1.3. Lighting System Performance

Purpose

While the Fort Carson Technology Evaluation project, in particular the Net Zero Retrofit Optimization research question, aims to address the path to net zero broadly, the purpose of this research question is to focus on the details of one system, lighting. **The questions answered through this work are:**

- To what level of energy efficiency are U.S. General Services Administration (GSA)/Fort Carson lighting systems performing currently and how does this compare to net zero building requirements?
- What components of the lighting systems do occupants generally accept or reject, and how can their lighting comfort be improved?
- Based on the previous two answers, what best practices can GSA and Army implement beyond current practice to make steps toward net zero energy?

Research Question

How well are the daylighting and lighting systems performing by space type?

Lighting systems typically use between **30%–40%** of a building's total energy consumption, making it an obvious focus area for net zero energy discussions. National Renewable Energy Laboratory's (NREL's) experience with net zero energy design and operation on its campus has shown that lighting systems in a net zero energy office facility should consume no more than 10% of the total building load, or closer to 6% when a data center or other equipment-heavy spaces are included. This translates to approximately 75% lighting energy use reduction versus an ASHRAE Standard 90.1-2007 baseline for new and retrofit buildings required to achieve net zero energy.

NREL's experience has also shown that the 75% building lighting energy savings can be broken down into savings expectations of 50% in non-daylit areas and as high as 90% in daylit spaces.[4] These numbers are used as lighting system goals in this research question because they have been proven to be achievable and because this level of efficiency is assumed for the Net Zero Retrofit Optimization lighting measures (See Net Zero Retrofit Optimization). The results of the retrofit optimization show that the electric lighting, daylighting, and general lighting control energy efficiency measures are necessary for cost-effective net zero energy design.

Lighting systems typically use between 30-40% of a building's total energy consumption, making it an obvious focus area for net zero energy discussions.

The approach for the lighting systems research question started with sampling the lighting energy use patterns of a subset of Fort Carson buildings for comparison to a 75% whole building lighting energy savings goal. Fort Carson presents a good litmus test for net zero energy, subsystem goal potential for a number of interconnected reasons. First, the Army has already implemented Leadership in Energy and Environmental Design (LEED) Silver and Gold certification on recent new construction and retrofit projects. The projects achieved Daylight and Views, and Optimize Energy Performance LEED credits, each of which imply that best practices for lighting efficiency were used. Second, Fort Carson is tracking toward net zero energy goals in design and operation and so the gap between current best practices for lighting efficiency in design and realized performance on this site are of particular interest to GSA and the Army. Lastly, comprehensive lighting strategies have been implemented and can therefore be observed for lessons learned. Comprehensive lighting strategies include:

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[4] The results for the space types assessed in this study show an average code allowance of 4.9 kWh/sf/yr and a possible energy use intensity of approximately 0.9 kWh/sf/yr.

- *Electric lighting reductions* such as the retrofit from fluorescent to Light Emitting Diode (LED) lighting in Building 1219
- *Daylighting features* such as skylights in new Company Operations Facilities (COFs) and Tactical Equipment Maintenance Facilities (TEMFs), and tubular daylighting devices in the new Dining Facility (DFAC), with lighting controls to proportionately reduce electric lighting when daylight is present
- *Lighting controls* such as occupancy sensors in the open offices of the new Headquarters (HQ) building, and
- Occupant engagement activities such as “Please turn off the lights” stickers in Building 1219.

Each of these elements must be included in a building to see lighting energy savings as low as 75% versus a code baseline. The lighting research question intends to evaluate these best practices with respect to design, installation, and commissioning to glean insights into their effectiveness for energy savings and the potential for low-cost changes or tweaks to further the goal of net zero energy.

The approach for evaluating the Fort Carson lighting systems was to select a sample of buildings and space types, observe occupancy and lighting patterns in these areas, model alternative solutions where appropriate, and translate the lessons learned from the observations and modeling into recommendations for closing the net zero energy gap. The buildings sampled include new LEED construction—the Brigade Headquarters Facility (HQ, Building 9420), Company Operations Facilities (COFs, Building 9447 and 9486) and Tactical Equipment Maintenance Facilities (TEMF, Building 9487) buildings on Wilderness Road—and an old barracks renovated into an office—Building 1219. Spaces examined in these buildings included private offices, open offices, classrooms, community spaces, hallways, break rooms and high bay modules.

The following sections detail this process; the *Methods* section explains the sample building selection and monitoring plan, the *Research Results* section presents space-by-space observations and monitoring results, with an emphasis on comparing the effectiveness of different buildings' lighting strategies, and the *Daylighting and Lighting System* section synthesized the space-by-space results into broader observations that can be incorporated into future Fort Carson and GSA project requirements.

Methods

As a first step in the lighting system evaluation NREL visited Fort Carson to survey the variety of electric lighting, daylighting, and lighting control systems installed and select representative space types for further study. The visit revealed that the HQ, COF, and TEMF buildings on Wilderness Road house a variety of intentional daylighting features including skylights, clerestory glazing, and tubular daylighting devices. The electric lighting is primarily fluorescent, which is layered with "manual on, automatic off" control strategies to reduce load in response to occupancy and daylight. Subsystem monitoring results in Figure 10 show that the HQ building (office example) is using 15% of its energy on lighting, which indicates an aggressive lighting system design but possibly less so than needed for net zero energy operation.

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The older, renovated office Building 1219 offers contrast to the newer Wilderness Road buildings. Although retrofit with common best practice lighting strategies, the building takes a slightly different design approach. Instead of fluorescent sources, the building uses LED ambient lighting. The lighting controls are a mix of "manual on and automatic off," and "automatic on and automatic off" occupancy controls. A limited number of photosensors for automatic daylighting control are incorporated in conference rooms. The existing light switches and circuiting remain intact from the original building design. Subsystem monitoring results in Figure 77 show that Building 1219 is using approximately 22% of its energy on lighting. As with the HQ building, this suggests an aggressive lighting system design but not quite aggressive enough for net zero energy operation.

Since the Fort Carson new construction and retrofit buildings that were visited are on track for low energy lighting operation but show potential for improvement with respect to net zero energy goals (less than 10% building energy going to lighting), these building types were selected for study. Although the COF and TEMF prototypes show less lighting use than the HQ building, they were also selected for study due to their space type variety (e.g., offices, classrooms, and high bays). The DFAC was not visited or selected for further study, as its 4% building energy use for lighting shown in Figure 11 makes it the least lighting-dominated building of the available prototypes, due to its already well-implemented daylighting strategies and its high miscellaneous equipment loads.

Percentage of energy use attributed to the lighting systems gives an indication if the building is on the path toward net zero energy and if there is room for improvement, but does not provide much information on specific lighting system successes and failures. In addition to lighting energy use percentages aggregating the effects of electric lighting and control energy efficiency measures, they also need to be weighed against the energy use of other end-use systems such as miscellaneous equipment in each building.

In order to take a finer-grained look at Fort Carson lighting systems, NREL developed a monitoring plan to investigate the operation of specific ***electric lighting, daylighting, and lighting control*** strategies. This level of disaggregation required measuring electric lighting status (on or off), occupancy (occupant present or not), and illuminance (lighting quantity at the workplane in foot candles [fc]) for each space type. The monitoring plan details are given in the following sections, broken out by each lighting system component. The results of the monitoring are presented in the Research Results section.

Methodology

Electric Lighting Evaluation

A critical step in low-energy lighting system design is to reduce the installed lighting power density (LPD) for the times when electric lights must be used. In order to evaluate the current Fort Carson efforts with respect to net zero energy goals, NREL determined preliminary evaluation criteria:

- Installed lighting power efficiency measures should be 40% or more below code levels for low-bay spaces.
- To maintain occupant comfort, illuminance should adequately meet the task requirements (e.g., a minimum of 25 fc for general office/computer work) and should not create glare.
- The electric lighting should be compatible with lighting controls and other building systems.

The criteria were determined through a combination of literature review, experience, and sample calculations based on net zero energy building designs. While these criteria guided the creation of the test plan and served as a baseline for observations, they were only meant to be a starting point for the investigation. The criteria were refined and specified into best practices as the result of this research question where the need or potential for LPD reduction and/or improved lighting design strategies were observed.

A critical step in low-energy lighting system design is to reduce the installed lighting power density (LPD) for the times when electric lights must be used

In order to compare current Fort Carson conditions to the electric lighting criteria: LPD calculations for each space were performed; occupant comfort feedback provided by Pacific Northwest National Laboratory (PNNL) was reviewed; single-point-in-time illuminance measurements were taken. The following are specifics of the illuminance measurements.

- **<u>Equipment type</u>**: NIST calibrated Extech Instruments HD450 illuminance meter.
- **<u>Equipment location</u>**: Illuminance measurements were taken in representative locations including: perimeter offices in Buildings 1219, 9487, and 9420; high bay spaces in Buildings 9487 and 9486; daylight and non-daylight corridors; stairs; break rooms; restrooms; and conference rooms. Measurements were taken with and without electric lighting when daylight was present and the electric lights were manually controllable.

Daylighting Evaluation

In most climate zones, including Colorado Springs (where Fort Carson is located), daylighting is selected by optimization engines as a necessary building feature for net zero energy. The first step is to get the architectural elements of daylighting right. NREL determined evaluation criteria for a daylighting system are:

- Minimized fenestration-to-surface-area ratios such as 25%–35% for walls and 5% for roofs.
- Daylight sufficiency is targeted through the façade design, meaning that daylight should provide just the base level of light needed to perform most tasks in the space to prevent over-glazing of façades. A daylight sufficiency goal dovetails with the envelope recommendations given in Thermal Envelope Optimization. For most spaces, this means achieving 25 fc or less from daylight on a typical daylight condition, in the working zone.

- Maintained occupant comfort. For daylighting alone (without controls) the primary consideration is to mitigate glare potential. More specifically, this means preventing direct sun in occupants' field of view and maintaining a balance of daylight on the various surfaces in a given space.

- The daylighting should be compatible with lighting control and other building systems.

The criteria were determined through a combination of literature review and experience. While these goals guided the creation of the test plan and served as a baseline for observations, as with the Electric Lighting Evaluation Criteria, these criteria were refined and specified into best practices when the need or potential for envelope tweaks or different daylighting strategies were observed.

In order to compare current Fort Carson conditions to the daylighting criteria: fenestration-to-surface-area ratio calculations were performed; occupant comfort feedback provided by PNNL was reviewed; illuminance measurements were taken over a period of time that captured a variety of daylight conditions. The following are specifics of the illuminance measurements.

- **Equipment type**: Two LI-COR illuminance sensors and a Campbell Scientific data logger with battery power.

- **Equipment location**: The locations selected for placement of illuminance sensors was one representative COF high-bay space.

- **Measurement timeframe**: Sensors for the lighting research question were deployed in November 2012 through January 2013. Metering occurred for four to six months with interim data collection at one month after deployment to provide preliminary data for assessing existing and proposed lighting system strategies.

The daylight illuminance measurements were a lower priority than the occupancy and light switching data described in the following sections because daylighting models of key spaces were created using Radiance to provide a means for evaluating daylighting strategies. The illuminance measurements were primarily used for model validation and electric lighting control monitored data crosschecks but are not presented in the results or analysis of the Research Results section.

Lighting Control Evaluation

Lighting controls were the primary focus of the lighting research question since they represent a high potential for energy savings (an additional 50% beyond the 40% LPD reduction criterion) but also a high potential for implementation failure. Realizing energy savings after design is critical for net zero energy operation. NREL determined evaluation criteria for a daylighting system are:

- Electric lighting is on only:
  - during the time needed by the occupants.
  - in the location needed by the occupants.
  - to the quantity of light required by the occupant for the typical space task.
- The control interfaces are intuitive and engage occupants, and the control algorithms do not cause distraction or discomfort to the occupants.

Lighting controls were the primary focus since they represent a high potential for energy savings but also a high potential for implementation failure.

The criteria were determined from a passive design perspective used in NREL's net zero energy design and operation experience: electric lighting should only be turned on where and when needed. Again, these criteria were refined and specified into best practices as the result of this research question when the need or potential for control system design strategy changes, specification detail additions, or commissioning practice enhancements were observed.

In order to compare current Fort Carson conditions to the lighting control criteria, occupancy and light status (on/off) were logged to determine how closely the lighting load profile matches the occupancy profile, with respect to available daylight in each representative space. The following are specifics of the light status and occupancy measurements.

Equipment type: WattStopper IT-200 occupancy and light loggers.

Equipment location: The locations selected for placement of occupancy and light loggers were: Ten representative office spaces (five in Building 1219 and five perimeter offices in a representative COF); one representative COF high bay space; two representative HQ classrooms; two representative HQ open offices.

Measurement timeframe: All sensors for the lighting research question were deployed in November 2012 through January 2013. Metering occurred for four to six months with interim data collection at one month after deployment to provide preliminary data for assessing existing and proposed lighting control strategies.

The lighting control strategies were evaluated in tandem with appropriate daylighting and electric lighting control strategies. The analysis in the Research Results section primarily consists of using measured data to create occupancy profiles and use patterns for visual inspection, although a control module for Radiance also was used to determine the lighting control savings of improved daylight parameters. Occupant satisfaction was considered when comparing different buildings' control strategies.

NREL installed the monitoring equipment over the three-month period, and returned to the site intermittently during the test period to check equipment and take additional observation notes not recorded on the first site visit.

Research Results

The following sections summarize the observations from site visits and findings from the ongoing monitoring of Fort Carson lighting systems. The results are grouped by building type but refer to the electric lighting, daylighting, and lighting control criteria described in the previous section to qualitatively benchmark each building's performance. Typical spaces such as hallways, private offices, open offices, classrooms, and high-bay spaces are presented.

Results are presented by building and major spaces, including hallways, private offices, open offices, classrooms and high-bay spaces.

Office Retrofit (Building 1219)

The electric lighting and control system of Building 1219 was recently retrofitted as part of a larger building equipment transition toward LEED Silver performance. The new features include LED electric lighting fixtures and occupancy sensors in community spaces. The private offices line the outside of the building, with approximately two windows per office. A perspective of the north façade is shown in Figure 14.

Hallways

Figure 14 Image of Building 1219, North Façade

The hallways in Building 1219 create the central spine for the private offices and community spaces. While the hallways have little access to daylight, the LED electric lighting is reduced from 30 fc minimum horizontal illuminance, with all lights on, to 10 fc minimum, with every-other-fixture switched off as shown in Figure 17. A 10 fc minimum is still high with respect to the Illuminating Engineering Society of North America's (IESNA's) recommendation of 5 fc maintained for hallways.

While the maximum-to-minimum illuminance ratio of 7:1, distributed across the floor in the every-other-fixture scenario is higher than the IESNA recommendation of 2:1, occupants do not seem to mind since the lights were switched to this configuration during each site visit. Lighting fixture status was not measured in the hallways; it is not clear that the manual control of the lights in the hallway ensures that lights are completely off at night, when no occupants are present. The lessons learned from this space survey is that providing manual, every-other fixture control leads to lighting energy savings but the space design can be improved for occupant comfort and energy savings by reducing the installed power of each hallway fixture to achieve a more uniform 5 fc across the floor, and by providing automatic control to turn lights off at night.

Break Rooms

Each break room has access to daylight through a single window. During each site visit, the blinds were drawn shut in a majority of the rooms and the LED ambient lights were on. Based on spot checks, the ceiling-mounted occupancy sensors in each space do turn off the lights but the relatively high traffic in the areas and long timeout period (greater than ten minutes) keep the lights on much of the day as shown in Figure 15.


Figure 15 Images of Building 1219, Break Rooms

Spot measurements show the horizontal illuminance at counter level to be 70-100 fc, which is high compared to the IESNA recommendation of 30-50 fc. Restrooms are also overlit at 50-100 fc horizontal near the sink. This is likely due to the first-time implementation of LED fixtures where a one-for-one replacement can lead to over lighting in early operations (and possibly for the life of the LED fixture).

As with the hallway, a lesson learned from this space-type survey is that ambient lighting fixtures should be specified at a lower power output to maintain light uniformity but reduce illuminance and power density. Time of lighting use can be reduced by providing manual-on type occupancy, or vacancy, sensors so that the available daylight is used for basic kitchen tasks. Since glare is not a major occupant comfort concern in kitchen areas, the blinds can be removed, or specified to a lighter color to balance heat rejection and daylight admittance.

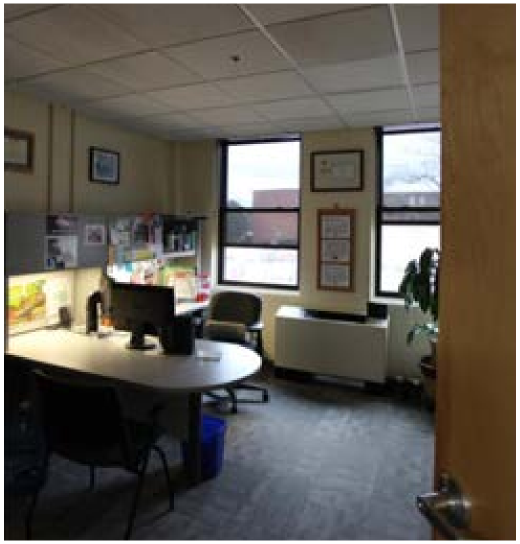


Figure 16 Image of Building 1219, Private Office

Figure 17 Image of Building 1219, First Floor Hallway

Private Offices

Figure 16 shows a typical private office in Building 1219 with the two overhead, ambient LED fixtures turned off and two linear fluorescent undercabinet fixtures turned on. The illuminance provided by each the ambient and task lights separately is approximately 50 fc. The private offices have a traditional on/off wall switch for the ambient lights. Each window has a full-length dark shade that is view preserving and lets in approximately 5% of the visible light that passes through the window.

Site visits revealed that most people do work with their ambient fixtures turned on—some people were noted as working with no electric lighting or only the task lights turned on as shown in Figure 16.

The following plots show the proportion of each hour that the office is occupied (in gray) and the proportion that the lights are turned on (in orange). This represents the typical lighting and occupancy schedule for the space type. If the lines were to overlap completely, this would imply that every time the space is occupied, the lights are on, and every time the space is unoccupied, the lights are off. Figure 18 shows a two-week light and occupancy pattern for private office 203. The office and dates are chosen to represent typical patterns during the data collection period. The data support a previous statement that at least some Building 1219 occupants work in their office without the ambient lights turned on (shown by the greater area under the gray, occupant line versus the orange, lighting line).

Hourly Lighting and Occupancy Schedules for 5/6/2013–5/20/2013, Private Office 203

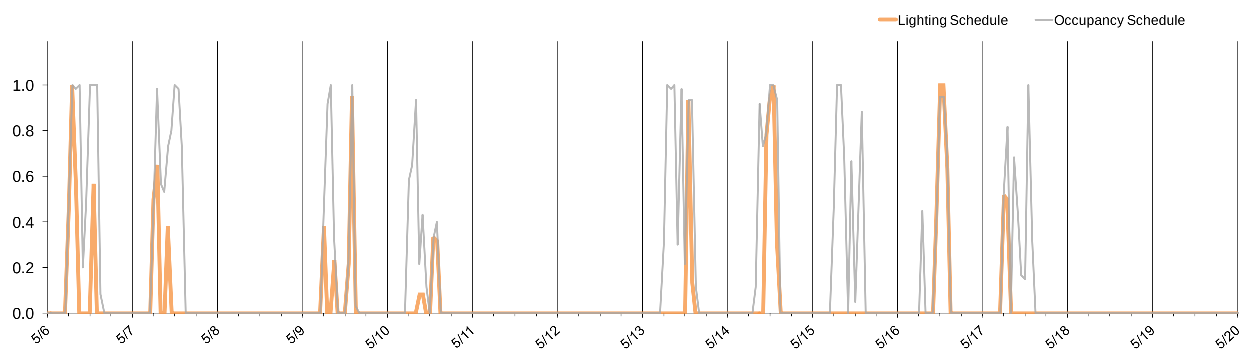


Figure 18 Measured Hourly Ambient Lighting and Occupancy Schedules for a Building 1219 Private Office

Figure 19 shows the private office lighting and occupancy schedules for the majority of the monitoring period. This display conceals some of the differences in lighting use and occupied hours but the general trend in each office can be seen: most occupants tend to use the lights when working but turn them off when they leave. Use of daylighting for working illuminance is not common. The three offices selected for display were those that had light loggers that were checked for accurate measurements during an interim site visit.

Hourly Lighting and Occupancy Schedules for 1/6/2013–5/19/2013, Private Offices 203, 208, and 216

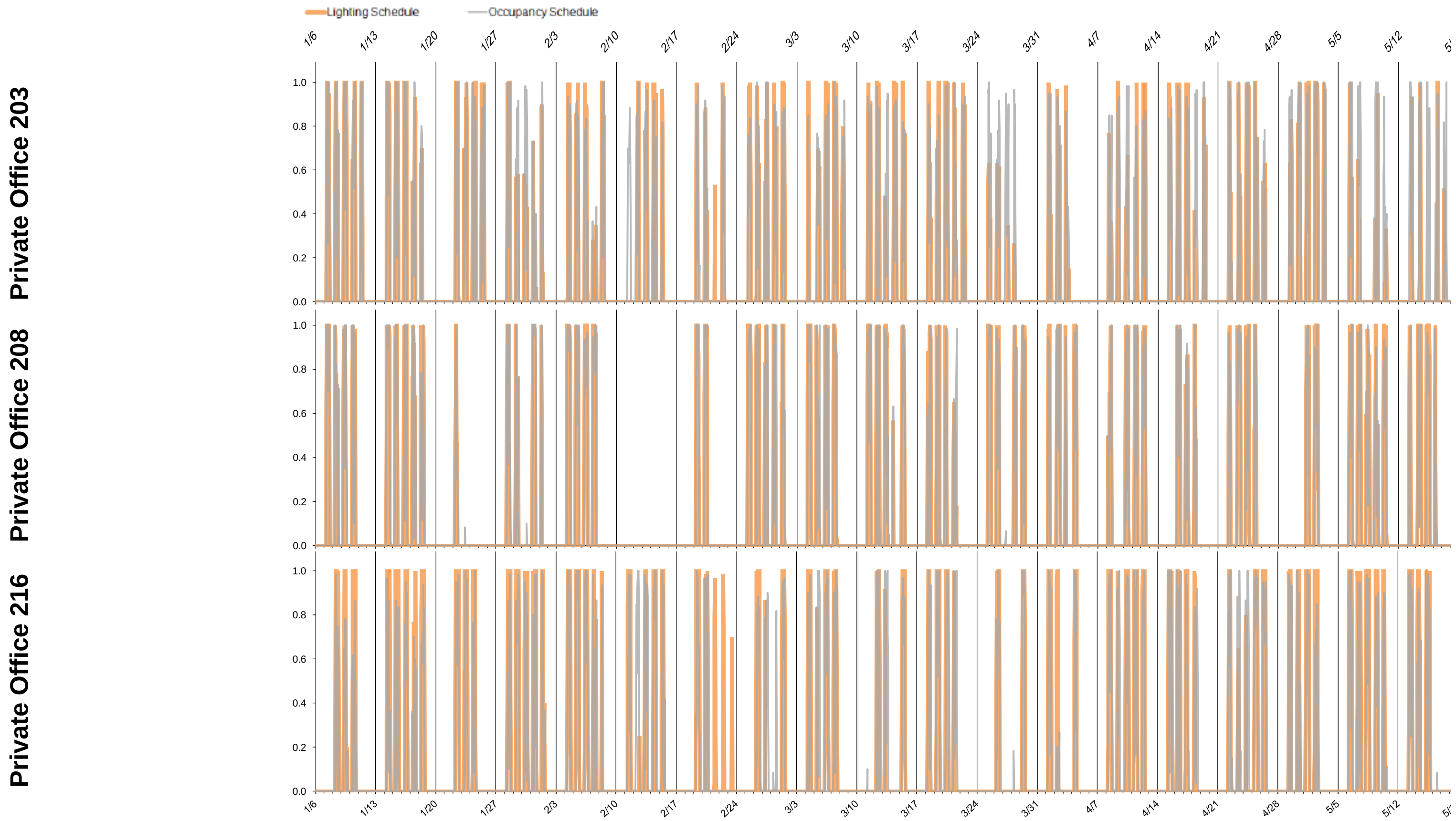


Figure 19 Measured Hourly Ambient Lighting and Occupancy Schedules for Building 1219 Private Offices

The charts show that the sensors are accurately measuring lighting and occupancy since the general patterns of lighting and occupancy track one another. It is possible that occupancy is not accurately tracked at all times since an occupant typing at the computer might not be detected by the WattStopper loggers. This potential inaccuracy in occupancy tracking does not affect energy saving numbers or light system recommendations.

Lessons learned from Building 1219 private office surveys are, again, that a one-for-one ambient lighting fixture replacement of LED for florescent should be evaluated for workplane illuminance rather than power equivalence. An ambient illuminance of 25 fc is sufficient for office tasks since task lighting is also provided. Designing to this illuminance will reduce the installed lighting power. Lighting energy, or time-of-use, can be reduced by engaging occupants to take advantage of the available daylight. Since occupants often forget to open blinds when they are involved in work, a passive strategy such as blinds that do not twist closed completely or shades that do not pull down completely will balance comfort/privacy and energy. Another consideration might be to move switches to the wall with the daylight feature. The data show that Building 1219 occupants are very successful at turning their lights off at night but there does not seem to be a culture or reminder for selecting daylight over electric lighting during the day. A daylighting analysis of a typical closed office is given in the Best Practices and Recommendations section, adding to the daylighting considerations discussed here.

Open Offices

The open offices in Building 1219 have high cubicle walls with a uniform pattern of ambient light fixtures set above, as shown in Figure 20.

The electric lighting is switched as one zone, leading to the noted conditions during site visits: (1) the perimeter electric lighting is on even when sufficient daylight is entering the windows as shown in Figure 21, and (2) makeshift solutions are used to alter the ambient illuminance for different occupant preferences as shown in Figure 22.

Figure 20 Image of Building 1219, Open Office

Figure 21 Image of Building 1219, Open Office Perimeter

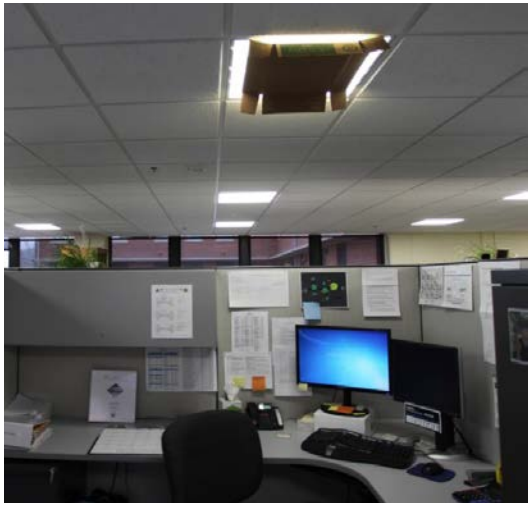


Figure 22 Image of Building 1219, Open Office Interior

The control system for the open office spaces consists of a ceiling-mounted occupancy sensor shown in Figure 23 and a wall switch shown in Figure 24. The occupant must turn on the wall switch for the occupancy sensor to trigger the ambient lights to go on. If the occupant forgets to turn off the switch then the occupancy sensor will do so, but in this case the lights will come back on automatically the next time someone enters the space. This is a typical occupancy sensor solution versus a “vacancy sensor” solution where the occupant must always choose to turn the lights on each time they enter a space.

Figure 23 Image of Building 1219, Open Office, Ceiling-Mounted Occupancy Sensor

Figure 24 Image of Building 1219, Open Office Manual Switch and Reminder Sticker

While the occupancy sensor solution is a cost-effective means to retrofit an open office with a traditional on/off switch, it often leads to unnecessary lighting-on time. As was shown for the private offices, the occupant training and awareness programs around turning lights off (e.g., light switch sticker in Figure 24) seems to be working since in monitored spaces, the lights are not left on once the occupant vacates the space for the day.

The lessons learned from the open office surveys are that finer-grained electric lighting zoning can reduce energy use due to daylighting and occupant preference, and lead to improved occupant comfort. Again, the ambient illuminance is high, at 50 fc, for an open office environment, which should provide closer to 25 fc without the added task lights.

New Company Operations Facility (COF, Building 9447)

Unlike Building 1219, Building 9447 is a new building that was designed and constructed initially for LEED Platinum certification. The building has private office and high-bay spaces, both of which are daylit using skylights and side lighting. The lighting control system has more automatic features as compared to Building 1219. The general strategy is that of true vacancy control where the occupant must turn on the lights on each entry to a space but the lights will turn off when no occupancy is detected. The front private office and rear high-bay modules are shown in Figure 25.

Figure 25 Image of Building 9447, Primary Façades

Private Offices

The private offices in Building 9447 each have two fluorescent troffers that provide 30–40 fc at the workplane. This illuminance is in line with IESNA recommendations for the space type.

The offices have prominent daylighting features. The perimeter windows are shaded by a louvered overhang and transom glass allows in borrowed daylight from the skylit hallway to the interior offices. These features can be seen in Figure 26. Note the difference between the overhang placement in the upper left versus upper right images. The upper right image is an interior view from the HQ building. The difference is the intent to divide the glass into daylight (upper) and vision (lower) glazing. While both solutions are helpful for reducing heat gain, neither is optimized for daylight quantity and quality.

Figure 26 Images of Building 9447, Private Office Components

The vacancy switch shown in the lower right corner is typical for the private offices. Figure 27 shows that the project documents specifically directed these switches to be programmed for vacancy operation, requiring the occupant to "opt-in" for electric light each time they enter the space.

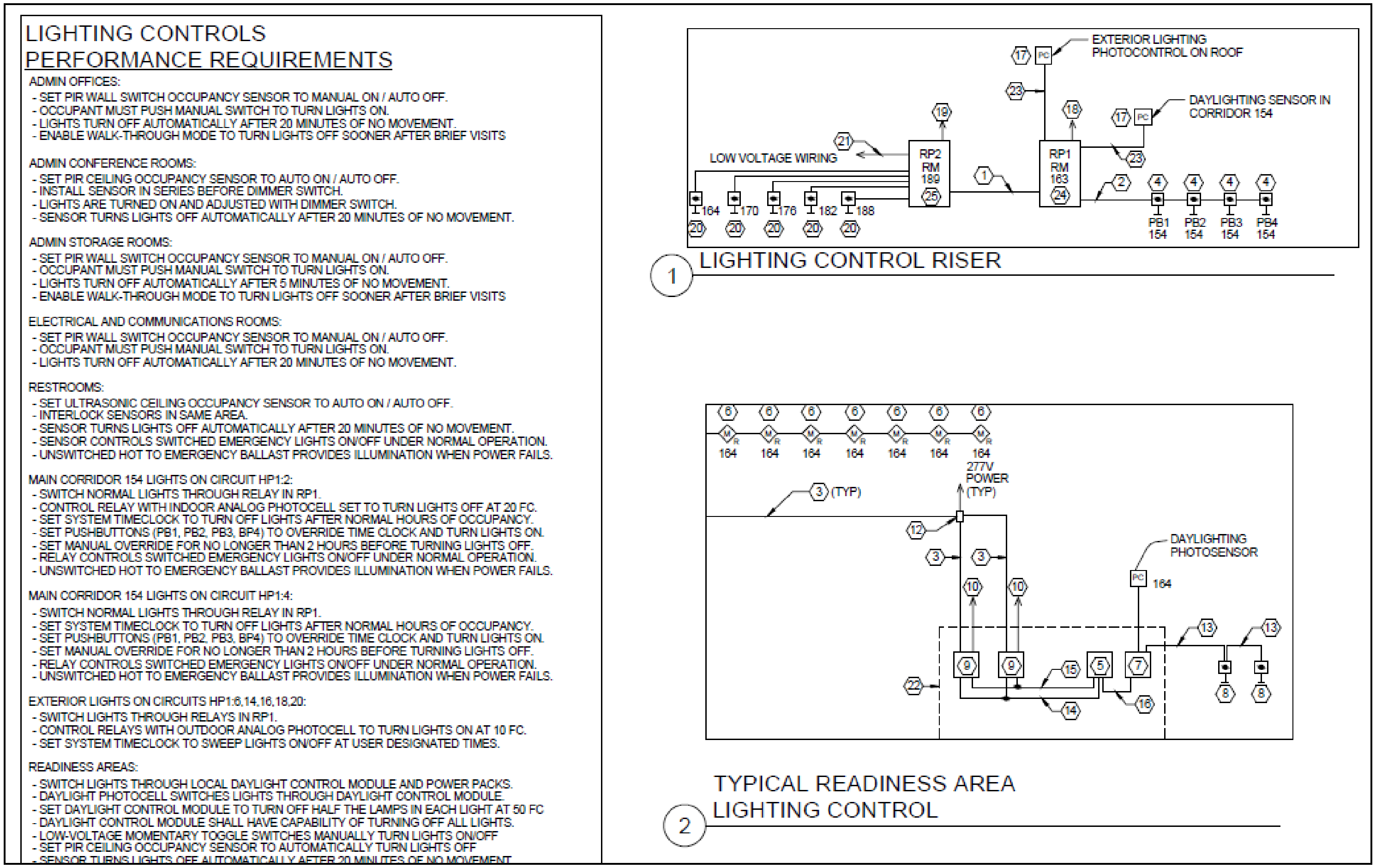


Figure 27 COF Lighting Sequence of Operations

Site visits showed that not all offices were set to vacancy control. It is not clear whether this was due to a lack of rigorous commissioning checks or after-occupancy changes. The switch settings are accessible by the occupant. Figure 28 shows that the vacancy specification is not meeting the net zero energy criteria of reducing electric lighting use while the space is occupied in response to daylight contribution. The electric lighting is on each time the space is occupied, regardless of daylight contribution (Office 101 is an interior office with transom glass facing the hallway).

Hourly Lighting and Occupancy Schedules for 5/6/2013–5/20/2013, Private Office 101

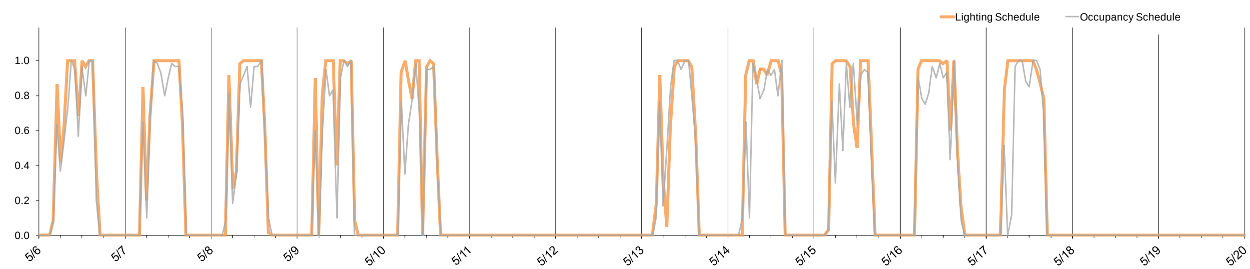


Figure 28 Measured Hourly Ambient Lighting and Occupancy Schedules for a Building 9447 Private Office

Hourly lighting and occupancy profiles for the monitoring period, shown in Figure 29 are meant to convey the high-level trend that ambient electric lighting is used when the spaces are occupied. Offices 101 and 106 are interior offices and office 119 is a perimeter office. Each office type has daylighting features yet the natural resource is not resulting in electric lighting energy savings. (The flat line from 2/2 to 4/14 is missing data. Although displayed, these flat values were not used for energy calculations).

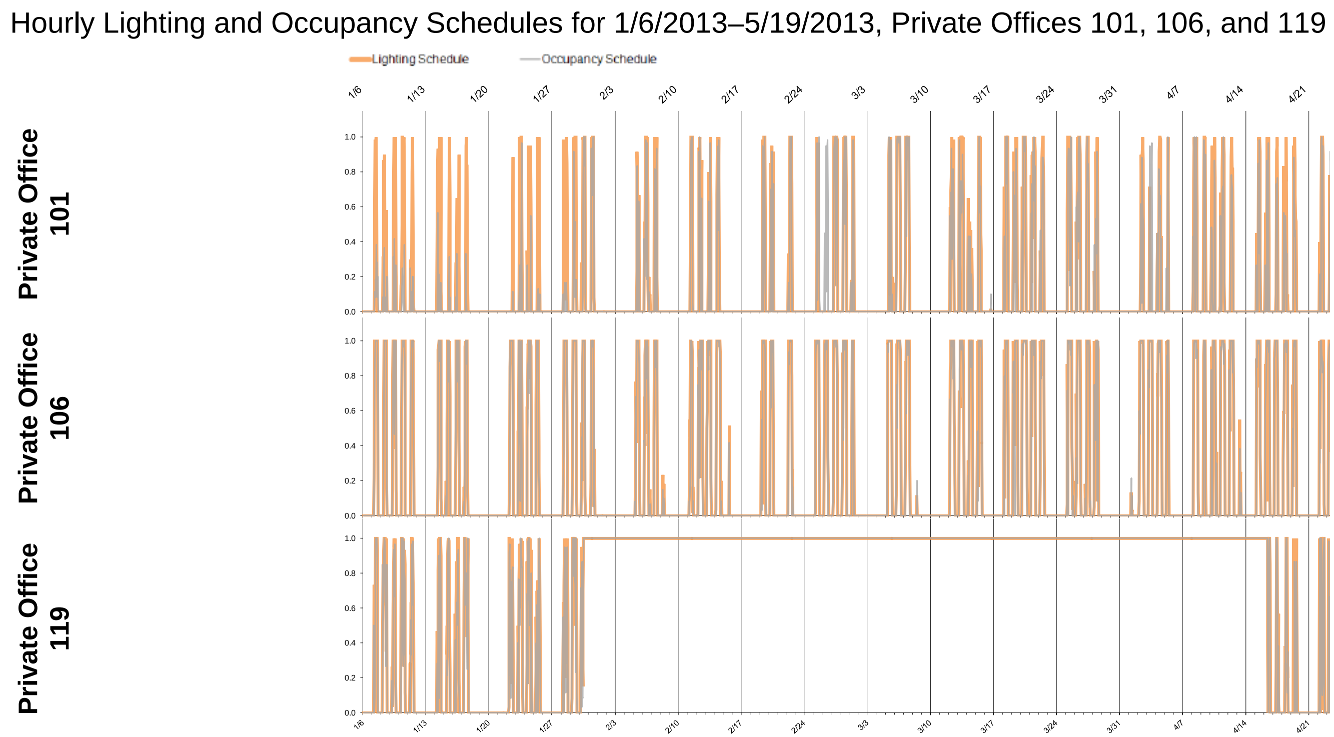


Figure 29 Measured Hourly Ambient Lighting and Occupancy Schedules for Building 9447 Private Offices

The plots show that the vacancy sensors are likely an energy saving feature since the lights are not left on at the end of the day. It is not clear from the lack of occupant switching, relative to Building 1219, that the lights would be turned off at night if the vacancy sensors were not installed.

The lessons learned from the COF private office survey are that the LEED requirements, particularly the Optimize Energy Performance credit, directed the design toward best practice electric lighting and lighting control features such as reduced LPD and vacancy lighting control. But the Daylight and Views credit, while apparent as a driver in the façade design, did not guide the result toward realized energy savings due to daylight since most office lights are on during the day when occupants are present.

High-Bay Modules

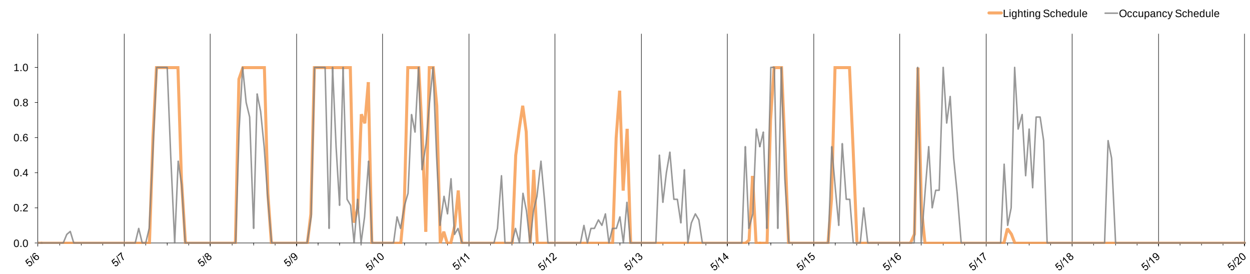
Figure 30 shows the skylights and vacancy sensor control system employed for a typical high-bay module. The daylighting system provides an average of 30 fc at the workplane for a mid-day, clear, Equinox sky condition. The electric lighting adds 30 fc to the workplane. The daylighting and electric lighting design are sufficient from a light quantity and quality perspective.

The lighting control system shown in Figure 30 looks different than the vacancy controls of the private office, although it functions in the same way. Ceiling-mounted occupancy sensors turn lights off if occupants forget—they are required to turn the lights on when they enter the space. The simple button interface (left image) does not seem to cause confusion based on observation of occupant interaction during the multiple site visits. The photocell (right) is mounted on the wall and switches the fluorescent troffers in two stages as daylight saturation reaches approximately 30 fc.

Figure 30 Images of Building 9447, High Bay Module Daylighting and Lighting Control Features

Figure 31 shows that the space is used without electric lighting (gray line only), substantiating the claim that the space meets the daylight sufficiency criteria for net zero energy. Conclusions regarding the lights being on when the space is unoccupied cannot be made since it was not possible to completely outfit the high-bay space with occupancy loggers. It is possible and likely that the space was occupied during most times that the lights are shown to be on.

Hourly Lighting and Occupancy Schedules for 5/6/2013–5/20/2013, High-Bay Mod 2



Hourly Lighting and Occupancy Schedules for 1/6/2013–5/19/2013, High-Bay Mod 2

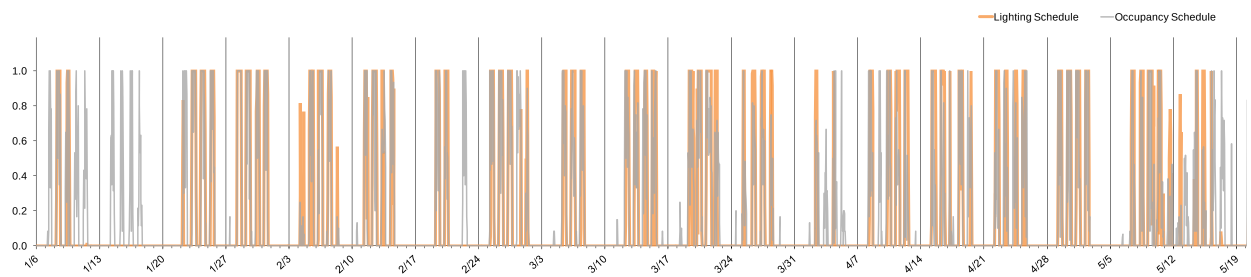


Figure 31 Measured Hourly Ambient Lighting and Occupancy Schedules for a Building 9447 High-Bay Module

New Brigade Headquarters Facility (Building 9420)

Like Building 9447, Building 9420 is a sustainably designed, newly constructed multi-use space. The primary space types in Building 9420 are private offices, open offices, and classrooms. The electric lighting is primarily fluorescent, with low lighting power densities and illuminance on par with IESNA recommendations. The lighting control system contains a mix of occupancy and vacancy sensors, classroom scene control (allowing one or more light fixtures in a space to be turned on/off/dimmed in groups to create different moods), and daylighting control.

Figure 32 Image of Building 9420, West Façade

Hallways

Figure 33 shows a mix of entry spaces and hallways. Each is lit with florescent fixtures. The images show an opportunity to take advantage of daylight or low illuminance requirements (5 fc for a hallway) to reduce the current lighting energy use.

Figure 33 Images of Building 9420, Shared Spaces

Open Offices

The open offices are similar to those of Building 1219 with high cubicle partition heights and a uniform grid of troffers for ambient lighting. The difference between the open office lighting scenarios is that some of those in Building 9420, shown at the top of Figure 34 are zoned so that the fixtures near the perimeter can be turned on automatically in response to daylight. This is not a universal design feature of the building, as shown by the lights on at the bottom of Figure 34. Opportunity exists for a more tightly integrated daylighting and lighting control system.

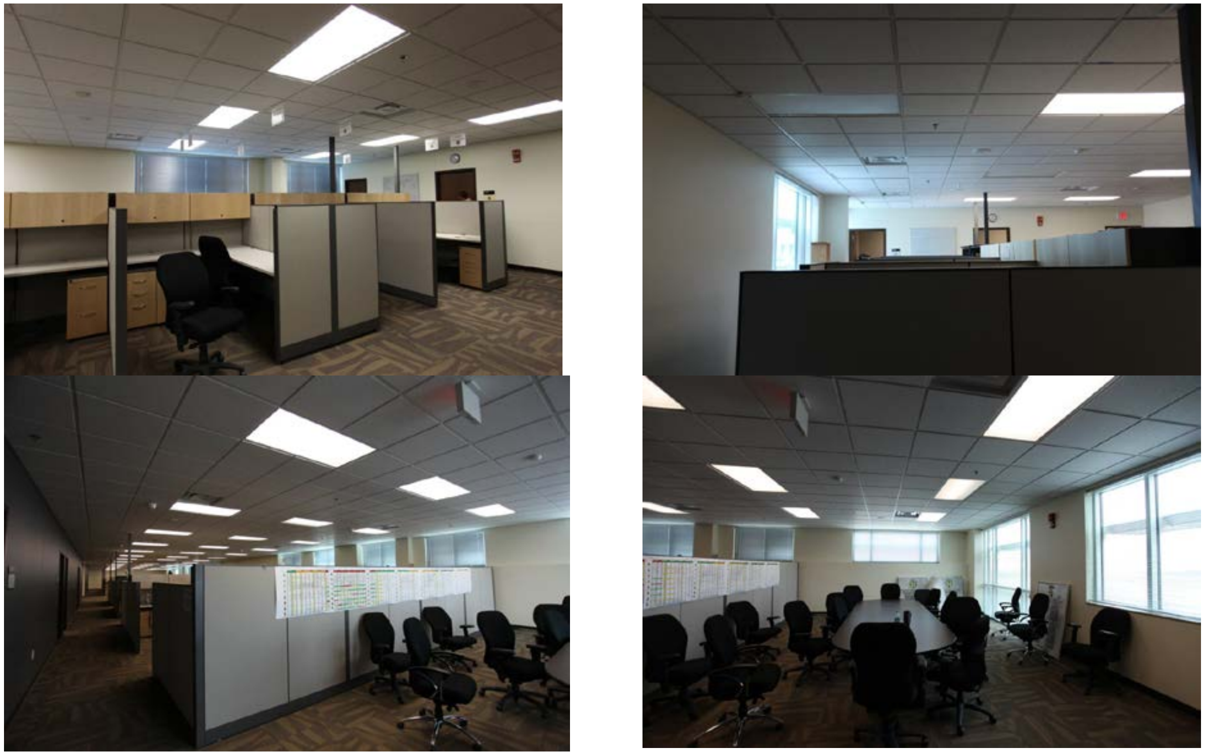


Figure 34 Images of Building 9420, Open Offices.

Figure 35 combined the lighting use of daylight controlled and non-daylight controlled electric lighting fixtures. The plots show that both the east and west offices have a heavy use of electric lights throughout the day and evening, and this trend does not differ between the west office that has perimeter windows and the east office that does not. While the afternoon and morning reduction of electric lighting is a good design result, allowed for by the ceiling-mounted vacancy sensors, there is opportunity to reduce electric lighting at night and to optimize the daylighting reduction for the space that contains windows.

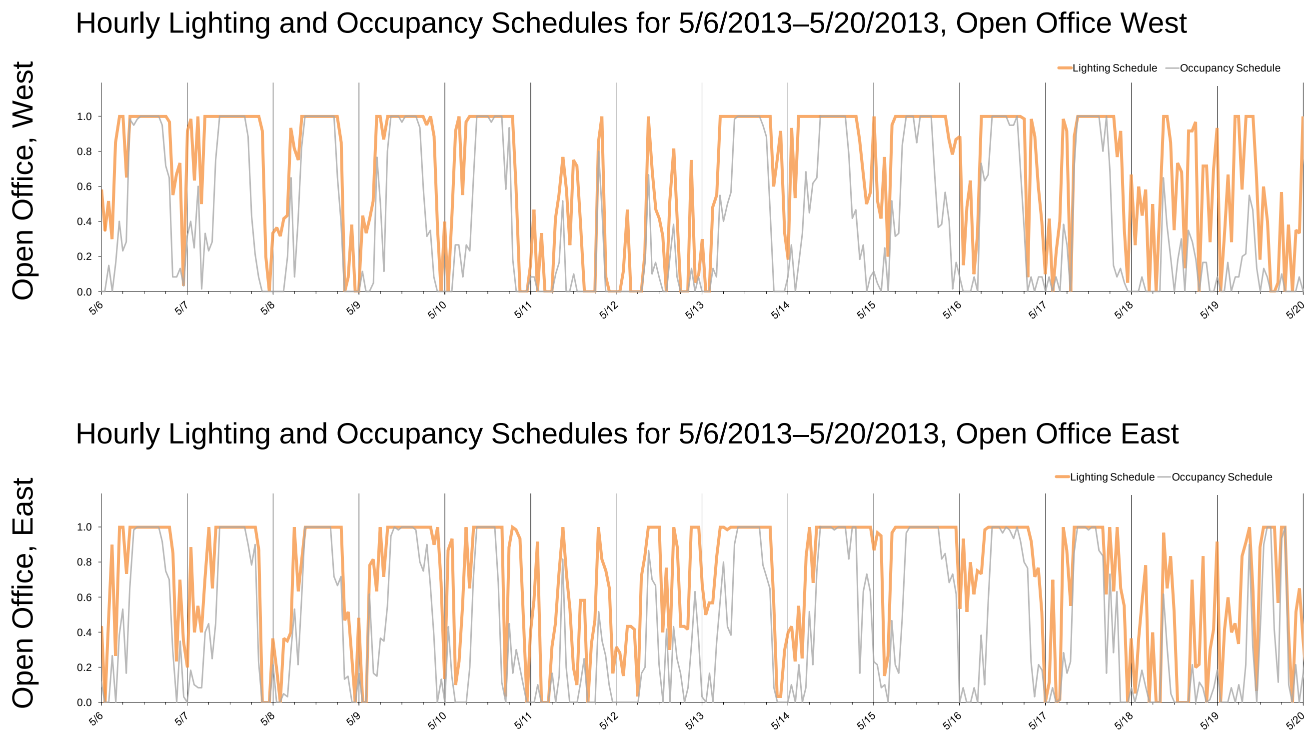


Figure 35 Measured Hourly Ambient Lighting and Occupancy Schedules for a Building 9447 High-Bay Module

Private Offices

Figure 36 shows the daylighting features of Building 9420's private offices. As noted in the private office discussion of Building 9447, the daylighting features do provide a view and opportunity for daylighting energy savings. But, the design solution does need to be optimized to prevent occupant overrides as shown in Figure 36 (center) and realized energy savings. A vacancy sensor is provided (bottom right), which is shown for comparison to the interface of Building 9447's vacancy sensors in Figure 26.

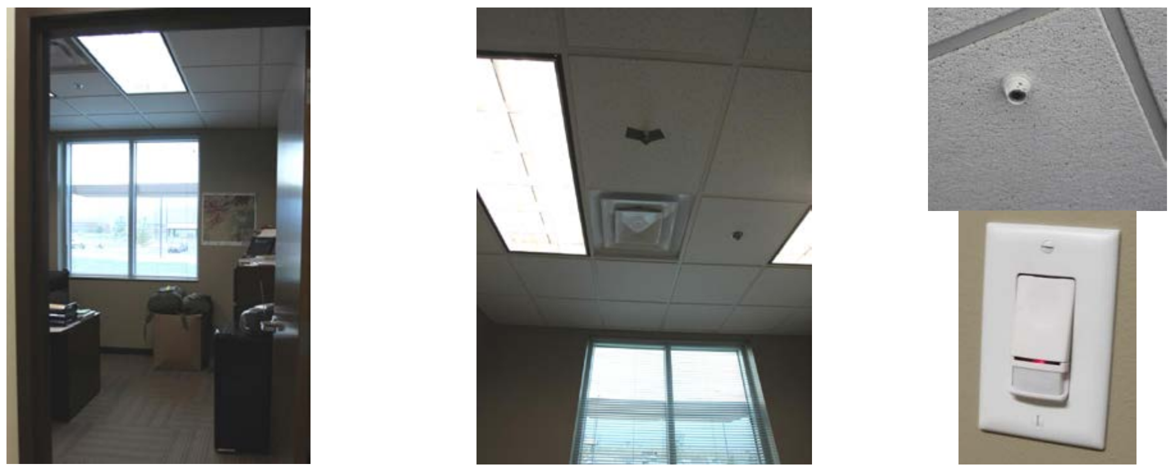


Figure 36 Images of Building 9420, Private Offices

Classrooms

Figure 37 shows a typical classroom lighting configuration in Building 9420. The electric lighting has three scenes for different teaching scenarios, which are manually controlled using the switches shown to the right. No occupancy or vacancy control exists.

Figure 37 Images of Building 9447, Classroom

The classrooms are not daylit, which is a wise energy choice (assuming not all spaces can have access to daylight) looking at the relatively low occupancy rate compared to other spaces in Building 9420. Figure 38 shows that the lights are often left on when the space is unoccupied so that the lighting energy use is twice the occupancy rate.

Hourly Lighting and Occupancy Schedules for 3/3/2013–4/16/2013, Typical Classroom

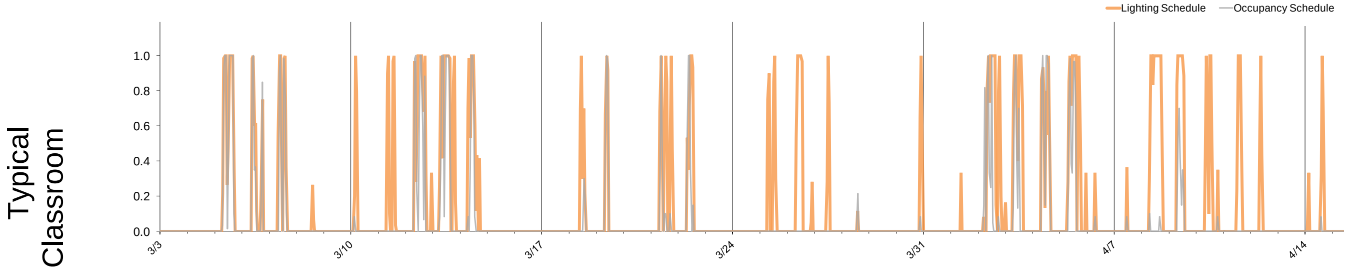


Figure 38 Measured Hourly Ambient Lighting and Occupancy Schedules for a Building 9420 Classroom

Figure 39 shows two of the additional control interfaces that were found in Wilderness Road building conference rooms. The occupancy and lighting patterns can be assumed to be similar to the Building 9420 classroom.

Figure 39 Images of Building 9447 and 9420, Conference Room Control Interfaces

Best Practices and Recommendations

The Army has made important steps toward realized energy savings by requiring LEED Silver and Gold certification in new construction and retrofits, and by incorporating net zero energy goals in recent new construction projects. The value of this lighting research question is in energy performance assurance: expanding on the currently used best practices to ensure that the design intent and predicted energy savings are being achieved in operation. Since LEED focuses on views and installed LPD, it is not always clear that even the most sustainably designed buildings, such as to LEED Platinum certification, show high performance in terms of occupant satisfaction and lighting energy use. This gap between intent and performance can widen at each stage of design and operations. The space surveys showed that Fort Carson's lighting systems are well designed, well implemented, and performing to most of the qualitative, net zero energy criteria outline in the Methods section. It is apparent that some gaps do exist though, in the energy performance and occupant acceptance needed to repeatedly produce and operate net zero energy buildings. The primary opportunities noted were:

- Retrofit space electric lighting can be reduced in power to achieve 25 fc.
- Retrofit space lighting control can all be vacancy type where occupants must manually turn lights on when they enter a space.
- All spaces' electric lighting zoning can be finer grained to take advantage of perimeter daylight and occupant preferences.
- All spaces' daylighting features can be more tightly integrated with occupant habits and electric lighting control to realize the predicted/expected daytime lighting energy savings.

Daylighting features can be more tightly integrated with occupant habits and electric lighting control to realize the predicted/expected energy savings.

These qualitative observations are evaluated in a more quantitative way in the following section, and then translated to best practices for Fort Carson and GSA.

Recommendations for Fort Carson

The recommendations for Fort Carson lighting systems are broken out by space type. Example analysis is shown to support recommendations made. The savings are extrapolated for building types to show potential energy savings for recommended solution sets.

Hallways

Reduce the installed LPD by targeting a 2:1 minimum-to-maximum uniformity ratio with a minimum of 5 fc between fixtures. Incorporate automatic control in all hallway spaces to either turn on/off with occupancy or sweep off at night. With automatic control, consideration must be given to the entry points and sensor or override switch location. A vestibule light should serve as an egress fixture to guide occupants entering the space to the sensor or switch that will turn the hallway lights on. Provide sequential pathways of light to ensure safety and comfort but do not continuously light all paths when occupants are not present.

Private and Open Offices

The electric lighting recommendation for the Fort Carson offices is to use LED ambient lighting fixtures but design to 25–30 fc. Currently, the Building 1219 office lighting power density is similar to that of other Wilderness Road office spaces but the illuminance is much higher. In other words, while Building 1219 is efficiently lit with LEDs, it appears overlit, providing further energy reduction opportunities. An LED fixture can be selected with lower light output, which will result in approximately proportionate reduction in electric lighting energy use.

A primary daylighting recommendation for all perimeter office spaces is to refine the daylight and vision glazing split. The overhang should sit above the vision glazing (<7.5 ft above the floor) and below the daylight glazing (>7.5 ft above the floor). The daylight glazing should be evaluated for glare potential with respect to the office furniture layout. If only brief periods of direct sun (<15 minutes) strike vertical surfaces in the space then consider leaving the daylight glazing without a glare treatment. Move the blinds or shades to the same elevation as the exterior overhang. If glare from the daylight glazing is deemed a potential problem, use daylight blinds, which are highly reflective and static, at the daylight glazing. The exterior shade and dropped blind configuration is shown in Figure 40.

Figure 40 Building 9420 open office section (left) with the blind head height at the top of the vision glazing (right)

Figure 41 Open Office Image (top left) and Radiance Renderings of base case blinds closed (top right), full blinds partially open (bottom left), and vision glazing blinds only (bottom right)

The workplane illuminance results for each scenario are shown in the following 4-ft by 4-ft grids. The typical grid represents a 40-ft by 36-ft partial floor plan of the space where the window wall is to the right of the grid.

Scenario	Annual Average Workplane Illuminance [fc]									
Blinds fixed :	1	1	1	1	1	1	2	2	2	2
	1	1	1	1	1	2	2	2	2	2
	1	1	1	1	1	2	2	2	2	3
	1	1	1	1	1	2	2	2	2	3
	1	1	1	1	2	2	2	2	3	3
	1	1	1	1	2	2	2	2	3	3
	1	1	1	1	2	2	2	2	3	3
	1	1	1	1	2	2	2	2	3	3
	1	1	1	1	1	2	2	2	3	3
Full blinds, ideal occupant :	6	6	7	7	8	9	10	10	10	10
	7	7	8	8	9	10	12	13	16	17
	6	7	8	9	10	11	13	16	19	23
	7	7	8	10	11	13	15	19	22	27
	7	8	9	10	11	14	17	20	25	30
	8	8	9	10	12	14	17	20	26	29
	8	8	9	10	12	14	17	20	26	30
	7	8	9	10	11	14	16	21	26	33
	7	8	9	10	11	13	16	19	24	28
Partial blinds, typical occupant :	11	11	11	11	11	12	13	12	12	11
	56	12	11	12	12	13	13	14	14	15
	57	12	12	12	13	14	15	16	17	17
	12	12	12	13	13	15	16	17	18	19
	57	12	12	13	14	15	17	18	20	22
	57	12	13	13	14	15	17	19	20	21
	12	12	12	13	14	15	17	19	21	22
	13	12	12	13	14	15	17	19	21	23
	12	12	12	12	13	14	16	18	20	21

(The window wall is on the right side of the page.)

The annual average light output for each office daylighting scenario is shown in Table 13. If the daylighting control system were ideally commissioned, the light output translates to annual energy use.

Table 13 Office Daylighting Alternatives, Light Output

Scenario	Annual Average Light Output
Blinds fixed	100%
Full blinds, ideal occupant	75%
Partial blinds, typical occupant	36%

In addition to the daylighting control tuning that would be needed to match the electric lighting use with the daylight resource as described in the previous table, additional control changes are conservatively estimated to reduce electric lighting use by 10%, based on case studies and the unnecessary on-time determined using the occupancy and light logging data. The control recommendations are to:

- Add bi-level control to all ambient light fixtures through multi-level ballast control or re-circuiting the fixtures. Change the control system to always turn on the lowest level of ambient lighting first, and require the occupant to use the control interface again to get the maximum ambient light output.
- Add a "walk-through" or security circuit to all open offices. This circuit should contain about 10% of the ambient lighting fixtures, or this can be the emergency or egress circuit depending on life safety system configuration. Add a control interface that allows the "walk-through" lights to be turned on for ten minutes with an automatic sweep off and label the switch for nighttime use.

Classrooms

The addition of occupancy sensors to the classrooms can ensure that lights turn off when the space is unoccupied, reducing the annual lighting energy use in half.

Community Spaces

Add daylighting control or re-commission daylighting control for fixtures near glazed entries, or glazed community spaces.

High Bay Modules

The high-bay modules are performing well. Skylight specification, placement, and size are adequate from a daylighting perspective. Electric lighting and lighting controls are performing well. No specific improvements are needed—the general strategies of the space type are included in the best practices.

Solution Sets

Using the solutions outlined in the previous sections paired with the energy savings potential calculated from the simulation results and the monitored data, space-by-space energy saving potential versus an ASHRAE 90.1 2007 baseline are given in Table 14, Table 15, and Table 16. Private offices, open offices, classrooms, and high bay spaces are selected for numerical analysis.

Table 14 gives the code-allowable LPD and assumed percentages of time lights are on (on-time) considering code requirements to turn lights off when occupants are not present. A 50% on-time is a conservative estimate for the energy savings calculations to follow since some of the spaces do not have automatic off mechanisms for nighttime reduction, such as the classrooms. The last row in the table translates the code allowances to energy use intensity values for comparison in the following tables.

Table 14 Solution Sets, ASHRAE 90.1 2007 Baseline

	Private Office	Open Office	Classrooms	High Bay
Code LPD [W/ft2]	1.1	1.1	1.4	0.9
Electric lighting on time [%]	50%	50%	50%	50%
Annual lighting energy use [kWh/sf/yr/space]	4.82	4.82	6.13	3.94

Table 15 shows the lighting power density and on-time for each space type. The LPD was derived from reflected ceiling and electrical plans, and the on-time was derived from the light logger data. The highlighted row shows the percent reduction of current Fort Carson lighting system energy use versus the code allowance shown in Table 14. The results reinforce the qualitative observations that Fort Carson buildings, and current GSA lighting best practices, rooted in LEED credits, are successful at producing real energy savings. Potential does exist, though, to become more aggressive in design and operation to realize the 75% lighting energy reduction goal for net zero energy readiness. The greatest potential exists in the open offices, which show the lowest LPD and lighting control reductions.

Table 15 Solution Sets, Current Lighting System Performance

	Private Office	Open Office	Classrooms	High Bay
LPD [W/ft2]	0.83	1.1	0.66	0.85
Electric lighting on time [%]	25%	33%	25%	15%
Annual lighting energy use [kWh/sf/yr/space]	1.83	3.18	1.45	1.12
Lighting energy savings versus code [%]	62%	34%	76%	72%

Table 16 takes the solutions described in the previous sections (listed in the first three shaded rows), and assigns LPD and light energy use reduction values that are known possible from NREL's experience operating net zero energy buildings, and substantiated through literature review and crosscheck calculations.

Table 16 Solution Sets, Potential Lighting System Performance

	Private Office	Open Office	Classrooms	High Bay
Electric lighting strategies	LED lighting to 30 fc	LED lighting to 30 fc	-	-
Daylighting strategies	Open daylight glazing	Open daylight glazing	-	-
Control strategies	Perimeter daylight control	Perimeter daylight control, "walk-through" and dual-level ambient fixture zoning	Occupancy sensors and dual-switching for ambient lighting	-
LPD [W/ft2]	0.5	0.66	0.66	0.85

	Private Office	Open Office	Classrooms	High Bay
Electric lighting on time [%]	15%	17%	13%	15%
Annual lighting energy use [kWh/sf/yr/space]	0.67	0.95	0.72	1.12
Lighting energy savings versus code [%]	86%	80%	88%	72%

These savings are possible with control system and daylighting element changes, and with an aggressive re-commissioning plan. A typical COF can see lighting energy savings of 75% with the measures outlined in this section; typical HQ building will see 80% lighting energy savings, extrapolating the space-by-space savings to the building footprint. The net zero energy criterion of 75% lighting energy savings versus an ASHRAE 90.1 2007 baseline can be achieved when the best practices given in the following section are considered early in the building planning and design process.

Best Practices for Federal buildings

Translate a percent energy savings goal, such as 75% versus ASHRAE, to a lighting energy use intensity goal.

For the early planning and design, the lighting best practices determined through or corroborated by this project are:

Daylighting

- Place overhangs on south and west glazing. Do not put overhangs on north glazing.
- Position blinds at the vision glazing top mullion instead of at daylight glazing top mullion.
- Use daylight blinds instead of traditional blinds or shades to block glare from glazing higher than 7.5 ft above the floor.
- Use transom glass at the inner wall of most perimeter spaces. Even a small amount of light such as 5 fc is often sufficient for tasks such as printing, taking lunch out of the break room refrigerator, or picking something up from a desk.

Electric Lighting

- Fine tune design and delivered illuminance to 25–30 fc in all working spaces.
- Use a task-ambient lighting strategy with multiple layers of ambient lighting and multiple zones so that the low-illuminance occupant preference is the base case and others must “opt-in” for more light.

- Write or plan the emergency fixture specification to have an emergency relay instead of battery backup to create security or walk-though circuits and allow for daylighting control of all fixtures.
- Use low partition heights and light interior surface color to reflect light and create bright vertical surfaces for a bright feeling room at 30 fc.

Lighting Control

- Use vacancy sensors in all locations so that occupants must choose to switch lights on even if they have left the space for just a few minutes.
- Consider dimming fixtures where appropriate to prevent the occupant distraction often caused by switching schemes.
- Consider using a central lighting control system that can be connected to other central control systems for continuity of operations across a campus and for ease of re-commissioning to maintain the designed energy savings.
- Use consistent and intuitive control interfaces across campuses so that transient occupants can easily learn and cannot disable commissioned systems
- Require that a detailed sequence of operations be produced by the lighting designer and electrical engineer, and require that this document be the basis of lighting commissioning.
- Translate a percent energy savings goal, such as 75% versus ASHRAE, to a lighting energy use intensity goal. Require that the lighting designer substantiate the design and that the commissioning agent verify that the goal is being met in early operations. This single step is the key to moving the discussion presented in this document to realized energy savings in operations.

The lighting system performance of Fort Carson is well designed and performing, **already nearing 50% annual lighting energy savings versus an ASHRAE 90.1 2007 baseline**. The broad-scoped investigation presented in this report allowed for investigation of the actual operational patterns of a high performance design. The results show that there are changes that can be made to the existing buildings' electric lighting, daylighting, and control systems that will allow for even deeper lighting energy savings than are currently being achieved. The realization of 75% energy savings versus code will require further space-by-space design analysis that accounts for system cost. Case studies such as NREL's Research Support Facility have shown this level of savings possible when best practices are considered early in design and validated in design and operations.

Fort Carson's lighting system performance is well designed and performing, already nearing 50% annual lighting energy savings.

Appendix B Lighting and Daylighting Glossary

Ambient lighting: General lighting in a space typically provided by uniformly spaced overhead light fixtures.

Bi (dual) -level control: Control of light source intensity at two discrete levels in addition to off. Typically, the discrete levels are 50% and 100%.

Clerestory glazing: Vertical glass portions of the building envelope that typically sit at least 9 ft above the finished floor.

Control interface: The components of the lighting control system with which occupants interact. Commonly, this includes wall-mounted on/off switches and slide dimmers.

Daylight blinds: Blinds that sit in the daylight glazing, that are static or operable, and serve to redirect direct sun into a space more deliberately than traditional blinds, while blocking glare from direct sun.

Daylight glazing: Vertical glass portions of the building envelope that sit above 7.5 ft on each floor.

Daylight quality: The distribution and color of daylight at a given point in time. Daylight quality metrics include uniformity and color temperature.

Daylight quantity: See Illuminance

Daylight sufficiency: The minimum daylight quantity needed for typical tasks in a space to be performed, without excess daylight.

Egress fixture (versus emergency): Egress pathway lighting, which is commonly about 10% of a space's lighting load placed near pathways that lead to exits for the space.

Electric lighting zones (switching, granularity): A zone encompasses the floor area lit by all the luminaires on a common controller.

Emergency lighting bypass relay: A relay that allows for emergency/egress fixtures to be powered by a backup power source in a normal power failure event while operating as a typical relay that can be controlled by the lighting control system at all other times.

Fenestration-to-surface-area: The ratio of glass to envelope area for a given plane, used as a daylighting and envelope design metric. Examples include window-to-wall area and skylight-to-floor area ratios.

Glare: The sensation produced by luminances within the visual field that are sufficiently greater than the luminance to which the eyes are adapted, which causes annoyance, discomfort, or loss in visual performance and visibility. There are a variety of glare types such as disability glare, which is a type of glare that causes a loss of visibility from stray light being scattered within the eye, and discomfort glare, which is the sensation of annoyance or even pain induced by overly bright sources.

Illuminance: The average density of luminous flux incident on a horizontal (unless another orientation is specified) surface, measured in foot candles (fc) or lux (lx). One fc equals 10.76 lx.

Lighting control algorithms: The way in which the light in the space responds to input (typically daylight quantity). Types of algorithms include continuous dimming or switching, and are further defined by settings such as dimming rate and deadband (buffer to prevent rapid cycling of lights). The settings result in a combined electric light and daylight quantity at any given point in time.

Lighting power density (LPD): The maximum lighting power per unit area of a building classification of space function.

Lighting schedule (0-1): A normalized measure of the number of lights used in a space each hour. All lights on results in a value of 1 and all lights off results in a value of 0.

Maximum-to-minimum illuminance ratio: uniformity metric; the degree of variation of illuminance over a given plane. Greater uniformity means less variation of illuminance.

Occupancy and light loggers: Measurement devices independent of the lighting control system that detect and record a change in light level and occupancy in the space. These devices must be set up (located and sensitivity adjusted) for a given space so that the change in light level corresponds to a group of lights being on or off and for all occupancy within a zone to be detected. The output of this type of device can be used to create lighting and occupancy schedules for a space.

Occupancy schedule (0-1): A normalized measure of the number of occupants in a space each hour. A value of 1 is associated with the maximum expected occupancy and a value of 0 is given to an empty space.

Passive lighting control design, same as: Occupant engaged(?)-lowest level first, and must be selected

Photosensor: A device used to integrate an electric lighting system with a daylighting system so lights operate only when daylighting is insufficient. A photosensor consists of a photocell (light sensitive diode) and a controller or logic device that determines the status of the lights in response to daylight. Often these components are packaged together and mounted on the ceiling.

Reflectance: A measure of the ability of an object to reflect or absorb light, expressed as a unitless value between 0 and 1. A perfectly dark object has a reflectance of 0, and a perfectly white object has a reflectance of 1.

Sweep: A timed lighting control event that turns a group or all of a space's lights off at once. Often, a warning such as a quick cycle of the lights on and off will be given to occupants approximately ten minutes prior to the event.

Task lighting: A secondary layer of light, in addition to the ambient lighting, that is focused in a particular area of the space. Task lighting typically takes the form of a desk lamp.

Transmittance: A property of glazing that expresses the percentage of visible light that passes through it.

Transom glass: High glass, typically above 7.5 ft above the finished floor, set into an interior wall that allows an interior space to borrow daylight from a perimeter space.

Troffers: Rectangular, overhead light fixtures that are recessed into a regular ceiling grid.

Tubular daylighting devices: A specific type of toplighting, or lighting from the ceiling, that uses a highly reflective tube to transfer light from the roof to a lower ceiling plane.

Vacancy control (versus occupancy, typically mounted on the ceiling): A manual switch control setup that requires an occupant to manually turn lights on but will automatically turn lights off after preset duration without detected motion.

Vision glazing: Vertical glass portions of the building envelope that sit below 7.5 ft on each floor (often considered only above 2.5 ft)

"Walk through" circuits (or security circuits): A group of lighting fixtures that lights an often traversed pathway in a space, such as that used by nighttime security staff, that can be switched on and off independently of other fixtures in the space.

Workplane: The working surface, which is often typical desk height, 2.5 ft above the finished floor, but can also be the floor in hallways.

Contributing references: Rensselaer Polytechnic Institute Lighting Research Center, National Lighting Product Information Program; Energy Center of Wisconsin; ASHRAE