Dynamic Solar Shading and Glare Control for Human Comfort and Energy Efficiency at UCSD: Integrated Design and Simulation Strategies

Christopher Meek
Department of Architecture
University of Washington
Seattle, WA 98179

John Breshears, AIA, PE, LEED AP
ZGF Architects llp.
1223 SW Washington Street
Portland, OR 97205

ABSTRACT

The University of California San Diego is in the design process for a new 177,000 square foot (16,444 square meter) Health Science Research Laboratory (HSRB2) on its main campus in La Jolla, CA. Based the on experience and mission of the institution, a goal for the project was set to create as nearly as possible a daylight-autonomous laboratory building and to create a façade system that would yield the maximum daylight benefit with minimal cooling penalty despite a context where site constraints dictate a multi-story structure with glazing facing largely due east and west. The extreme dynamic solar exposure suggests a dynamic solar and light control system. This paper describes criteria development, design, simulation, and analysis findings used to develop and specify the optimized system currently in construction.

1. INTRODUCTION

The University of California at San Diego, birthplace of the Keeling Curve, was the first campus on the West Coast to join the Chicago Climate Exchange and to be recognized by the California Climate Action Registry. UCSD created their own Principles of Sustainability, which they have deemed a foundational value of the institution, equivalent to the importance of diversity, free expression, and open inquiry. Added to this context are a new commitment to lifecycle decision processes, a campus cogeneration plant already at full capacity, a current statewide fiscal emergency eliminating most building maintenance, and a regional water shortage prompting emergency action in the state legislature.

With the implementation of a master plan and rigorous design review process more than two decades ago, the campus has developed a collection of academic and residential buildings by distinguished design firms. However, observation and measurement on campus has revealed that actual building performance frequently falls short of intended. The benign climate belies some challenging factors that have defeated well-intended passive design in the past: such as mismanagement of abundant natural light to cause glare, and neglect of a corrosive marine fog causing damage to naturally–ventilated spaces. In particular, many buildings designed with extensive glazing for the purpose of providing daylight and views were operating with blinds permanently deployed in the “closed” position to maintain visual comfort. Commonly, this creates a condition where the expense and energy performance penalties associated with glazing are incurred without realizing the qualitative or energy benefits of daylight or views to the exterior.

Fig. 1: “Blinds Closed” position commonly observed at many UCSD campus buildings

Representatives from UCSD Facility Design and Construction Department are determined to address this concern with the design of the HSRB2 project. A goal for the design of the new building was to create, as closely as possible, a daylight autonomous building while balancing the daylight benefits against solar heat gain penalties. The framework of façade performance goals include: (1) Meeting ambient illumination levels with daylight during daylight hours, (2) Maximizing the duration of unobstructed views to the exterior, (3) Limiting peak solar heat gains to 16 W/m2 to enable the ventilation system to operate at the minimum levels determined for safety of the occupants. Setting goals for daylight, thermal, and energy performance and comprehensively testing design decisions formed the core of the design process. Climate responsive façade design emerged as the key component of achieving these goals.

2. CLIMATE AND CONTEXT

La Jolla, CA provides exceedingly mild outdoor air temperatures with summer average highs rarely exceeding 25 C (78 F), and monthly average temperatures ranging from 14 C (57 F) to 22 C (72 F)[1]. It exhibits dominantly clear skies, with likelihood of cloud cover from fog around 80% in mornings in May, June, July and August, which serves to temper outdoor air temperatures in summer. However, insolation remains high with June daily horizontal incident solar radiation at roughly 7 kWh/m2/day, approximately equivalent to Tucson, AZ[2]. This combination of mild air temperature and high solar irradiance offers an opportunity for substantial glazing with minimal thermal penalty, if glazing is continuously shaded from exposure to direct sunlight.

3. SITE PLANNING AND BUILDING MASSING

A master plan for the School of Medicine at UCSD created in 2000 had identified several sites for future research buildings. Project stakeholders settled on parcel AM1 as a site for the new building: an elongated plot oriented in a true north-south direction and across a planned academic mall from the recently completed Pharmaceutical Sciences Building.

The primary mass of the building, a block nominally 100’ x 200’ (30.5 m x 70 m), is dedicated to research labs. A 30’ (9.1 m) wide bay of open labs on each side of the block flanks a 40’ (12.2 m) central support core. This plan is repeated over five floors. Lab benches extend from the exterior wall inward to a depth of 25’ (7.6 m), leaving the inner 5’ (1.5 m) of lab bay as a circulation zone. As the most continuously occupied portion of the building, the 25’ depth of lab bench became the target for the primary daylight zone. The challenge, in addition to distributing daylight from a sidelighting condition over a depth of 25’, is the extreme dynamics of solar exposure. With due east and west exposures of the lab walls, each face experiences the full arc of solar altitude over a half of the daylight hours and clear sky conditions for the remaining hours.

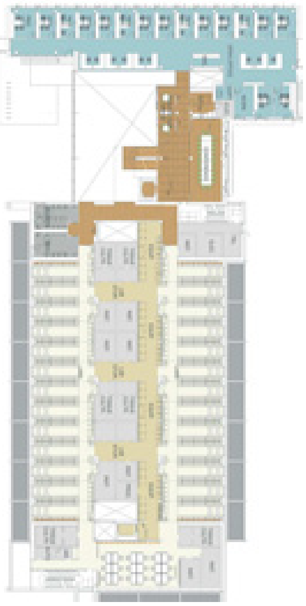


Fig. 2: Typical lab floor plan

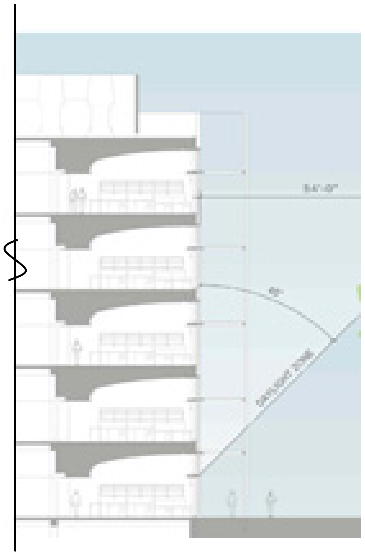


Fig. 2: Typical section through laboratory bay

4. BUILDING DESIGN STRATEGIES

In addition to the daylight redirection and comfort control strategies addressed in this paper, considerable thought and study was devoted to the perceptual nature of illumination in the space. To ensure optimum visual comfort and to enable occupant acceptance of aggressive lighting controls, it was determined to strive to create a single "daylight zone" that would encompass the entire lab bay. The intention with this is to maintain a consistent range of contrast within the entire architectural volume and visual field despite ongoing variability in daylight intensity. Careful coordination of HVAC and service systems above the laboratory ceilings allowed some opportunity to sculpt the ceiling form within the 17' (5.2 m) floor-to-floor heights. With the 25' depth from perimeter wall to end of lab bench defined as a 'perceptual daylight zone', a series of ceiling forms were studied for their effectiveness in creating the perception of symmetrical illuminance. An elliptically-curved white reflective ceiling plane provides a combination of height at the perimeter window head, vertical fascia at the inward edge, and a downward focusing quality for light that strikes its surface.

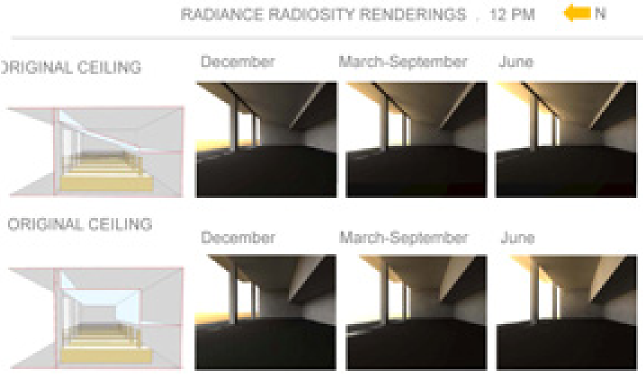


Fig. 4: Illuminance Studies – Perception of a "Daylit' Zone

The glazing pattern of the laboratory facades evolved as balance between performance and aesthetic architectural goals. The daylight and vision zones are separated by a deep external horizontal shade of metal grating located 9.5' (2.9 m) above the floor level. The shade is intended to provide maintenance access to the daylight zone windows, keep direct sun off the vision zone glazing for the maximum possible duration of each day, and increase the duration of unobstructed views to the surrounding campus (by reducing the times of automated shading system deployment at the vision glazing). A continuous 3' (0.9 m) high band of glazing runs the length of the laboratory bay above the external shade. Below the external shade, panes of vision glass run to the floor in the aisle ways between lab benches, while opaque, insulated metal spandrel panels form the walls at the ends of the lab furnishings.

5. INTEGRATED DESIGN PROCESS AND ANALYSIS

Ventilation rates in laboratory buildings typically range between 6 and 12 air changes per hour (ACH) with no recirculation of ventilation air. These requirements are driven by safety concerns in the event of contamination. The fan energy required to move this volume of air continuously can easily constitute the largest single energy end-use in the building, particularly in a mild climate such as San Diego that requires little conditioning of ventilation air. Airflow rates in laboratories can frequently be driven higher than the minimum ACH rates dictated for safety when thermal loads in the lab require additional cooling capacity.

Two paths to avoid this cooling-demand-driven energy waste are i) to handle the excess cooling requirement with a non-air based system, such as hydronic chilled beams or fan coils or ii) to design a building whose demand never exceeds the cooling capacity inherent in the 6 ACH airflow rate designated for this project. With a VAV system already selected for use in the project, option ii) became the operative strategy. The cooling capacity of the basic lab airflow as well as the approximate anticipated cooling loads are shown in Table 1 below. Based on these assumptions, the performance goal for the exterior lab facades became the maximization of useful, controlled daylight in the labs while maintaining peak heat gains of combined solar and electric lighting below 1.44 W/ft^2 (15.50 W/m^2) of floor area in the perimeter zone.

TABLE 1: COOLING CAPACITY AND LOADS

Total Cooling Capacity Provided by 6 ACH	8.34 W/sf
Assumed Lab Equipment Load	6.0 W/sf
Assumed Occupant Load	0.9 W/sf
Remaining Capacity to Handle Lighting And Solar Gain	1.44 W/sf

After investigating options for dynamic façade solar and daylight control systems, the design team determined that a field-validated and market-available automated venetian blind solution would be most appropriate. Blind products are available in internal and external variations. The internal blinds are also available with an inverted slat (concave up) and optically improved surface for enhanced daylight guidance. Three different configurations of blinds were determined, and a comparative analysis method was developed to evaluate their effectiveness against the goals.

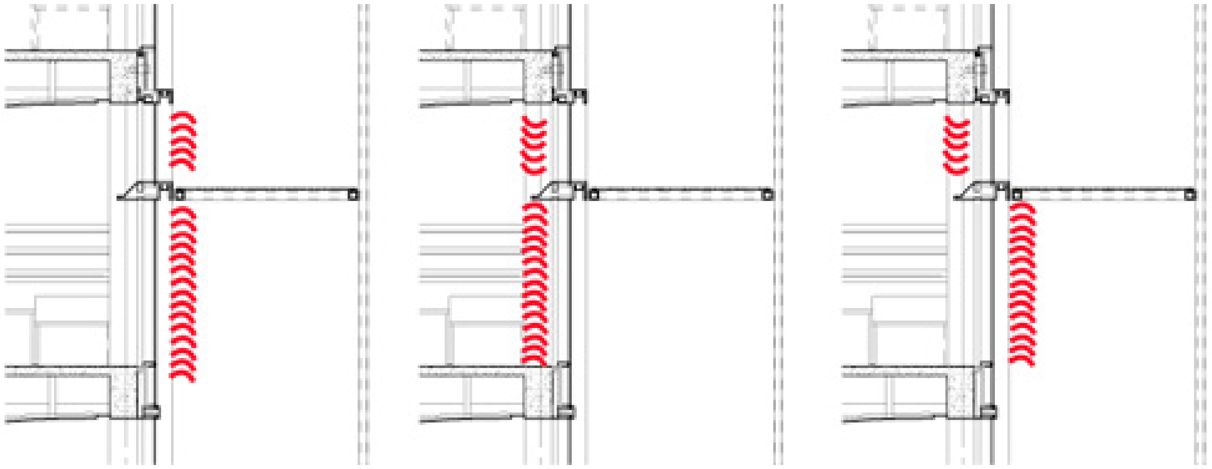


Fig. 5: Blind Configurations- Option A, B & C

5.1 Solar Heat Gain Analysis

Comparative performance of the options was evaluated on three key days- summer and winter solstices and one typical equinox at bi-hourly intervals. COMFEN[3], a Lawrence Berkeley Laboratory-developed tool, was used to evaluate hourly solar heat gain through a window system controlled on a defined schedule. As a front-end for the DOE-developed EnergyPlus[4] simulation tool, COMFEN is capable of accounting for the complex interactions of blinds, shading devices, and glazing properties together. EnergyPlus output codes were manipulated to report both hourly total heat gain through the window systems as well as hourly total solar incidence on the wall system. The second piece of data was key in implementing the window assembly performance information into a whole-building simulation. Because the whole building simulation tool employed for the task was not capable of considering variable glazing properties, the effective Solar Heat Gain Coefficient (SHGC) was determined for each analysis point as the ratio of total window transmitted heat vs. total window incident radiation. Despite standard NFRC definitions of SHGC as a single, constant value measured at the normal incidence angle, the SHGC is actually highly variable and incidence-angle specific. The effective assembly SHGC was found to be both fairly constant and fairly low.

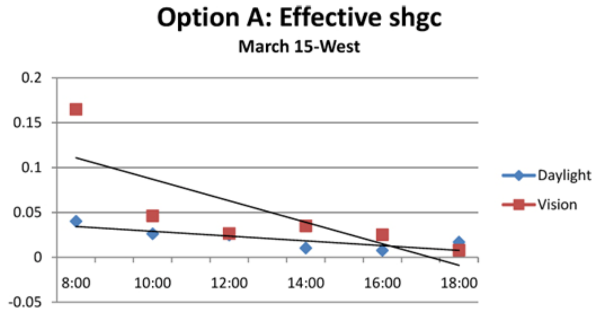


Fig. 6: Typical Determination of Window/Blind Assembly Effective SHGC

6. DAYLIGHTING

The University of Washington Integrated Design Lab (UW IDL) developed daylighting performance criteria and investigated the performance of architectural configurations for daylight illuminance, luminance, and visual comfort performance of multiple dynamic shading systems. The specifications for effective daylight performance at the lab and office areas of the UCSD Health Sciences Research Unit #2 were developed as follows: (1)Provide effective building geometry, aperture size, location, orientation, and interior surface relationships and reflectance characteristics to meet ambient illumination requirements from one hour after sunrise to one hour prior to sunset under typical design days; (2) Provide exterior shading devices sufficient to effectively control solar load on the building skin while increasing the quality of interior luminous distribution and without substantially compromising interior illumination levels; (3) Provide interior or exterior shading devices to effectively *and persistently* maintain visual comfort at critical visual task areas during all occupied hours without compromising interior illumination levels; (4) Provide for appropriate reduction in electric light output relative to the presence of daylight to reduce lighting power consumption and internal heat gains.

To meet these goals, design and simulation was undertaken using a variety of digital software tools as described below. Specific daylighting and visual comfort criteria to asses performance was defined as: (1) No direct sunlight penetration at labs; (2) 300 lux of ambient daylight at the bench tops (discussed further below); (3) Interior luminance below 2000 cd/m2 in the primary visual field at visual task areas (to reduce the probability of glare[5]); (4) Comparative duration of unobstructed views to the exterior; (5) Subjective criteria relative to the distribution of brightness on the ceiling and primary vertical surfaces to ensure a balanced composition.

6.1 Direct Sunlight Management

Initial shadow studies using the building analysis program, Ecotect, indicated that both east and west laboratory bays were subject to daily low angle sunlight, and that adjacent buildings and landscape provided no relief from direct sunlight exposure. Considering an occupancy time of 24 hours, it became apparent that "fixed" solar shading devices substantial enough to control glare would occlude diffuse sky illumination through windows to a degree that meeting daylight illuminance goals would be unlikely.

To address the management of solar load and glare control, a range of commercially available dynamic solar shading and light redirection systems were investigated for the upper "daylight window." Despite initial promise, dynamic vertical fins were eliminated due to their inability to easily retract on overcast days and during time periods on clear days when direct sunlight was not present (e.g. west facing windows during morning hours) which is required to ensure maximum diffuse daylight penetration. Automated fabric roller shades were considered, though the need to provide complete opacity to direct sun resulted in the severe reduction of diffuse daylight during all hours of deployment. Given these constraints, the design team chose to focus on automated horizontal venetian blinds for their potential to enable complete retraction and allow for light redirection to the ceiling.

To understand the requirements for complete solar shading and comprehensive direct sunlight control, simple shadow studies were conducted and an hourly shading schedule was developed for each façade and blind type to identify the deployment times and slat angles required to block direct sunlight at each window.

6.2 Daylight Illuminance and Surface Luminance

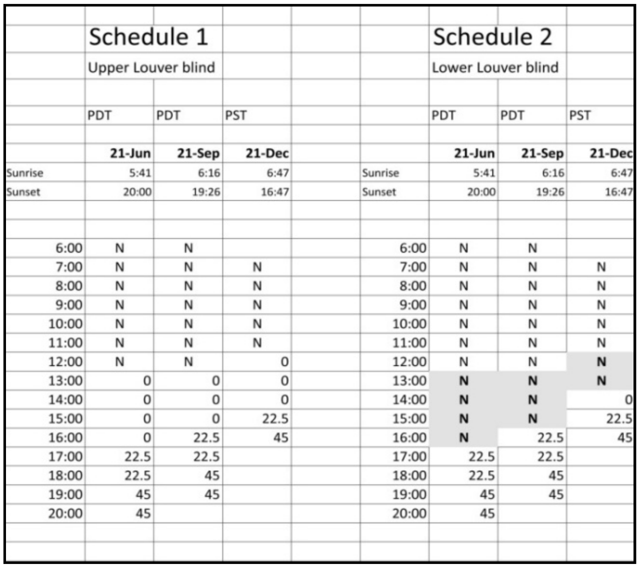
Laboratory lighting criteria is frequently set at 750 lux[6] horizontal at the laboratory bench top. However, the daylighting criteria was established at 300 lux. This aligns with a lighting strategy that provides lower illumination levels for general space lighting where lights would be automatically dimmed by photocell control based on available daylight. Localized, occupant-controlled task lighting will supplement the general illumination to ensure the minimum illuminance criteria are met continuously at the bench tops. To assess the daylight performance of the façade design against the ambient lighting criteria, a digital daylighting model of the lab bay was created. Glazing above 8' (2.4 m) was simulated with a visible light transmission of 63%. All glazing in the vision zone was assigned a visible light transmission of 52%. Subsequently, a "blinds model" was created using data provided by a major manufacturer[7] . Interior blinds were simulated with a slat reflectance value of 70%. Exterior blinds were simulated with a slat reflectance of 50% a limitation imposed by more durable exterior grade finish. Each slat angle configuration was simulated under its respective sun position for each hour of the day under clear skies on June 21, September/Mar 21, and December 21 and under overcast skies at noon on September 21 for each of three primary design options (fig. 5):

Option A: Exterior Venetian Blinds on Upper (Daylight) and Lower (Vision) Glazing

Option B: Interior Venetian Blinds on Upper (Daylight) and Lower (Vision) Glazing

Option C: Interior Venetian on Upper Window Exterior Venetian Blinds on Lower (Vision) Glazing

Using results from the Radiance[8] software tool, hourly illuminance data was taken at representative points every 4' (1.2 m) across the bench tops. Point illuminance values were compiled into a spreadsheet to establish expected horizontal illuminance contributions from daylight at two theoretical electric lighting zones. This data was assembled to determine the approximate percentage of ambient lighting levels met by daylight at any given time. This data was then converted to percentages of lighting power consumption based on commonly available 0-10v dimming ballast[9] for use in assessing reductions in lighting and cooling demands.



	Schedule 1		
	Upper Louver blind		
	PDT	PDT	PST
	21-Jun	21-Sep	21-Dec
Sunrise	5:41	6:16	6:47
Sunset	20:00	19:26	16:47
6:00	N	N	
7:00	N	N	N
8:00	N	N	N
9:00	N	N	N
10:00	N	N	N
11:00	N	N	N
12:00	N	N	0
13:00	0	0	0
14:00	0	0	0
15:00	0	0	22.5
16:00	0	22.5	45
17:00	22.5	22.5	
18:00	22.5	45	
19:00	45	45	
20:00	45		

	Schedule 2		
	Lower Louver blind		
	PDT	PDT	PST
	21-Jun	21-Sep	21-Dec
Sunrise	5:41	6:16	6:47
Sunset	20:00	19:26	16:47
6:00	N	N	
7:00	N	N	N
8:00	N	N	N
9:00	N	N	N
10:00	N	N	N
11:00	N	N	N
12:00	N	N	**N**
13:00	**N**	**N**	**N**
14:00	**N**	**N**	0
15:00	**N**	**N**	22.5
16:00	**N**	22.5	45
17:00	22.5	22.5	
18:00	22.5	45	
19:00	45	45	
20:00	45		

Fig. 7: Blinds deployment and slat angle schedule for multiple windows on west façade. Shaded areas indicate times when views are preserved due to the presence of an 8’-0” fixed horizontal exterior sun shade.

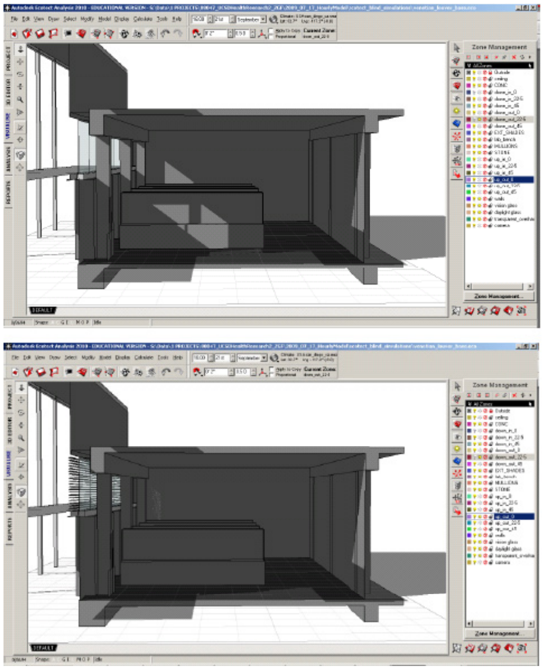


Fig. 8: Lab bay blind and shadow model

Findings included: (1) Option “A” meets or exceeds the daylight illuminance criteria at the lab bench approximately 76% of the year. (2) Option “B” meets or exceeds the daylight illuminance criteria at the lab bench approximately 80% of the year. (3) Option “C” meets or exceeds the daylight illuminance criteria at the lab bench approximately 80% of the year. (4) Options “B” and “C” have nearly identical performance. (5) Option “A” is 4% less effective than “B” and “C” in June and September, and 9% less effective in December.

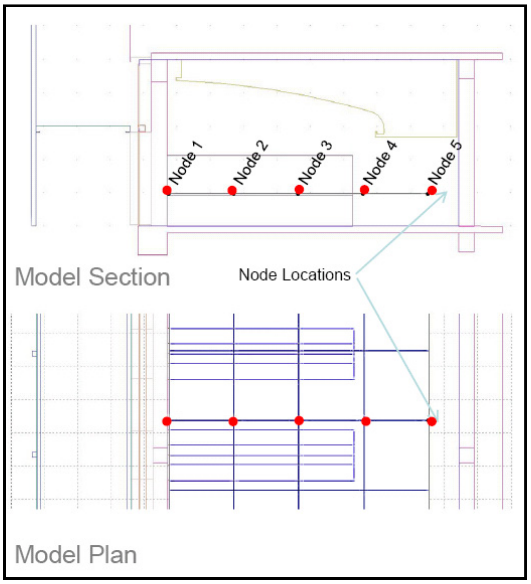
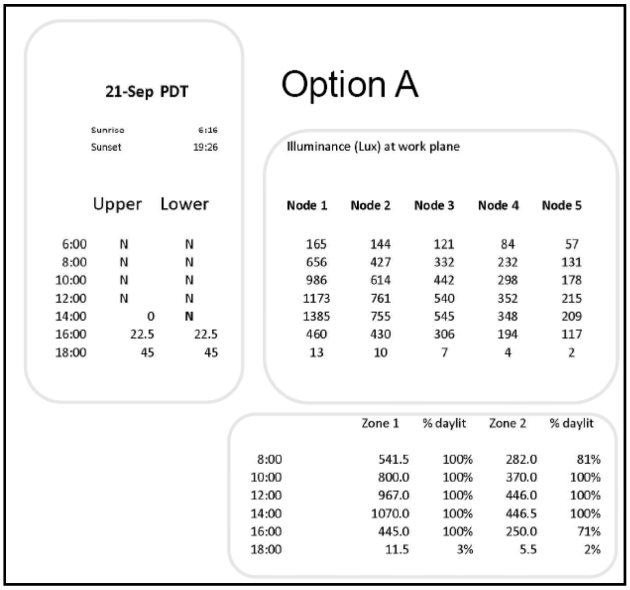


Fig. 9: Illuminance data collection points



21-Sep PDT

Sunrise	6:16
Sunset	19:26

Option A

Illuminance (Lux) at work plane

	Upper	Lower	Node 1	Node 2	Node 3	Node 4	Node 5
6:00	N	N	165	144	121	84	57
8:00	N	N	656	427	332	232	131
10:00	N	N	986	614	442	298	178
12:00	N	N	1173	761	540	352	215
14:00	0	**N**	1385	755	545	348	209
16:00	22.5	22.5	460	430	306	194	117
18:00	45	45	13	10	7	4	2

	Zone 1	% daylit	Zone 2	% daylit
8:00	541.5	100%	282.0	81%
10:00	800.0	100%	370.0	100%
12:00	967.0	100%	446.0	100%
14:00	1070.0	100%	446.5	100%
16:00	445.0	100%	250.0	71%
18:00	11.5	3%	5.5	2%

Fig. 10: Example of expected daylight illuminance data at lab bench tops per venetian blinds deployment and slat angle schedule compiled from Radiance simulations.

Furthermore, it was found that a 45 degree slat angle provided a zero degree cutoff angle occluding all direct sunlight and that daylight performance was significantly reduced at the bench tops whenever a slat angle exceeded 22.5 degrees. Not surprisingly, it was also discovered that the exterior overhang significantly extends times when vision windows have unobstructed view exterior. Based on this finding it was deemed crucial to provide separate control schedules for the upper and lower louver blinds are necessary to benefit from the fixed architectural shading.

Concurrent with simulation of daylight illuminance, the UW IDL investigated the luminous distribution on the interior surfaces of the lab bays. This included an hourly assessment of ceiling luminance under three ceiling profiles: a flat horizontal ceiling, a sloping ceiling, and a curved interior ceiling. Physical measurements of proposed ceiling materials were conducted to ensure accurate interior reflectance assumptions. Subjective assessment and measured point luminance data indicated that the curved ceiling option provided the most desirable combination of uniformity on the ceiling plane and surface brightness on the near vertical surfaces opposite the window wall. Luminance simulation indicated that during periods of direct sunlight exposure interior surfaces and blind slats in were consistently below the glare threshold of 2000 cd/m2. However tests indicated that during overcast skies when blinds would e retracted sky luminance peaked at approximately 2400 cd/m2 at noon.

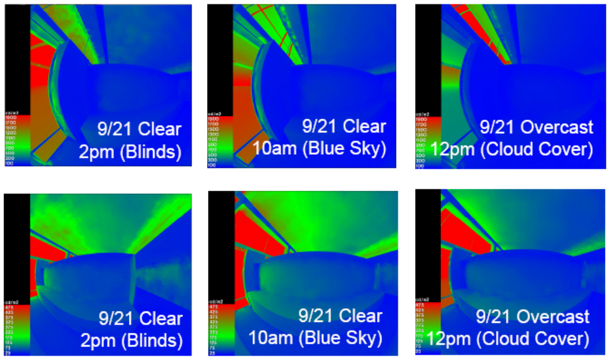


Fig. 10: Example of interior ambient daylight luminance on the ceiling plane and through glazing to the sky dome.

Despite these findings it was determined to allow the automated blind system to retract during overcast days to maximize diffuse daylight penetration and to adjust the blind deployment schedule in the during occupancy based on user feedback. It is hypothesized that increased interior surface luminance during periods of peak sky luminance will allow for an expanded comfort range of acceptable visual brightness levels. Regardless, manual overrides for space darkening and individual glare control will be provided to ensure continuous user satisfaction, visual comfort, and unparalleled flexibility. A measurement and verification program will assess energy, thermal, and lighting performance. Post occupancy evaluation will be undertaken to understand system performance and to adjust dynamic systems to meet unforeseen user requirements.

7. CONCLUSION

The three schemes were compared in terms of total daily as well as peak electrical demands on each of the three reference days. In order to make the comparison, electrical demand of lighting required to supplement the daylight to achieve target ambient levels was added to the electrical demand required to meet the heat gain incurred by the window system and the electric lighting system. Taken as a total aggregate electrical demand, the results of the blinds systems showed substantial variations in overall impact on building electrical demand and concurrent CO2 emissions. External blinds dramatically decreased the solar cooling loads. However, the option including optically tuned interior blinds in the daylight zone provided the lowest electrical demand during most of the evaluated hours, indicating that enhanced daylight performance offset the increased cooling load.
The result is a state-of-the-art health sciences research building that is designed to meets aggressive performance goals. The dynamic exterior shading provides the highest indoor environmental quality including continuous daylight and views to its occupants, with the lowest possible energy consumption, rarely requiring greater than the minimum building ventilation rates.

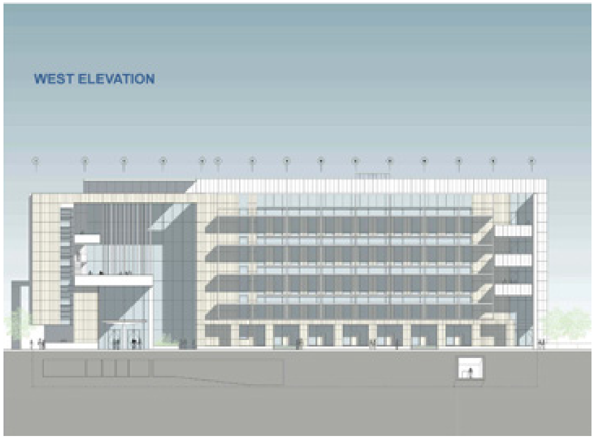
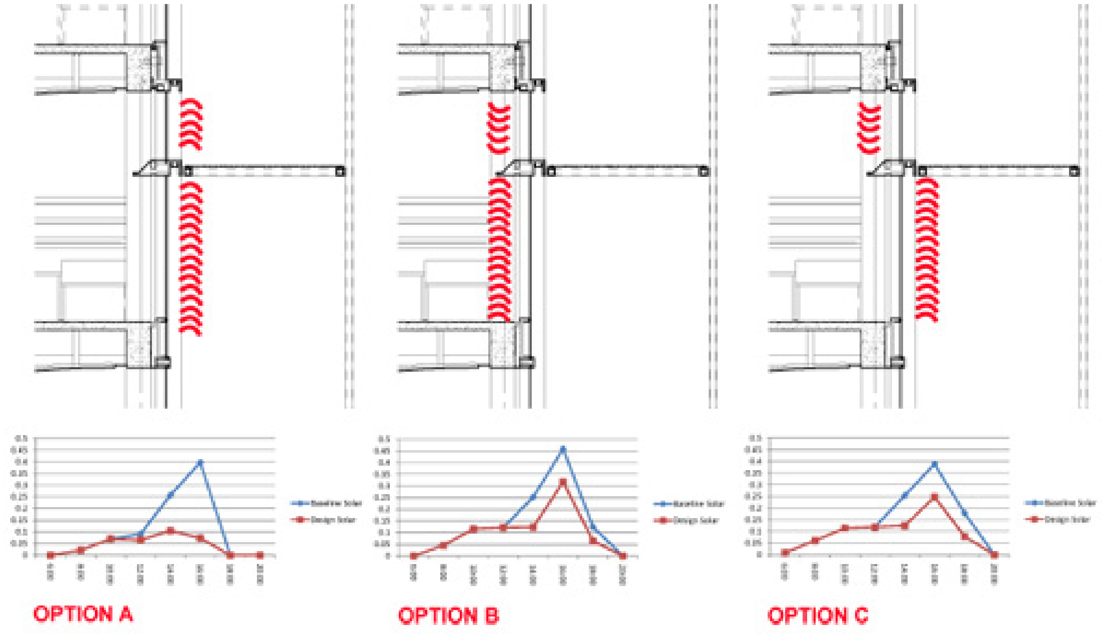


Fig. 11: West Elevation Showing Laboratory Exterior and Atrium/Entry



OPTION A

OPTION B

OPTION C

Fig. 12: Comparative Total Electrical Demand Results for June 21st

8. ACKNOWLEDGEMENTS

Thanks to Craig F. Johnson, P.E., Principal Mechanical Engineer for UCSD Facility Design and Construction for his dedication and support of the design inquiry described herein. Thanks, also to Professor Joel Loveland, Director of the University of Washington Integrated Design Lab for providing support to this project and paper.

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