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Laboratories Best Practices: Efficient Electrical Lighting

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Laboratories for the 21st Century: Best Practice Guide

Efficient Electric Lighting in Laboratories

Introduction

There is a considerable body of research that describes the impact of the visual quality of the work environment on worker comfort, health, and productivity. The appropriate design of lighting systems is especially important in laboratories, given the intensity and significance of work carried out in laboratories and the long work hours spent by researchers. In addition, the lighting energy intensity in laboratories is up to twice that of a typical office space. Lighting energy use typically accounts for between 8% and 25% of total electricity use, depending on the percentage of lab area (see Figure 1). While not a significant percentage compared to HVAC systems, it nonetheless provides several opportunities for energy efficiency.

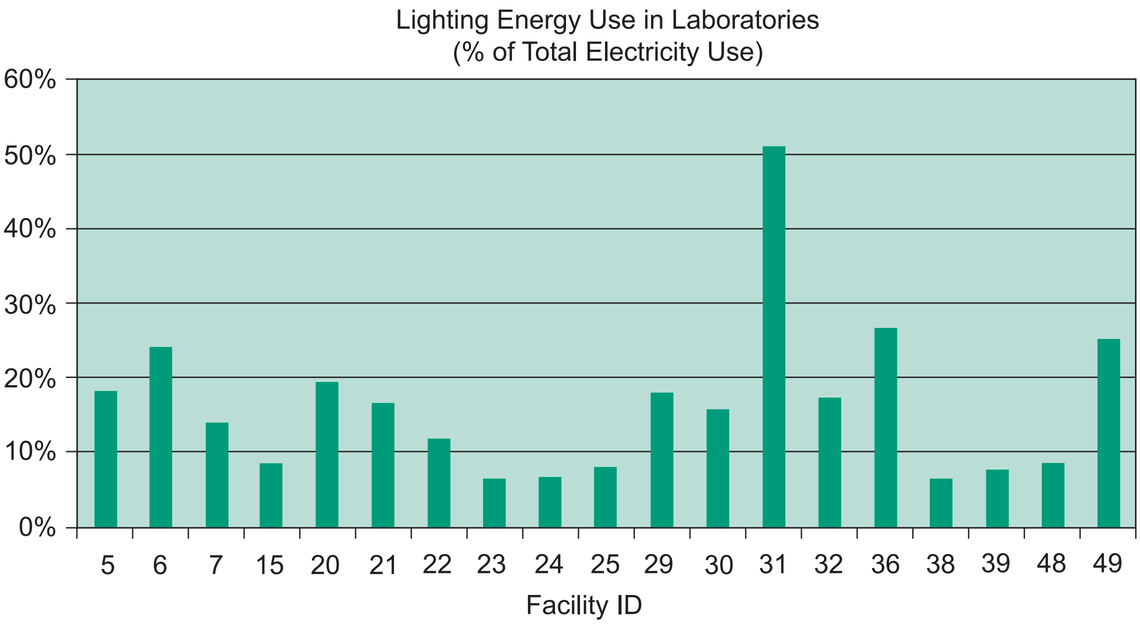

Figure 1. Data from the Labs21 Energy Benchmarking database indicates that lighting energy varies from about 8% to 25% of total electricity use in most laboratory facilities.

EPA United States Environmental Protection Agency

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Federal Energy Management Program

This best-practice guide is one in a series created by the Laboratories for the 21st Century ("Labs21") program, a joint program of the U.S. Environmental Protection Agency and U.S. Department of Energy. Geared towards architects, engineers, and facility managers, these guides provide information about technologies and practices to use in the design, construction, and operation of safe, sustainable, high-performance laboratories.

The intent of this guide is to highlight and summarize best practice strategies for high-performance, energy-efficient lighting in laboratories. This guide is not intended to serve as a general guide on how to design lighting for a laboratory. Comprehensive "how-to" information on lighting design can be found in the Illumination Engineering Society of North America (IESNA) handbooks as well as other resources listed in the references.

The next section describes best practice strategies for systems and components (fixtures, lamps, controls). The section following that describes the best practices pertaining to lighting performance parameters (illuminance levels, color rendition, etc.).

Systems and Components

Daylight Integration

Strategy #1: Electric lighting should always be designed as a supplement to daylighting.

Whenever feasible, use natural light as the primary daytime light source. It is the most visually effective and energy-efficient source of lighting. The National Institutes of Health (NIH) guidelines state, "Laboratories and offices shall be provided with natural light and views to the outside, as long as they do not conflict with functional requirements."

Although this guide is specifically focused on the design and operation of electric lighting systems, it is well understood that the integration of any electric lighting system is only a part of an overall lighting design scheme that includes daylighting and significant integration with mechanical systems. The overall lighting design must also acknowledge the psychological stimuli that light presents to most living things and reinforce, rather than conflict with, physiological conditions such as human circadian cycle entrainment. The intensity of light, light source color, and controls can all play a key role in satisfying both physiological and psychological needs.

The Labs21 Daylighting Best Practice Guide provides design guidance and examples of how to effectively use daylighting in laboratories and integrate it with electric lighting.

Fixture Configuration

Strategy #2: Use direct-indirect ambient lighting parallel to benchtop.

There are two primary aspects of the ambient lighting fixture configuration in a laboratory:

- Beam direction: direct, indirect, or direct/indirect.
- Fixture location relative to bench top: parallel, perpendicular, or other.

While there is no single "best" fixture configuration, a direct-indirect configuration oriented parallel to the bench is, typically, the preferred option. (A notable exception to this guidance would be laboratories that require wash-down capabilities.)

Direct-indirect fixtures direct a certain percentage of the light upwards and the remainder downwards, thereby capturing the advantages and minimizing the disadvantages of both components. A 100% direct fixture is more effective in producing high illuminance levels at the benchtop, but also more likely to produce glare, high contrast ratios and shadowing, and poor vertical brightness. Because indirect lighting reduces shadowing, it often requires a lower level of illuminance than would direct lighting to perform tasks equally well (Watch 2001, p. 225). On the other hand, while a 100% indirect fixture minimizes glare and shadowing, the lack of any direct component creates an impression of dullness, even if illuminance levels are adequate.

In labs, the direct component should preferably be between 20% and 40%. Figure 2 shows two typical direct/indirect lighting system installations located parallel to the benchtop and directly above the front edge of the benchtop.

An alternative to placing lighting fixtures directly above each benchtop is to place them between benches. This placement usually necessitates primarily indirect lighting to avoid shadowing at the bench. The advantage of this approach is reduced lighting power density. For example, at the U.S. EPA's Research Triangle Park Facility, this approach (Figure 3) allowed power density to be reduced from 1.85 W/sf to 1.35 W/sf, providing an estimated annual savings of over $200,000. The first cost premium was about $200,000, resulting in a simple payback of about one year.

To make indirect lighting efficient, the ceiling should have at least 80% reflectance, and walls should have 65% or greater. Ceiling height is an important consideration. Fixtures should be located at least 18 to 24 inches below the ceiling to avoid hot spots (although there are some new luminaire designs that allow for shorter suspension lengths). This mounting recommendation is especially true for T5 technology, primarily because the high lumen output

Figure 2: Left - Typical installation of direct-indirect lighting at the Donald Danforth Plant Science Center. Source: HOK. Right - Typical T8 direct/indirect lighting installation, University of Wisconsin Chemistry Building. This example shows that indirect lighting can be implemented even without a conventional ceiling. Source: Pivotal Lighting Design/Affiliated Engineers.

and luminaire-lamp combination can have more directional performance characteristics (i.e. it acts more like a point source).

If ceiling height or other factors preclude the use of suspended luminaires, consider using a recessed direct-indirect fixture. This fixture is recessed into the ceiling. It has a concave reflector and perforated metal drop basket in the center. Since the drop basket extends below the ceiling plane, light is directed high-up on vertical surfaces and onto the ceiling, providing a much more uniformly lit work environment than conventional recessed fixtures (Losnegard 2004).

Strategy #3: Consider alternative ambient lighting options for movable benches.

Movable lab benches are an approach to laboratory design that is gaining momentum. They give the researcher the flexibility to reconfigure an entire lab bay rather quickly using overhead service trunks as the pivoting points for new bench layouts. Several designers have addressed this issue by designing lighting systems that are mounted directly to the benches themselves, thereby taking the lighting along with the benches as they are relocated (see Figure 4). One drawback of bench-mounted lighting is that, if benches are moved often, the resulting vibrations may have a detrimental effect on expected lamp life. Also, there are often problems with uniformity if the bench configurations are very different from the original design. Another complexity to overcome is how to provide separately controlled electrical lighting circuits (often at 277 volts) to bench-mounted locations from raceways already carrying multiple circuits from several electrical sources. It is also likely that some degree of redundant ambient lighting is needed so that, if a bench is replaced with open floor space for equipment or movable tables, there will still be adequate illumination at that point.

A different approach to providing effective lighting for the movable bench lab plan is to place the 100% indirect lighting in direct relation to the possible bench configurations. Because electrical power, data and gases are usually fed from overhead service trunks located at modular intervals (typically between 10.5 ft and 11.0 ft in labs with movable benches) arranging area lighting on the same planning module assures that the lighting emphasis is above the benches, where it is desired (Figure 5). This approach eliminates the potential drawbacks of bench-mounted luminaires cited above, while still allowing for movable, bench-mounted task lighting wherever needed for supplementary illumination.

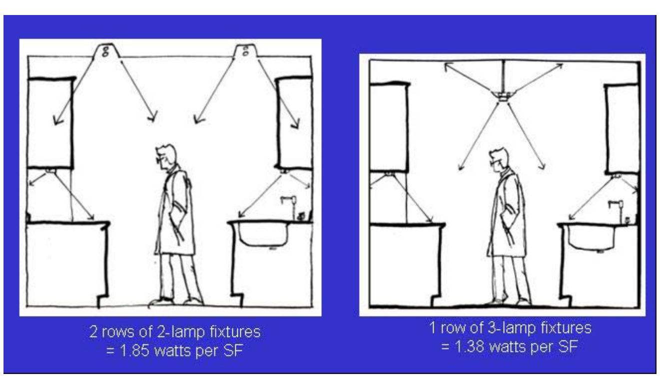

Figure 3: Lighting configuration options considered for the US EPA Research Triangle Park facility. Source: HOK.

Figure 4: Mock-up of a lab module for Memorial Sloan Kettering Cancer Center, showing bench-mounted ambient lighting with under-cabinet task lighting. Source: ZGF Architects.

Figure 5: Aisle-mounted indirect luminaires suspended in relation to the overhead service trunk can maintain good-quality lighting regardless of the position of the movable benches, as long as the ceiling remains somewhat consistent.

Figure 6 shows a fixture configured around vertical service trunks. This allows benches to be located along two perpendicular horizontal axes, thereby affording even more flexibility.

Physical mock-ups are an effective way to study different lighting configurations for a lab module. The mock-up should include, as a minimum, a sample installation of the proposed ceiling material as well as any mechanical diffusers or other ceiling elements that are likely to be within the beam spread of the indirect portion of the lighting system distribution pattern. An actual lab bench, fitted out with full-height shelving as specified, will provide very revealing clues about how the visual environment is shaped with these elements.

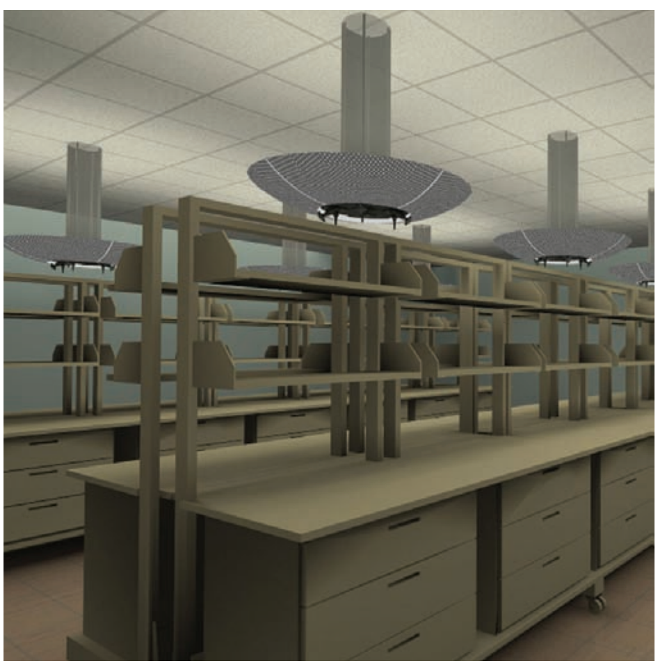

Figure 6: Conceptual study of a lighting array incorporated within the electrical, data, gases overhead service trunk. This scheme provides good lighting for benches located either parallel or perpendicular to the service trunks. Source: Flad Associates and Pivotal Lighting Design/ Affiliated Engineers.

Strategy #4: Use task lighting.

The various types of tasks carried out in a laboratory often have different lighting requirements. Separating task and ambient lighting allows for greater user flexibility and energy efficiency. Consider using articulated-arm task lighting for maximum flexibility in meeting user needs. If this cannot be done, then consider under-cabinet task lighting (see Figure 7). However, the heat generated from under-cabinet task lighting may limit the types of chemicals stored on the shelf directly above the task light. Under-cabinet task lights also require that the space below the task light be free of clutter and storage that could potentially block the light. It is important to ensure that task lighting is explicitly integrated into the overall lighting design early in the design process. Energy efficiency is achieved by reducing ambient light levels (e.g., 30 fc) and ensuring that task lights are turned off when not needed. If task lighting is seen as an optional supplement to ambient lighting (e.g., as part of furniture and finishes), designers will likely configure ambient lighting to meet task requirements, negating the energy efficiency benefits of separating task and ambient lighting, and reducing its overall cost-effectiveness.

Figure 7. Under-cabinet task lighting in a USDA laboratory. Source: HOK.

Lamps and Ballasts

Strategy #5: Use energy-efficient lamps and ballasts.

Over the past two decades, significant progress has been made in efficiency improvements to lamps and ballasts, and they are one of the most cost-effective measures for improving energy efficiency in buildings. Many publications, some of which are listed at the end of this guide, provide comparative analyses of lamps and ballasts. Figure 8 summarizes the range of efficiencies in terms of lumens per watt, which is the primary measure of lamp efficacy. It is interesting to note that daylight, in addition to all its other benefits, is also the most efficacious light source.

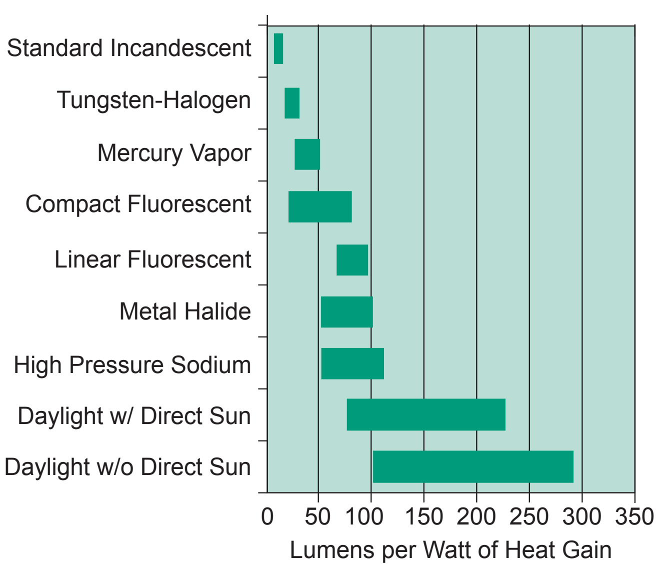

Figure 8. Luminous efficacy of various light sources. Daylight ranges calculated inside of single-pane clear and high-performance glass. Data source: Advanced Lighting Guidelines.

Efficacy can be evaluated on at least three levels:

- Lamp efficacy – which compares the efficacy of different lamps, without considering ballasts.
- Combined lamp and ballast efficacy – which includes ballast losses.
- Luminaire efficacy – which considers the efficacy of the luminaire system within the context of architectural space.

Efficacy metrics can be obtained from manufacturers and other resources. Some lamp and ballast considerations that apply specifically to laboratories include the following:

- Consider the use of T5 lamps in new construction. The smaller lamp size translates to smaller and sleeker luminaire designs and can yield far better optical control and greater luminaire efficiency, compared to T8s. T5s are also better in terms of reduced material use, consuming 60% less glass and phosphor material, and up to 50% less packaging when compared to T12 lamps (Yancey 1998).
- Always use electronic ballasts. In instrument labs where standard electronic ballasts and lamps may interfere with instrument operation, use radio-frequency-shielding luminaires. Alternatively, consider using light pipes or fiber-optic cables to provide lighting from a remote source.
- Always use compact fluorescent (CFL) or low wattage ceramic metal halide lamps instead of incandescent; the newer CFL and halide lamps have addressed color rendition issues.
- For fume hoods and bio-safety cabinets, which usually have their own lighting, coordinate the lamp color and type with the manufacturer to ensure compatibility with the overall visual environment requirements.

Controls

Strategy #6: Use daylight controls for ambient lighting in perimeter zones.

One of the major benefits of daylighting is the ability to save energy by reducing the use of electrical lighting by dimming or switching. The cost-effectiveness of daylight-based dimming is a function of electricity prices and the cost of dimming systems. One way to improve cost-effectiveness is to right-size the HVAC system by accounting for the reductions in cooling load that result from lower internal heat gains achieved by reducing electrical lighting

loads. Another way to improve cost-effectiveness is to use dimming technology further into the occupied space rather than at the perimeter. The rationale for this is that a well-daylit space provides enough daylight at the perimeter so that perimeter luminaires can be switched rather than dimmed. It is more economical to limit use of daylight-harvesting dimming ballasts to luminaires further away from the fenestration, where they will be most effective. A caveat to this approach is that it assumes users at the perimeter will turn off the lights when there is adequate daylight. Consider the use of physical models or computation daylight simulation software such as RADIANCE to optimize integrated daylight designs and establish life cycle costs.

Strategy #7: Ensure that lighting zones are small enough to provide local control.

Occupants generally prefer manual control of their environments over automatic control. Something as simple as an override to a larger low-voltage switching/dimming system satisfies this desire for direct local control. To limit lighting in unoccupied areas in periods of low occupancy, use smaller lighting zones of about 800 to 1000 sf. Note that task lighting effectively provides local control.

Strategy #8: Use bi-level switching.

Light levels are often greater than required, but occupants do not have the choice to reduce them. Bi-level controls are a low-cost or no-cost add-on (if done at construction) and allow two or three levels. In a typical installation, one switch controls 1/3 of the lamps in a space while the other controls 2/3 of the lamps. This allows for four light levels: off, 1/3, 2/3, and full. Bi-level switching is now required by code in some locations, and may be very appropriate for laboratory spaces, because they are designed to high light levels that many tasks may not even require.

Strategy #9: Use occupancy sensors for ambient and task lighting.

Lighting in general and task lights in particular tend to be left on by users. They become part of the visual "landscape," and users are not consciously aware that they should be turned off when not required. Occupancy sensors are an effective way to reduce energy waste for both ambient and task lighting in laboratories. Dual sensors, composed of both passive infrared and ultrasonic technologies, require the absence of both heat and motion to shut off, minimizing false-triggering problems. To maximize savings, lighting should be controlled separately for each bay. The cost-effectiveness of occupancy controls can be improved if they are also used for laboratory HVAC system control. As in other building types, occupancy sensors are also effective in conference rooms, rest rooms, and other intermittently used rooms.

Strategy #10: Use sweep-off lighting schedule with manual overrides.

This is appropriate for labs that tend to be occupied on a predictable schedule, and are not occupied around the clock. Lights are turned off according to preset schedules, based on occupancy patterns. Safety concerns should be carefully evaluated when considering such a system. In Washington State, code requires that lighting for areas larger than 5000 sf must have automatic controls to turn off lights at night.

Strategy #11: Commission lighting controls.

Commissioning and calibration of lighting controls are essential if energy savings are to be achieved and maintained. For example, occupancy sensors with sensitivity set too high can fail to save energy, but occupancy sensors with too low a sensitivity or too short a delay time can be annoying or even potentially hazardous to occupants. Similarly, improperly adjusted daylighting controls or improperly located photosensors can dim the lights too low, causing occupants to override them (e.g., by taping over the sensor), or can fail to dim the lights at all.

Performance Parameters

Required Illumination Levels

The goal of good lighting design is to provide the quantity and quality of light needed for the task. Lighting designed for laboratories has many things in common with lighting designed for offices or other places where mixed visual tasks are performed. One significant difference is that the work surfaces in labs are typically at various heights, hence most tasks are of a three-dimensional nature, involving multiple horizontal and vertical work surfaces. Lighting for good visual acuity necessarily includes a balance between horizontal work surface illumination and the brightness of other surfaces near and distant in the field of view. Minimizing dramatic contrast in the entire field of view will help to reduce eyestrain and visual fatigue, although some contrast is essential to prevent visual dullness, which can also cause fatigue.

Strategy #12: Don't overdesign. Carefully assess required illuminance levels in conjunction with other performance parameters.

While designers have traditionally focused on the required illumination levels for a space, there are several other aspects of lighting design that significantly affect visual performance and the overall visual perception of the space, as will be discussed later. Therefore, it is important to recognize at the outset that illuminance requirements must always be considered in conjunction with other visual performance parameters. For example, the "see-ability" of 50 to 70 footcandles (fc) of indirect lighting is comparable to 100 to 130 fc of direct lighting, due to the elimination of glare with indirect sources (Doberdruk 1999). Thus, "qualitative" factors directly affect lighting energy use.

The 9th edition of the IESNA Handbook has revised its illuminance recommendations for laboratories downward from the previous edition, as indicated in Figure 9. Many owners of laboratory facilities are questioning traditionally conservative engineering practices, which frequently led to significant over-sizing of basic building services, costing owners more money for both construction and ongoing operation.

IESNA Lighting Handbook- 9th Edition 2000 Illuminance Maintained (fc)	IESNA Lighting Handbook- 8th Edition 1993 Illuminance Maintained (fc) (horizontal)
Specimen collecting	**Specimen collecting**
horizontal 50 vertical 10	50 - 75 - 100
Science laboratory	**Laboratories**
horizontal 50 vertical 30	Tissue laboratories 100 - 150 - 200 Microscopic reading room 20 - 30 - 50 Gross specimen review 100 - 150 - 200
	Chemistry room
	50 - 70 - 100
	Bacteriology rooms
	General 50 - 75 - 100 Reading culture plates 100 - 150 - 200
	Hematology
Design Guide Section (Interior pg. 4, 6, 7)	50 - 75 - 100 (pg. 461, 462)

Figure 9. A comparison between the IESNA laboratory illuminance recommendations in the current (9th) edition and the previous (8th) edition. Data source: IESNA.

There are no universally applicable standards for illuminance in laboratory spaces. While there may be a need to light a specific task to between 80 and 100 fc, it is rarely necessary to light the whole laboratory to that level. In fact, high illuminance levels may *reduce* visual acuity for tasks that require reading monitors and other electronic displays. Therefore, the lighting designer should carefully assess illumination needs based on the task. If flexibility is required, then incorporate appropriate strategies to vary the light levels. For example, a design guideline developed for a University of California laboratory advocated a flexible configuration which had 30 to 50 fc of ambient lighting, with additional illuminance provided by under-cabinet task lighting, and a re-locatable articulated-arm task light in a few locations for high-illuminance tasks.

Brightness, Uniformity and Other Qualitative Factors

As noted earlier, visual acuity is a function of several factors beyond illuminance levels. The 9th edition of the IESNA handbook lists 23 criteria, including color appearance, direct glare, and surface light distribution. The resources at the end of this guide provide more information on these factors. Some important considerations for laboratory spaces are discussed below.

Strategy #13: Balance brightness of walls, ceiling, floor, and work-surfaces.

Balanced vertical illumination in the field of view reduces contrast, enhancing visual acuity. This can be achieved using wall-washing with down-lights on perimeter surfaces.

No other surface in a typical room will contribute more to the distribution of light than the ceiling. To aid in the proper distribution of light, a white or nearly white ceiling is recommended, with a minimum reflectance value between 0.80 and 0.85, as noted earlier. A matte finish is preferred over a semi-gloss or semi-specular finish because it eliminates the possibility of reflecting the images of bright light sources from within the indirect component of luminaires. Any color or tint present in the ceiling material will also be contained in the light reflected off that surface, so care is needed in specifying any finish other than white or near white.

Floors have more to do with contrast reduction in the visual field than with contributing significantly to the ambient light level in a room. The reflectance value of a cream-colored tile is 0.45, while a dark brown floor has a reflectance value of 0.1. These two color choices will create

Figure 10: Balance of surface brightness in this lab is achieved with energy-efficient recessed lab lighting using T8 technology and compact fluorescent down lights with 4100-K lamp color. Photo courtesy of Pivotal Lighting Design/Affiliated Engineers.

significantly different impressions of brightness, even though the calculated illuminance levels will be almost identical.

Finally, dark bench tops and reagent shelves with miscellaneous items contribute to an impression of overall lower brightness even though the design meets the target luminance at the bench. Dark bench tops should therefore be avoided, if possible.

Strategy #14: Select lamps with high CRI and optimal color temperature.

Improved color rendition of the ambient lighting supports greater visual acuity, saving energy by allowing lower illuminance levels. Higher color-rendering T8 and T5 light sources are also more compatible with daylight and with most compact fluorescent lamps. Specify fluorescent light sources with a minimum CRI of 82. Where color rendition is very critical (e.g., analysis of blood specimens and organ tissues), consider the use of 5-phosphor or full spectrum lamps.

Typically, for laboratories, a color temperature of 4100-5000K is recommended. It is important to coordinate the color temperature of ambient and task lighting, since differences can be visually distracting.

Strategy #15: Balance uniformity and variation.

There should be a balance of light between benches, aisles and room perimeters. It is important that luminaires provide wall brightness at the tops of walls, to avoid the "cave" effect. This is especially important in labs, because top shelves are often used for storage (even though code stipulates that nothing should be within 18 in. of the ceiling).

While a reasonable amount of uniformity is important, it is also important to have some visual variation and interest (e.g., accent lighting with wall sconces), otherwise the space will appear dull. Totally indirect lighting systems can often provide a virtually shadowless visual environment. By flattening perspective within the evenness of surround-lighting, this lack of direct-light emphasis presents the three-dimensional lab and its accompanying apparatus to the eye as a mere two-dimensional visual task. Bench-mounted adjustable task lighting can help to enhance the visual environment significantly by adding sparkle and revealing 3D form. This adds variation and visual interest, which, in turn, support visual acuity.

Maintenance

Lighting system maintenance should be addressed beginning with the actual luminaire specification. Newer lamp technologies with reduced physical size have driven the design of sleeker, smaller luminaires. These have become correspondingly harder to physically maintain than larger versions simply because appropriate clearances between lamps, reflectors and luminaire housings are often forsaken for aesthetics. It is the lighting designer's responsibility to specify lighting fixtures that are clearly well-constructed and assembled with maintainability in mind. Accessories to avoid are those that require special tools to remove or that complicate routine maintenance procedures, such as clipped-on external baffles or louvers with sharp edges that snag dust cloths.

Codes and Standards

The IESNA Lighting Handbook is the primary reference for illumination criteria. Some of the energy efficiency requirements for laboratory lighting found in codes and standards include the following:

- ASHRAE Standard 90.1-2004 specifies lighting power densities for various space types. Laboratories are limited to 1.4 W/sf.
- California Title 24 (2005) limits lighting in high-precision work environments to 1.3 W/sf.
- The 2004 Seattle Energy Code limits lighting in laboratories to 1.8 W/sf.

Design Process Action Items

An integrated team-based approach requires involvement by all stakeholders from the very beginning of the conceptual and schematic stages. This is especially true because of the increasing complexity of most building systems, and the demand for better integration of sustainable construction techniques.

Pre-design

Define goals for daylight integration. Identify visual tasks and any special requirements (for example, RF shielding). Determine appropriate illuminance requirements, develop daylight integration strategies, and set a target for lighting installed W/sf.

Schematic Design

Conduct preliminary modeling to assess alternative fixture configurations in terms of visual performance, life cycle cost, implications for lab module design, ceiling height, maintenance, and potential for daylight integration.

Design Development

Conduct detailed modeling and mock-ups to evaluate alternative electrical lighting and control configurations. Evaluate installed W/sf, illuminance, brightness ratios, uniformity, color rendition.

Determine zone size, switching requirements.

Construction Documents

Ensure that documents define the process for commissioning electrical lighting control systems, especially occupancy and daylight-based controls.

Conclusion

Lighting in laboratories impacts worker comfort, health and performance, and energy efficiency. Electrical lighting must always be designed as a supplement to effective daylighting. Some of the key best-practice strategies for electrical lighting include the use of direct-indirect luminaires for ambient lighting, the use of under-cabinet and/or articulated-arm task lights, and daylighting and occupancy-based controls that are properly commissioned. It is important to note that the effectiveness of lighting is a function of a wide range of performance parameters, not just task illuminance. Designers should take care to avoid overestimating required illuminance levels. An effective lighting design should achieve visual acuity by taking into account task illuminance levels in conjunction with other parameters such as surface brightness, color rendition, and visual variation. This guide highlighted some examples of laboratories with lighting systems that meet high visual performance requirements while minimizing life-cycle energy use.

Figure 11: San Mateo County Forensic Laboratory incorporates integrated daylighting and lighting controls, contributing to anticipated energy consumption that is 50% less than mandated by California Title 24. Source: HOK.

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Best Practices Guides on the Web:

www.labs21century.gov/toolkit/bp_guide.htm

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