375 inch and (1) 48 x 80.375 inch, black (both sides) woven fabric, motorized shades (Mermet Satine Charcoal 5%) with a 5% openness factor. The shades were raised and lowered with an AC tubular motor located at the head of the window (Figure 6.14).

FIGURE 6.14 PHOTOGRAPH OF EXTERIOR SHADING SYSTEM S-DYN.

Zippers along the side edges of the roller shade panel were held in place by fabric retainers within aluminum side channels, allowing the fabric shade to remain lowered under high winds. The vendor indicated that the system had been tested in a wind tunnel and was capable of withstanding wind speeds of up to 90 mph. A full or partially lowered shade should not be adjusted during high wind conditions, in freezing temperatures (due to potential ice build-up in the side channels), or if there is dirt build up or other obstructions that could interfere with the operation of the system.

The distance between the inside face of the fabric and the outdoor face of the window glazing was 2.25 inches. When fully raised, the shade lower hembar and headbox shaded

the upper vision portion of the window by 5.8-6.2 inches. The side rails shaded the edges of the vision portion of the window by 0.25-0.94 inches.

The shade was adjusted automatically to move to one of five heights to control glare and solar heat gains based on readings of exterior horizontal illuminance (Embedia Solarai ControlPoint MSTP IP). The shade was lowered when the sensor reading exceeded 40,000 lux (3-second delay) and was raised when the reading fell below this threshold (20-min delay). The shade was also raised when the wind speed exceeded 8 m/s (18 mph). Sensors used for control were installed on the southeast side of the roof of test room 3B. Shade status data were not available.

6.4. Test Plan

As described in Section 5, six façade technologies and the reference condition were evaluated over a six month, solstice-to-solstice period from June 22, 2015 to January 11, 2016. Each test condition was installed and evaluated for one week during each of the three equinox or solstice periods, irrespective of weather conditions. The core period of evaluation was between 6 AM to 6 PM but monitoring occurred over the full 24-hour period. On occasion, maintenance or operational changes were made in the evenings between 6-9 PM. The reference condition and all salient aspects of the test condition (lighting, HVAC, equipment loads) remained the same between change out of each of the six technologies. Test periods were as follows:

- Summer solstice: June 22 to August 5
- Equinox: September 21 to November 8
- Winter solstice: November 23 to January 11

6.5. Instrumentation Plan

The FLEXLAB facility is fully instrumented with hundreds of sensors available for evaluating indoor environmental conditions and performance of the various installed systems in the FLEXLAB. In general, data were sampled at a 1 sec interval then averaged and recorded at a 1-min interval. Key data used in this analysis are listed in Table 6.1 and are shown in Figure 6.15. In addition to this monitored data, data from the vendor's control systems were used to characterize the performance of the operable fenestration systems.

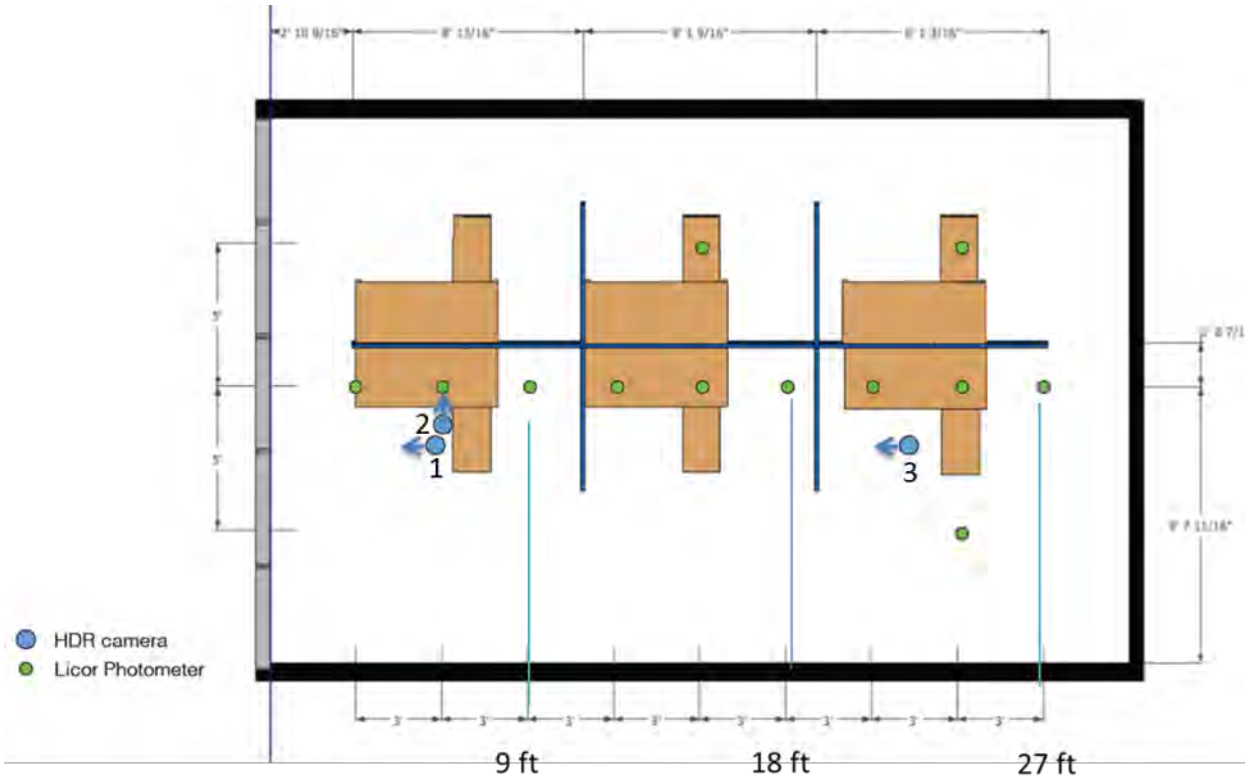

FIGURE 6.15 FLOOR PLAN SHOWING LOCATION OF FURNITURE AND SENSORS USED TO EVALUATE LIGHTING AND VISUAL COMFORT PERFORMANCE. SENSORS RELATED TO MONITORING THE HVAC LOAD AND ELECTRICAL SYSTEMS ARE NOT SHOWN.

TABLE 6.1 LIST OF FLEXLAB INSTRUMENTATION

NO. OF UNITS	MONITORED VARIABLE	SENSOR	RANGE, ACCURACY	SAMPLE AND RECORD RATES
Outdoor weather data (roof of FLEXLAB facility)				
1	Exterior global and diffuse horizontal illuminance	Delta-T Devices, BF5 Sunshine Sensor	0-200 ± 0.6 klux	1 scan/s, 1-min average
1	Exterior global and diffuse horizontal irradiance	Delta-T Devices, SPN1 Sunshine pyranometer	0-2000 W/m^2, ± 8%	1 scan/s, 1-min average
1	Outdoor dry-bulb temperature, shielded	Building Automation Products, Inc., BA/10K-2(XP) thermistor	-7–48°C, ± 0.5°C	1 scan/s, 1-min average
Indoor measurements for each test room				
12	Workplane illuminance	Li-Cor, LI-210SA photometer	Period 1: range of 0-125,000 ± 40 lux for 10 sensors; 12,500 ± 4 lux for 2 sensors; Periods 2&3: 10,000 ± 3 lux for sensor nearest window; 5000 lux ± 1.5 lux for all other sensors	1 scan/s, 1-min average
3	Field of view luminance	Canon EOS 60D and 5D, Sigma 4.5 mm fisheye lens	0-100,000 cd/m^2, 5% of reading	1 scan/s, 1-min average
2	AHU chilled and hot water flow rate	Siemens, SITRANS F M Mag 5100-W electromagnetic flow meter	Period 1: 0-10 gpm; Period 2-3: 0-2 gpm, ± 1% of reading both periods	1 scan/s, 1-min average
2	AHU chilled and hot water temperature	Building Automation Products, Inc., BA/10K-2(XP)-I-4" Thermistor	0-100°C, ± 0.03°C	1 scan/s, 1-min average
10	Electricity use (AHU, lights, plug)	Verivolt Envoy current transducers, Triad VPT12 voltage transformer	0 to 1000 W or 3500 W, 2% of reading	1 scan/s, 1-min average

6.6. EVALUATION METRICS

6.6.1. LIGHTING ENERGY USE

Lighting energy use of each daylight controlled fluorescent or LED fixture was metered directly using instrumentation indicated in Table 6.1 of the instrumentation plan. The measured data were then post processed using methods described below for each period of measurement. The resultant values represent the energy consumption in each of three 10 ft deep daylit zones using a lighting control system that continuously dimmed the lights in proportion to available daylight to meet the setpoint workplane illuminance level of 300 lux.

Daily lighting energy use was computed for the period of 8 AM to 6 PM Local Time to evaluate savings based on a typical office work schedule. Savings reflect the impact of the window on lighting energy use without occupancy-based lighting controls.

Period 1: Summer Solstice

The lighting control system was set up to dim in proportion to available daylight as described in Section 6.1.3. During Period 1 testing, an evaluation was conducted to determine if the system was dimming as intended. The lighting system was found to dim improperly, resulting in inadequate illuminance levels in some areas. The problem was caused by an error in the initial set up of the illuminance sensors where the calibration coefficients were improperly assigned, which then affected commissioning of the lighting control system (the error was therefore unique to this setup, not to the control system design). As a result, a decision was made to evaluate the energy savings potential of the facade systems based on measured daylight illuminance. This also eliminated the codependency of results on the design and commissioning of a specific lighting system.

To determine daylight illuminance, nighttime tests were conducted where each fixture was dimmed while all other fixtures were turned off. The power level of each fixture was correlated to the electric lighting illuminance at each of the workplane sensors. These correlations were then used to derive the total electric lighting contribution to each of the sensors during the day. This total electric lighting contribution was then subtracted from the sensor's total illuminance to arrive at the daylight illuminance at that sensor.

The daylight illuminance at the sensor was then used to determine lighting energy use based on the dimming profile of the fixtures (i.e., LED in the test room and fluorescent in the reference room). Sensors at a distance of 6 ft, 15 ft and 24 ft were used to determine the lighting energy use in the first, second, and third row of fixtures from the window, corresponding to zone depths of 0-10 ft, 10-20 ft, and 20-30 ft, respectively. With this method, there was no co-dependency between zones; i.e., the fixtures in each zone were dimmed to provide the setpoint illuminance of 300 lux using only the two fixtures in the 10 ft zone. For the reference condition, the third zone (20-30 ft) was not dimmed, as defined by the Title-24 2013 code.
Note that during Period 1, ten of the 12 amplifiers for the illuminance sensors in both test rooms were erroneously set to the "outdoor" range with a maximum illuminance of 125,000 lux for the 0-10 V range. The data acquisition system was able to read this data at a resolution of 0.0003 V or an equivalent of 38 lux but the data were susceptible to noise when the signal was lower than 0.001 V or 125 lux. Data was measured every second and then recorded as a one minute average which reduced this noise to about 40 lux. (The other two amplifiers were set to a range of 12,500 lux ± 4 lux.) When analysis was conducted on Period 1 data, a 5-min running median filter was applied to the one minute data to filter out outliers due to the remaining electronic noise. Before the start of Period 2, the amplifiers were corrected to a range of 10,000 ± 3 lux maximum for the first sensor nearest the window and a 5000 ± 1.5 lux maximum for all other sensors.

Periods 2 and 3: Equinox and Winter Solstice

During the subsequent two periods, the lighting control system was set up to provide a fixed illuminance level of 300 lux on the workplane. Daylight illuminance and lighting energy use were determined using the methods used to analyze the first period of measurement.

6.6.2. HVAC Load

In the analysis, the HVAC load due to the window wall was determined for each test room by computing the total heating and cooling load extracted by the HVAC system. Internal loads were subtracted from this load in order to isolate the measured load to the window wall.

The measured HVAC load was calculated as:

Equation 1: QRoom

$$Qroom = Cooling - Heating - Lighting - Equipment - AHU \quad (1)$$

where,

Equation 2: Cooling and Heating

$$Cooling\ or\ Heating = \rho * Cp * f * (Tin - Tout) \quad (2)$$

Where,
ρ = density of water
Cp = specific heat of water
f = measured flow rate
Tin = inlet temperature of the chilled or hot water loop
Tout = outlet temperature of the chilled or hot water loop

Lighting, equipment, and AHU were measured heat added by the respective systems. These were measured directly using current transducers and voltage readings (accuracy was within ±3% of reading). A 100% conversion of the internal loads to room heat gains was assumed since all equipment operated within the boundary of the room interior.
All data were sampled every 1 s then averaged over 1 min. These data were then averaged over hourly intervals (the average value for 11:00-11:59 is given for hour 12:00 PM). The daily cooling load due to the window wall, Qw, was then computed over the 10-h period defined by 8:00 AM to 6:00 PM LT.

Peak cooling load due to the window wall was defined in each room by the hour when the cooling load was greatest over the 10-h period. The peak cooling load reduction due to the solar control technology was determined by the difference in peak load in each room for non-coincident hours.

No corrections were made to the data to account for differences in HVAC operations, construction of the test rooms, infiltration, or exposure to the outdoor environment. Models to correct for these differences had not yet been developed by the conclusion of this study. HVAC energy use is therefore indicative of the load reductions due to the solar control devices. HVAC loads due to the daylighting devices were not reported in this study because there was insufficient resolution/ accuracy to detect small (10% or less) between-room differences in HVAC energy use at this time.

6.6.3. Visual Comfort

In this analysis of innovative technologies for commercial office buildings, visual comfort is a constraint that determines the effectiveness and applicability of an energy efficiency technology for broad market adoption. Visual comfort is defined by subjective impressions of the visual environment and is commonly defined by the absence of discomfort due to glare and the amount and distribution of light. Because there is no single metric that defines visual comfort and outcomes are dependent on how the assessment is made both spatially and temporally, an evaluation of visual comfort can be complicated.

The first and most critical factor in this analysis is the evaluation of discomfort glare, which causes a gradual reduction in visual performance and feeling of discomfort resulting from tiring of the eyes, headaches, eye strain, etc. A second factor, visibility of a task, is defined in part by an adequate amount of light for a given task (i.e., reading, writing, computer work, face-to-face communications) and how uniformly the light is distributed over the task area. The final factor, poor uniformity, can cause visual discomfort as the eye adapts to both bright and low lit areas within the field of view. The factors and acceptability criteria used in this study to evaluate these three aspects of visual comfort are defined below.

Discomfort Glare

Discomfort glare is the uncomfortable physical sensation produced by luminance within the visual field that is greater than the luminance to which the eye is adapted to. We have been able to only recently measure field of view luminance using digital imaging systems developed over the past 15 years. Accordingly, there has been significant work conducted worldwide to develop new metrics for visual discomfort using this new measurement capability. In this study, we use the daylight glare probability (DGP) index to evaluate discomfort glare (Wienold and Christoffersen 2006). The index defines comfort based on acceptability thresholds and a method for assessing time-varying performance so that an overall assessment can be made.

Field of view, hemispherical luminance measurements were made with commercial grade digital cameras (Canon 5D and 60D) equipped with an equidistant fisheye lens. We selected three seated view positions within each of the test rooms: a) facing the window 6 ft from the window (view 1), b) looking toward the west side wall 6 ft from the window (view 2), and c) looking toward the window 23 ft from the window (view 3) (Figure 6.15). All measurements were taken at a seated eye height of 4 ft above the floor.

Bracketed images (f-stop=5.6, between 4-7 images, depending on the brightness of the scene) were taken automatically (software: *hdrcaposx*) at 5-min intervals from 7:00 AM to 7:00 PM. These low dynamic range (LDR) images were compiled into a single high dynamic range (HDR) image using the *hdrgen* tool, where the camera response function was determined by the software and the vignetting function of the fisheye lens was determined from prior laboratory tests at LBNL. Vertical illuminance was measured adjacent to each camera's lens, immediately before and after the bracketed set of images, then used in the *hdrgen* compositing process to convert pixel data to photometric data. A lesser number of bracketed images were taken at low light levels to avoid excessively long exposures.

Evaluation of visual comfort was conducted using these HDR images with the *evalglare* software tool. This tool identifies glare sources within a fisheye HDR image then computes various discomfort glare metrics, including daylight glare probability (DGP). HDR images were first reduced to 799x799 pixels (pfilt -x /4.31 -y /4.31) prior to use in *evalglare*.

Arbitrarily located glare sources with a solid angle greater than 0.002 steradians (st) were identified in each image by *evalglare* using the default method: pixels with a luminance greater than the threshold luminance were identified as a potential glare source. The threshold luminance was defined as five times the average luminance within the entire 180° field of view or scene. Glare source pixels were then merged to one glare source given a search radius between pixels of 0.2 steradians. Non-glare source pixels were included with glare sources if they were surrounded by a glare source (i.e., smoothing option was used). Luminance peaks (>50,000 cd/m^2) were extracted as separate glare sources.

The DGP was derived from HDR luminance data and subjective responses from 76 people in a full-scale daylit office mockup with a variety of façade technologies, including sunlight-redirecting systems. The DGP describes the probability that a person is disturbed by glare from daylight (0-1 range of values):

EQUATION 3: DGP

$$\mathrm{DGP} = c_1 E_v + c_2 \log\left(1 + \sum_i \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{c_4} P_i^2}\right) + c_3 \quad (3)$$

where,

c1=5.87x10^{-5}, c2=9.18x10^{-2}, c3=0.16, and c4=1.87;

Ev = vertical illuminance at the eye (lux);

Ls = luminance of the source I (cd/m^2);

ωs = solid angle of source I (steradians, st); and

P = position index.

DGP is valid between 0.2-0.8 when the vertical illuminance at the eye is greater than 380 lux. Subjective ratings correspond to DGP values as follows:

- 0.30 "just imperceptible"
- 0.35 "just perceptible"
- 0.40 "just disturbing"
- 0.45 "just intolerable".

DGP values were computed for each 5-min interval from 8 AM to 6 PM. Since some small percentage of discomfort is tolerated by occupants, long term assessments were made based on the percentage of day when the DGP exceeded threshold values. The maximum DGP value for 95% of the data and the average DGP for the top 5% of DGP data were calculated then used to classify the level of discomfort glare, as defined in Table **6.2**.

TABLE 6.2 DAYLIGHT GLARE PROBABILTY (DGP) CLASSIFICATION

MAX DGP OF 95% OFFICE TIME		AVERAGE DGP OF 5% OFFICE TIME	CLASS	MEANING
≤ 0.35 ("imperceptible" glare)	And	≤ 0.38 ("perceptible" glare)	A	Best
	And	> 0.38	B	Good
≤ 0.40 ("perceptible" glare)	And	≤ 0.42 ("disturbing" glare)	B	Good
	And	> 0.42	C	Reasonable
≤ 0.45 ("disturbing" glare)	And	≤ 0.53 ("intolerable" glare)	C	Reasonable
	And	> 0.53	Discomfort	Discomfort
> 0.45			Discomfort	Discomfort

A detailed analysis was conducted focusing on discomfort glare under stable clear sky conditions. Annual performance was based on a comparative analysis of all days collected for each system over the solstice-to-solstice period.

DAYLIGHT ADEQUACY

Useful daylight illuminance (UDI) provides a method of evaluating the adequacy of daylight in a space, based on the percentage of time when illuminance levels are excessive, within an acceptable range, or are too low. A space where the majority of the time the daylight illuminance levels are in the "too low" or "too high" ranges of illuminance defined by the UDI would be considered inadequately daylit and gloomy or too bright and glary, respectively (Nabil and Mardaljevic 2006).

Workplane illuminance was measured in the center of the space at incremental distances of 3 ft from the window wall. For each of the 10 ft deep window, center or rear zones, illuminance data from each of the three sensors were binned based on three ranges of illuminance: 0-100 lux, 100-2000 lux, and greater than 2000 lux for the period from 8 AM to 6 PM. For each bin, we then calculated the percentage of day that daylight was within the defined binned range. A daylighting system that is able to deliver daylight to the workplane within the range of 100-2000 lux for the majority of the day in all areas of the room would be considered to be successful in providing qualitatively acceptable daylight.

Annual performance was based on a comparative analysis of all days collected for each system over the solstice-to-solstice period.

DAYLIGHT UNIFORMITY

Uniformity of illuminance across a task surface has historically been used to evaluate the degree of brightness contrast within a local field of view and therefore provides an assessment of visual comfort. For this study, we evaluate the uniformity of the daylight distribution across the 30 ft depth of the space to determine how well the daylight-redirecting technologies distribute light within a deep space. Conventional sidelight windows create an asymptotic distribution of daylight, where light levels near the window are typically a factor of 10 or more greater than light levels 15 ft or more from the window. If significant redirection is occurring across the depth of the space, then illuminance uniformity should be improved.

The uniformity ratio was defined by a ratio of minimum to average workplane illuminance across the 30 ft deep office zone. This ratio was computed for each 1-min time step between 8 AM to 6 PM then averaged to provide a daily value. For tasks performed within a limited area (e.g., desk area of 2 ft width), the Illuminating Engineering Society of North America (IESNA) recommends a work plane uniformity ratio of 0.8 for office spaces. With 3 ft or more between sensors, the ratio within a range of 1-5 is likely acceptable. A comparative analysis of all measured days over the solstice-to-solstice period was used to evaluate the systems.

7. RESULTS

7.1. DAYLIGHTING TECHNOLOGIES

7.1.1. SOLAR-OPTICAL CHARACTERISTICS

A sample of the daylighting films was adhered to a 1x1 ft, 3 mm, uncoated clear glass substrate and measured using a scanning goniophotometer. The resultant bidirectional scattering distribution function (BSDF) data characterizes how the systems transmit light from a particular incident direction (Figure 7.0). These data can be used in energy simulation modeling tools like Radiance and EnergyPlus to evaluate annual performance for any arbitrary building design and climate.

Figures 7.1 and 7.2 show the outgoing distribution of light from the DL-L1 and DL-L2 systems for six incident directions of light. For a south-facing window, these directions would coincide with a solar azimuth angle of 0° and 45° (from due south) and and solar altitude angles of 28°, 52°, and 75°, which correspond approximately to the minimum and maximum solar altitudes for the summer and winter solstices for the Berkeley latitude. The manufacturer of the DL-P film did not provide a sample for measurement. The dynamic blinds (DL-Dyn) were also not measured.

For an ideal system, the outgoing flux would exit in the upper half of the circle about mid-height, representing sunlight being redirected upwards at a shallow angle towards the back of the room. In Figures 7.1 and 7.2 (lower row), we see that this ideal redirection occurs during the winter period around noon.

To avoid direct sunlight and the need for indoor shades, an ideal system would transmit little to no flux in the lower half of the circle, representing daylight that passed through the system without change in direction. In Figures 7.1 and 7.2, there is some directly transmitted sunlight. For this system, the manufacturer indicated that indoor blinds would be needed for some applications.

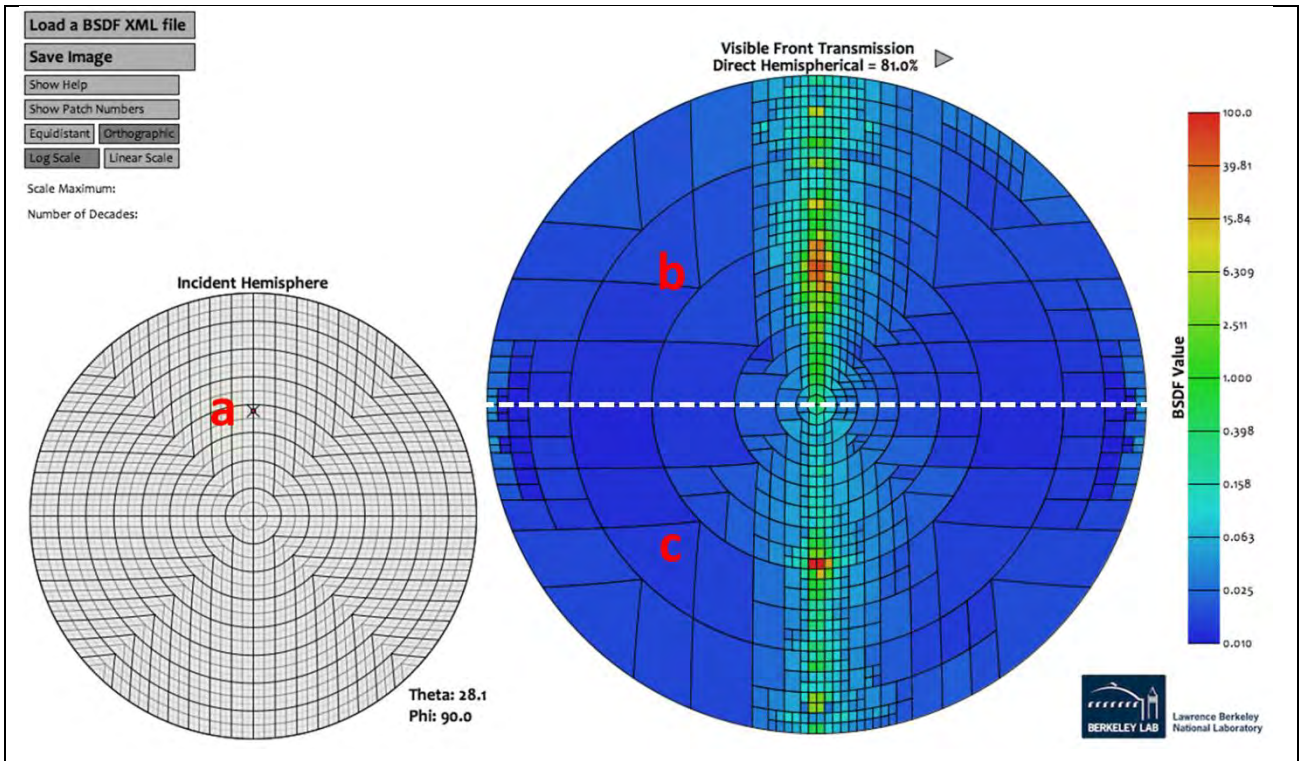

FIGURE 7.0 VISUALIZATION OF THE BSDF FOR THE DL-L1 REDIRECTING FILM. INCOMING LIGHT STRIKING THE FILM AT AN ANGLE ABOVE THE HORIZON (LOCATION "X" WITH LABEL "A") WILL EXIT THE FILM EITHER INTO AREA "B" (UPPER HALF OF THE BLUE RIGHTHAND HEMISPHERE) TOWARDS THE CEILING OR INTO AREA "C" (LOWER HALF OF THE HEMISPHERE) TOWARDS THE FLOOR.

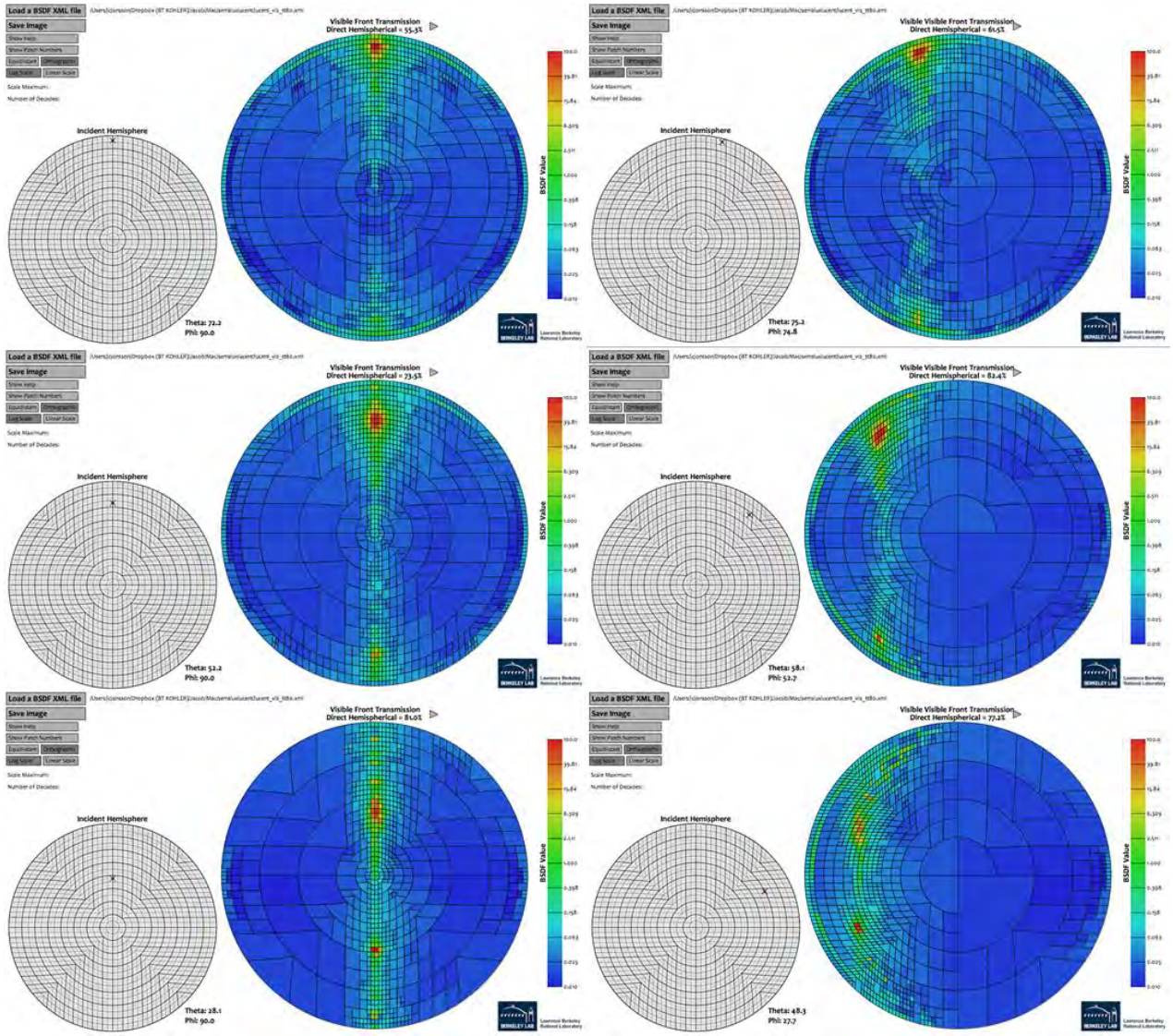

FIGURE 7.1 VISUALIZATION OF THE BSDF FOR THE DL-L1 REDIRECTING FILM: AZIMUTH=0° LEFT COLUMN, AZIMUTH = 45° RIGHT COLUMN; SOLAR ALTITUDES OF 75° TOP ROW, 52° MIDDLE ROW, AND 28° LOWER ROW, ASSUMING A SOUTH-FACING WINDOW.

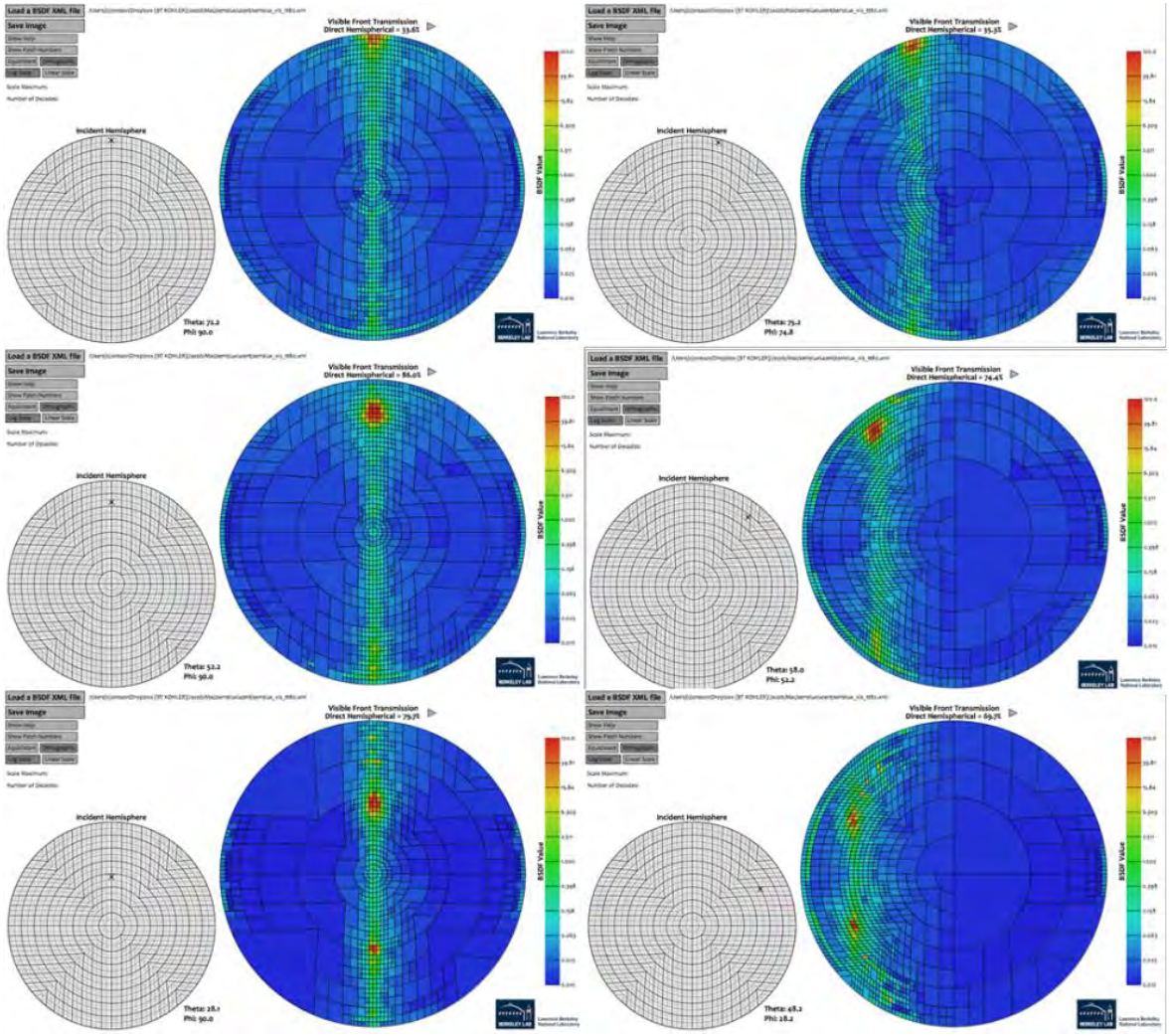

FIGURE 7.2 FIGURE 7.2. VISUALIZATION OF THE BSDF FOR THE DL-L2 REDIRECTING FILM : AZIMUTH=0° LEFT COLUMN, AZIMUTH = 45° RIGHT COLUMN; SOLAR ALTITUDES OF 75° TOP ROW, 52° MIDDLE ROW, AND 28° LOWER ROW, ASSUMING A SOUTH-FACING WINDOW.

7.1.2. DAYLIGHTING PERFORMANCE UNDER CLEAR SKY CONDITIONS

For these subsequent sections, monitored data from the FLEXLAB are presented. In this section, we present a detailed example of results for one day to explain how to interpret the performance data then discuss trends in solstice-to-solstice performance in Section 7.1.3.

An example of the spatial distribution of daylight produced by one of the daylight-redirecting systems under equinox clear sky conditions (October 5) is shown in Figure 7.3. Daylight illuminance was calculated using the method described in Section 6.6.1. The data were plotted with two y-axis scales: 0-6000 lux to show the distribution across the 30-ft depth of the test room and 0-600 lux so that the difference in illuminance between the reference and test rooms in the rear zone could be more easily compared. For example, at noon the DL-L2 system provides significantly greater daylight in the area nearest the window and about 50-100 lux greater illuminance in the 20-30 ft area at the rear of the room compared to the reference condition.

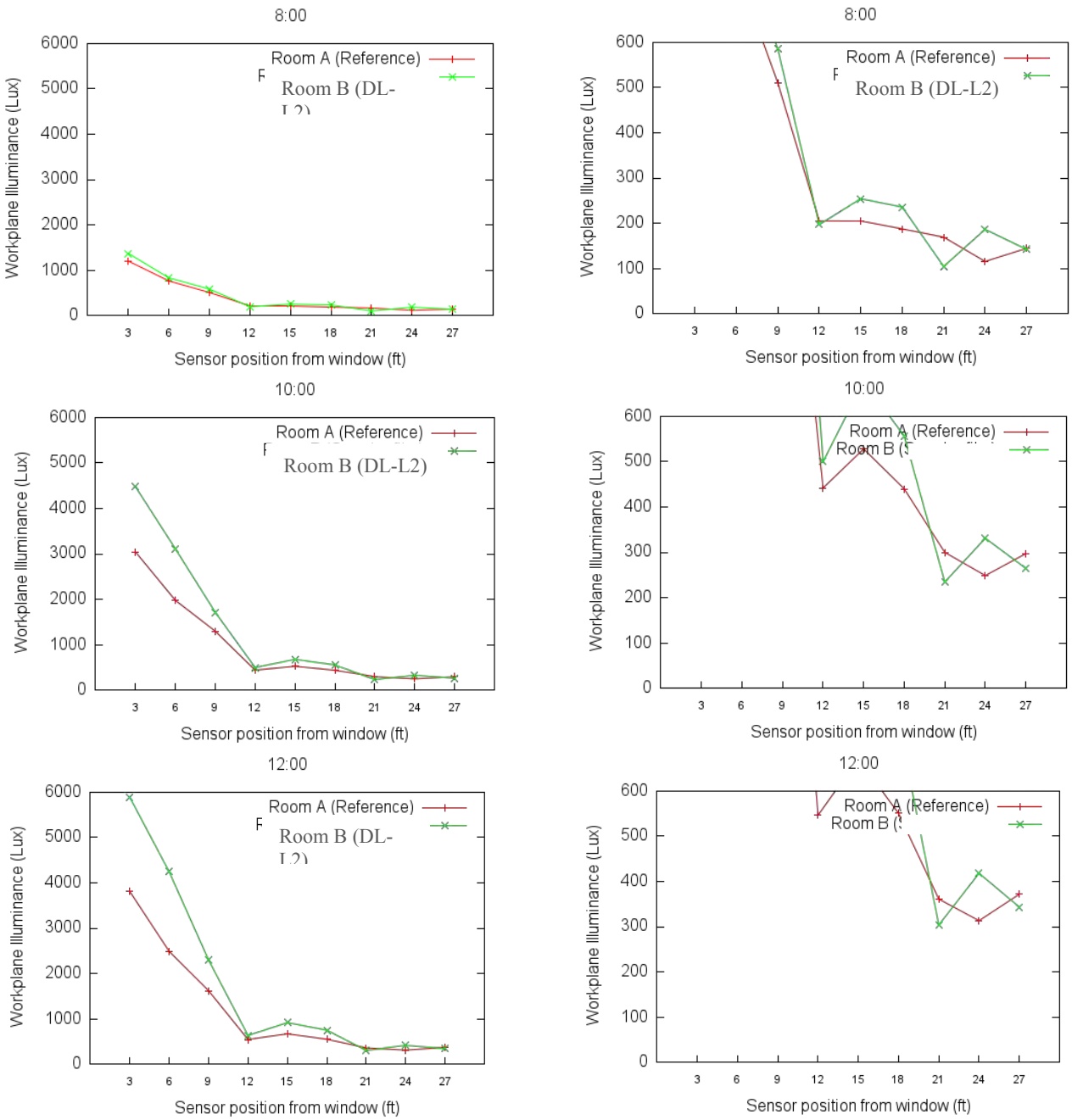

FIGURE 7.3 WORKPLANE ILLUMINANCE (LUX) DUE TO DAYLIGHT VERSUS DISTANCE FROM THE WINDOW (FT) FOR 8:00 AM, 10:00 AM, AND 12:00 PM STANDARD TIME (ST) FOR THE REFERENCE (ROOM A) AND TEST (ROOM B, DL-L2) CONDITIONS UNDER CLEAR SKY CONDITIONS ON OCTOBER 5, 2015. THE RIGHTHAND COLUMN OF GRAPHS REPLICATES THE LEFTHAND GRAPHS BUT HAS A LOWER RANGE FOR THE Y-AXIS.

The same data are presented in a falsecolor spatial-temporal map in Figure 7.4 where the x-axis is distance from the window (3 ft intervals), the y-axis is time of day (1-min resolution), and the z-axis is daylight illuminance. This figure illustrates where and when the daylight-redirecting system is effective at increasing daylight levels. During the equinox, both the intensity and depth of increased illuminance occurs primarily during the core hours of 10:00 AM to 2:00 PM to a depth of about 10-20 ft (the 50-100 lux increase is

just discernible at this scale). This distribution is consistent with the solar-optical characterization for the equinox period (see Figure 7.2 in Section 7.1.1) where the outgoing angle of redirected sunlight places the flux primarily on the ceiling near the window.

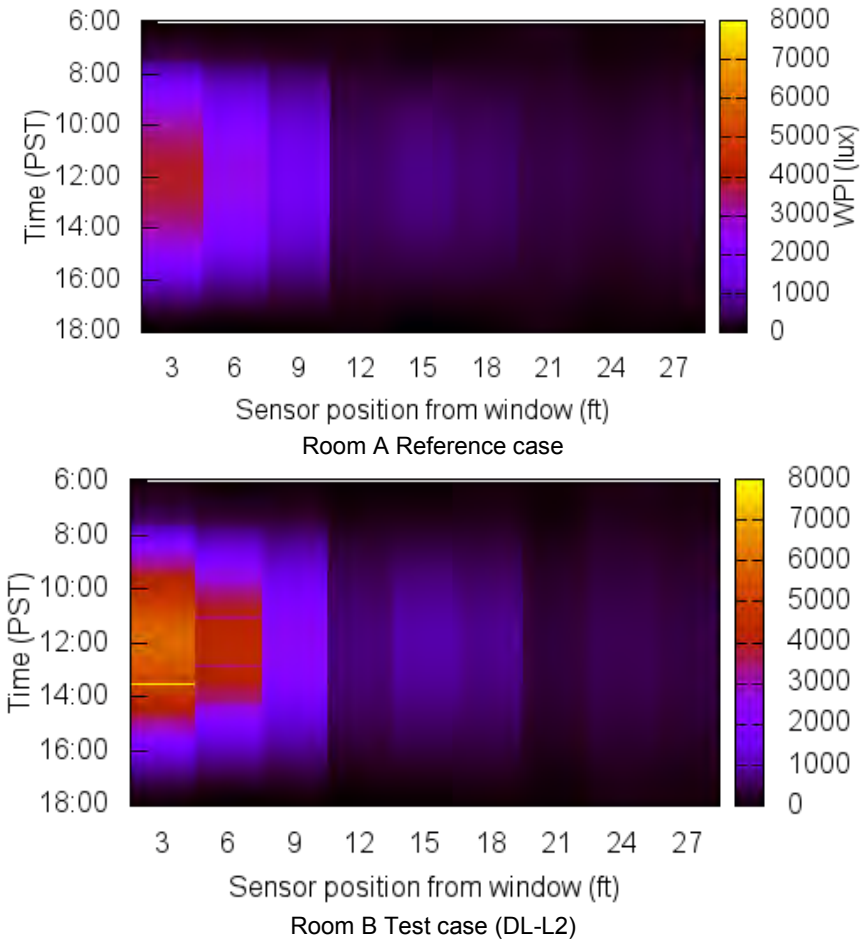

FIGURE 7.4 WORKPLANE ILLUMINANCE (LUX) DUE TO DAYLIGHT VERSUS DISTANCE FROM THE WINDOW (FT) AND TIME OF DAY (ST) FOR THE REFERENCE (LEFT) AND TEST (RIGHT, DL-L2 SYSTEM) UNDER CLEAR SKY CONDITIONS ON OCTOBER 5, 2015. TEMPORAL DATA WERE TAKEN AT 1-MIN INTERVALS. SPATIAL DATA WERE TAKEN AT 3 FT INTERVALS.

Figure 7.5 shows the falsecolor luminance distribution across the room cavity at 8:05 AM, 10:10 AM and 12:00 PM ST. Notice that there are bright specularly transmitted, downward patches of sunlight on the wall near the window at 8:05 AM, the same with less intensity at 10:10 AM, and an area of redirected sunlight on the ceiling near the window during all three times of the day. At noon, the 5000 cd/m^2 source of daylight on the ceiling plane was sufficient to raise illuminance levels within the first 10-20 ft from the window. (Note: The electric lights were not dimmed during the equinox period, as explained in Section 6.6.1.)

As a result of the daylight-redirecting system and dimmable LED lighting, lighting energy use in the test room on October 5th was significantly lower than the Title-24 2013 baseline:

- The baseline level for the reference room on October 5th was defined as follows:
  - First, the installed lighting power density (LPD) allowed by Title-24 2013 was 0.75 W/ft^2. The actual installed LPD in the FLEXLAB reference room was 0.62 W/ft^2 (18% lower than Title-24), which provided 300 lux at the work plane.

With no dimming, daily lighting energy use for the daytime period from 8 AM to 6 PM was 3808 Wh.

- Second, with daylight dimming in the 0-20 ft deep area near the window with the 300 lux setpoint, daily lighting energy use in the reference room was reduced by 82% from 3708 Wh (no dimming) to 653 Wh. This defined the Title-24 2013 reference or baseline level for lighting energy use on October 5th.

- In the test room, the daylight-redirecting system, additional daylighting controls in the 20-30 ft area, and the same installed fluorescent lighting system as the reference room reduced lighting energy use from 653 Wh to 343 Wh (47% savings). These savings were due solely to the daylight-redirecting system (compared to the venetian blind system).
- With the daylight-redirecting system, daylighting controls in the 0-30 ft area, and a LED dimmable lighting system (with an installed LPD of 0.32 W/ft^2), lighting energy use was reduced from 653 Wh to 160 Wh (76% savings). The difference in savings between the fluorescent and LED lighting cases was due to increased source efficiency and dimming response of the LED system to available daylight. Daylight levels between the two lighting control cases were the same.

Peak electric demand due to lighting during the summer in the Bay Area (i.e., early afternoon hours on clear sunny days during late Indian summer) was reduced by a nominal amount (~0.05 W/ft^2 * 400 ft^2 = 20 Wh) due to additional daylight dimming compared to the reference condition.

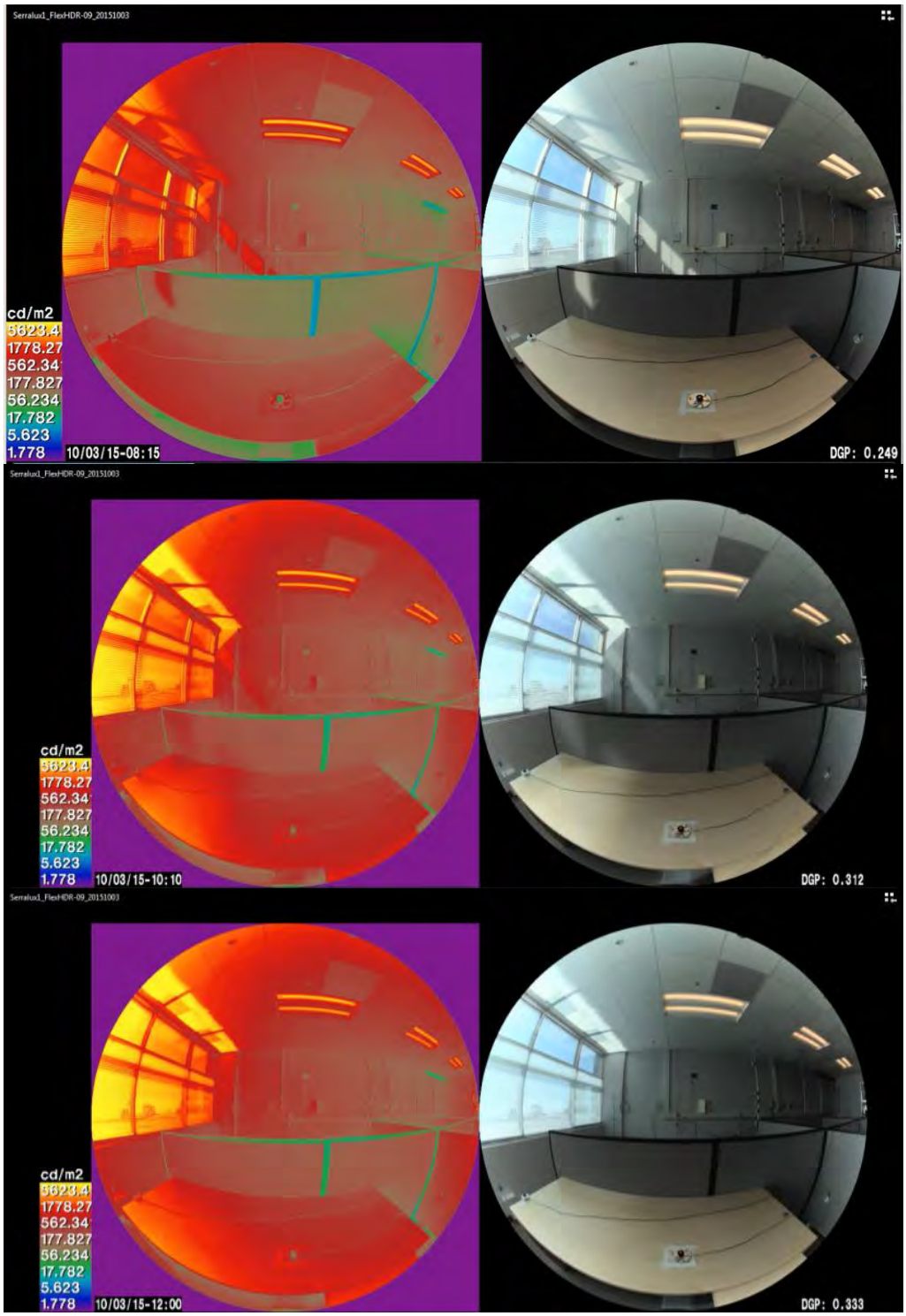

FIGURE 7.5 SYSTEM DL-L2 – FALSECOLOR LUMINANCE MAP (CD/M^2, LEFT) AND PHOTOGRAPHIC IMAGE (RIGHT) OF THE TEST ROOM AT A DEPTH OF 6 FT FROM THE WINDOW LOOKING AT THE WEST WALL. TOP ROW: 8:15 AM; MIDDLE ROW: 10:10 AM, BOTTOM ROW: 12:00 PM ST. CLEAR SKY CONDITIONS, OCTOBER 3, 2015.

Discomfort glare was controlled adequately at locations near the window facing the side wall and near the back of the room looking towards the window – both the reference and test rooms had Class A DGP levels for these locations on October 5th. For the view 5 ft from the

window looking toward the window, both rooms had significant glare for much of the day (i.e., Class D "Discomfort"). The maximum DGP value for 95% of the day was 0.46 and 0.54 for the reference and test rooms respectively, where a value of 0.35 is "just perceptible" and a value of 0.45 is "just intolerable". HDR images illustrate the cause of glare: for this period, direct sunlight through the daylight aperture caused direct source glare (Figure 7.6). The total illuminance at the eye was also very high, causing significant discomfort in both the reference and test rooms. The indoor blinds in the lower aperture would need to be closed further to reduce glare. Sunlight through the upper daylight aperture would also need to be controlled with an indoor blind, as advised by the manufacturer.

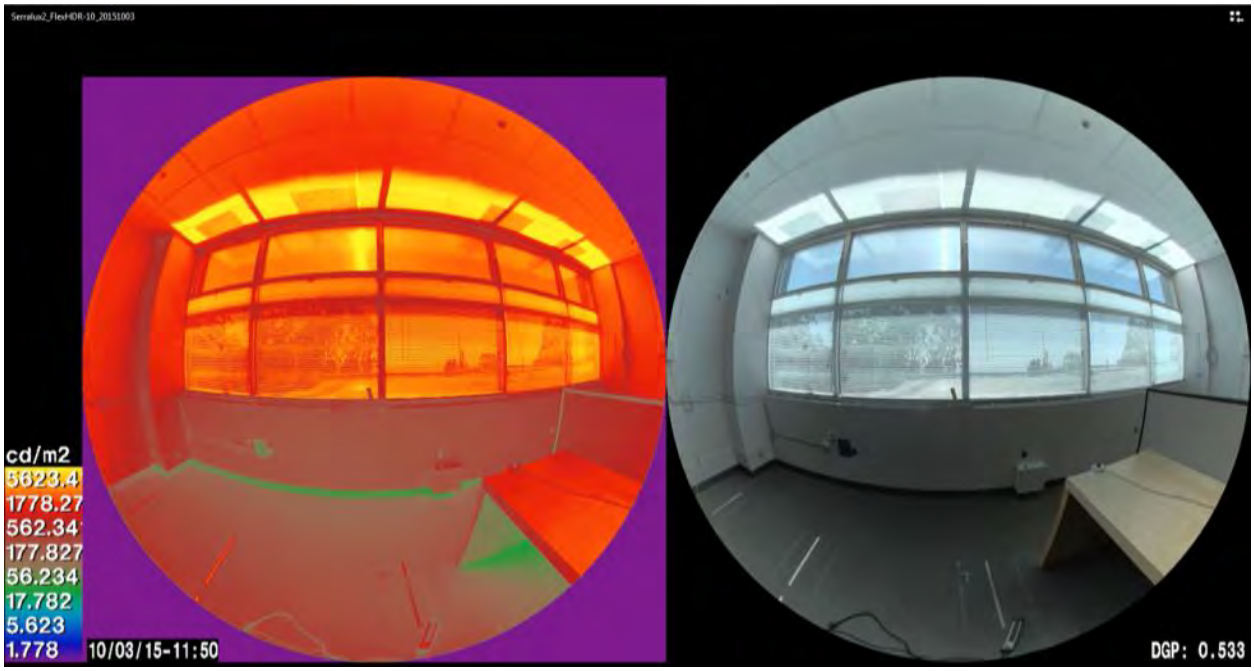

FIGURE 7.6 SYSTEM DL-L2 – FALSECOLOR LUMINANCE MAP (CD/M², LEFT) AND PHOTOGRAPHIC IMAGE (RIGHT) OF THE TEST ROOM AT A DEPTH OF 6 FT FROM THE WINDOW LOOKING AT THE WINDOW. CLEAR SKY CONDITIONS, OCTOBER 3, 2015 AT 11:50 AM ST. THE DGP FOR THIS IMAGE IS 0.53.FIGURE 7.6.

For this same example day, daylight adequacy remained nearly the same between the reference and test cases. The percentage of day when daylight illuminance was within the desired 100-2000 lux in the center zone was increased from 95% to 97% between the reference and test cases. Daylight illuminance levels within 10-20 ft from the window were not too bright or too dim for the majority of the day.

7.1.3. SOLSTICE-TO-SOLSTICE PERFORMANCE

LIGHTING ENERGY USE

If we evaluate performance across the solstice-to-solstice period, we see that the daily lighting energy use is inversely proportional to average outdoor illuminance levels. As outdoor daylight levels decrease from summer to winter, daily lighting energy use increases. Figure 7.7 shows the day of year versus average daily exterior horizontal global illuminance (Eglo) and daily lighting energy use for the reference and all test cases over the

monitored period. The example given in Section 7.1.2 for October 5th is the 274th day of the year (DOY) – daily lighting energy use of 653 Wh (blue symbols) and 160 Wh (red) for the reference and test rooms, respectively, are shown on this plot. Eglo (green) was 45 klux on this day (2nd y-axis).

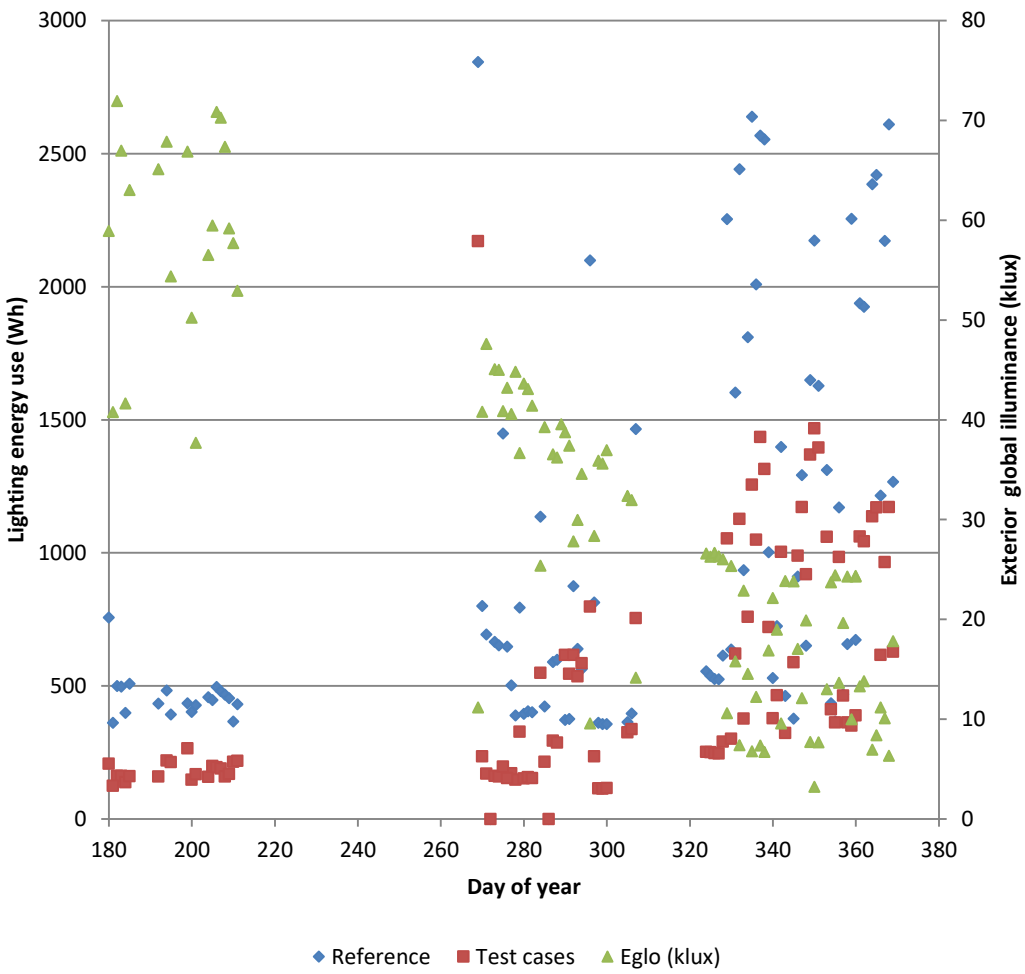

FIGURE 7.7 AVERAGE DAILY EXTERIOR GLOBAL HORIZONTAL ILLUMINANCE (KLUX) AND DAILY LIGHTING ENERGY USE (WH) FOR THE REFERENCE AND SIX TEST CASES VERSUS DAY OF YEAR (JULY 1, 2015 TO JANUARY 10, 2016).

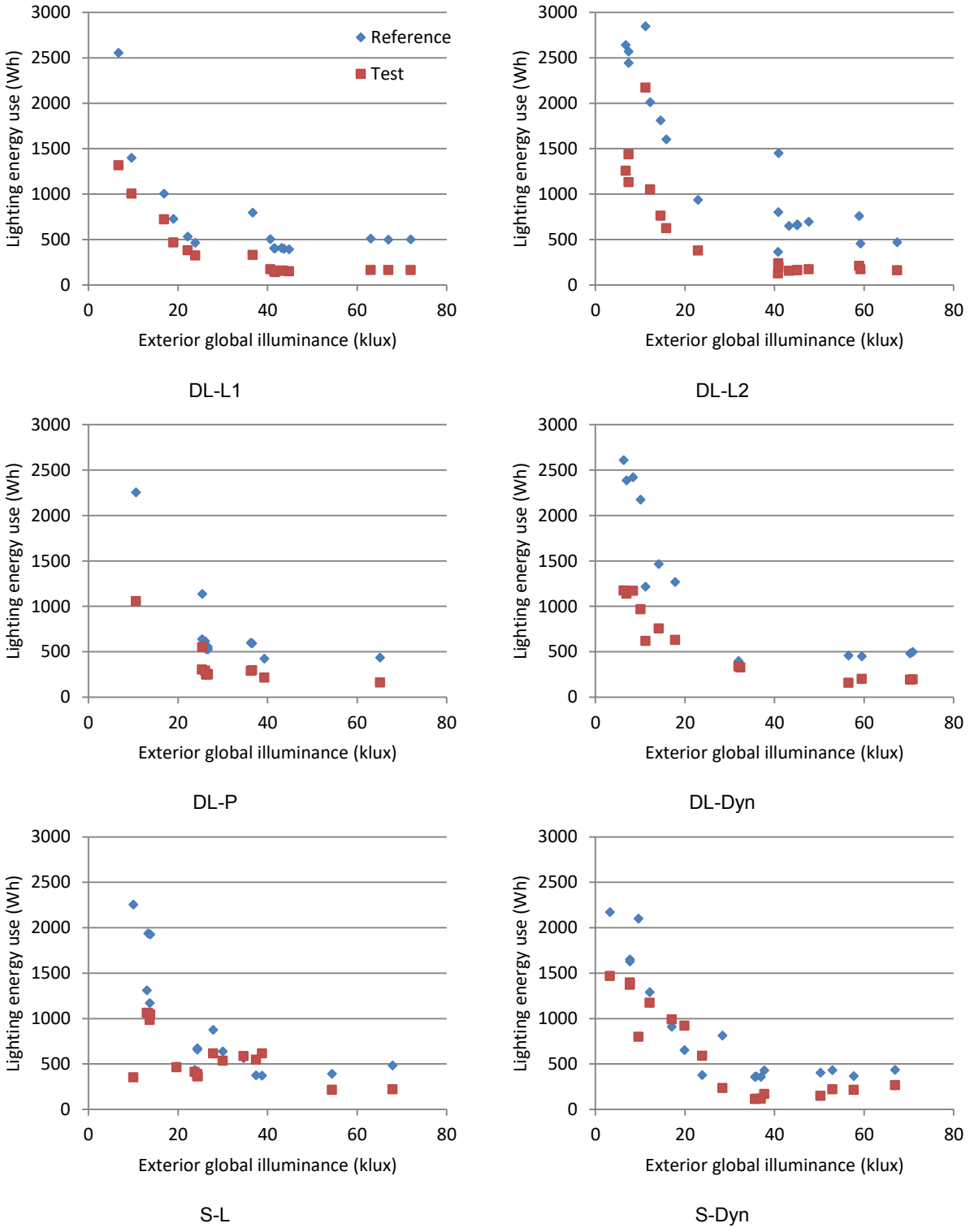

FIGURE 7.8 AVERAGE DAILY EXTERIOR HORIZONTAL ILLUMINANCE (KLUX) VERSUS DAILY LIGHTING ENERGY USE (WH) FOR EACH OF THE REFERENCE AND SIX TEST CASES. DATA ARE GIVEN FOR JULY 1, 2015 TO JANUARY 10, 2016.

The same data are shown in Figure 7.8 by system type where we see the typical exponential decrease in daily lighting energy use as daylight availability increases. Given

sufficient representative datapoints, these data could be used to assess annual performance. In the figures, data points for the winter period are to the left of the graph for values of Eglo that are less than 26 klux. The equinox period is within the range of 25-48 klux. The summer period is to the right within the range of 38-72 klux. The vertical offset between the reference and test cases in Figure 7.8 is due in part to the differences in minimum power of the dimmable fluorescent versus LED lighting and the differences in dimming response to the daylight provided by the daylight-redirecting systems.

The scatter exhibited by the test and reference cases is due to variable sky conditions and also to the different optical characteristics exhibited during each measurement period (e.g., see Section 7.1.1).

Because the proportion of clear, dynamic, and overcast days varied between each of the tested systems, annual energy use was not extrapolated from the limited monitored data set on a per system basis. Lighting energy use of the four systems, however, exhibited very similar trends with outdoor daylight availability (Figure 7.9). Annual lighting energy use savings were therefore determined by averaging monitored energy use data from all four systems (Table 7.1).

- Average annual lighting energy savings due to the four daylight-redirecting systems and LED dimmable lighting system ranged from 48% to 63%, with an average savings of 55% (Figure 7.10).
- If the <u>same</u> dimmable fluorescent lighting system was used in both the reference and test rooms, then the average annual lighting energy savings due to the daylight-redirecting system alone (which were affected in part by the lighting power dimming profile of the fluorescent lighting system) ranged from 3% to 25% with an average savings of 8%. Note: the percent savings due to the daylight-redirecting system would be greater if both rooms had dimmable LED lighting because the power dimming profile of the LED lighting system is more efficient than the dimmable fluorescent lighting system.
- Under clear sky conditions (given that this was an El Niño year for high precipitation/ cloudy weather), average annual lighting energy savings due to the four daylight-redirecting systems and LED dimmable lighting was 62%, while savings due to the daylight-redirecting systems alone (with dimmable fluorescent lighting) was 22%.

TABLE 7.1 MONITORED LIGHTING ENERGY USE (KWH/FT2-YR) AND PERCENTAGE SAVINGS (%)

Test case		N (days)	Eglo* (klux)	Annualized lighting energy use (kWh/ft^2-yr) and savings (%) A-FL	B-LED	Savings[1]	A-FL	B-FL	Savings[2]
DL-Dyn	avg	13	30.5	0.519	0.252	48%	0.519	0.549	9%
	stdev		25.1	0.368	0.167	17%	0.368	0.348	11%
	savings				0.267			-0.030	
DL-L1	avg	16	37.0	0.299	0.155	52%	0.299	0.312	3%
	stdev		19.6	0.234	0.146	17%	0.234	0.287	32%
	savings				0.144			-0.014	
D-L2	avg	18	32.6	0.551	0.244	63%	0.551	0.484	25%
	stdev		20.3	0.358	0.247	15%	0.358	0.469	27%
	savings				0.307			0.067	
DL-P	avg	12	30.9	0.307	0.144	53%	0.307	0.294	4%
	stdev		13.1	0.213	0.101	3%	0.213	0.202	7%
	savings				0.163			0.013	
All DL	avg	59		0.397	0.201	55%	0.426	0.404	8%
	savings				0.196			0.022	

* Eglo = average exterior global horizontal illuminance (klux); FL=fluorescent lighting; LED=LED lighting.
[1] Savings between the reference room with venetian blinds and dimmable fluorescent lighting versus the test room B with the daylight-redirecting technology and dimmable LED lighting. Savings computed for 8 AM to 6 PM, daylight controls only, 30-ft deep south-facing perimeter zone.
[2] Savings between the reference room with venetian blinds and dimmable fluorescent lighting versus the test room B with the daylight-redirecting technology and the same fluorescent lighting system as the reference room.

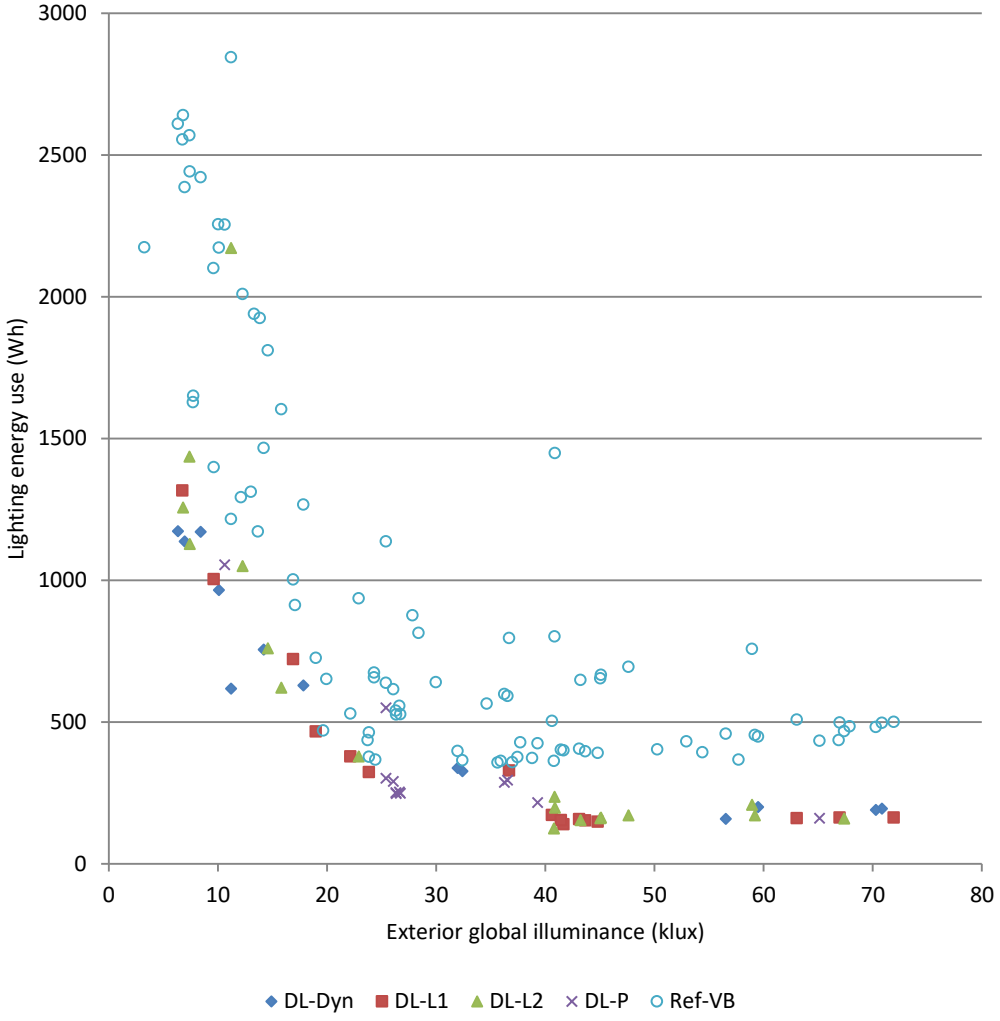

FIGURE 7.9 AVERAGE DAILY EXTERIOR HORIZONTAL ILLUMINANCE (KLUX) VERSUS DAILY LIGHTING ENERGY USE (WH) FOR THE REFERENCE AND FOUR DAYLIGHT-REDIRECTING TEST CASES. DATA ARE GIVEN FOR JULY 1, 2015 TO JANUARY 10, 2016.

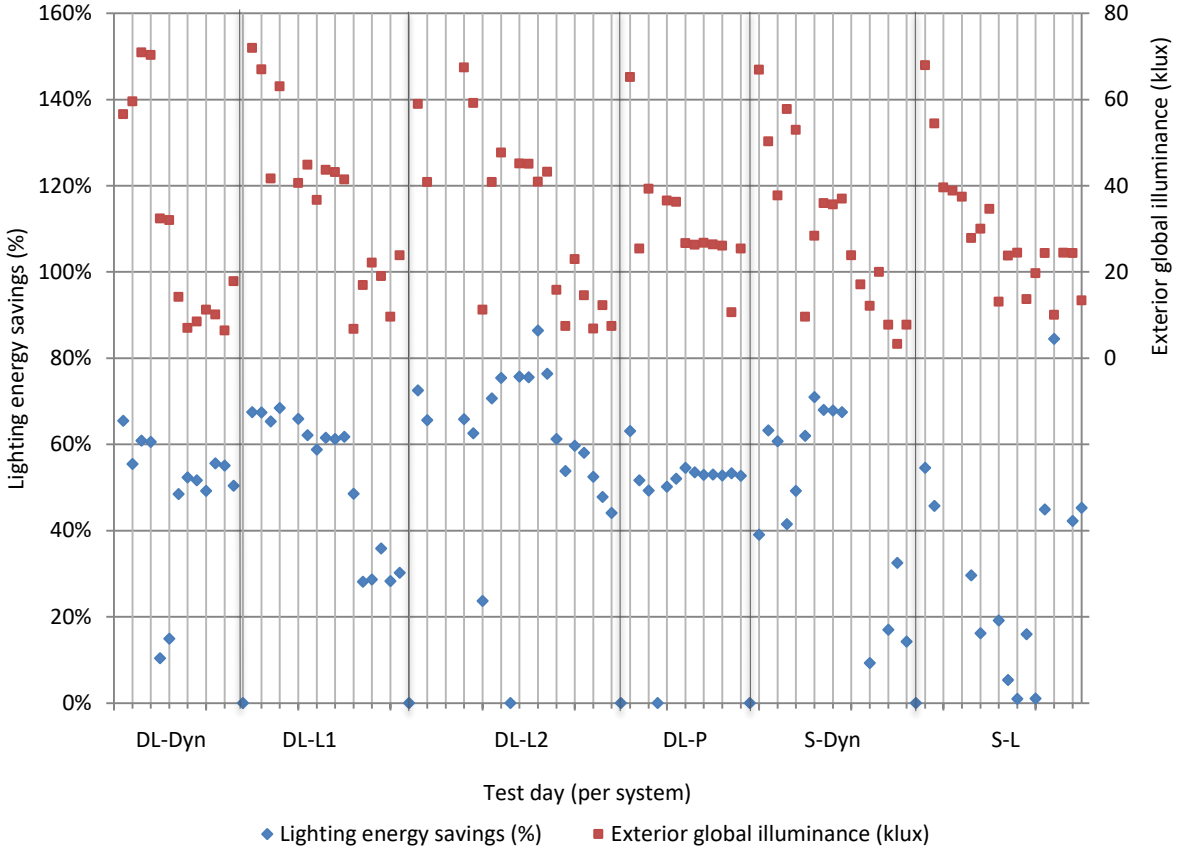

FIGURE 7.10 PERCENTAGE SAVINGS IN DAILY LIGHTING ENERGY USE VERSUS DAY OF YEAR. EACH COLUMN REPRESENTS ONE OF THE SIX TESTED SYSTEMS, WHERE SUMMER DATA ARE TO THE LEFT AND WINTER DATA ARE TO THE RIGHT IN EACH COLUMN FOR THE PERIOD FROM JULY 1, 2015 TO JANUARY 10, 2016. REFERENCE ROOM DATA AND AVERAGE DAILY EXTERIOR HORIZONTAL ILLUMINANCE (KLUX) ARE ALSO GIVEN. SAVINGS ARE GIVEN FOR EACH TEST CASE WITH DIMMABLE LED LIGHTING COMPARED TO THE REFERENCE CASE WITH DIMMABLE FLUORESCENT LIGHTING

Annual lighting energy use savings were small due to both the efficiency and operating mode of the dimmable lighting systems (Table 7.2):

- For reference, a Title-24 2013 compliant lighting control system would have an installed LPD of 0.75 W/ft^2. Actual installed LPD in the FLEXLAB was 0.618 W/ft^2, so if the lighting was on at full power for 24 hours on weekdays throughout the year, the lighting energy use intensity (EUI) would be 5.4 kWh/ft^2-yr. If on at full power only during daytime weekday hours from 8 AM to 6 PM, then the EUI would be 1.55 kWh/ft^2-yr. With dimming fluorescent lighting (300 lux setpoint) and indoor venetian blind (reference case), the EUI was 0.40 kWh/ft^2-yr.
- For the installed LED lighting system with an LPD of 0.324 W/ft^2, if this system was on at full power only during daytime weekday hours from 8 AM to 6 PM, then the EUI would be 0.81 kWh/ft^2-yr. With dimming LED lighting (300 lux setpoint) and the daylight-redirecting systems, the average energy use intensity was 0.20 kWh/ft^2-yr.
- Average lighting energy use savings due to daylight-redirecting systems and dimmable LED lighting (300 lux setpoint) was 0.20 kWh/ft^2-yr.

- Peak demand reductions due to the daylighting were negligible at noon on peak summer days with clear sky conditions. Workplane illuminance levels in both the reference and test cases were greater than the 300 lux setpoint level, resulting in the same reduction in lighting energy use.
- Note: these monitored savings are reported for the 30-ft deep perimeter zone.

TABLE 7.2 LIGHTING ENERGY USE INTENSITY (EUI) FOR WEEKDAYS IN THE 600 FT^2 FLEXLAB PERIMETER OFFICE

Case	Installed LPD	Setpoint (lux)	Lighting EUI (Wh) 8AM-6PM		Lighting EUI (kWh/ft^2-yr) 24h	Lighting EUI (kWh/ft^2-yr) 8AM-6PM	
	W/ft^2		100% on, 10h	Oct 5, DLC		100% on, 10h	Dimmable, 10h
Title 24-2013	0.750		4500		6.570	1.875	
Reference - FL	0.618	300	3708	653	5.414	1.545	0.397
Test - FL	0.618	300	3708	343	5.414	1.545	0.404
Test - LED	0.324	300	1944	160	2.838	0.810	0.201

Note: LPD = lighting power density, DLC = dimmable daylighting controls,

DISCOMFORT GLARE

Daylight glare probability (DGP) levels for all systems are given for the test period in Figure 7.11.

- Similar to findings in Section 7.1.2, discomfort glare in the reference room was below "just perceptible" levels (DGP=0.35) for 95% of the day throughout the 6-month monitored period for viewpoints near the window looking at the side wall (view 2A) and at the rear of the space looking toward the window (view 3A).
- Discomfort glare was also below "just perceptible" levels for the summer and equinox periods for the viewpoint near the window looking at the side wall (view 2B) in the test room.
- Discomfort glare was within and above the "just disturbing" (DGP=0.40) and "just intolerable" (DGP=0.45) thresholds for 95% of the day for all systems in the reference and test rooms for the view point near the window looking directly at the window (view 1A, 1B). In the test room, the maximum DGP for 95% of the day was 1.0 during many days in the winter.
- Glare levels in the reference room (Room A) were lower than in the test room (Room B), particularly during the winter period.

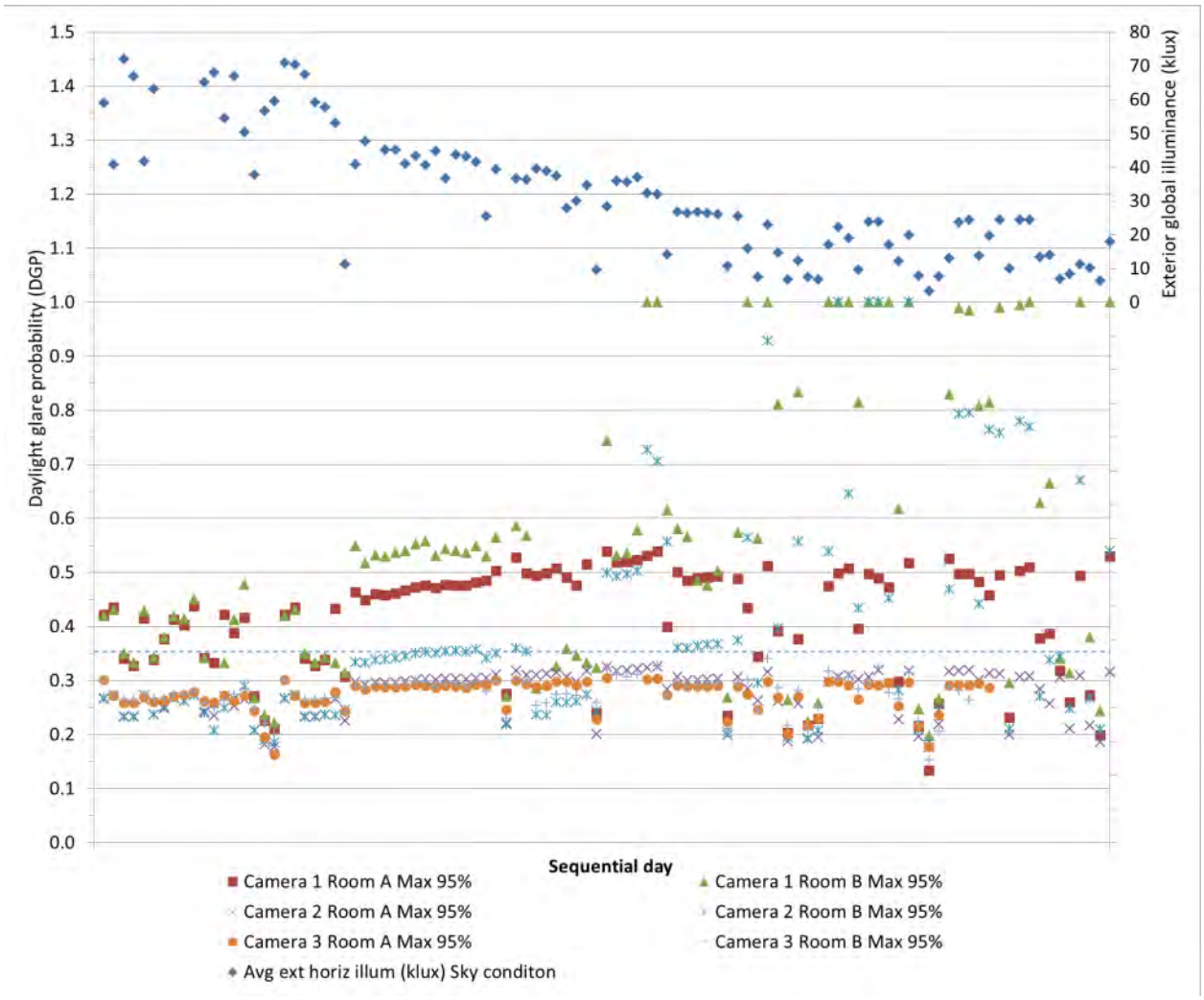

FIGURE 7.11 MAXIMUM DAYLIGHT GLARE PROBABILITY (DGP) FOR 95% OF THE DAY VERSUS SEQUENTIAL TEST DAY FOR THE REFERENCE (ROOM A) AND ALL SIX TEST CONDITIONS (ROOM B). DATA ARE GIVEN FOR THE THREE VIEWPOINTS IN EACH ROOM. THE AVERAGE DAILY EXTERIOR HORIZONTAL ILLUMINANCE (KLUX) IS ALSO GIVEN. THE THRESHOLD FOR "JUST PERCEPTIBLE" LEVELS OF DISCOMFORT GLARE (DGP=0.35) IS SHOWN AS A DOTTED LINE ON THE GRAPH.

Discomfort glare could be caused by several factors: a) excessive total illuminance at the eye and/or b) bright glare sources within the field of view. For the seated location 6 ft from the window looking towards the window (view 1A and 1B), total illuminance at the eye can be very high due to proximity to the window, size of the window within the field of view (WWR=0.50), and the high daylight transmitting properties of the glass (Tvis=0.64), particularly during sunny winter periods when the sun is low in the sky.

In the case of systems DL-L1 and DL-L2, specular or direct sunlight transmission occurred for the lower equinox and winter solar incidence angles as depicted in Section 7.1.2. During these periods, an indoor shade over the upper daylighting aperture would need to be used to control glare, which would also reduce lighting energy use savings. Trends for the monitored period for each system are shown in Figure 7.12. Data points for DGP levels equal to 1.0 occurred with the DL-Dyn, DL-L1, and DL-L2 systems – these are likely due to

the optics of the daylight-redirecting films or the way the blinds were controlled in the case of the DL-Dyn system.

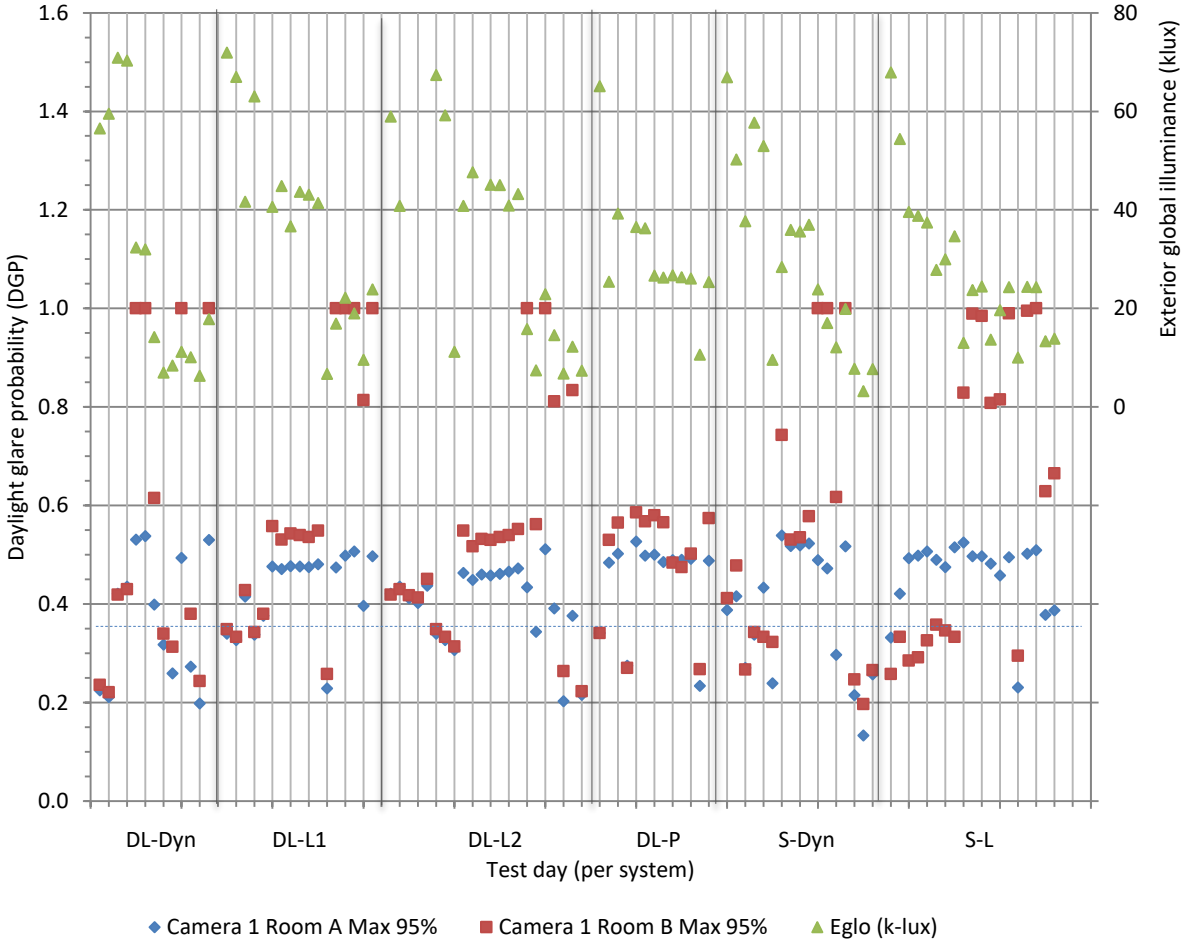

FIGURE 7.12 MAXIMUM DAYLIGHT GLARE PROBABILITY (DGP) FOR 95% OF THE DAY VERSUS SEQUENTIAL TEST DAY. EACH COLUMN REPRESENTS ONE OF THE SIX TESTED SYSTEMS, WHERE SUMMER DATA ARE TO THE LEFT AND WINTER DATA ARE TO THE RIGHT IN EACH COLUMN FOR THE PERIOD FROM JULY 1, 2015 TO JANUARY 10, 2016. REFERENCE ROOM DGP DATA AND AVERAGE DAILY EXTERIOR HORIZONTAL ILLUMINANCE (KLUX) ARE ALSO GIVEN. THE THRESHOLD FOR "JUST PERCEPTIBLE" LEVELS OF DISCOMFORT GLARE (DGP=0.35) IS SHOWN AS A DOTTED LINE ON THE GRAPH.

Bright glare sources were evident for some of the systems when the orb of the sun was imaged through the daylight-redirecting system. An example of this is shown in Figure 7.5 for system DL-L2. The luminance level of this glare source was well above the maximum value shown on the falsecolor scale (>5623 cd/m^2). A similar glare source was evident with DL-L1. These glare sources would also require an indoor shade capable of blocking sunlight (e.g., venetian blind) to reduce brightness to acceptable levels.

These glare sources would also require an indoor shade capable of blocking downward sunlight (e.g., venetian blind) to reduce brightness to acceptable levels. For DL-L2, for example, the manufacturer suggests that during periods of low sun elevation, positioning

the louvers of a venetian blind on the interior side of the film would block downward sunlight while preserving the transmission of daylight to the ceiling.

Note, the DL-P system did not have any monitored days when the maximum DGP value for 95% of the day was 1.0, whereas the other three systems did. The DGP values for the DL-P system were however still too high for views near the window, looking toward the window.

In the case of the DL-Dyn, this system has the potential to outperform the three other systems if it was controlled properly – this was evident in the scatter of the data points with both excessive and acceptable levels of glare. An example image of the test room is given in Figure 7.13.

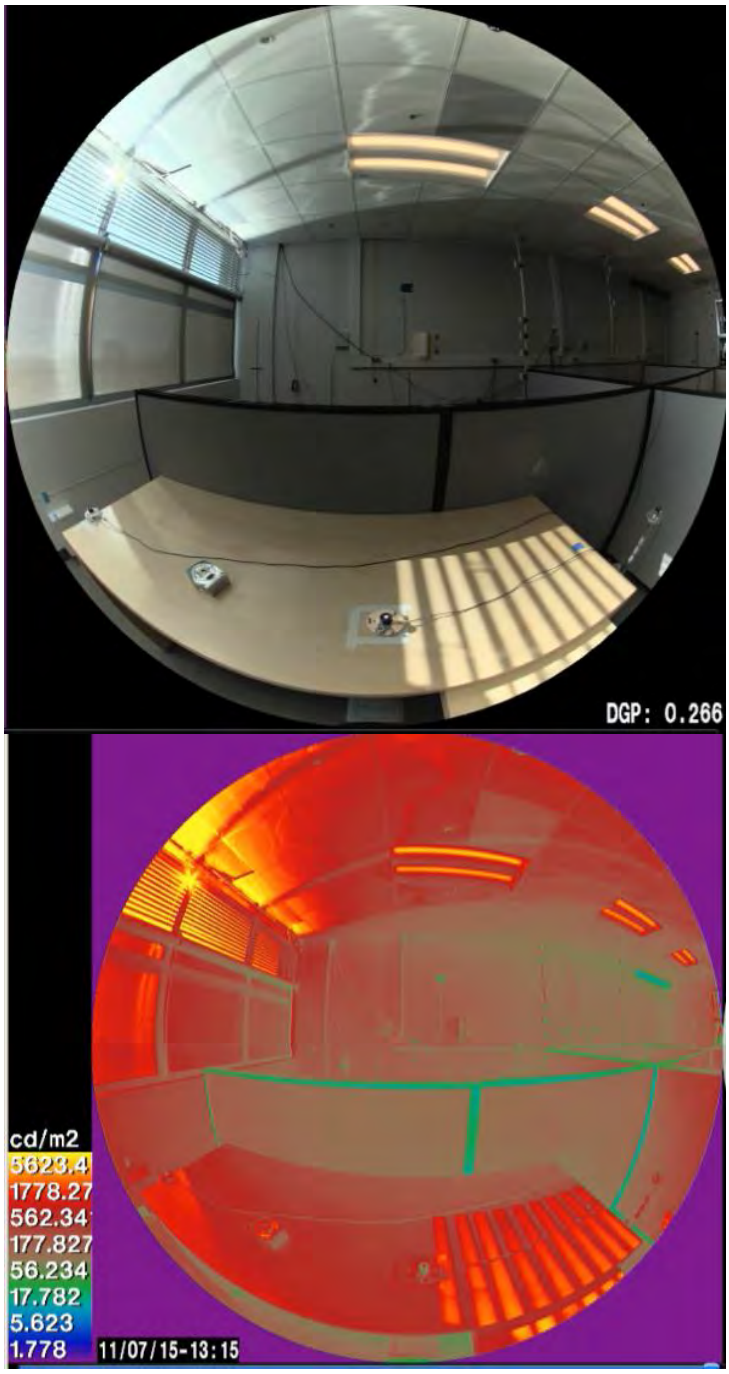

FIGURE 7.13 SYSTEM DL-DYN – FALSECOLOR LUMINANCE MAP (CD/M2, LEFT) AND PHOTOGRAPHIC IMAGE (RIGHT) OF THE TEST ROOM AT A DEPTH OF 6 FT FROM THE WINDOW LOOKING AT THE WEST WALL. CLEAR SKY CONDITIONS, NOVEMBER 5, 2015 AT 1:00 PM. THE DGP WAS 0.256 (LESS THAN THE 0.30 "JUST IMPERCEPTIBLE" THRESHOLD). NOTICE HOW THE CEILING PLANE IS WASHED WITH REDIRECTED SUNLIGHT TO THE 30 FT DEPTH FROM

THE WINDOW. NOTICE ALSO THE DIRECT SUN PATCHES ON THE WORK PLANE. THE MIRRORED SURFACE OF THE CLERESTORY BLINDS CREATED REFLECTIONS ON THE CEILING.

DAYLIGHT ADEQUACY

Daylight adequacy was defined by the percentage of the day when illuminance levels were within excessive, acceptable, or too low ranges of illuminance. There was only one day between all measured reference and test cases when the percentage of the day was greater than 0% for the "excessive" range of illuminance. Therefore, the percentage of day when the illuminance levels were within the "acceptable" range in the center zone (10-20 ft) is shown for each system in Figure 7.14. The "too low" range would simply be 1.0 minus the value shown in the figure.

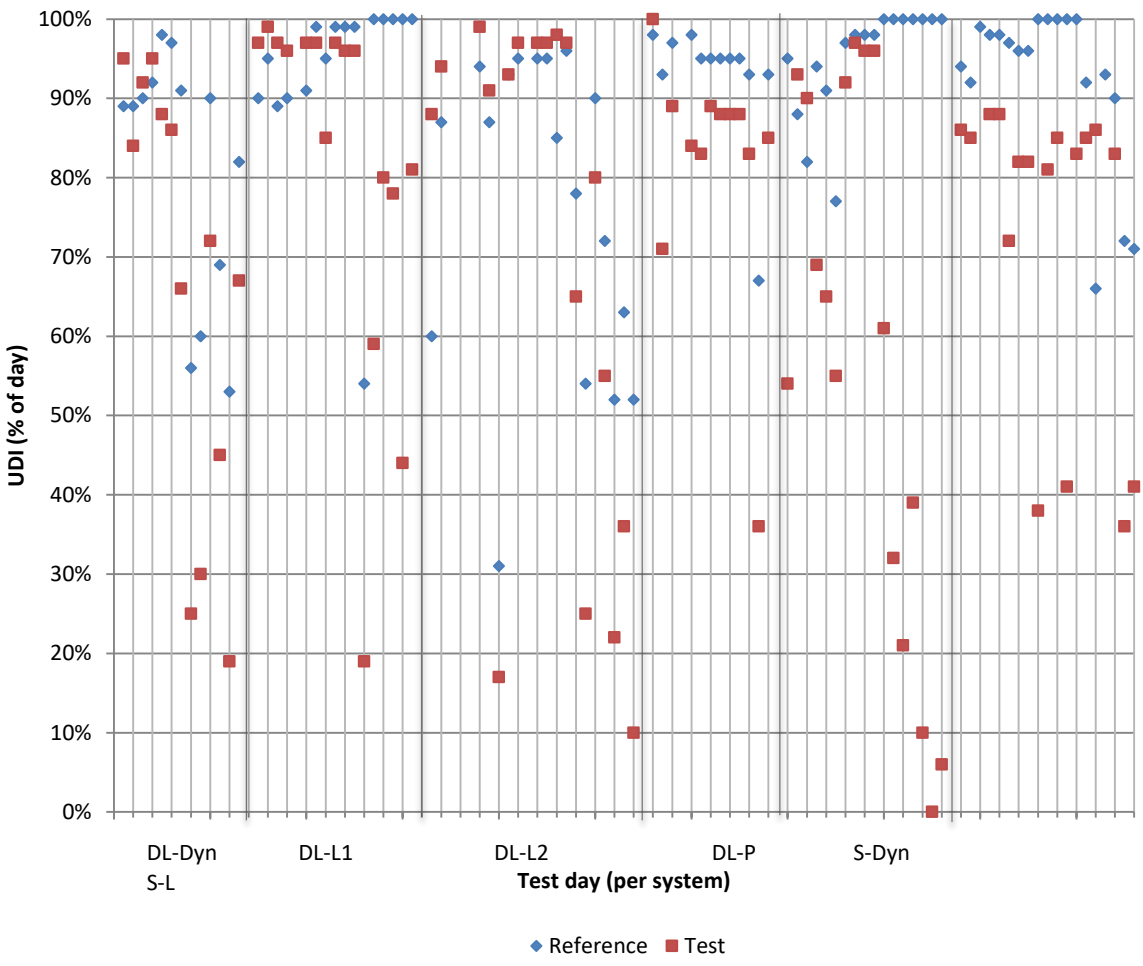

FIGURE 7.14 PERCENTAGE OF DAY WHEN THE WORKPLANE ILLUMINANCE LEVELS IN THE CENTER ZONE (10-20 FT FROM THE WINDOW) WERE WITHIN THE 100-2000 LUX RANGE FROM 8 AM TO 6 PM. DATA ARE GIVEN FOR EACH SYSTEM VERSUS SEQUENTIAL TEST DAY. EACH COLUMN REPRESENTS ONE OF THE SIX TESTED SYSTEMS. SUMMER DATA ARE TO THE LEFT AND WINTER DATA ARE TO THE RIGHT IN EACH COLUMN FOR THE PERIOD FROM JULY 1, 2015 TO JANUARY 10, 2016. REFERENCE ROOM DGP DATA AND AVERAGE DAILY EXTERIOR HORIZONTAL ILLUMINANCE (KLUX) ARE ALSO GIVEN.

Several observations can be made from these data. During the summer period, all reference and daylight-redirecting systems provide adequate daylight within the "acceptable" range for the majority of the day (80-100% of the day). As the sun angles transition to the equinox and winter solstice periods and daylight availability decreases, the daylighting systems provide daylight within the "acceptable" range between 20-80% of the day while the reference venetian blind provides acceptable daylight between 50-100% of the day. The daylight systems provide less adequate daylight during this period. The DL-P system appears to be the exception but outdoor conditions were sunnier during this system's test days over the equinox to winter solstice period.

Daylight uniformity

The average daily daylight uniformity ratio was not improved by the daylight-redirecting systems. The reference case had a ratio of minimum to average workplane illuminance across the 30 ft depth of the zone of 1:4 (0.25) to 1:3 (0.3) throughout most of the monitored period whereas the daylight-redirecting systems produced less uniformity with a lower ratio of 1:5 (0.20), see Figure 7.15. Under clear sky conditions when these systems were most effective at daylight redirection, daily ratios were the same. Cloudy and dynamic conditions produced the greatest variation in the uniformity ratio.

This lack of improvement to the uniformity ratio likely reflects the small number of hours over the 10 hour daytime period when significant daylight redirection occurred within the 10-30 ft zone (i.e., clear sunny winter days between about 10 AM and 2 PM). During the summer, if the daylight flux was redirected towards the ceiling, daylight levels would be raised primarily in the area near the window where there was already sufficient light from the lower window.

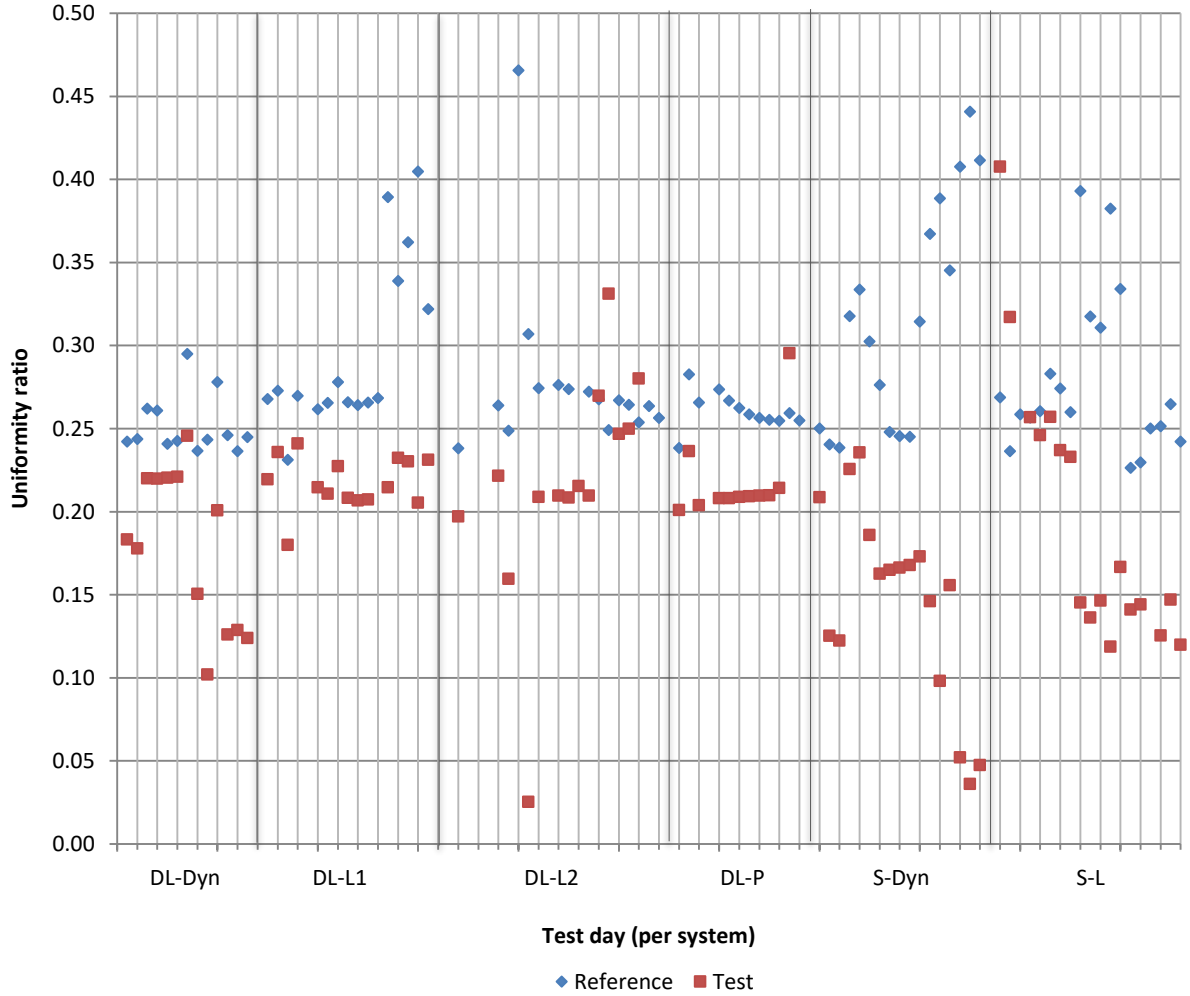

FIGURE 7.15 AVERAGE DAILY DAYLIGHT UNIFORMITY RATIO VERSUS SEQUENTIAL TEST DAY. EACH COLUMN REPRESENTS ONE OF THE SIX TESTED SYSTEMS. SUMMER DATA ARE TO THE LEFT AND WINTER DATA ARE TO THE RIGHT IN EACH COLUMN FOR THE PERIOD FROM JULY 1, 2015 TO JANUARY 10, 2016. REFERENCE ROOM DATA AND AVERAGE DAILY EXTERIOR HORIZONTAL ILLUMINANCE (KLUX) ARE ALSO GIVEN.

7.1.4. RADIANCE SIMULATIONS

Radiance simulations were conducted on an earlier version of the DL-P film in a prior project (McNeil et al. 2013). Results are given here to provide some context for the outcomes from the field study. Analogies were drawn between the two studies but validation of the simulation results was out of scope of this study.

The simulation study modeled an open plan office zone with an upper clerestory and lower view window, similar to that evaluated in the FLEXLAB. The visible transmittance of the upper and lower windows was 0.62 and 0.29, respectively. The window-to-exterior-wall area ratio was 0.60. For the reference case, an interior venetian blind was modeled with a tilt angle of 45°. The film similar to the DL-P film, named "P2" in the Radiance study, was modeled in the upper clerestory as a triple-pane insulating glass unit with the daylight redirecting film on surface #4 and a light diffusing film on surface #5. The fluorescent

lighting system was modeled with a lighting power density of 0.75 W/ft^2, 20-100% power dimming range and daylighting controls with a 500 lux setpoint throughout the 40-ft deep space.

For the climate of Sacramento, the Radiance study found that for the 30-ft deep, south-facing perimeter zone:

- Annual site lighting energy savings were 0.354 kWh/ft^2-yr or 28%.
- Peak site electric lighting demand savings were 0.13 W/ft^2 (31%) for peak summer afternoons (August, 2 PM).
- Glare occurred for 13% of annual work hours with the P2 system and 0% with the venetian blind. Glare was determined for nine views, including one facing the window at a distance of 5 ft from the window. If any of the views exceeded the threshold for "perceptible" glare, then that hour was binned in the total work hours.
- Annual discomfort glare for the P2 system met the Class A requirements for seven out the nine views and the Class B requirements for the two views facing the window at 5 and 10 ft from the window. The venetian blind met the Class A requirements for all views in the space.

Differences in performance between the simulation and field studies can be attributed to several factors: climatic differences between Berkeley and Sacramento, differences in performance for a typical meteorological year versus 15 monitored days per system for a specific year, differences in efficiency of the lighting control system and operation (e.g., 300 versus 500 lux setpoint), differences between the actual and modelled space and surrounding environment, and differences between modeled and actual properties of the venetian blinds and daylighting film.

- If annual site lighting energy use intensity of the Radiance reference case of 1.28 kWh/ft^2-yr is compared to the FLEXLAB monitored reference case of 0.397 kWh/ft^2-yr, for which there is substantial data (N=95 days), we can attribute 0.65 kWh/ft^2-yr (75%) of the 0.86 kWh/ft^2-yr difference between the simulated and measured cases to the difference in lighting power density (0.618 vs 0.75 W/ft^2) and lighting control setpoint (300 vs 500 lux). With the addition of climatic differences, the modeled EUI data is within the ballpark of what we are measuring in the field.
- Discomfort glare was modeled with the three-phase method (146x146 modified Klems basis) in Radiance, which is acknowledged to be less accurate than the more advanced five-phase modeling approach using high resolution BSDF data. In this study, we attribute more accuracy to the monitored data of the actual fabricated systems in the field.

Overall, simulated <u>source</u> lighting energy use savings for 40-ft deep, south, east, and west-facing perimeter zones in Sacramento and Burbank were (site-to-source conversion factor of 3.3):

- 3.4 kWh/ft^2-floor-yr (41%) or a reduction from 8.4 to 5.0 kWh/ft^2-yr if the baseline was Title-24 2008 (no daylighting controls);
- 1.5 kWh/ft^2-floor-yr (28%) or a reduction from 5.3 to 3.8 kWh/ft^2-yr if the baseline was Title-24 2013;
- Peak site demand reductions were 0.26-0.48 W/ft^2-floor in the 40-ft zone (27-49%) assuming the Title 24-2008 baseline;

- The manufacturer estimated that the installed cost of their window film would be $20/ft^2 for a volume purchase (>2500 ft^2), where the film is installed as a retrofit option on the indoor face of the window (e.g., surface #4 on an insulating glass unit). For this cost, the simple payback would be 2-6 years, assuming a utility rate of $0.20/kWh.

Performance of the DL-L1 and DL-L2 systems are expected to differ significantly from that of the DL-P system, particularly if shades are modeled to block direct sun from the upper clerestory window during the equinox-to-winter solstice period. The installed cost of the DL-L2 system is comparable to that of the DL-P film so the payback is likely to be similar if the application does not warrant use of indoor shades. The installed cost of the DL-L1 film is estimated by the manufacturer to $5-15/ft^2, with the lower end value corresponding to a mature market and high volume production.

The DL-Dyn system would also require modeling to assess performance; the new photon mapping capability in Radiance (Schregle 2015) enables optical modeling of caustics resulting from use of curved mirrored surfaces.

7.2. SHADING TECHNOLOGIES

7.2.1. COOLING LOAD

Cooling load profiles comparing the reference window with indoor venetian blinds to the same window with exterior shades (S-L) are shown for a sunny day in Figure 7.16. Results are summarized in Table 7.3. The profiles show the difference in cooling load due to the window with all other differential loads removed from the comparison. Differential loads included between-room differences in operation of the lights, equipment, and HVAC system, as described in Section 6.6.2. Data for dynamic and overcast days were not included in this analysis. The FLEXLAB test cells were not calibrated at the time of the test (the PG&E study was the first conducted in the test rooms) and so when the loads were low, the "noise" produced by differences in construction, siting, operations, and sensing between rooms were expected to exceed the differential signal we were trying to measure. As such, the between-room differences in cooling load when the rooms were configured to be the same were estimated to be within ±10% when loads were sufficiently high.

TABLE 7.3 DAILY COOLING LOAD, PEAK COOLING DEMAND, AND SAVINGS DUE TO THE WINDOW (8 AM – 6 PM. 21° SETPOINT)

Date	Period	Sky	Avg horiz irrad (W/m^2)	Cooling load due to the window (Wh) Room A (Wh)	Room B (Wh)	Savings (Wh)	Savings (Wh/ft^2-window)	Savings (%)
S-L								
7/15/15	Summer	Clear	332	12,555	10,563	1,992	17.1	16%
7/16/15	Summer	Dynamic	274	12,700	10,538	2,162	18.5	17%
10/20/15	Equinox	Clear	195	12,332	3,919	8,413	72.1	68%
10/21/15	Equinox	Clear	189	12,919	4,422	8,497	72.8	66%
1/1/16	Winter	Clear	113	16,258	8,706	7,552	64.7	46%
1/2/16	Winter	Dynamic	59	9,298	5,894	3,404	29.2	37%
1/3/16	Winter	Dynamic	58	11,621	8,020	3,601	30.9	31%
S-Dyn								
8/1/15	Summer	Clear	275	14,458	11,004	3,454	29.6	24%
8/2/15	Summer	Dyn+Clear	257	12,860	9,989	2,871	24.6	22%
11/29/15	Winter	Clear	136	18,476	16,256	2,220	19.0	12%

Date	Period	Sky	Avg horiz irrad (W/m^2)	Peak cooling demand (W/ft^2-window) Room A	Room B	Savings	Savings (%)
S-L							
7/15/15	Summer	Clear	332	14.0	11.4	2.6	19%
7/16/15	Summer	Dynamic	274	14.2	10.7	3.5	25%
10/20/15	Equinox	Clear	195	18.1	6.9	11.3	62%
10/21/15	Equinox	Clear	189	18.8	7.2	11.5	61%
1/1/16	Winter	Clear	113	19.4	10.6	8.8	46%
1/2/16	Winter	Dynamic	59	12.5	6.1	6.4	51%
1/3/16	Winter	Dynamic	58	13.8	8.8	5.0	36%
S-Dyn							
8/1/15	Summer	Clear	275	15.7	11.6	4.0	26%
8/2/15	Summer	Dyn+Clear	257	14.6	10.4	4.2	29%
11/29/15	Winter	Clear	136	22.5	19.9	2.6	12%

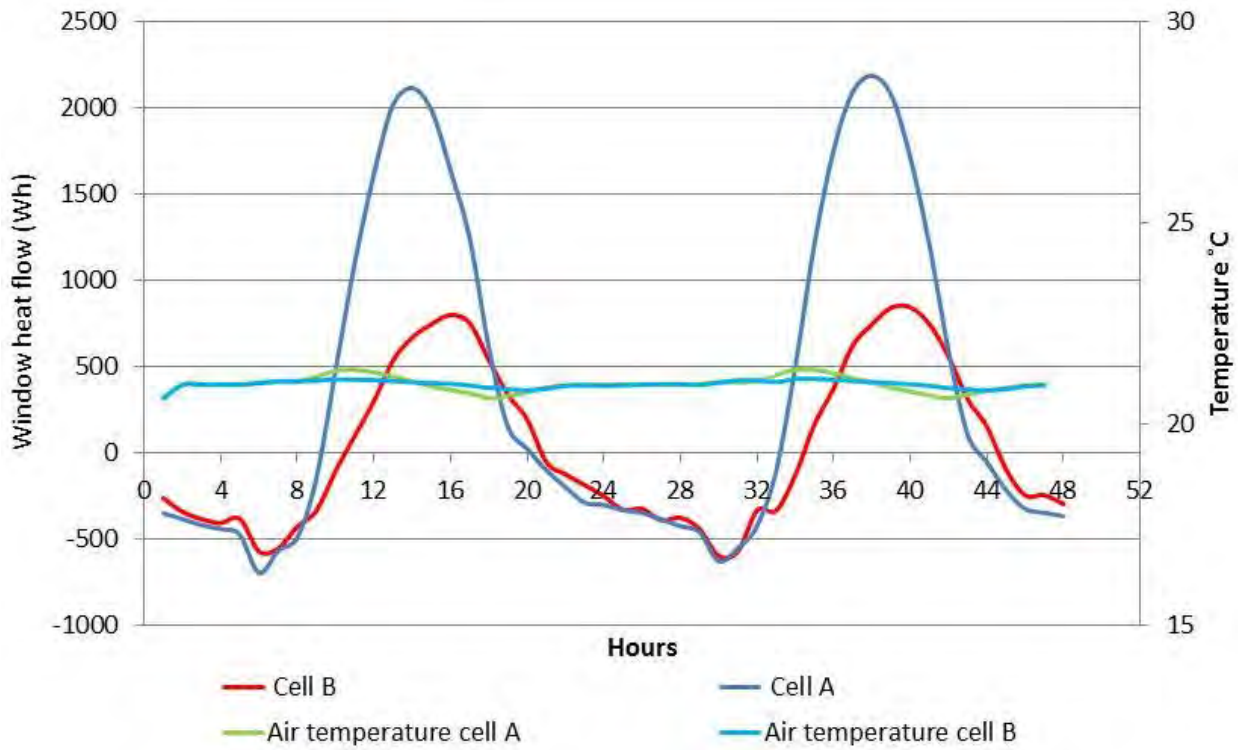

FIGURE 7.16 COOLING LOAD (WH) DUE TO THE REFERENCE (ROOM A) VERSUS THE S-L TEST SYSTEM (ROOM B) FOR A 48-HOUR PERIOD. INDOOR AIR TEMPERATURE IS ALSO SHOWN ON THE GRAPH. DATA ARE GIVEN FOR OCTOBER 21-22, 2015.

For the static exterior shading system S-L, monitored results indicate that the daily cooling load due to the window was reduced by 16%, 68%, and 46% during the summer, equinox, and winter periods, respectively. Peak cooling demand was reduced by 2.6-11.5 W/ft^2-window or 19%, 62%, and 46%, respectively, during the mid-afternoon. Note that the Title 24 2013 reference low-e windows were already fairly energy efficient with a low solar heat gain coefficient and U-value (SHGC=0.27, U-value=0.28 Btu/h-ft^2-°F).

Similar to the static shading system, the automated exterior roller shade, S-Dyn, reduced daily cooling load due to the window: 22-24% during the summer and 12% during the winter. Peak summer cooling demand was reduced by 4.0 W/ft^2-window or 26% during the mid-afternoon. The test was unsuccessful during the equinox period due to coordination issues between LBNL and the manufacturer during the time of the test. During the winter period, the temperature channel on the FLEXLAB acquisition system was corrupted due to an electronic glitch, leading to an elevated temperature in the reference room of 45°C (as opposed to the setpoint of 21°C) which added heat flow to the adjacent test room B of 37 W. This additional load was removed from the test room's load. Results were then compared to reference room results from a previous day when the HVAC system was operating as intended.

7.2.2. LIGHTING ENERGY USE

Daylight availability was however adversely affected by the fixed exterior shading system. Average lighting energy savings over monitored period due to the S-L shading system and

LED dimmable lighting system was 0.083 kWh/ft^2-yr (16%). If the same dimmable fluorescent lighting system was used in both the reference and test rooms, then energy use was greater than the reference window by 0.175 kWh/ft^2-yr (74%). The different savings in lighting energy use were due to differences in efficiency between the fluorescent and LED lighting systems. See Table 7.4.

Daylight availability was less adversely affected by the automated exterior shading system because the shade was raised during periods of low daylight availability. Average lighting energy savings due to the S-Dyn shading system and LED dimmable lighting system was 0.109 kWh/ft^2-yr (33%). If the same dimmable fluorescent lighting system was used in both the reference and test rooms, then energy was still greater than the reference window by 0.141 kWh/ft^2-yr (34%).

In both these cases, savings should be interpreted as indicative of annual performance. Unlike the daylighting technologies where data from all four systems were aggregated to derive an average annual savings, the number of days measured in these cases were insufficient to be representative of the range of solar and sky conditions over a year. Figures 7.8 and 7.10 show this performance as a function of daylight availability.

TABLE 7.4 MONITORED LIGHTING ENERGY USE (KWH/FT2-YR) AND PERCENTAGE SAVINGS (%)

Test case		N (days)	Eglo* (klux)	Annualized lighting energy use (kWh/ft^2-yr) and savings (%) A-FL	B-LED	savings[1]	A-FL	B-FL	savings[2]
S-Dyn	avg	17	29.62	0.361	0.253	33%	0.361	0.502	-34%
	stdev		19.35	0.264	0.215	39%	0.273	0.421	77%
	savings				0.109			-0.141	
S-L	avg	16	28.82	0.330	0.247	16%	0.330	0.505	-74%
	stdev		15.28	0.219	0.122	34%	0.219	0.241	75%
	savings				0.083			-0.175	

* Eglo = average exterior global horizontal illuminance (klux); FL=fluorescent lighting; LED=LED lighting.
[1] Savings between the reference room with venetian blinds and dimmable fluorescent lighting versus the test room B with the daylight-redirecting technology and dimmable LED lighting. Savings computed for 8 AM to 6 PM, daylight controls only, 30-ft deep south-facing perimeter zone.
[2] Savings between the reference room with venetian blinds and dimmable fluorescent lighting versus the test room B with the daylight-redirecting technology and the same fluorescent lighting system as the reference room.

7.2.3. VISUAL COMFORT AND ENVIRONMENTAL QUALITY

DISCOMFORT GLARE

During the summer and equinox periods, the static S-L system was able to maintain acceptable visual comfort conditions in the room because it occluded direct sunlight and minimized reflectance of light within the system itself given the black finish of the microlouvers (Figure 7.12). The microlouvers had a cut-off angle of 40° so high summer sunlight was blocked by the slats. During the winter, however, low angle sunlight was transmitted through the system. Therefore, the S-L system was unable to control glare adequately during the winter near the window looking either toward the window or at the sidewall (views 1 and 2); glare levels were significantly greater than that in the reference room. During this period, an indoor shade would be needed in combination with the exterior shade to block low-angle sunlight for those seated near the window (Figure 7.17). Discomfort glare was within acceptable levels for viewpoints from the rear of the space looking toward the window (view 3).

With the S-Dyn system, one would expect with the right control, direct sun would be controlled as well as bright sky luminance. The fabric of the roller shade was charcoal black minimizing window luminance when lowered. The roller shade fabric, however, had an openness factor of 5% and sunlight passing through the fabric likely caused glare. During the summer, visual comfort conditions were acceptable. During the winter solstice period when the sun path was lower in the sky, discomfort levels were unacceptable for view points looking either toward the window or at the sidewall (views 1 and 2) and these levels were significantly greater than that of the reference room. Discomfort glare was within acceptable levels in both the reference and test rooms for viewpoints from the rear of the space looking toward the window (view 3).

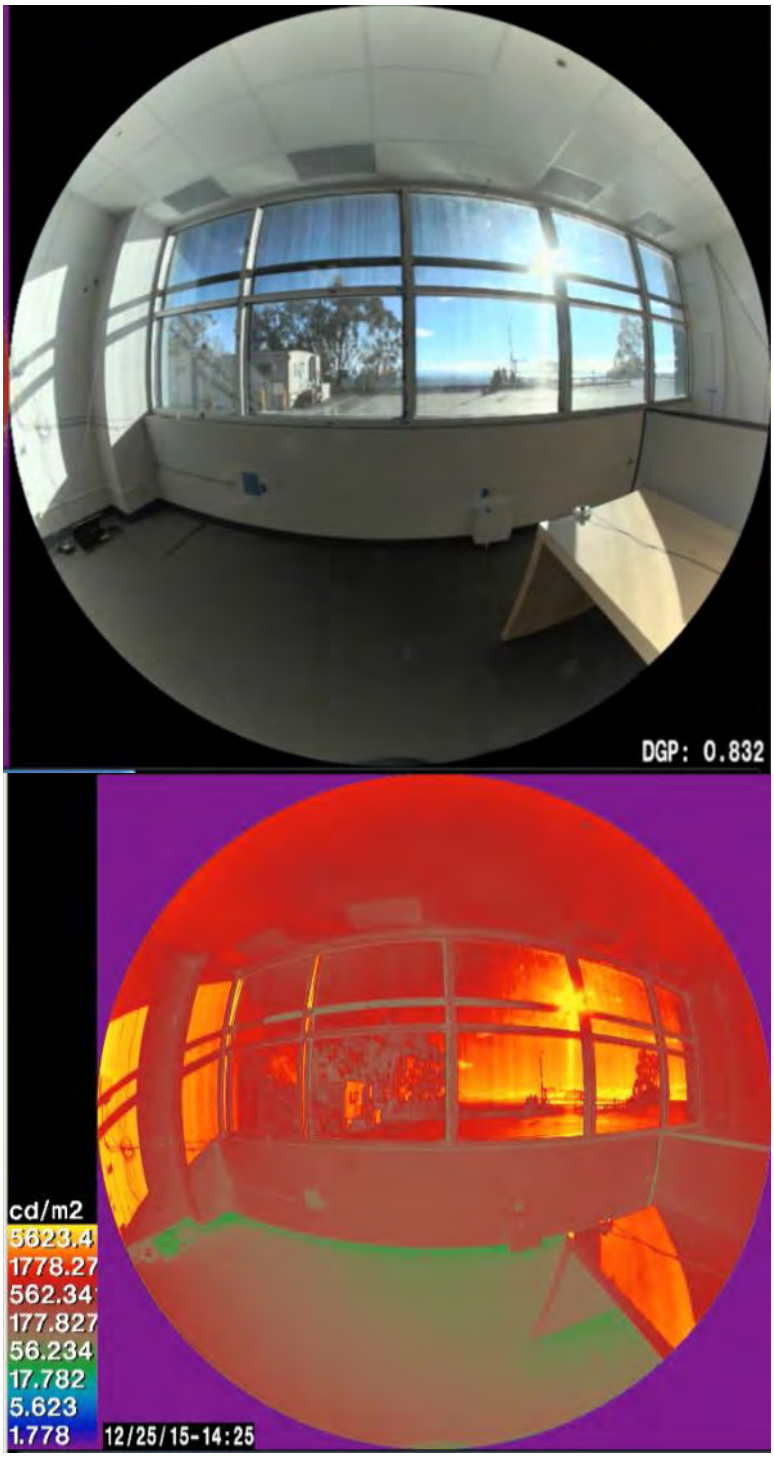

FIGURE 7.17 COOLING LOAD (WH) DUE TO THE REFERENCE (ROOM A) VERSUS THE S-L TEST SYSTEM (ROOM B) FOR A 48-HOUR PERIOD.

DAYLIGHT ADEQUACY

Figure 7.14 shows that the S-L system was able to maintain daylight levels within the "acceptable" range in the center zone (10-20 ft) for greater than 80% of the day for all days except during the winter when sky conditions were dynamic/ partly cloudy. During winter periods when daylight levels were in the "too low" range, the frequency of occurrence was between 50-57% of the day compared to 10-35% of the day in the reference room with venetian blinds. The S-L space may be perceived as gloomy during winter days with partly cloudy to overcast sky conditions. Daylight levels never exceeded 2000 lux ("too bright" range) in either the reference or test rooms.

The S-Dyn system on the other hand was less successful at maintaining acceptable daylight levels in the center zone: during the summer and equinox periods, daylight levels were "acceptable" for 55-96% of the day while during the winter period, daylight levels were acceptable for 6-60% of the day. The reference condition maintained daylight levels within the acceptable range for 77-100% of the day for the same days as the S-Dyn system throughout all three periods. Like the S-L system, the indoor environment may be perceived as gloomy even though the shade was raised during periods of low daylight.

DAYLIGHT UNIFORMITY

For the S-L system, daylight uniformity was comparable to the reference case during the summer but considerably less during the winter. With the S-Dyn system, uniformity was less during all three periods. Both systems did not improve the distribution of daylight throughout the 30 ft depth of the space nor was it expected to. Performance data for both systems are given in Figure 7.15.

VIEWS

Views out were partially blocked by the S-L microlouvers, similar to that of an insect screen; the views were filtered and non-distorted.

Views out through the dynamic system were either unobstructed when the shade was raised or filtered and non-distorted through the roller shade fabric, when the shade was lowered. The shade tended to be lowered for much of the day and raised during early morning/ late afternoon periods.

7.2.4. ANNUAL PERFORMANCE

CEC FIELD STUDY

Findings from the FLEXLAB study corroborate findings from an earlier 3-year field study conducted in the LBNL Advanced Windows Testbed facility, Berkeley, California through a California Energy Commission (CEC) supported research program (Lee et al. 2009). This facility was designed to provide near adiabatic isothermal conditions around each test cell and data from the study was calibrated to account for the construction and operational differences between test rooms. While the shading systems differed from those in this study, monitored from this previous study can be used to support the findings from the

FLEXLAB study. Data from the FLEXLAB study are indicative of performance for the climate and solar conditions of the days that were measured. Extrapolation to annual performance based on this limited data set is not possible.

The prior study concluded that static exterior shading systems were able to reduce cooling load due to the window by 78-94%, reduce peak cooling load by 1.6-3.1 W/ft^2-floor or 2.7-5.3 W/ft^2-window (71-84%), and reduce lighting energy use by 53-63% compared to an indoor venetian blind reference case with no daylighting controls. Savings were given for a 10x15 ft private office facing due south with a spectrally-selective low-e reference window in both rooms (WWR=0.59, SHGC=0.40, U-value=0.30 Btu/h-ft^2-°F, Tvis=0.62).

The dynamic, automated exterior shading systems were also effective at reducing cooling loads due to the window: cooling load reductions were 80-87% and peak cooling load reductions were 2.0-2.6 W/ft^2-floor or 3.5 to 4.4 W/ft^2-window (76-78%). Lighting energy use savings were 58-67%.

Building Energy Simulations

Building energy simulations were performed in a prior study supported by the California Energy Commission and the U.S. Department of Energy (Hoffmann et al. 2016). EnergyPlus (https://energyplus.net/) and Radiance (http://radiance-online.org/) are two open source software tools that enable modeling and analysis of building energy use and daylighting systems. These tools were used for the study.

Because the shading systems were optically complex, bidirectional scattering distribution function (BSDF) data were used in combination with Radiance simulations to determine both lighting energy use and incident solar irradiance on the glazing layers of the window. The latter quantity was then used within EnergyPlus in the window heat balance calculation which in turn was used to conduct the room heat balance calculation for each time step. Operable interior shades were modeled to control glare using this method, where glare was computed from multiple view points using Radiance. Overall, this modeling approach is not part of the standard suite of tools. The daylighting calculations within EnergyPlus (that use BSDF data) use a simpler, unvalidated algorithm to compute daylight and glare levels and therefore are inadequate for an accurate analysis.

Twelve exterior shading systems were modeled, five of which were variants of the S-L shade where the slat cut-off angle was varied to evaluate cooling/ lighting/ glare trade-offs (named "shd 1-5" in the simulation study; "shd 2" was the system tested in this study). The exterior shades were modeled with a Title-24 2013 compliant dual-pane low-e reference window (SHGC=0.30,Tvis=0.65, U-value=0.26 Btu/h-ft^2-°F) with variable window area (WWR=0-0.60) and orientation, a dimmable lighting control system (LPD=0.75 W/ft^2, 500 lux setpoint), and a variable air volume system in a prototypical large commercial office building designed to be compliant with the Title 24 2013 Standard. An operable light gray interior roller shade (openness factor of 3%) was also modeled and was fully lowered at the first occurrence of glare and remained lowered for the rest of the day.

For a south-facing, 15-ft deep perimeter zone in Oakland, California with a large-area window (WWR=0.60) and no interior shade to control glare in both the reference and test cases, the exterior S-L (shd 2) system reduced annual source energy use due to heating, cooling, fan, and lighting from 13.5 kWh/ft^2-yr (reference case) to 8.4 kWh/ft^2-yr (test case), or a savings of 5.1 kWh/ft^2-yr (38%). If interior shades were used to control glare in

both the reference and test cases, the exterior system reduced perimeter zone annual source energy use from 14.9 to 11.2 kWh/ft^2-yr (25%).

The manufacturer estimated that the installed cost for the S-L system would be \$23-27/ft^2 for a volume purchase (>2500 ft^2). Assuming a utility rate of \$0.20/kWh and a technology life of 30 years, the simple payback would be 10 years for the Oakland example above. A similar analysis was not conducted on the dynamic shade.

Looking across the range of performance for the twelve static exterior shading systems with an operable interior shade to control glare, the maximum total source energy savings ranged from 3-28% as window area varied from WWR=0.30-0.60 in Oakland for a west-facing perimeter zone and 20-30% in the hotter climate of Burbank, California. The larger percentage savings were associated with the larger window areas. Exterior shading provided little to no benefit for small-area windows (WWR<0.30). Savings were also found to be highly dependent on the type of exterior shade and glass/ window type, which in combination then dictated the energy balance between cooling, heating, and lighting energy use and the need for interior shades to maintain visual comfort.

This analysis cannot be directly related to the data collected in the FLEXLAB but it does point to the degree of impact glare control can have on energy savings. Note that use of interior shades in the real world can vary considerably depending on space layout, task, and sensitivity of the occupant to glare. In Europe, where the sun path is considerably lower than that of the U.S. due to its higher latitude, exterior shading is used extensively despite the mild climate because cooling systems are often not installed in commercial buildings. The systems tend to be operable, lowered during the summer to minimize solar loads then raised during the winter season.

8. EVALUATIONS

8.1. DAYLIGHTING TECHNOLOGIES

Four daylight-redirecting technologies were evaluated in the LBNL FLEXLAB facility over a six month, solstice-to-solstice period. Each technology was tested for about five to seven days within each of the summer solstice, equinox, and winter solstice periods. Lighting energy use was monitored and compared to simultaneous measurements taken in an adjacent reference test cell configured to be compliant with Title-24 2013 requirements. Visual comfort and daylight quality were also assessed.

Findings were as follows:

- Monitored data demonstrated that annual lighting energy savings of 48-63% were achieved with the daylight-redirecting technologies and dimmable LED lighting. These savings were achieved above and beyond a reference case that had an installed lighting power density that was already 18% lower than the Title-24 code and an energy use intensity of 0.40 kWh/ft^2-yr. Average annual savings were 0.20 kWh/ft^2-yr over the 30 ft deep space. Under clear sky conditions, average savings were 62%.

- Annual monitored lighting energy savings of 3-25% were achieved with the daylight-redirecting technologies and the same dimmable fluorescent lighting as the reference case. Under clear sky conditions, average savings were 22%.
- Peak demand reductions during the noon hour were negligible because daylight was sufficiently high enough to meet the 300 lux setpoint in both the reference and test rooms, enabling the lights to be shut off.
- Visual comfort was acceptable if the occupant's primary view was toward the sidewall. If the view was looking at the window and near the window (6 ft from the window), discomfort glare levels were unacceptable, particularly during the equinox to winter solstice period. This assessment was conducted in a space with low-height partitions (3.57 ft) so views of the window wall were fairly unobstructed. The vendors of systems DL-L1 and DL-L2 recommend use of venetian blinds over the clerestory window to control glare and direct sun during the equinox to winter solstice period, but this would likely increase lighting energy use if the blinds were used sub-optimally.
- With the daylight redirecting systems, daylight levels in the center of the room (10-20 ft from the window) were within the "too low" range of illuminance for a greater percentage of the day during the equinox and winter periods compared to the reference case, but were within the "acceptable" range during the summer period.
- Average daily daylight uniformity as measured by workplane illuminance was not improved with the daylight redirecting systems. Subjectively, the room cavity however was observed to be more brightly and uniformly daylit on sunny days when significant daylight redirection occurred.
- Views to the outdoors were slightly distorted by the DL-L1 and DL-L2 films. Views were obstructed by the slats of the DL-Dyn system but a clear view between the slats was possible during some times of the day. The DL-P film is translucent and obstructs clear views out. In all cases, views through the lower window could be fully unobstructed, depending on how the occupant operated the venetian blind.
- Daylight simulations from a prior project estimated annual lighting energy savings of 0.35 kWh/ft^2-yr (28%) and peak lighting demand savings of 0.13 W/ft^2 (31%) from an earlier version of the DL-P film compared to a reference case with venetian blinds and dimmable fluorescent lighting (Sacramento, 40-ft deep south-facing perimeter zone). The modeled lighting system was less efficient than that tested in the FLEXLAB; simulated EUI levels were within the range of that measured in the FLEXLAB if differences in lighting controls and climate were adjusted for.
- Using the annual savings projected in Section 7.1.4, a simple payback of 2-6 years was determined given an installed cost of \$20/ft^2 and a utility cost of \$0.20/kWh.

Design considerations

- Applicable to large open spaces with primarily daytime occupancy.
- Best used on south-facing windows (i.e., orientation is 180 ± 45° from due north) with a moderate to high visible transmittance (Tvis=0.40-0.60). A continuous horizontal clerestory window would provide the most uniform ceiling luminance.
- The lower edge of the daylight-redirecting technology should be no lower than 6.5-7 ft above the floor. If there are sit-stand desks or tasks that involve prolonged standing, then the lower edge of the technology should be installed possibly higher

than 7 ft. The ceiling and window head height should be at minimum 9 ft or greater. Energy performance would likely increase if the height of the daylight-redirecting aperture were greater than 2 ft (assuming that the HVAC load was adequately controlled).

- Recessed windows, exterior shading, low-transmittance windows, obstructions such as tall buildings, mountains, etc. will reduce the daylighting potential of the technology. Placing the daylight-redirecting technology as close to the exterior plane of the façade will increase performance, particularly during the summer period.
- Work space planning – to increase depth of redirection to 20-30 ft from the window, wall or partition heights would be ideally no more than 4-5 ft high. Avoid fixed furniture that forces the occupant to face the window to do computer related tasks.
- Ceiling surface reflectance should be high (e.g., white, Rvis=0.75-0.90) with a matte, light-scattering surface; shiny surfaces at or near the ceiling plane should be avoided (e.g., shiny metallic light fixtures).

Implementation – The following observations were made during the implementation phase of this study in the FLEXLAB and in related demonstrations by the U.S. General Services Administration (GSA) Green Proving Ground and the U.S. Department of Energy Commercial Building Integration program:

- For retrofit applications, implementation of daylight-redirecting technologies should be considered when upgrades to the windows, interior shading, or lighting controls are being considered in order to achieve economies of scale. If daylighting controls are to be installed with the lighting system, bundling the upgrade with the daylight-redirecting technology would be prudent so that technical issues related to shielding the photosensor from upward daylight could be addressed at the same time. Distribution of the film would be best done through the manufacturer until design guidance and/or adequate simulation tools have been developed to define the appropriate conditions for use.
- This study assumes that the existing windows meet the Title-24 2013 code requirements for solar heat gain and U-value. If the windows are non-compliant, then a solution to control solar heat gains in the upper aperture of the window may be required in addition to the daylighting film.
- For windows with an existing indoor-applied solar control film, the retrofit solution for the three daylight-redirecting films will depend on the properties of the existing window glazing. The existing solar control film will likely need to be removed and replaced in the upper portion of the window.
- If the daylighting film is to be applied to the upper portion of a continuous sheet of glass (as opposed to separate upper and lower windows), thermal breakage issues will need to be considered if the existing glass is not tempered or heat strengthened and has an existing absorptive solar control film or other film that might cause a temperature differential between the upper and lower areas of the glass.
- It will be important to install the daylight-redirecting film (DL-P and DL-L2) with the correct orientation. If installation is incorrect (e.g., upside down), direct sunlight will be redirected downwards and will cause significant visual and thermal discomfort.
- In the case of the microprismatic window film (DL-P) and dynamic shade (DL-Dyn), the indoor shade will need to be re-mounted below the clerestory daylighting

aperture. For some applications with wide windows, a beam may need to be installed across the width of the glazed area to support the header of the shading device (e.g., venetian blind or motorized roller shade).

- In the case of the other two daylighting films (DL-L1, DL-L2), the vendor recommends that interior blinds or shades be installed at ceiling level or the top of the clerestory window and used to control sunlight and glare from the upper clerestory and lower view window. Separate interior blinds or shades can be installed on the lower view window to maximize daylight through the clerestory (e.g., if horizontal blinds are angled to reduce glare during periods of low angle direct sun).
- In the case of the DL-Dyn system, the controls can be tuned to the specific site conditions. The system has schedules to alter control settings and sensor thresholds by time of day and season, enabling priorities for solar control versus daylighting to shift according to HVAC and lighting energy minimization requirements or comfort requirements.
- The exterior appearance of the façade will change in retrofit applications so the installation will need to be coordinated with the property manager or owner.
- Potential need to add daylight dimming in the primary, secondary and possibly tertiary zone from the window, if not yet implemented.
- Potential need for photosensor modifications (if the original photosensors were not shielded adequately from the redirected daylight) and recalibration of the existing daylighting control system in retrofit applications.

Recommendations

- The static daylight-redirecting films are recommended for adoption with the proviso that the application be designed to mitigate glare, either through informed use of venetian blinds and/or space layout.
- The dynamic, automated daylight-redirecting system did not provide significant energy savings above and beyond that of the films and is therefore not able to justify its added cost and complexity based on energy savings alone. The dynamic system however may have the potential to improve its performance if designed and controlled more optimally.
- Monitored data from the FLEXLAB demonstrated that the findings from earlier simulations were at minimum consistent with field test outcomes. The comparison also illustrated how significantly the energy and peak demand savings can vary with climate, façade design, and the lighting system and controls. To determine applicability for a given site, we recommend that the technology be modeled prior to final specification or that design guidelines be developed in order to achieve the best balance between daylight, glare, and solar control. Radiance tools have recently been developed (Lee et al., 2014) to assess such technologies but these tools are not yet turn-key.
- Use of manually-operated shades over the DL-L1 and DL-L2 technologies was not investigated in this study. After observing and taking measurements in the FLEXLAB space on sunny days during the equinox to winter period, it became clear that shades would be required over the upper clerestory to control glare for occupants sitting next to the window. Shades covering the upper clerestory aperture will likely diminish energy savings if there is a single shade installed for both the upper and

lower window apertures. It would be useful to confirm user interactions with a monitored demonstration.

- The integration of daylighting controls and daylight-redirecting technologies was not investigated in detail in this field study. For dimming systems, proper shielding and calibration of the lighting control system will be required to obtain energy and demand savings. Further investigation should be conducted to ensure that reliable dimming can occur with these systems.
- The qualitative improvements to indoor environmental quality were not satisfactorily assessed in this study. Daylight redirecting technologies have the potential to create a greater connection to the outdoors throughout a larger area of the interior floor plate. Human factors studies are recommended in occupied spaces to better understand whether such benefits are perceived and appreciated by occupants.
- Glare is a critical issue with respect to these technologies, particularly if there is no fallback for mitigating glare, as is the case with the DL-P where shades are installed below the daylight clerestory aperture. Recent developments with the Radiance simulation tool will enable more accurate assessments of discomfort glare but further validation is required to assure accuracy. These same tools can be applied to further develop more optimal daylight-redirecting technologies.

8.2. SHADING TECHNOLOGIES

Two exterior coplanar shading systems were evaluated; one an operable and automated roller shade (S-Dyn) able to withstand high wind loads, the other a static microlouvered screen (S-L). HVAC and lighting energy use, and visual comfort and quality were monitored in the FLEXLAB facility, where the performance of the exterior shading system was compared simultaneously to an adjacent reference room with an interior venetian blind and dimmable lighting.

In summary, findings were as follows:

- Monitored data demonstrated that the daily perimeter zone cooling load due to the window was reduced with the static exterior shading system (S-L) by 16-68% and peak cooling demand was reduced by 2.6-11.5 W/ft^2-window (19-62%) during the mid-afternoon.
- Monitored data for the dynamic system (S-Dyn) indicated cooling load reductions of 12-22% with peak summer cooling demand reductions of 4.0 W/ft^2-window (26%).
- The FLEXLAB test cells were not calibrated at the time of the test (the PG&E study was the first conducted in the test rooms) and so when the loads were low, as was the case on cloudy days, the "noise" produced by differences in construction, siting, operations, and sensing between rooms were expected to exceed the differential signal we were trying to measure. As such, the between-room differences in cooling load when the rooms were configured to be the same were estimated to be within ±10% when loads were sufficiently high. Another factor that contributed to potential error was the assumption that "core" loads in the 15-30 ft deep rear area of the test rooms were comparable between test rooms, with all differences in loads attributable to the window wall. Subsequent tests (after the completion of this field test) indicated that the test rooms were not adiabatic so considerable noise may also be

attributed to differences in non-window envelope loads (floor, roof, side walls, and rear wall). These errors were not characterized at the conclusion of this study.

- Daily lighting energy use was decreased by 0.08 kWh/ft^2-floor-yr (16%) with the S-L system if the test case had LED lighting or was increased by 0.18 kWh/ft^2-yr (74%) if the same fluorescent lighting was used in both rooms (30 ft depth). For the S-Dyn system, lighting was less affected because the shade could be raised during periods of low daylight availability; energy use decreased by 0.11 kWh/ft^2-yr and increased by 0.14 kWh/ft^2-yr, respectively.
- Annual performance could not be extrapolated from the limited FLEXLAB data set. Comparisons with a prior LBNL field study involving a longer period of testing per system with well calibrated test cells (between-room accuracy to within 20-60 W on hourly basis) indicated that the south-facing perimeter zone performance trends were somewhat consistent with that of the FLEXLAB study. The prior study measured daily cooling load reductions due to the window of 78-94%, peak cooling load reductions of 2.7-5.3 W/ft^2-window (71-84%), and reduced lighting energy use (15-ft depth) by 53-63% compared to an indoor venetian blind reference case with no daylighting controls. The greater daily cooling load reductions in the case of this prior study were in part due to the poorer glazing system: the SHGC and U-value of the prior test was greater than that of the FLEXLAB study.
- Comparisons with a prior Radiance/ EnergyPlus simulation study provided insights as to the decrement in total perimeter zone energy use one could expect if glare was taken into account. Without glare control, the S-L system reduced total annual source energy use by 38% compared to the Title-24 2013 compliant reference case. With glare control using interior shades, annual source energy use was reduced by 25%.
- The monitored data in the FLEXLAB demonstrated the importance of considering glare when designing with exterior shading. Glare was adequately controlled during the summer but during the winter when the sun path was lower, it was evident that for some viewpoints within the space, particularly for those seated near the window, glare was significant on sunny days. It may be best to design the exterior shade to optimize for solar control and daylighting without the consideration of glare and then install interior shades and allow the occupants to control the shades according to their preference. Depending on view orientation and task being performed, the interior shades may or may not be deployed and lighting energy use may or may not be affected.
- The monitored data in the FLEXLAB also demonstrated the importance of getting the automated control system for the exterior shading system "right" in order to achieve an optimal balance between competing performance goals. It may be easier to focus on getting an optimal balance between cooling and lighting loads without considering glare and then leaving the occupant to control an indoor shade to maintain visual comfort.
- The monitored data also demonstrated the importance of selecting an appropriate fabric for the exterior roller shade or an appropriate finish for the static shade. The color, weave, openness, and surface reflectance of the shade will dictate solar occlusion, daylight, glare, and views to the outdoors.

- The FLEXLAB data indicated that the quality of daylight may be perceived as gloomy with either the S-L or S-Dyn systems. Daylight uniformity was not positively affected by the exterior shading system compared to the reference condition.
- Outdoor views were blocked by the S-L microlouvers but the views were filtered and undistorted. Filtered views were possible through the fabric roller shade when lowered and unobstructed views were possible when the shade was raised.

Design considerations

- Exterior, coplanar shading systems solve some of the structural and wind loading challenges of exterior shading and maintains a façade appearance that is to some degree architecturally within character of the original facade design. The dynamic roller shade with side rails offers a solution that can withstand high wind loads and is potentially applicable to high-rise buildings. The static micro-louvered solution is light-weight and avoids some of the problems of its macro-louvered counterparts which can encourage nesting birds, snow and ice accumulation, etc.
- The systems are applicable to south-, east-, and west-facing facades with significant exposure to direct sun (i.e., unshaded by nearby buildings and other obstructions). Benefits are greater in hotter climates and for facades with moderate- to large-area windows.
- The exterior shading systems may require use of interior shades to control glare and direct sun. In the case of the S-Dyn system, use of a fabric with a 1%- or 3%-openness factor on the exterior would likely be sufficient to control glare from direct sunlight. If a more open fabric is used, an interior shade would likely be needed. Note that using a second roller shade fabric with the S-Dyn system could produce a moiré (interference) pattern which could be visually distracting; an interior venetian blind is recommended. In the case of the S-L microlouvered system, the cut-off angle of the louvers was 30°, which balanced the need for solar occlusion and daylight admission. For further glare control, use of a second interior venetian blind could also produce a visually disturbing pattern. Use of a roller shade is recommended with the S-L system.
- Applicability as a retrofit option has not been characterized in this study, particularly for single pane windows and windows with no low-emittance coating. A more detailed study is required to understand cooling load performance; the static S-L shade will absorb solar radiation and re-radiate this heat gain to the interior if the existing window system is transparent in the near infrared. Heat buildup between the exterior shade and the window could also diminish cooling load performance, particularly if ventilation between the shade and the window is constrained.

Implementation

- Implementation of exterior shading technologies should be considered either before or when upgrades to the HVAC or lighting controls are being considered. Exterior shading can enable significant reductions in peak cooling demand, enabling reduction in peak cooling capacity of the HVAC system (chiller plant, air handler units, and air distribution systems) and savings in capital costs if synergies between the two systems are considered. If lighting controls are being considered, impacts on daylighting should be evaluated prior to final design and specification of the lighting

controls. Daylighting controls should be designed and commissioned with the final window configuration. For the static exterior shading, distribution could occur directly through the manufacturer to avoid unnecessary markups. For the automated exterior shading system, distribution should also occur directly through the manufacturer and controls engineer to ensure that the system is set up and commissioned properly.

- Structural engineering will be required to determine if the façade can bear the additional dead and live load of the shading system. Attachment points to the structure of the building will also need to be identified, which may difficult for retrofit applications.
- For low-rise applications where the window is used for egress, details of attachment of the shading system to the façade should consider fire, safety, and security issues.
- The S-L system can be applied to operable windows but the shading may not be effective, depending on the how the windows are operated.
- The S-L system must be installed with the correct orientation in order to be effective. This includes proper re-installation if the shades are removed for cleaning the windows behind the shades.
- For the S-Dyn system, details on how adjacent shades are controlled will need to be worked out: e.g., together at the same height or varied by office, whether manual override switches are provided to the occupants, where to install the exterior sensor, how the control system should be commissioned, how often and to what heights the shades should be positioned, etc. These details will affect performance and end user satisfaction with the exterior shades. The dynamic system has an advantage of fixed coplanar shades in that window washing can be accomplished by raising the shades.
- Details for supplying power and networking/ communications on the exterior window wall will need to be considered for the automated shade.
- Since exterior shading reduces the peak cooling load, it could improve the load balance between north and south zones, improve air handler unit operations, improve thermal comfort, and require less chiller peak capacity. The HVAC may need to be adjusted after the shade retrofit.
- Prior demonstrations have mandated scheduled use of exterior shades with a disregard to weather (i.e., irrespective of sunny or cloudy weather, the shades will be lowered; ACTT 1992). These installations have resulted in significant occupant dissatisfaction and disabling of the control system. It will be important to balance the desire for guaranteed energy savings and occupant satisfaction with the indoor environment to gain market acceptance of this technology.
- Note that the Title 24 Standard encourages use of alternate types of exterior shading, pointing designers to the NFRC-200 standard (NFRC 2010) in order to determine how to calculate the SHGC of the combined window and shading system. Unfortunately, the NFRC-200 standard does not yet accommodate exterior shading.

Recommendations

- The static microlouvered exterior shading system is recommended for adoption. The system is simple and can be potentially a low cost option given reductions in operating cost and the potential to downsize the capacity of the central chiller and air distribution system in deep retrofit applications.

- The automated exterior shading system is also recommended for adoption. The system offers greater amenity to the occupant and enables demand response through more optimal control based on the relative efficacy of the HVAC and lighting systems over the life of the building.
- Because exterior shading can significantly reduce cooling peak demand, both systems are particularly applicable to low energy buildings that are reliant on innovative cooling strategies such as radiant cooling, nighttime ventilation, and thermal mass to achieve very low energy use.
- Like the daylight-redirecting technologies, details of the application will be site dependent. To achieve the best balance between daylight, glare, and solar control, the existing conditions should be modeled to evaluate performance. Radiance and EnergyPlus tools enable such an evaluation but the tools are not yet turn-key.
- Human factors studies are needed to better understand user interactions with respect to visual and thermal comfort and their impact on actual performance.

2. REFERENCES

ACTT 1992. Final Project Report. San Ramon Demonstration, Advanced Customer Technology Test (ACT^2) for Maximum Energy Efficiency, Pacific Gas and Electric Company. http://207.67.203.54/elibsql05_p40007_documents/ACT2/act2fnl.pdf, accessed August 15, 2016.

CEC, Nonresidential Compliance Manual for the 2013 Building Energy Efficiency Standards, Title 24, Part 6, California Energy Commission, CEC-400-2013-002-CMF.

Hoffmann, Sabine, Eleanor S. Lee, Andrew McNeil, Luis Fernandes, Dragan Vidanovic, Anothai Thanachareonkit; Balancing daylight, glare, and energy-efficiency goals: An evaluation of exterior coplanar shading systems using complex fenestration modeling tools; *Energy and Buildings* 112 (2016): 279-298.

Inkarojrit, V. 2005. Balancing Comfort: Occupants' Control of Window Blinds in Private Offices. PhD Thesis, University of California Berkeley, 2005.

Lee, E. S., S. E. Selkowitz, D. L. DiBartolomeo, J. H. Klems, R. D. Clear, K. Konis, R. Hitchcock, M. Yazdanian, R. Mitchell, and M. Konstantoglou. High Performance Building Façade Solutions. California Energy Commission, PIER. 2009. http://eetd.lbl.gov/sites/all/files/publications/lbnl-4583e.pdf

Lee, Eleanor S., Brian Coffey, Luis Fernandes, Sabine Hoffmann, Andrew McNeil, Anothai Thanachareonkit, Gregory Ward, High Performance Building Façade Solutions–Phase II, Final project report, California Energy Commission, CEC 500-2014, 2014.

McNeil, A, Lee, ES, Jonsson, J, Daylight performance of a microstructured prismatic window film in deep open plan offices, Technical report, CEC Deliverable, 2013.

Nabil, A, Mardaljevic, J, Useful daylight illuminances: A replacement for daylight factors, *Energy and Buildings* 38(7): 905-913 (2006).

NFRC 200-2010: Procedure for Determining Fenestration Product Solar Heat Gain Coefficient and Visible Transmittance at Normal Incidence. National Fenestration Rating Council, Inc.

Schregle, R. The Radiance Photon Map Extension User Manual, Revision 1.19, May 28, 2015. http://www.radiance-online.org/learning/documentation/photonmap-user-guide

Serralux website, http://serraluxinc.com/serraglaze-daylight-redirecting-film/serraglaze-behavior/
Accessed 10/6/15.

Wienold, J., Christoffersen, J., Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras, *Energy and Buildings* 38(7):743–57 (2006).

GLOSSARY/ DEFINITIONS

Daylighting: strategies involving glazing, shading, sensors and electric lighting control, intended to deliver high quality lighting environment for occupants with minimal energy and demand impacts.

FLEXLAB: Facility for Low Energy Experiments in Buildings, a new LBNL user facility for field testing of integrating building systems performance.

Low-e (low-emittance) coating: A thin (<100 nm) metal, metal oxide, or multilayer coating deposited on glass to reduce its thermal infrared emittance and radiative heat transfer.

Solar heat gain coefficient (SHGC): The fraction of solar radiation admitted through a window including both directly transmitted and absorbed radiation that is released inward to the building. The SHGC has replaced the shading coefficient (SC) as the standard indicator of solar control. It is expressed as a number between 0 and 1. The lower the value, the less solar heat the window transmits.

U-value: The heat transmission per unit time through a unit area of material or construction (including the boundary air films on the surface of the material) induced by a unit temperature difference between the environments on each side of the material. The lower the U-value, the greater the insulating value or the window's resistance to heat flow. Also known as the U-factor.

Window-to-wall ratio (WWR): The ratio of the total area of the windows (glass area plus frame) divided by the total area of the floor-to-floor exterior wall.

Visible transmittance (Tvis): The fraction of solar radiation transmitted by the glazing system between the limits of 380 to 770 nanometers at normal incidence. It is weighted

according to the photopic response of the human eye and is expressed as a number between 0 and 1.