Customer Advanced Technologies Program Presents…

FINAL REPORT

Advanced Sidelighting Products

Prepared by Tim Perry (HMG), Lisa Heschong (HMG) & Bruce Baccei (SMUD)

Energy Research & Development
Sacramento Municipal Utility District
December 14, 2012

Report #: ET12SMUD1022
HMG Job#: 1105e

About the Customer Advanced Technologies Program…

SMUD's Customer Advanced Technologies (C.A.T.) program works with customers to encourage the use and evaluation of new or underutilized technologies. The program provides funding for customers in exchange for monitoring rights. Completed demonstration projects include lighting technologies, light emitting diodes (LEDs), indirect/direct evaporative cooling, non-chemical water treatment systems, daylighting and a variety of other technologies.

For more program information, please visit:
https://www.smud.org/en/business/save-energy/rebates-incentives-financing/customer-advanced-technologies.htm

TABLE OF CONTENTS

LIST OF FIGURES

1 EXECUTIVE SUMMARY

1.1 INTRODUCTION/PROJECT DESCRIPTION

The two products evaluated in this study, LightLouver™ Daylighting System (hereafter called LightLouver™) and the 3M Company's Daylight Redirecting Window Film (hereafter called 3M Window Film), claim to expand the area in which daylighting is possible. These savings are created by products utilizing the luminous power of direct sunlight, about 10-20 times that of light from just the sky, and redirecting it at upward shallow angles, deep into the space. By increasing the amount of daylight deeper into spaces, more electric lighting can be turned off or dimmed, increasing annual electricity savings.

Both products are passive systems. The 3M Company's Window Film uses micro-scale prisms to redirect incident sunlight and other sources of daylight toward the ceiling. LightLouver™ uses macro-scale mirrored louvers to redirect sunlight above 5° solar elevation upward toward the ceiling. The products are also designed to work on any sunlit facade, including east or west facing clerestory windows, thereby further expanding the applicable area that could be daylit.

However, the use of intense sunlight, at low incident angles, has potential to create serious glare problems for the occupants. Obscuring the upper windows with a light-redirecting device also changes the aesthetics of the space, and may negatively impact occupants' access to outside views. New systems applied to windows might impact maintenance and safety in the buildings.

Thus, specific project goals of this project were to determine:

- If occupant comfort was negatively impacted by any product and, if so, how.
- If occupants have an aesthetic preference for the products.
- If the products created any unexpected installation or maintenance challenges.
- If daylight illumination increased; and if so, where, when and by how much.
- The potential annual electric-lighting-energy-savings for the products.

1.1.1 Study Location and Time Period

All technologies were installed on the third floor of the Customer Service Center (CSC) building at SMUD's headquarters in south-facing windows on the third floor of the NW wing. These windows have 36% visible light transmittance glazing, include an upper clerestory, and are recessed into a deep façade which completely shades the windows in the summer time. Occupants can control the perforated vertical blinds in the lower view windows. SMUD's carpenters installed the LightLouver™ in the upper clerestory windows of one 20' wide window bay in the study area. The 3M Company installed the Window Film in an adjacent 20' wide window bay. Surrounding window bays retained the original light shelves.

A study area was identified that included 54 cubicles in the open office area that were within view of either the treatment or the control windows. This area was about seven cubicles wide and six cubicles deep, extending to the north wall 64’ back from the treated south windows.

The study began December 2011 and continued until July 2012. This report is based on site observations, informal interviews, occupant comfort surveys, illuminance field monitoring, and simulation analysis of the product’s performance.

1.2 ANALYSIS FINDINGS

Occupant satisfaction, installation and maintenance impacts, lighting energy savings, whole building energy savings, are described in the sections below.

1.2.1 Site Observations, Interviews and Surveys

Preliminary observations at solar noon on a sunny, mid-winter day showed observable shadows from redirected sunlight at the back of the study space, from both products, and a slight shadow even observable form the existing light shelves. Handheld illuminance measurements on the same day showed increases in horizontal illuminance in the treated areas from about 10 am to 3 pm. The distribution patterns of the diffused daylight were complex and overlapping, and so difficult to attribute to one product.

Photographic and luminance meter measurements showed very high luminance peaks at certain angles, especially above standing eye-level, and as expected close to the ceiling. The glare and glint seemed to transect fairly narrow horizontal angles, of 1-10 degrees. However, no complaints were received from the occupants about glare from the test products. All occupant complaints about glare sources were based on sun light that bypassed the existing light shelves, or the difficulty of operating the existing window blinds.

About 50% of the study-space occupants responded to formal surveys that were administered in winter and spring, and 30% to a final poll in summer. Overall, a majority preferred the aesthetics of the test technologies to the pre-existing light shelves. Occupants generally professed dislike of the existing light shelves, and described the test products as ‘more modern’. There were a few incidents of ‘optical confusion’ where occupants misinterpreted the 3M film as having created a ‘cloudy day’ or mysteriously obscuring the existing view. However, at the end of the study, only one occupant complained about losing the view through the upper windows. In a final poll, at the completion of the study period, more respondents preferred the aesthetics of the 3M Window Film product to the alternatives.

1.2.2 Installation and Maintenance Impacts

Both products were installed with a minimum of issues. Access to the windows was complicated by the existing office furniture located along the targeted façade. The team recommends that installers be equipped with mobile, lightweight, and easily assembled scaffolding to speed future installations.

There are fewer fire safety concerns with both the 3M and LightLouver™ products compared to the existing light shelves, since they do not extend into the room and interfere with fire sprinkler operation.

Both products improve access to the window surface for maintenance compared to the light shelves which must be un-hinged and lowered in order for maintenance staff to reach the upper window surface. The 3M product is purportedly easier to clean and maintain than the other products, since its planar glass surface can be cleaned with normal window cleaning methods. Cleaning the LightLouver™ product requires use of a cleaner that will not mar the surface finish. These cleaners are widely available. In addition, the LightLouver™ product must be tilted away from the window to allow cleaning of the window pane. To date, the SMUD maintenance staff has not cleaned either product.

1.2.3 Hourly Illuminance Monitoring

Forty Hobos were installed in the study space to record variations in daylight illuminance in 5 minute time intervals. Illuminance monitoring clearly showed that the test products are increasing the amount of daylight in the space on sunny days. Figure 29 and Figure 30 in the body of the report show hourly plots of ceiling and workplane illuminance for the two test products and the control light shelf on one cloudy and one sunny winter day respectively. Figure 29 shows no increased daylight illumination due to the test products on cloudy day, as expected. Figure 30 shows increased daylight illuminance due to the products, especially in the first two daylit zones. However, resulting impact on electric lighting savings were difficult to interpret.

Hourly illuminance monitoring of the study area was difficult to interpret for four reasons:

- **Insufficient monitoring granularity**: The influence of the test products overlapped in both time and space. Monitoring devices should have been installed at much higher density in order to distinguish specific contributions from the test technologies, or the test products should have been installed independently, so their impacts could be isolated. Extrapolation from the few data points available was not sufficient to estimate resulting electric lighting energy savings.
- **Interaction of products with photosensors is not understood:** Response of the ceiling mounted photosensors to the distribution patterns of sunlight from the test products was not understood. Unusual responses could not be ruled out.
- **The electric lighting could not be isolated out of the equation**: Fixtures were dimmed locally, and not consistently calibrated. A variety of vintages and types of lamps and ballasts throughout the study area had unknown output. The dimming response of the emergency (24/7) lighting also complicated interpretations of results, such that there was never a daylight-only condition.
- **Limited study period**: Heavy shading of the upper windows after spring solstice impeded efforts to resolve the above issues.

Thus, illuminance monitoring in the space could not provide the clarity on illuminance results desired. Attempts to address these challenges will be discussed in the body of the report. Consequently, annual daylighting computer simulations, discussed below, were used to estimate the potential daylighting savings for the two test products.

1.2.4 Simulation Estimates of Annual Lighting Energy Savings

Simulations were conducted using the Radiance software package. Simulations were conducted on rectangular spaces representing prototypical open office spaces. Seven room depths ranging from 16’ to 64’ were modeled with cubicle furniture. Lighting circuits were simulated in rows parallel to the windowed façade – a configuration ideal for daylighting.

The simulation methodology used the best-available (BSDF[1]) method to describe the light redirection by the products. The BSDF methodology has not been verified against field measurements for these products, and may introduce inaccuracies into the results. The details of the simulation methodology are discussed in the report body.

Simulation results suggest significant additional annual electric lighting energy savings from both LightLouver™ (Figure 1) and 3M Window Film (Figure 2) compared to the same windows with full height blinds. Savings shown are the percentage of full-load-equivalent (FLE) ON hours saved by installing products compared the T-24 baseline (3,071 FLE ON hours) for each daylit zone (DZ), each 8’ deep, starting with Zone 1 adjacent to the south windows. Results are presented for a lighting system with 30 foot-candle target for dimming to off photocontrols.

Both products increase daylighting savings throughout a south-facing 60’ wide x 64’ deep room, but savings are concentrated in the first three rows. Relative savings due to the products are much larger when blinds are always closed (Closed) than when blinds are actively operated (Auto), but absolute savings are highest with active (Auto) operation of window blinds. Savings are shown for a space with a 9’ ceiling and 40% VLT glazing.

---

[1] BSDF = Bidirectional Scatter Distribution Function. BSDF’s describe the three dimensional relationship between two hemispheres of incoming light and outgoing light across the planar surface of a complex glazing system. In current practice, the two hemispheres, are described each using a system of 145 “patches” or solid angles, thus creating a 145x145 matrix. These BSDF’s provide a better representation of optical distribution than previous methods, but the patches are relatively large and introduce some noise into the results, especially for glazing systems with specular reflections.

	Closed			Auto		
DZ	PC	PC & LL	LL Savings	PC	PC & LL	LL Savings
1	26%	47%	22%	53%	70%	18%
2	7%	20%	13%	30%	35%	5%
3	1%	5%	3%	9%	9%	1%
4	0%	2%	1%	3%	4%	0%
5	0%	1%	1%	2%	2%	0%
6	0%	1%	0%	1%	1%	0%
7	0%	1%	1%	1%	2%	1%
8	0%	1%	1%	1%	2%	1%

Figure 1. Annual lighting energy savings per Daylit Zone (DZ) from photocontrols (PC) alone and with photocontrols and LightLouver™ (PC & LL) on the clerestory.

	Closed			Auto		
DZ	PC	PC & 3M	3M Savings	PC	PC & 3M	3M Savings
1	26%	59%	34%	53%	73%	21%
2	7%	37%	30%	30%	51%	20%
3	1%	10%	9%	9%	15%	6%
4	0%	4%	4%	3%	6%	2%
5	0%	2%	1%	2%	3%	1%
6	0%	1%	1%	1%	1%	1%
7	0%	1%	1%	1%	2%	1%
8	0%	1%	1%	1%	2%	1%

Figure 2. Annual lighting energy savings per Daylit Zone (DZ) from photocontrols (PC) alone and with photocontrols and 3M Window Film (PC & 3M) on the clerestory.

The most important observation from this simulation exercise is that the electric lighting savings with the test products under worst case conditions (blinds always Closed) is very similar to, and often better than, the electric lighting savings potential for the same windows with no test product under best case conditions (Auto). Thus, the test products completely eliminate the downside risk of poor blinds operation, and greatly increase the upside opportunity for daylight savings.

1.2.5 Annual Whole Building Energy Savings

Energy savings increase when feedback with the building HVAC system is considered. Since daylighting reduces electric lighting usage, the HVAC system does not need to remove waste heat from electric lighting when in cooling mode. However, the HVAC must provide slightly more heat to replace the lost heat from electric lighting when in heating mode.

According to the DEER database, reducing electric lighting by one kWh is estimated to produce an additional 0.1098 kWh reduction in HVAC load in the Sacramento climate. Consequently, whole building electricity savings should be larger than the electric lighting savings alone. However, this is offset by a slight increase in gas used for heating (0.0070 therms / kWh) for both LightLouver™ (Figure 3) and 3M Window Film (Figure 4).

All estimates assume 1.2 W/sf installed lighting load for an existing building retrofit. If the lighting system is more efficient than 1.2 W/sf, or if hours of operation are substantially less than the Title 24 assumptions, either due to the building operation schedule or the presence of other control technologies, whole building savings will be correspondingly less.

			60' x 48'					
		Blinds Operation	Zone 1-3 Savings per Sq. Ft.			Zone 4-6 Savings per Sq. Ft.		
			LTG kWh	Bldg kWh	Therms	LTG kWh	Bldg kWh	Therms
9' Ceilng w/ 1.25' Clerestory	South	Closed	0.86	.95	-0.006	0.05	0.06	0.000
		Auto	1.37	1.52	-0.010	0.10	0.12	-0.001
	West	Closed	0.69	.77	-0.005	0.04	0.05	0.000
		Auto	1.54	1.71	-0.011	0.15	0.17	-0.001
10' Ceilng w/ 2.25' Clerestory	South	Closed	1.23	1.37	-0.009	0.12	0.14	-0.001
		Auto	1.70	1.89	-0.012	0.18	0.20	-0.001
	West	Closed	1.00	1.11	-0.007	0.10	0.11	-0.001
		Auto	1.79	1.98	-0.013	0.23	0.25	-0.002

Figure 3. LightLouver™ annual whole-building-energy savings estimated for spaces with 40% VT glazing.

			60' x 48'					
		Blinds Operation	Zone 1-3 Savings per Sq. Ft.			Zone 4-6 Savings per Sq. Ft.		
			LTG kWh	Bldg kWh	Therms	LTG kWh	Bldg kWh	Therms
9' Ceilng w/ 1.25' Clerestory	South	Closed	1.30	1.45	-0.009	0.10	0.11	-0.001
		Auto	1.70	1.88	-0.012	0.15	0.17	-0.001
	West	Closed	1.23	1.36	-0.009	0.11	0.12	-0.001
		Auto	1.82	2.02	-0.013	0.22	0.24	-0.002
10' Ceilng w/ 2.25' Clerestory	South	Closed	1.75	1.95	-0.012	0.22	0.24	-0.002
		Auto	2.04	2.27	-0.014	0.28	0.31	-0.002
	West	Closed	1.65	1.83	-0.012	0.25	0.28	-0.002
		Auto	2.07	2.30	-0.015	0.38	0.42	-0.003

Figure 4. 3M Window Film annual whole-building-energy savings estimated for spaces with 40% VT glazing.

Peak energy savings were not calculated as they are far more complicated, and were outside the scope of this project. However, demand savings would likely result from installing these products in some, but not all, orientations. Greatest demand reduction impacts are expected for south-west and west facing orientations, when direct sun is incident upon those windows during summer afternoons. Further simulation could be performed to quantify expected savings for a range of orientations.

1.3 CONCLUSIONS

Both products were found to provide additional lighting energy savings, especially significant in the first 24’ from a south window. Annual simulation results suggest that lighting and whole building energy savings are significant for all three orientations considered, south, southwest, and west. The taller the treated clerestory windows, and the higher the VLT of the clerestory glazing, the greater the savings. Additional savings due to reflected light off of back walls is important, especially within 24’ to 36’ from the window, and greater for east or west orientations. Daylight savings progressively deeper into the space are likely to occur, but further from the windows may become too negligible to be measurable.

Key findings are:

- As a preliminary rule of thumb, based on simulations, each additional 1’ height of treated clerestory window provides about an additional 8’ of useful daylight savings.
- Most importantly, the products eliminate the risk of reduced daylight savings due to occupants leaving window blinds closed. Simulations show that even if the lower blinds are left closed all year, daylighting savings with the products installed is at least as good as, if not slightly better, than optimized blind operation covering all the window area.
- Occupants did not report any additional visual discomfort from either product. In general, they preferred both products to the current window treatment using site-built light shelves. When given a choice, more occupants preferred the aesthetics of the 3M product. Occupant acceptance was not tested for east or west orientations, or for high summer sun angles on south windows.
- Installation and maintenance for both products is easier than for light shelves. No prohibitive problems were encountered during this field test. Maintenance for the 3M film assembly, as installed at SMUD, is no different than standard window glass, and thus likely to cause the fewest issues.

1.3.1 Lessons Learned and Next Steps

The field monitoring of the products performance was inconclusive, due to many confounding influences, and lack of sufficient isolation of the products from each other. Now that the hourly variation in light distribution patterns of the products is better understood, via the BSDF files created by LBNL and provided by the manufacturers, more detailed monitoring in the future may be more productive. Specifically, given the movement of reflected light on the ceiling by the products as the sun tracks across the sky, a grid of recording illuminance sensors, ideally spaced 5’ to 10’ apart, should be uniformly mounted in the study space. If mounted on the ceiling, sensitivity of the sensors to angle of incidence and spectral content of reflected sunlight should also be studied.

All possible solar angles should be considered in future studies, thus east, west, and intermediate orientations should be included. This is especially a concern for glare assessment, which may be more problematic at the very low sun angles incident on east and west windows.

Another important variable is operation of blinds in the view windows. It is very possible that occupant preferences and behavior relative to blind or shade operation may change in the presence of such products. Thus, observations of pre- and post-intervention blinds operation over time would be informative.

Ideally, a field study would be conducted to compare field monitoring results to BSDF based simulations, and be able to account for observed blinds operation. BSDF-based simulation methods should be validated, and the 145x145 matrix for the three-phase Dynamic Radiance approach, especially precision of hourly light distribution for these optically sophisticated products. Once validated, annual simulations could then be used to better predict lighting savings in other climate zones, and importantly, predict annual whole building energy savings and peak demand impacts.

2 INTRODUCTION

2.1 TECHNOLOGY DESCIPTION

Recent developments in the types and effectiveness of light redirecting technologies have created new opportunities for energy savings from daylighting in side-lit spaces. Light shelves have been the most common architectural solution to redirecting sunlight from clerestory windows. However, new technologies take up less space, may require less maintenance, and may redirect sunlight deeper into spaces.

Retrofitting all existing office buildings in California with basic daylighting controls could achieve peak-demand savings of 141 MW and annual-energy savings of 406 GWh, according to a recent PIER-funded study[2]. Within Sacramento Municipal Utility District (SMUD) territory basic daylighting controls in existing office buildings could save 7 MW of peak demand and 20.59 GWh of annual energy usage. Since daylight is available during hours of California's peak electricity consumption, typically hot summer afternoons, daylighting can potentially also reduce peak electricity demand, both by directly reducing electric lighting consumption and indirectly reducing cooling loads.

When daylighting is implemented via vertical glazing and traditional window coverings (blinds or shades), daylighting savings are concentrated nearest the fenestration. The majority of savings are obtained in the primary daylit zone, i.e. within one window head-height of the window. Smaller, but still cost-effective, savings are often achievable in the secondary daylight zone (between one and two window head-heights of the window). Lighting savings are rarely significant beyond the second daylit zone.

Light shelves were implemented in the SMUD Customer Services Center (CSC) to direct sunlight incident on south facing upper windows deeper into the space, thereby increasing daylighting savings. Per the PIER study quoted above, adding light shelves to facades with high windows and a southerly orientation could increase peak savings for those buildings by another 1% and annual whole building energy savings by about 3%.

These new technologies are relatively unproven and their performance characteristics need to be assessed. In addition, many of the advanced sidelighting technologies take advantage of highly reflective surfaces or microscopic lens structures. These surfaces behave in a specular, or mirror-like, manner, and provide a different appearance to windows, and so it is important to assess occupants' visual comfort and aesthetic preferences as to ensure energy savings do not come at the cost of occupant satisfaction.

---

[2] Saxena, Mudit. (Heschong Mahone Group). 2011. ***Office Daylighting Potential***. California Energy Commission. Publication number: TBD.

This study assessed the performance of two new products. The manufacturers of the LightLouver™ Daylighting System (hereafter called LightLouver™) and the 3M Company's Daylight Redirecting Window Film (hereafter called 3M Window Film) claim their products redirect sunlight and daylight deep into a space far more efficiently than a light shelf system. LightLouver™ also claims to reduce heat gain during the summer by reflecting some energy back out of the space.

For the field study, the performance of the two products was compared to the existing light shelves which were site-built in 1994. Photos of the products installed at the study site are shown in Figure 5 below with the light shelves first, on the left, 3M's Window Film in the center, and LightLouver™ located on the right.

Figure 5. Products tested left-to-right: light shelves, 3M's Window Film, and LightLouver™.

The SMUD Customer Service Center (CSC) building was made available as a study site, with high south-facing clerestory windows, from 9' to 11' AFF, and no major exterior obstructions to the sun or sky, other than the building's own facade. All glazing on the southern façade is 36% visual light transmittance (VLT). In addition, exterior light shelves directly outside of and beneath the clerestory windows provide some additional upward redirection of sunlight while helping to shade the lower view windows (see Figure 6). The lower windows, from 30" to 8'6" AFF, have perforated vertical blinds installed, which allow some filtered view even when closed.

The study area selected was a section of a large south facing façade on third floor of the northwest wing (see Figure 11. Aerial Photograph of SMUD's Customer Service Center) which provides daylight into a continuous open office area, described further in Section 2.2. The south façade of the SCS was designed with deep reveals to optimize daylight transmission in the winter months, and minimize solar gains in the summer months.

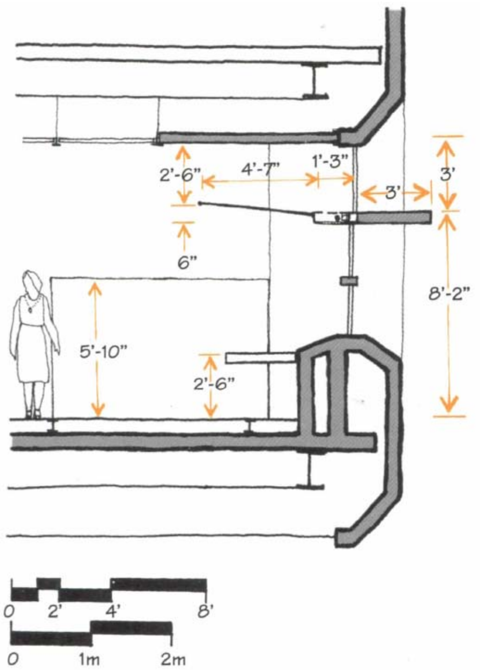


Figure 6. Section through the interior and exterior light shelves[3].

---

[3] Lighting Research Center, ***Demonstration and Evaluation of Lighting Technologies and Applications***, Delta Portfolio, Volume 2, Issue 2, 1997

2.1.1 Light Shelves (Existing Condition)

The lights shelves (Figure 7) installed at Sacramento Municipal Utility District (SMUD) were designed by the Architectural Energy Corporation. Light shelves represent the most commonly used sunlight redirecting technology over the past few decades. Light shelves are designed to intercept sunlight and redirect it towards the ceiling providing three benefits: occupants are shaded from direct solar radiation, redirected light is diffused over larger portion of the space providing more uniform daylighting, and glare from direct views of the sun are reduced.

Light shelves are most effective on south-facing windows in the northern hemisphere where they intercept high-angle sun for most of the day. Light shelves are less effective in east and west orientations because the light shelf must be very deep to intercept low-angle sun, but which only occurs for ½ the day or less; typically additional blinds or shades must be provided to control low-angle sun, or occupants must endure the trespass of direct sun for several hours a day.

Figure 7. Light shelves as installed in the study area.

Technology

The light shelves at SMUD are mounted at a slight upward slant, starting at about 8’6” AFF at the window. They extend 6’ into the space, with 1’3” of that nearest the windows including a grill and luminaire (Figure 6).The remaining 4’7” consists of a translucent vinyl fabric stretched over a metal frame. The frames are supported by metal wires connected to the window frames as shown in Figure 7 above. The wires include a heat-sensitive strip which will melt in the event of a fire. The heat-sensitive strip was added after the fire marshal expressed concern the light shelf would interfere with the operation of the overhead fire sprinklers.

The light shelves used at SMUD CSC do not impact overall window assembly U-value, SHGC or VLT.

Installation

The light shelves at SMUD CSC were fabricated on site, per architectural drawings.

Light shelves can potentially be difficult to install. The window wall may require reinforcement to support the cantilevered weight of the light shelf. In addition, care must be taken to ensure that installation of the light shelves does not impair the functionality of fire sprinklers or ceiling-mounted light fixtures. Nobody was interviewed about the installation of the existing light shelves which were installed almost 20 years ago.

Maintenance

Cleaning the light shelf involves vacuuming the upper surface, which collect some dust and dead bugs over time. In addition, the light shelf must be removed from the walls to enable washing of the upper, clerestory windows.

Appearance

Light shelves reduce the view through the upper windows, but do allow a partial view, especially when far away from the window. Thus, they preserve the transparency and visual clarity of the window glass. Light shelves can appear dark from underneath and brighter on the walls and ceiling above as the light from the upper window is redirected upwards in a fairly diffuse, soft pattern. In an effort to balance the relative brightness of the two surfaces, the SMUD light shelf material was selected to be somewhat translucent. As a result, patches of sunlight can be perceived through the fabric material, so it is quite clear when they are doing their job of redirecting sunlight.

One additional problem of the light shelf assembly is unique to the SMUD building design. There is a metallic grill directly above the view window, set into the recess of the window jambs, as the spring point where the fabric “light sail” begins. This grill was provided to diffuse and direct light from two T8 lamps mounted above it. In the case of the windows with a light shelf, this grill receives direct sunlight for some portion of the year, especially in winter midday. At some solar angles, the sunlight bounces through the reflective grill and causes uncomfortable glare sources for occupants sitting directly below the window. The site surveyors received a number of complaints from the occupants about this particular source of glare.

This grill was left in place for the two test technologies, even though the fabric ‘light sail’ and frame was removed. However, both the LightLouver™ and the 3M Window Film mitigate this glare problem by preventing direct sunlight from striking the grill, thus both the test products prevent this source of glare. If the light shelves remain in place in the building, ideally SMUD facility staff should find some other method to mitigate this glare source.

2.1.2 3M Daylight Redirecting Window Film

The 3M Window Film (Figure 8) installed at SMUD was produced and installed by the 3M Company. The product is not yet commercially available, although the manufacturer plans to bring it to market soon.

Figure 8. 3M's Daylight Redirecting Window Film installed in study area.

Technology

The key piece to 3M's Window Film system is their proprietary daylight redirecting window film. The film has micro features similar to a prism or a Fresnel lens which refract light to the ceiling. The effect is similar to a specular surface and so a second, diffusing film is added to soften the effect and reduce the potential for glare.

If integrated into a new dual-pane glass unit, the daylight redirecting film would be installed on the #2 surface and the diffusing film would be mounted on the #3 surface. In this retrofit installation, a triple pane window was created by adding a third pane of glass using Climate Seal™ Thermal Series Window Inserts. The daylight redirecting window film was installed on the #4 surface and the diffuser was installed on the #5 surface.

Because of the additional pane of glass and the resulting static air gap, and system also improves the U-value of the upper window, equivalent to a triple pane window. Because the film also includes some spectrally selective properties, a portion of the infrared and ultraviolet light are rejected, improving the U-value, SHGC, and VLT of the upper window system. The resulting changes to the window assembly U-value, SHGC and VLT are not known at this time. In addition, 3M has stated that existing test methodologies for VLT and SHGC do not adequately describe the anisotropic characteristics of these products.

Shipping and Installation

The Window Film system is shipped as two sets of plastic film, along with a custom sized frame kit and additional glass pane. The film is applied to the glass using a simple water and squeegee wetting system. The additional pane of glass sits in a frame which is attached to the existing window frame via screws or magnets. Compared to a light shelf, the vertical installation of 3M's Window Film reduces the need for wall supports and does not interfere with the dispersal of water from fire sprinklers or light from overhead light fixtures.

Labor to install the 3M's Window Film was about 8 hours (two installers for 4 hours). The product was installed by a 3M employee involved with developing the film and a professional installer. The 3M team felt installation time should not be extrapolated to larger installations for two reasons: (1) they did not have significant experience with product installation and (2) much time was consumed setting up before installation and cleaning up after installation.

Maintenance

Cleaning the 3M's Window Film System involves washing the inside pane of glass, using only normal soap and water. It has no other maintenance needs and thus is the simplest system to maintain of the three products. The interior surface is glass, and so is quite scratch resistant.

Appearance

The Window Film appears as a glowing, bright 'frosted' glass surface. The area immediately adjacent on walls and ceilings is also generally quite bright in a soft, diffuse glow, which is brighter than around the view windows below, especially when the upper window is in sunlight. Given its diffusing properties, the Window Film does not cast any obvious shadows, so it is not immediately obvious when it is redirecting sunlight, nor is there a noticeable difference in appearance between sunny and cloudy conditions. The difference in appearance between a sunny day and a cloudy day is only of intensity.

The disappearance of this view was confusing to some occupants, who interpreted that suddenly either the day had become foggy or their eyes unfocused. For example, there is another wing of the CSC building which can be viewed through the clerestory windows fitted with light shelves, but not through the diffusing surface of the 3M Window Film. The loss of this view prompted the comments from the occupant.

2.1.3 LightLouver™ Daylighting System

The LightLouver™ Daylighting System (Figure 9) installed at SMUD was produced by LightLouver LLC. The product is commercially available from the manufacturer.

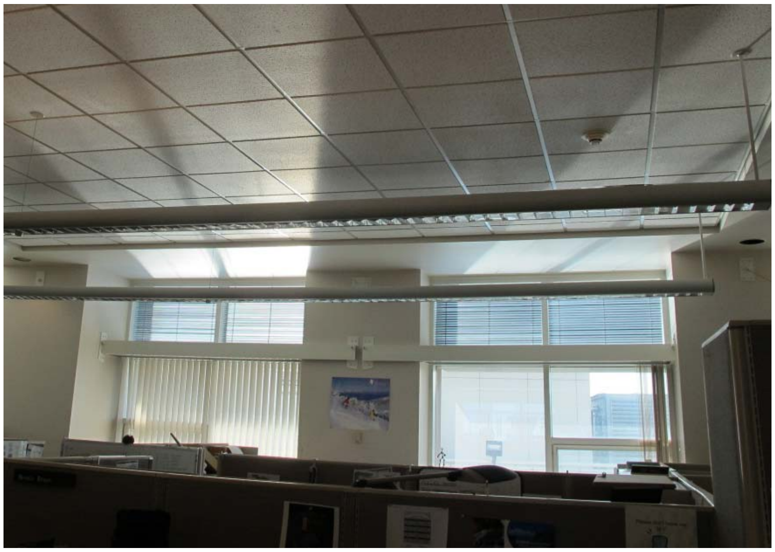


Figure 9. LightLouver™ Daylighting System installed in study area.

Technology

The LightLouver™ Daylighting System (henceforth LightLouver™) uses reflective louvers (3-dimensional slats) to redirect light towards the ceiling (Figure 10). The plastic slats have an optically engineered three dimensional cross section, and are coated with a high reflective coating. According the manufacturer, because of its special optical design, LightLouver™ redirects a higher percentage of incident sunlight "much deeper inside a building than previously possible [with] a light shelf while eliminating glare."[4]

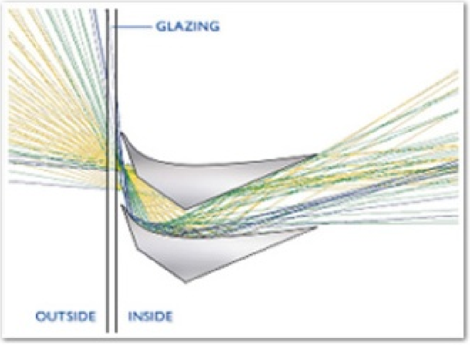


Figure 10. LightLouver™ light redirection.[5]

---

[4] http://lightlouver.com/faqs/#id57

[5] http://lightlouver.com/lightlouver-description/

In addition, because LightLouver™ intercepts any incident sunlight originating more than 5° above the horizon, LightLouver™ effectively controls glare caused by direct sunlight on east- and west-facing façades while still bringing sunlight into the space. Thus, LightLouver™ can be useful on more façade orientations than a light shelf.

However, one important difference between LightLouver™ and the other two products should be noted: LightLouver™ does not transmit much diffuse daylight from the sky dome or reflected sunlight from below. Since the SMUD CSC clerestory windows see both a fairly large area of sky, and receive upward reflected sunlight from the roof, paving and exterior light shelves below, the LightLouver™ system transmits considerably less of the total diffuse daylight resource than the other two products.

The LightLouver™ system clearly reduces the VLT of the upper window, and may also improve the net SHGC and U-values to some degree; however the magnitude of these effects are not known at this time.

Shipping and Installation

The 3" plastic slats are shipped pre-cut to a custom width and mounted on vertical bars. The assembly is hung, using a hinge, to the upper wall or frame of the clerestory window. Compared to a light shelf, the vertical installation of the LightLouver™ Daylighting System reduces the need for wall supports and does not interfere with the dispersal of water from fire sprinklers or light from overhead light fixtures.

Labor to install the product in the study space was about 16 hours (two employees working for one day). A few slats were slightly misaligned and needed to be readjusted after initial installation. The carpenters noted most of their time was consumed building scaffolding to reach the window area. Consequently this information should not be generalized to other sites. Future installation teams should be equipped with light-weight, easy to assemble scaffolding to minimize labor costs.

Maintenance

Cleaning the LightLouver™ System involves both dusting the LightLouver™ slats and washing the window behind it. According to the maintenance manual on the LightLouver™ website, cleaning should occur at least twice a year. LightLouver™ stated that one year of dust accumulation caused a 3% decrease in light transmission at one site where the performance of their product was monitored[6].

To wash the windows, the LightLouver™ must be pivoted out of the way. According to the manufacturer's online instructions, pivoting the LightLouver™ requires two people working in tandem[7]. The manufacturer, in written comments on a draft of this report, stated that only one person should be needed to pivot LightLouver™ out of the way for cleaning at SMUD since the panel was of relatively small size. However, there is no guidance on the manufacturer's website or in the maintenance manual[8]

---

[6] Mike Plann, pers. comm., May 4, 2012

[7] http://lightlouver.com/design-information/installation-and-maintenance/maintenance-information1/

[8] http://lightlouver.com/uploads/LLMaintenanceManual2010.pdf

telling an interested party which sizes need to be pivoted by two people and which sizes could safely be pivoted by one.

Appearance

The LightLouver™ appears as a series of opaque grey or silver louvers. The louvers' undersides remain dark at all times, although some reflected sunlight can be seen on them. When the louvers are in sunlight, the reflected sunlight appears as bright striations on the ceiling and adjacent walls, with crisp edges and shadows cast from window mullions and frames. Thus, it is very easy to see when the product is doing its job of redirecting sunlight. Under cloudy conditions, the louvers appear dark.

Since the louvers are opaque, there is no view through them,. However, there are some tall trees outside of the building which catch the late afternoon sun striking the louvers. When this happens, the movement of the leaves in the breeze can be perceived via the moving sunlight and shadow patterns reflected up on the ceiling. This can provide an interesting sense of animation deep into the space.

2.2 FACILITY DESCRIPTION: SMUD CSC, THIRD FLOOR

The study site is located on the third floor of the northeast wing of the Customer Service Center (CSC) at SMUD campus, located at the corner of S Street and 65th Street. The study area is occupied by software developers, managers, and support staff. The area is an open office with most employees sitting in cubicle workstations, approximately 8'x8' square with 5' high grey partitions, in regular rectilinear rows parallel to the windows. Employee schedules depend on work load, but most employees work from 8AM to 5PM.

The study site is nearly ideal for evaluating advanced sidelighting products due to the building orientation, geometry, glass types, and electric lighting configuration. The study site is located on the rectangular-shaped third floor with the long, windowed façades facing essentially true South and North. The study site façade is not shaded by trees or adjoining wings of the CSC building for most of the day. However, the recessed window glass is shaded by the depth of the façade, with both vertical and horizontal shading patterns, that completely shade the window glass by mid-summer. The study area is in the north-east wing of the large building pictured in Figure 11.

Figure 11. Aerial Photograph of SMUD's Customer Service Center[9],

The building was previously highlighted in a Delta Portfolio article published in 1997[10]. The article presented results indicating occupant visual comfort to be above average for comparable buildings. The authors found occupant comfort was preserved while providing access to daylight in an open-office space. They noted employees appreciate task lights because it gives them "flexibility and control over the lighting conditions in their workspace." They also noted that window blinds help employees control excess "glare, heat or illumination by changing the angle of the blinds as the sun tracks across the sky."

2.2.1 Window Properties

The south façade has lower view windows and upper clerestory windows. All south facing windows have are dual pane low-E glass (36% VLT) with perforated, vertical blinds. Above the lower windows are both interior and exterior light shelves. Above the light shelves are clerestory windows with no window

---

[9] Picture from Google Maps downloaded May 4, 2012

[10] Lighting Research Center, ***Demonstration and Evaluation of Lighting Technologies and Applications***, Delta Portfolio, Volume 2, Issue 2, 1997

coverings (blinds or shades). The rough opening of the clerestory windows is 7’6” wide and 3’ high.[11] A window bay is composed of two clerestory windows separated by a 4’ wide column.

The windows of the south façade were designed with a careful shading strategy that takes advantage of both horizontal and vertical shading from the window recess. Later analysis by the study team verified that the upper, clerestory window glass, receives little direct sunlight during the summer months. Figure 12 below illustrates the annual shading pattern on these windows, which became an important limiting factor for the field observations of this study.

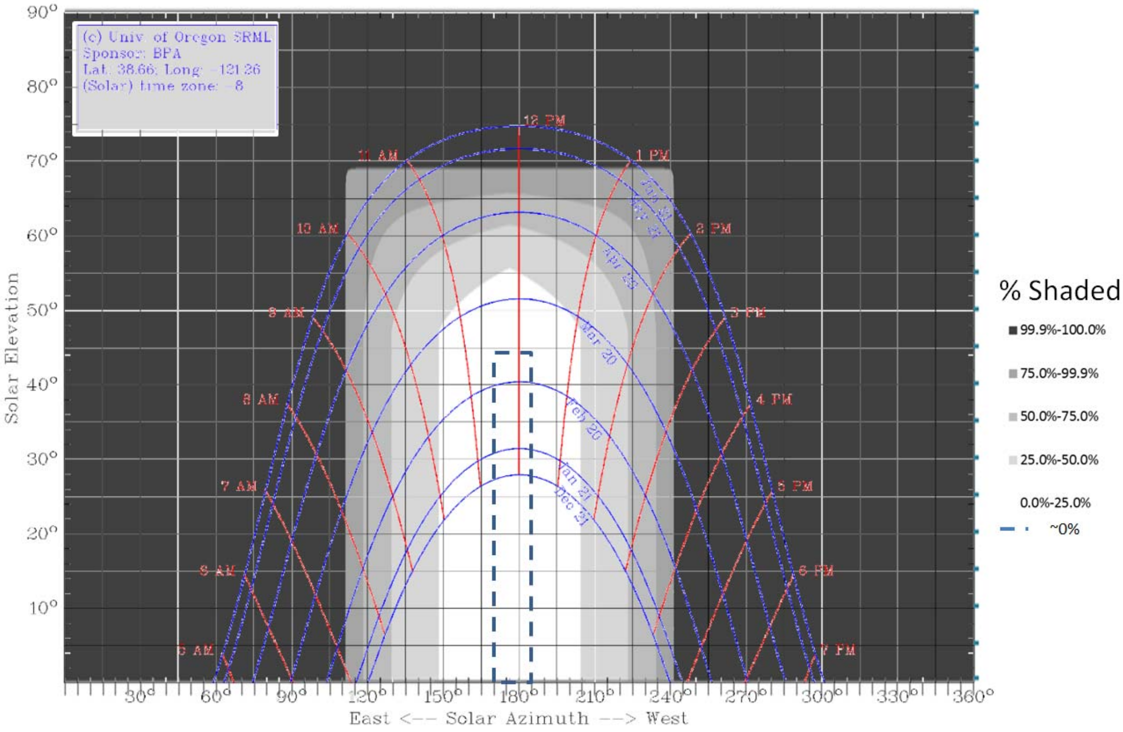


Figure 12. Shading diagram for clerestory windows in study space.

With the permission of the occupants next to the windows, the blinds slats in the study area were all adjusted at the start of the study to 45 degrees to the glazing, so as to best block direct sunlight to the nearest occupant. The angle blocked most sunlight falling on the adjacent desk, but allowed a view through the blinds. The occupants were asked to keep the blinds in that fixed position for the duration of the study. Many occupants were initially agreeable to this request, but on a subsequent site visit on April 26th about one third of blinds positions were observed to have been changed to block all possible daylight sometime in the interim.

---

[11] Lighting Research Center, ***Demonstration and Evaluation of Lighting Technologies and Applications***, Delta Portfolio, Volume 2, Issue 2, 1997

2.2.2 Electric Lighting System

Electric lighting is provided by 70% up / 30% down pendant linear fluorescent fixtures, with a one lamp cross section. Each 20’ long fixture in a daylit zone has a centrally located photosensor which dims the five T8 lamps in response to changes ambient light levels. Visual observation suggested that light output varied by luminaire, and anecdotal information suggested that each luminaire’s output relative to the photosensor input had been individually tuned to occupants’ preferences over time. Variation in color temperature of the lamps at the time of the study start indicated that there were at least three different lamp products in use, also suggesting different vintages of lamp aging.

There had been an intention to replace all lamps with a uniform product and age, and calibrate all diming controls to a single setting before data monitoring began, in order to standardize light output in the study area. However, this did not happen. There were a few lamps and ballasts which were not functional during the study. These were noted on plans. By turning off all the overhead lighting with a floor-level circuit breaker, the location of pairs of emergency egress lamps on 24/7 operation and back-up power were also noted. It was expected that the emergency lamps were kept on at full power, but later data analysis showed that these emergency fixtures were also dimmed via the local photosensor controls.

2.3 SIZE OF EXISTING MARKET

The potential market for advanced sidelighting products includes all south-, east-, or west-facing façades with a ceiling and window height above 9’ where adjoining space has significant lighting energy usage and does not have skylights. Ideally the window glazing will also be relatively clear (50% or greater VLT) and have incident sunlight for the majority of the year, unobstructed by shading, trees, or other buildings.

Additionally, spaces with dropped ceilings below 9’ could be retrofit opportunities if the windows extend at least 9’ above the finished floor (AFF) and the drop ceiling could be removed. This has often been observed in older school and office buildings. Offices are also one of the most appropriate building types for daylighting optimization, due to patterns of occupant use and hours of operation predominantly during daylit hours.

A recent study for PIER[12] found that approximately 11% of the existing office space square foot in California could be retrofitted with light shelves. Given that there is about 1 billion square feet of existing office space in California, and SMUD share of that is about 13%, the initial estimate of existing office area to which these technologies could potentially be applied is about 14 million square feet in

---

[12] Saxena, Mudit. (Heschong Mahone Group). 2011. ***Office Daylighting Potential***. California Energy Commission. Publication number: TBD.

SMUD's territory. Office space constitutes about 40% of the commercial and industrial square footage in the state, and an even higher percentage in SMUD territory, thus it is a large target market for these products. SMUD's territory has a large stock of existing buildings that potentially meet these criteria, especially older office buildings downtown and newer office buildings along the Route 50 corridor.

Simulation results in this study support manufacturer claims that the product can be usefully employed to reduce electric lighting use in east and west orientations. However, it is important to note that occupant comfort results presented here only apply to the sun altitudes experienced on the southern façade during the winter, i.e. from about 30 to 60 degrees. Lower solar altitudes, such as would be experience on east or west facades, might have different visual comfort results.

2.4 REASON FOR THIS PROJECT

Energy savings are an important goal for many utilities. SMUD has committed to reducing greenhouse gas emissions to 10% of 1990 levels by 2050[13]. In order to meet this goal, SMUD plans to meet these goals through energy efficiency measures and increase non-carbon emitting electricity generation[14].

In the building sciences, "daylighting" refers to turning off or dimming electric lighting when daylight provides sufficient illumination in the area. Daylighting reduces electricity consumption by directly reducing the need for electric lighting and indirectly reducing the cooling loads created electric lighting. Daylighting has the added advantage that its greatest load reduction tends to occur during peak demand hours, such as summer afternoons. In new construction, daylighting can be a cost-effective approach to reducing electricity demand if a sufficient reduction in electric lighting energy consumption is realized to offset any increased cooling loads due to fenestration. In existing buildings, where the fenestration system already exists, any reduction in electric lighting is an overall savings benefit. Thus, retrofitting photocontrols into existing daylit spaces has a strong beneficial impact on system load profiles.

Generally, a balance must be struck between bringing light into a space and maximizing occupant comfort and productivity. A wall of clear glass can bring voluminous quantities of light into a space and provide electric lighting energy savings if combined with photocontrols. However, this configuration can also oversaturate the space with light making it too bright, glary for the occupants, and create radiant heating problems that leave the occupants too cold in the winter and too hot in the summer.

A more nuanced approach is to install window attachments such as blinds or drapes that an occupant can close to manage glare and thermal discomfort. However, these window attachments when closed also reduce the available daylight and therefore defeat the efficacy of daylighting the space. While

---

[13] https://www.smud.org/en/about-smud/environment/greenhouse-gas-reduction.htm
[14] ibid.

daylighting might still be cost effective in the space, both the energy savings and the area that can be controlled will be reduced in magnitude.

A more advanced solution is to split fenestration into lower, view windows and an upper, clerestory windows. Occupants are given control of window attachments on the lower window so as to maintain their comfort as the sun position changes throughout the day. A light shelf or other sidelighting technology spreads daylight from the clerestory through the room, redirecting daylight away from the windows, where there is typically an oversupply of daylight, to areas further back which are relatively dim. If well designed, the sidelighting product balances the daylight throughout the room and increases potential energy savings. A number of specialty sidelighting products are available which accomplish these goals by bouncing sunlight off the ceiling which both distributes and diffuses the sunlight.

This study assessed how two advanced sidelighting products affect energy savings and occupant comfort to take fuller advantage of daylighting-energy savings in SMUD territory. From an energy point of view, these products may help SMUD meet its energy efficiency goals if the products provide reliable energy savings in the Sacramento metropolitan area. From a market acceptance point of view, products will be acceptable if occupant comfort is either improved or unaffected by these products. For retrofit projects, these products should be easy and inexpensive to install and maintain, and not negatively impact the aesthetics of the interior or exterior of the building.

Consequently, SMUD's Emerging Technology program requested an evaluation of two, new, advanced sidelighting products.

3 DATA COLLECTION

Data collection for this project involved a number of methodologies:

- Site observations, handheld measurements and photography
- Interviews with occupants, facility staff and manufactures
- Occupant surveys
- Hourly illuminance monitoring
- Annual simulation of daylight distribution for prototypical conditions

The methodology and initial observations for each will be discussed in turn below.

3.1 SITE OBSERVATIONS

The study team spent two days at the site collecting visual observations, photographs and handheld illuminance observations, once during normal operating hours in late December after all the test products were installed, and once on a Saturday in early January when the monitoring equipment was installed. The Saturday visit in January enabled the team to study the space under almost purely daylit conditions, since only the emergency lighting was left on.

Many of the light redirection properties of these products are unusual compared to products commonly encountered in office buildings. Unusual patterns were documented using standard digital photographs. These have been very useful in communicating the qualitative differences between the products.

Systematic illuminance and luminance measurements were taken with light meters and a luminance gun. The light meter was an Illuminance Meter T-10 manufactured by Konica Minolta. The T-10 light meters spectral response curve closely matches the human-eye’s spectral response curve (Figure 13). Meter response to light at non-normal angles is cosine corrected.

Illuminance readings were taken along transects parallel to the southern façade at multiple times. Full sets of readings were obtained with all electric lighting turned off (at the floor level) and with electric lighting functioning normally. When electric lighting was turned on, electric lights were allowed to burn for at least ten minutes before collecting readings to ensure the fluorescent lamps were up to full light output. Transects were 12, 20 and 28 feet from the façade.

HDR photometry was conducted along transects in the space using a fish-eye lens. However, glare metrics could not be computed due to the overlapping influence of the products. Regular photographs are more accessible to the reader and communicated all relevant information about light distribution by the products. Consequently, HDR photometry results were dropped from the report.

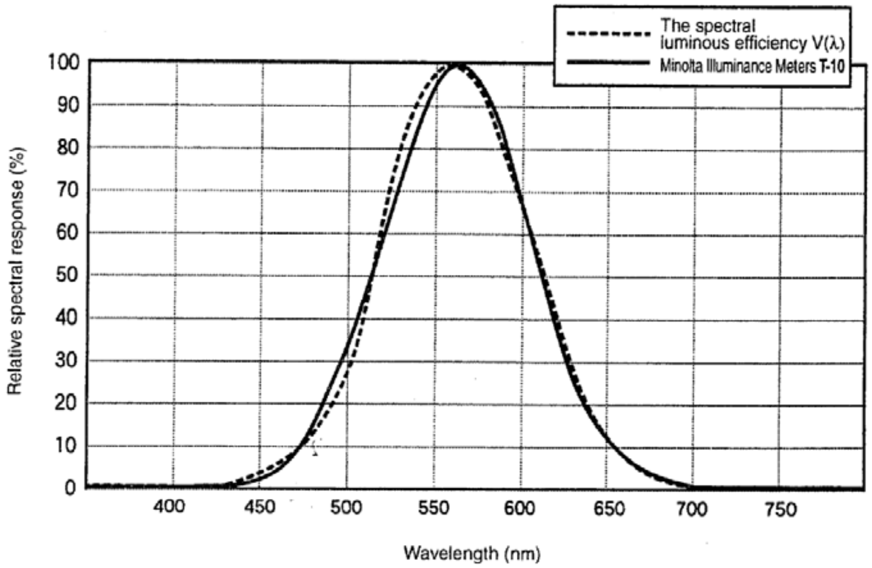


Figure 13. Spectral response of the Minolta T-10 illuminance meter[15].

3.2 INTERVIEWS

Occupants were interviewed for any anomalous or unexpected experiences. This was only been performed in an informal fashion during site visits.

SMUD maintenance staff, carpenter staff, and outside contractors who have helped to install and/or maintain the products were interviewed for this interim report. The goal was to understand the installation and maintenance issues for the first six months the products were installed.

3.3 OCCUPANT SURVEYS

Occupants of the study space were asked about their comfort and opinion of three products through periodic surveys. The surveys were administered online using the SurveyMonkey™ tool[16]. Screenshots of the survey are presented in Appendix A. The study plan called for administering surveys during both sunny and cloudy weather in three seasons (winter, spring, and summer), for a total of six surveys. The surveys were intended to capture issues associated with a particular weather types or sun angles.

Surveys were distributed to the occupants by the floor supervisor. Occupants were asked to complete the survey at the end of their work day and assess their comfort separately for the morning, mid-day, and afternoon time periods.

---

[15] Illuminance Meter T-10 / T-10M Instruction Manual

[16] http://www.surveymonkey.com

The survey was administered when several days of similar weather were forecast by the National Weather Service. Occupants were asked to fill out the survey at the end of their work day. The survey was a mix of short answer and Likert Scale questions. On the Likert scale, 1 indicates bad or strongly disagree, 5 is neutral, and 9 is good or strongly agree.

Only sunny-winter survey results and cloudy-spring survey results were collected. Winter was unusually sunny and spring was unusually clouding precluding the possibility of administering the other survey during cloudy weather in winter and sunny weather in spring.

SMUD determined that they did not want to administer the final, summer, occupant survey, given that there was currently then no sun exposure on the clerestory windows and concern that “survey fatigue” was setting in. SMUD proposed allowing occupants to vote on if they would like to have one of the test products (LightLouver™ or 3M Window Film) replace the light shelves. An e-mail was sent to all staff on the floor asking them to “Please respond…by email…[and state] which product you would prefer to have installed throughout the floor, and why.” The full text of the e-mail is shown in Appendix B.

3.4 HOURLY ILLUMINANCE MONITORING

The monitoring objective was to collect sufficient data to compare the performance of the two advanced sidelighting products to the existing light shelves. Monitoring began January 7th and continued until July 16, 2012 (Figure 14).

Monitoring was conducted in two phases: a preliminary monitoring period to support the interim report (1/7 through 4/16) and a final phase of monitoring (4/17 through 6/22) to capture the remaining sun positions. During the preliminary period, the solar altitude ranged from 29° to 62° at solar noon.

ID	Task Name	Start Date	End Date
1	Logger Installation / Spot Measurements	1/7/2012	4/16/2012
2	Preliminary Continuous Illuminance Monitoring	1/7/2012	4/16/2012
3	Logger Removal/Data Download & Logger Re-launch	4/16/2012	4/16/2012
4	Final Continuous Illuminance Monitoring	4/16/2012	7/16/2012
5	Final Logger Removal / Data Download	7/16/2012	7/16/2012

Figure 14. Dates of monitoring phases.

During the final period, very little if any sunlight was present on the test windows, (see Figure 12) and thus only the first monitoring period proved useful for analysis.

3.4.1 Exterior Illuminance and Weather Monitoring

Exterior illuminance and weather records were downloaded from publicly available sources for the monitoring periods outlined above. Solar elevation (Altitude Angle) and azimuth were calculated following a procedure published by NOAA[17].

Weather data from the Mather Field airport (~7 miles from study location) was downloaded from MesoWest[18]. Mather Field is equipped with an automated weather station which reports air temperature, dew point, sky condition, and visibility in miles. Observations occurred hourly unless visibility or sky condition changed significantly. In that case an intermediate observation was recorded to aid aviation. Fortuitously, these changes were relevant to the study and enabled identification of changes from clear to cloudy weather and vice versa. Sky type was categorized for each reading as clear sky, cloudy sky, or mixed (partially cloudy) sky based on the weather data from Mather Field.

Exterior illuminance was captured by two HOBO UA-002-64 pendant loggers positioned in the clerestory windows. One was placed horizontally on an un-shaded sill. The other was placed vertically on an un-shaded clerestory window. The logger position is denoted by a circle in Figure 15.

3.4.2 Interior Illuminance Monitoring

Forty (40) HOBO U-12 data loggers were employed for this study. A research plan was proposed to try to capture sufficient data throughout the 64’ deep study space to understand the variation in daylight patterns created by the two test products and the base case. Figure 15 shows the sensor locations and Figure 16 documents data logger manufacturer and model numbers. There were two types of sensors locations:

A.) Horizontal illuminance: three sets of matched pairs of sensors on the ceiling and on top of partitions along a transect through the middle of each test bay and base case. These transects are highlighted by the (red) lines in Figure 15. Circles mark work-level sensors locations. Dots mark ceiling sensors locations. As best as possible, given existing furniture locations, these pair of sensors were located directly over each other, and midway between the pendant luminaires. Loggers were approximately 13’, 21’ and 29’ from the window glazing.

B.) Vertical illuminance: HOBO data loggers were also attached to columns in the space. These loggers were mounted vertically looking back at the south windows. There were two sets: five at the midpoint of the floor, about 33’ from the south windows, and three at the far north (henceforth “rear”) wall, about 68’ from the south windows. On the middle-floor row of columns, loggers were positioned 11’0”,

---

[17] http://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html

[18] http://mesowest.utah.edu/cgi-bin/droman/download.cgi?stn=KMHR&year1=2012&timetype=LOCAL

9’6”, and 8’0” AFF to record any changes in vertical daylight levels. On the rear row of columns, loggers were placed at the top, 11’0” AFF, to record any changes in vertical illuminance levels.

It had been observed during initial mid-winter site visits that both the Window Film and LightLouver cast noticeable sunlight and creating shadows on the mid-floor and rear columns at solar noon. The challenge was to understand how the intensity and distribution of this light varied by solar angle over the course of the year, and if it could usefully reduce the need for electric lighting deep into the space.

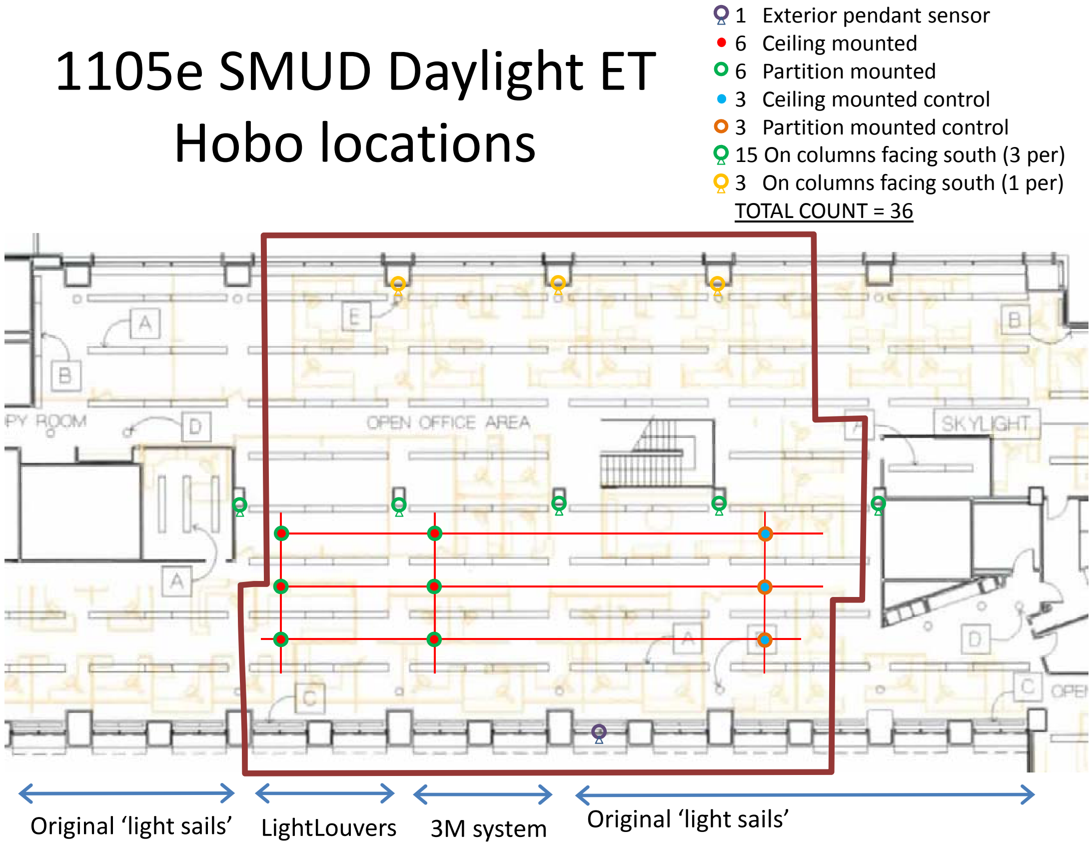


Figure 15. HOBO sensor locations in the study space

	Equipment	Quantity	Logger Type	Measurements	Units
1	Partition-top Transects	9	HOBO U12-12	Illuminance	fc
2	Ceiling Transects	9	HOBO U12-12	Illuminance	fc
3	Column Brightness	18	HOBO U12-12	Illuminance	fc
4	Sky and Sun Brightness	2	HOBO UA-002-64	Illuminance	fc

Figure 16. Monitoring Parameters and Equipment

3.4.3 Specification of Monitoring Equipment

Logger positions are color keyed in Figure 15. Logger types and measurement types are shown in Figure 16. The HOBO U12-12 records light arriving with-in 30° of perpendicular (Figure 17).

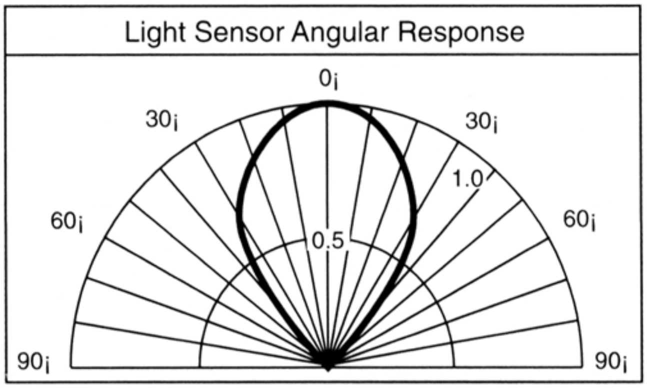
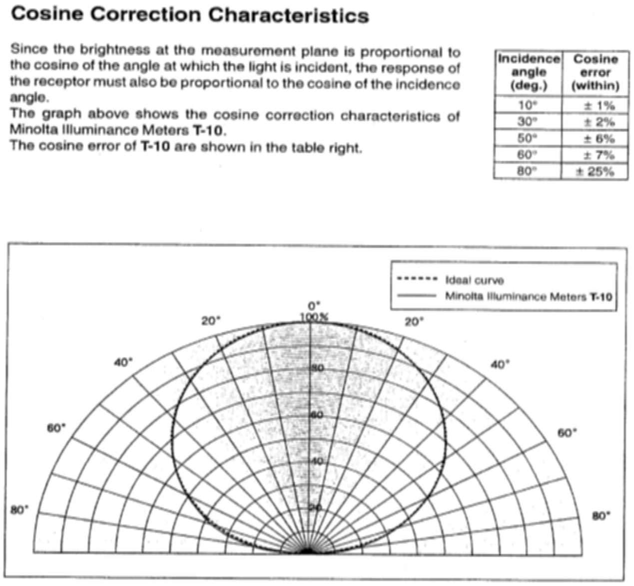


Figure 17. Angular response of the HOBO U12-12 illuminance sensor.

The specifications of monitoring equipment are presented here in Figure 18. All loggers recorded illuminance at a ten minute interval continuously from January 7th to July 16th, 2012. Illuminance readings from illuminance loggers were calibrated against readings from a hand-held, Minolta T-10 illuminance meter which is cosine corrected (Figure 19)

Logger Type	Measurement Range	Accuracy
HOBO U12-12	Illuminance: 1 – 3000 fc	+/- 5% of reading.
HOBO UA-002-64	Illuminance: 0 – 30,000 fc	Relative values only.

Figure 18. Specifications of Monitoring Equipment



Cosine Correction Characteristics

Since the brightness at the measurement plane is proportional to the cosine of the angle at which the light is incident, the response of the receptor must also be proportional to the cosine of the incidence angle.
The graph above shows the cosine correction characteristics of Minolta Illuminance Meters **T-10**.
The cosine error of **T-10** are shown in the table right.

Incidence angle (deg.)	Cosine error (within)
10°	± 1%
30°	± 2%
50°	± 6%
60°	± 7%
80°	± 25%

Figure 19. Minolta T-10 cosine correction characteristics.

3.5 SIMULATION METHODS

Simulation results were used to estimate energy savings for retrofitting the advanced daylighting products and photocontrols into open office spaces. The use of generic open office models and TMY2 data allowed us to estimate annual impacts from the test products were they to be used in office-building retrofit programs.

Illuminance values were simulated with ray tracing in the Radiance software package using the Dynamic Radiance approach (also known as the three-phase method). This approach is described in more detail in the next section.

Whole-building-energy savings were estimated from electric lighting energy savings by multiplying with savings coefficients for heating and cooling interactions published in DEER. Whole-building-energy savings could also be estimated by creating a lighting schedule in a simulation tool such as eQuest or EnergyPlus based on the radiance results. However, that methodology was not used for this report.

While the SMUD CSC is an excellent example of a daylit building, it has limitations for testing daylight redirecting products. The biggest limitation is the façade design, which is unique compared to the population of buildings both in the Sacramento metropolitan area and the population of buildings in California as a whole. The SMUD CSC façade shades the clerestory during summer months, effectively reducing the potential savings compared to buildings without deep fins and overhangs.

In order to generate savings values closer to average office building design, a generic 'box' with flush mounted windows and no overhangs or fins was used in the simulations. As an added advantage, these results are also comparable to statewide savings estimates in recent PIER reports[19] utilizing the same simulation methodology.

3.5.1 Dynamic Radiance approach

The Dynamic Radiance approach was built on the annual daylight illuminance simulation capabilities previously developed in Daysim. It has extended the two-step Daylight Coefficient approach, which allows for faster simulation of annual weather conditions by reducing the number of hourly computations, into a three-step approach, which inserted an additional matrix describing fenestration light transmission properties into the calculation of room illuminance. This matrix consists of a three-dimensional description of how light moves through the plane of windows or skylights, as effected by blinds or special glazing optics. It is called a ‘bi-direction scatter distribution function’, or BSDF, described further below.

The three step process used by Dynamic Radiance is described by the equation: ***i = VTDs***, with the variables described below. It is also illustrated below in Figure 20.

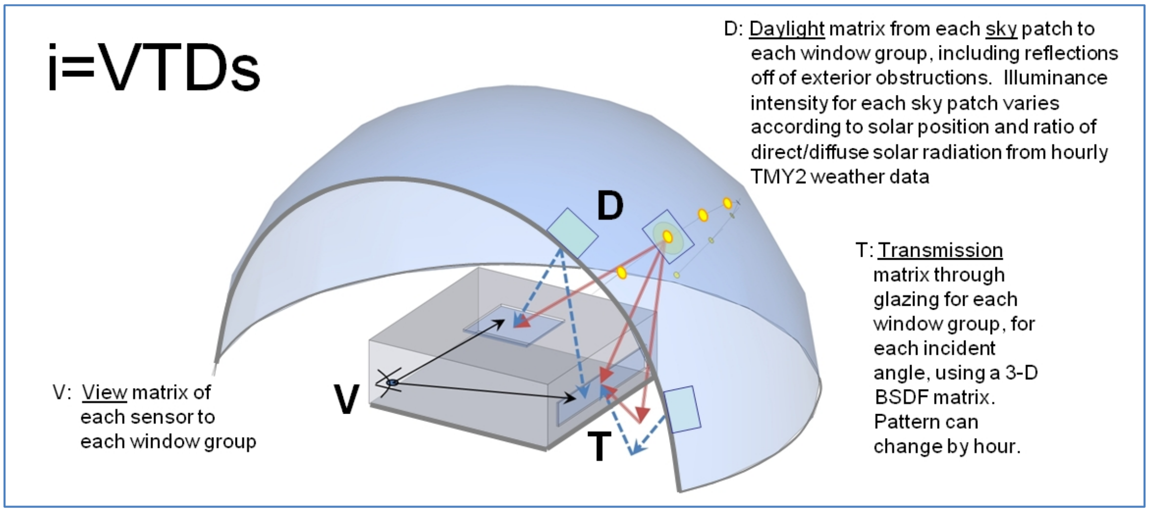


Figure 20. Dynamic Radiance approach

- where i = resultant illuminance vector,
- V = a "view matrix" that defines the relation between measurements and exiting window directions;
- T = the transmission portion of the BSDF;
- Ds = the "daylight matrix" that defines the relation between incoming window directions and sky patches, varied by ‘s’ = skypatch intensity

---

[19] Saxena, Mudit. (Heschong Mahone Group). 2011. ***Office Daylighting Potential***. California Energy Commission. Publication number: TBD.

The use of a BSDF matrix gives Dynamic Radiance the capability to model angularly dependent, complex glazing assemblies and dynamic fenestration, which includes systems as simple as manually operated Venetian Blinds to sophisticated optically tracking skylights. As such, it is highly applicable to the advanced sidelighting products evaluated in this project: both have highly specular, anisotropic light redirecting properties that would be difficult or impossible to capture without the BSDF matrix.

For this project BSDF's were used to represent all fenestration. BSDF's represent the transmission of light through an assembly by creating coefficients describing light exiting the assembly in each of 145 outgoing patches (solid angles) for a light entering the assembly from each of 145 incoming patches (solid angles). The coefficients are stored in a 145x145 matrix inside an XML file. Due to the relatively large area of the patches in the BSDF, some amount of noise is introduced into the simulation. LBNL has estimated this introduces approximately ±5% noise into annual simulation results.

While this daylight simulation method is state of the art at this point in time, it has not been verified in the field. Furthermore, the two test products under consideration have some unusual optical characteristics which may not be properly captured in the BSDF method. It is unknown if the BSDF approach overestimates, underestimates, or produces a reasonably representative distribution of light over the course of yearly analysis.

3.5.2 Simulation Parametrics

The simulation study compared a base case model to an improved model, where the window covering on the upper, clerestory window was varied. Parametric runs compared relative savings for various orientations, ceiling heights, window visible light transmittance (VLTs), photocontrol assumptions, lighting schedules, blind control options and office sizes (Figure 21).

A key issue is how deep products send daylight into the space and what useful daylighting it provides. In on-site surveys it became clear light from the products was casting sunlight and creating shadows more than 60 feet from the products. In the on-site surveys it also became clear that the stairwell wall was intercepting light that would have reached the back wall and instead reflecting it into middle work areas. This appreciably increased brightness in these work areas and would result in electric-lighting-energy savings with an appropriately calibrated photocontrol. Simulations with various model depths were run to determine if, for a given location, reflections off the back wall increased energy savings in narrower spaces compared to deeper spaces.

Variable	Base Case	LightLouver™	3M Window Film
Orientation	S SW W	S SW W	S SW W
Ceiling Ht.	9’ 10’	9’ 10’	9’ 10’
Window VT	40% 70%	40% 70%	40% 70%
Office Furniture	60” Cubicle	60” Cubicles	60” Cubicles
Photocontrols	None Lighting Row 1 Lighting Row 1, 2, & 3	All Rows All Rows All Rows	All Rows All Rows All Rows
Lighting Schedule	T24 Lighting 8760 On	T24 Lighting 8760 On	T24 Lighting 8760 On
Blinds Control	All Closed Auto	All Closed Auto	All Closed Auto
Office Size	60x16 60x24 60x32 60x40 60x48 60x56 60x64	60x16 60x24 60x32 60x40 60x48 60x56 60x64	60x16 60x24 60x32 60x40 60x48 60x56 60x64

Figure 21: Variable values in parametric simulations.

Simulations were only run for the Sacramento climate zone. Savings will vary by latitude and climate due to differences in solar elevations and weather. For example, summertime savings in San Francisco are likely to be much smaller than those observed in Sacramento, despite the similar latitude, because overcast and foggy weather is common in the San Francisco area during this season.

All open office models had a 60’ windowed façade. All offices had a 70% reflective ceiling, 50% reflective walls, 20% reflective flooring and 50% reflective cubicle furniture.

3.5.2.1 Orientation

Sunlight redirecting products could logically be installed on façades oriented east, south-east, south, south-west, and west, which receive substantial direct sunlight over the course of the year. Savings per façade should logically be symmetrical around true south, with the exception of local climate conditions that vary between morning and afternoon, such as morning fog. For this analysis, savings were only modeled for south, south west, and west orientations, as western orientations are likely to have more energy savings associated with late afternoon operation.

3.5.2.2 Ceiling and Clerestory Height

Two ceiling heights were modeled: a 9’ ceiling and a 10’ ceiling. All configurations had a 60’ windowed façade with a lower window and an upper window. The lower window sill was 3’6” above AFF and the header was 7’2” AFF. The upper window sill was 7’6” AFF and the header was placed 3” below the ceiling (8’9” in the 9’ ceiling model and 9’9” in the 10’ ceiling model). An example of this façade is pictured in Figure 22 below. The 10’ ceiling model had a **net** window-to-wall area ratio of 59% and the 9’ ceiling model had a **net** window-to-wall area ratio of 54%. The **net** window-to-wall area ratio is the ratio of window to wall as seen from inside the room, from floor to ceiling. Building designers may be more familiar with **gross** window-to-wall area ratios which include plenum walls and structural area.

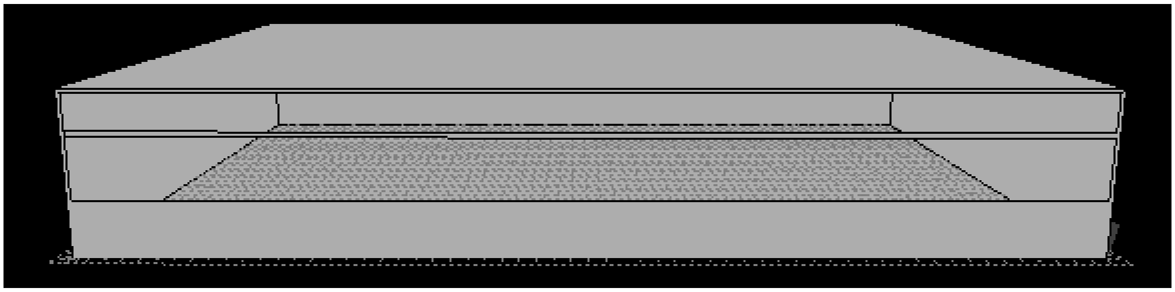


Figure 22: Office Façade for the 10’ ceiling.

Clerestory height and area changed with ceiling height, but not with room depth. Consequently, as rooms grew deeper, the clerestory window-to-floor-area ratio declined. Larger clerestory window-to - floor-area ratios increase daylighting savings regardless of technology used.

		Room Size						
		60' x 16'	60' x 24'	60' x 32'	60' x 40'	60' x 48'	60' x 56'	60' x 64'
Clerestory Height	2.25'	13.9%	9.3%	7.0%	5.6%	4.6%	4.0%	3.5%
	1.25'	7.7%	5.2%	3.9%	3.1%	2.6%	2.2%	1.9%

Figure 23. Clerestory window to floor area ratio of each model configuration.

3.5.2.3 Window Visual Transmittance

Two window visible light transmittances (VT's) were modeled: 40% and 70%. Dark tinted glass, such as 20% VT, was not modeled as buildings with dark glass are usually poor candidates for daylighting.

3.5.2.4 BSDF files for blinds and daylighting products.

Windows blinds or shades (hereafter, referred to as `blinds'), and their operation play a critical role in determining the quantity of daylight in a space. In their Daylight Metrics report, the Heschong Mahone Group found operable blinds or shades were present in 84% of all the spaces studied[20]. The study also found that assumptions about modeling the operation of blinds had a significant impact on daylighting availability. This analysis uses the same assumptions that were developed by the PIER research group, and are consistent with the new IES LM-83 document describing procedures for modeling spatial daylight autonomy.

Blinds Operation

For this project, automatic (auto) blinds operation was simulated using the same standardized blinds-operation trigger developed for the Daylight Metrics study – excess direct sunlight in the space. Blinds were closed for each hour when 2% or more of the sensors in the simulated space were in direct sunlight. Direct sunlight is defined as illuminance greater than 1000 lux (100 fc), excluding contributions from the sky or reflected sunlight—in other words, the illuminance in a sun patch. This 'auto' schedule is most similar to occupants who want to optimize their view and minimize their exposure to direct sunlight.

However, it is also observed that many occupants do not actively operate their blinds and leave them closed most of the time. To capture this variation, results of this analysis are presented for both automatically operated (auto) blinds and for always closed (all-closed) blinds. The operated (auto) blinds represent the optimal-case for daylighting and the all-closed blinds represent the worst case for daylighting. Actual savings will fall between these two extremes due to variations in occupant behavior.

---

[20] Heschong, Lisa. Heschong Mahone Group. 2011. ***Daylight Metrics***. California Energy Commission. Publication number: CEC-500-2012-053.

In the base case model for this analysis, a single, full-height blind covered both the clerestory and view window entirely when closed. In the open condition, the blinds did not interfere with light entering the room from either upper or lower window. For the test products model, the clerestory had a BSDF file (discussed below) representing the test daylighting product, and the blinds only covered the lower, view windows when closed.

Daylighting Product BSDF Modeling

BSDF files for LightLouver™ and the 3M Window Film were created by Lawrence Berkeley National Lab (LBNL) and provided by the product manufacturers. These files contained only the daylighting product – not the glazing they would be mounted in front of in a retrofit project. The BSDF files from LBNL were combined with glazing layers in LBNL's WINDOW 7 software to create window assemblies representative of the products as they would be deployed in a daylighting retrofit project. Final simulation included the products mounted inside of 70% VLT, dual pane glazing and 40% VLT, dual pane glazing.

Blinds BSDF modeling

In order to model window blinds accurately, for the annual daylighting simulations, the project team used the WINDOW 6 software from LBNL to generate a model of 1" thick, dark-red mini-blinds. The WINDOW 6 software generates a three-dimensional descriptive matrix of values of blinds transmittance in all directions, known as a Bi-Direction Scatter Distribution Function or BSDF. This BSDF is subsequently used in the Radiance simulations using the Dynamic Radiance Approach (Saxena, 2010)[21]. These window models including the glazing and mini-blinds were applied to the view windows (and upper window in the base case).

3.5.2.5 Electric Lighting Assumptions

Electric lighting was provided by 2'x4' troffers oriented with the longer side of the fixture parallel to the windowed façade. Each troffer served an 8'x10' area. Thus, the rows serve 8' deep daylit zones parallel to the windowed façade.

Photocontrol Operation

Dimming photocontrols were modeled for this assessment. This complies with the new (2013) T-24 regulations pertaining to adding photocontrols in a large office space, which requires at least 4 lighting steps plus off for fluorescent fixtures. To meet these requirements, lighting designers and electrical contractors are likely to specify dimming controls and ballasts.

---

[21] Saxena, Mudit (Heschong Mahone Group) 2010, ***Dynamic radiance – predicting annual daylighting with variable fenestration optics using BSDFs***, SimBuild 2010

The dimming strategy modeled in this report is pictured in Figure 24. This system turns off once the target illuminance is reached to maximize energy savings. This type of system generally provides optimal daylight energy savings.

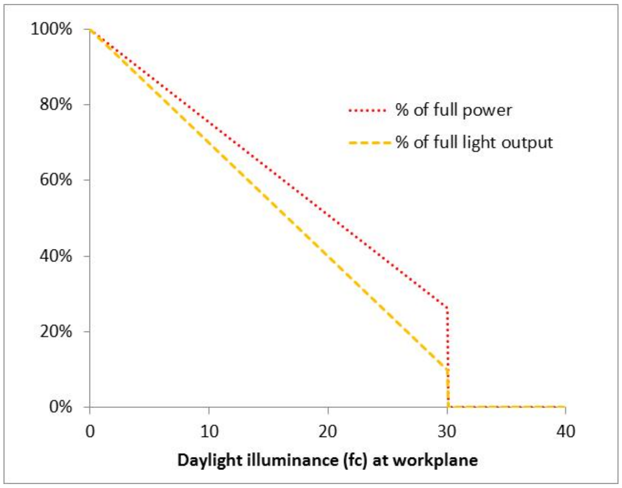


Figure 24. Simulated dimming system energy consumption and light output.

Retrofit Base Case Assumptions

Retrofit scenarios assumed there were no photocontrols in the base case building. Energy savings are presented as full-load-equivalent off hours and percent reduction.

Two other reasonable, but not provided, base cases would be (1) photocontrols only on the first row of electric lighting (2008 T-24 compliant) and (2) photocontrols on the first three rows of electric lighting (2013 T-24 compliant).

The California T24 schedule from the Nonresidential Alternative Calculation Manual (ACM) Approval Method was used as the baseline to calculate savings.

4 ANALYSIS METHODOLOGIES AND RESULTS

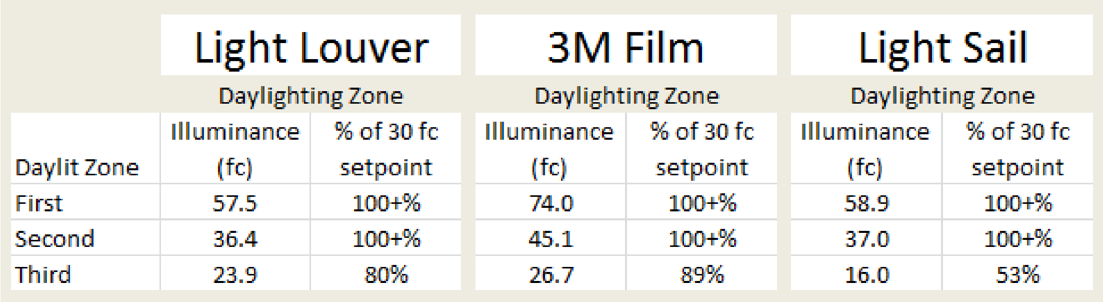
This section provides detailed site observations, interview results, occupant survey results, monitoring results and simulation results.

4.1 SITE OBSERVATIONS

Onsite observations were conducted during normal working hours on December 20th, 2011 and Saturday, January 7th, 2012, both bright, sunny days. Surveys included observations of luminaire status (broken, working properly, emergency lighting), hand-held illuminance and luminance measurements, and regular digital photography to record daylight patterns.

Handheld illuminance measurements on January 7th were conducted while electric lighting was entirely turned off (Figure 25). Readings at midday show all three technologies provide sufficient daylighting to turn electric lighting entirely off in the first two daylit zones.

In the third daylit zone, LightLouver™ provided sufficient illumination to dim the electric lights to 20% of full output, 3M's Window Film provided sufficient illumination to dim the electric lights to 11% of full output, but the light shelf only provides enough illumination to dim the electric lighting to 47% of full light output. These results generally agree with simulation data which shows significant savings in the first, second and third daylighting zones for both LightLouver™ and 3M Window Film.



	Light Louver		3M Film		Light Sail	
	Daylighting Zone		Daylighting Zone		Daylighting Zone	
Daylit Zone	Illuminance (fc)	% of 30 fc setpoint	Illuminance (fc)	% of 30 fc setpoint	Illuminance (fc)	% of 30 fc setpoint
First	57.5	100+%	74.0	100+%	58.9	100+%
Second	36.4	100+%	45.1	100+%	37.0	100+%
Third	23.9	80%	26.7	89%	16.0	53%

Figure 25. Handheld illuminance readings on a sunny, winter day with electric lighting entirely off (Jan 7th, 2012, 11:30 am).

Photographs of the space captured the distribution of light from the three technologies. In Figure 26 direct sunlight fell onto the light shelf seen in the top-left corner of the photo. Just past the light shelf, the 3M's Window Film was directing light onto the ceiling creating bright, fuzzy areas of light stretching all the way to the right edge of the photo. Just past this, LightLouver™ is directing light in slightly dimmer, but sharp-edged bands of light which stretch all the way to the right edge of the photo. Just past the LightLouver™, the light shelves can be seen again throwing significant patches of light up onto the ceiling between the fenestration and the first row of luminaires. Ceiling tiles are visibly brighter in the areas affected by LightLouver™ and 3M's Window Film.

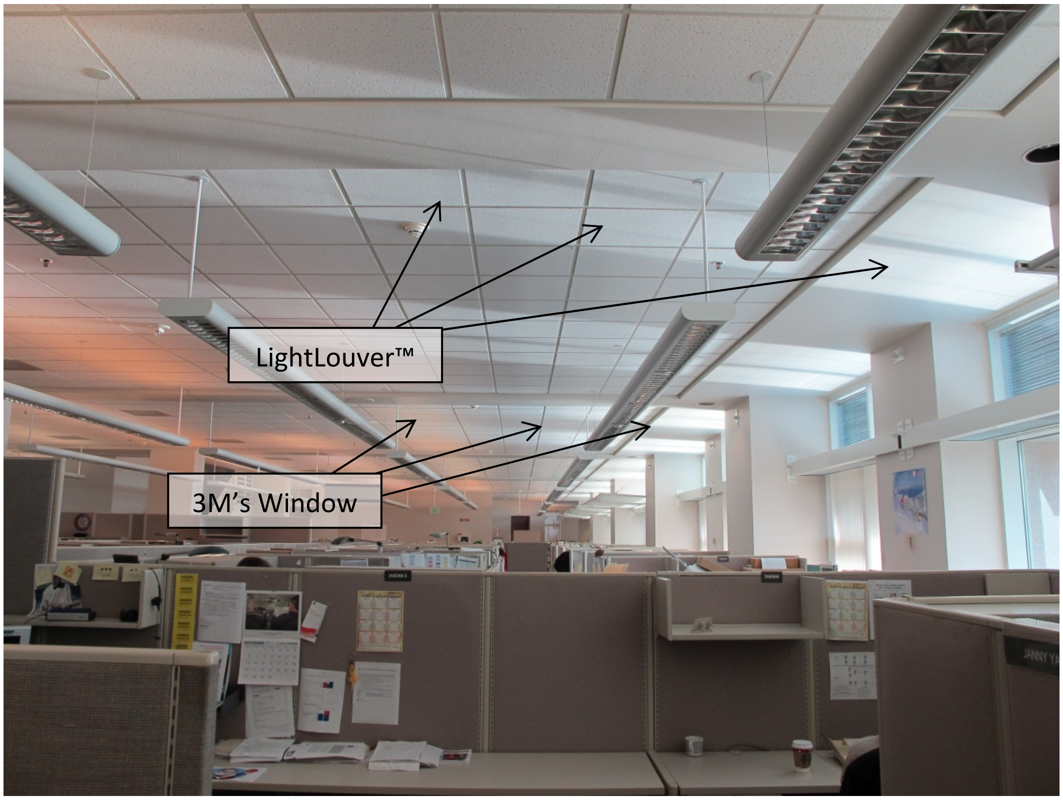


Figure 26. Light distribution from the three technologies.

Photographs in Figure 27 show sunlight redirected by the three technologies, making it to the back wall, 65' from the south windows, and casting shadows of the nearby light fixtures. Electric lighting was switched off during photography. The shadows from LightLouver™ shows distinct stepped shadows from each slat or exit angle. The shadow from the 3M's Window Film is more blurred due to the diffuser. The light shelves provide the least distinct shadow, yet it is still present. These results support the simulation results that show small increases in daylighting savings due to reflections off a wall 56' away.

Figure 27. Redirected daylight and light fixture shadows on rear wall from the three different technologies. From left to right: LightLouver™, 3M's Window Film, and light shelves. Sunny conditions at noon on Jan 7, 2012.

4.2 INTERVIEWS

Interviews covered installation and maintenance, aesthetics, and glare issues.

4.2.1 Installation and Maintenance

One member of the installation teams for both LightLouver™ and 3M Window Film were interviewed. Both teams stated that lack of familiarity with product installation slowed them down and that an experienced team would complete the tasks much more quickly. Existing office furniture obstructed access to the windows and slowed down both teams. Both teams commented that light-easy to assemble and position scaffolding should be provided to any future team installing the products.

According the SMUD staff, no maintenance or cleaning has occurred to date. Consequently, no data about the relative ease of cleaning the different advanced daylighting products has been gathered for this report.

4.2.2 Aesthetics

During study team site visits, several occupants were asked informally what they thought of the new products installed. Two employees replied that they hadn't noticed. Several stated they were glad to see the light shelves removed because they found them ominous and dated. One employee stated they preferred the LightLouver™ because it was easy to understand how it worked. Two employees stated they preferred 3M's Window Film because it looked more "modern".

These conversations support the survey data which showed a preference for both 3M's Window Film and LightLouver™ over the existing light shelves.

4.2.3 Glare

Only two respondents reported glare coming from the upper, clerestory windows, however both of these respondents sit underneath the light shelves. As described in the interviews section, this was due to light making it through gaps around the light shelves, not due to the LightLouver™ or 3M Window film. During an onsite interview, one of them explained that sunlight could make it through the reflective grill mounted between the windows and the translucent light shelf. A study team surveyor confirmed that this was possible, and recommended to SMUD facility staff present at the time that they place a diffusing translucent surface, such as a strip of frosted acrylic, on top of the grill to solve the problem.

4.3 OCCUPANT SURVEYS

Survey responses were categorized and plotted on a schematic of the cubicle layout (Figure 28). Patterns were assessed visually. Categorized occupant responses were compared to responses to Likert-scale questions and conflicts were identified.

In one case, an occupant described being very comfortable in the free text responses and reported comfort of “2” highly uncomfortable on the Likert scale. The Likert scale responses were dropped this case since the occupant likely miss-understood the questions.

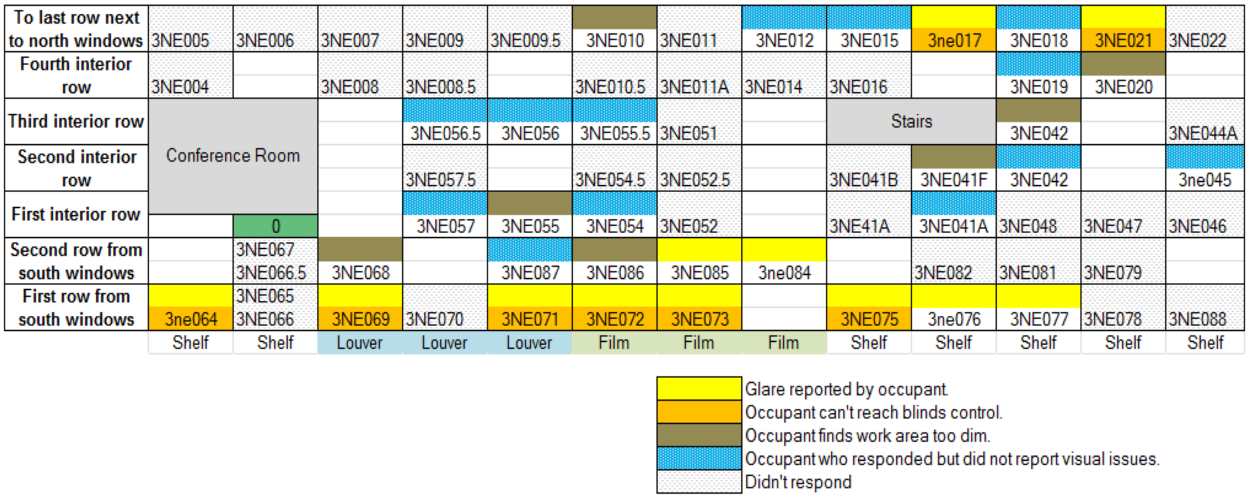
Surveys were administered twice. The survey was administered once under winter, sunny weather and once under spring, cloudy weather. The survey was sent to 54 people who routinely work in the study area and about half of them responded to each survey – twenty-seven occupants responded to the winter survey and 23 occupants responded to the spring survey.

Although the occupant survey was structured to allow occupants to differentiate their comfort by time of day, the occupants rarely did so. Instead, they generally gave identical answers for all three periods. The few who did differentiate their responses by time, only distinguished the brighter period around noon, and the symmetrically less bright periods in the morning and evening. Thus, the team concluded that the time of day questions were not useful and/or took up too much of the occupants’ time.

Overall, it was clear that occupants were more concerned about glare from the view windows and difficult access to the blinds controls, than they were about discomfort from any of the test technologies.

4.3.1 Visual Discomfort

Comments summarized from the occupant survey relative to discomfort issues are plotted by cubical location in Figure 28. Three main sources of complaint were reported: (1) areas occupants described as “dim” (colored brown), (2) areas with glare (colored yellow), and (3) areas where the vertical-blind controls were inaccessible (colored orange). The first issue is discussed below. The second and third issues are discussed in the Glare from Lower, View Windows section below.



To last row next to north windows	3NE005	3NE006	3NE007	3NE009	3NE009.5	3NE010	3NE011	3NE012	3NE015	3ne017	3NE018	3NE021	3NE022
Fourth interior row	3NE004		3NE008	3NE008.5		3NE010.5	3NE011A	3NE014	3NE016		3NE019	3NE020	
Third interior row	Conference Room			3NE056.5	3NE056	3NE055.5	3NE051		Stairs		3NE042		3NE044A
Second interior row				3NE057.5		3NE054.5	3NE052.5		3NE041B	3NE041F	3NE042		3ne045
First interior row		0		3NE057	3NE055	3NE054	3NE052		3NE41A	3NE041A	3NE048	3NE047	3NE046
Second row from south windows		3NE067 3NE066.5	3NE068		3NE087	3NE086	3NE085	3ne084		3NE082	3NE081	3NE079	
First row from south windows	3ne064	3NE065 3NE066	3NE069	3NE070	3NE071	3NE072	3NE073		3NE075	3ne076	3NE077	3NE078	3NE088
	Shelf	Shelf	Louver	Louver	Louver	Film	Film	Film	Shelf	Shelf	Shelf	Shelf	Shelf

🟨 Glare reported by occupant.
🟧 Occupant can't reach blinds control.
🟫 Occupant finds work area too dim.
🟦 Occupant who responded but did not report visual issues.
⬜ Didn't respond

Figure 28. Issues reported in Occupant Surveys

Generally, the dim areas, highlighted in brown were located away from the windows. In particular, a number of dim areas were located near the stairwell, which blocked daylight, and also near burnt out lights (cubicles 3NE055 and 3NE086). In addition, occupants of cubicles 3NE010 and 3NE068 appear to prefer more light than average. It is unfortunate that the daylighting products did not bring enough light to satisfy the occupant of 3NE068, but this may be difficult given that their overhead luminaire is already adjusted to provide maximum light output and they have two task lights in their work area. In written comments, the occupant of cubicle 3NE068 observed that the LightLouver™ brought in more light than the light shelf it replaced. They also noted that the 3M's Window Film seemed to bring in more light than the LightLouver™.

4.3.2 Glare from Upper Window Treatments

Only two respondents reported glare coming from the upper, clerestory windows, however both of these respondents sit underneath the light shelves. As described in the interviews section, this was due to light making it through the grills, or through gaps around the light shelves, not due to the LightLouver™ or 3M Window film.

Occupants in cubicles 3ne085 and 3ne084 both report experiencing indeterminate glare. These two cubicles are one row back form the 3M film, but also within direct line of sight of the LightLouver and the light shelves. Their responses to the surveys did not help us understand the source or timing of the glare. Unfortunately, the team was unable to interview these occupants in person. Based on the team's experience in the space, it seems likely that the view window is the glare source. However, further studies of the products should include in-person interviews with any respondent that reports glare to understand more about the cause.

4.3.3 Glare from Lower, View Windows

Visual discomfort from the lower, view windows was concentrated along the south-wall. All eight of the respondents who sit adjacent to the south façade reported glare issues. Two respondents sitting one row from the south façade also reported glare issues (discussed above). Not coincidently six of the eight respondents who sit along the south wall also reported difficulty reaching the window blinds controls.

Some glare issues were also observed along the rear, or northern, façade where two of five respondents commented on glare issues. Both of these respondents also reported difficulty reaching the blinds controls. Onsite surveyors noted that the blinds controls are located on the far side of the desk and cannot be reached without climbing on or over the desk. A number of occupants have rigged special ways to get their blinds controls within reach, via wall hooks or extensions.

Only one respondent in the middle of the room reported glare in the Likert Scale questions (cube 3NE045). It is likely the respondent misunderstood the scale because they reported having no view of the outside and only seeing walls. Consequently, this response was dropped from the analysis. Similarly, only one occupant in the second row from the rear façade reported visual discomfort from daylight (cube 3NE056). Again, it is believed the occupant misunderstood the questions because they reported enjoying the view of the trees outside in separate question. This response was dropped from the analysis. If these responses had been retained in the analysis, it would not significantly change the outcome since neither one specified the glare was caused by the light shelves, LightLouver™ or 3M's Window Film.

Respondents reported glare occurs in the morning and afternoon when the sun is low in the sky. This is consistent with the design of the building – the deep fins and overhangs protect the occupants from direct sunlight trespass between the spring equinox and fall equinox. Direct sunlight trespass occurs during the winter.

4.3.4 Optical Confusion

During onsite work, one occupant commented that when 3M's Window Film was first installed they thought their eyes were failing. Previously, when the occupant stood up at their cubicle they could see out to the adjoining building and sky. With 3M's Window Film installed they did not see any of these details and had a momentary concern that their eyes had blurred. They stated they are now used to the new appearance and are no longer confused by it.

4.3.5 Occupant Compensations to Discomfort

One occupant reported re-adjusting their monitor several times a day to reduce glare. This respondent requested a computer setup that was easier to move.

All occupants sitting adjacent to the southern façade reported glare occurred at some time during the day. Most of these occupants requested easier access to the vertical blind controls.

None of the occupants requested that the light shelves, 3M Window Film, or LightLouver™ be removed. This is good news – this façade is oriented to the south which should provide the least opportunity for glare problems. If glare was a problem here, the products would likely be more uncomfortable in other orientations.

4.3.6 Occupant Product Aesthetic Preferences

Occupants were asked if they liked the aesthetics of each product, on a scale of one to nine. The light shelves received an average rating of 3.7 on the Likert scale of 1-9.

Occupants rated LightLouver™ 5.1 on average. Occupants rated LightLouver™ higher than light shelves and the difference in preference was statistically significant ($p = 7.1\text{E}10^{-7}$).

Occupants rated 3M's Window Film 6.4. Occupants rated 3M's Window Film higher than light shelves and the difference was statistically significant ($p = 2.6\text{E}10^{-16}$).

SMUD determined that they did not want to administer the final, summer, occupant survey, given that there was currently then no sun exposure on the clerestory windows. Instead, the floor manager decided to poll the study area occupants about their preferences for the two test products or the base case condition. They were sent the following email: "Please respond…by email…[and state] which product you would prefer to have installed throughout the floor, and why."

17 of the 54 polled employees responded (31%). Of these, one employee preferred the existing light shelves, with the note: "I like to see out of the little windows". Three employees preferred the LightLouver, with two making brief comments about "best distribution of light". One employee was fine with either LightLouver or the 3M product, with no added comments. The remainder (12) preferred the 3M product, with 10 of these providing fairly detailed and varied comments about their rationale. Comments included aesthetic preferences, such as "looks cleaner", "smoother", "softer"; that it seems to perform better, such as "brings in more daylight"; and a few comments about ease of installation, maintenance, and less dust collection.

It is notable that there were no complaints about either product causing discomfort, whereas the current light shelve do elicit complaints from some occupants. The 17 people who responded to the poll were clearly motivated to encourage some form of change to the windows on their floor, and 11 took further the time to write out their rationales. Based on past experience, the team interpreted the non-respondents (69%) as being fairly indifferent to the outcome of the poll and thus probably also did not have any strong opinions about discomfort.

4.4 HOURLY ILLUMINANCE MONITORING

Daily illuminance plots were generated and examined for anomalies. Plots combined illuminance readings for sensors equidistant from the southern façade at either the work-level or ceiling. Outside illuminance is presented from the HOBO UA-002-64 mounted horizontally in a clerestory window in the study area. An example cloudy-day plot is shown in Figure 29 and an example sunny-day plot is shown in Figure 30.

As expected, on cloudy days illuminance levels remained essentially constant through-out the day for all three technologies (Figure 29). Illuminance levels differed more by location than time of day, which could be attributable to different output settings on the overhead luminaires or different locations for the sensors relative to the luminaires. Figure 29 clearly shows that exterior illuminance (dotted line) had very little relationship to interior illuminance, regardless of the nearby technology.

Illuminance patterns on sunny days are more complicated, and more challenging to interpret. Figure 30 clearly shows that, on this sunny day, interior illuminance was a function of exterior illuminance (dotted line). The ceiling level sensors integrate signals from the illuminance reflected from below, which is a mix of daylight and electric light, but also, importantly, the ceiling sensors also report any redirected sunlight incident on the ceiling sensor itself, which can be a blend of one or two of the test technologies, depending on time of day.

The sensors affected by LightLouver may have the most noticeable response to redirected sunlight, as LightLouver generates a specular pattern on the ceiling, with sharp-edged dark areas of ceiling adjacent to daylit areas of the ceiling. Thus, sudden decrease and increases in monitored illuminance levels at the ceiling sensor as the bright daylit area of the central column for each test bay passes by should be most noticeable for LightLouver, less for the 3M film, which has some horizontal diffusion, and even less so for the light shelves, which have the most horizontal diffusion. These patterns are apparent in Figure 30 which shows short term jumps in ceiling illuminance reported for the LightLouver sensor (blue line), less for the 3M film (red line) and the most gradual daily variations for the light shelves (green line).

It is also possible that the existing photosensors have differential response to sunlight compared to diffuse daylight, based on either the angle of incidence or the spectral content of the incident sunlight. If so, the responses of photocontrols near the LightLouver™ product would be the most exaggerated since it delivers the most concentrated beams of sunlight onto the sensors.

The ‘shoulders’ of work-level illuminance in the morning (7-8 am) and evening (16-18 pm) clearly illustrate the variation in electric light output at each location (Figure 30). For example, in the secondary zone, the electric lighting in the LightLouver area is almost 20 fc higher than the 3M and light shelf area. But the electric lights in the LightLouver area are also dimming fairly dramatically, dropping 25 fc between 8-9 am. If these curves are normalized to the initial electric light output, the 3M curves are noticeably higher than the LightLouver curves. However, the relative contribution of the electric lights and proportional dimming to the equation is unknown, especially given the varying output and calibration of the individual fixtures. Overall, data suggests electric lights in the LightLouver area were both set to higher output, and were being dimmed much more aggressively, than the other two areas. Examination of plots for weekend sunny days, when all electric lighting should have been off, were still compromised by contributions from nearby emergency lighting which still dimmed in response to daylight.

This issue is illustrated even more vividly in Figure 31, plotting data for February 29th, a cloudy day when the sun breaks through the clouds multiple times. In this case, the illuminance levels near the LightLouver™ (blue line) have a negative correlation to the outside illuminance (dotted orange line) but the illuminance levels near the 3M’s Window Film (red line) and light shelves (green line) have a positive correlation to outside illuminance.

Analysis of these various conditions convinced the study team that the photocontrol response varied considerably among the various luminaires. In order to isolate the daylight contribution to the Hobo readings, it would have been useful to cover the photocontrols, forcing all the luminaires into full light output throughout the day. (The team had initially hesitated in doing so, not wanting to alter the normal illumination conditions experienced by the occupants. The team had assumed that the differential between weekday and weekend hours for similar days could produce a reasonable estimate of electric lighting behavior.) However, by the time the degree of photo control variation was discovered, the clerestories were receiving substantial shading from the façade. Thus, further analysis of the sunlight redirection patterns was no longer possible.

Thus, the field monitoring results are suggestive, but inconclusive. It appears likely that both advanced daylighting products provide more daylight illumination than the existing light shelves. However, due to the difficulty understanding the fixture-by-fixture dimming behavior it is difficult to understand what daylight levels, or resulting electric lighting energy savings, these products could produce.

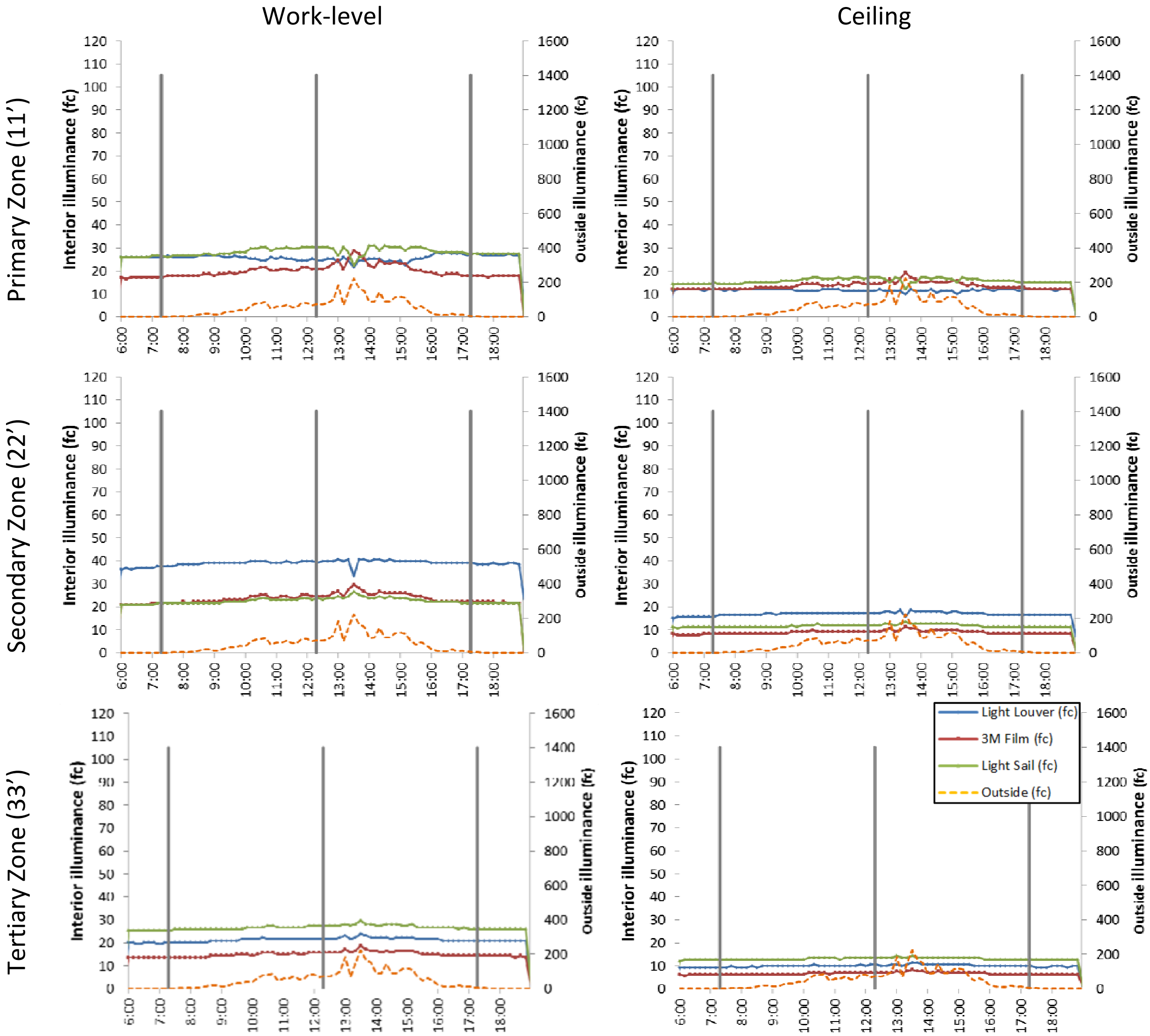


Figure 29. Work-level and ceiling illuminance plots for a cloudy day (Jan 23, 2012) in three daylit zones each.

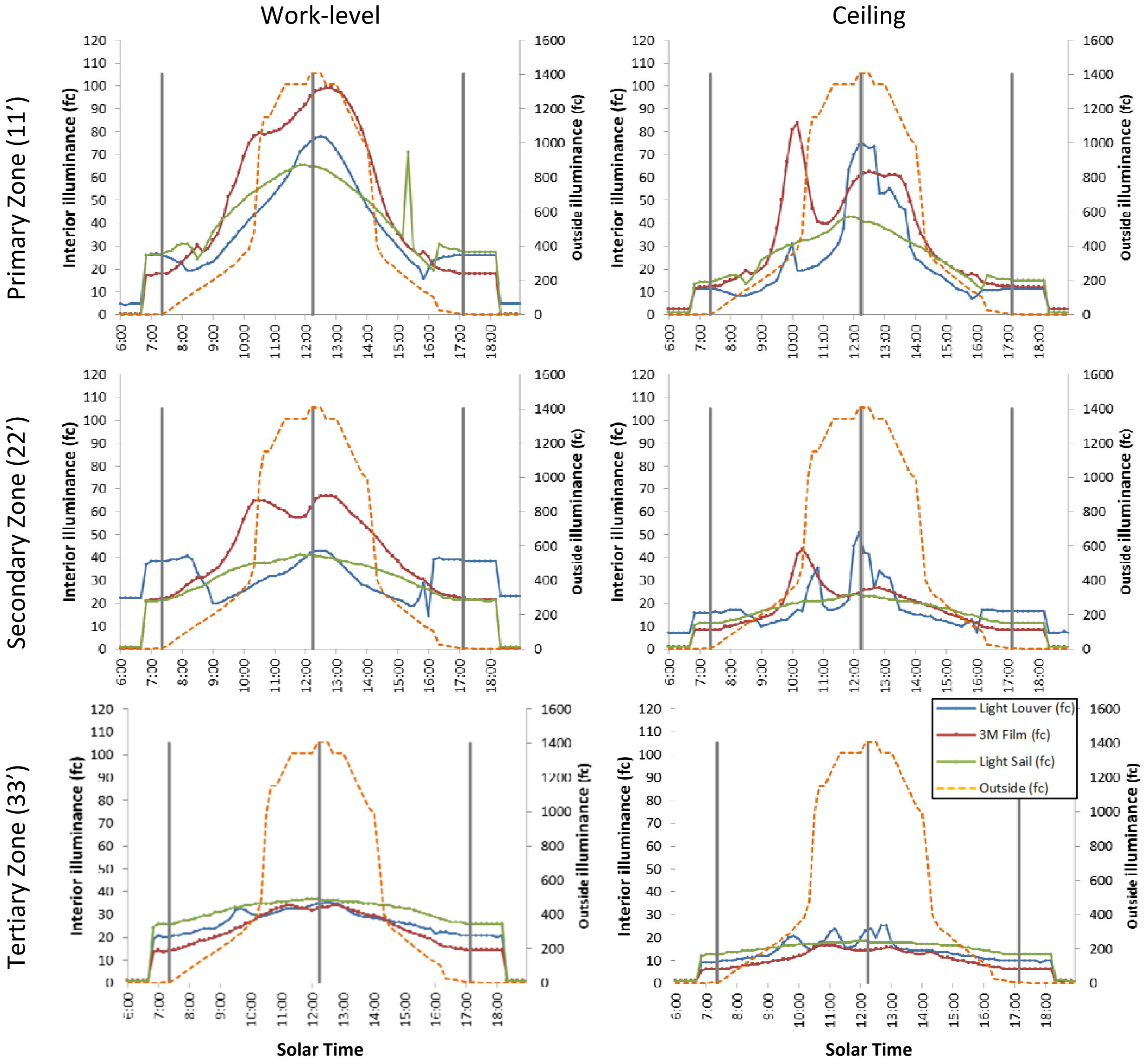


Figure 30. Work-level and ceiling illuminance plots for sunny, mid-winter, day (Jan 16, 2012) at three daylit zones.

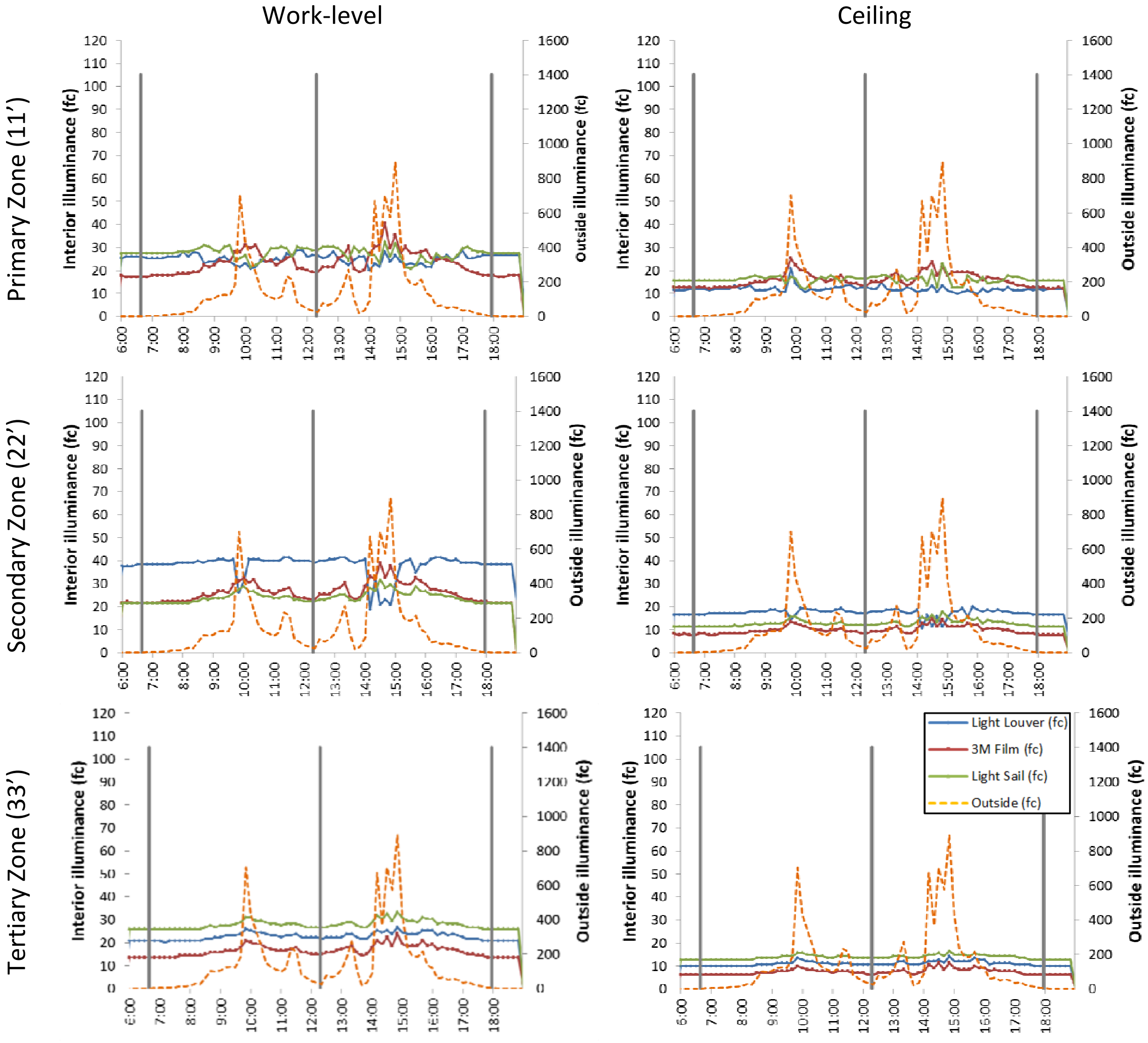


Figure 31. Work-level and ceiling illuminance plots for a day with passing clouds (Feb 29, 2012) at three daylit zones.

4.5 SIMULATION

Simulation results for LightLouver and 3M Window Film, applied in a generic south-facing office space, with no external shading, are presented in the in following sections. Results show both products significantly increase daylighting savings in the first three daylit zones (first 24’ from the windows). The annual summary of simulation results for the two test products are very similar, varying only in magnitude. The LightLouver results are discussed first in sections 4.5.1, along with fundamental observations about the importance of various parameters, and then the 3M results are presented in section 4.5.2.

Savings were calculated as an annual reduction in full-load-equivalent ON hours (FLE ON hours) and percent reduction in FLE hours. Savings were calculated for each 8’ deep daylit zone separately. In the following plots, daylit zones are numbered 1-8, representing luminaire rows starting 4’ from the windowed façade and spaced 8’ apart running down the center of each daylit zone. The last row of luminaires is 4’ from the rear wall. **Unless otherwise noted, the savings base case is a south-facing space with a 9’ ceiling, no pre-existing photocontrols, 40% VLT glass, and closed (worst-case) blinds.**

4.5.1 Simulated savings for LightLouver™

Figure 32 illustrates the spatial distribution of savings for LightLouver™ in a 64’ deep space both as the absolute reduction in annual full-load-equivalent (FLE) ON hours and also as the percent reduction in annual consumption. The largest reductions in FLE ON hours are found in the first three daylighting zones, i.e. within 24’ of the windowed façade. Thus, while the products can throw detectable sunlight onto the ceiling 50-60 feet deep into a space, the resulting annual energy savings may be negligible and outside of the normal sensitivity response of photocontrols once a certain distance from the windowed façade is reached. This distance will vary depending on façade design. There is a slight uptick in daylight availability in the back of the room (daylit zones #7 & #8 in Figure 32). This phenomenon is due to redirected sunlight reflecting and diffusing off the back wall.

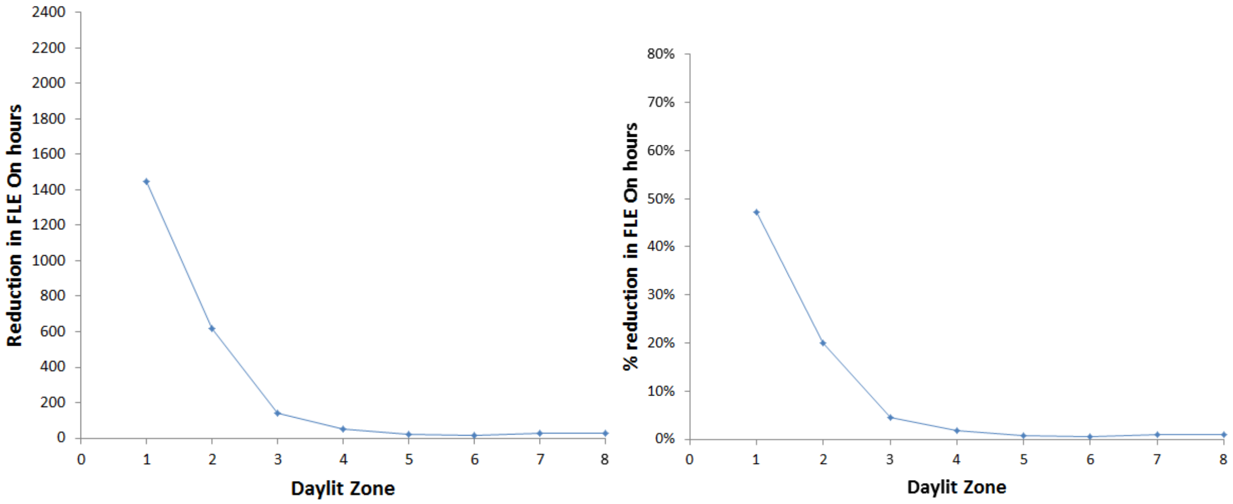


Figure 32. LightLouver™ lighting energy savings in hours and as a percentage of annual usage.

The remainder of the report will only show percent reduction in annual FLE ON hours. The percent reduction can be converted to FLE ON hours using the table in Figure 33.

Percent Reduction	FLE On Hour Reduction
0%	0 hrs
10%	307 hrs
20%	614 hrs
30%	921 hrs
40%	1,228 hrs
50%	1,535 hrs
60%	1,843 hrs
70%	2,150 hrs
80%	2,457 hrs
90%	2,764 hrs
100%	3,071 hrs

Figure 33. Reductions in FLE ON hours for a percent reduction in lighting energy use.

For both test products, lighting savings increased in the zone immediately adjacent to the back wall, for all room depths considered. Redirected sunlight reflecting off the back wall makes an observable difference in annual energy savings in the back row of a room compared to the a room 8’ or more deeper (although the effect is nearly negligible if the room is more than 56’ or more deep). Figure 34 illustrates the slight uptick in savings for the LightLouver™ product for shallower rooms, compared to the largest room considered, a 64’ deep room.

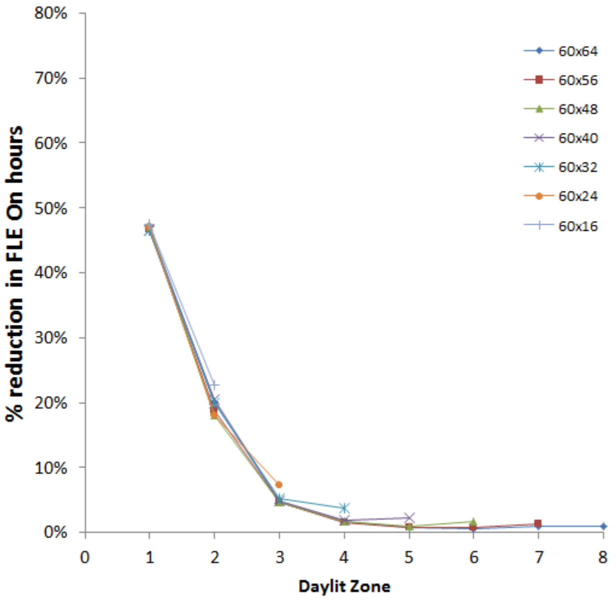


Figure 34. LightLouver™: effect of room depth on lighting energy savings.

Due to this ‘back-wall bounce” effect, there may be an optimum depth for rooms using these products. For example, per Figure 35, savings are increased by about 2.1% of FLE ON in a 24’ deep room due to bounce off the back wall, but only an additional 1.8% in a 32’ deep room.

Space Size	If last row	If 2nd to last row	Improvement
2nd Row Savings	22.7%	18.1%	4.6%
3rd Row Savings	7.3%	5.2%	2.1%
4rth Row Savings	3.7%	1.9%	1.8%
5th Row Savings	2.3%	1.0%	1.3%
6th Row Savings	1.7%	0.7%	1.0%
7th Row Savings	1.3%	1.0%	0.3%

Figure 35. LightLouver™ savings increase when light reflects light off wall behind last row of lighting.

Figure 36 illustrates the impact of window blinds operation on energy savings. Blinds were assumed to cover the whole lover (view) window, and could be open or closed to prevent glare. Binds were simulated as “auto” (solid line), i.e. operating optimally via automatic controls or motivated occupants, and as “all closed” (dashed line). Optimal blinds operation greatly increases absolute daylighting savings. Savings increase by nearly 1/3 in the first daylit zone and double in the second through fourth daylit zones. Actual savings will depend on actual blinds configuration and operation, but are bounded by these two conditions. “Auto” blinds can be considered the maximum daylight savings potential, and “all-closed” blinds the maximum downside risk of losing savings due to poor operation.

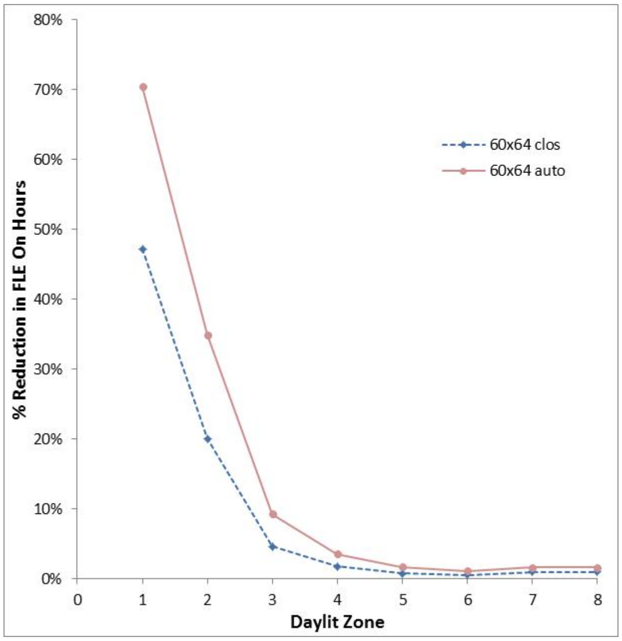


Figure 36. LightLouver™: effect of blinds operation on lighting energy savings.

All lighting energy savings are created by not just one, but two changes: (1) adding photocontrols and (2) adding the test product to the clerestory. Figure 37 compares the potential savings for the windows with photocontrols and full-height blinds only, versus adding LightLouver™ to the upper window. Relative savings decline if blinds are optimally controlled. In Figure 37 dashed lines indicate savings from photocontrols alone and solid lines indicate savings from adding the test product to a room with pre-existing photocontrols.

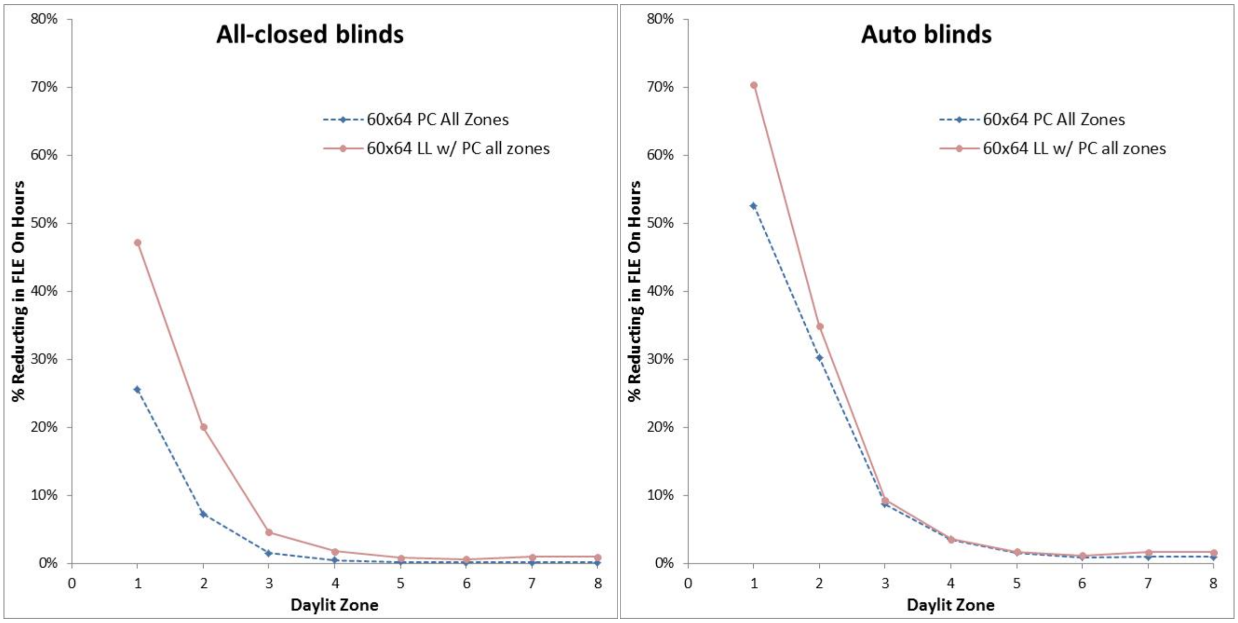
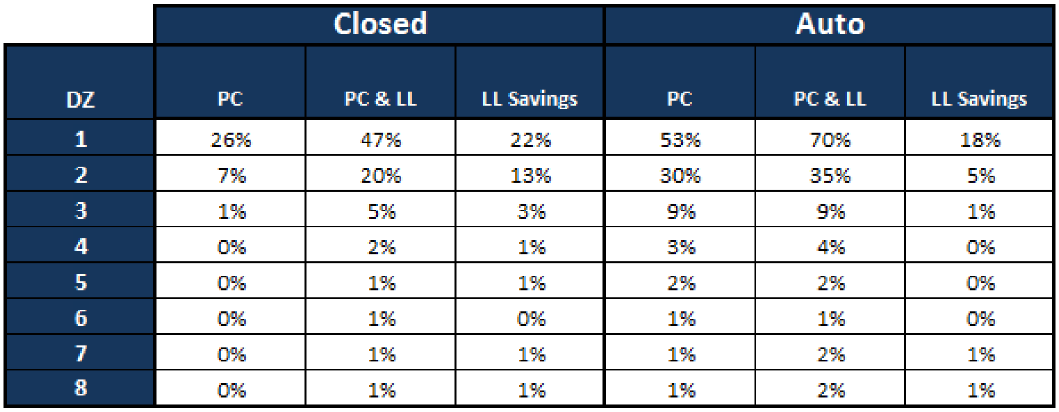


Figure 37. LightLouver™: effect of blinds operation on lighting energy savings with pre-existing photocontrols.

The data presented graphically in Figure 37 is presented in tabular form in Figure 38. Adding LightLouver™ increases savings significantly when blinds are always closed in the first three zones. However, these savings diminish if the blinds are controlled optimally (automatically). Aggregate savings for a large number of spaces is likely to fall somewhere in the middle between these two extremes, assuming a normal variation in occupant behavior. Ease of access to blinds controls is an important factor in how actively blinds are adjusted by occupants.



	Closed			Auto		
DZ	PC	PC & LL	LL Savings	PC	PC & LL	LL Savings
1	26%	47%	22%	53%	70%	18%
2	7%	20%	13%	30%	35%	5%
3	1%	5%	3%	9%	9%	1%
4	0%	2%	1%	3%	4%	0%
5	0%	1%	1%	2%	2%	0%
6	0%	1%	0%	1%	1%	0%
7	0%	1%	1%	1%	2%	1%
8	0%	1%	1%	1%	2%	1%

Figure 38. LightLouver™: lighting energy savings.

The most important observation from this simulation exercise is that the electric lighting savings with the test products under worst case conditions (blinds always Closed) is similar to the electric lighting savings potential for the same windows with no test product under best case conditions (Auto). Thus, the test product reduces the downside risk of poor blinds operation, and increase the upside opportunity for daylight savings.

Window VLT also significantly affects savings (Figure 39). Increasing window VLT from 40% to 70% has a smaller improvement in savings that automating blinds control (Figure 39 vs. Figure 36). Figure 39 shows results for LightLouver™ with 40% VLT glazing (dashed line) and 70% VLT glazing results (solid line).

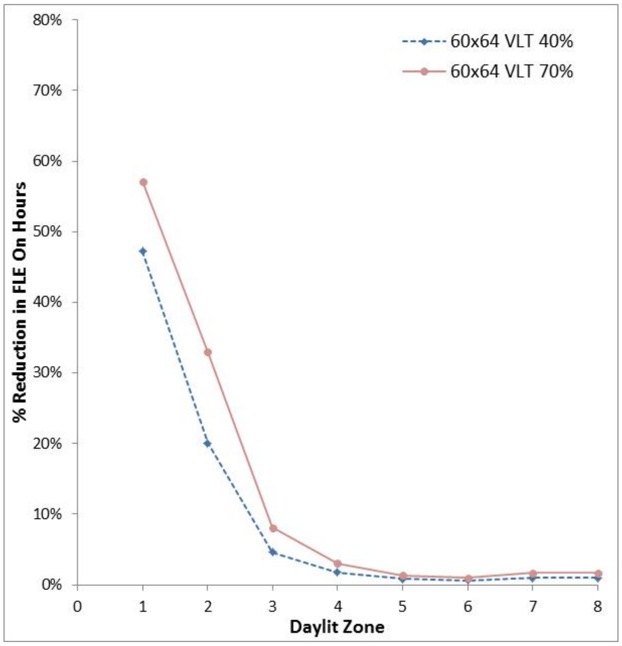


Figure 39. LightLouver™: effect of window VLT on lighting energy savings.

Figure 40 shows savings vary little by orientation which may be somewhat surprising to the reader. However, it is important to note that a west facing window at latitude 40 degree (Sacramento is 38.6 degrees) will receive 2000 hours of direct sunlight per year, while a south or southwest facing window will receive slightly over 3000 hours per year. (See Figure 14.7 and 14.8 in the IES Handbook, 10th edition.) However, almost 1/3 of the south and southwest facing hours of sunlight are above a 60 degree profile angle where high angles of incidence reduce transmission both due to reflection by the products and by the window glass itself. Thus, according to these simulations, the net effect of oreintation on the performance of the product is negligable.

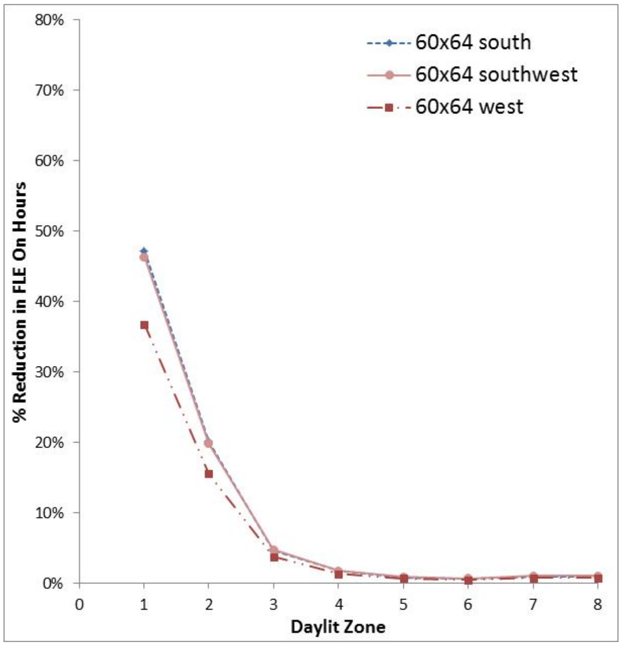


Figure 40. LightLouver™: effect of façade orientation on lighting energy savings.

An important finding of the simulation analysis is that the test products can produce similar levels of annual savings across window orientations, from east to south to west. If true (as verfied in future field studies) the potential market for these products will greatly increase. However, it is important to note that the lower sun angles experienced on east and west facing facades may have different impacts on occupant comfort, and were not studied in the occupant assessment portion of this project, which only considered south facing windows.

Savings increase in the space when the ceiling height, and clerestory window, increases from 9’ to 10’ (Figure 41). In the 10’ model, the clerestory head height increased from 8’9” to 9’9”. The clerestory sill height remained unchanged at 7’6”. The view window size and position remained constant. Savings in the primary zone increase the least as the zone is already nearly saturated but savings increase 15% in the secondary zone and 10% in the tertiary daylit zone. With the higher ceiling and clerestory, the impact of the test product, in this case LightLouver™, is apprarent deeper into the space, primarily in the second and third daylit zones.

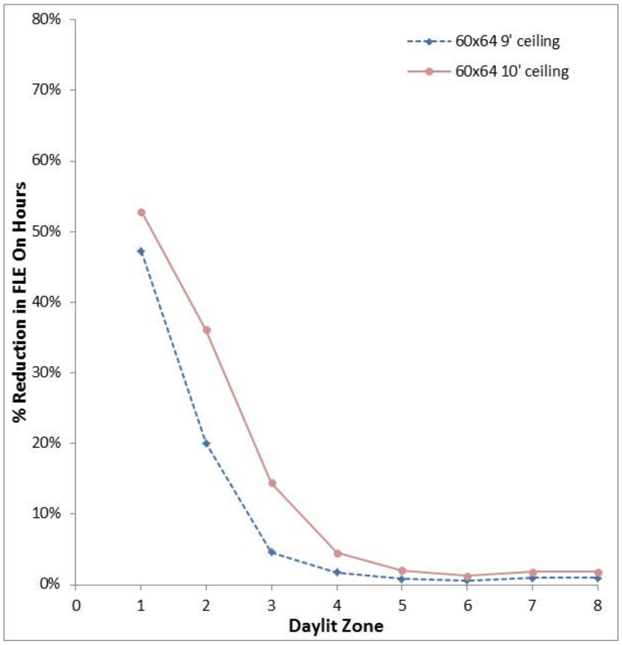


Figure 41. LightLouver™: effect of ceiling height on lighting energy savings.

These findings, based on ceiling and clerestory window height suggest that additional savings due to the addition of the product become more significant in deeper rooms, as the clerestory window becomes taller. Thus, there may be an optimum relationship between height of the treated clerestory window and the depth of the room and resulting daylight control zones. Figure 41 suggests a rule of thumb that an increase in 1’ in product height produces equivalent additional savings 8’ deeper into the room. Figure 57 and Figure 58 also show the increased savings from the back wall reflection for the three orientations studied. It is noticeably higher for west facing windows compared to south facing rooms, as might be expected since lower sun angles are more common on a west orientation. It might be that these products will eventually be optimized for different window orientations, such that products applied to east or west facing windows are more optimized for low sun angles, and south facing window for higher sun angles.

The patterns outlined above were observed for LightLouver™ in all simulation results. More detailed results are available in Appendix C.

Approximate whole building energy savings are summarized in Figure 42 for the first three zones and second three zones with 40% VLT glazing, 9' and 10' ceiling heights, south and west facing spaces, and auto and all-closed blinds operation. Figure 43 summarizes annual energy savings for the same spaces, but with 70% VLT glazing. Annual energy savings include a DEER database correction to heating and cooling loads due to electric lighting reductions, but do not include any changes in the SHGC or U-value of the window assembly due to addition of the test products (which are currently unknown). Because these whole building factors were not produced via a simulation, but rather by multiplying the uniform DEER factor, they also may not reflect variations in whole building heating and cooling impacts due to window orientation and solar angle. All results assume an LPD of 1.2 Watts / square foot. Annual energy savings do not include reductions in cooling and increases in heating necessary to offset changes in the SHGC and other characteristics of the window assembly.

			60' x 48'					
		Blinds Operation	Zone 1-3 Savings per Sq. Ft.			Zone 4-6 Savings per Sq. Ft.		
			LTG kWh	Bldg kWh	Therms	LTG kWh	Bldg kWh	Therms
9' Ceilng w/ 1.25' Clerestory	South	Closed	0.86	.95	-0.006	0.05	0.06	0.000
		Auto	1.37	1.52	-0.010	0.10	0.12	-0.001
	West	Closed	0.69	.77	-0.005	0.04	0.05	0.000
		Auto	1.54	1.71	-0.011	0.15	0.17	-0.001
10' Ceilng w/ 2.25' Clerestory	South	Closed	1.23	1.37	-0.009	0.12	0.14	-0.001
		Auto	1.70	1.89	-0.012	0.18	0.20	-0.001
	West	Closed	1.00	1.11	-0.007	0.10	0.11	-0.001
		Auto	1.79	1.98	-0.013	0.23	0.25	-0.002

Figure 42. LightLovuer™ annual whole-building energy savings for spaces with 40% VLT glass.

			60' x 48'					
		Blinds Operation	Zone 1-3 Savings per Sq. Ft.			Zone 4-6 Savings per Sq. Ft.		
			LTG kWh	Bldg kWh	Therms	LTG kWh	Bldg kWh	Therms
9' Ceilng w/ 1.25' Clerestory	South	Closed	1.18	1.31	-0.008	0.09	0.10	-0.001
		Auto	1.70	1.88	-0.012	0.17	0.19	-0.001
	West	Closed	0.99	1.10	-0.007	0.08	0.08	-0.001
		Auto	1.86	2.06	-0.013	0.26	0.29	-0.002
10' Ceilng w/ 2.25' Clerestory	South	Closed	1.62	1.80	-0.011	0.21	0.24	-0.001
		Auto	2.08	2.31	-0.015	0.31	0.34	-0.002
	West	Closed	1.35	1.50	-0.009	0.18	0.20	-0.001
		Auto	2.14	2.38	-0.015	0.39	0.43	-0.003

Figure 43. LightLouver™ annual whole-building energy savings for spaces with 70% VLT glass.

4.5.2 Simulated savings for 3M Window Film

Savings were calculated as a reduction in full-load-equivalent on hours (FLE hours) and percent reduction in FLE hours. Savings were calculated for each daylit zone separately. Unless otherwise noted, the savings base case is a south-facing space with a 9’ ceiling, no pre-existing photocontrols, 40% VLT glass, and blinds which are all closed.

Figure 44 illustrates the spatial distribution of savings for 3M Window Film in a 64’ deep space both as reduction in annual full-load-equivalent (FLE) on hours and percent reduction in annual consumption. The largest reductions in FLE On hours are found in the first three daylighting zones, i.e. within 24’ of the windowed façade. Thus, while the products can throw detectable sunlight onto the ceiling 50-60 feet deep into a space, the resulting annual energy savings may be negligible and outside of the normal sensitivity response of photocontrols once a certain distance from the windowed façade is reached. This distance will vary depending on façade design. There is a slight uptick in daylight availability in the back of the room (daylit zones #7 & #8 in Figure 44). This phenomenon is due to redirected sunlight reflecting and diffusing off the back wall.

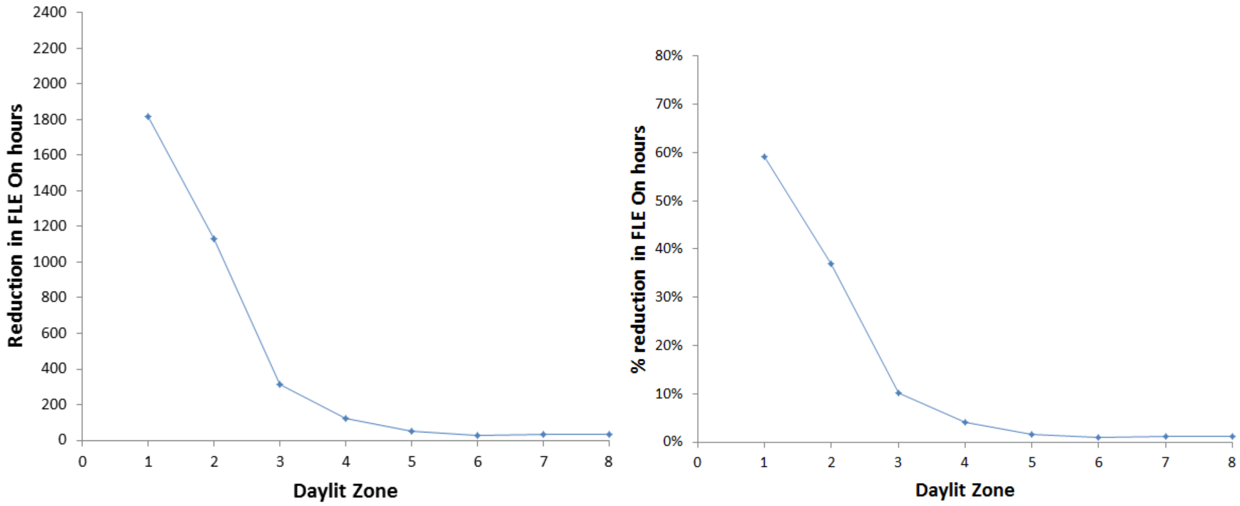


Figure 44. 3M Window Film: lighting energy savings in hours and as a percentage of annual usage.

The remainder of the report will only show percent reduction in annual FLE ON hours. The percent reduction can be converted to FLE ON hours using the table in Figure 33.

For both test products, lighting savings increased in the zone immediately adjacent to the back wall, for all room depths considered. Redirected sunlight reflecting off the back wall makes an observable difference in annual energy savings in the back row of a room compared to the a room 8' or more deeper (although the effect is nearly negligible if the room is more than 56' or more deep). Figure 45 illustrates the slight uptick in savings for the 3M Window Film product for shallower rooms, compared to the largest room considered, a 64' deep room.

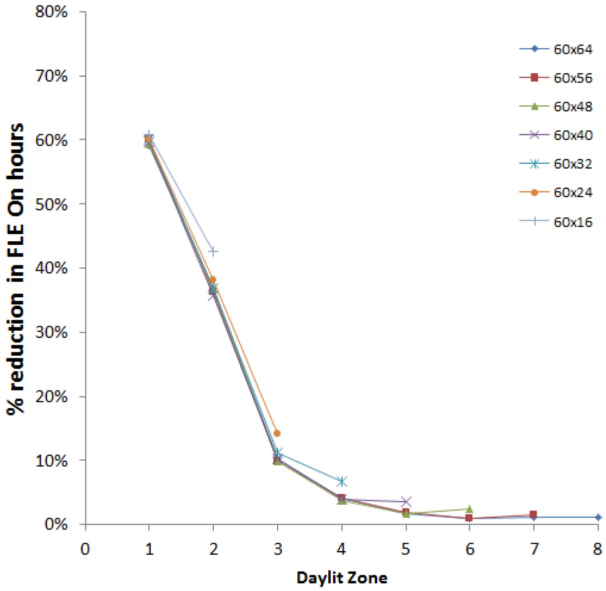


Figure 45. 3M Window Film: effect of room depth on lighting energy savings.

Due to this 'back-wall bounce" effect, there may be an optimum depth for rooms using these products. For example, per Figure 46, savings are increased by about 3.1% of FLE ON in a 24' deep room due to bounce off the back wall, but only by 2.7% in a 32' deep room.

Space Size	If last row	If 2nd to last row	Improvement
2nd Row Savings	42.6%	38.1%	4.5%
3rd Row Savings	14.2%	11.1%	3.1%
4rth Row Savings	6.7%	4.0%	2.7%
5th Row Savings	3.5%	1.8%	1.8%
6th Row Savings	2.5%	1.0%	1.5%
7th Row Savings	1.6%	1.2%	0.4%

Figure 46. 3M Window Film: effect of light reflecting off back wall on lighting energy savings.

Figure 47 illustrates the impact of window blinds operation on energy savings. Blinds were assumed to cover the whole lover (view) window, and could be open or closed to prevent glare. Binds were simulated as "auto" (solid line), i.e. operating optimally via automatic controls or motivated occupants, and as “all closed” (dashed line). Optimal blinds operation greatly increases absolute daylighting savings. Savings increase by nearly 1/3 in the first daylit zone and double in the second through fourth daylit zones. Actual savings will depend on actual blinds configuration and operation, but are bounded by these two conditions. “Auto” blinds can be considered the maximum daylight savings potential, and “all-closed” blinds the maximum downside risk of losing savings due to poor operation.

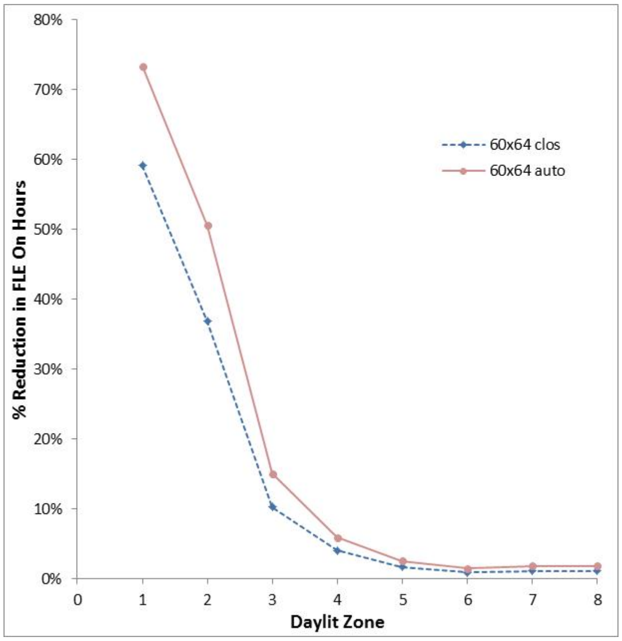


Figure 47. 3M Window Film: effect of blinds operation on lighting energy savings.

All energy savings are created by not just one, but two changes: (1) adding photocontrols and (2) adding 3M Window Film to the clerestory. Figure 48 compares the potential savings for the windows with photocontrols and full-height blinds only, versus adding 3M Window Film to the upper window. Relative savings decline if blinds are optimally controlled. In Figure 48 dashed lines indicate savings from photocontrols alone and solid lines indicate savings from adding the test product to a room with pre-existing photocontrols.

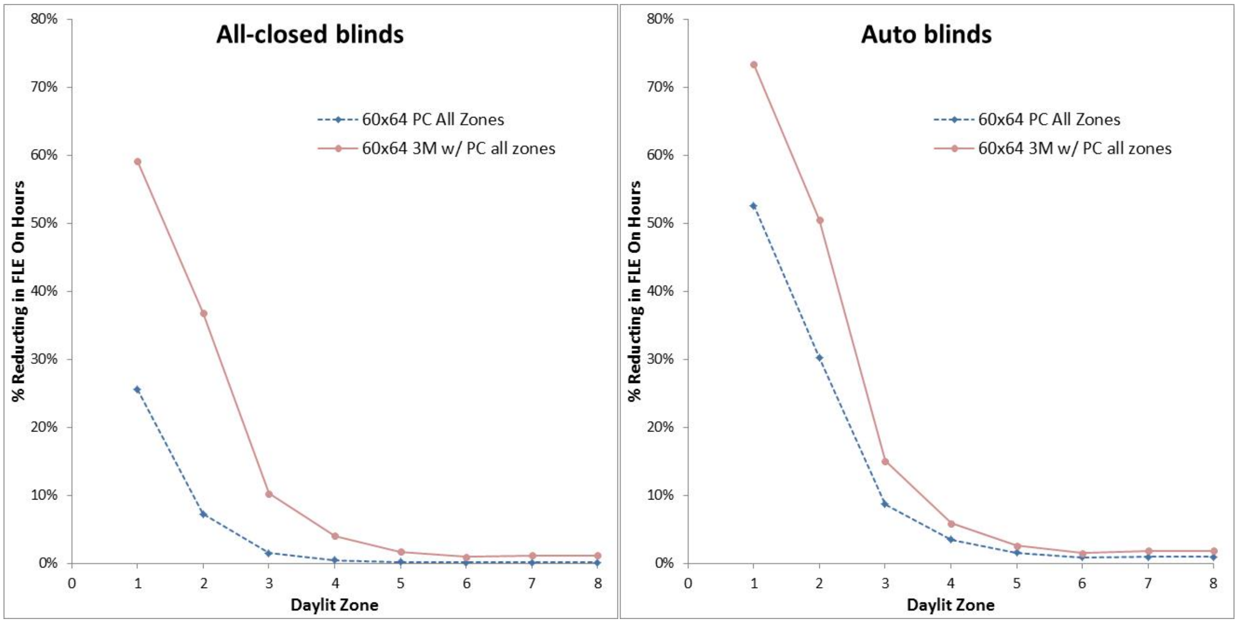
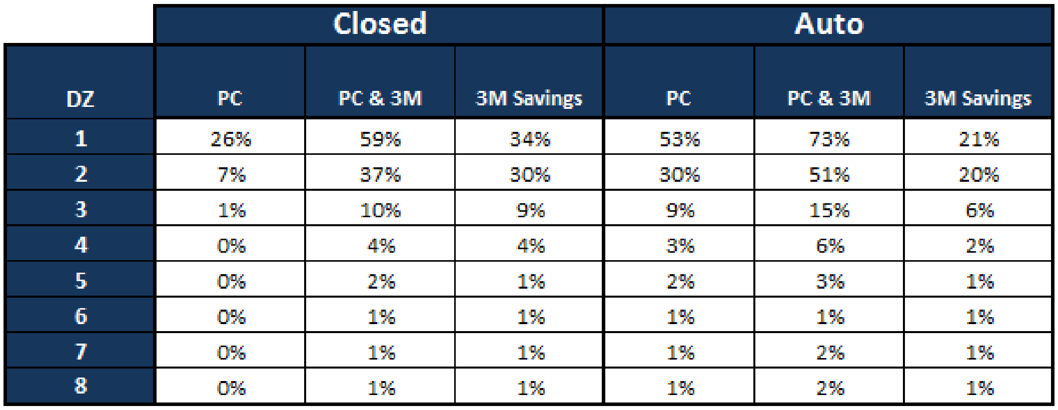


Figure 48. 3M Window Film: effect of blinds operation on lighting energy savings with pre-existing photocontrols.

The data presented graphically in Figure 48 is presented in tabular form in Figure 49. If the blinds are always closed, adding 3M Window Film increases savings by more than 30% in the first two daylighting zones and by 9% in the third daylighting zone if blinds are always closed. However, these savings are only two-thirds as large if the blinds are controlled optimally (automatically). Aggregate savings for a large number of spaces is likely to fall somewhere in the middle between these two extremes, assuming a normal variation in occupant behavior. Ease of access to blinds controls is an important factor in how actively blinds are adjusted by occupants.



	Closed			Auto		
DZ	PC	PC & 3M	3M Savings	PC	PC & 3M	3M Savings
1	26%	59%	34%	53%	73%	21%
2	7%	37%	30%	30%	51%	20%
3	1%	10%	9%	9%	15%	6%
4	0%	4%	4%	3%	6%	2%
5	0%	2%	1%	2%	3%	1%
6	0%	1%	1%	1%	1%	1%
7	0%	1%	1%	1%	2%	1%
8	0%	1%	1%	1%	2%	1%

Figure 49. 3M Window Film: lighting energy savings.

The most important observation from this simulation exercise is that the electric lighting savings with the test products under worst case conditions (blinds always Closed) is very similar to, and often better than, the electric lighting savings potential for the same windows with no test product under best case conditions (Auto). Thus, the test products completely eliminate the downside risk of poor blinds operation, and greatly increase the upside opportunity for daylight savings.

Window VLT also significantly affects savings. Increasing window VLT from 40% to 70% (Figure 50) has a smaller effect that automating blinds control (Figure 50 vs. Figure 47). Figure 50 shows results for 3M Window Film with 40% VLT glazing plotted with dashed lines and 70% VLT glazing results are plotted with solid lines.

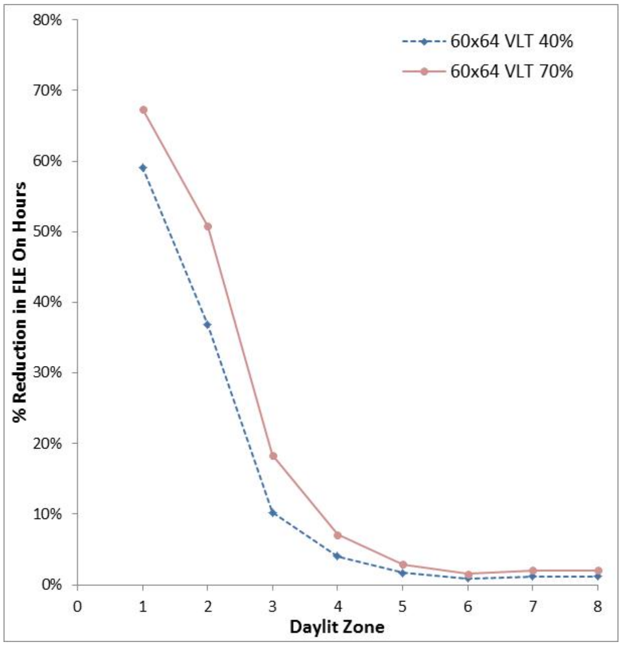


Figure 50. 3M Window Film: effect of window VLT on lighting energy savings.

Figure 51 shows savings vary little by orientation which may be somewhat surprising to the reader. However, it is important to note that a west facing window at latitude 40 degree (Sacramento is 38.6 degrees) will receive 2000 hours of direct sunlight per year, while a south or southwest facing window will receive slightly over 3000 hours per year. (See Figure 14.7 and 14.8 in the IES Handbook, 10th edition.) However, almost 1/3 of the south and southwest facing hours of sunlight are above a 60 degree profile angle where high angles of incidence reduce transmission both due to reflection by the products and by the window glass itself. Thus, according to these simulations, the net effect of orientation on the performance of the product is negligible.

An important finding of the simulation analysis is that the test products can produce similar levels of annual savings across window orientations, from east to south to west. If true (as verified in future field studies) the potential market for these products will greatly increase. However, it is important to note that the lower sun angles experienced on east and west facing facades may have different impacts on occupant comfort, and were not studied in the occupant assessment portion of this project, which only considered south facing windows.

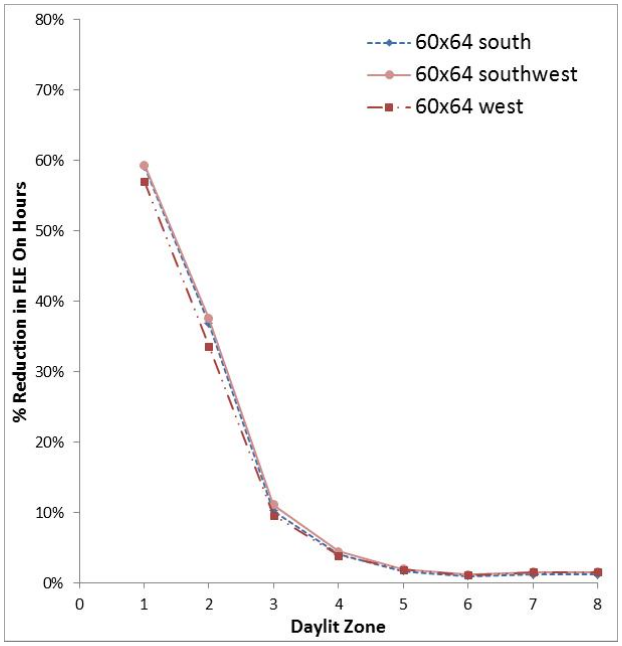


Figure 51. 3M Window Film: effect of orientation on lighting energy savings.

Savings increase in the space when the ceiling height, and clerestory window, increases from 9’ to 10’ (Figure 52). In the 10’ model, the clerestory head height increased from 8’9” to 9’9”. The clerestory sill height remained unchanged at 7’6”. The view window size and position remained constant as well. Savings in the first daylit zone increase only about 5% since the zone was already saturated with light, but savings increase by about 15% in the second and third zones.

These findings, based on ceiling and clerestory window height suggest that additional savings due to the addition of the product become more significant in deeper rooms, as the clerestory window becomes taller. Thus, there may be an optimum relationship between height of the treated clerestory window and the depth of the room and resulting daylight control zones. Figure 52 suggests a rule of thumb that an increase in 1’ in product height produces equivalent additional savings 8’ deeper into the room. Figure 55 and Figure 56 also show the increased savings from the back wall reflection for the three orientations studied. It is noticeably higher for west facing windows compared to south facing rooms, as might be expected since lower sun angles are more common on a west orientation. It might be that these products will eventually be optimized for different window orientations, such that products applied to east or west facing windows are more optimized for low sun angles, and south facing window for higher sun angles.

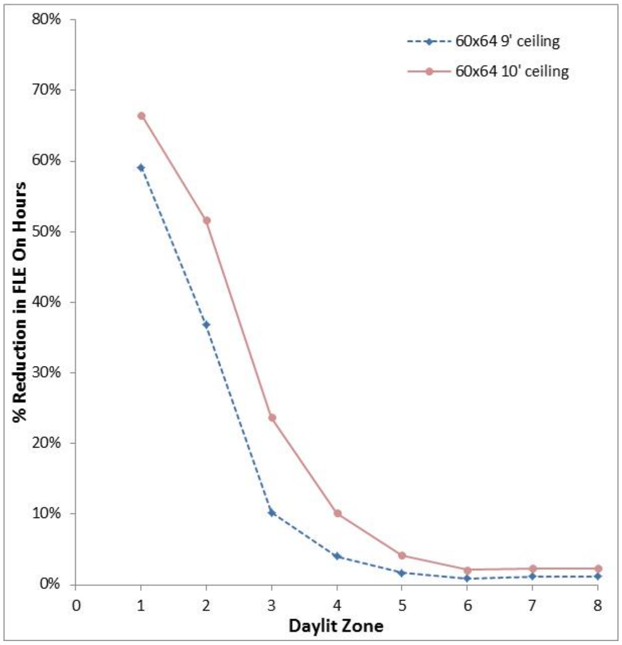
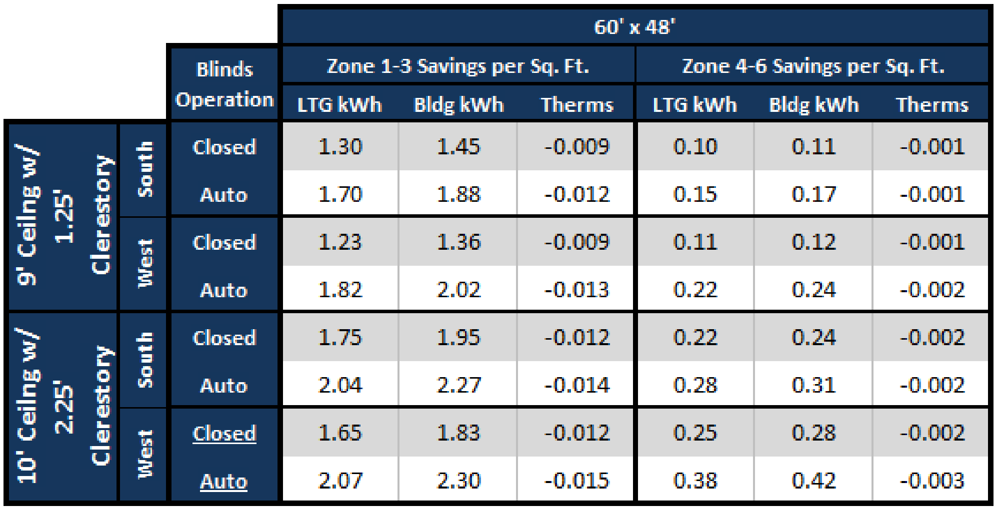


Figure 52. 3M Window Film: effect of ceiling height on lighting energy savings.

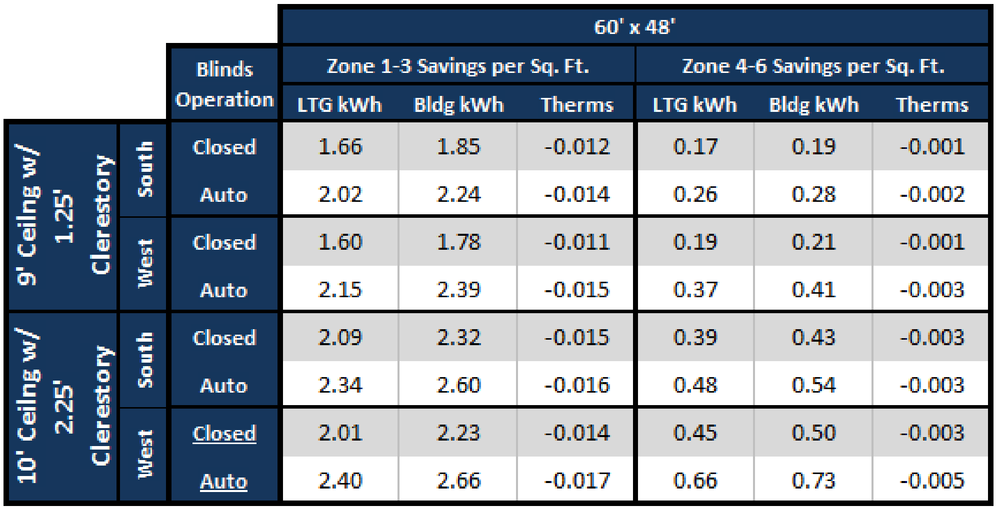
The patterns outlined above were observed in all simulation results. The patterns are results of the light redirection of the 3M Window Film as represented by the BSDF. Further work should validate these results in the field. The patterns outlined above were observed in all simulation results. More detailed results are available in Appendix C.

Approximate whole building energy savings are summarized in Figure 53 for the first three zones and second three zones with 9' and 10' ceiling heights, south and west facing spaces, and all-closed and auto blinds operation for 40% VLT glazing. Figure 54 shows annual energy savings for the same configurations with 70% VLT glazing. Annual energy savings include a DEER database correction to heating and cooling loads due to electric lighting reductions, but do not include any changes in the SHGC or U-value of the window assembly due to addition of the test products (which are currently unknown). Because these whole building factors were not produced via a simulation, but rather by multiplying the uniform DEER factor, they also may not reflect variations in whole building heating and cooling impacts due to window orientation and solar angle. All results assume an LPD of 1.2 Watts / square foot. Annual energy savings do not include reductions in cooling and increases in heating necessary to offset changes in the SHGC and other characteristics of the window assembly.



			60' x 48'					
		Blinds Operation	Zone 1-3 Savings per Sq. Ft.			Zone 4-6 Savings per Sq. Ft.		
			LTG kWh	Bldg kWh	Therms	LTG kWh	Bldg kWh	Therms
9' Ceilng w/ 1.25' Clerestory	South	Closed	1.30	1.45	-0.009	0.10	0.11	-0.001
		Auto	1.70	1.88	-0.012	0.15	0.17	-0.001
	West	Closed	1.23	1.36	-0.009	0.11	0.12	-0.001
		Auto	1.82	2.02	-0.013	0.22	0.24	-0.002
10' Ceilng w/ 2.25' Clerestory	South	Closed	1.75	1.95	-0.012	0.22	0.24	-0.002
		Auto	2.04	2.27	-0.014	0.28	0.31	-0.002
	West	Closed	1.65	1.83	-0.012	0.25	0.28	-0.002
		Auto	2.07	2.30	-0.015	0.38	0.42	-0.003

Figure 53. 3M Window Film annual whole-building energy savings summary with 40%VLT Glass.



			60' x 48'					
		Blinds Operation	Zone 1-3 Savings per Sq. Ft.			Zone 4-6 Savings per Sq. Ft.		
			LTG kWh	Bldg kWh	Therms	LTG kWh	Bldg kWh	Therms
9' Ceilng w/ 1.25' Clerestory	South	Closed	1.66	1.85	-0.012	0.17	0.19	-0.001
		Auto	2.02	2.24	-0.014	0.26	0.28	-0.002
	West	Closed	1.60	1.78	-0.011	0.19	0.21	-0.001
		Auto	2.15	2.39	-0.015	0.37	0.41	-0.003
10' Ceilng w/ 2.25' Clerestory	South	Closed	2.09	2.32	-0.015	0.39	0.43	-0.003
		Auto	2.34	2.60	-0.016	0.48	0.54	-0.003
	West	Closed	2.01	2.23	-0.014	0.45	0.50	-0.003
		Auto	2.40	2.66	-0.017	0.66	0.73	-0.005

Figure 54. 3M Window Film annual whole-building energy savings summary with 70% VLT glass.

5 DISCUSSION AND CONCLUSIONS

Both 3M Window Film and LightLouver™ provide the opportunity for significant electric lighting energy savings by redirecting sunlight incident on upper windows up onto the ceiling and thus deeper into the space. Importantly, both products reduce the risk that daylighting savings will be lost if occupants leave the view-window blinds closed.

The products change the appearance of the space in different ways, and should also be considered for their impacts on aesthetics and visual comfort in the treated space. Both reduce the maintenance and safety issues compared to the existing light shelves, making it easier to keep the window area clean, dust free, and accessible to fire suppression sprinklers.

5.1 OCCUPANT ACCEPTANCE

Overall, the two test technologies were not found to create any negative impacts on occupant visual comfort. Although high levels of transient luminance and 'glint' were measured at various locations in the study space during the winter site observations, no occupant complained about glare specifically due to the products. In comparison, a few occupants did complain about glare form the existing window and light shelf configuration.

From the outset of the study, occupants at this site clearly preferred the aesthetics of both the 3M system and LightLouver™ to the existing light shelves; and in a final survey, more occupants preferred the aesthetics of the 3M system to LightLouver. Given that the occupants of this space were already found to be significantly happier with their workspace than the average office worker[22], these results supports the claim that the 3M Window Film and LightLouver™ both offer savings while preserving occupant comfort.

5.2 DAYLIGHT ILLUMINATION PERFORMANCE

Results show that blinds operation is a significant determinant of both total savings and the fraction of savings that can be attributed to the advanced sidelighting product in a room already containing photocontrols. Total savings are largest in a room with automated (optimal) blinds control for the view windows, but the relative savings contributed by the advanced daylighting product increase when view window blinds are assumed to be left continuously closed.

---

[22] Lighting Research Center, *Demonstration and Evaluation of Lighting Technologies and Applications*, Delta Portfolio, Volume 2, Issue 2, 1997

Based on simulation findings, savings from the advanced sidelighting products do not change substantially with façade orientation, between true east, south, west, and intermediate southeast and southwest. This indicates these technologies may be applicable to a larger range of spaces than simpler technologies such as light shelves.

As would be expected, simulations also show that savings increase when window VLT is increased, from 40 to 70% VLT. The increase is nearly equal in magnitude to the change associated with moving from always-closed (worst-case) blinds to automated (optimal) blinds.

Savings also increase when the clerestory window is taller, as when ceiling height is increased in the simulation model from 9’ to 10’. The taller the clerestory window, the greater the savings deeper into the space. The primary daylit zone is already saturated with daylight from the view window. Consequently, the deeper the desired daylight zone, the taller the clerestory window with the daylight redirecting product should be. Applying the advanced products at 7’6” above finished floor, for 18” should be considered a minimum specification. Lower installation, those below 7’6”, are very likely to create intolerable glare conditions for the occupants when standing at the back of the room. Higher installations (starting at 8’ or 9’ AFF) and taller (2’ to 4’) should be considered for deeper spaces that desire aggressive daylight savings.

5.3 BENEFIT COST IMPLICATIONS

When moving from the 9’ model to the 10’ model, electric energy savings increased less quickly than the glazing area that must be covered with the product. If the benefit cost ratio was driven solely by the area of product installed, then the 1.25’ strip of product required for the 9’ space would be more cost effect than the 2.25’ strip of product needed in the 10’ space, because installing only 55% of the product retains 80% of the savings. However, the economics of a retrofit are complex and the benefit cost ratio will be sensitive to many variables including product cost, labor costs, glazing area the product will cover, blinds operation, room size, whether or not photocontrols are already installed, whether or not existing wiring must be replaced, the cost of electricity, and the occupancy schedule.

Consequently, this report does not provide benefit cost guidance. It does provide guidance on the electric lighting savings attributable to adding photocontrols to the lighting system and the product to the upper windows. Using this data, a rough calculation of system savings should be possible with project specific cost data.

5.4 VERTICAL ILLUMINANCE LEVELS

Analysis of the vertical illuminance levels at the mid-floor columns supported the hypothesis that the products throw measurable daylight deep in the space. Over the first phase, winter monitoring period, the top sensor on the column in front of LightLouver™ was brighter than the equivalent top sensor in line with 3M’s Film and the light shelves. However, the lower sensors (3’ down from the 11’ ceiling) were dimmer on the column in front of LightLouver™ than 3M’s Film or lightshelves. This suggested that

LightLouver™ may create less direct glare at the back of the room at eye level, since more sunlight is directed above horizontal plane.

Simulation helped answer some of these questions about light distribution, but not glare or visual perception. Simulation results show daylighting savings for both advanced products increase slightly near the rear wall because of light intercepted and reflected by the wall's surface. This magnitude of this effect declines as room depth increases. The simulation results suggest that in very deep rooms the redirected sunlight becomes too thinly spread out to provide meaningful energy savings. It may be useful to use beams or other vertical interruptions of the horizontal ceiling plane to intercept this redirected sunlight within 30-40' of the windowed façade, thus concentrating the benefits where daylighting will be more cost effective.

The perception of 'sunlight' of the back wall of a space may contribute to occupant's assessment of the visual quality in the space. From other studies it is known that occupants generally prefer a 'bright horizon' on upper walls, such as from cove lighting, and will judge a space to be brighter based on upper wall illumination levels. From this study, it is unknown how important such an effect of sun lighting on the upper walls might be on occupant perceptions.

5.5 CEILING ILLUMINANCE LEVELS AND PHOTOSENSOR RESPONSE

The HOBO data loggers are biased towards measuring light received from a cone of 30 degrees normal to their view, and they discount light received at shallow angles. Consequently, the ceiling sensors primarily recorded the quantity of light reflecting off surfaces below them, not the sunlight emanating directly from the products to the HOBO sensors. Based on monitoring results, one could conclude that the useful light on work surfaces and floor is similar between sidelighting products.

However, the response of the existing photosensors to the redirected sunlight at shallow angles is not known. For a true 'closed loop' control system controlling horizontal illumination level at the desk plane, any photosensors on the ceiling should be shielded from a direct view of the redirected sunlight. However, a hybrid system, with sensors sensing luminance from both below and the window may better reflect occupants' perception of the space. Anyone employing these advanced products with photocontrols should give careful consideration integration of the photosensors with the expected light distribution of the products.

5.6 STUDY LIMITATIONS

This study attempted to compare monitored performance of the daylight illumination levels provided by the two test technologies to the existing light shelves. However, confounding situations with the adjacency of the products, variable output of the electric lighting, and existing shading systems greatly limited the level of resolution that could be achieved on the monitored data. Simulation studies proved more useful in predicting available energy savings, but are also limited by the precision of the simulation tools and the optical description of the products in the BSDF files provided by the manufacturers.

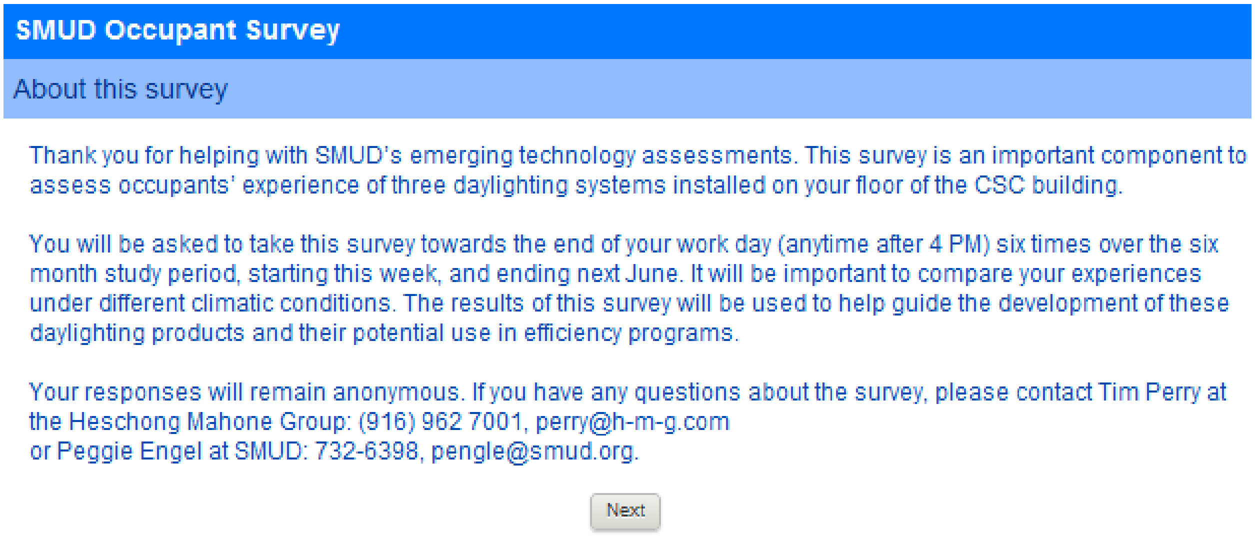
From the monitored data, findings for winter sunlight on a south facing façade have the greatest certainty. Occupant surveys and interviews provided reassurance that the occupants did not have any strong objections to either product, and actually were found to prefer both over the existing light shelves. However, the occupants did not experience the products redirecting sunlight during the high solar angles of summer, due to pre-existing shading systems, nor did they experience the very low sun angles which would occur on more easterly or westerly facades. Thus, further study of occupant reactions, in a wider range of applications is highly recommended.

6 ACKNOWLEDGEMENTS

This report is the interim project report for the Sacramento Municipal Utility District's Emerging Technologies daylighting technical assessment. The research presented herein was carried out by the Heschong Mahone Group Inc. under subcontract to Nexant Inc. The Nexant project manager was Safdar Chaudhry. The Sacramento Municipal Utility District project manager was Bruce Baccei.

HMG project manager was Tim Perry, who was responsible for overall project management, research direction, analysis and report writing; principal in-charge was Lisa Heschong, who provided oversight and input. The HMG team that worked on this project consisted of Associate Directors Mudit Saxena and Abhijeet Pande who provided technical assistance and methodology advice; Research Associate Anil Ganti, who assisted with data analysis and site visits; Stephen Wilson, who assisted in monitoring equipment maintenance and inventory.

Appendix A. Survey Instrument



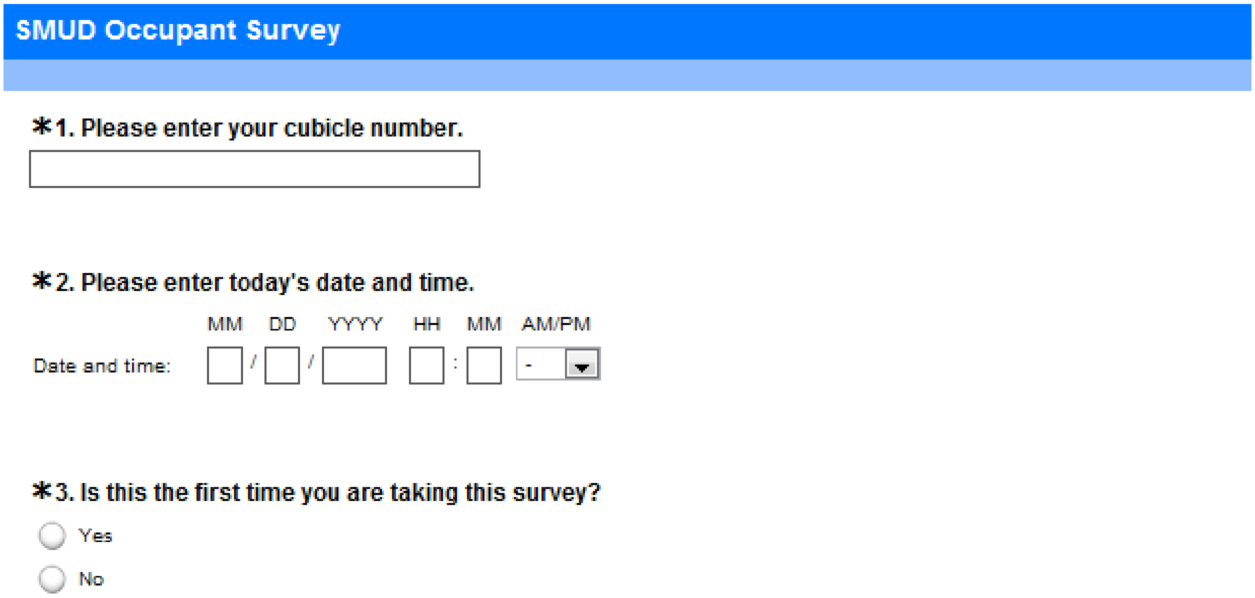
SMUD Occupant Survey

About this survey

Thank you for helping with SMUD's emerging technology assessments. This survey is an important component to assess occupants' experience of three daylighting systems installed on your floor of the CSC building.

You will be asked to take this survey towards the end of your work day (anytime after 4 PM) six times over the six month study period, starting this week, and ending next June. It will be important to compare your experiences under different climatic conditions. The results of this survey will be used to help guide the development of these daylighting products and their potential use in efficiency programs.

Your responses will remain anonymous. If you have any questions about the survey, please contact Tim Perry at the Heschong Mahone Group: (916) 962 7001, perry@h-m-g.com
or Peggie Engel at SMUD: 732-6398, pengle@smud.org.



SMUD Occupant Survey

***1. Please enter your cubicle number.**

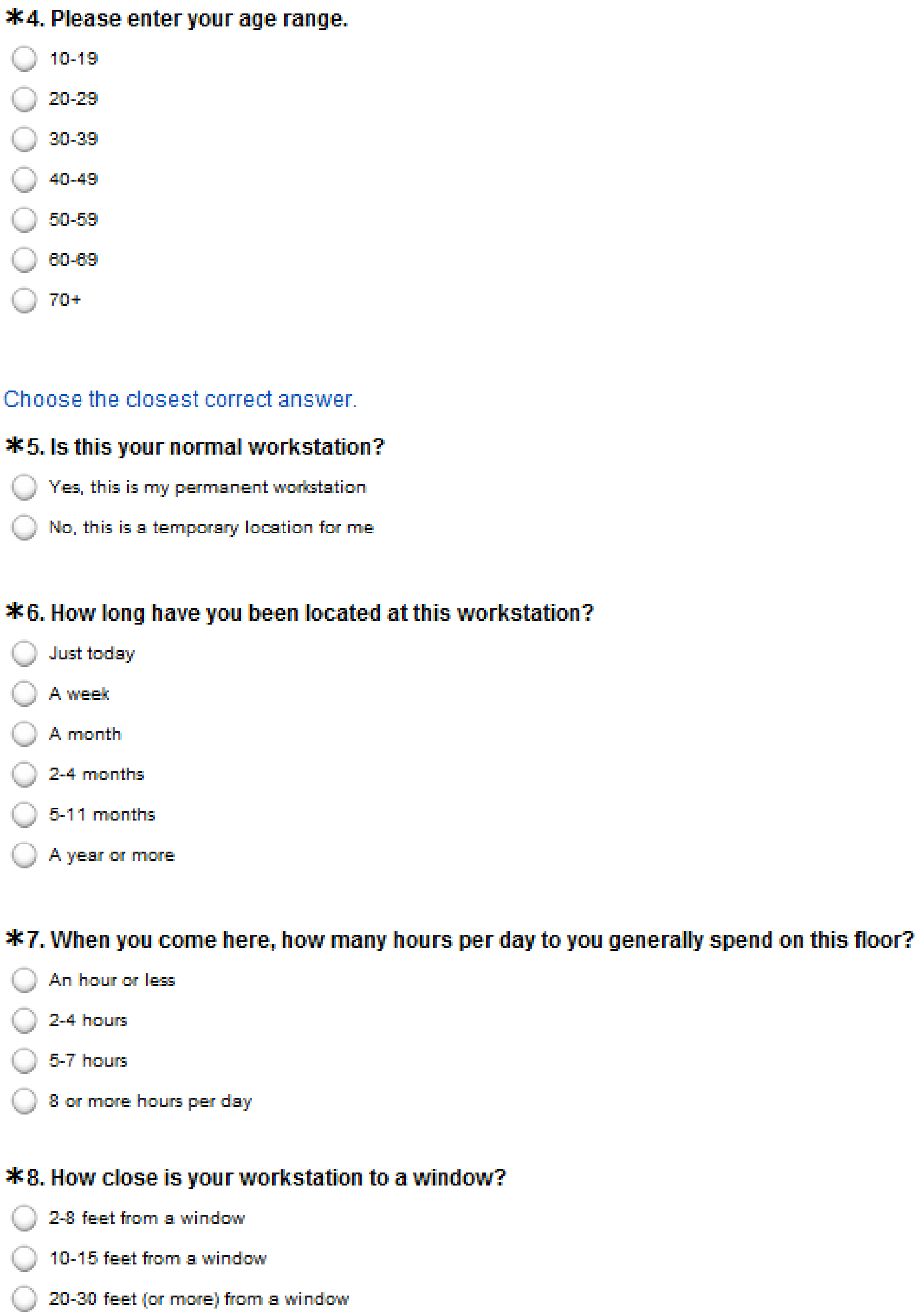
***2. Please enter today's date and time.**

	MM		DD		YYYY	HH		MM	AM/PM
Date and time:		/		/			:		-

***3. Is this the first time you are taking this survey?**

○ Yes

○ No



*4. Please enter your age range.

○ 10-19
○ 20-29
○ 30-39
○ 40-49
○ 50-59
○ 60-69
○ 70+

Choose the closest correct answer.

*5. Is this your normal workstation?

○ Yes, this is my permanent workstation
○ No, this is a temporary location for me

*6. How long have you been located at this workstation?

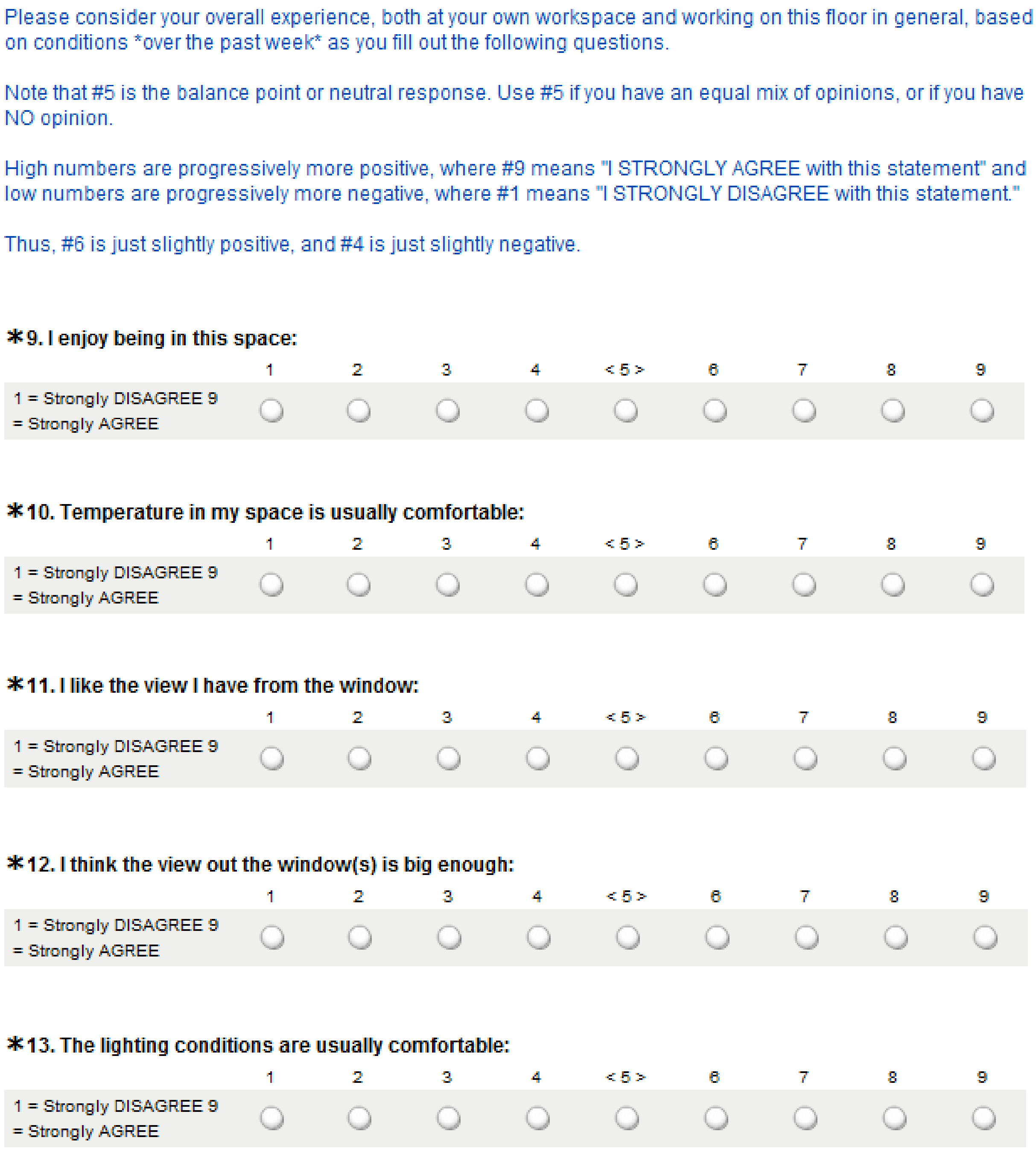
○ Just today
○ A week
○ A month
○ 2-4 months
○ 5-11 months
○ A year or more

*7. When you come here, how many hours per day to you generally spend on this floor?

○ An hour or less
○ 2-4 hours
○ 5-7 hours
○ 8 or more hours per day

*8. How close is your workstation to a window?

○ 2-8 feet from a window
○ 10-15 feet from a window
○ 20-30 feet (or more) from a window



Please consider your overall experience, both at your own workspace and working on this floor in general, based on conditions *over the past week* as you fill out the following questions.

Note that #5 is the balance point or neutral response. Use #5 if you have an equal mix of opinions, or if you have NO opinion.

High numbers are progressively more positive, where #9 means "I STRONGLY AGREE with this statement" and low numbers are progressively more negative, where #1 means "I STRONGLY DISAGREE with this statement."

Thus, #6 is just slightly positive, and #4 is just slightly negative.

***9. I enjoy being in this space:**

	1	2	3	4	< 5 >	6	7	8	9
1 = Strongly DISAGREE 9 = Strongly AGREE	○	○	○	○	○	○	○	○	○

***10. Temperature in my space is usually comfortable:**

	1	2	3	4	< 5 >	6	7	8	9
1 = Strongly DISAGREE 9 = Strongly AGREE	○	○	○	○	○	○	○	○	○

***11. I like the view I have from the window:**

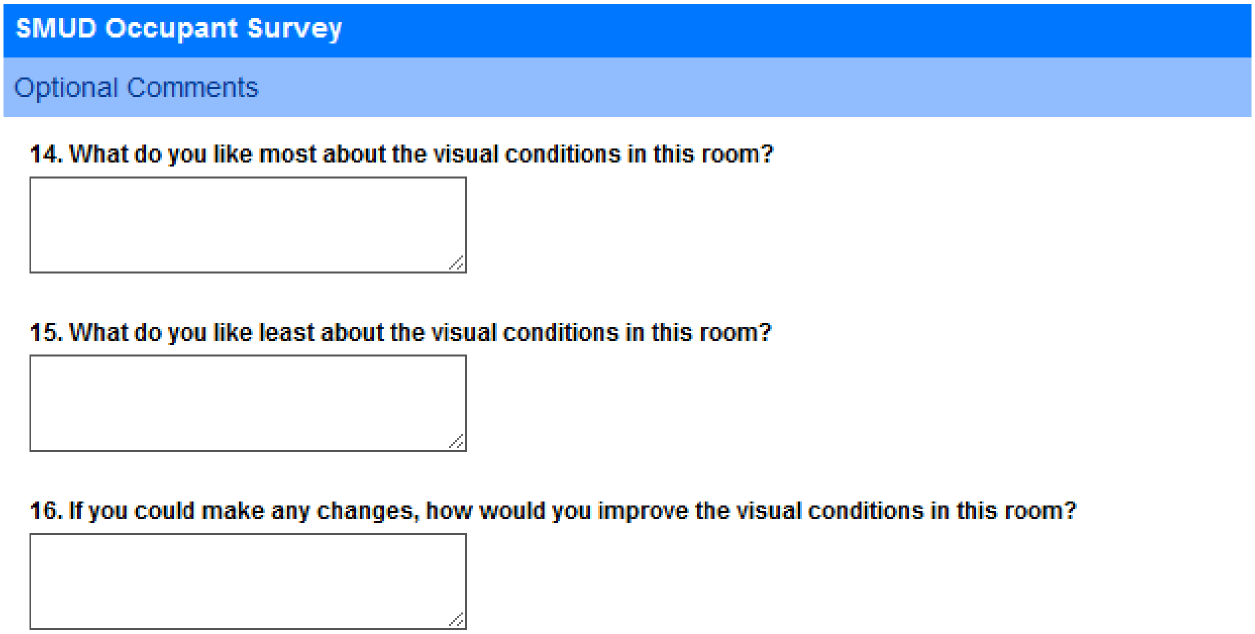
	1	2	3	4	< 5 >	6	7	8	9
1 = Strongly DISAGREE 9 = Strongly AGREE	○	○	○	○	○	○	○	○	○

***12. I think the view out the window(s) is big enough:**

	1	2	3	4	< 5 >	6	7	8	9
1 = Strongly DISAGREE 9 = Strongly AGREE	○	○	○	○	○	○	○	○	○

***13. The lighting conditions are usually comfortable:**

	1	2	3	4	< 5 >	6	7	8	9
1 = Strongly DISAGREE 9 = Strongly AGREE	○	○	○	○	○	○	○	○	○



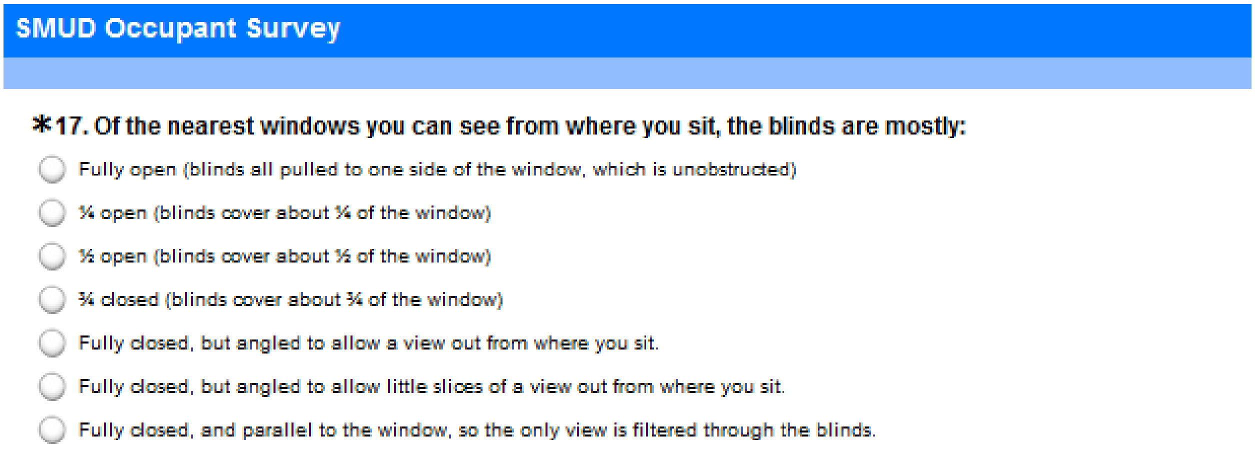
SMUD Occupant Survey

Optional Comments

14. What do you like most about the visual conditions in this room?

15. What do you like least about the visual conditions in this room?

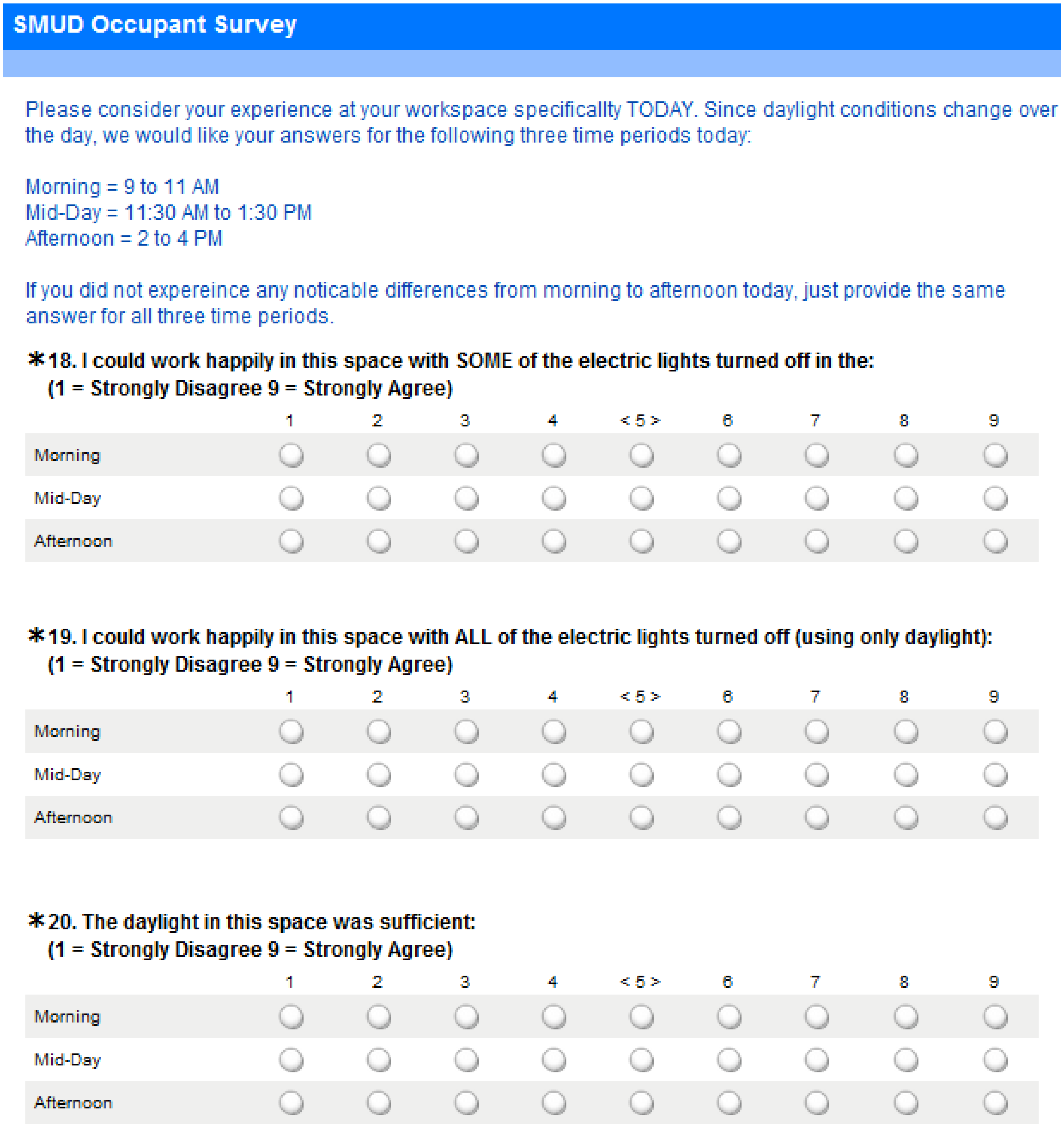
16. If you could make any changes, how would you improve the visual conditions in this room?



SMUD Occupant Survey

***17. Of the nearest windows you can see from where you sit, the blinds are mostly:**

○ Fully open (blinds all pulled to one side of the window, which is unobstructed)
○ ¼ open (blinds cover about ¼ of the window)
○ ½ open (blinds cover about ½ of the window)
○ ¾ closed (blinds cover about ¾ of the window)
○ Fully closed, but angled to allow a view out from where you sit.
○ Fully closed, but angled to allow little slices of a view out from where you sit.
○ Fully closed, and parallel to the window, so the only view is filtered through the blinds.



SMUD Occupant Survey

Please consider your experience at your workspace specificallty TODAY. Since daylight conditions change over the day, we would like your answers for the following three time periods today:

Morning = 9 to 11 AM
Mid-Day = 11:30 AM to 1:30 PM
Afternoon = 2 to 4 PM

If you did not expereince any noticable differences from morning to afternoon today, just provide the same answer for all three time periods.

***18. I could work happily in this space with SOME of the electric lights turned off in the:**
(1 = Strongly Disagree 9 = Strongly Agree)

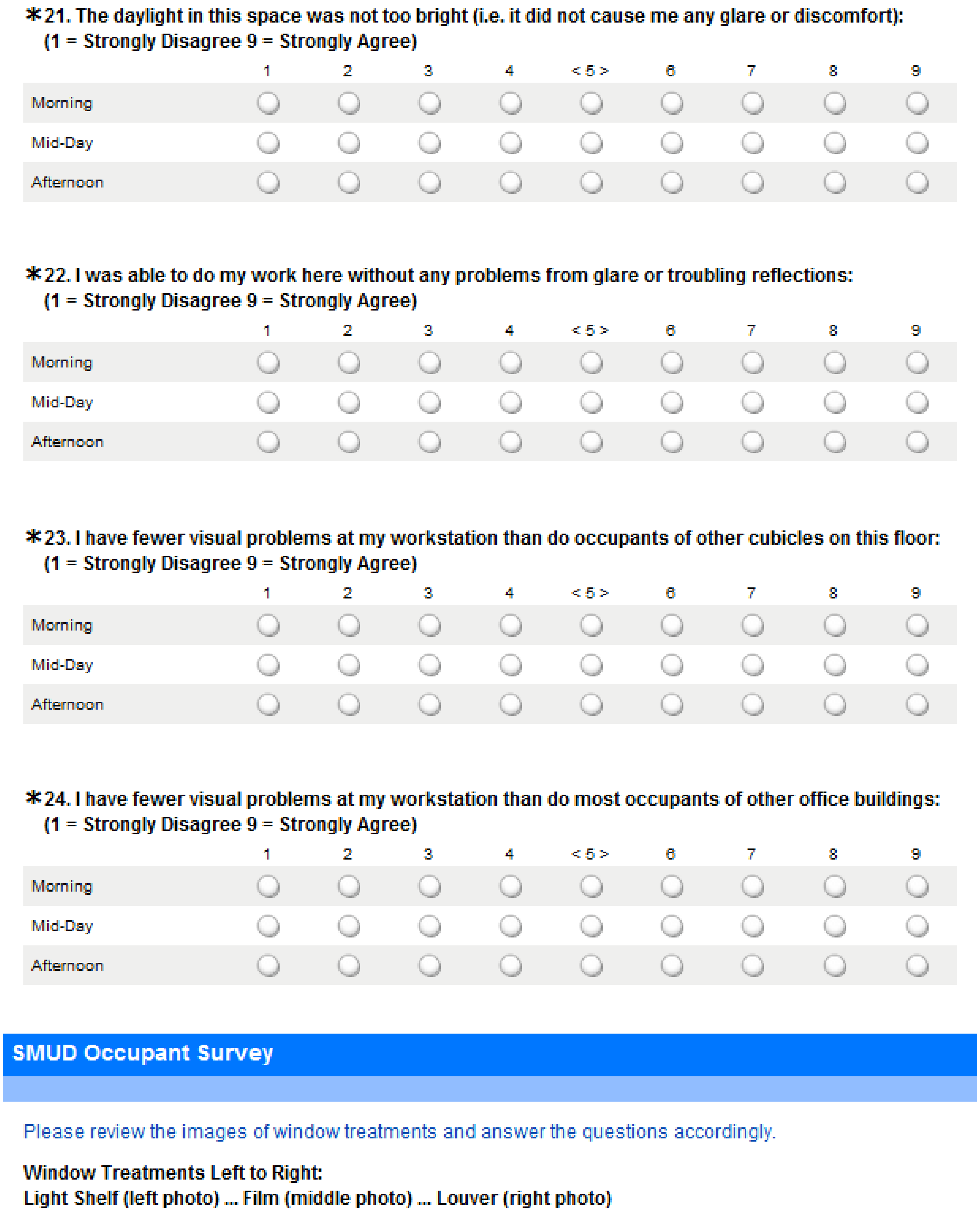
	1	2	3	4	< 5 >	6	7	8	9
Morning	○	○	○	○	○	○	○	○	○
Mid-Day	○	○	○	○	○	○	○	○	○
Afternoon	○	○	○	○	○	○	○	○	○

***19. I could work happily in this space with ALL of the electric lights turned off (using only daylight):**
(1 = Strongly Disagree 9 = Strongly Agree)

	1	2	3	4	< 5 >	6	7	8	9
Morning	○	○	○	○	○	○	○	○	○
Mid-Day	○	○	○	○	○	○	○	○	○
Afternoon	○	○	○	○	○	○	○	○	○

***20. The daylight in this space was sufficient:**
(1 = Strongly Disagree 9 = Strongly Agree)

	1	2	3	4	< 5 >	6	7	8	9
Morning	○	○	○	○	○	○	○	○	○
Mid-Day	○	○	○	○	○	○	○	○	○
Afternoon	○	○	○	○	○	○	○	○	○



✱21. The daylight in this space was not too bright (i.e. it did not cause me any glare or discomfort):
(1 = Strongly Disagree 9 = Strongly Agree)

	1	2	3	4	< 5 >	6	7	8	9
Morning	○	○	○	○	○	○	○	○	○
Mid-Day	○	○	○	○	○	○	○	○	○
Afternoon	○	○	○	○	○	○	○	○	○

✱22. I was able to do my work here without any problems from glare or troubling reflections:
(1 = Strongly Disagree 9 = Strongly Agree)

	1	2	3	4	< 5 >	6	7	8	9
Morning	○	○	○	○	○	○	○	○	○
Mid-Day	○	○	○	○	○	○	○	○	○
Afternoon	○	○	○	○	○	○	○	○	○

✱23. I have fewer visual problems at my workstation than do occupants of other cubicles on this floor:
(1 = Strongly Disagree 9 = Strongly Agree)

	1	2	3	4	< 5 >	6	7	8	9
Morning	○	○	○	○	○	○	○	○	○
Mid-Day	○	○	○	○	○	○	○	○	○
Afternoon	○	○	○	○	○	○	○	○	○

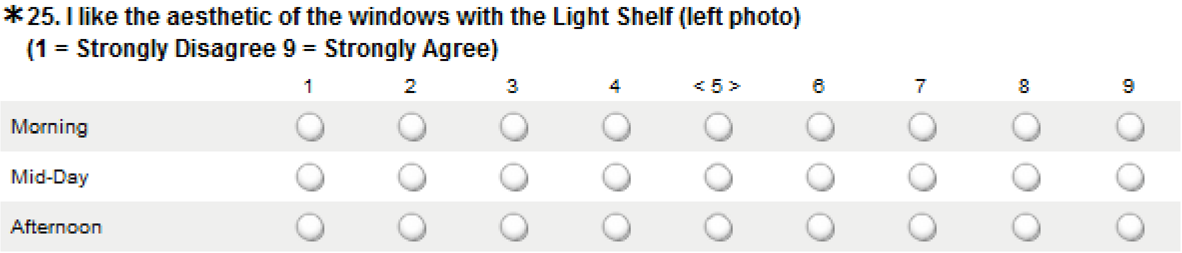
✱24. I have fewer visual problems at my workstation than do most occupants of other office buildings:
(1 = Strongly Disagree 9 = Strongly Agree)

	1	2	3	4	< 5 >	6	7	8	9
Morning	○	○	○	○	○	○	○	○	○
Mid-Day	○	○	○	○	○	○	○	○	○
Afternoon	○	○	○	○	○	○	○	○	○

SMUD Occupant Survey

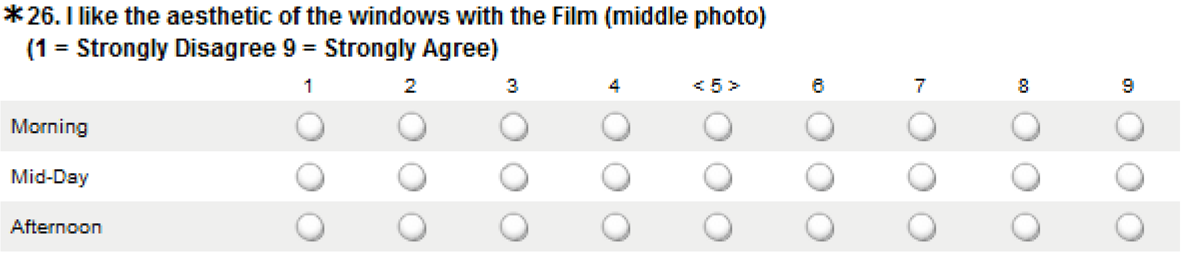
Please review the images of window treatments and answer the questions accordingly.

Window Treatments Left to Right:
Light Shelf (left photo) ... Film (middle photo) ... Louver (right photo)



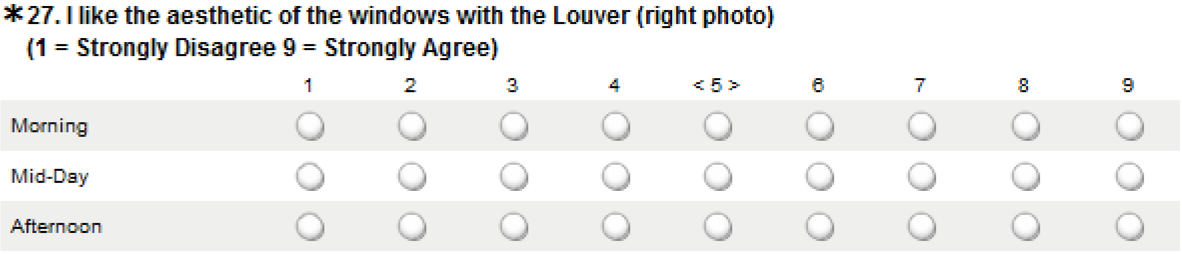
***25. I like the aesthetic of the windows with the Light Shelf (left photo)**
(1 = Strongly Disagree 9 = Strongly Agree)

	1	2	3	4	< 5 >	6	7	8	9
Morning	○	○	○	○	○	○	○	○	○
Mid-Day	○	○	○	○	○	○	○	○	○
Afternoon	○	○	○	○	○	○	○	○	○



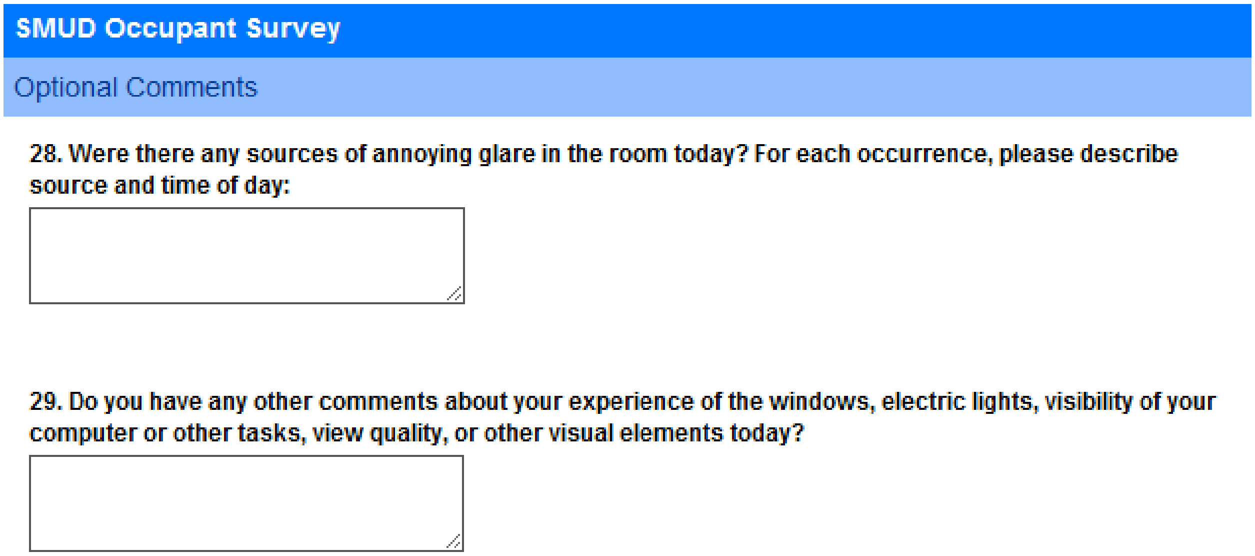
***26. I like the aesthetic of the windows with the Film (middle photo)**
(1 = Strongly Disagree 9 = Strongly Agree)

	1	2	3	4	< 5 >	6	7	8	9
Morning	○	○	○	○	○	○	○	○	○
Mid-Day	○	○	○	○	○	○	○	○	○
Afternoon	○	○	○	○	○	○	○	○	○



***27. I like the aesthetic of the windows with the Louver (right photo)**
(1 = Strongly Disagree 9 = Strongly Agree)

	1	2	3	4	< 5 >	6	7	8	9
Morning	○	○	○	○	○	○	○	○	○
Mid-Day	○	○	○	○	○	○	○	○	○
Afternoon	○	○	○	○	○	○	○	○	○

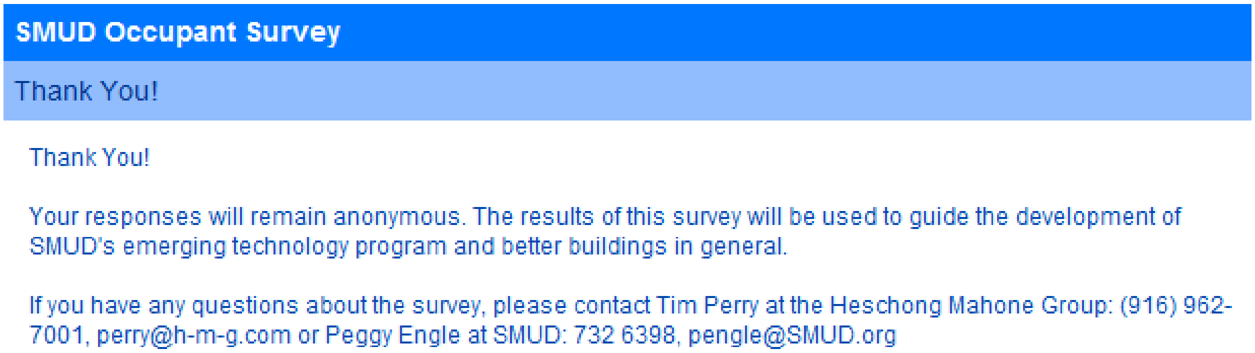


SMUD Occupant Survey

Optional Comments

28. Were there any sources of annoying glare in the room today? For each occurrence, please describe source and time of day:

29. Do you have any other comments about your experience of the windows, electric lights, visibility of your computer or other tasks, view quality, or other visual elements today?



SMUD Occupant Survey

Thank You!

Thank You!

Your responses will remain anonymous. The results of this survey will be used to guide the development of SMUD's emerging technology program and better buildings in general.

If you have any questions about the survey, please contact Tim Perry at the Heschong Mahone Group: (916) 962-7001, perry@h-m-g.com or Peggy Engle at SMUD: 732 6398, pengle@SMUD.org

Appendix B. Product Vote

Good morning.

As a member of the SMUD staff on this floor, you have been participating in an evaluation of two new daylighting products—The LightLouver and 3M's Daylight Redirecting Film—which were installed in the upper windows of two bays along the south wall six months ago, back in last December.

We have asked you to evaluate your experience via a number of repeated surveys, since as daylight changes over the course of the day and/or seasons, your experience might change. Thank you for your input!

Now, the SMUD facilities staff is considering the possibility of extending one or the other of these products across more windows, or keeping all the windows as-is. Before they investigate such a decision further, they would like to know your opinion.

A: existing light shelf B. 3M Daylight Redirecting Film C: Light Louver

Do you have a preference for which of the three options shown above might get applied to all the south windows on your floor?

Please respond to Peggy Engle by email which product you would prefer to have installed throughout the floor, and why.

Appendix C. Simulation Details

C.1. DETAILED SIMULATION RESULTS

To provide easy reference, energy savings for spaces with a 9’ and 10’ ceilings, 40% and 70% VLT and both auto and all-closed blinds are shown below. Figure 55 shows results for LightLouver™ in a 9’ office space. Figure 56 show results for LightLouver in a 10’ office space. Figure 57 shows results for 3M Window Film in a 9’ office space. Figure 58 shows results for 3M Window Film in a 10’ office space.

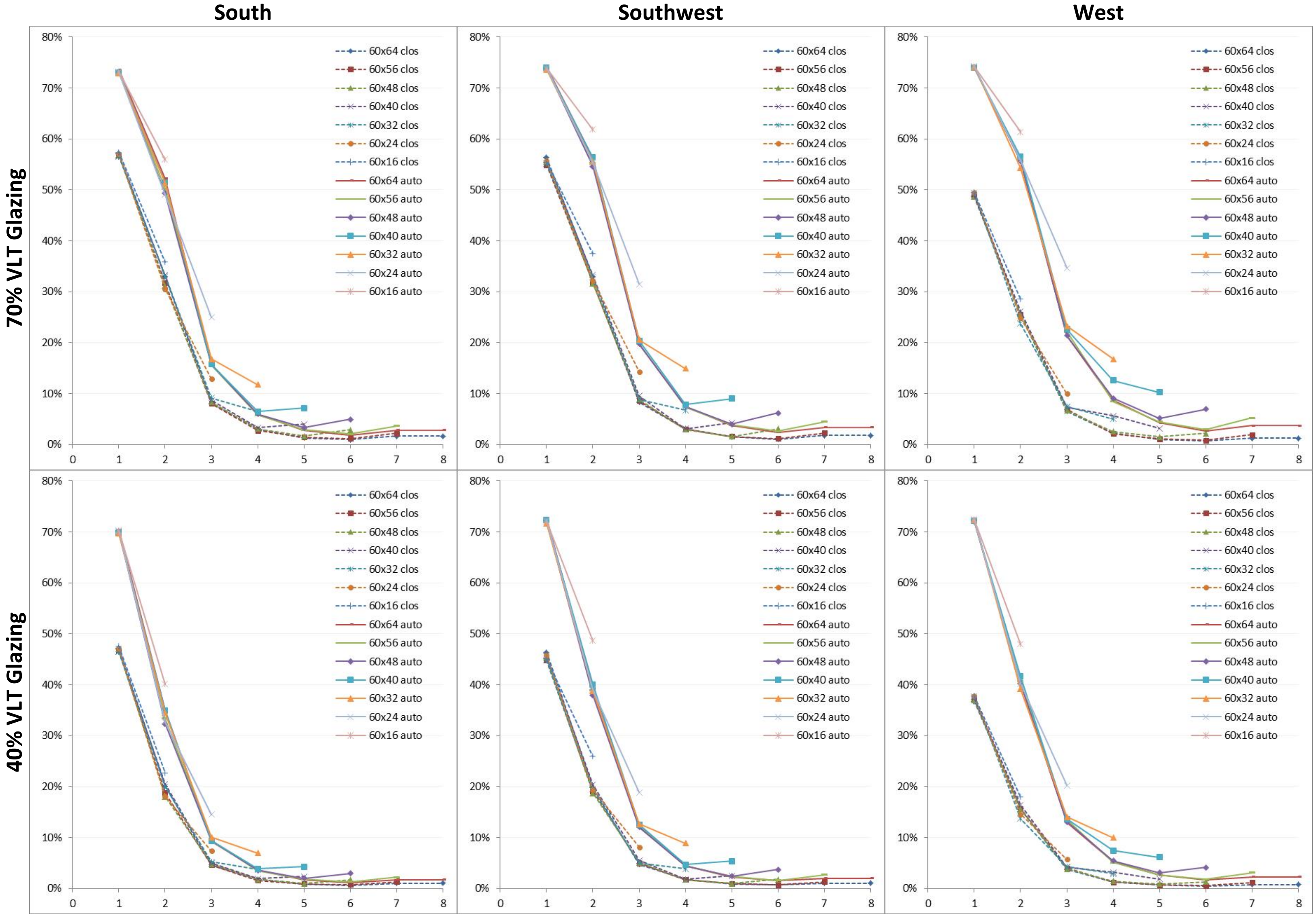


Figure 55. LightLouver™ lighting energy savings for spaces with a 9' ceiling.

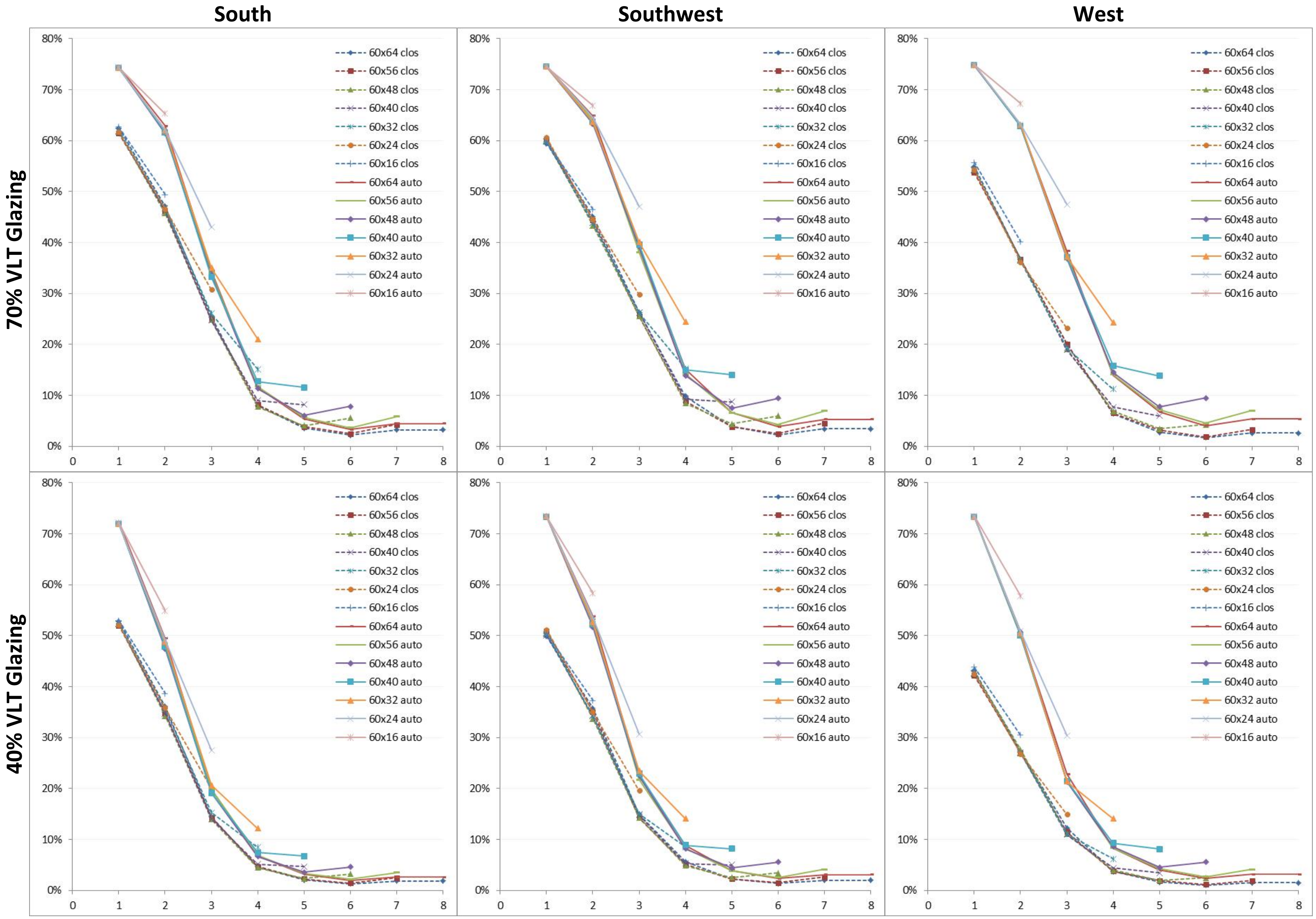
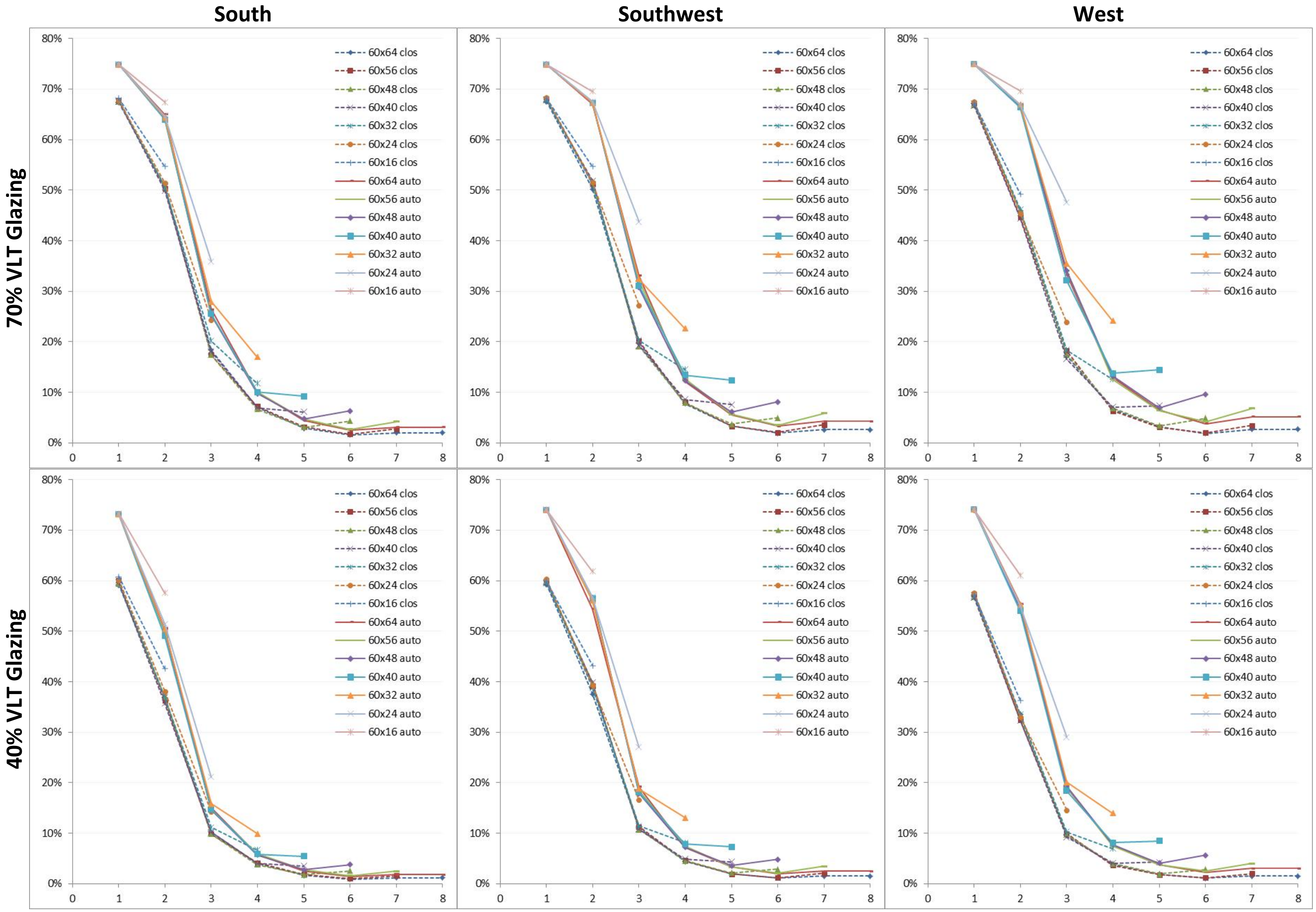


Figure 56. LightLouver™ lighting energy savings for spaces with a 10' ceiling.



South

Southwest

West

70% VLT Glazing

40% VLT Glazing

Figure 57. 3M Window Film lighting energy savings for spaces with a 9’ ceiling.

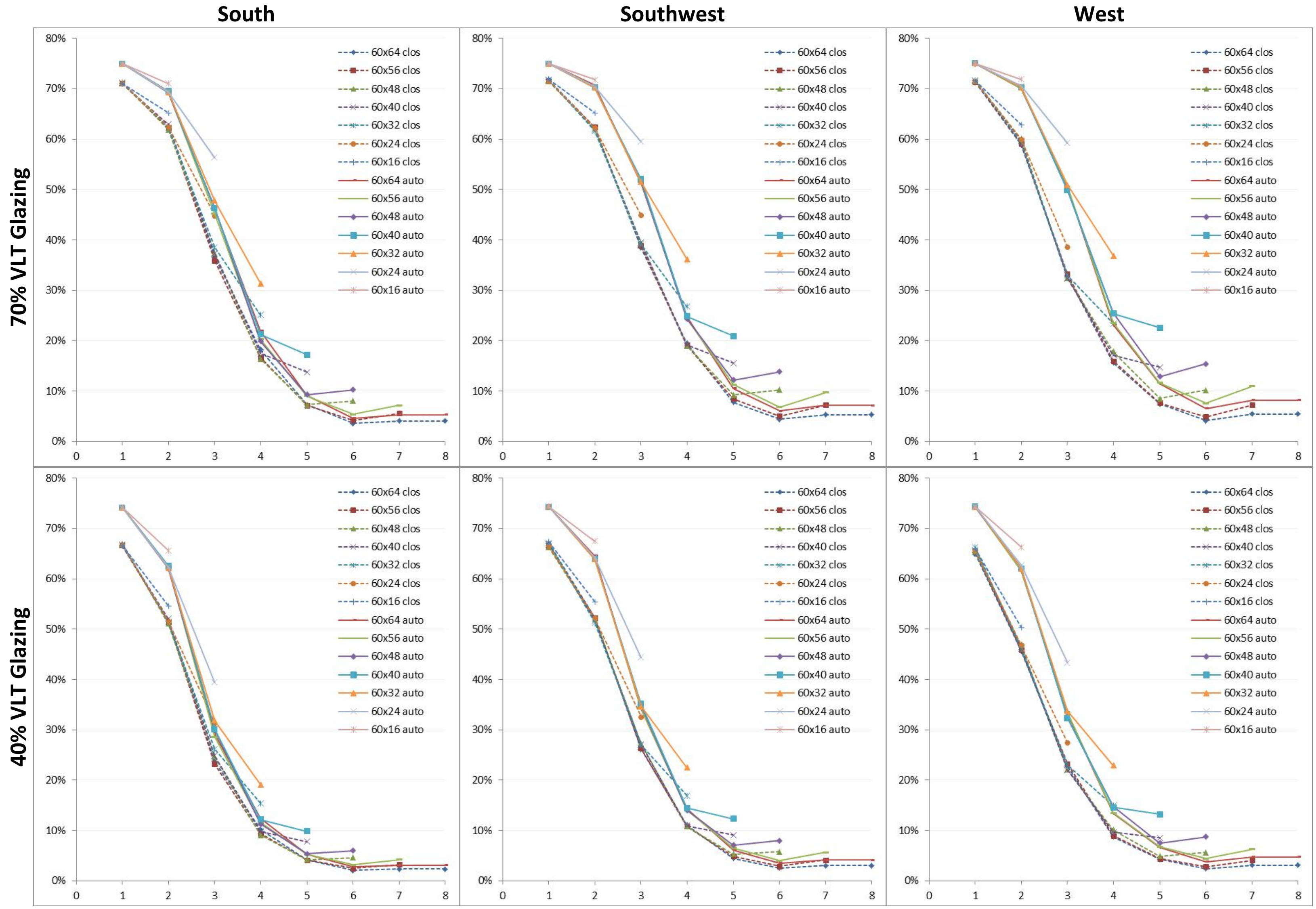


Figure 58. 3M Window Film lighting energy savings for spaces with a 10’ ceiling.

C.2. SIMULATION PARAMETRICS

Section 0 described parametrics modeled in this report. Other important variables that affect daylighting, but were outside the scope of this project, include:

- External shading of the windowed façade – daylight redirecting products performs best when exposed to direct sunlight many hours a day. Any external shading will reduce savings and project specific modeling should be considered when external shading is present.
- Variations in the design of the windowed façade – changes in the windowed façade will change daylight availability. However, modeling a range of façade types was outside the scope of this project. The team selected a façade that would not unfairly bias the results towards any technology or the base case.
- Overhangs – overhangs could be positioned below the clerestory to allow the view window coverings to remain open more often.
- Furniture height variations – variations in furniture height affect daylighting.
- Climate – only building climate zone 12 (Sacramento) was modeled.

C.3. OFFICE SIZE, REFLECTIVITY, AND FURNITURE

All open office models had a 60’ windowed façade. Seven space depths were modeled: 16’, 24’, 32’, 40’, 48’, 56’, and 64’. All offices had a 70% reflective ceiling, 50% reflective walls, 20% reflective flooring and 50% reflective cubicle furniture.

For the mini-blinds, red blinds were used as there is a wide variance in the color of blinds installed in real-world office spaces. Compared to the red blinds used, white blinds would have yielded more savings and black blinds would have yielded fewer savings. In the absence of data describing the distribution of blinds in the real-world, red blinds were used to provide a middle-of-the-road estimate of potential savings. These same blinds were used for simulations for the ASHREA envelope committee who vetted and accepted this blind model as a conservative estimate of view-window daylighting potential.

All configurations included “cubicle” furniture with 60” high partitions (Figure 59). Each cubicle is 8’ by 8’. Rows of cubicles were added or subtracted as necessary depending on the depth of the space. Thus the 16’ deep model had 2 rows of cubicles and the 64’ deep model had 8 rows of furniture. A row of fluorescent 2’x4’ troffer fixtures served each row of cubicles. Hence, the 16’ model had 2 rows of fixtures and the 64’ model had 8 rows of fixtures. Electric lighting assumptions are described in detail in the next section.

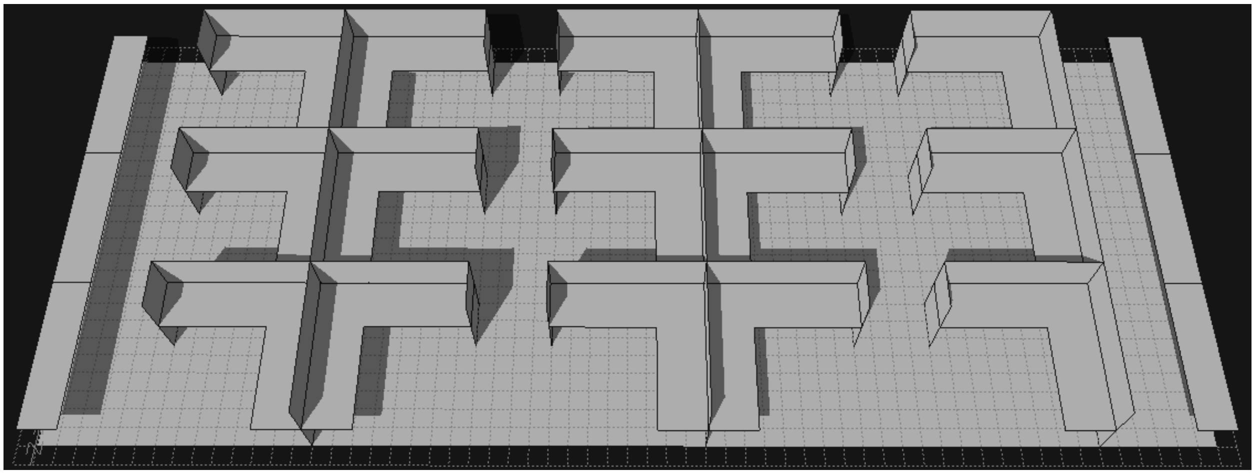


Figure 59: Furniture in a 60' wide by 24' deep space. The windowed façade is located at the bottom of the image.

C.4. ELECTRIC LIGHTING ASSUMPTIONS

Electric lighting was provided by 2’x4’ troffers, 10’ o.c., oriented with the longer side of the fixture parallel to the windowed façade. Each row of fixtures serves an 8’ deep daylit zones parallel to the windowed façade – a configuration ideal for daylighting. The illuminance target level was chosen as 300 lux (30 fc), the current IES recommended minimum illuminance for office spaces. Photocontrol sensor points were located one foot from the rear of the daylit zone along the midline of the room. The illuminance values recorded by each photocontrol sensor (8,760 hours of daylight illuminance in lux) was then used to estimate lighting system operation in each respective zone.

C.4.1. Photosensor location

A photosensor location was identified for each daylit zone in each template space. The sensor location represents a point on the workplane used to calibrate a photosensor. The photocontrols then dim or switch electric lights serving that zone to continuously maintain a threshold illuminance level. For this study, the threshold illuminance level was chosen as 300 lux (30 fc), which is the IES recommended minimum illuminance for office spaces.

The sensor point is typically a point in a daylit zone that represents close to the lowest daylight levels for that zone, so that when electric lights are controlled to maintain a threshold illuminance level for that point, the rest of the zone has a combined daylight and electric lighting illuminance of more than the threshold value. Annual simulation programs such as DOE2 (eQuest), and Energy Plus have a default location for this sensor, which is 2/3rd the distance from the façade into the daylit zone from the mid-point of the facade.

For this study photocontrol sensor points were identified for the template-spaces: all were located one foot from the rear of the daylit zone, and along the midline of the room. Thus for the 24’ deep space with three zones, the sensors were located at 7’, 15’ and 23’ from the window.

The illuminance values recorded by each photocontrol sensor (8,760 hours of daylight illuminance in lux) was then used to determine the operation of a dimming or switching system, that dims or switches electric lighting in each respective zone.

Lighting Schedules and LPD

The California T24 schedule from the Nonresidential Alternative Calculation Manual (ACM) Approval Method was used as the baseline to calculate savings. Savings calculated using the T24 ACM schedule could be used for program design.

Based on CEUS, the average lighting power density for existing office buildings in California is 1.2 watts / square foot. Thus, this value was used for both base case and improved case energy calculations. This is the same LPD assumption used in the PIER Office Daylighting study, and thus the energy impacts of this study can be directly compared to the findings of that study, and some extrapolations made to other climate zones.

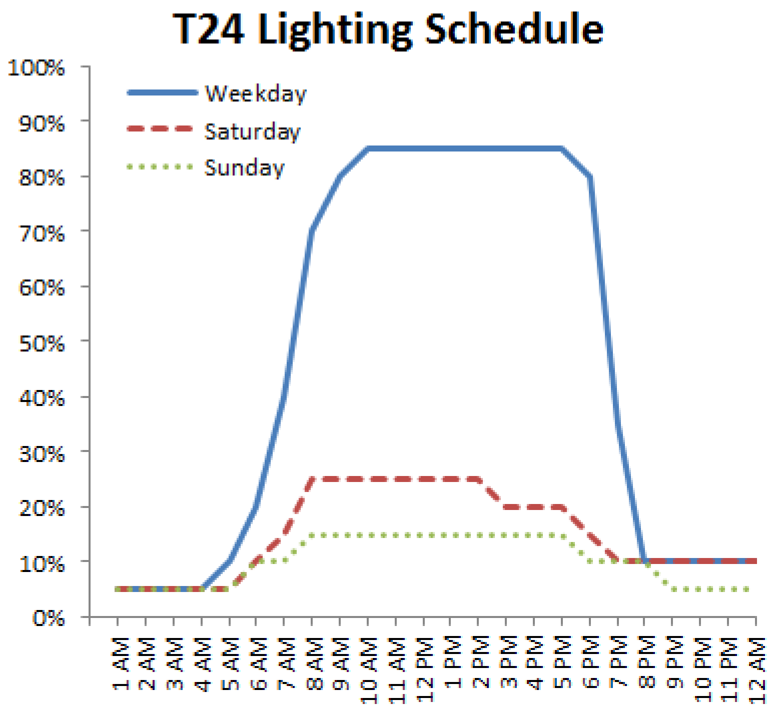


Figure 60: California T-24 schedule from the ACM.

Photocontrol Operation

Dimming photocontrols were modeled for this assessment. This complies with the new (2013) T-24 regulations pertaining to adding photocontrols in a large office space. Namely, there must be at least 4 lighting steps plus off.

To meet these requirements, lighting designers and electrical contractors are likely to specify dimming controls and ballasts to meet these requirements.

C.4.2. Sensor Layouts for Simulation

Sensors were laid out in an even grid across the entire space. Sensors were located 31 inches above the floor – one inch above the desktops in the models. Sensors were spaced two feet apart starting one foot from each wall. The largest office contained 990 sensors and the smallest office contained 270 sensors. Walls and partitions were positioned to avoid covering a sensor.

The same sensor grids were used for work-plane illuminance and sun penetration results. This methodology is consistent with the Daylight Metrics work by HMG. Other Radiance parameters used in the analysis are identical to those listed in the Appendices of the Daylight Metrics report[23].

C.4.3. Whole Building Energy Estimates

When electric lights are turned off or dimmed, the associated heat from those lights is also reduced. This is seen as a reduced cooling load in the summer time, and an increased heating load for the HAVC system. Given California climate conditions, the magnitude of cooling energy savings is typically higher than the magnitude of heating energy increase.

To estimate the effect of reduced electric lighting usage on HVAC energy use, the project team utilized the 2008 Database for Energy Efficient Resources (DEER) interactive HVAC factors. These factors provide a means to scale the energy savings calculated from lighting-only to lighting and HVAC savings. The savings are calculated based on the Large Office DEER prototype buildings. Further details on the HVAC assumptions and the prototype buildings can be found in 2008 DEER report.

For climate zone 12, which encompasses Sacramento, DEER estimates each kWh of lighting energy saved results in 1.1098 kWh in whole energy building savings (0.1098 kWh of cooling energy savings). In addition, the building requires an additional 0.0070 therms for heating for each kWh of electricity savings results.

---

[23] H eschong, Lisa. Heschong Mahone Group. 2011. ***Daylight Metrics***. California Energy Commission. Publication number: CEC-500-2012-053.