Ernest Orlando Lawrence Berkeley National Laboratory

# High Performance Building Mockup in FLEXLAB

Andrew McNeil, Christian Kohler, Eleanor S. Lee, Stephen Selkowitz

Energy Technologies Area
December 2014

## Disclaimer



## Acknowledgments

The work described in this report was funded by Genentech and by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs, Office of Building Research and Standards of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

# High Performance Building Mockup in FLEXLAB

18 December, 2014


Andrew McNeil, Christian Kohler, Eleanor Lee, Stephen Selkowitz

Lawrence Berkeley National Laboratory
Windows and Envelope Materials Group
Building Technology and Urban Systems Department
Environmental Energy Technologies Division

# Table of Contents

Executive Summary ....3

1. Introduction....6
    1.1 Building 35....7
    1.2 FLEXLAB ....7
    1.3 Project Objectives ....8
    1.4 Project Participants ....8

2. Test Procedure....9
    2.1 Test Cell Fit Out ....10
    2.2 Test Schedule ....12
    2.3 Sensors and Measurements....13
    2.4 Evaluative Metrics & Diagrams....16

3. Light Fixtures (Vode) ....20
    3.1 Description ....21
    3.2 Performance ....21

4. Lighting Control System #1 - Encelium ....23
    4.1 System Description ....24
    4.2 System Configuration and Commissioning....25
    4.3 Testing ....25
    4.4 Conclusions....27

5. Lighting Control System #2 - Enlighted....30
    5.1 System Overview....31
    5.2 System Configuration and Commissioning....31
    5.3 Testing ....32
    5.4 Conclusions....35

6. Lighting Control System Comparison....36

7. Shading Control System - MechoSystems....37
    7.1 System Overview....38
    7.2 System Operation and Commissioning....38
    7.3 Testing ....40
    7.4 Conclusions....45
    8.1 HVAC Performance ....48
    8.2 Thermal Comfort ....52
    8.3 Visual Comfort ....60
    8.4 Furniture Position Relative to Facade ....62
    8.4 Lighting Energy Savings ....66
    8.5 Phase Change Floor Tiles....67

9. Lessons Learned ....69
    9.1 Specific Lessons for B35....69
    9.2 General Lessons for other Genentech Buildings....69

10. Acknowledgements ....71

# Executive Summary

Genentech has ambitious energy and indoor environmental quality performance goals for Building 35 (B35) being constructed by Webcor at the South San Francisco campus. Genentech and Webcor contracted with the Lawrence Berkeley National Laboratory (LBNL) to test building systems including lighting, lighting controls, shade fabric, and automated shading controls in LBNL's new FLEXLAB facility. The goal of the testing is to ensure that the systems installed in the new office building will function in a way that reduces energy consumption and provides a comfortable work environment for employees.

LBNL tested three facades of the new office building in the rotating FLEXLAB testbed: west, south and east. External shading, lighting, and internal shading control was configured for each orientation to replicate the conditions of B35. The three facades were each tested for one week three times between July and October 2014. Changes were made between each test to improve the performance of the systems.

Linear pendant LED light fixtures will illuminate the open office areas of the office building. These fixtures were installed in FLEXLAB. The wide spacing between rows of light fixtures results in a low lighting power density of 0.57 W/ft$^2$ in the open office areas, while still meeting the average illuminance criteria of 300 lux (28 footcandles). A combination of the wide spacing and optics of the light fixture creates a non-uniform lighting pattern on the ceiling of the space. Changing to a diffuse lens on the uplight will help reduce abrupt changes in luminance on the ceiling but non-uniformity will persist due to the wide spacing.

The pendant light fixtures allow separate control of the downward and upward light. The lighting control design aims to enhance the quality of space by dimming upward light unison providing uniform patterns of electric light on the ceiling. The downward light of each fixture dims to provide just enough light to meet illuminance criteria below the fixture.

Webcor installed two lighting control systems manufactured by Enlighted and Encelium for testing in FLEXLAB. The Encelium system uses an open loop control architecture with a ceiling-mounted photosensor at each facade (inside of the automated shade). While there is greater variation in workplane illuminance provided by the Encelium system, the system is better able to control upward versus downward lighting and is able to control the lighting according to the lighting design intent. The architecture of the Encelium system offers more functional flexibility by allowing any input (sensors, switches etc.) or multiple inputs to affect any fixture.

The Enlighted control system uses closed loop architecture with two photosensors per fixture (one for upward light and one for downward light). The Enlighted system controlled the lights more precisely than the Encelium system to meet workplane illuminance requirements, however the upward versus downward light control did not behave according to the lighting design intent.

MechoSystems provided motorized window shades and automated control. The shades in each window had a different color fabric, one dark grey and one medium grey. Both shade fabrics were an open weave with 3% openness. Genentech selected the dark colored shade because it provides a better view of the exterior compared to the lighter colored shade. Anecdotal evidence suggests that some occupants may experience direct glare with 3% open fabric while other occupants will not experience glare under the same conditions. Visual discomfort during the worst case sunny winter condition was not evaluated. However, the east-facing orientation during the equinox period was exposed to low sun angles in the third test period so findings of just acceptable visual discomfort are expected to be similar to what might be experienced during the winter.

The shades operated as expected on sunny days (which was the predominant condition during the test period). The testing identified substantial potential energy savings for the lighting systems by stopping the shade above the sill, preventing the shade from completely covering the window and allowing the sun to shine deeper into the space through the bottom few inches of the window. On partly cloudy days, which occurred more frequently after our testing concluded, anecdotal evidence suggests that the shades could be raised more often. LBNL suggests that a second threshold be implemented which drops the shade partway to prevent direct glare from bright sun, but doesn't close the shade down to the height required to limit sunshine depth.

Thermal comfort analysis suggests that occupants seated near the shaded window will be comfortable around 80% of the time. The 20% of time where the observed conditions fall outside the ASHRAE Standard 55 are almost always due to occupants being cold in the morning. This discomfort is mostly driven by cold surrounding surfaces causing a low mean radiant temperature and overcooling from outside air during economizer mode. Only one thermal comfort station, located near the facade, was used for the experiment. Thermal comfort further from the facade is unknown but is likely to be better due to the increased distance from the relatively cold facade.

Visual comfort studies indicated that occupants could sit as close as 3.5 feet to the east and west facade and 2.5 feet to the south facade when facing parallel to the window. Occupants must sit further away from the window to be comfortable when facing the window directly. Occupants should be 3.5 feet away when facing the south facade, 4.5 feet away when facing the west facade and 5.5 feet away when facing the east facade. Thermal comfort studies show that sitting within 30 inches of the facade has a negligible effect on comfort ratings.

Daylighting controls reduced lighting energy use in FLEXLAB by 46% for east facade, 34% for south facade and 35% for west facade over 30 feet deep perimeter zone between 7 AM and 7 PM local time at autumn equinox. Occupancy controls will further reduce lighting energy use, though they were not implemented for the test due to the cell being tested unoccupied.

Genentech, Webcor, and the architectural and engineering team had access to the FLEXLAB during and for a month following the test period to observe, work, and discuss operational issues with employees and staff. The project team made their own qualitative observations about the space in terms of view, adequacy of lighting and daylight levels, color, furniture placement, etc. The project team worked collaboratively with the LBNL team to fine tune details of component design, control settings, troubleshooting, and operations. Because Genentech is introducing a new model for their work environment, a non-assigned workplace, there were detailed discussions on how to educate the occupants about the new technologies and their operational modes. Commissioning and tuning procedures were also discussed.

# 1. Introduction

1.1 Building 35 ..........7

1.2 FLEXLAB ..........7

1.3 Project Objectives ..........8

1.4 Project Participants ..........8

**Figure 1.1** - Rendering of B35 viewed from the south west.

## 1.1 Building 35

Genentech engaged Webcor to construct a new seven-story (255,000 $ft^2$) office building at their South San Francisco campus about 10 miles south of San Francisco, California (figure 1.1). The design intent of the new building, designated Building 35 (B35), includes creating a real-estate asset with long-term value based on rigorous energy efficiency requirements, functional flexibility, and an environment that enhances employee-well being.

The design of B35 includes dimmable LED lighting and automated interior shades. The operation of lighting and shades has a substantial impact on energy consumption and occupant satisfaction. Webcor and Genentech collaborated with Lawerence Berkeley National Lab (LBNL) to guide the procurement specifications and preemptively discover and solve operating issues before completing construction and occupying the building.

## 1.2 FLEXLAB

The U.S. Department of Energy's FLEXLAB at Berkeley Lab provides researchers an unparalleled facility to study energy efficiency of building systems (figure 1.2). Eight test cells (including two high bay test cells and two rotating test cells) each have the ability to test HVAC, lighting, fenestration, facade, control systems and plug loads under real-world conditions. FLEXLAB users (building owners, developers and/or contractors) are able to test individual or integrated systems before construction.

By providing the ability to install customized systems into a test cell, FLEXLAB allows users to test the functionality and performance of a specific building configuration. The result is a better understanding of


**Figure 1.2** - Photo of DOE's FLEXLAB facility at LBNL. The B35 facade has been installed in the rotational test cell to the right in the photo.

real-world performance than can be achieved through simulation alone. FLEXLAB customization options include building systems such as lighting, HVAC and controls and architectural elements including external shading, fenestration, interior shading, ceiling, floors, furniture and finishes.

## 1.3 Project Objectives

The technical objectives of this study are to:

1. Evaluate the lighting and automated shading control system performance and the resultant indoor environment, determine if comfort criteria are being met, then adjust the shading and lighting systems' design and control system to the extent possible to improve overall perimeter zone performance;
2. Quantify lighting energy and HVAC system load energy performance over a summer test period for various shading and lighting test configurations;
3. Evaluate space planning issues that impact occupant density and allocation of space, including thermal comfort and glare issues related to proximity to facade and location of light fixtures.
4. Conduct evaluations noted above for three primary prototypical spaces in B35 by rotating the testbed, repositioning the exterior shading and repositioning the interior lighting.

## 1.4 Project Participants

Several entities were involved with the B35 - FLEXLAB project. The primary collaborators were Genentech (building owner), Webcor (building contractor) and LBNL (research partner). Webcor and their subcontractors fit out the test cell with systems and products according to the B35 design. LBNL performed space reconfigurations to convert between facade orientations, collected data, and analyzed results. Guidance regarding what testing was important and what decisions could be informed by testing was provided by Genentech and the project design team. System and product vendors responded to enquiries and provided assistance modifying system operation. The acknowledgements section contains a full list of companies and individuals that contributed to the success of this project.

# 2. Test Procedure

2.1 Test Cell Fit Out ....................................................................................................10

2.2 Test Schedule ..........................................................................................................12

2.3 Sensors and Measurements.....................................................................................13

2.4 Evaluative Metrics & Diagrams ................................................................................16

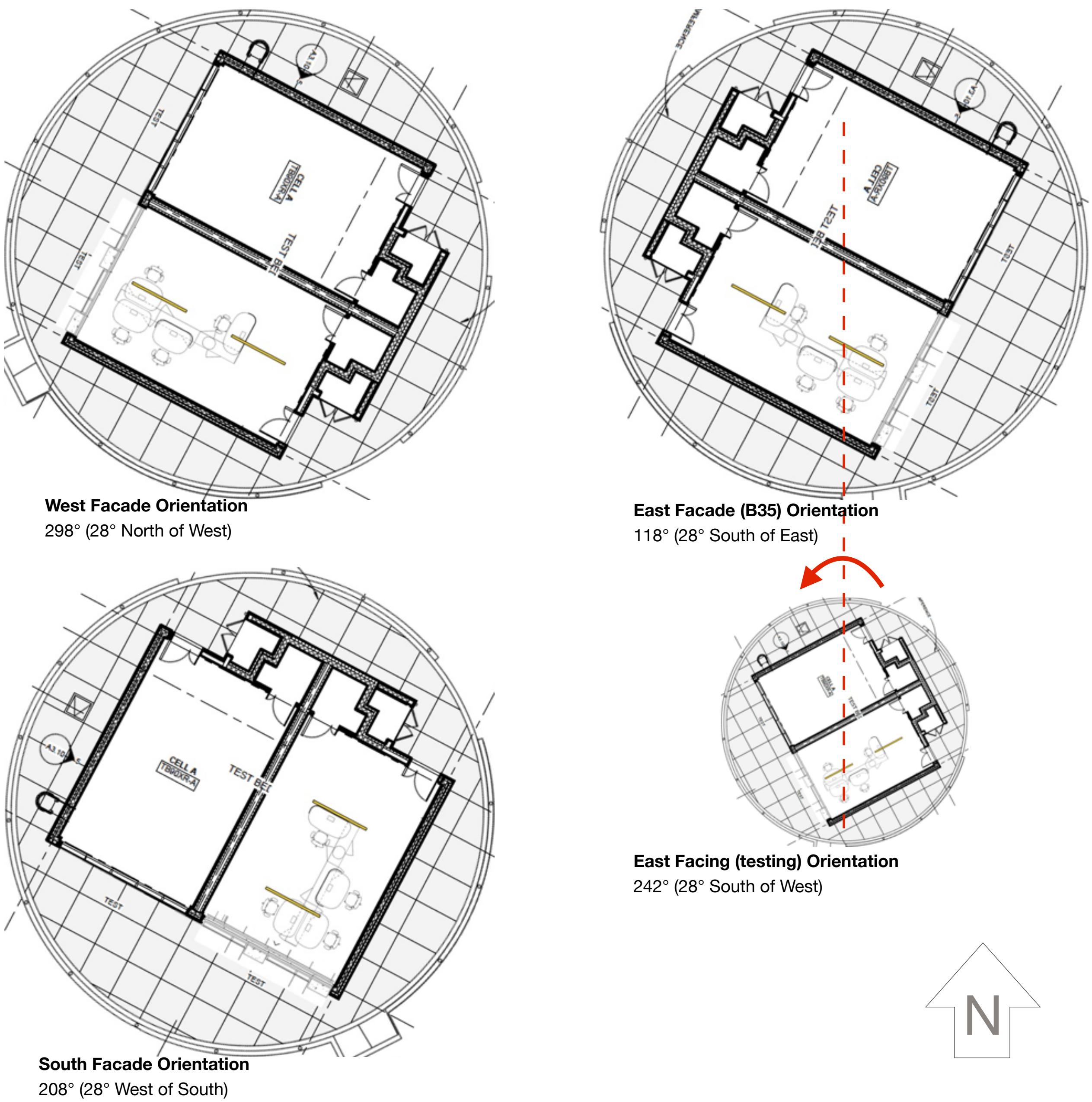



**Figure 2.1** - Test cell orientations. Note that the lighting is arranged in each facade condition so that the global orientation is consistent. The East facade was tested in a mirror orientation to avoid shading effects from the adjacent building to the East.

## 2.1 Test Cell Fit Out

One of FLEXLAB's two side-by-side rotational test cells was modified to match the design conditions of B35. The Modifications included a facade with external shading elements, automated internal roller shades, raised flooring system, carpet, suspended ceiling, light fixtures, lighting controls, overhead HVAC space conditioning, desk furniture system, chairs and computer monitors. Each light fixture has two sets of mounting positions to allow the fixture to be hung in the proper direction for each facade orientation (figure 2.2). Each test cell is 20 feet wide by 30 feet deep by 13 feet high. The test cell's floor and ceiling were fit out the full width of the test cell to a depth of 24 feet from the window wall. The side walls remained the basic FLEXLAB color while the opaque portion of the window wall was painted after installation of the facade insulation and drywall in August 2014.

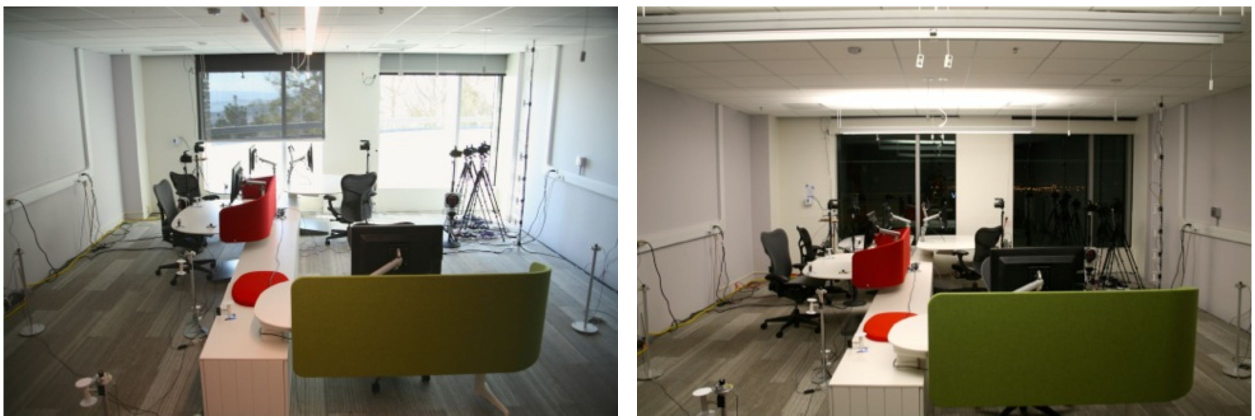


**Figure 2.2** - Interior conditions of the mockup. Fixtures are hung perpendicular to the facade (left) to match the east and west facade condition and parallel to the facade (right) to match the south facade condition.

In order to help with the selection of shade fabric, two different fabrics were used for each window (figure 2.3). The shade fabric in the left window (viewed from inside the space) was dark grey color (MechoSystems 1570, Shadow Grey, 3% open) and shade in the right window was a medium grey color (MechoSystems 1563. Grey, 3% open).

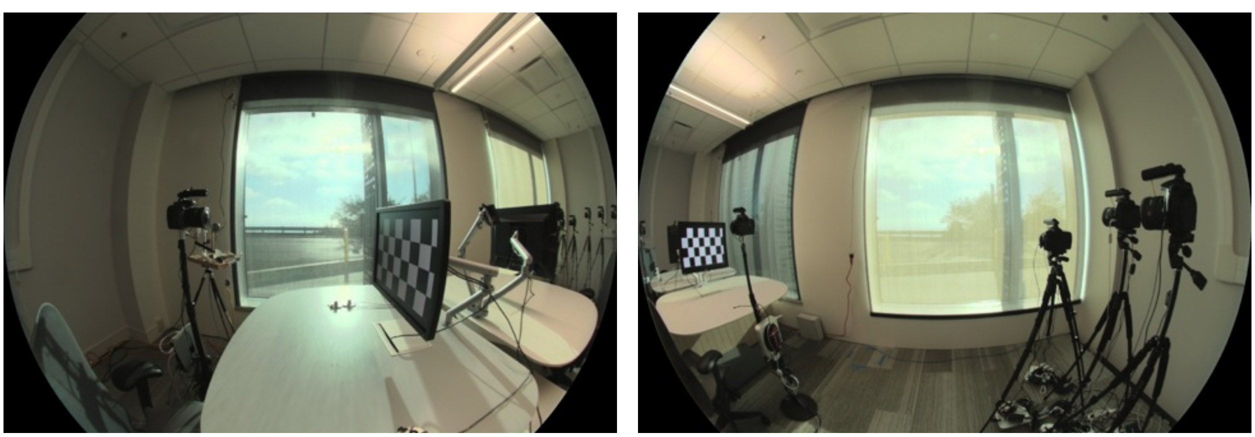


**Figure 2.3** - Views of the two types of shade fabric at a time when the sun is shining on the window. The left image is a dark grey colored shade. The right image shows a medium gray colored shade.

The glazing installed in Flexlab is typical of B35's east and west facing facades. The B35 south facade has both more glazed area and higher transmittance glazing than the facade installed in FLEXLAB (table 2.1). Our testing will exhibit significantly less daylight in the south orientation than will be present in the completed building. Additionally, the position of the windows in FLEXLAB is eight inches lower (relative to the floor and ceiling) than the windows in B35.

**Table 2.1** - Facade Properties

| FACADE DESIGNATION | FACADE ORIENTATION | GLAZING TYPE | VLT | SHGC | WINDOW TO WALL RATIO | EXTERNAL SHADING |
|---|---|---|---|---|---|---|
| East | 118° (242° test) | GL-1 | 42% | 0.23 | 0.31 | One vertical fin /10' |
| West | 298° | GL-1 | 42% | 0.23 | 0.31 | Two vertical fins / 10' |
| South | 208° | GL-2 | 64% | 0.27 | 0.47 | Two horizontal overhangs |
| FLEXLAB Fit Out | Rotating | GL-1 | 42% | 0.23 | 0.31 | Modified to suit orientation |

The reconfigurable external shading elements (figure 2.4) can be changed to match the conditions on the east facade (one vertical fin per 10 ft bay), west facade (two vertical fins per 10 ft bay) or south facade (two horizontal overhangs). We are able to test the performance of the building systems for the three facade orientations by rotating the building (figure 2.1), re-configuring the external shading, and changing the orientation parameter of the roller shade control.


**Figure 2.4** - Facade Elevations (top) and FLEXLAB configuration (bottom) for East facade (left) with one vertical fin per 10' facade bay, West facade (center) with two vertical fins per 10' facade bay and South facade (right) with two horizontal overhangs.

The HVAC system in FLEXLAB for the Webcor/Genentech experiment is a single zone forced air system, operating in a variable air volume (VAV) mode. A central plant provides chilled and hot water to the air handler in the test cell. The central plant and air handler are controlled by a Johnson Controls system, and have been programmed to operate in accordance with the sequence of operations and setpoints provided by Webcor and Southland Industries.

## 2.2 Test Schedule

LBNL conducted tests in three cycles consisting of a one-week test of each facade orientation. Observations made during each test cycle were used to inform changes in the subsequent test cycle.

### First Test Cycle

The first cycle occurred during July 2014. Lighting control systems were setup by the electrical contractor according to vendor instructions. The left automated window shade was installed in the mockup for the first test cycle (the second window shade installation was delayed and the window remained unshaded during the first and second test cycles). The first test cycle was focused on evaluating the performance of the lighting control systems, so the unshaded window presented a more challenging condition for the lighting controls because the non-uniform illuminance patterns caused by direct sunlight are known to skew some photosensor readings. Lighting control systems that are able to perform well under these circumstances are likely to perform well under real world conditions.

**Table 2.2** - Schedule for first test cycle

| ORIENTATION | START | FINISH |
|---|---|---|
| East Test | July 11 | July 14 |
| West Test | July 16 | July 21 |
| South Test | July 26 | August 3 |

### Second Test Cycle

In response to findings from the first test cycle, at the start of the second test cycle the lighting control systems were reconfigured so that the upward lights were controlled together in order to attain a more uniformly lit appearance across the ceiling plane. Additionally, the minimum dim level was set to 15% for the downward lights and 0% for the upward lights (previously Encelium was 40% both upward and downward, Enlighted was 15% both upward and downward). These thresholds were chosen so that occupants could observe the lights as being in an ON state at times when electric lighting may not be necessary but at a lower level to reduce energy use.

The shading condition was the same as the first test cycle. HDR cameras for measuring visual comfort (see section 2.3) facing the windows were moved closer to the window to assess glare for a closer furniture placement.

The non-glazed portion of the facade was insulated before starting the second test cycle enabling a more accurate assessment of thermal comfort and HVAC loads.

**Table 2.3** - Schedule for second test cycle

| ORIENTATION | START | FINISH |
|---|---|---|
| South Test | August 9 | August 14 |
| East Test | August 16 | August 21 |
| West Test | August 23 | August 28 |

### Third Test Cycle

Because of the importance of the shades in determining lighting energy and HVAC energy conditions, the start of this test cycle was delayed until the shade for the second window was installed and operational. Measurements were taken during the delay, but the building remained in the west configuration for the duration of the delay.

During the third test cycle additional HDR camera setups were placed at various distances from the window with the new shade to inform the minimum seating distance from the window and the shade fabric selection.

**Table 2.4** - Schedule for third test cycle

| ORIENTATION | START | FINISH |
|---|---|---|
| West Test | September 20 | September 25 |
| East Test | September 27 | October 2 |
| South Test | October 4 | October 12 |
| Tunable White | October 13 | October 19 |

## 2.3 Sensors and Measurements

The following table contains a list of FLEXLAB sensors used in this study. Figure 2.5 contains a plan drawing showing the positions of some of the sensors.

**Table 2.5** - Measurements and Sensors

| MEASUREMENT | UNITS | SENSOR(S) | POSITION |
|---|---|---|---|
| Workplane Illuminance | Lux (lumens/meter Footcandle (lumens/ft =10.79 lux) | Licor Photosensor | (7) positioned at 3' increments from the facade along the centerline of the left window to a depth of 21 ft. (see figure 2.X) |
| Dimming Signal to Ballast | Volts | Volt Meter | Connected to each ballast |
| Lighting energy use (Current & Voltage) | Watts (Amps & Volts) | Current Transducer & Volt Meter<br><br>(Amps) & (Watts) | On each lighting branch circuit |

**Table 2.5** - Measurements and Sensors

| MEASUREMENT | UNITS | SENSOR(S) | POSITION |
|---|---|---|---|
| Temperature | Degrees Celsius | Shielded Thermistor | (7) Positioned at 3' increments from the facade along the centerline of the left window to a depth of 21 ft. (same location as illuminance sensors in figure 2.5)<br>(6) attached to a pole to measure vertical stratification of air. |
| Thermal Comfort (temperature, mean radiant temperature, and air velocity) | PPD (Degrees Celsius, meters/second) | Shielded Dry-bulb Thermistor, Gray globe (radiant) temperature, and omni directional air velocity sensor. | Positioned at the desk nearest the facade 40" adobe the floor, |
| Relative Humidity | %RH | RH Sensor | On the floor 20 fee from the facade |
| Discomfort Glare (Luminance Map) | DGP (candela/meter | HDR imaging setup<br>4 cameras during cycles 1&2<br>8 cameras for cycle 3. | All test cycles: Two cameras positioned at desks 54 inches from the facade facing the monitor (see figure 2.5)<br>Test cycle 1 & 3: Two cameras cameras at 80 inches from the facade centered on the window and facing each window (see figure 2.5)<br>Test cycle 2: Two cameras at 42 inches from the facade facing each window<br>Test cycle 3: Four additional cameras at 2.5 ft, 3.5 ft, 4.5 ft and 5.5ft from the right window.<br>All are 4 ft above the floor except for two cameras closest to the window in test cycle 3, which were 44 inches above the floor. |
| Blind Position | | Retrieved log from MechoSystems | |
| Room Temperature | Degrees Fahrenheit | Two Shielded Thermistors (averaged) | On the west wall 10 feet and 20 feet from the facade. Four feet above the floor. |
| Supply Air temperature | Degrees Fahrenheit | Thermistor | Inside supply air duct |
| Supply Air Flow | Cubic Feet per Minute (CFM) | Flow sensor | Inside supply air duct |
| Outside Air Temperature | Degrees Fahrenheit | Thermistor | Inside outside air duct |
| IR Imaging | Degrees Celsius | FLIR Camera | Back of the room and near the facade |
| Exterior Global Horizontal Irradiance | Watts/Meter | Pyranometer | Roof of FLEXLAB high bay cell. |
| Direct Normal Irradiance | Watts/Meter | Heliostat | Outside of Building 71T |
| HDR Sky luminance Map | Candela/Meter | TerrestrialLight Skycam | Roof of FLEXLAB high bay cell. |

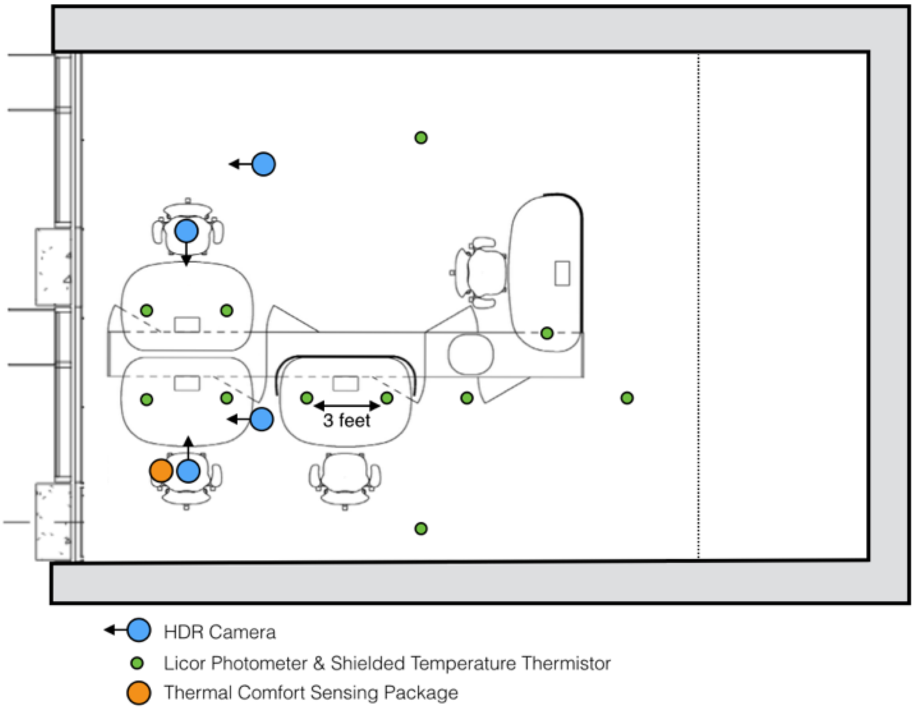



**Figure 2.5** - Test cell plan showing locations of licor photometers (illuminance) and HDR cameras at the start of testing.

**Figure 2.6** - Photo of a desk with workplane illuminance sensors and shielded thermistor.

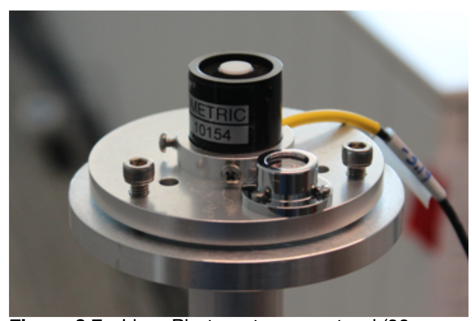


**Figure 2.7** - Licor Photometer on a stand (30 inches above the floor).

## 2.4 Evaluative Metrics & Diagrams

Two metrics used to evaluate system performance may not be familiar to the reader: 'appropriately dimmed' and daylight glare probability (DGP). In this section we describe these metrics and introduce diagrams used in this report to describe performance.

### Lighting Power & Illuminance Profile Diagrams

Figure 2.8 shows a diagram used to convey the lighting condition in the mockup at a moment in time. The orange dials indicate power use for the fixture closest to the window (left) and the fixture furthest from the window (right). Maximum power for the fixtures is 128 W. The yellow dials show the dimming level for the upward and downward portions of each fixture, with the triangle to the left indicating the direction represented by the dial. Between the light fixture status boxes a table of illuminance statistics displays mean, minimum and maximum illuminance over the seven sensors. The chart at the bottom of the diagram shows the illuminance measured by the seven illuminance sensors in the space. The stacked lines illustrate the source of the illuminance. The bottom line (below which is shaded blue) indicates the illuminance from daylight. The top line is the total illuminance at the sensor, and the distance between the two lines (shaded yellow) is the contribution from electric light. The x-axis on the chart is the distance from the window. The leftmost dot is for the sensor 3 feet from the window. The sensors are spaced three feet apart. The y-axis is illuminance in lux. The design illuminance criteria of 300 lux is depicted by a solid gridline.

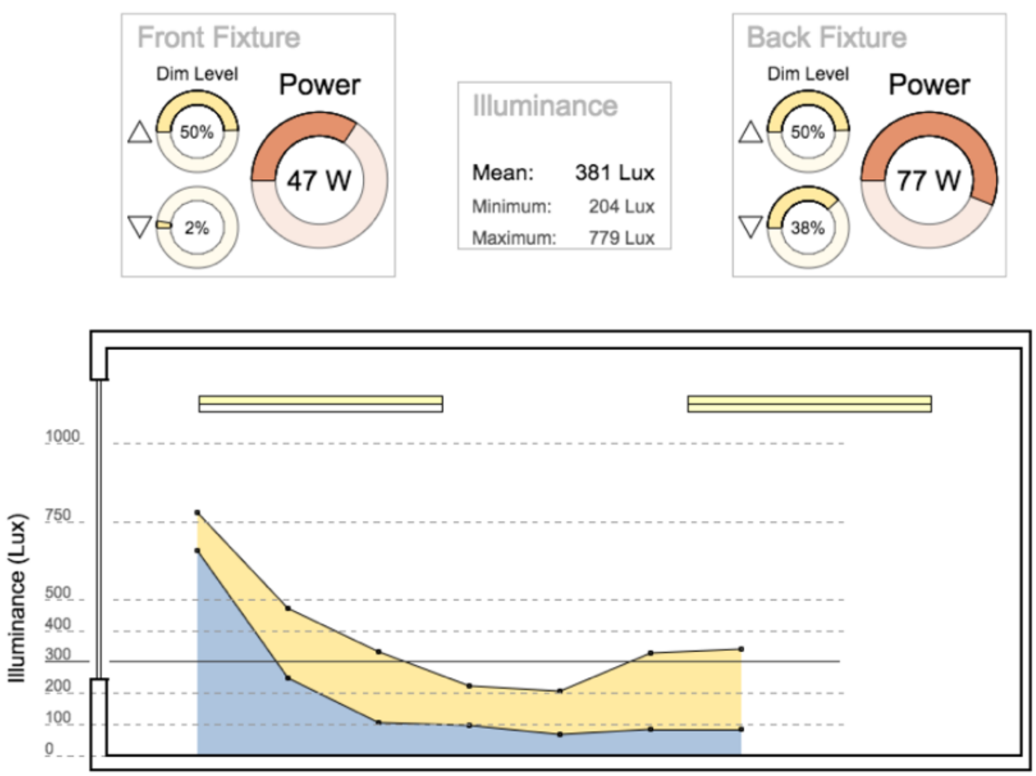



**Figure 2.8** - Lighting power and illuminance profile diagram illustrating lighting conditions in the mockup at a moment in time.

## Appropriately Dimmed Metric

We use minimum illuminance to judge the ability of the lighting control system to provide adequate illumination for the space. Average illuminance is avoided because often times high illuminance levels near the window skew the average well above the design criteria while areas further from the window may be below the target criteria, which isn't apparent in the average illuminance value (figure 2.9).

The design illuminance criteria for B35 is a 300 lux (28 footcandle) average on the work plane, which is consistent with current guidance from the Illuminating Engineering Society of North America (IESNA). IESNA also recommends a work plane uniformity ratio (average to minimum) of 1.5:1 for office spaces, allowing for a minimum work plane illuminance of 200 lux.

We categorize times when the minimum illuminance on the workplane falls below 200 lux as times that the control system under provides electric lighting. And times when the minimum illuminance is above 300 lux we deem as times that the lighting control system over provides electric lighting (figure 2.10).

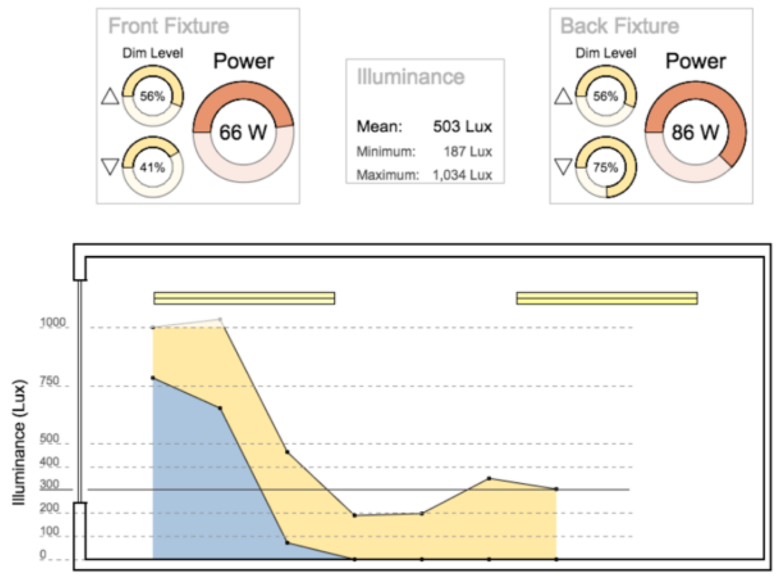



**Figure 2.9** - Illuminance profile at 8:45 PST on September 27, 2014 (East facade). The average illuminance is 503 lux, buoyed by the 1000 lux seen near the window. The minimum illuminance, located between the two light fixtures is 187 lux.

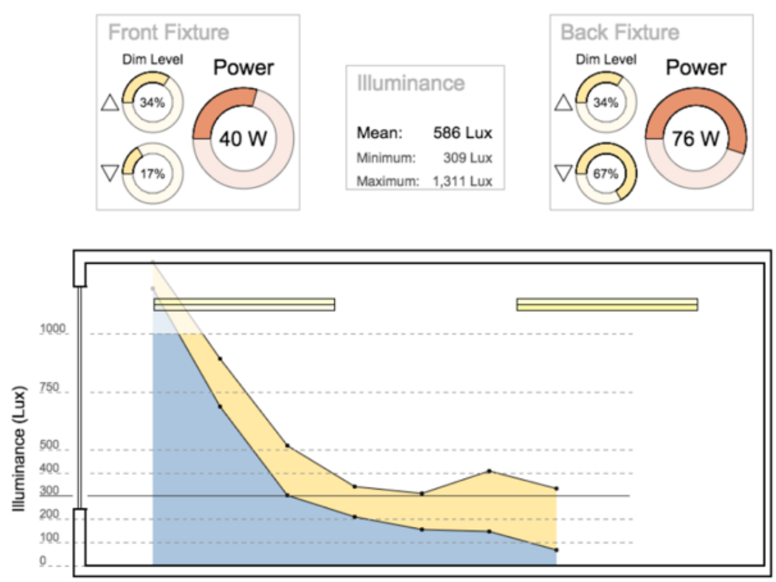



**Figure 2.10** - Illuminance profile at 14:15 PST on September 27, 2014 (East facade). The average illuminance is 586 lux. The minimum illuminance, located between the two light fixtures is 309 lux, above the design criteria.

## Daylight Glare Probability

Visual comfort ratings are based on Daylight Glare Probability (DGP), a metric developed by Jan Wienold and Jens Christoffersen that related subjective responses in a daylit environment to detailed luminance images. DGP values range from 0-1; Table 2.6 contains correlations for instantaneous DGP values with subjective impressions.

**Table 2.6** - DGP correlations to subjective impressions

| SUBJECTIVE IMPRESSION | DGP |
|---|---|
| Imperceptible Glare | < 0.35 |
| Perceptible Glare | 0.35 - 0.40 |
| Disturbing Glare | 0.40 - 0.45 |
| Intolerable Glare | > 0.45 |

The HDR imaging setups captured photos of varying exposure, obtaining brightness of the brightest and darkest regions in the room (figure 2.11). The exposures are combined into a single high dynamic range (HDR) image for glare analysis. The HDR image has luminance data for all pixels in the image. Image based glare analysis software Evalglare, created by Jan Wienold, analyzes the HDR image for potential glare sources. Evalglare generates glare metrics, including DGP, based on location, size, and brightness of potential glare sources identified in the HDR image.

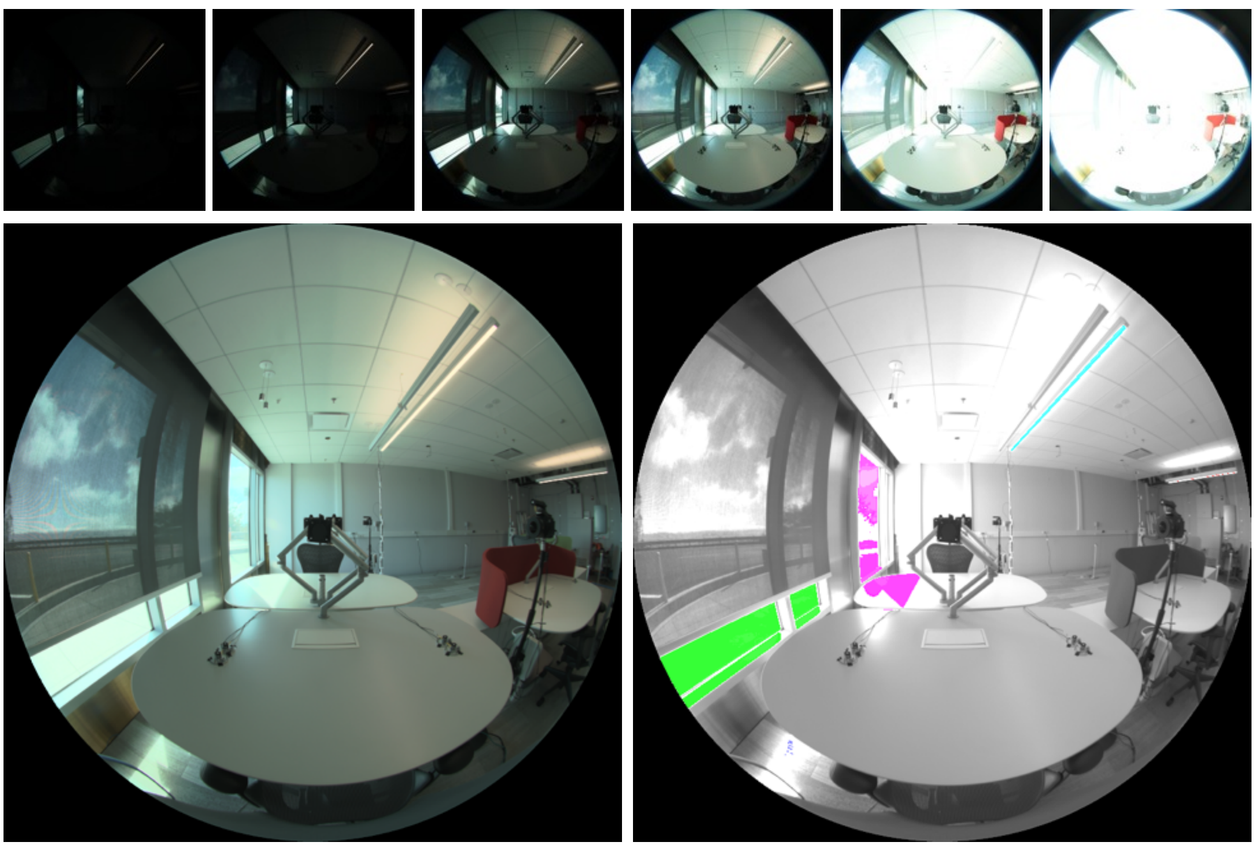


**Figure 2.11** - Bracketed exposures (top) used to generate a high dynamic range image (lower left). Evalglare scans the HDR image to identify potential glare sources, which are shown as colored regions in a check image (lower right).

We evaluated DGP over test periods using Wienold's recommendations for three classes of office (table 2.7). Wienold's method involves creating cumulative distribution charts of the glare rating (figure 2.12). The rating is based on DGP at the 95% threshold and the average DGP in the top 5% band. A class A office will experience DGP above 0.35 (perceptible glare) for 5% of occupied hours or 36 minutes over a 12-hour day on average.

**Table 2.7** - Visual comfort ratings based on DGP glare index.

| | A<br>BEST CLASS<br><br>95% of office time glare is weaker than ‘imperceptible | B<br>GOOD CLASS<br><br>95% of office time glare is weaker than ‘perceptible | C<br>REASONABLE CLASS<br><br>95% of office time glare is weaker than ‘disturbing’ |
|---|---|---|---|
| DGP Limit (95%) | 0.35 | 0.40 | 0.45 |
| Average DGP within top 5% band | 0.38 | 0.42 | 0.53 |

Source: Wienold, J., 2009. Dynamic Daylight Glare Evaluation. Eleventh International IBPSA Conference, Glascow Scotland

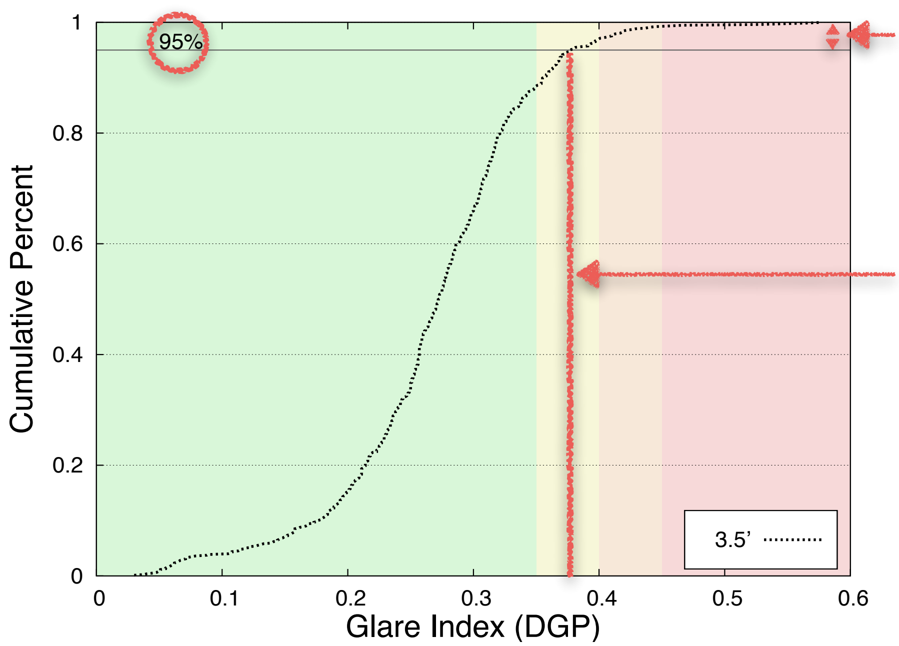



**Figure 2.12** - A cumulative distribution function plot with the 95% DGP value and top 5% band marked.

# 3. Light Fixtures (Vode)

3.1 Description......................................................................................................21

3.2 Performance ......................................................................................................21

**Figure 3.1** - Photo of the pendant LED light fixture installed in FLEXLAB manufactured by Vode Lighting.

## 3.1 Description

Linear LED fixtures manufactured by Vode lighting (Model DB-107) were selected to illuminate the open plan office areas in B35. The fixture is eight feet long with a small (2.5 inch x 1.1 inch) rectangular profile. The pendant fixture, suspended 14 inches from the ceiling, emits light upward and downward. The LEDs that emit light downwards are shielded by a diffuser. The LEDs emitting light upwards are protected by a clear lens without optical shielding and are not visible from below the fixture. The fixture allows separate control of upward and downward light. LED drivers are housed remotely above the ceiling.

Fixtures in B35 will be arranged in rows spaced 14 feet on center. In each row the 8-foot long fixtures are spaced 16 feet on center (8 feet between fixtures end to end). The fixture efficiency is 80 lumens per watt, total fixture power is 128W per 8-foot fixture (64W for upward light and 64W for downward light). The color rendering index (CRI) of the LEDs are 85. The design lighting power density is 0.57 $W/ft^2$.

The design team explored the possibility of tunable white lighting, where the color of the lights shifts from warm white to cool white throughout the day. Dynamic white lighting is thought to reinforce Circadian rhythms humans developed based on daylight. However the project opted for static 4000K white lighting due to costs and the higher than average amount of daylight available in B35 by design (93% of regularly occupied spaces have access to daylight). Regardless, testing of controls for tunable white fixtures was performed between the second and third test cycle and again after the third test cycle. The results from these tests will inform future retrofits of Genentech buildings with less daylight.

## 3.2 Performance

The upward directed light from the Vode LED light fixtures has a sharp cutoff on the ceiling about two feet either side of the fixture centerline (figure 3.3). This creates distinct patterns of light and dark on the ceiling at night. The shadows stem from the geometric relationship between the LEDs in the fixture and the top edge of the fixture (figure 3.2).

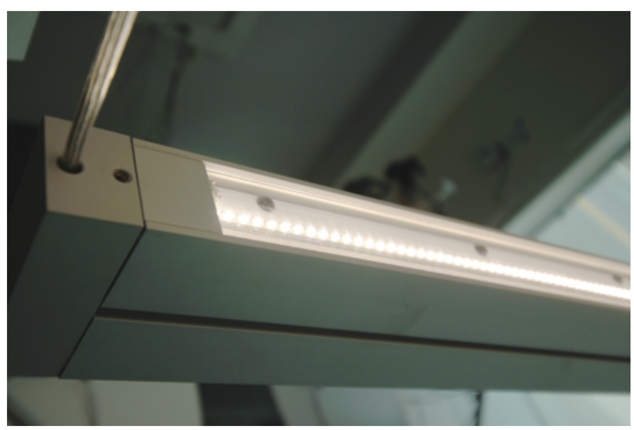


**Figure 3.2** - Photo of the upward light of the Vode light fixture. The geometric relationship between the edge of the fixture and the LED location causes the sharp cutoff on the ceiling.

The computer monitor casts a shadow on the work area of the desk when a fixture is parallel to and behind the monitor (figure 3.4). The number of desks with prominent shadows can be reduced through creative furniture arrangement. Task lights can be used to eliminate prominent shadows on on desks with problematic light fixture, monitor, work surface geometric arrangement. Additionally, the diffuser on the bottom of the fixture gets to be quite bright - our HDR camera setups reported a luminance of nearly 15,000 cd/m2 on the diffuser, which is well above the IES RP-1 Office Standard maximum of 850 cd/m2 for controlling direct source glare from fixtures.

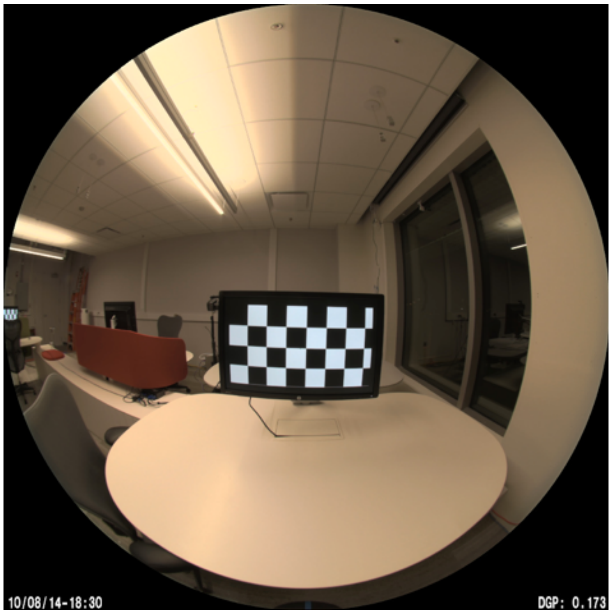



**Figure 3.3** - Nighttime photo of the electric lighting at full power with the light fixtures oriented parallel to the windows (south facade condition). The sharp cutoff from bright to dark is apparent on the ceiling.

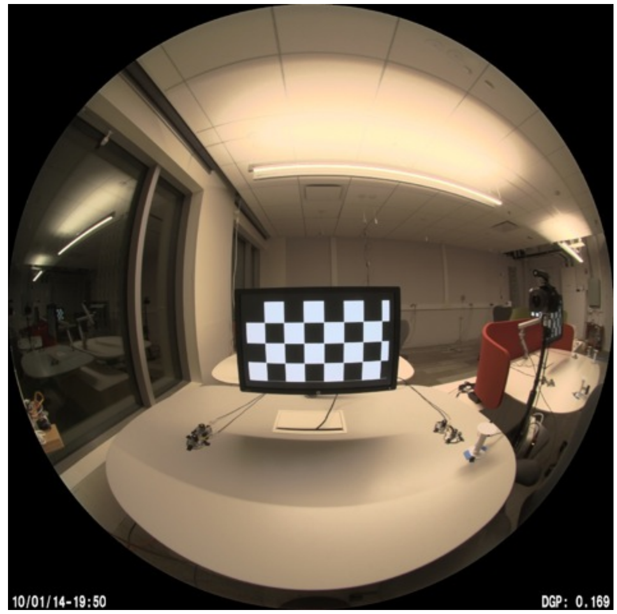



**Figure 3.4** - Nighttime photo of the electric lighting at full power with the light fixtures oriented perpendicular to the window (east and west facade condition). The monitor casts a shadow on the desk.

# 4. Lighting Control System #1 - Encelium


4.1 System Description....24

4.2 System Configuration and Commissioning....25

4.3 Testing....25

4.4 Conclusions....27



**Figure 4.1** - Encelium's Rack mounted Energy Control Unit (ECU)

# 4.1 System Description

The lighting control system provided by Encelium uses a rack mounted Energy Control Unit (ECU) to communicate with all the system components (figure 4.1). System components include Luminaire Control Modules (LCM), Sensor Interface Modules (SIM), and wall mounted switches. Communication between the ECU and lighting devices occurs over Encelium's proprietary communication bus, Greenbus, via a proprietary protocol. Polaris3D, Encelium's proprietary software running on the ECU, collects information from sensors and sends control signals to LCMs. Additionally a Server Support Unit (SSU) stores all system settings and records operational data. A web based system interface allows users to view performance data and reconfigure control parameters. Figure 4.2 depicts a typical configuration of Encelium hardware.

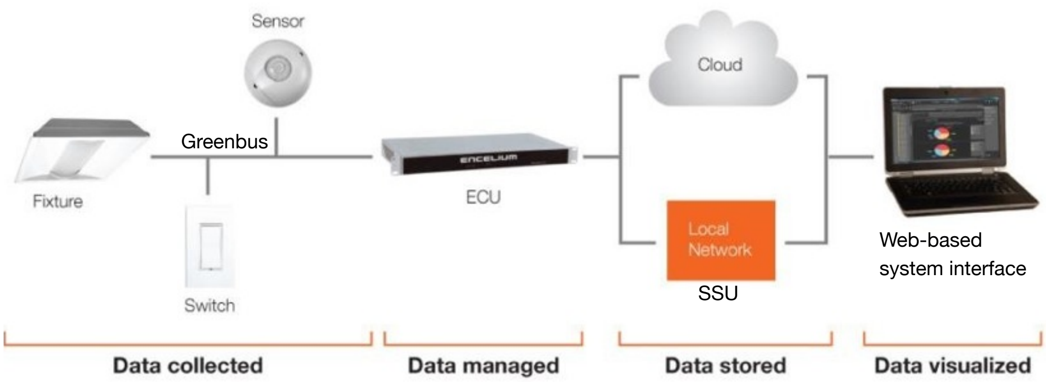



**Figure 4.2** - Encelium system configuration (from Encelium website).

In FLEXLAB, the Encelium system controls two light fixtures connected to the Encelium controller. Each light fixture has two control channels for separate control of upward and downward directed light. Four LCMs each control one the lighting channels.

The Encelium control system in FLEXLAB uses input from a photosensor, an occupancy sensor (Figure 4.3) and two wall switches to determine the appropriate dim setting for the lights. The daylight photosensor (model PLC-CES/ILF-24-0-10 60fc), near the window (figure 4.4) centered in the ceiling tile between the windows, controls the dimming for both fixtures (all four control channels) in the space. The occupancy sensor was disabled for the test since the cell was unoccupied during testing and the wall switches were not used during testing.

**Figure 4.3** - Encelium photo sensor (left) and occupancy sensor (right) installed in FLEXLAB.

**Figure 4.4** - Location of the Encelium photosensor (circled in red).

## 4.2 System Configuration and Commissioning

In FLEXLAB, the Encelium ECU and SSU were installed in the server rack. Greenbus cables ran into the test cell and connected to the wall switches, sensors and LCMs. The LCMs provided a 0-10V signal to the LED driver to dim the LEDs. The LCMs also contain a relay that can switch off power to the LED driver, reducing standby power consumption.

The photosensor determines the amount of daylight present in the space. The first night after the system is commissioned the ECU determines contribution from each electric light to the sensor by turning on fixtures individually and recording the sensor reading. During normal operation Encelium can subtract the electric lighting contribution from sensor value to determine daylight present at the sensor. By subtracting electric lighting the system operates with an open loop typology.

During night time calibration the ECU also establishes the dimming curve for the fixtures by adjusting the 0-10V signal to each fixture and recording the relative change in photosensor signal. Encelium refers to this process as ‘linearization’. Running the linearization process allows the system to know how to adjust the dim level to produce a required amount of electric light.

The control system needs to know the relationship between daylight present at the sensor and daylight illuminance on the workplace. To accomplish this, the commissioning agent enters measured illuminance (using an illuminance meter) at regular intervals from the window into the control system software. The control system then relates the illuminance measured with the sensor value at the time of measurement to understand the relationship between photosensor reading and workplane illuminance. The same process is repeated with each electric light control channel individually at full power so the system knows how much light each fixture provides to the workplane points.

Once these relationships are known, the control system determines the ‘dependency’ for each light fixture. The dependency relates daylight illuminance measured at the photo sensor, predicts daylight workplace illuminance, then determines the desired dimming level for the fixture. The actual time dependent daylight dimming operation is then based on the dependency setting for each fixture and the photosensor signal.

## 4.3 Testing

During the first test cycle the minimum dimming parameter in the Encelium system prevented the fixtures from dimming below 40% for both upward and downward light. Minimum dimming levels are intended convey to occupants that the lights are on and the space is ‘open.’ The default 40% level used by Encelium stems from the dimming curve associated with fluorescent lighting. Incremental lighting energy savings starts to diminish below 40% light output for fluorescent lighting. Since the dimming curve of LEDs is close to linear, continuing to dim below 40% of full light output will yield worthwhile energy savings for LED fixtures. Additionally, the upward light is less visible to occupants during brightly daylight conditions. Maintaining a minimum light output for the upward lighting doesn’t contribute substantially to an occupant's perception of the space being 'open.' For the second and third test phases the Encelium system was modified to maintain a minimum light output of 15% for the downward lighting. The minimum light output setting was disabled for upward lighting, allowing them to turn off when daylight is sufficient.

During the first test cycle the Encelium dimmed the upward and downward light in each fixture in unison. The designer's lighting control intent specifies that all the upward lights in an open office area should be dim together while the downward lights should be dimmed individually. Upward lights provide uniform electric lighting on the ceiling while downward lights provide supplemental illumination required local to the fixture. The designed control intent was achieved for the second and third test cycles by using the same dependency for the upward portion of all light fixtures. Using individually tailored dependency values for each fixture's downward light provided appropriate illumination to supplement daylight illuminance at each fixture. The dependency values were tuned (via trial and error) through the second and third test cycles to improve the performance of the control system.

Table 4.1 shows the percent of time that minimum illuminance falls into 50-lux bins during each test period, with accompanying histograms in figure 4.5. The Encelium system performed poorly during the first test cycle, the system was only appropriately dimmed 20-35% of the time for the each orientation. Modifications improved performance in the second test cycle. While the system was appropriately dimmed 44.3% of the time in the south condition (first condition in the second cycle) mid-cycle improvements made during the subsequent East (74.9% appropriately dimmed) and West (93.2% appropriately dimmed) tests demonstrate improvements. Shading for the second window was installed prior to the start of the second test cycle. The new condition affected the performance of the system at first. And again, mid-cycle adjustments improved the performance during the test cycle.

**Table 4.1** - Dimming Performance based on measured illuminance for Encelium lighting control system.

| | UNDER PROVIDE | | APPROPRIATE DIM | | OVER PROVIDE | | |
|---|---|---|---|---|---|---|---|
| | <150 | 150-200 | 200-250 | 250-300 | 300-350 | 350-400 | >400 |
| EAST TEST #1 | 0.0% | 6.6% | 9.2% | 10.8% | 31.5% | 35.7% | 6.2% |
| WEST TEST #1 | 3.8% | 26.6% | 17.0% | 36.8% | 14.3% | 1.5% | 0.1% |
| SOUTH TEST #1 | 1.2% | 13.9% | 16.5% | 17.9% | 17.9% | 22.2% | 10.4% |
| SOUTH TEST #2 | 9.9% | 45.8% | 36.3% | 8.0% | 0.0% | 0.0% | 0.0% |
| EAST TEST #2 | 1.9% | 8.6% | 20.3% | 54.6% | 11.8% | 1.5% | 1.3% |
| WEST TEST #2 | 0.3% | 0.3% | 38.4% | 54.8% | 1.8% | 2.9% | 1.6% |
| WEST TEST #3 | 0.0% | 47.1% | 40.7% | 12.3% | 0.0% | 0.0% | 0.0% |
| EAST TEST #3 | 0.0% | 28.3% | 36.2% | 26.6% | 7.3% | 1.4% | 0.4% |
| SOUTH TEST #3 | 0.0% | 0.5% | 82.5% | 12.9% | 4.0% | 0.1% | 0.0% |

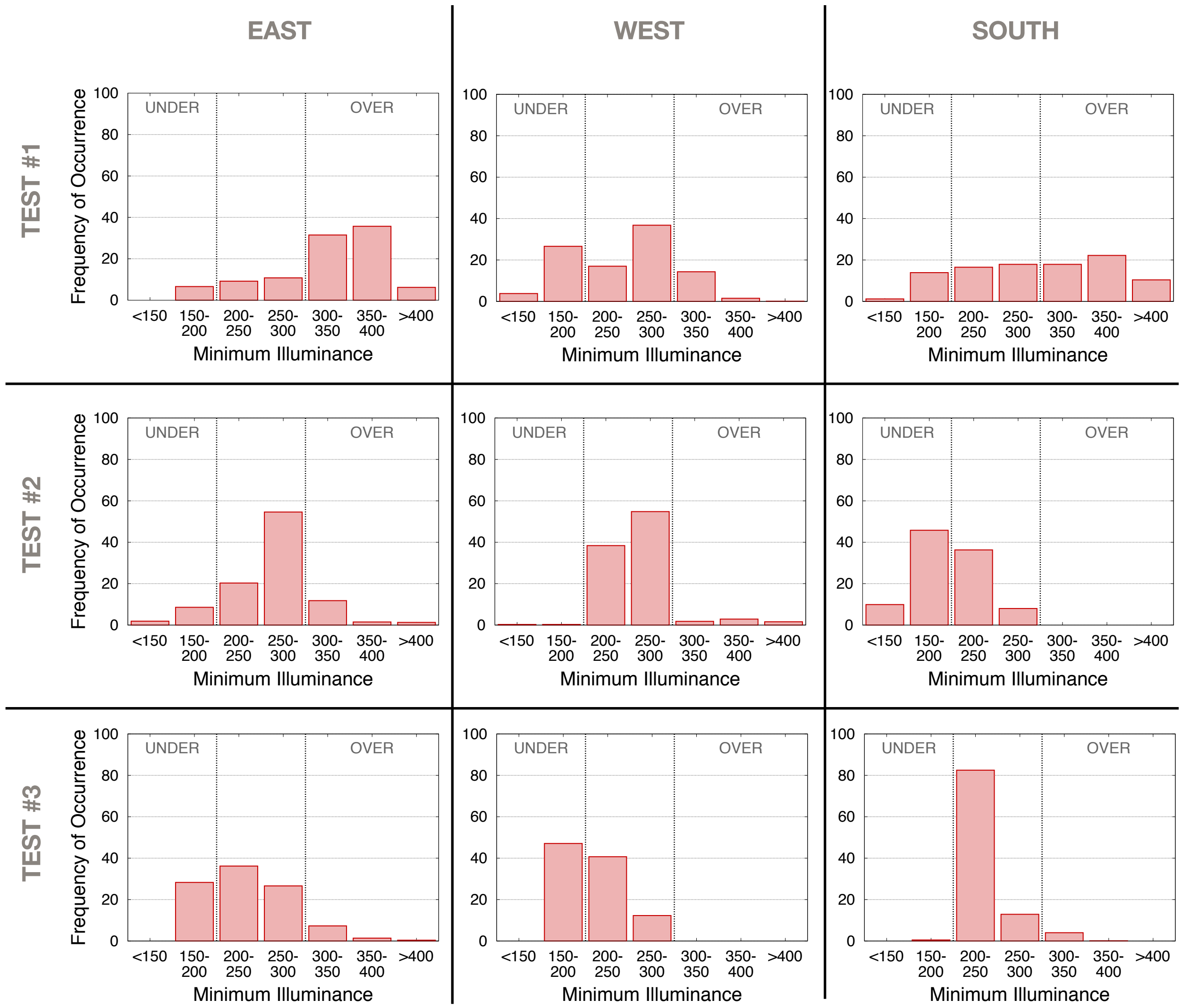



**Figure 4.5** -Histograms of minimum workplane illuminance for each facade orientation and test period for the Encelium control system.

## 4.4 Conclusions

The Encelium system provided logical sequencing of the lighting in the space. In the morning, as daylight begins to enter the space, the downward light from the fixture near the window begins to dim first. As the day progresses and daylight increases, the uplights begin to dim and then finally the rear downlight dims. Shade movement is apparent in the control system response. When the shade deploys, the electric lighting increases to compensate for the drop in daylight. The final dependency values for each of the control channels are provided in table 4.2. The higher the dependency value the more a fixture is dimmed in response to the photosensor signal.

**Table 4.2** - Final FLEXLAB dependency values for Encelium controls

| CONTROL CHANNEL | DEPENDENCY |
| --- | --- |
| Downward light near window | 0.30 |
| Downward light at back | 0.045 |
| Upward light near window | 0.07 |
| Upward light at back | 0.07 |

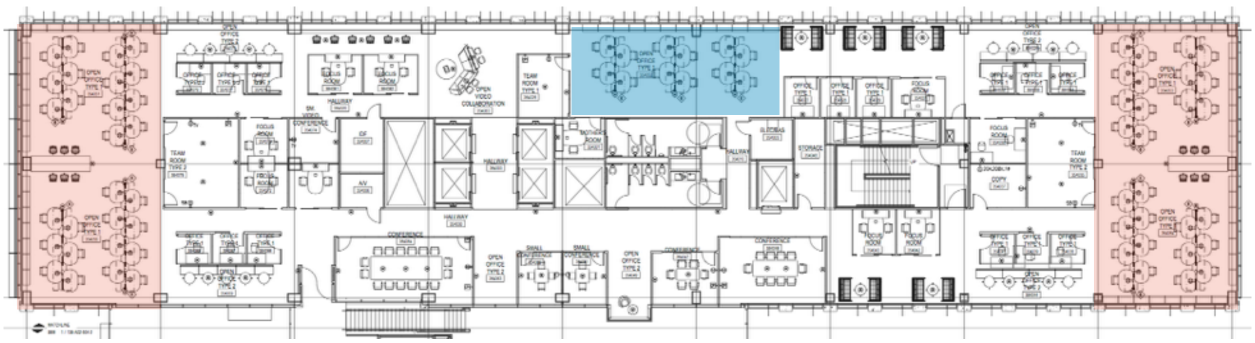


**Figure 4.6** -Floor plan of one office bar with open office areas shaded. The mid-bar office area (shaded blue) resembles the FLEXLAB configuration with a facade on one side of the space. The open office areas at the north and south ends of the bar (shaded pink) have facades on three sides and require additional consideration during commissioning lighting controls. In this diagram north is to the right.

Genentech selected Encelium for controlling lighting in B35. The dependency values presented in table 4.2 provide a suitable starting point for commissioning in the final building. The mid-bar open office space (blue in figure 4.6) resembles the conditions in FLEXLAB — one facade contributing daylight to the space. The final dependency values in FLEXLAB provide a good starting point for commissioning the mid-bar office areas (figure 4.7).

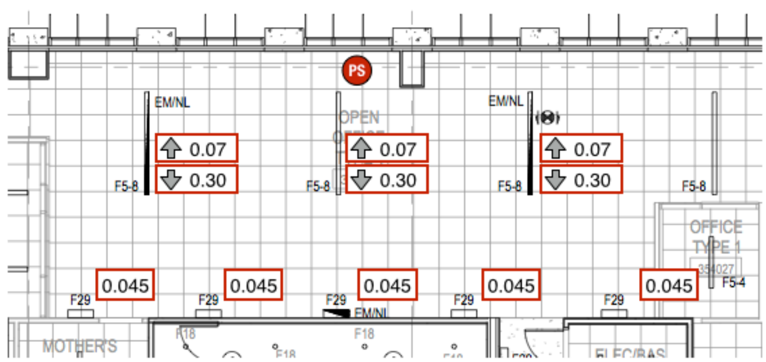



**Figure 4.7** - Reflected ceiling plan showing the starting point dependency values for the fixtures in the mid-bar open office areas.

The end office areas (pink in figure 4.6) have three facades that contribute daylight to the space. The overlapping influence of the facades makes open-loop daylight control more challenging to commission. Encelium's control system is able to take input from multiple photosensors to determine the dim setting for each fixture. Figure 4.8 gives suggested starting dependency values for pre-commissioning. With three photocells (one per facade) each control channel would have three inputs to determine appropriate dimming level. All the upward channels of the light fixtures have the same dependency setting for each photocell input so all the fixtures in the area provide a uniform amount of upward light. The downward channels are varied according to location relative to the facade. Dependencies for fixtures adjacent to the facade are 0.3 for the photocell on that facade. The dependences drop for fixtures further from the facade.

After the control system is commissioned Genentech could measure workplane illuminance and fixture dim levels in representative areas of B35 to confirm optimal operation of the lighting control system. Data collected could be used to further tune the dependency values and other settings in the control system.

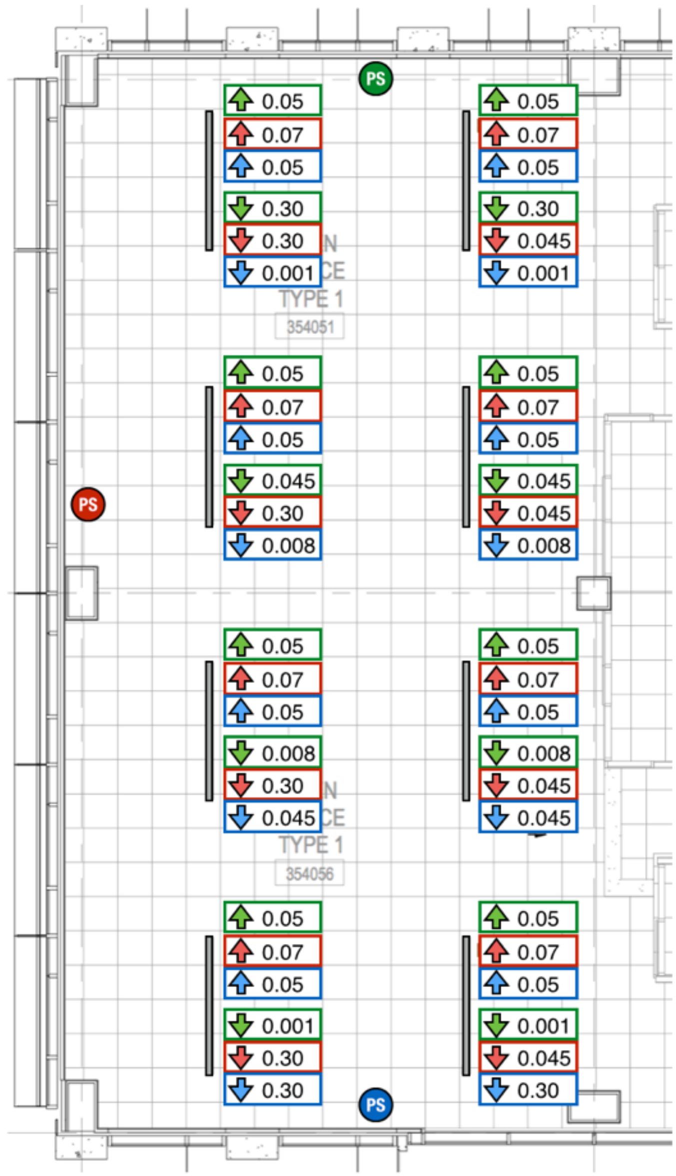



**Figure 4.8** - Reflected ceiling plan showing the starting point dependency values for the fixtures in the end of bar open office areas. Values are color coordinated with influencing photosensors (indicated by a circle with PS).

# 5. Lighting Control System #2 - Enlighted

5.1 System Overview ....................................................................................................31
5.2 System Configuration and Commissioning .............................................................31
5.3 Testing....................................................................................................................32
5.4 Conclusions ............................................................................................................35


**Figure 5.1** - The Enlighted energy manager located in the server closet.

## 5.1 System Overview


**Figure 5.2** - Diagram of Enlighted's system configuration (from Enlighted's website).

The Enlighted control system is based on an architecture of one "smart sensor" per light fixture. The sensor measures light, occupancy and temperature. The sensor is wired directly to the fixture ballast and provides dimming/switching commands based on sensor data. Sensors communicate wirelessly with a gateway (figure 5.2). The gateway gathers data from the sensors and can issue commands to fixtures, for example when a wall switch is pressed. The central energy manager stores data from the sensors and acts as an interface to the system. Sensor data can be viewed and sensor settings can be adjusted using the energy manager interface. The energy manager hardware consists of a compact aluminum enclosure housing a Linux (Ubuntu) server (figure 5.1).

**Figure 5.3** - Two Enlighted sensors attached to one Vode light fixture. The sensors were adhered to the side of the fixture because sensor integration hadn't been coordinated between manufacturers yet.

The controls installed in FLEXLAB used Enlighted's compact sensor, a small sensor that can be integrated into a fixture or recessed in a ceiling tile. Since the Vode fixtures in FLEXLAB had two control channels (separate channels for controlling upward and downward lighting from the fixture) the Enlighted system required two sensors per fixture, one per control channel (figure 5.3). Sensors can be individually configured or assigned one of many customizable profiles. Settings include min and max dimming percentages, ramp up time, motion sensitivity and ambient light sensitivity.

## 5.2 System Configuration and Commissioning

The Enlighted system has a closed loop typology with each fixture/sensor pair acting as an autonomous controller. In the software version available during the test, only information from the local sensor can affect the daylight harvesting response. Enlighted will be releasing a firmware upgrade which allows sensors to take other sensor input when computing the daylight harvesting response.

Commissioning the Enlighted system occurs at night using the energy manager interface. First the electric lights are turned on and (if task tuning is desired) levels are set to achieve the workplane illuminance criteria. Once the electric lighting is configured to desired levels, the user selects "set daylight harvesting target" for each sensor. The sensor will then record the ambient light level and will adjust the fixture light output during the day to maintain this target sensor reading.

Implementing the B35 lighting control design intent proved challenging since the up and downward lighting were controlled independently. These independent control loops prevented equilibrium conditions with a mix of up and downward lighting. One of the loops will dominate the other and provide all the necessary light. The submissive control loop will only switch on when the dominant light is unable to meet the illumination requirement alone.

## 5.3 Testing

During the first test the Enlighted system performed reasonably well at providing suitable workplane illuminance. Electric lighting was dimmed appropriately 70-80% of the time (Table 5.1, Figure 5.4) during the first test cycle with the Enlighted control system.

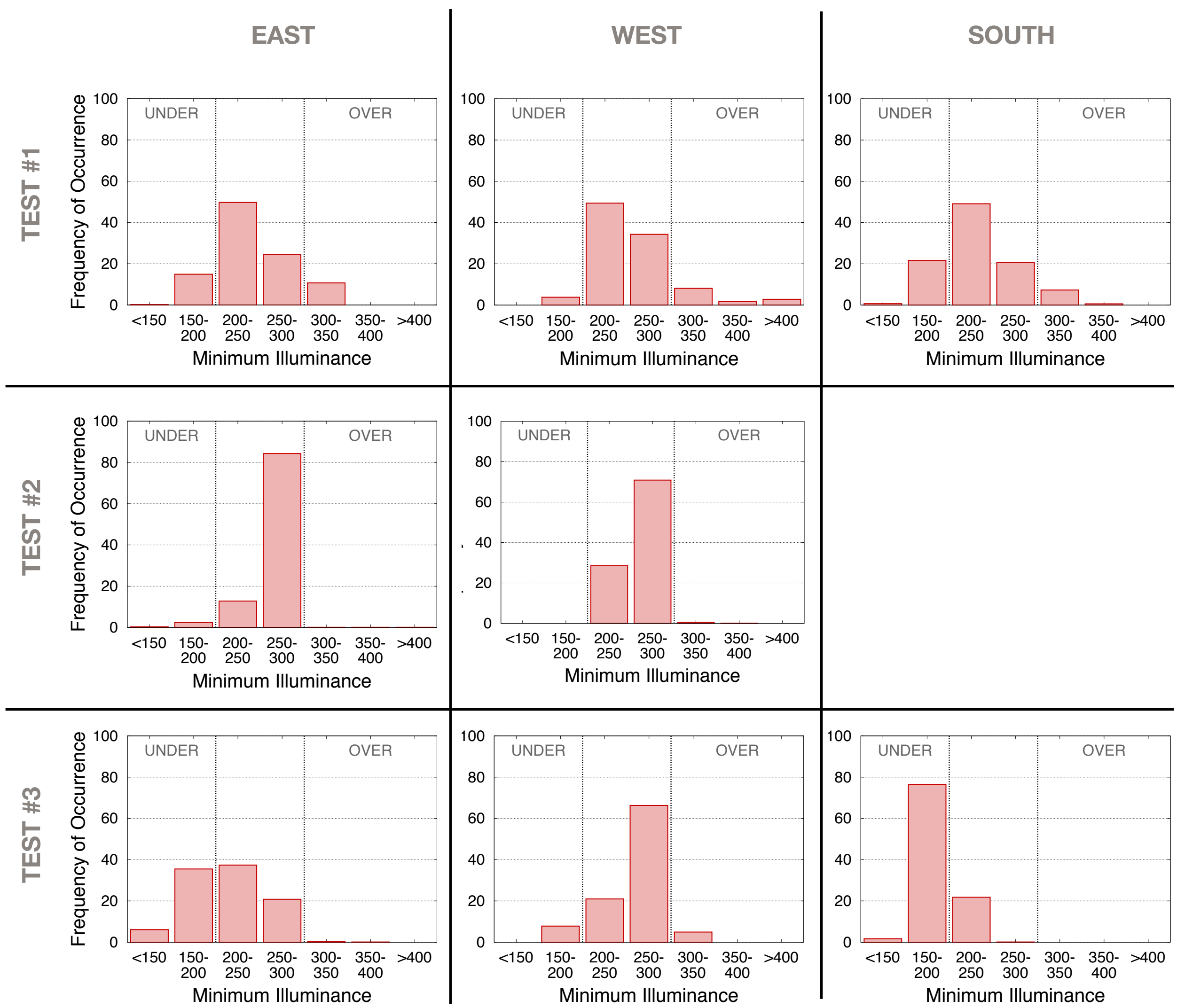



**Figure 5.4** -Histograms of minimum workplane illuminance for each facade orientation and test period for the Enlighted control system.

**Table 5.1** - Dimming Performance based on measured illuminance for Enlighted lighting control system.

| | UNDER PROVIDE | | APPROPRIATE DIM | | OVER PROVIDE | | |
|---|---|---|---|---|---|---|---|
| | <150 | 150-200 | 200-250 | 250-300 | 300-350 | 350-400 | >400 |
| EAST TEST #1 | 0.2% | 14.9% | 49.7% | 24.5% | 10.7% | 0.0% | 0.0% |
| WEST TEST #1 | 0.0% | 3.8% | 49.4% | 34.3% | 8.1% | 1.7% | 2.8% |
| SOUTH TEST #1 | 0.7% | 21.6% | 49.1% | 20.6% | 7.3% | 0.6% | 0.0% |
| SOUTH TEST #2 | | | | | | | |
| EAST TEST #2 | 0.3% | 2.4% | 12.8% | 84.3% | 0.1% | 0.1% | 0.1% |
| WEST TEST #2 | 0.0% | 0.0% | 28.6% | 70.9% | 0.5% | 0.1% | 0.0% |
| WEST TEST #3 | 0.0% | 7.8% | 21.0% | 66.3% | 4.9% | 0.0% | 0.0% |
| EAST TEST #3 | 6.1% | 35.5% | 37.4% | 20.8% | 0.2% | 0.1% | 0.0% |
| SOUTH TEST #3 | 1.7% | 76.5% | 21.8% | 0.1% | 0.0% | 0.0% | 0.0% |

The Enlighted system managed workplane illuminance well, but adjustments to the initial configuration of the sensors were required to conform to the specified design of the test. The upward lights dominated the downward lights, providing all necessary illumination for most of the time. In the morning both lights would turn on (figure 5.5). However as the day progressed and daylight levels changed the upward lights remained on increasing output while the downward lights dimmed to off (figure 5.6). The Enlighted controls have a dampening mechanism that will wait until a large (user configurable) adjustment is required. This prevents rapid fluctuations and cycling, and explains why it takes hours for the dominant control loop to completely overpower the submissive control loop.

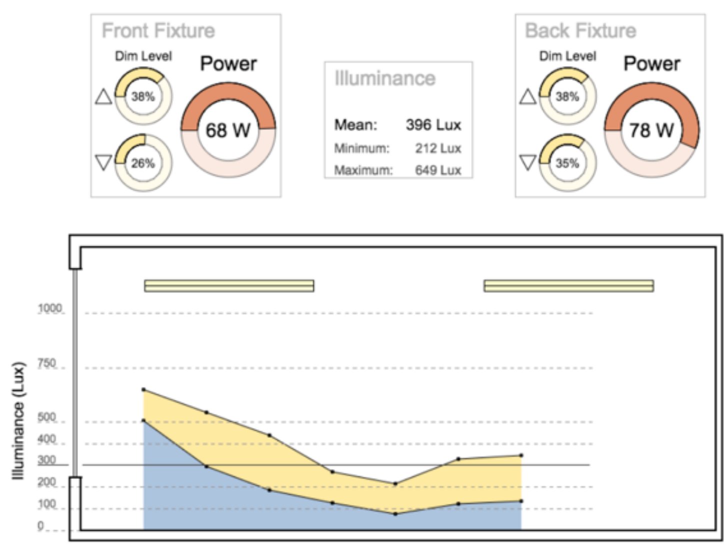



**Figure 5.5** - At 8:00 on July 21, both upward and downward light are both on at roughly equal output.

As previously mentioned, the Enlighted controls did not meet the design as initially installed during the first test cycle. The lighting control design intent stipulated that the upward lights in an area should all dim together, providing a consistent amount of electric light on the ceiling, while the downward lights would dim individually to suit the workplane illuminance needs local to the fixture. Enlighted can accommodate the intent for the upward lighting at B35 with upcoming ambient groups feature. This new feature will allow sensors to share ambient sensor data while still maintaining a sensor per fixture architecture. However, the ambient grouping behavior wasn't included in the Enlighted firmware version available at the time of this test.

We achieved the design intent in FLEXLAB by wiring both uplights to a single sensor. The appropriate sensor position was determined through trial and error during the East test of the second cycle (the rewiring was not performed in time to test Enlighted during the South condition of the second test cycle). The uplight sensor was initially positioned near the window, but was subsequently moved to a location between the two light fixtures (figure 5.7).

The reconfigured Enlighted system again performed well with regard to workplane illuminance during the second test cycle. We hoped that separating the sensors would solve the issue presented by overlapping closed loop controls however on the first day of testing we determined that in this configuration the downward lighting control loops were dominant while the upward lighting control loops were submissive.

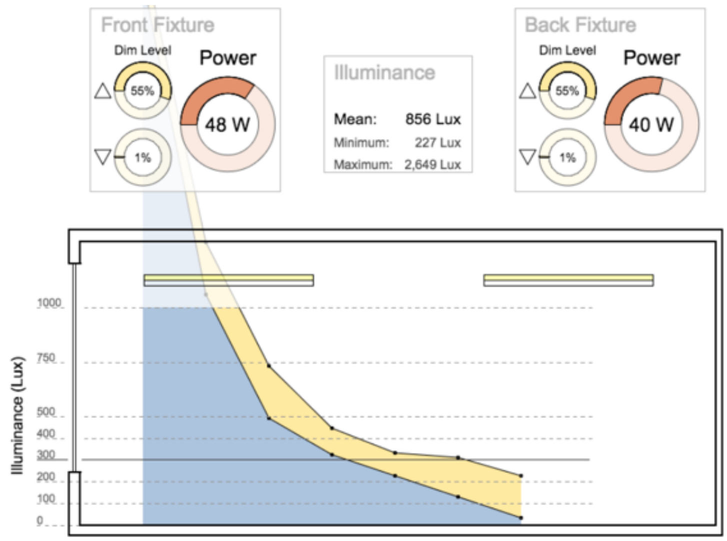



**Figure 5.6** - By 12:00 on July 21, the downward lights are off and the upward lights are providing all necessary electric lighting.

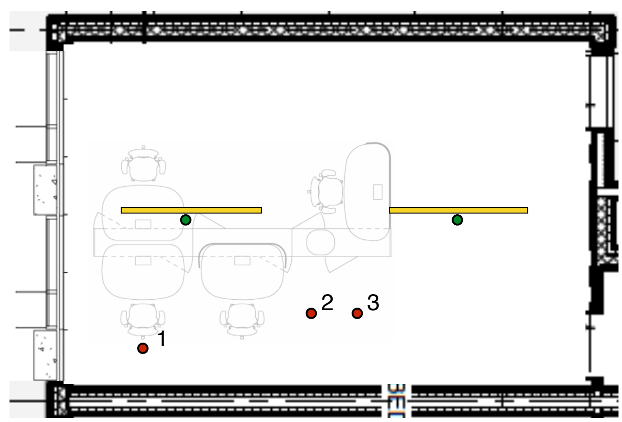



**Figure 5.7** - Diagram showing locations of the sensor for the uplights during the second test cycle. The position marked 1 was the initial position. The sensor was moved to position 2 then position 3. The sensors for the downward light was located on the fixture (green dots).

Dominant control channels are not incompatible with the desired dimming operation sequence for the FLEXLAB mockup, as long as the proper ordering of dominance can be achieved. As daylight increases in the morning the front downward light (nearest to the window) should dim first, followed by both upward lights and finally the rear downward light (furthest from the window). If the rear downward light is the most dominant, followed by the upward lights, and the front downward light the least dominant then the desired operation would be achieved. Unfortunately the Enlighted system doesn't provide the ability to select an order of dominance for control loops. We were able to achieve the desired ordering with creative commissioning techniques. At night turned all the lights on to they're desired full output and set the daylight harvesting target for the most dominant fixture (the rear downward light). Then we dimmed the lighting slightly and set the daylight harvesting target for the upward lights. Finally we dimmed the lighting a touch more and set the daylight harvesting target for the front downward light. Commissioning this way insured that the control loops we wanted to be dominant would attempt to provide slightly more light than the fixtures we wanted to be submissive. That way the submissive fixture would dim sooner and more than the dominant fixture. After commissioning the Enlighted system in this manner, the fixtures dimmed in accordance with the lighting control design intent.

## 5.4 Conclusions

The Enlighted closed loop control system was most successful at providing adequate workplane illuminance with minimal commissioning required. However, in situations where control loops overlap spatially one of the control loops will dominate the other. The dominance of one control loop doesn't affect the system's ability to provide adequate workplane illuminance, though it poses challenges implementing designs where more controlled behavior is desired.

Separate dimming control is desired for upward and downward light in the same fixture, creating overlapping closed loop controls which leads to the dominance of one control loop over the other. We were able to overcome the problem with creative commissioning, however the process used was more laborious and would be difficult to implement at a larger scale. Further, in spaces with more than one facade contributing daylight establishing an appropriate pecking order for the fixtures becomes more complex.

The version of Enlighted's control firmware available during this test was limited by its inability to group fixtures and sensors to provide coordinated control. In FLEXLAB we had to wire the upward light portion of both fixtures to the same sensor to achieve the design intent. An upcoming firmware release will provide this support.

# 6. Lighting Control System Comparison

| | ENCELIUM | ENLIGHTED |
|---|---|---|
| CONTROL TYPOLOGY | Open Loop | Closed Loop |
| SENSORS | Separate occupancy and daylight photosensor sensor.<br>One occupancy sensor per space, more for larger spaces.<br>One daylight photosensor per space per facade (approximately 14 per floor). | Combined occupancy & photosensor<br>One sensor per lighting control channel (two sensors for pendant fixture where up/down is controlled separately). |
| FIXTURE CONTROLLERS | Light fixtures are controlled by Luminaire Control Modules (LCM) wired directly to the fixtures. | Fixtures are controlled by the sensor modules, which are wired directly to the fixture ballast/driver. |
| NETWORK | Sensors and LCMs are wired in a linear daisy chain arrangement back to the Encelium Energy Control Unit. The network uses Encelium's proprietary green bus wiring. | Sensors communicate wirelessly to the Enlighted gateways, which are wired to the central energy manager. |
| TEST CYCLE 1 | 36% Appropriately dimmed | 76% Appropriately dimmed |
| TEST CYCLE 2 | 71% Appropriately dimmed | 98% Appropriately dimmed |
| TEST CYCLE 3 | 70% Appropriately dimmed | 56% Appropriately dimmed |
| COMMENTS | Encelium's system requires a longer commissioning process.<br>Implementing the desired daylight control sequencing was possible by altering photosensor dependency values for each fixture.<br>Open loop controls are not able to control lighting as precisely as closed loop controls. | Enlighted's system excelled at providing desired workplane illuminance with simple commissioning, however implementing the desired daylight control sequencing required creativity.<br>Separate closed loop sensors for upward and downward components of a pendant fixture resulted in one becoming dominant and overpowering the other loop.<br>Sequenced dimming operation is not possible with Enlighted's control software. The desired sequencing was achieved using creative commissioning to establish dominant and submissive control loops.<br>Coordinated control of the uplight portion of several fixtures is not possible with Enlighted's control software. All fixtures had to be hard wired to a single sensor to achieve desired results. |

# 7. Shading Control System - MechoSystems


7.1 System Overview .......................................................................................................38

7.2 System Operation and Commissioning ......................................................................38

7.3 Testing........................................................................................................................40

Limiting Sunshine Depth ..........................................................................................40

Daylighting vs. Glare Tradeoff...................................................................................41

Overcast Sky Glare ..................................................................................................42

Shade Fabric Selection .............................................................................................43

Anecdotal Experience ...............................................................................................45

7.4 Conclusions ................................................................................................................45


**Figure 7.1** - Photographs of MechoSystems components. Clockwise from top left: motorized roller shade (medium grey color), rooftop irradiance sensor, illuminance sensor mounted to the window frame, MechoSystems control cabinet.

## 7.1 System Overview

The MechoSystems shade system consists of two motorized roller shades (one in each window) a rooftop irradiance sensor, a window mounted illuminance sensor and a central control server (figure 7.1). The system uses the rooftop irradiance sensor to determine whether the sky clear or overcast. If the sky is clear according to the rooftop irradiance sensor, the controller will lower the shade to a position that limits sunshine depth into the building based on the calculated position of the sun. The sensor mounted to the window frame between the glazing and the shade measures illuminance just inside the window and can lower the shade if the sky is overcast but the sensor detects high illuminance on the facade.

Genentech intends that shades in B35 operate automatically at all times with no accommodation for occupant override. Occupants that experience discomfort glare will be encouraged to relocate, since desks in B35 are unassigned. Providing occupants with information about how the automated shading system works and its control intent prior to move in will help with user satisfaction and acceptance. Programming adjustments be made based on interior space configuration will be possible (ie lowering brightness threshold for a laptop bar along a facade). Additionally, system wide changes can be accommodated if a threshold is determined to be too high or low based on volume of complaints.

MechoSystems uses its proprietary SolarTrac software to determine how the shade should be positioned. Additional SolarTrac modules (provided at additional cost) allow SolarTrac to consider shading from site context (neighboring buildings, trees and terrain) and can include the ability to control shades to mitigate specular reflections from buildings with glass facades.

We tested two shade fabrics in FLEXLAB. Both were 3% open woven shade cloth (PVC free), however the color of the shades varied. One shade used a dark-grey colored fabric (MS-1570 shadow grey). The other shade used a medium grey colored fabric (MS-1563 grey).

**Table 7.1** - MechoSystems Fabric Properties

| MODEL | COLOR | OPENNESS | $T_V$ | $T_S$ | $R_S$ | $A_S$ |
|---|---|---|---|---|---|---|
| **1563** | Grey | 3% | 0.06 | 0.04 | 0.31 | 0.65 |
| **1570** | Shadow Grey | 3% | 0.05 | 0.03 | 0.10 | 0.87 |

## 7.2 System Operation and Commissioning

The shade motors are programmed with limits for the top and bottom of the window. The shade control systems can tell the motors to deploy the shade to any one of six positions: the lower limit, fully retracted, or at one of four positions equally spaced vertically along the window. The positions are identified in the SolarTrac software as positions 0-5, with 0 being fully raised and 5 being fully lowered. The windows in FLEXLAB are 70 inches tall. The window sill is 16 inches above the floor. Table 7.2 and figure 7.2 shows the shade stopping positions in FLEXLAB.

**Table 7.2** - Shade Stopping Positions in FLEXLAB

| POSITION | HEIGHT ABOVE FLOOR | HEIGHT ABOVE WINDOW SILL |
|---|---|---|
| 0 | 98 inches | 72 inches |
| 1 | 81.5 inches | 65.5 inches |
| 2 | 63.75 inches | 47.75 inches |
| 3 | 46.5 inches | 30.5 inches |
| 4 | 30 inches | 14 inches |
| 5 | 14 inches | -3 inches |

**Figure 7.2** - Photos of the shade in each position

SolarTrac pre-calculates the clear sky horizontal irradiance based on IESNA/ASHRAE sky model for the following day. Throughout the day the software compares the measured horizontal irradiance to the pre-calculated irradiance (7.3). If the irradiance is above an irradiance threshold, the sky condition is determined to be clear. During FLEXLAB testing the threshold was set at 60% of the calculated clear sky irradiance, though this percentage is configurable in SolarTrac.

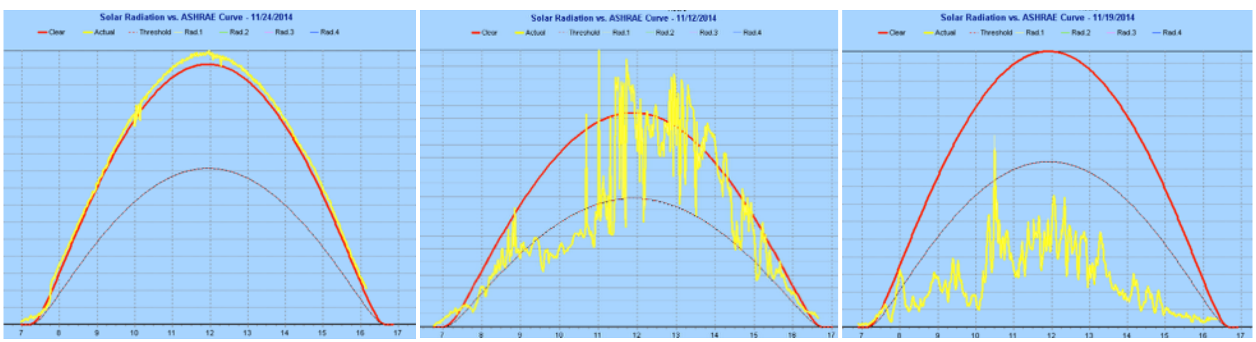



**Figure 7.3** - SolarTrac irradiance plots for November 24th (right), 12th (center), and 19th (right) 2014. The x-axis is time of day and the y-axis is irradiance. The thick red line is pre-calculated irradiance for clear sky conditions on that day. The thin red line represents the 60% clear sky irradiance threshold. The yellow line is the irradiance measured by the rooftop sensor (Note the y-axis is scaled based on plotted data and is different between the plots). The left plot is a day with clear sky conditions all day, note the measured irradiance (yellow) follows the clear sky irradiance (red). The center plot is a day with partly cloudy sky conditions, note the irradiance transitions above and below the 60% threshold many times. The right plot is a day with overcast conditions, note the measured irradiance stays below the 60% threshold for most of the day.

When the sun is shining the controller positions the shade to limit the depth to which the sun shines into the building. In FLEXLAB the sun was permitted to shine 36 inches into the space, this distance is configurable in SolarTrac. The depth of penetration is calculated using the solar profile angle (figure 7.4). The profile angle is the sun angle above the horizon when the sun is projected into a plane perpendicular to the facade.

When the irradiance is below the threshold, SolarTrac considers the sky condition to be overcast and the shade is kept up. When the sky transitions from cloudy to sunny (the measured irradiance goes above the threshold) the shade will deploy to the depth limiting position immediately. However if the sky transitions from sunny to cloudy, the controller will delay raising the shade until after the irradiance remains below the threshold for 10 minutes. The delay prevents frequent shade movements during partly cloudy conditions.

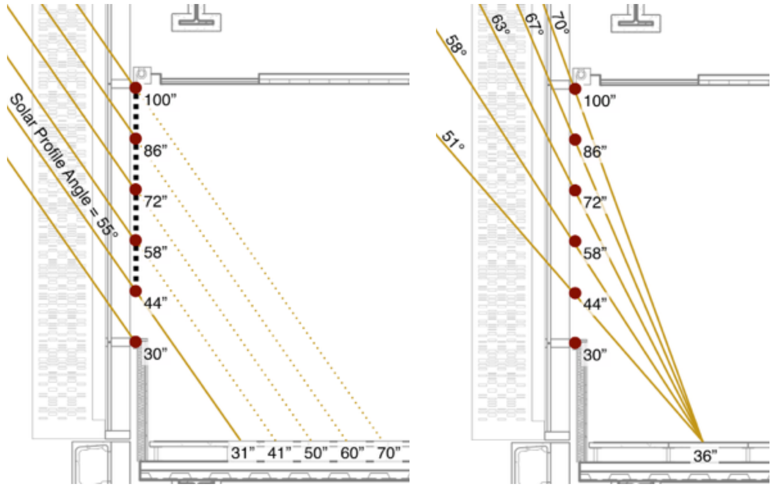


**Figure 7.4** - Section detail illustrating solar profile angle calculations. Left: Calculating sunshine depth for each shade stop position using solar profile angle. Right: Calculating cutoff profile angles for each shade stop position for a 36" sunshine depth (user defined). Window positions and shade stop heights shown are for B35 (Flexlab windows were positioned lower in the facade).

In addition to the rooftop sensor, the MechoSystems shade system has a window mounted illuminance sensor ("glare sensor") that monitors illuminance on the window. If the illuminance is above a threshold (7000 lux) the window shade is lowered. The window sensor detects bright overcast conditions that may cause glare, and causes the shade to lower when the system would otherwise tell the shade to be up (based on the rooftop sensor). In addition, the window sensor can supplement the rooftop sensor when the sun is low in the sky. The rooftop sensor is less reliable at determining sky conditions for low sun angles, but the window sensor can detect high illuminance on the facade from low angle sun.

## 7.3 Testing

### Limiting Sunshine Depth

The charts in figure 7.5 illustrate how well the shading system adheres to the goal of limiting sunshine depth to 36 inches. When the red line is below the shaded area the sun shines further than 36 inches into the building. Generally the shade movements track the profile angle curve (red line), though the shade movements might be more conservative than necessary. For example on November 4th at 11am the shade goes to fully closed about an hour before the profile angle crosses the cutoff threshold (user defined). The shade raising before sunset is caused by ocean fog, which typically engulfs Berkeley in the evening from the west. For the East facade, recall from section 2 that we are testing the mirror orientation, so conditions plotted on the chart in figure 7.5 as sunrise (just before 6 am) in reality occurred at sunset.

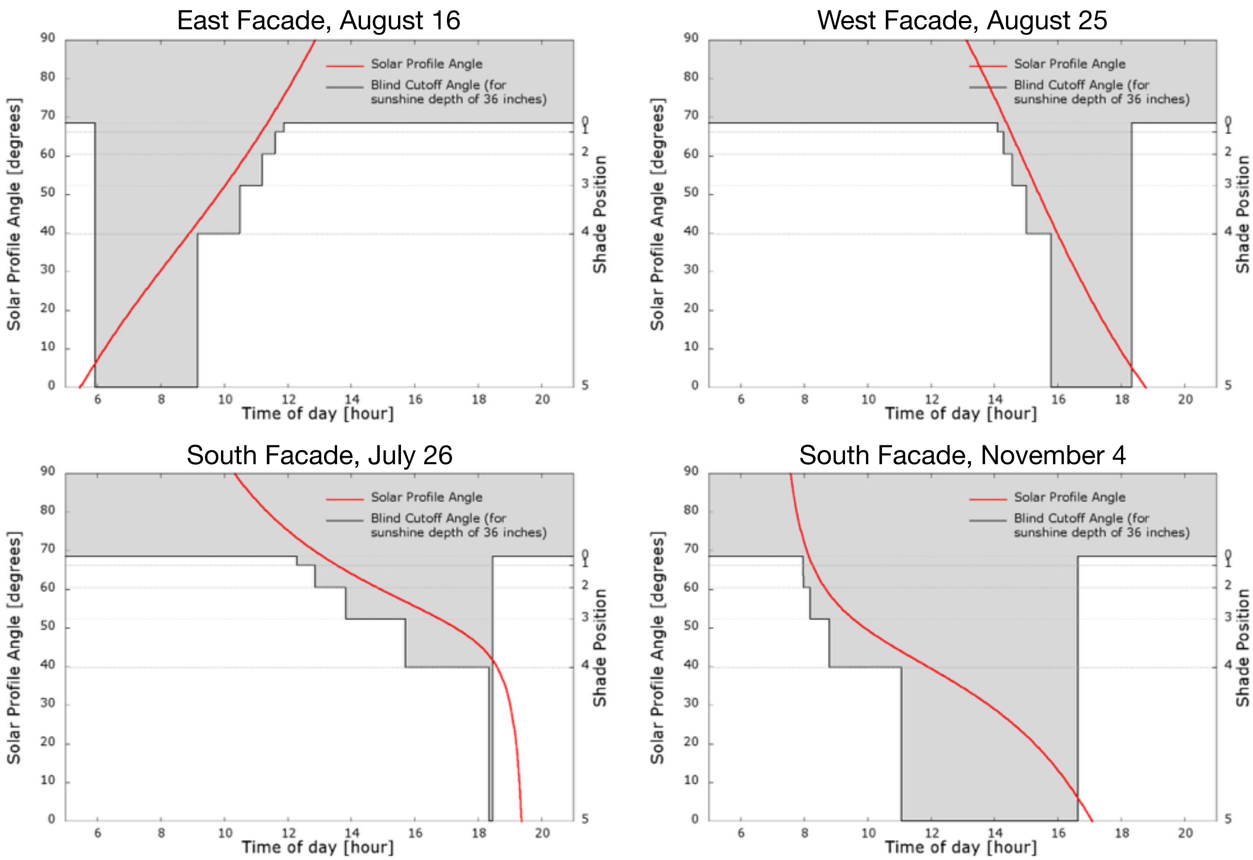



**Figure 7.5** - Charts of shade movements overlaid with solar profile angle for sunny days. The right y-axis shows the shade stop position number while the right axis shows the solar profile angle. The shade stops are plotted at the profile angle of the shade taken from a point on the floor 36" from the window. If the solar profile angle (red) is lower than the blind cutoff angle (shaded) the sun will shine deeper than 36" into the building.

## Daylighting vs. Glare Tradeoff

As the shades close the electric lighting increases output to compensate for the reduction in daylight. To understand the tradeoff between lowering the shade one position and using additional energy for lighting we can examine the lighting power consumed by both fixates in the test cell just before and just after the shade moves. Table 7.3 shows the average lighting power just before and just after the shade moves from one position to another for all of test cycle 3. Moving the shade position 0 to 1 has little effect on the lighting power (3%) while moving the shade from position 4 to 5 has a much greater effect on lighting power (+76%).

This demonstrates that keeping the shade open just a little bit helps reduce lighting energy use. Sunshine depths exceeding 36 inches have little consequence as long as the sun is not shining on people or desks. We recommend setting the bottom shade limit above the sill to allow daylight to enter below the shade.

**Table 7.3** - Effect of shade movements on lighting power.

| OLD POSITION | NEW POSITION | AVERAGE LIGHTING POWER BEFORE | AVERAGE LIGHTING POWER AFTER | PERCENT CHANGE IN LIGHTING POWER |
|---|---|---|---|---|
| 0 | 1 | 68 W | 70 W | +3% |
| 1 | 2 | 73 W | 87 W | +16% |
| 2 | 3 | 84 W | 112 W | +33% |
| 3 | 4 | 97 W | 141 W | +45% |
| 4 | 5 | 98 W | 174 W | +76% |

## Overcast Sky Glare

There were a few instances during overcast conditions where the daylight glare index crossed the threshold into perceptible glare. These occurred at times of bright cloud cover when the shade was fully raised. Ideally the sensor in the window would recognize that despite being overcast, the sky viewed through the window is bright enough to cause glare, and trigger the shade to deploy.

During the first test, when the camera was 80 inches from the window, DGP during overcast conditions peaked at 0.376, subjectively ‘perceptible glare’ (figure 7.6). During the second test cycle, when the cameras were placed 3 feet from the window, there were a few days when glare reached the intolerable glare level. The glare reached this level at times when the sky was transitioning from overcast to clear and the shade didn’t react until late in the sky transition. There were also times where the glare was in the “perceptible” and “disturbing” and the shade remained up (Figure 7.7). At these times the sky was overcast. This shows that a person sitting with their head three feet from the window may experience discomfort at times when the shade is raised and the sky is overcast.

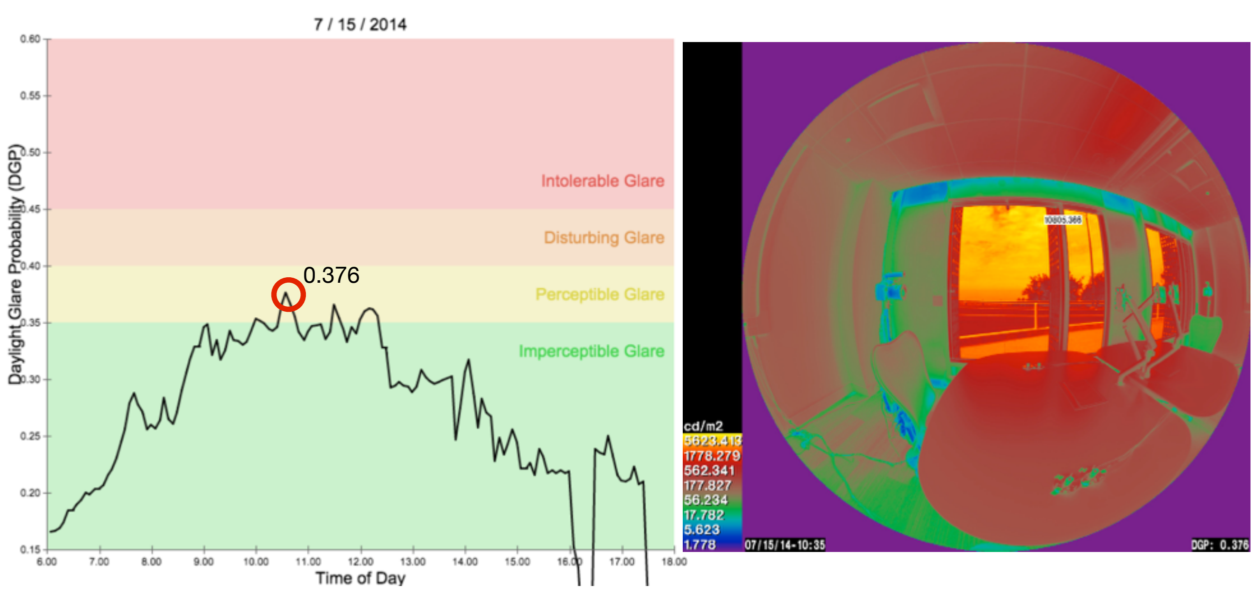



**Figure 7.6** - July 15 - When the shades are up on an overcast day, glare rating crosses into the “Perceptible Glare” range on three occasions with a peak DGP of 0.376 at 10:35 PST. The image on the right shows the field of view during the peak DGP occurrence.

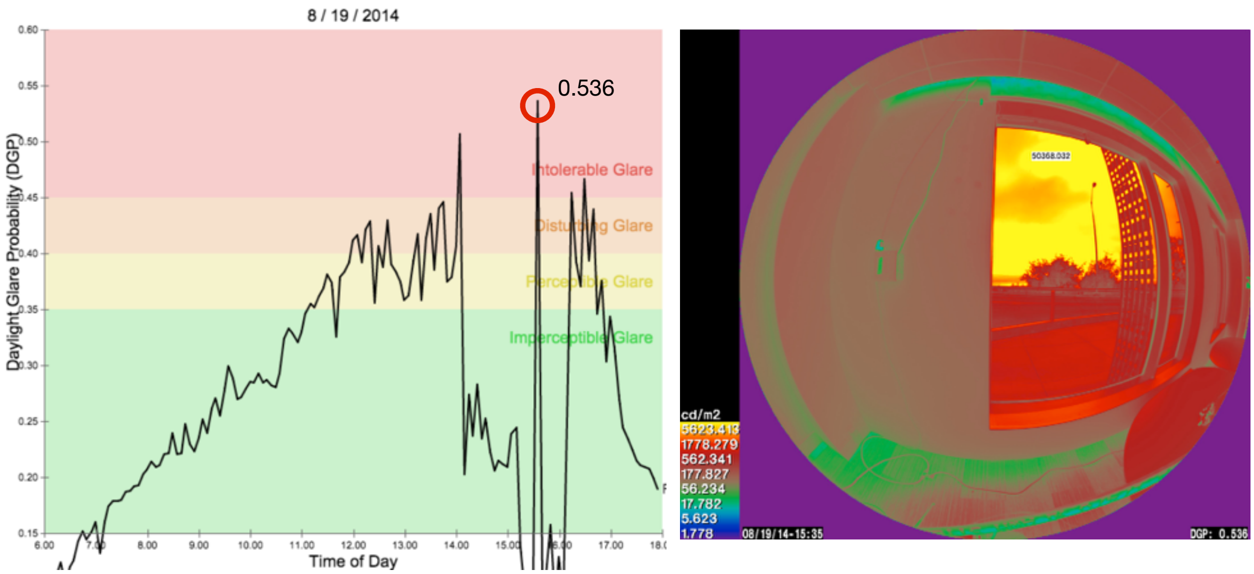



**Figure 7.7** - July 19 - When the shades are up on an overcast day, glare rating crosses into the “Intolerable Glare” range (shaded red) on three occasions when the sky was transitioning between overcast and clear. The image on the right shows the field of view during the peak DGP occurrence at 15:35.

Based on these results the threshold for the windows based sensor should be reduced at locations where occupants will sit within 3 feet of the facade and face towards the window.

## Shade Fabric Selection

Two roller shade fabrics were installed in the FLEXLAB mockup. Properties of the shades are provided in table 7.1. The dark colored shade offered a better view through the shade, particularly when the sun was shining on the shade. The lighter colored shade had a higher diffuse transmission reflection compared to the dark shade. The additional diffuse light emanating from the lighter shade creates a veiling luminance that masks the outdoor view. The difference in view is illustrated in figure 7.8.

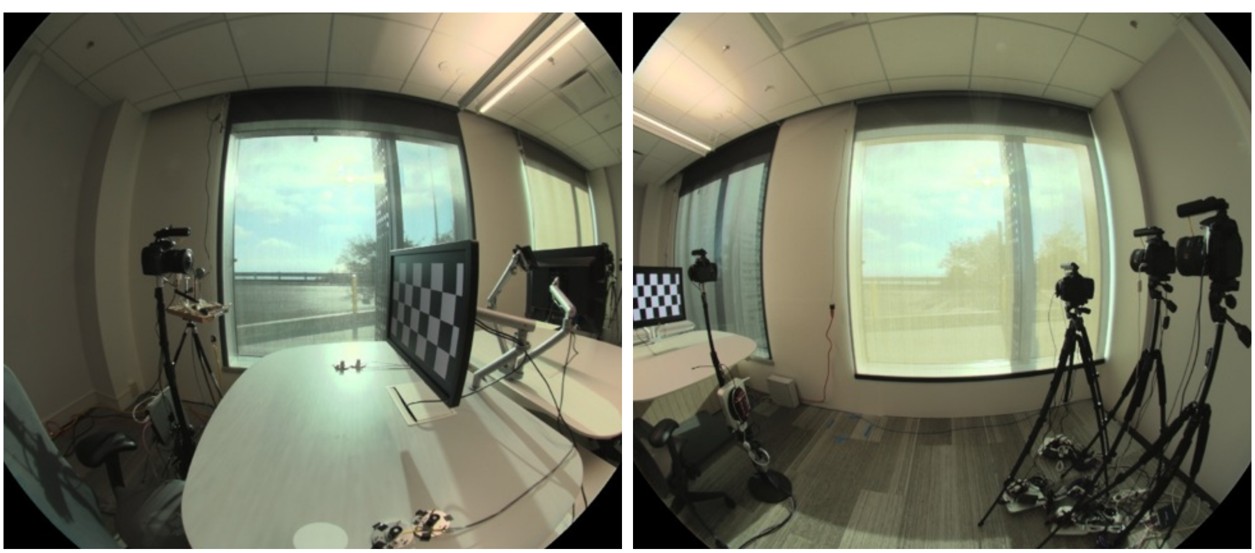
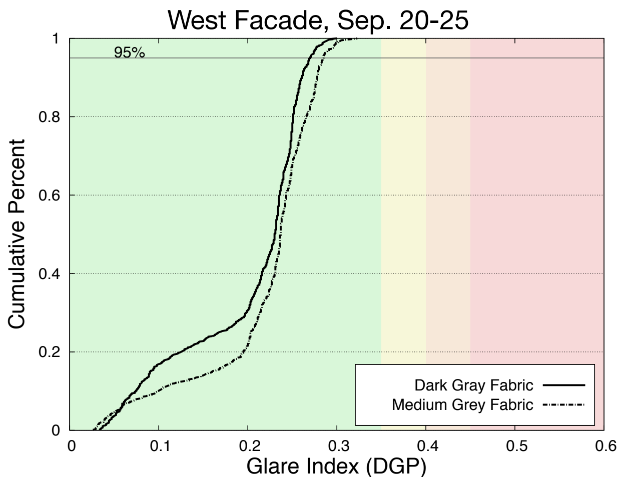
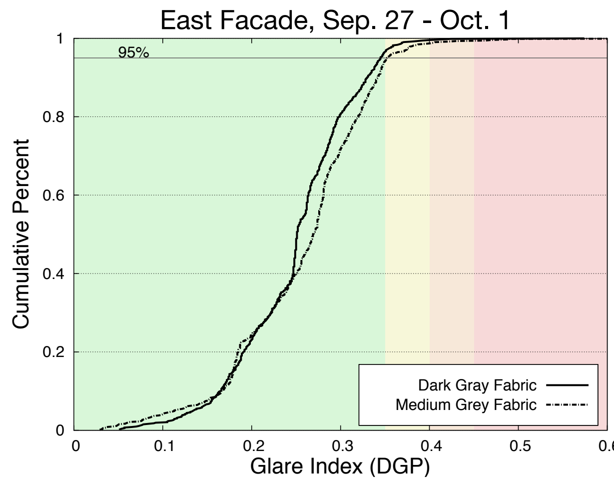
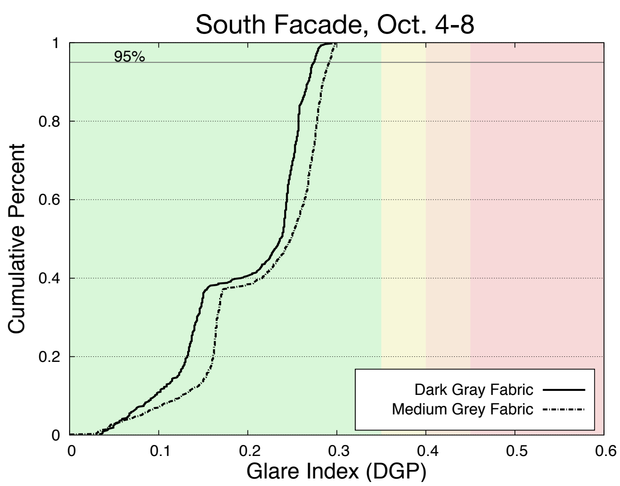


**Figure 7.8** - Views of the two types of shade fabric at a time when the sun is shining on the window. The left image is a dark grey colored shade. The right image shows a medium gray colored shade. The lighter shade fabric exhibits more veiling luminance that hinders view through the facade. Glare is slightly lower in the left image (DGP=0.341) compared to the right (DGP=0.345).

The lighter colored shade exhibited a consistently higher DGP than the darker shade. The difference in DGP between the two shades is generally small for any snapshot in time as illustrated by figure 7.9. The cumulative distribution plots in figure 7.9 illustrate that the dark shade has more occurrences of DGP below a given threshold for any threshold above 0.28, though the CDF curves for each shade are relatively close together. Applying Weinold's glare class ratings, both shade fabrics are class 'A' for West and South. For the east facade, the dark shade provides an 'A' class environment, while the lighter shade provides a 'B' class environment.




| FACADE | SHADE COLOR | 95% LIMIT | TOP 5% BAND | CLASS |
|---|---|---|---|---|
| WEST | Light | 0.285 | 0.299 | A |
| | Dark | 0.270 | 0.283 | A |
| EAST | Light | 0.353 | 0.406 | B |
| | Dark | 0.345 | 0.375 | A |
| SOUTH | Light | 0.292 | 0.301 | A |
| | Dark | 0.274 | 0.289 | A |

**Figure 7.9** - Cumulative distribution plots comparing two shade fabric colors for each facade orientation tested. Cameras were positioned cameras were centered on the window at a distance of 80 inches from the window. The table shows the 95% DGP threshold, the average DGP in the top 5% band and the Wienold office class rating for each shade color.

Since the lighter colored shade transmits more light, we expect that lighting energy savings would be greater if light colored shade fabrics were used. However, since both shade fabrics were installed at the same time, we are unable to determine the extent of additional energy savings that could be achieved with lighter colored shade fabric.

## Anecdotal Experience

After testing concluded, various LBNL staff have occupied the test cell (on a volunteer basis). The occupants performed computer based work while sitting in the desk near the window for three hours or more. Of the six people who have worked at the desk close to the window to date, only three were in the FLEXLAB mockup during a clear sky conditions. Two of the three occupants felt that the shade provided sufficient protection from the orb of the sun, while the third thought that the sun was somewhat distracting and thought the shade fabric could be a little bit denser.

During partly cloudy conditions occupants felt that the shades could have been up more often. Determining whether the shade should have been up is difficult, though perhaps on dynamic days when the irradiance is between the calculated clear sky and 60% threshold the shade could go to a moderate protection position (perhaps 54 inches) instead of deploying to the sun blocking position, when the sun blocking position is lower than the moderate protection position.

# 7.4 Conclusions

- MechoSystems's SolarTrac software does a good job adjusting the shade to tracking sun movement, though it might be overly conservative. **Recommendation:** Reduce safety factor in SolarTrac or increase the permitted sunshine depth to counteract conservative adjustment.
- Overcast sky glare may be a problem if occupants are seated within three feet of the window and facing towards the window. **Recommendation:** Where desks are situated so that people are sitting within three feet of the facade and facing the facade the window sensor threshold should be reduced to deploy the shades at lower sky luminance.
- Moving the shade from position 4 to 5 (fully closed) on average increases required lighting power by 76% while moving from position 0 (fully open) to 1 only increases required lighting power by 3%. **Recommendation:** Program the lower stop limit to be 6-10 inches above the window will admit some daylight and reduce lighting energy use at times when the shade would otherwise have been fully closed (see figure 7.10).
- The dark grey shade fabric provides a better view to the outside compared to the medium grey shade fabric. **Recommendation:** Use dark shade fabric to improve views to the exterior.

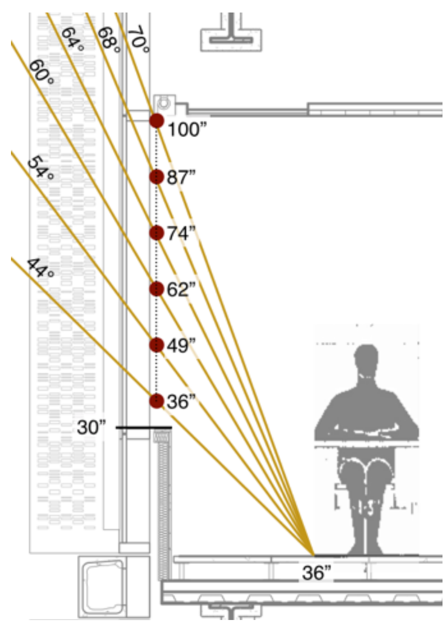



**Figure 7.10** - Section detail illustrating the proposed shade stops. The lowest stop is 36" above the floor, 6" above the sill. Seated eye height is typically 44-48 inches above the floor.

- The dark grey shade results in marginally lower DGP compared to the medium grey fabric. **Recommendation:** Use dark shade fabric to improve visual comfort.
- Anecdotally, 3% openness provides sufficient glare protection for some people but not for others. **Recommendation:** Inform occupants that they should consider their preference for shading when selecting a seat for the day.
- Zoning and manual override controls were not investigated in this study. **Recommendation:** It will be important to provide occupants with information about how the automated shading system works and its control intent prior to move in. In prior studies, education was one of the most significant factors that correlated to end user satisfaction with automated controls.

8. Comfort and System Performance

8.1 HVAC Performance....48
8.2 Thermal Comfort....52
8.3 Visual Comfort....60
8.4 Furniture Position Relative to Facade....62
8.4 Lighting Energy Savings....66
8.5 Phase Change Floor Tiles....67

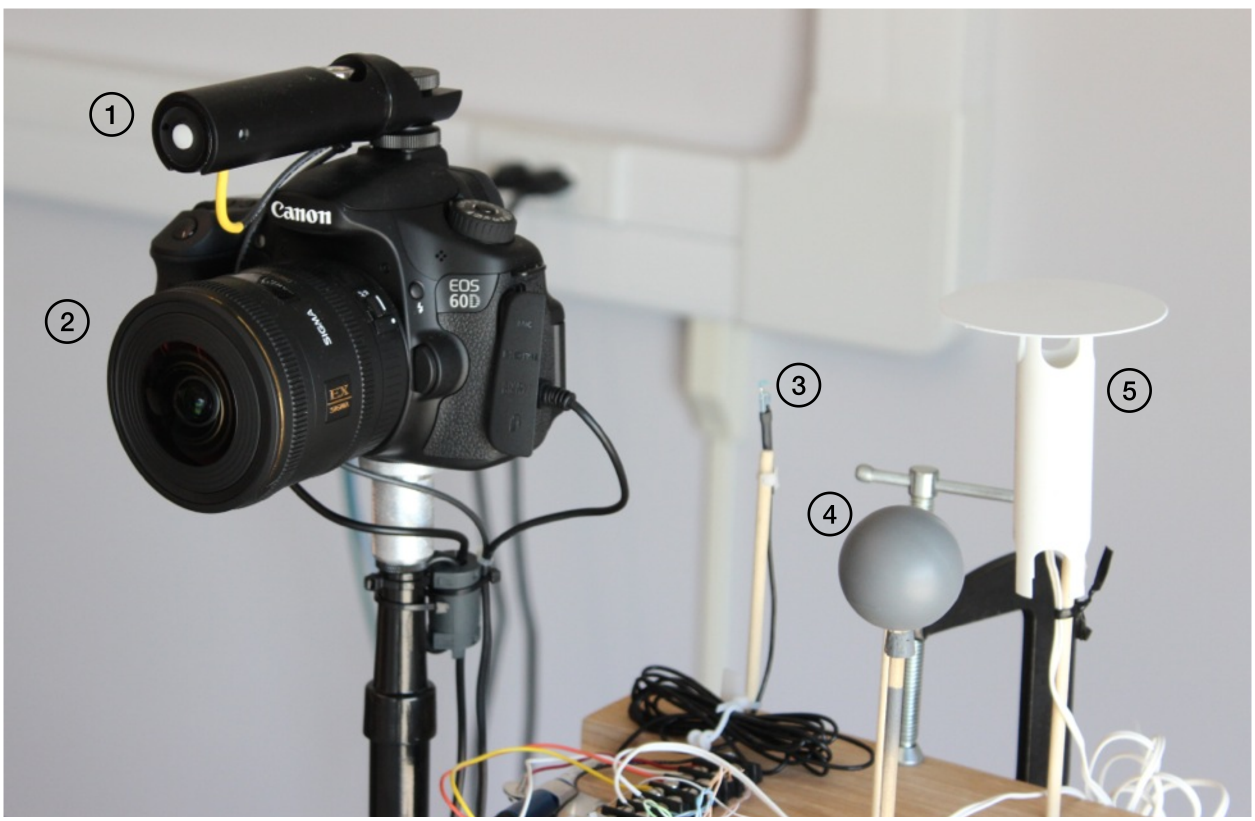



**Figure 8.1** - Comfort sensing equipment: (1) Licor illuminance sensor for calibrating HDR images taken by (2) DSLR camera with 180° lens, (3) air velocity sensor, (4) mean radiant globe temperature sensor, and (5) shielded temperature sensor.

## 8.1 HVAC Performance

As part of the FLEXLAB experiment for Webcor/Genentech, LBNL performed a limited thermal comfort and thermal load study. The analysis period for both HVAC and Thermal comfort was September 20th – October 12th. During this period two different façade orientations were evaluated (West and South). Each orientation was evaluated for 6-7 days. The data for September 20th and 21st is not usable since these were weekend days, and the HVAC system initially was programmed to only control the temperatures on weekdays, after September 22nd the HVAC system operated 7 days a week. The South orientation was also tested for 2 days with the interior shade permanently retracted (October 11,12). The unshaded condition gives a good impression of the thermal comfort impact of the shade. All times in this section of the report (including graphs) are in Pacific Daylight Time (PDT).

### HVAC setpoints

Based on the information provided by Webcor, the setpoints and targets in table 8.1 were used to control the HVAC system in the FLEXLAB mockup space.

The system was operated from 7am-7pm local time (PDT) and was forced to be 'occupied' through an override. Outside of the 7am-7pm period the system was floating without any control. Even though the Sequence Of Operation (SOO) called for control from Monday – Friday only, the setpoints were maintained on Saturday and Sunday to gather more data during the limited test period. The Summer and Winter setpoints were used as Cooling and Heating setpoints, the system does not cool or heat using the plant when the space temperature is between 68 F and 74 F.

**Table 8.1** - HVAC system setpoints

| PARAMETER | SETPOINT |
|---|---|
| Cooling airflow max | 790 CFM |
| Heating airflow max | 390 CFM |
| Minimum airflow | 235 CFM |
| Cooling supply air temperature | 55 F |
| Heating supply air temperature | 90 F |
| Summer Room temperature setpoint | 74 F |
| Winter Room temperature setpoint | 68 F |
| Minimum outside air percentage | 10% |

Figure 8.2 shows the HVAC performance on a typical day with a south facing test. Figure 8.3 and 8.4 show the climatic conditions for this day. The fan turns on at 7am to the maximum speed and cools the space using outside air (the outside air damper is 100% open) because the space temperature is >74F. The outside air damper remains open until after 9am and the space is continued to be cooled by outside air. This 'pre-cooling' with outside air in the morning delayed the moment at which the chiller had to turn on (around 2pm) therefor saving energy, but at the expense of thermal comfort as it will be discussed in section 8.2. Around 1:45pm the space temperature reached 74F and the supply air fan speed increases, cooling the space until 7pm when the system was shut off.

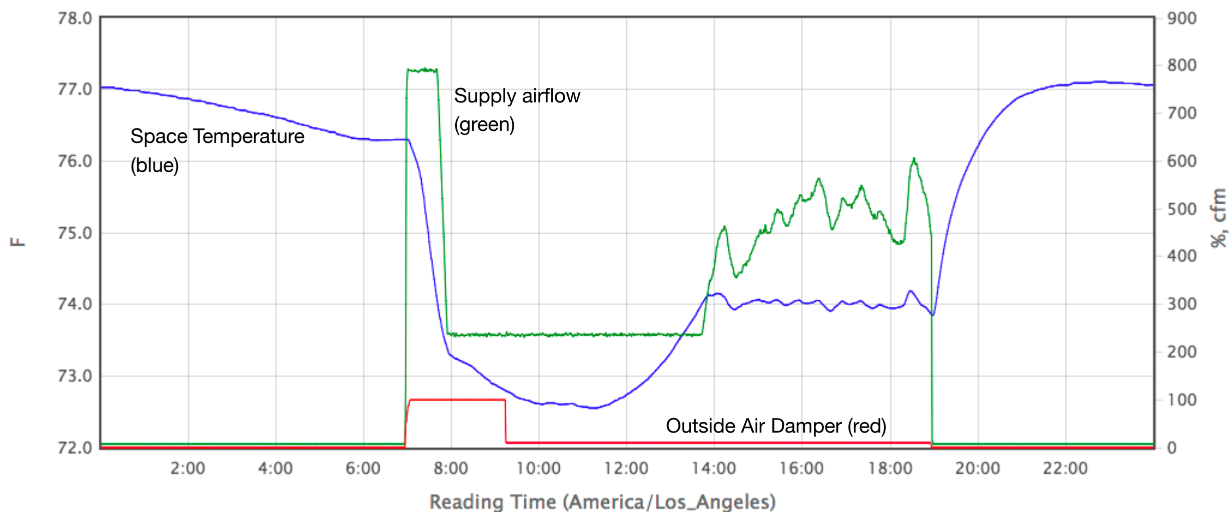


**Figure 8.2** - HVAC operation on October 5th 2014.

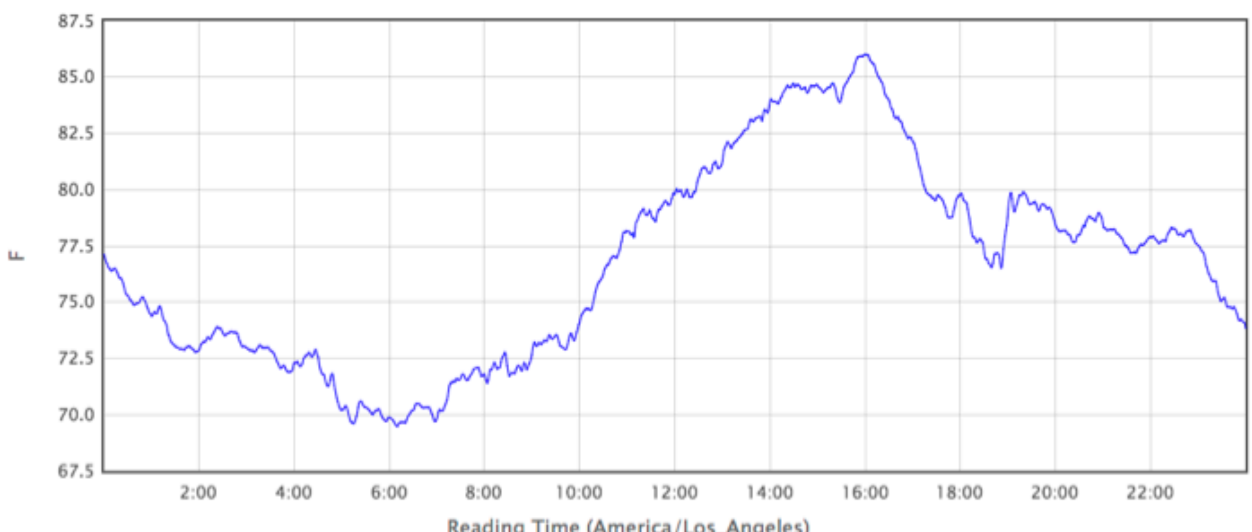


**Figure 8.3** - Outside air temperature on October 5th, 2015

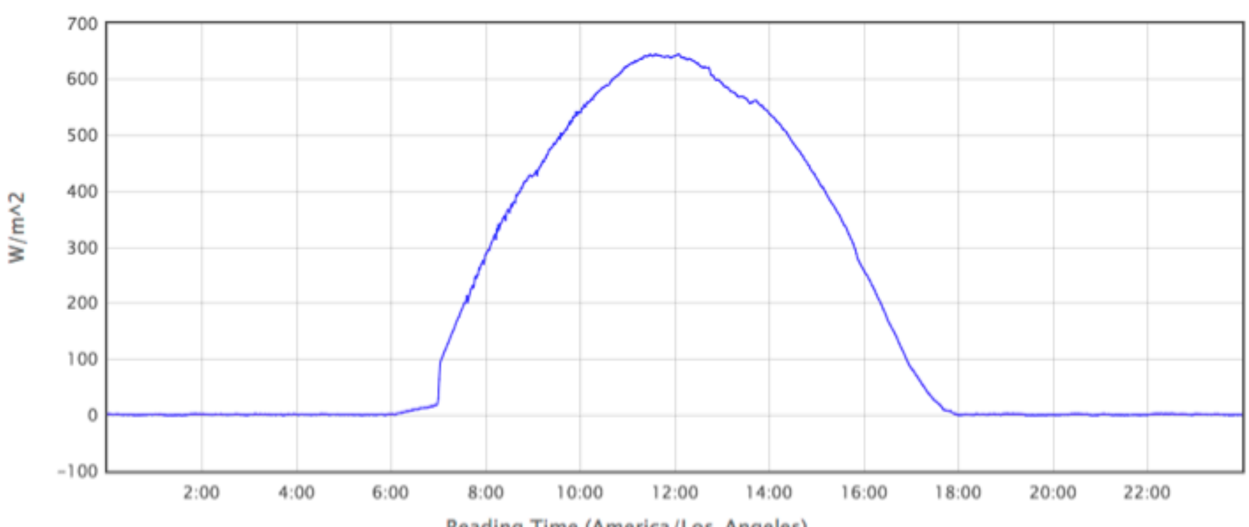


**Figure 8.4** - Global solar irradiation on October 5th, 2015

The thermal load in the space was calculated by multiplying the supply air flow by the difference between space temperature and supply air temperature measured in the air handler. The thermal load is dominated by heat transfer through the façade. There was minimal electrical load in the space (LED lighting and 4 LCD monitors). All other walls, roof and the floor surfaces are highly insulated, though the door to the space is only slightly insulated and had a marginal seal. To ensure thermal equilibrium, data were only used if no one entered the test facility 12 hours prior to and during the measurement period. Figure 8.3 shows the thermal load for October 5th 2014 (the same day as used in Figure 8.2). The total space cooling energy for that day was 22.4 kWh from 7am-7pm (PDT). This is not necessary the HVAC load, since the free cooling in the morning only takes fan energy, no chiller energy. The HVAC system and the sensors in this FLEXLAB test cell have not been calibrated, therefor the thermal load numbers should be used with caution.

Figure 8.5 shows the space cooling load for both the south and west facing test periods. The total cooling load for each day from 7am-7pm was integrated. Figure 8.6 shows the daily solar horizontal irradiance (not corrected for vertical incidence and façade orientation) and figure 8.7 shows the minimum, maximum and average outdoor air temperatures. The missing data from September 26th through October 3rd is because the facility was facing a 'simulated' east orientation for daylighting purposes only, the data was not usable for thermal analysis. The average cooling energy during the west orientation (September 22-25) test period was 6.3 kWh/day and during the south orientation (October 4-10) it was 17.2 kWh/day.

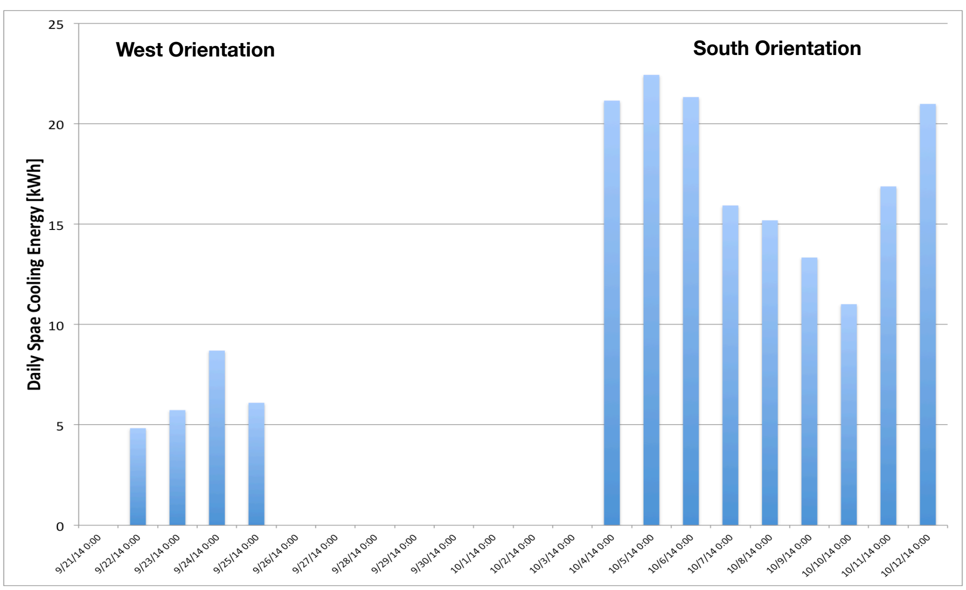


**Figure 8.5** – Daily cumulative space cooling energy from 7am-7pm

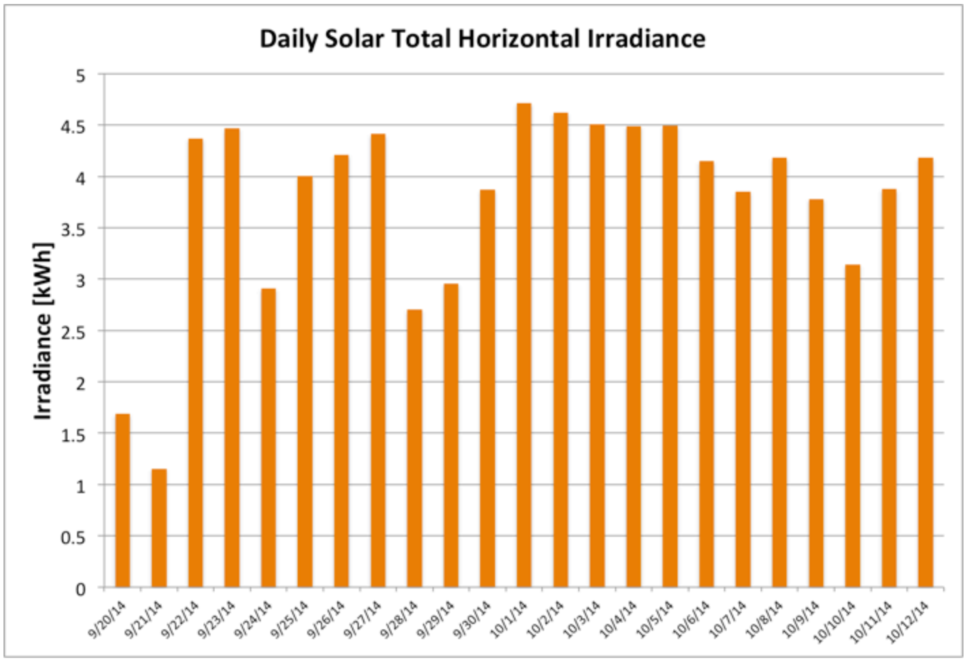



**Figure 8.6** – Daily solar total global horizontal irradiance (7am-7pm)

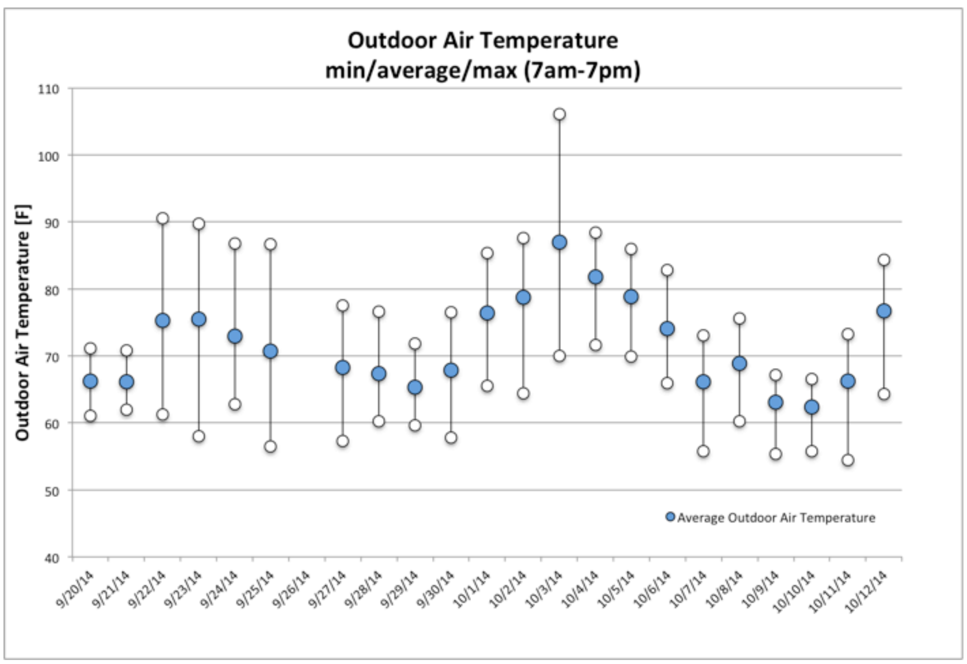



**Figure 8.7** – Daily outdoor air temperature, min,avg,max (7am-7pm)

## 8.2 Thermal Comfort

Thermal comfort was evaluated using the Predicted Mean Vote (PMV) method, developed by Fanger, which forms the basis for ASHRAE Standard 55-2010 “Thermal Environmental Conditions for Human Occupancy”. Calculations were performed using the UC Berkeley Center for the Built Environment Thermal Comfort Tool (http://smap.cbe.berkeley.edu/comforttool). PMV values range from +3 (hot sensation for occupants) to -3 (cold sensation for occupants). A PMV of +1 indicates a slightly warm thermal sensation and -1 slightly cold. ASHRAE Standard 55 specifies that the PMV should be between -0.5 and +0.5 to meet the standard for comfort. Another indicator is the Predicted Percent Dissatisfied (PPD) which is a quantitative measure of the thermal comfort of a group of people at a particular thermal environment. Figure 8.8 shows the relationship between PPD and PMV. The figure shows that at -0.5 and +0.5 the PPD is 10%, the PPD never gets below 5%.

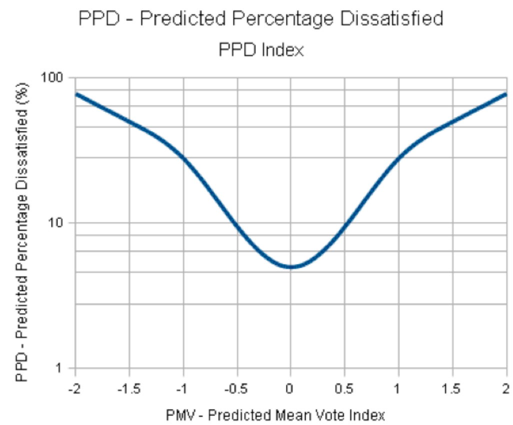



**Figure 8.8** – relationship between PPD and PMV from engineeringtoolbox.com

### Measurement setup

A thermal comfort station (TCS) (see Figure 8.9) was placed within one of the workstations near the left window. The TCS includes a radiation shielded air temperature sensor, a globe temperature sensor (grey painted ping-pong ball) and an air velocity sensor. Mean-radiant-temperature (MRT) is calculated from the globe temperature, correcting for local air temperature and air speed. The TCS was placed at seated head height. The TCS was placed 42” away from the glass. A relative humidity (RH) sensor was also added to the room. For the comfort calculations we assumed a seated typing person (met=1.1), dressed in typical summer male indoor clothing for Genentech consisting of underwear, t-shirt, calf-length socks, shoes, long-sleeve dress shirt, straight thick trousers, which results in a clo value of 0.66. This matches well with a female outfit from ASHRAE 55 of knee-length skirt, long-sleeve shirt, full slip (clo=0.67). The


**Figure 8.9** - Thermal Comfort Station, the white tube with cover contains the shielded air temperature sensor, the grey ball is the mean radiant temperature sensor the small blue sensor is the air velocity sensor.

typical summer indoor clothing suggested in ASHRAE 55 with a clo value of 0.5, was considered not representative for Genentech based on discussions with Genentech team members.

## Results

In figure 8.10 we can see the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) for a typical day. In the morning around 7:30am the calculated PMV is around -0.72 (see arrow in figure 8.10). This falls outside of the ASHRAE Standard 55 range of -0.5 to +0.5. The Predicted Percentage of Dissatisfied (PPD) is around 16%. The PPD and PMV are calculated for each minute of the day.

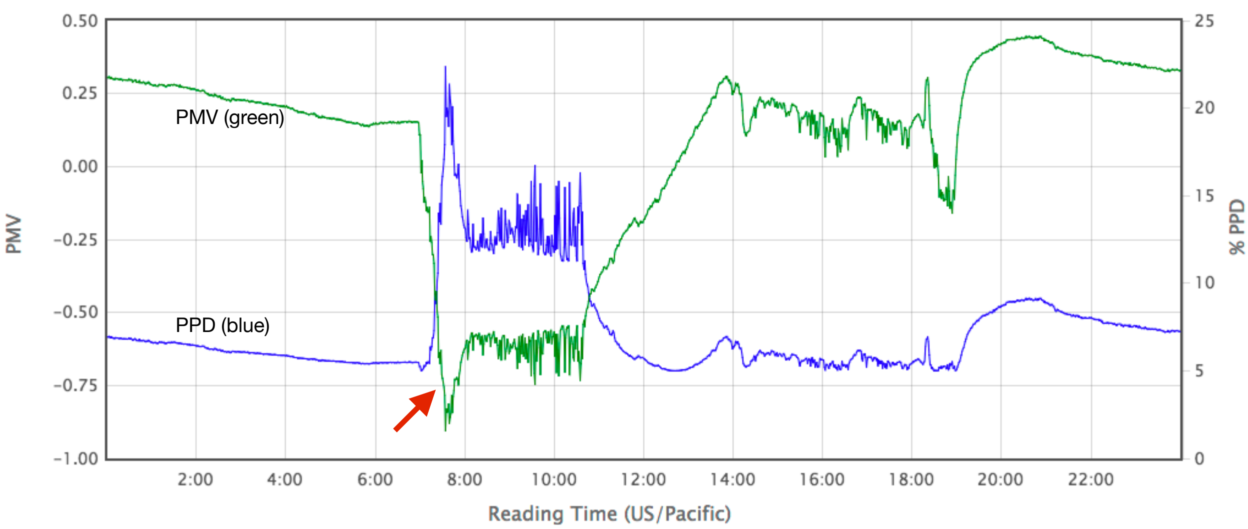



**Figure 8.10** - PPD and PMV on a typical day with the façade facing south, October 5, 2014

When we look closer at the observed conditions, we can investigate what causes the discomfort. On October 5th 2014 at 7:30am, the shielded air temperature was 74.7 F, the mean radiant temperature was 71.5 F, the air velocity was 24 f/m (0.12 m/s) and the relative humidity was 21.5%. Figure 8.11 shows the result of entering these values into the UC Berkeley Center for the Built Environment Comfort Tool. The bull's-eye symbol should be in the shaded region to meet the ASHRAE Standard 55. There are several methods to make this situation more comfortable. If the mean radiant temperature could be increased from 71.5F to 75F, the PMV would be -0.46 and the PPD 9%. Alternatively the occupants could wear warmer clothes.

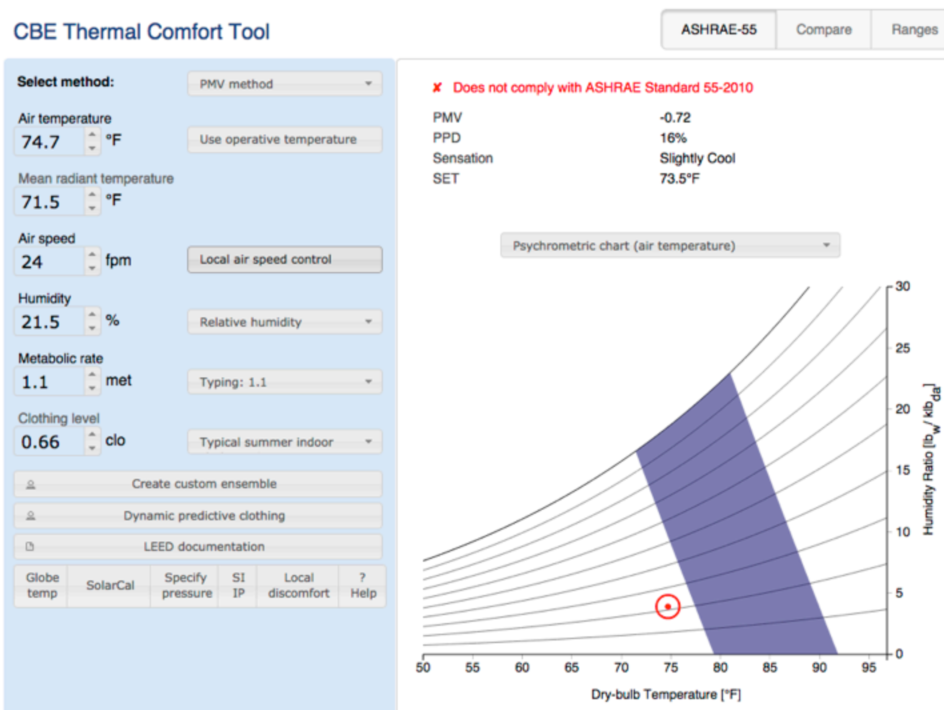



**Figure 8.11** - Output from Thermal Comfort Tool

When we modify the clothing assumption to a warmer outfit by adding a long-sleeve thin sweater (clo=0.25) we get a total clo value of (0.66+0.25)=0.91 which results in a PMV=-0.19which is quite good (figure 8.12).

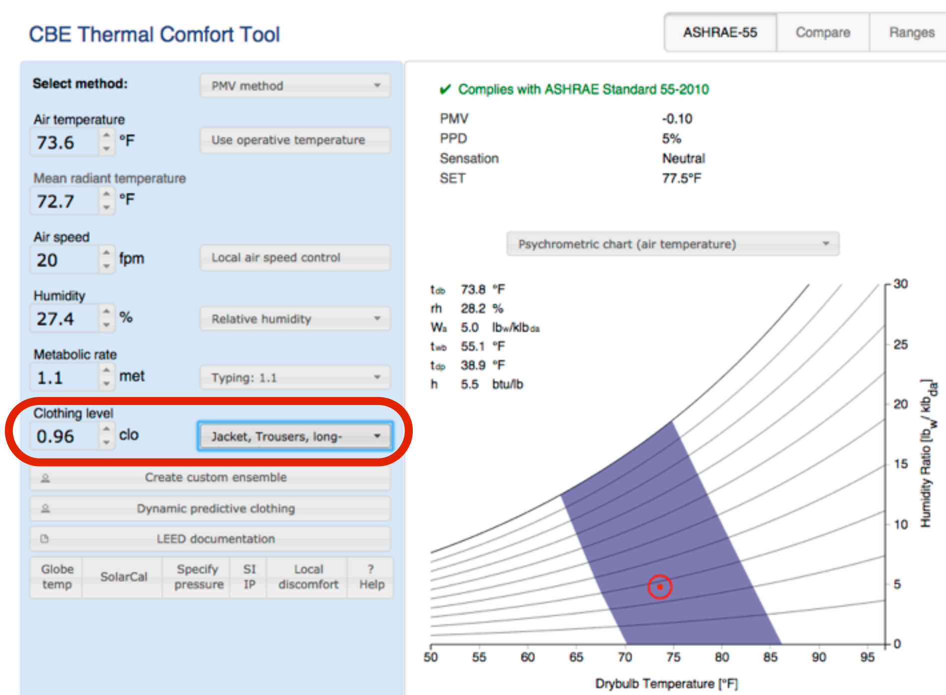



**Figure 8.12** - Results from increased clothing level.

Figure 8.13 shows the air temperature and mean radiant temperature (MRT) throughout the day on October 5th 2014. We can see that during the night and in the morning, when the glass is cold, the MRT is below the air temperature. This trend reverses around 11am when the shade gets warmed up from the sun. The local shielded air temperature is around 77F in the afternoon. Figure 8.10 shows that the average space temperature used to control the HVAC is 74F (meeting the setpoint) during this time. The local air temperature is higher near the window. The radiation shield reduces the effect of local short and long wave radiation, but does not completely eliminate it.

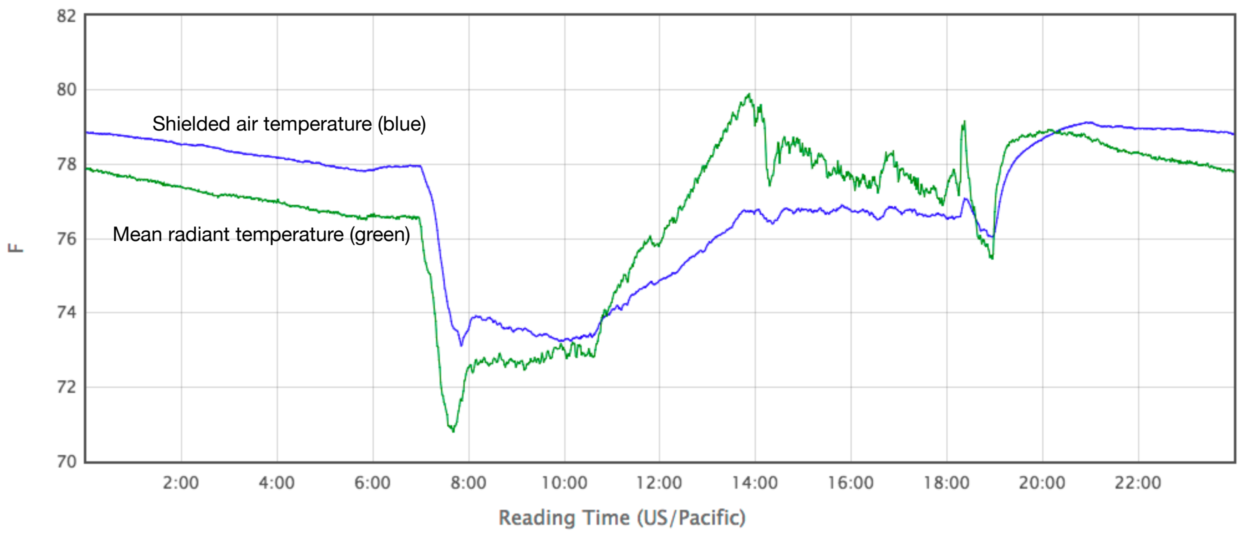



**Figure 8.13** - Air temperature and Mean Radiant Temperature (MRT) on Oct 5th

## Comfort Distribution

For each façade orientation, we can look at the distribution of PMV values throughout the day (7am-7pm). Data is collected each minute. Figure 8.14 shows a histogram of the PMV values from October 4th – 6th , during which the building was facing south and the thermal comfort station was

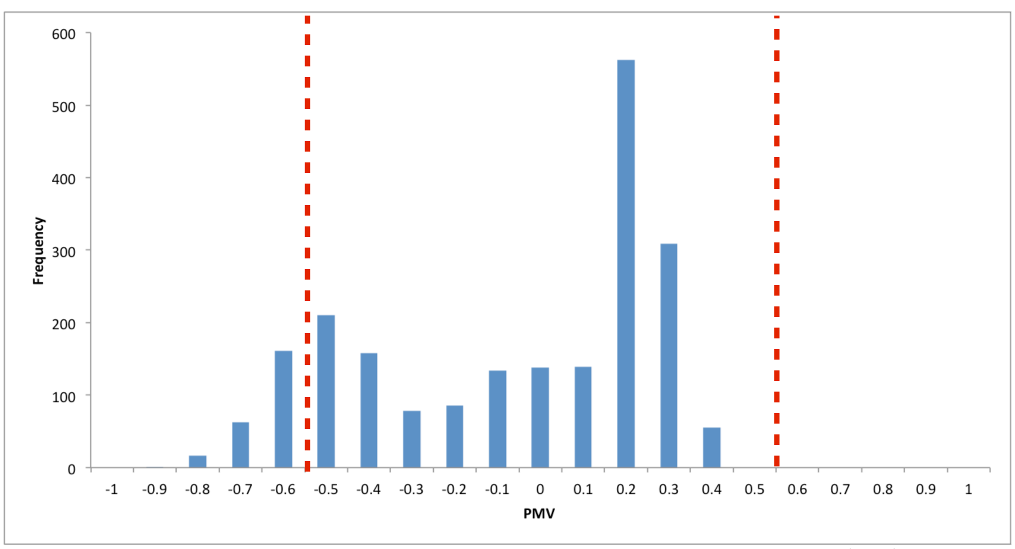



**Figure 8.14** - Predicted Mean Vote histogram for the south façade – 30” from glass, October 4th – 6th

placed close to the glass (30” from the glass). About 21% of the time between 7am-7pm the PMV was outside of the ASHRAE 55 comfort range. From October 7th-10th we placed the TCS at 42” away from the glass, which was the standard position. The PMV results are displayed in Figure 8.15. In this configuration the PMV is 19% of the time outside of the ASHRAE Standard 55 range. Note that the x-axis labels show the maximum value in the histogram bin, for example: the bar labeled -0.5 represents values between -0.6 and -0.5.

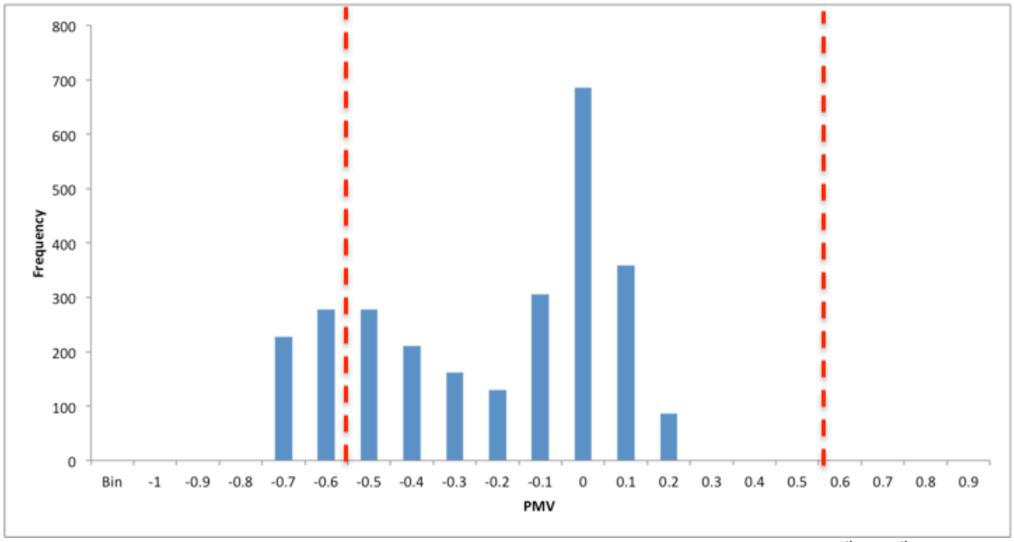


**Figure 8.15** - Predicted Mean Vote histogram for the south façade – 42” from glass, October 7th – 10th.

The same analysis was performed for the west façade. The thermal comfort 42” away from this façade is 18% of the time outside of the -0.5 to +0.5 PMV range. See figure 8.16 for the distribution of PMVs. If the PMV could be increased at each timestep by about +0.2 then all values would fall in the ASHRAE Standard 55 comfort range of -0.5 to +0.5

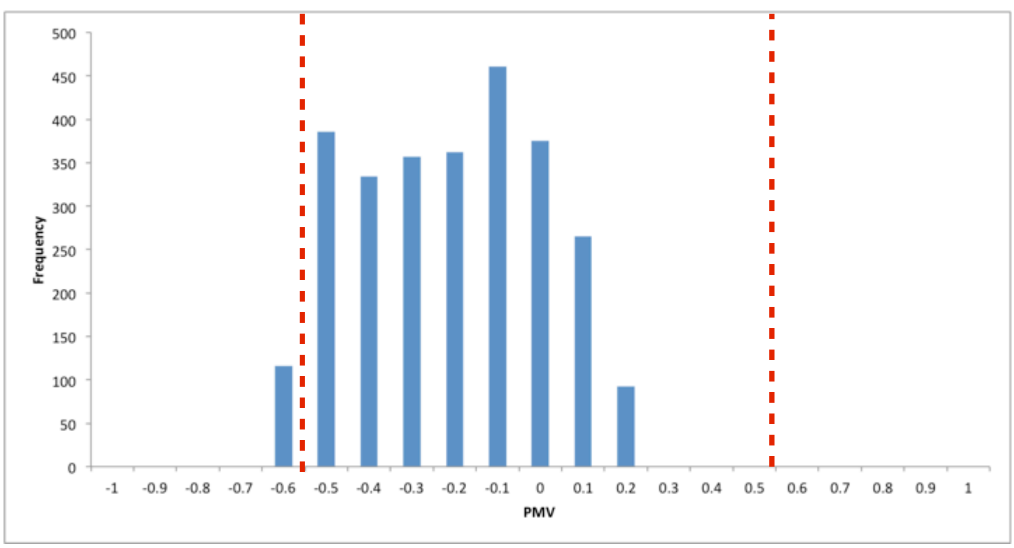


**Figure 8.16** - Predicted Mean Vote histogram for the west façade – 42” from glass, September 22nd – 25th

On October 11th and 12th the automated shade was overridden and the shade was fully retracted both days. Figure 8.17 shows the PMV for these two days, and figure 8.18 shows a distribution of PMV. Occupants were expected to be uncomfortable 28% of the time (PMV outside of -0.5 - +0.5 range). The overhangs provided partial shading which prevented the PMV values from increasing more. See figure 8.19 for a view of the shading.

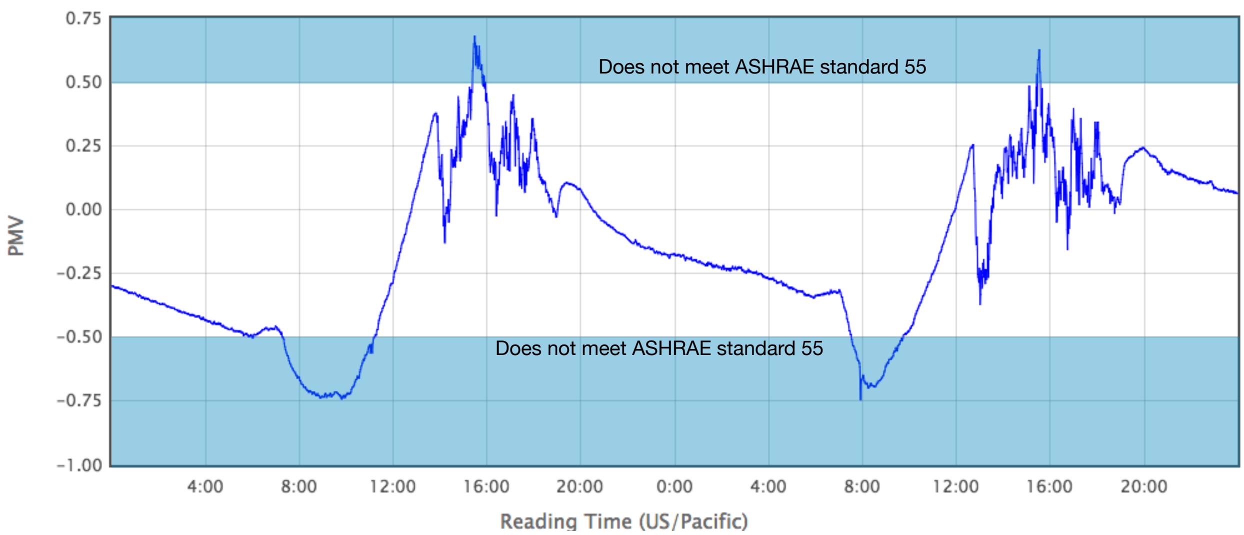



**Figure 8.17** - Predicted Mean Vote, 42” from south façade, no shade, Oct 11th and 12th.

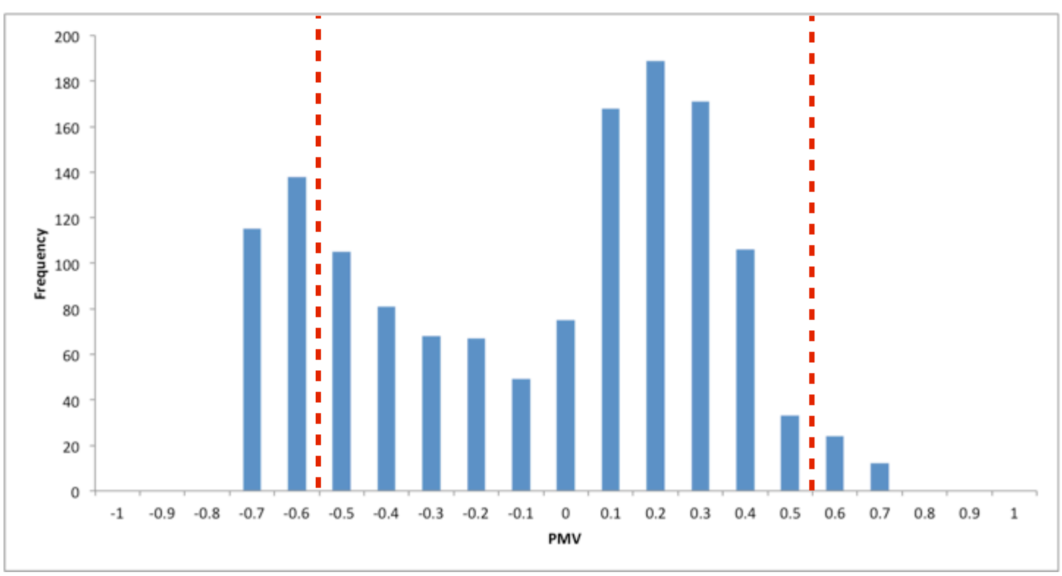



**Figure 8.18** - Predicted Mean Vote distribution, 42” from south façade, no shade, Oct 11th and 12th.

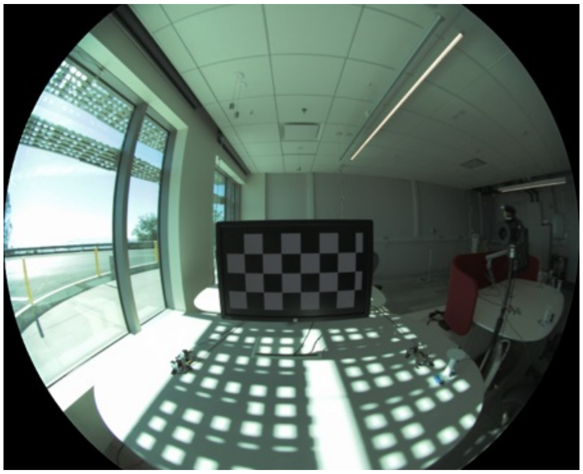


**Figure 8.19** - Partial shading provided by overhangs when the shade was retracted.

## Infrared Thermography

We performed Infrared Thermography on October 6th to look at the temperature distribution in the space. Figure 8.20 shows that the darker shade on the left has a slightly higher surface temperature than the shade on the right. The shadow pattern from the overhang can be clearly seen in the surface temperatures of the shade. The shade surface is as expected significantly hotter than the surrounding walls (39 C/102 F for the shade and 28 C / 82 F for the walls.) The image shows some hot air escaping from behind the shade and heating up the wall in the top 1/3 area of the shade (triangular yellow/green areas on the wall).


**Figure 8.20** - Infrared Thermography image with shade deployed – October 6th 3:45pm PDT.

## Conclusions

The thermal comfort analysis suggests that occupants seated near the facade will be comfortable around 80% of the time. The 20% of time where the observed conditions fall outside the ASHRAE Standard 55 are almost always due to occupants being cold (PMV <-0.5). Morning discomfort is mostly driven by cold surrounding surfaces, which results in a low mean radiant temperature. Sitting closer to the glass (30” instead of 42”) does not seem to make a large difference in the comfort ratings (21% vs 19% of time uncomfortable) (figure 8.14 and 8.14). The absorbed heat radiating from the shade when it is irradiated by the sun did not result in a sensation of being slightly warm (PMV >0.5) during the regular test period. Thermal comfort with the shade retracted (overridden) during sunny periods (figure 8.18) can result in some occupants feeling slightly warm (PMV >0.5), but glare concerns during these periods would result in more severe visual discomfort.

Only one thermal comfort station, located near the facade, was used for the experiment. Thermal comfort further from the facade is unknown but is likely to be better due to the increased distance from the relatively cold facade.

Using free cooling by supplying the space with outside air can delay the onset of the chiller, but needs to be carefully monitored because of potential comfort issues, especially in the early morning. Solutions that allow individual occupants to control their local thermal climate, such as controlling individual VAV boxes, can allow for greater comfort, and also result in more occupant satisfaction because of the feeling of control. The Comfy app from Building Robotics is an example of such a solution.

Daily cooling energy during the west facing experiments were around 6.3 kWh/day but significantly higher for the south facing experiment (17.2 kWh/day), see figure 8.5.

Reference:
Hoyt Tyler, Schiavon Stefano, Piccioli Alberto, Moon Dustin, and Steinfeld Kyle, 2013, CBE Thermal Comfort Tool. Center for the Built Environment, University of California Berkeley, http://cbe.berkeley.edu/comforttool/

## 8.3 Visual Comfort

HDR camera setups measured visual comfort during testing. Cameras were positioned as depicted in figure 2.5 for both the solstice and equinox periods.

### Summer Solstice

Visual comfort measurements close to the summer solstice were impacted by the lack of a shade in the right window. The camera oriented perpendicular to the right window looks directly at a window without a shade during the solstice condition. Additionally, there were occasions late in the day where the sun would shine through the unshaded window and affect visual comfort from the viewpoints close to the shaded window (figure 8.21). Nevertheless, visual comfort received an ‘A’ class rating for all facade orientations and all views (figures 8.20, 8.21 and 8.22), except for the view facing the unshaded window (Labeled ‘Perp. Right’ in the charts).

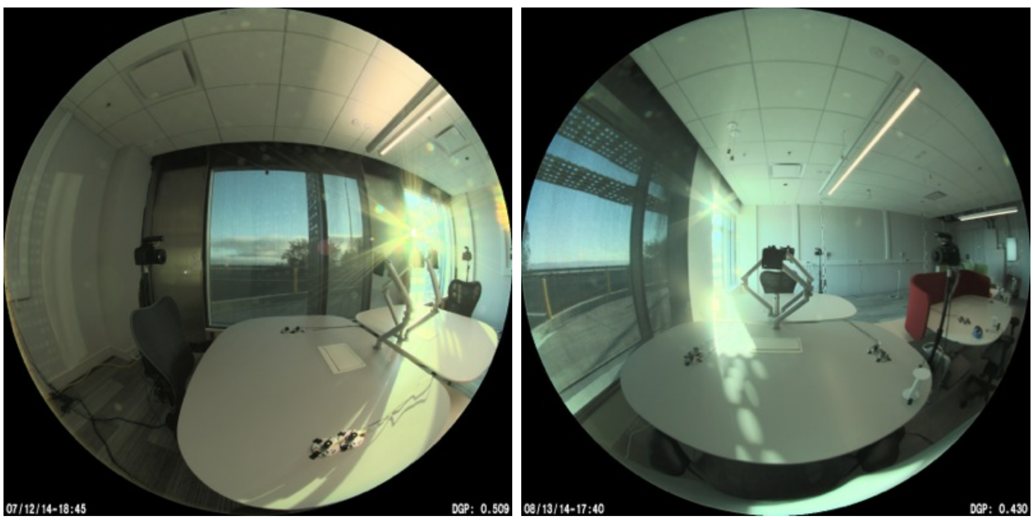
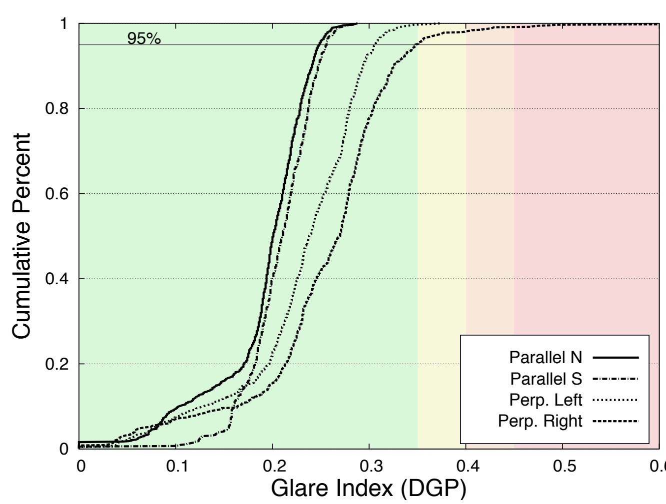



**Figure 8.21** - Instances where the sun shines through the unshaded window and affects visual comfort near the shaded window.

WEST FACADE - SUMMER SOLSTICE

| VIEWPOINT | 95% LIMIT | TOP 5% BAND | CLASS |
|---|---|---|---|
| Parallel to the window facing north | 0.249 | 0.262 | A |
| Parallel to the window facing south | 0.256 | 0.270 | A |
| Perpendicular to the left window (shaded) | 0.306 | 0.327 | A |
| Perpendicular to the right window (unshaded) | 0.348 | 0.422 | C |

**Figure 8.22** - Glare class ratings for views of the the west facade between July 16 and July 21.



SOUTH FACADE - SUMMER SOLSTICE

| VIEWPOINT | 95% LIMIT | TOP 5% BAND | CLASS |
|---|---|---|---|
| Parallel to the window facing north | 0.267 | 0.301 | A |
| Parallel to the window facing south | 0.263 | 0.275 | A |
| Perpendicular to the left window (shaded) | 0.312 | 0.331 | A |
| Perpendicular to the right window (unshaded) | 0.378 | 0.387 | B |

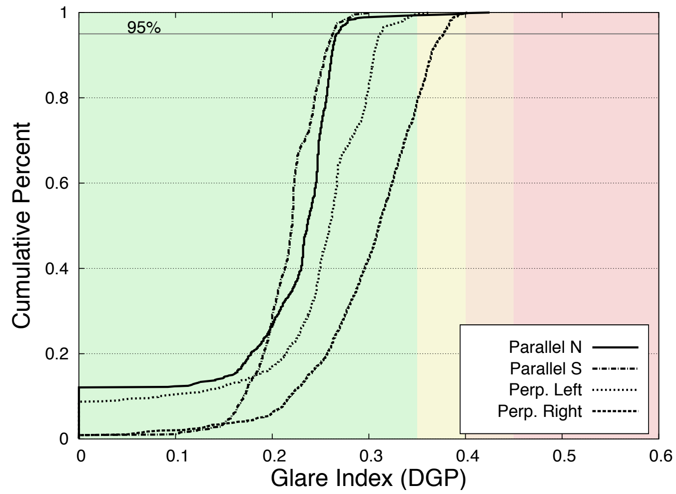



**Figure 8.23** - Glare class ratings for views of the the south facade between July 26 and August 3.

EAST FACADE - SUMMER SOLSTICE

| VIEWPOINT | 95% LIMIT | TOP 5% BAND | CLASS |
|---|---|---|---|
| Parallel to the window facing north | 0.274 | 0.291 | A |
| Parallel to the window facing south | 0.294 | 0.313 | A |
| Perpendicular to the left window (shaded) | 0.342 | 0.368 | A |
| Perpendicular to the right window (unshaded) | 0.409 | 0.446 | C |

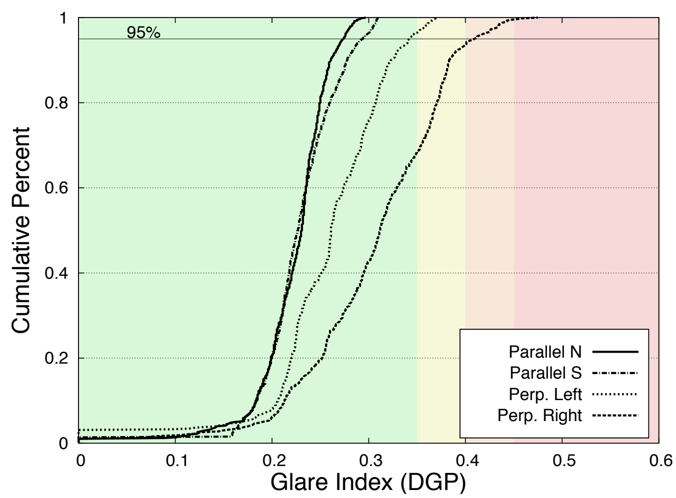



**Figure 8.24** - Glare class ratings for views of the the east facade between July 11 and July 14.

## Equinox

A shade was installed in the right window for the equinox test periods. Figures 8.23, 8.24 and 8.25 show that all facade orientations and all views with one exception received an 'A' comfort class rating. The view perpendicular to the left window (lighter shade color) on the east facade received a 'B' class rating.

EAST FACADE - EQUINOX

| VIEWPOINT | 95% LIMIT | TOP 5% BAND | CLASS |
|---|---|---|---|
| Parallel to the window facing north | 0.263 | 0.278 | A |
| Parallel to the window facing south | 0.266 | 0.286 | A |
| Perpendicular to the left window (dark shade) | 0.345 | 0.375 | A |
| Perpendicular to the right window (light shade) | 0.353 | 0.406 | B |

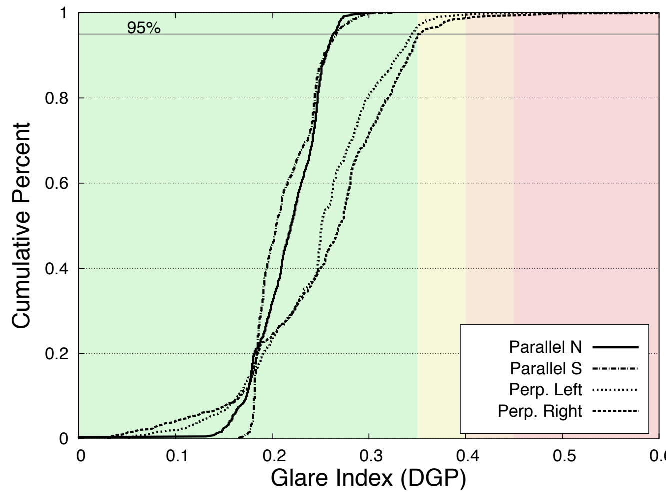



**Figure 8.25** - Glare class ratings for views of the the east facade between September 27 and October 1.

WEST FACADE - EQUINOX

| VIEWPOINT | 95% LIMIT | TOP 5% BAND | CLASS |
|---|---|---|---|
| Parallel to the window facing north | 0.240 | 0.258 | A |
| Parallel to the window facing south | 0.256 | 0.288 | A |
| Perpendicular to the left window (dark shade) | 0.270 | 0.283 | A |
| Perpendicular to the right window (light shade) | 0.285 | 0.298 | A |

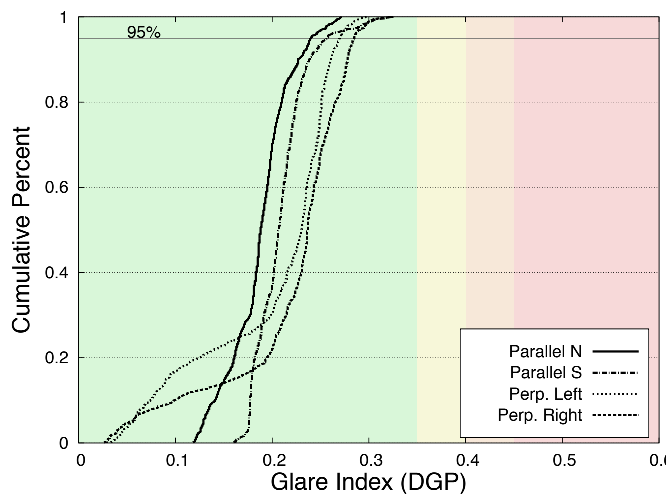



**Figure 8.26** - Glare class ratings for views of the the east facade between September 20 and 25.

SOUTH FACADE - EQUINOX

| VIEWPOINT | 95% LIMIT | TOP 5% BAND | CLASS |
|---|---|---|---|
| Parallel to the window facing north | 0.214 | 0.230 | A |
| Parallel to the window facing south | 0.253 | 0.259 | A |
| Perpendicular to the left window (dark shade) | 0.274 | 0.289 | A |
| Perpendicular to the right window (light shade) | 0.289 | 0.299 | A |

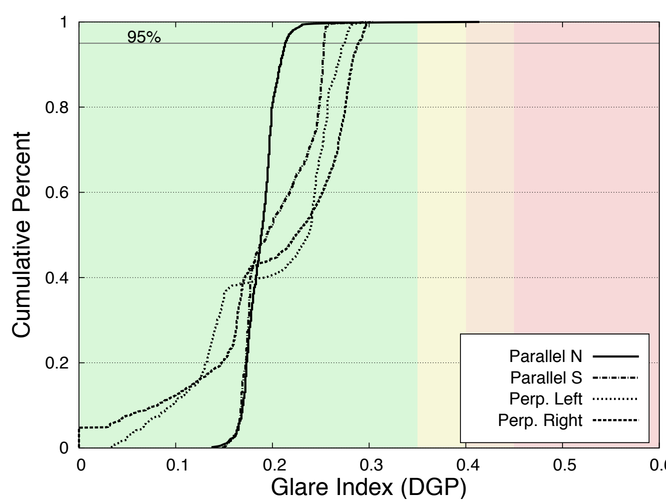



**Figure 8.27** - Glare class ratings for views of the the east facade between October 4 and 10.

# 8.4 Furniture Position Relative to Facade

Genentech wanted to understand how close to the window occupants could work without experiencing undue discomfort. Visual comfort (glare) and thermal comfort dictate the proximity to the facade which desks can be comfortably placed for each orientation. We measured visual comfort at four distances from the facade by placing additional HDR camera setups in the space (figure 8.28). Staggering the placement of cameras reduced view obstructions for the rear cameras from the front cameras (figure 8.29). The additional cameras were in place for the entirety of test cycle #3 (equinox conditions).

The four additional cameras for testing furniture position were all facing the window, the worst-case scenario for direct glare. If the desks are arranged so that occupants are generally facing parallel to the windows the glare condition will be better than is reported in this section.


**Figure 8.28** - Additional HDR camera setups placed in the mockup (circled in the left image) at increasing distance from the window (distance marked in right image).

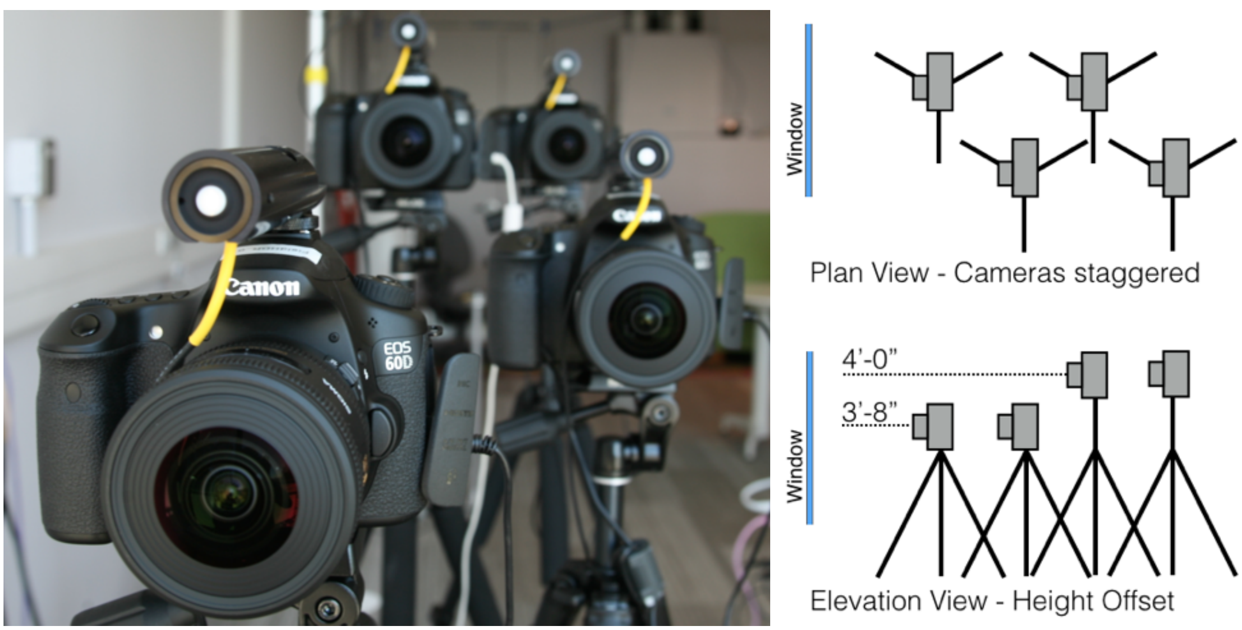



**Figure 8.29** - Staggered positioning and height offsets reduced obstruction in the view of the rear cameras from the front cameras.

**SOUTH FACADE**

| DISTANCE | 95% LIMIT | TOP 5% BAND | CLASS |
|---|---|---|---|
| 5.5 feet | 0.299 | 0.302 | A |
| 4.5 feet | 0.302 | 0.317 | A |
| 3.5 feet | 0.326 | 0.341 | A |
| 2.5 feet | 0.370 | 0.397 | B |

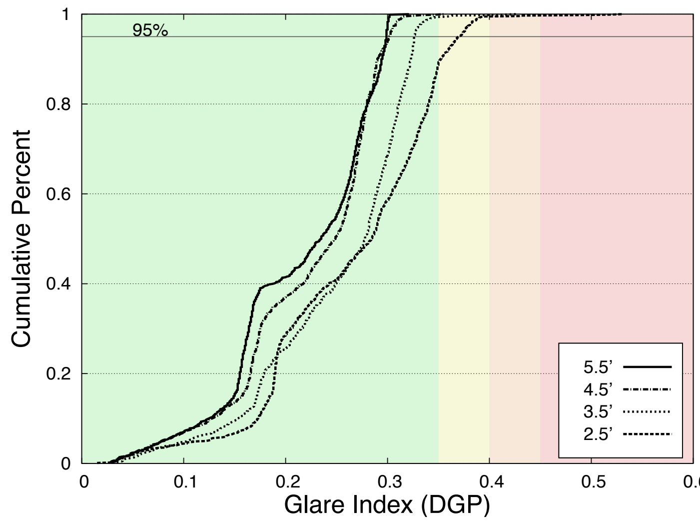



**Figure 8.30** - Visual comfort rating at each camera position for the west facade (table above). Cumulative distribution chart for each camera position (right).

**EAST FACADE**

| DISTANCE | 95% LIMIT | TOP 5% BAND | CLASS |
|---|---|---|---|
| 5.5 feet | 0.376 | 0.418 | B |
| 4.5 feet | 0.397 | 0.457 | C |
| 3.5 feet | 0.443 | 0.505 | C |
| 2.5 feet | 0.508 | 0.535 | - |

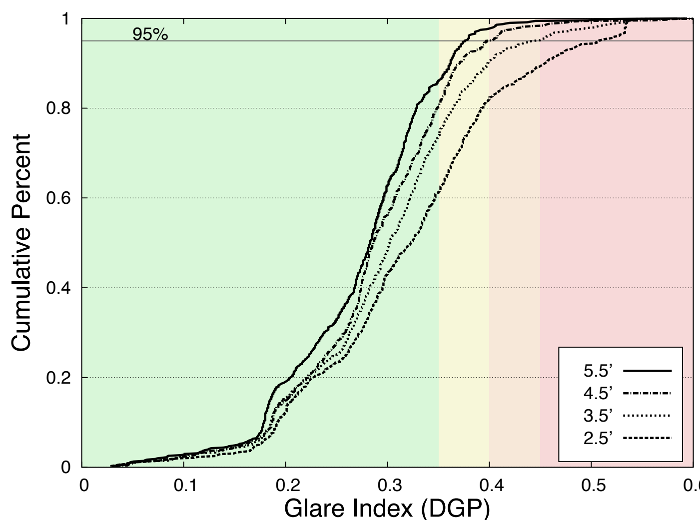



**Figure 8.31** - Visual comfort rating at each camera position for the east facade (table above). Cumulative distribution chart for each camera position (right).

**WEST FACADE**

| DISTANCE | 95% LIMIT | TOP 5% BAND | CLASS |
|---|---|---|---|
| 5.5 feet | 0.309 | 0.332 | A |
| 4.5 feet | 0.345 | 0.400 | B |
| 3.5 feet | 0.380 | 0.436 | C |
| 2.5 feet | 0.435 | 0.485 | C |

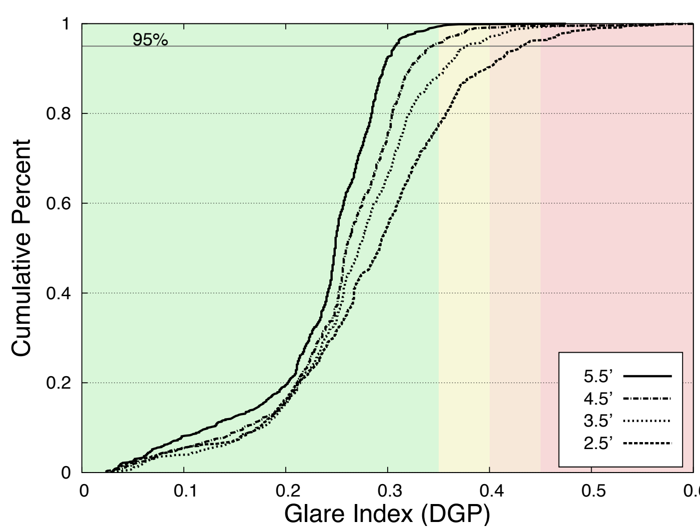



**Figure 8.32** - Visual comfort rating at each camera position for the west facade (table above). Cumulative distribution chart for each camera position (right).

Results from testing in FLEXLAB (figures 8.28, 8.29 and 8.30) indicate that desks can be placed closer to the south facade than other facades. However, recall that the south facade of B35 has more glazed area and higher transmittance glazing than was tested in FLEXLAB (see table 2.1 in section 2). The increased transmittance and glazing ratio will likely affect the closest furniture placement possible for the south facade.

The position of HDR cameras is equivalent to the position of an occupant's eyes. Assuming occupants typically sit centered on the width of the desk, the edge of the desk can be positioned two feet closer to the window than the distance of the camera from the window. For example, if comfort is achieved at a distance of 5.5 feet from the window, the edge of the desk can be placed at 3.5 feet from the window (figure 8.33).

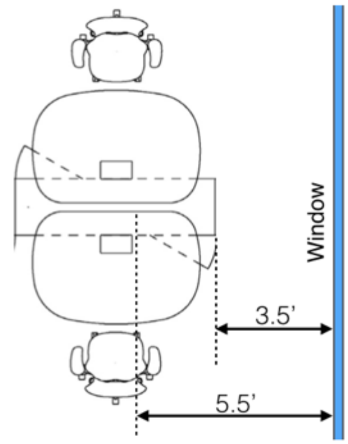



**Figure 8.33** - If comfort is achieved at 5.5 feet from the window, the edge of the desk can be placed at 3.5 feet from the window.

A position that has a class B glare rating when facing the window likely has an A or better rating when facing perpendicular to the window. If desks are arranged so that the occupant faces parallel to the window then desk can probably be arranged at the distance that yields a B rating for perpendicular facing views. Many of the open office areas of B35 have facades facing three directions. The recommendations provided in Table 8.2 might help to determine which way the furniture should face in the corner cases.

**Table 8.2** - Recommended distance from occupant's head to facade by facade direction.

| FACADE | VIEW FACING WINDOW | VIEW PARALLEL TO WINDOW |
|---|---|---|
| SOUTH | 3.5 feet * | 2.5 feet * |
| WEST | 5.5 feet | 3.5 feet ** |
| EAST | > 6 feet | 3.5 feet ** |

* This distance assumes glazing and glazed area installed in FLEXLAB. This distance might need to be increased to account for increased area and transmittance.
** Based on visual comfort analysis from the previous section.

## 8.4 Lighting Energy Savings

We can calculate lighting energy savings resulting solely from daylight dimming by subtracting the instantaneous lighting power from the after-dark task tuned lighting power and integrating over each hour. Table 8.3 contains lighting energy savings from daylight dimming by hour for each facade and each test period. We only considered lighting energy savings during the third test cycle when both shades were installed and operating in FLEXLAB. Thus, the lighting energy savings data includes the effects of normal shade operation on daylight within the space. The savings provided in the table 8.3 are for both fixtures in FLEXLAB, represent a zone 30 feet deep from the facade, with occupancy sensors disabled.

**Table 8.3** - Hourly lighting energy savings from daylight dimming in a 30-foot deep zone for each facade during the third test cycle.

| HOUR | EAST | SOUTH | WEST |
|---|---|---|---|
| 6-7 | 25.2% | 14.6% | 19.2% |
| 7-8 | 34.1% | 33.6% | 23.6% |
| 8-9 | 40.7% | 42.9% | 29.2% |
| 9-10 | 28.8% | 49.0% | 35.0% |
| 10-11 | 56.4% | 50.6% | 41.6% |
| 11-12 | 61.7% | 58.9% | 49.0% |
| 12-13 | 71.3% | 58.8% | 53.9% |
| 13-14 | 64.7% | 23.7% | 58.2% |
| 14-15 | 59.5% | 17.8% | 47.0% |
| 15-16 | 50.9% | 17.9% | 27.0% |
| 16-17 | 38.4% | 19.9% | 21.0% |
| 17-18 | 20.6% | 18.2% | 19.4% |

Note: The measured values for the south facade will be lower than the estimated values for B35 due to discrepancies between the facade installed in FLEXLAB and the B35 facade.

The East Facade has higher lighting energy savings in the afternoon when the shade is raised, than in the morning when the shade is down. Figure 8.34 shows the shade positions for the east facade on a sunny day during the third testing cycle. The energy savings are greatest between the hours of 12 noon and 1 PM where the shade is almost all the way up, and the external horizontal illuminance is highest. Outside of the first and last hour of the day, the lighting energy savings is lowest between 9 AM and 10 AM, when the shade is fully deployed and the sun shines at a steeper angle on the facade.

The south facade has highest lighting energy savings at mid-day before the shade goes to the lowest stop position. After 1 PM PST the shade covers the full window and lighting energy savings drops substantially. Figure 8.35 shows the shade positions for the south facade during a day in the third test cycle.

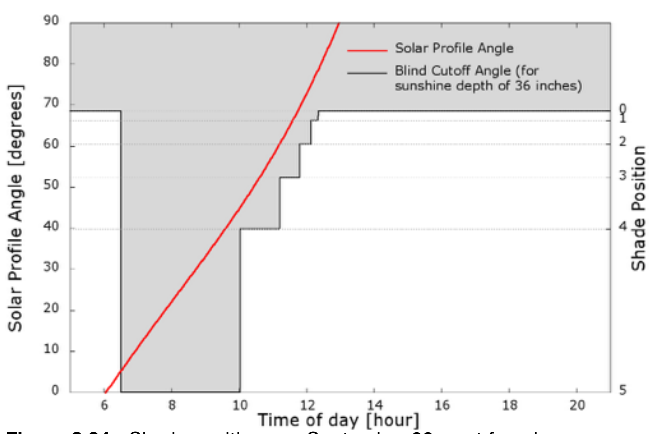



**Figure 8.34** - Shade positions on September 28, east facade.

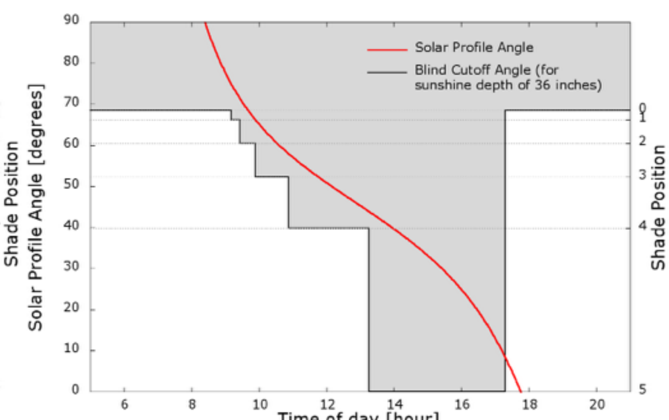



**Figure 8.35** - Shade positions on October 4, south facade.

The greatest lighting energy savings on the west facade occur in the early afternoon just before the sun begins to shine on the facade. Lighting energy savings are high until 3 PM PST at which time the shade lowers to completely covers the window, blocking low angle sun. Figure 8.36 shows shade positions for the west facade on a sunny day during the third test cycle.

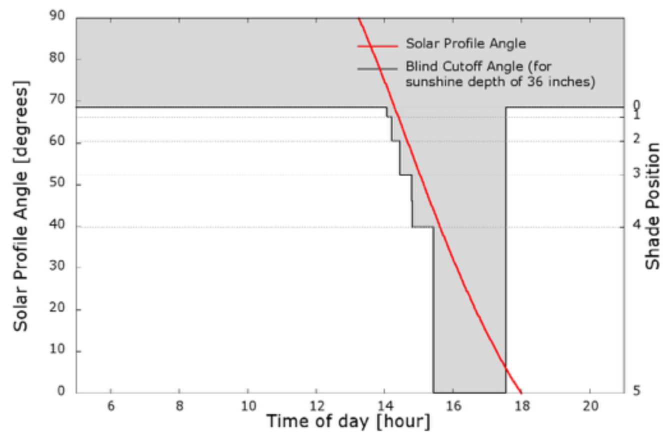



**Figure 8.36** - Shade positions on September 25, west facade.

## 8.5 Phase Change Floor Tiles

The flooring system installed in FLEXLAB included three rows of floor tiles (45 tiles total) containing a phase change material (PCM) near the facade. The PCM tiles were rearranged into a checker board pattern interleaving non-PCM tiles with PCM tiles to allow side-by side comparison of thermal properties of the tiles (figure 8.37). A 3.5 hour time series of infrared (IR) images of the floor near the windows (one image every 5 minutes) was collected on a sunny day in late May. The series began as sun had begun to fall on the floor for the day. There was no finished floor covering installed at the time.

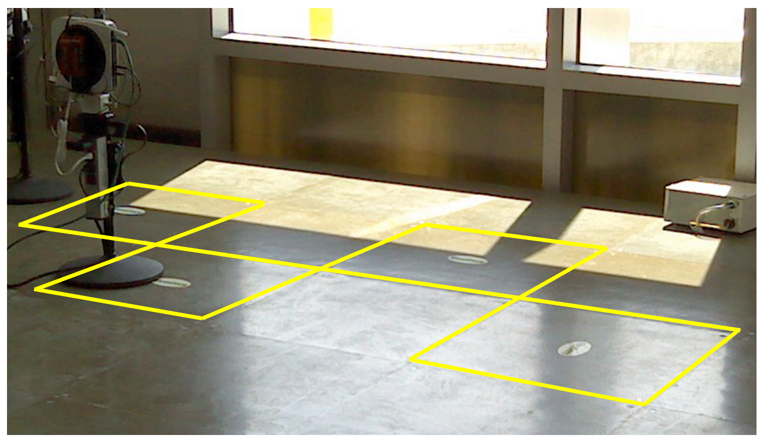


**Figure 8.37** - Layout of phase change floor tiles. The PCM tiles are outlined in yellow.

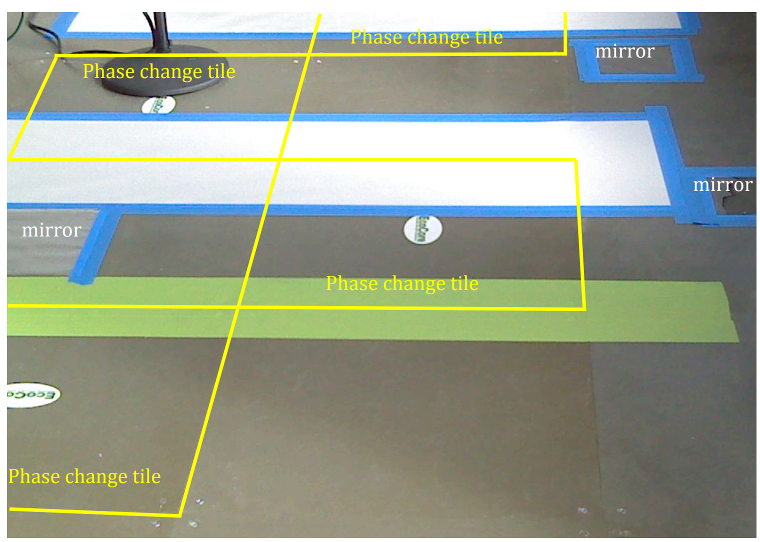



**Figure 8.38** - Coverage of tiles for IR imaging (side view looking parallel to the window wall on the right).

The IR images measured tile surface temperature directly. Because initial IR imaging of the floor tiles revealed that there was a strong reflection component to the IR radiation leaving the tiles, masking tape and paper sheeting were placed over areas of the tiles (figure 8.38) to reduce the long wave IR reflection to normal levels (emissivity ~0.9, and reflection ~0.1). It is typical to make a background correction for the reflected IR radiation portion of the signal in an IR image, however, because the bare floor tile had a higher reflection than normal and its emissivity was unknown, it was necessary to cover the tile with a thin material of known properties to improve the IR measurement accuracy. The thin materials layers introduced on the tile surface present negligible thermal resistance, such that they should not be considered as an influence on the observed floor tile temperatures. Likewise, a real floor covering such as carpet or wood would introduce more thermal resistance than this test condition. The condition tested is the most direct coupling of the floor to the occupied space and would be most representative of a thin laminate flooring.

In the visible spectrum there were two levels of solar absorption. A portion of the tiles were covered with green or blue masking tape of light to medium tone. The solar absorption of these tapes is probably similar to a light to medium toned finished floor covering materials. Larger areas of the tiles were covered with white butcher paper, however this area will have a direct solar absorption that is lower than typical floor covering materials. There were also small shiny mylar films placed on the floor to serve as a background radiation reference for the image.

The PCM tiles which had been in thermal equilibrium with the room overnight lagged the temperature rise observed on the normal floor tiles as the absorbed direct sunlight warmed them. The difference in temperature rise was small (1 - 2.5 C°), but it was observable in the surface temperature patterns of the IR images. It is difficult to interpret which lines of thermal contrast are associated with the tiles and which are associated with the patches of tape and paper floor covering used to improve imaging accuracy. Figure 8.39 shows a temperature map of the floor, phase change tiles are outlined in yellow. Temperatures are labeled on either side of borders between PCM and non-PCM tiles.

The temperature difference across the tile boundary on the green tape in the foreground was 0.8 C°. The other temperature difference was taken on the blue tape (border of the white paper area) and measured 2.5 C°. The white paper did not diminish the temperature rise as much as expected and showed a similar ~1 C° difference to that of the light green tape.

The row of tiles closest to the facade did not have PCM tiles since the tiles in the first row were cut to accommodate facade mullions. At the time of year of the test, the first row had the longest duration of direct sun coverage and the highest temperature rise.

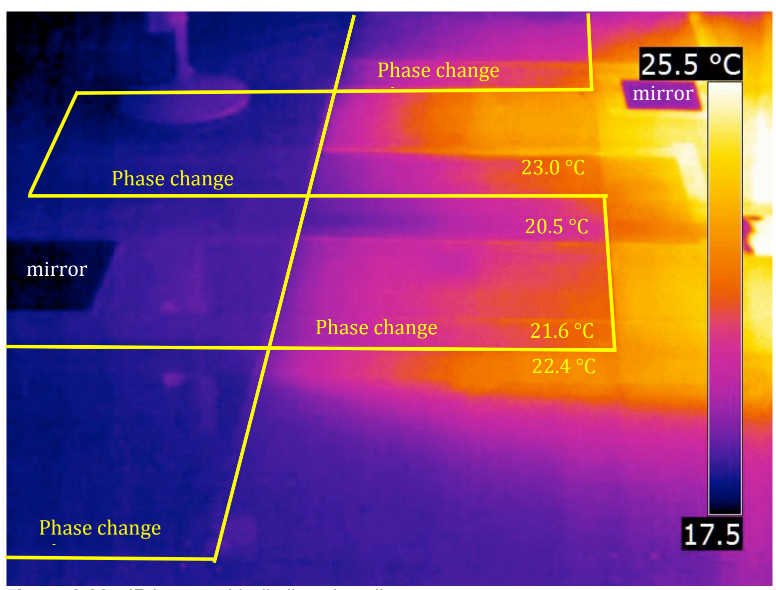



**Figure 8.39** - IR image with tile lines in yellow.

# 9. Lessons Learned

## 9.1 Specific Lessons for B35

### Lighting Control

- The Encelium lighting control system can manage fixtures with separately controlled upward and downward lighting better than the Enlighted control system.

### Window Shade Fabric

- Color: The dark colored shade fabric offers a better view of the exterior during the day time and has a lower DGP. The light colored shade fabric transmits more daylight and reflects more electric light if deployed at night. (Section 7.3)
- Density: 3% shade openness provides adequate direct sun mitigation for some occupants, but not for others. Flexibility in seating will likely help reduce complaints of inadequate shading (those who find it inadequate won't sit by the west windows). (Section 7.3)

### Shade Controls

- Substantial energy savings can be realized by limiting shade deployment to 38 inches from the floor (8 inches above desk height). (Section 7.3)

### Furniture Layout

- Visual comfort studies show that when facing the facade, occupants can sit as close as 42" to the south facade, but should be at least 66" from the east and west facades. (Section 8.4)
- When facing parallel to the facade, occupants can sit 54" from the facade (and potentially closer) for all four orientations. (Section 8.3)

## 9.2 General Lessons for other Genentech Buildings

### Light Fixture Selection

- Consider the optics of the upward light from an LED fixture. Poorly designed optics can cause distinct patterns of light and shadow on the ceiling. (Section 3)

### Lighting Control Selection

- Multi-sensor closed loop control (one sensor per fixture) provides more precisely controlled work plane illuminance. (Section 5)
- When closed loop control zones overlap, one loop will dominate resulting in an unbalanced equilibrium. (Section 5)

- Control systems that can take information from multiple sensors, process the data and control fixture individually provide the most functional flexibility. (Section 4)

## Window Shade Fabric Selection

- For a given openness, dark colored shades provide a better view, reduce glare. (Section 7.3)

- Some occupants may complain about direct sun glare with 3% open shade fabric (Section 7.3). If desks assignments are fixed 2% or less open shade fabric may be require to satisfy all occupants.

## Shade Controls

- Stopping the shade 14 inches above the sill provided substantial energy savings in FLEXLAB (section 7.3). Designing future buildings to accommodate some unshaded glazing will reduce lighting energy use.

# 10. Acknowledgements

This research was conducted using FLEXLAB, the Facility for Low Energy eXperiments in Buildings, a resource provided by the Building Technologies and Urban Systems Division at the Lawrence Berkeley National Laboratory, supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology of the U.S. Department of Energy for construction and operations under Contract No. DE-AC02-05CH11231.

In addition, we would like to thank all the companies and individuals that contributed to this project:

PRIMARY COLLABORATORS

| | |
|---|---|
| **Genentech** | Chris Ahn, Andrew Keller, Greg Burg, Michael Perkocha, Carla Boragno, Mark Johnson, Habib Zehtab |
| **Webcor** | Joanne Verrips, Todd Mercer, Tyran Shivers |
| **Delos** | Phil Williams (formerly Webcor) |
| **LBNL** | Cindy Regnier, John Mejia, Darryl Dickerhoff, Jonathan Slack, Howdy Goudy, Ryan Dickerhoff, Stephen Czarnecki, Ling Zhu, Anna Liao, Steve Greenberg, Douglas Brunkow, Joshua Brown |

B35 DESIGN TEAM

| | |
|---|---|
| **Perkins & Will** | Sarah Rege, Sara Andersen |
| **Arup** | Toby Lewis |

CONTRACTORS

| | |
|---|---|
| **Desert Fire Protection** | Jeff Michell, Al Starnes, Jennifer Doty |
| **Pivot Interiors** | Jesse Michael |
| **Magnum Drywall** | Mark Malloy, Elisha Dawid, Gary Robinson |
| **Peninsulators** | Ryan Whitaker |
| **Pugliese** | Robert Freddie |
| **Redwood Electric** | Julian Dodge, Steve Finau |
| **Southland Mechanical** | Matt Terry, Tony Lowe |
| **Walters & Wolf** | Jim Amber |

## VENDORS

| | |
|---|---|
| **Cal Lighting** | Dick Brecher, Brendan Forney |
| **Enlighted Inc.** | Sanjeev Patel, Scott Harmon |
| **Encelium** | Jason Moorehead |
| **Interface** | |
| **MechoSystems** | Jeffrey Glick, Bhaumik Raval |
| **Tate Access Floors** | David Wickstrom |
| **Vode Lighting** | Stuart Kennedy |

## OTHER SUPPORT

| | |
|---|---|
| **Center for the Built Environment, UC Berkeley** | Tyler Hoyt, Charlie Huizenga, Ed Arens, Hui Zang |