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Introduction

Ergonomic designed manufacturing and test labs for the aerospace industry play an important role in that industry's contribution to quality. The stringent manufacturing and testing requirements of space hardware demand that the delivered product is of the highest quality and reliability. Engineers and technicians handling hardware must have appropriate lighting to perform their jobs to the highest level of workmanship. Much of the work is highly detailed and there are many visual inspections during the manufacturing process.

Lighting should satisfy the facilitation of work and support visual-related tasks. If lab lighting is inadequate, risk is added to the processes performed in the lab. This could contribute to quality problems, test failures, and questionable reliability. This paper will discuss one of the labs that I support in my job and its specific lighting requirements.

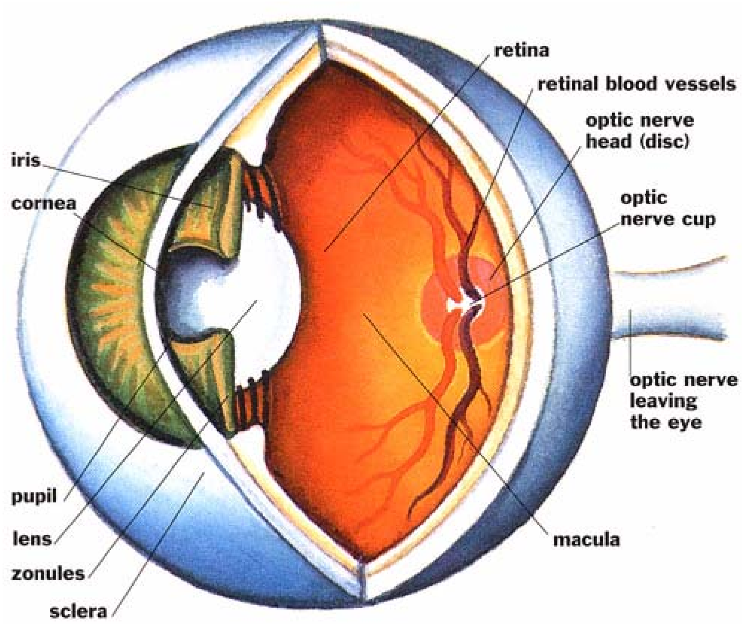
Ergonomists study human capabilities in relationship to work demands (http://www.ergonomics.org/, 3/22/06). Ergonomics is a discipline that involves arranging the environment to fit the person in it. When ergonomics is applied correctly in the work environment, visual and musculoskeletal discomfort and fatigue are reduced significantly (http://www.cdc.gov/niosh/topics/ergonomics/, 3/25/06). The Human Factors Engineer also develops lighting criteria to ensure that labs are illuminated for visual clarity. When designing lighting systems, it is important to understand the relationships among human sight, and the quantity and quality of illumination. In doing lighting efficiency work, light intensity must be measured. One must also know how to express light intensity in order to select luminaries and for laying out the overall lighting configuration.

Illumination theory is a science into and of itself. The Illuminating Engineering Society Lighting Handbook is the most widely respected guide for selecting luminaires (lights). The IES handbook contains lighting tables that correspond to a number of considerations such as room size, type of work to be performed in the room, suggested placement of luminaires, and more. The IES handbook allows the designer to choose the best luminaire(s) for a given application.

Vision and the Human Eye

Of all the human senses, vision is probably best understood. Understanding how the human eye works and its limitations is important when designing a lighting system for a specific application. Vision is a complex sense with a number of elements. The human eye is a conduit to what we call vision. The eyeball's shape is spherical, approximately one inch in diameter. The internal elements of the human eye work together to enable sight.

The human eye is comprised of layers and internal elements. The outside portion of the eye is made of a tough protective tissue called the sclera. Besides protection, the sclera helps to maintain the eye's shape. Also in the front portion of the eye is the cornea. The cornea allows light into the eye and bends the light. The next layer of the eye is the choroids. It carries the blood supply needed to nourish the eye's internal elements. Then there is the retina, which lines the inside of the eye. The retina is sensitive to light and receives stimulus.



Internal elements of the human eye

Vision occurs as a result of a succession of processes involving the elements within the eye and the brain. Light travels through the eye and focuses on the retina. A number of elements are involved and bend or refract light so that it focuses properly. Light first passes through the clear cornea at the front of the eye, and then through a liquid portion of the eye known as the aqueous humor. As light moves through the eye, it passes through the pupil which is a round opening in the center of the iris. The iris is the part of the eye we associate with eye color. The iris is made of specialized muscles that are able to vary the pupil’s size. The range is about 2 mm to about 8 mm. The pupil regulates the amount of light that enters inside of the eye.

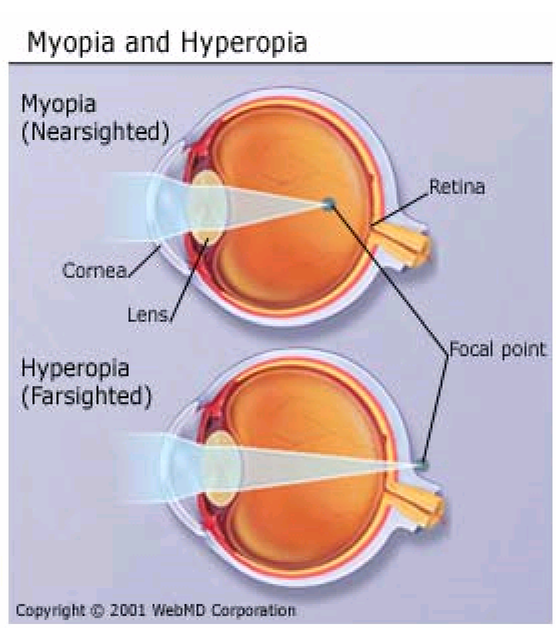
The lens is the next element of the eye that light enters. It is a clear, layered element shaped like a large lentil approximately 10 mm in diameter. The lens is connected to muscles which relax or contract to change the shape of the lens. The changing lens shape helps light to be focused in response to see with more clarity. The ability to focus decreases with age. This is a natural occurrence, and is the reason why so many adults over 40 depend on reading glasses.

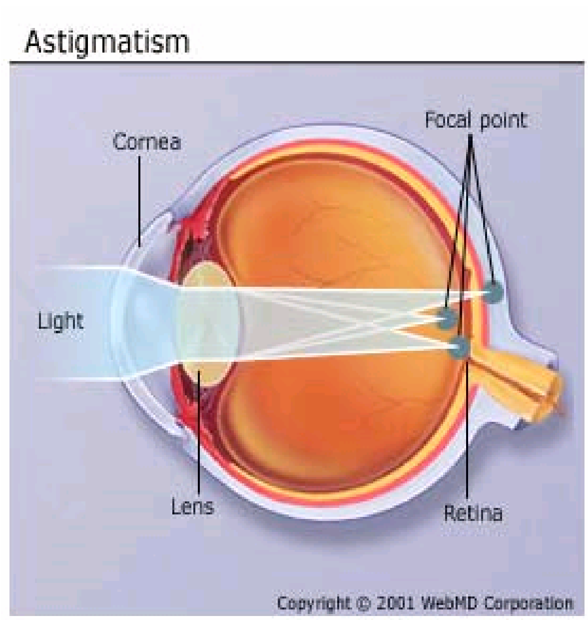
Once light gets through the pupil and lens, light passes through the larger back portion of the eye called the vitreous humor. It is filled with a clear, jelly-like substance. From there, the light goes to the retina, where the rod cells and cone cells are stimulated. When stimulated, a chain chemical reactions occurs converting light into electrical impulses. The cone cells (approximately 7 million in number) are located in greatest concentration in the small, central part of the retina called the macula. The macula produces sharp, detail vision and color vision. The rod cells (approximately 100 million) are found in the peripheral retina, away from the macula. These cells provide vision in dim light.

However, what we recognize as vision cannot happen without the brain's interpreting the electrical impulses sent by the retina. The optic nerve is a bundle of retinal fibers that exits the back of the eye and sends electrical impulses to the brain where they are interpreted in the primary visual cortex.

The visual system allows the eyes to move together, adapt to light and dark, perceive color, and accurately determine an object's location in space. The human eye is sensitive to differences in contrast. Visual acuity is the expression used when discussing the accuracy of ones vision. We think of normal vision as being 20/20 vision. When the lower number increases, one's visual acuity decreases. For example, when a person with a visual acuity of 20/200 is tested, he sees at 20' what a person with 20/20 vision can see at 200'.

Everyone's eyes are different. Eyes are also imperfect. Some eyes are either too long or have too much focusing power. When this occurs the person is said to be myopic (nearsighted). Those who are too short or do not have sufficient focusing power are said to be hyperopic (farsighted). Some eyes may have the problem of uneven curvature. This is called astigmatism. Treatments are available to correct these problems including standard eyeglasses, contact lenses or refractive surgery.





(http://www.webmd.com/content/article/6/1680_53542.htm, 3/1/06)

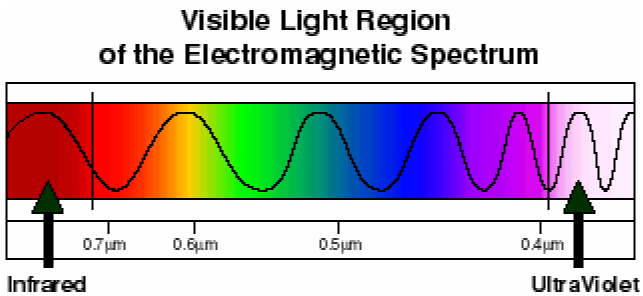
Near vision is known as *accommodation,* the process by which the eye changes focus from one distance to another. The amount of near focusing power decreases throughout life. Presbyopia is blurred vision at normal reading distance. Presbyopia occurs when the eye has insufficient focusing power for reading and other close-up tasks. It generally starts at about age 40 in most people and is the reason why older adults rely on reading glasses. Bifocal lenses allow one to see more clearly at objects that are both near and distant.

Adaptation refers to the change made by the eyes whenever there is an increase or decrease in brightness in the field of view. Harm to the eyes may occur when there is a significant change in brightness from high to low. If one turns their head from a given task and looks at an area of high brightness, eyesight is temporarily impaired when the eyes return to the original task. The lighting engineer needs to pay attention to the changes in adaptation that occur from moment to moment as the eyes change fixation from one point to another. The lighting engineer needs to ensure that lighting is uniform and that patches of brightness are avoided. In addition, the engineer must take into account the comfort of the worker. The worker may work on a number of tasks in the same lab or two or more workers may be working in the lab at the same time. The final lighting design must satisfy the needs of each task.

Eyestrain is another common problem. Eyestrain is discomfort attributed to an uncorrected refractive problem and may occur while performing distant visual activities such as driving or performing close-up tasks like inspections. If the light in the work area is either too bright or too dim, the human eye has to work extra hard to compensate for these harsh environmental factors. People may not even be aware that their eyes are under duress, but over time they may develop symptoms of eyestrain (http://www.sfwa.org/ergonomics/eyestrain.htm, 3/1/06). Eyestrain dissipates if the refractive problem is resolved.

Light

Sir Isaac Newton was first to explain the physical nature of light. Newton was the first to realize that white light is composed of a spectrum of light. He found that if white light was passed through a prism, the prism would break down the white light into its spectral components or wavelengths. The process can also be reversed if the spectra are passed through a second prism whose output will be white light. The visible range of the human eye is from approximately 380nm (violet) to 770nm (red). Every color of the visible spectra has its own wavelength. Outside this range is ultraviolet and infrared light.



(http://imagers.gsfc.nasa.gov/ems/visible.html, 3/12/06)

Light rays can travel through a solid medium or a vacuum. A light wave consists of energy in the form of electromagnetic fields. Because light has both electric and magnetic fields, it is also referred to as electromagnetic radiation. When electromagnetic radiation with a wavelength between 380 and 770 nm hits our eye, we see it. The perceived color depends on the wavelength of the radiation.

Instead of describing light using photons, the concept of light rays can work better for the sake of explanation--using a candle as an example of a light source emitting many individual measurable rays of light instead of photons, or a field of electromagnetic flux. These rays are straight lines that extend in every direction from a light source. They may be refracted through lenses, reflected by surfaces, and are often absorbed.

Basic light is measured in lumens. A light source such as a candle or flashlight produces a certain number of lumens. One could think of the light source as having some number of rays going out in all directions. A candle has a few rays. A flashlight has many more rays than a candle.

The Luminous Intensity of a source is the number of lumens or rays it emits. Luminous intensity or “candlepower” is expressed in units of candles or candelas. Candles are actually a measure of lumens per steradian, a cone shaped sector of the total space around the light source. Again, it is easier to think of candlepower as a measure of the number of rays emanating from the source.

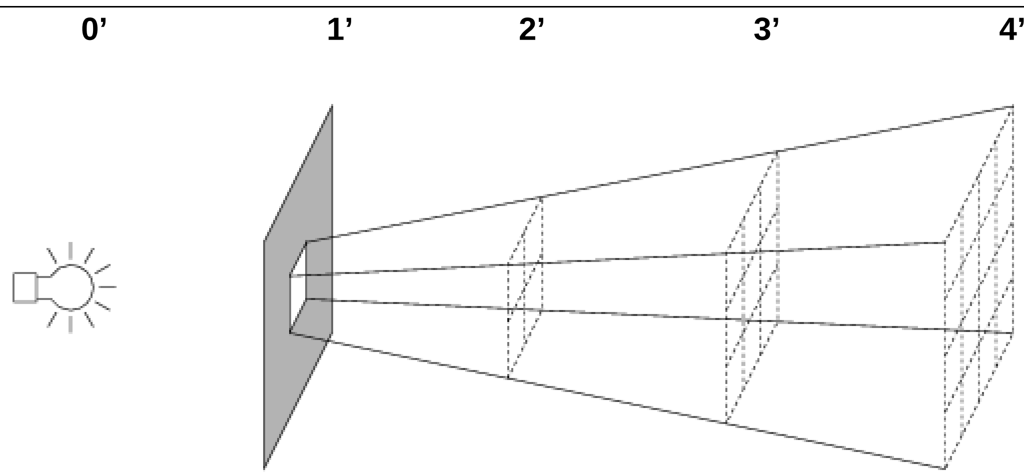
Measuring Light

How are the light rays measured? One way is to place a card in the path of light rays and count the number of lumens, or light rays that hit the card. In a dark room there are not very many light rays. As a room gets brighter, more light rays are able to be counted. The density of the light rays in a field of light, as measured by how many strike a card of a fixed size, is the illuminance, or amount of illumination.

The cards come in three different sizes. The three sizes are 1 square meter, 1 square foot, and 1 square centimeter. If we measure the density of an evenly distributed field of light rays, more light rays will fall on a larger card. Three different unit names are used for the three different card sizes. For a 1 square foot card, the unit is footcandles (fc) and is the measure of how many light rays fall on this size card. The unit term Lux (lx) is used for light rays striking a card that is 1 square meter. The unit term phots are used for light rays striking a 1 square centimeter card. All three units (lux phots, and footcandles) measure the same thing; illumination, but at different scales.

Hypothetically, a measuring card can be used to count the number of light rays coming from a light source. However there is a problem. As the card is moved farther away from a light source, the light rays diverge such that fewer and fewer light rays actually fall on the card. Light travels in straight lines, so when the card is moved twice as far from the source, the light rays will diverge so far that we would need a card with twice the height and width to catch all of the same light rays. This is four times the area of the original card. If we move the card three times the distance away from the original spot, a card that is three times the height and width of the original card or a card that is nine times as large will be needed to catch all of the original light rays.

Mathematically, the relationship is described by stating that the size of the card increases with the square of the distance, meaning the size card needed at each distance is the square of the distance from the light source. The distance squared is equal to the required card area. Another way of expressing this relationship is that if instead of looking at the size of the card at each distance, we look at how many rays fall on a card of the original size we see that at two times the distance we get ¼ the number of light rays, and at three times the distance we get 1/9 the number of light rays. The amount of light falling on the card is the reciprocal, or inverse, of the square of the distance. This is called the inverse square law. Simply put, the light measured on an object is inversely proportional to the distance the object is from the light source.



The illustration above demonstrates the inverse-square law. A certain amount of light passes through the hole at a distance of 1 foot from the light-bulb. At distances of 2 feet, 3 feet, and 4 feet from the bulb, the same amount of light spreads out to cover 4, 9, and 16 times the hole's area, respectively (http://www.ifa.hawaii.edu/~barnes/ASTR110L_F03/inversesquare.html, 3/27/06).

Calculating Lighting Requirements

In calculating a lighting requirement the inverse square law is applied to determine in advance how much illumination a fixture will deliver from a particular distance. If one knows the candlepower of the light source and the distance for which one wants to calculate the illumination, one can simply divide the candlepower in lumens by the distance squared. If we measured the distance in feet, the answer will be in footcandles. If the measurement is in meters, it will be expressed in lux. If measured in centimeters the result will be expressed in phots.

Luminance and brightness are terms used when one wants to measure how much light is reflected by a surface like a large painted wall or a face. It is important to understand that a large wall or face can have the same brightness. As such, it is undesirable to measure the total light reflected from the wall, but how much light is reflected from a standard measuring area in order to compare brightness between the two surfaces no matter what their size is. This situation is also an inside-out measurement. Previously a card was used with a standard area to count light rays that arrived at one point which was our eye from a surface of a standard size.

If one sits in a large auditorium and looks at the stage, light rays falling on a uniformly flat painted surface are scattered. From each square foot of the flat surface, a number of light rays are detected by our eyes. The brightness of the flat surface is expressed in footlamberts. The brightness of the number of light rays coming from one square meter is expressed in meter-lamberts or nits and the brightness of light rays reflected from an area of one square centimeter is expressed in lamberts. How one sees the surface depends on how the flat surface is painted and lighted.

Brightness is measured in candles per area, not lumens per area, because the receptor is a point (the eye) rather than an area (the card). That is, if one could measure area on a point it would be in steradians. In the inside-out measurement of brightness, candles are used (lumens per steradian) instead of straight lumens.

Basic measuring units:

Lumens are units of energy like watts or horsepower and are expressed as 1/683 joules per second, measured at a wavelength of 555 nanometers. A lumen is equal to 1 footcandle (fc) falling on a square foot of area. Illuminance is calculated as the number of lumens (lm) per unit area. Lumens denote the rate of energy flow.

The measures of luminous intensity of a point source are called ***candles, candelas*****,** and ***candlepower*** and are equal to the number of lumens per steradian. A steradian is a solid angle subtending an area of R^2 at distance R from the apex. Candlepower is a way if measuring how much light is produced by a light source. Candlepower is commonly expressed as candelas. The candela is a measure of how much light the light source produces, measured at the light source, rather than how much light falls upon an object. Another important consideration is how much candlepower can be focused on a given spot. The more candlepower that can be focused on a given spot, the higher the illumunance. A candlepower as a unit of measure is not identical to a footcandle. *A* candlepower is a measurement of the light at the source, not at the object.

The illumination of a surface by a point source is measured in ***lux (lx)*** which equals the number of lumens per square meter (1lx = .0929fc), ***footcandles (fc)*** which equals the number of lumens per square foot or fc = lm/ft² (1fc = 10.764 lux). One footcandle of light is the amount of light that a candle generates one foot away. A 100 fc lamp produces 100 fc at a distance of 1' away from the lamp. Lx and fc units indicate the density of light that falls on a surface. Measured by light meters to denote the adequacy of lighting of a task area. The general term is illuminance.

Illuminance is the intensity or degree to which something is illuminated and is not the amount of light produced by the light source. Illuminance measured and expressed in footcandles for the English system and lux for the metric system. For example, lux (lx) is the measurement of actual light available at a given distance. A lux equals one lumen incident per square meter of illuminated surface area.

Brightness either reflected or emitted from a surface is measured in ***lamberts*** which equals the number of candles per square centimeter, ***foot-lamberts*** which equals the number of candles per square foot, or ***meter-lamberts*** or ***nits*** which equals the number of candles per square meter.

Typical illuminance values expressed in lux from the <u>IES Handbook</u> are:

Full moon	≈	1 lx
Street lighting	≈	10 lx
Workstation lighting	≈	100 – 1,000 lx
Operating room	≈	10,000 lx
Plain sunshine	≈	100,000 lx

<u>Human Factors Problem in the Work Area</u>

The requirements of a space program lab demand lighting that provides unhampered sight from many angles and directions. While overhead lighting is the foundation or main source of light, other sources of light are present for the use of photography, close-up inspection, and manufacturing of specialty products. The lighting system currently in the lab, however, does not meet the needs of our program. This lab area was previously used for storage by another space program. When this lab was prepared for the current program, it was enlarged, and additional lighting was added. The human factors problem is that the lighting that was added does not provide adequate visual conditions for the work that is now performed. From the perspective of HFE, the current lighting system also causes eyestrain when used for detailed space hardware work. Task lighting also needs to be added at workstations where additional lighting is required for specific operations.

Determination of the Area Needing Improvement

Using a lighting checklist, it was determined that the existing lighting was inadequate for the needs of our program (http://www.ccohs.ca/oshanswers/ergonomics/lighting_checklist.html, 3/26/06). The illuminance was measured with a handheld meter like the one shown below.

(http://www.dasdistribution.com/products/lm-economical_models.htm 3/15/06)

Its range is 0 to 50,000 Lux or 0 to 5,000 Footcandles with an accuracy of ±5%. When the room was first evaluated, its illuminance level ranged from 850 Lux to 1150 Lux. The light was also not uniform throughout the area.

As mentioned previously, the lab must be reconfigured for the needs of our program. The entire lighting system of the lab needs to be refitted to provide suitable conditions for the work that will be done. The lab overhead lighting needs to be brighter for better illumination across the entire work area. The lighting also needs to be spread out in a more uniform manner. Currently, there are insufficient luminaries, in the lab and they are located too far apart. Focused lighting for workstation tasks is non-existent, inadequate, or located incorrectly. The glossy, light-colored furniture increases glare at workstations.

Intervention

The utilitarian goal of a lighting system is to provide for optimal performance of a given task (IES Lighting Handbook, *3rd edition,* 1959). The IES Lighting Handbook provides recommendations for illuminance values for a variety of lighting applications. These recommendations are categorized according to the level of complexity of the visual task being performed. Visual tasks can range from simple, where visual performance is not as important to very specialized, where visual performance is of critical importance such as assembling very small or detailed parts. Lighting requirements for labs such as this one dictate illuminance that is relatively brighter than the current configuration.

Designers of lighting systems need to familiar with three basic relationships of how we see, the quantity of illumination, and the quality of lighting. *How we see* was previously discussed. The *Quantity of illumination* for objects on a large uniform background the ability to see increases as illumination increases and applies to contrast sensitivity, visual acuity, and speed of vision. To start, one must determine what constitutes adequate illumination for objects which have to be seen with central vision during a given phase of a given task. The direction of illumination is important for certain types of tasks especially for three dimensional objects in a three dimensional setting. This is important for controlling reflected glare. The *Quality of lighting* pertains to the distribution of brightness in the entire visual field. Other important aspects of quality of lighting include discomfort glare and reflected glare. Discomfort glare is the sensation one experiences when brightness relationships in the field of view cause discomfort. Reflected glare is caused by the brightness of the reflected image of a light source usually in the work surface.

Applying Countermeasures

When a company lab is in development, one of the sections to be completed by a facilities designer is illumination requirements. The lab already has overhead fluorescent luminaires installed. In order to illuminate the lab more uniformly, additional luminaires with diffusers will be added and spaced as recommended in the IES handbook.

Overhead diffuse fluorescent illumination as opposed to a single concentrated light source helps to eliminate shadows and protects against glare. Glare is a visual sensation caused by excessive and uncontrolled brightness. Glare can be disabling or simply uncomfortable. It is subjective, and sensitivity to glare can vary widely.

T8 fluorescent 4-lamp fixtures with diffusers and parabolic baffles will be used. Diffusers help to scatter light in all directions and reduce glare. This is appropriate according to the IES handbook section on uniformity of brightness. The IES handbook offers recommendations for luminaires and the appropriate spacing between them for a given size area to be illuminated. The designer must ensure that the lighting is not too bright. Too much light can be as visually fatiguing as too little (http://www.uwm.edu/Dept/EHSRM/GENINFO/genergotips.html, 3/26/06).

Another countermeasure will be using workstations with flat, non-glossy surfaces to reduce glare. Workstations will be equipped with indirect/direct T8 fluorescent 2-lamp fixtures with parabolic baffles mounted over the benches. If needed, these luminaires supply additional task illumination with good overall visibility and minimal glare. This will provide the technician with the capability to increase the illuminance level at the bench by approximately 100 Lux. Dark-colored lab chairs will be selected to minimize reflection from luminaires. LCD monitors will be used to reduce glare at the monitor due to the overall brightness in the lab. Computer work generally requires levels from 300 to 500 lux (http://www.labour.gov.on.ca/english/hs/guidelines/comp_erg/gl_comp_erg_3html, 2/28/06).

Labs such as this one should accommodate those individuals who perform a wide variety of tasks ranging from delicate manufacturing operations to reading computer monitors. In laboratories indirect/direct T8 fluorescent 2-lamp fixtures with parabolic baffles mounted over the benches supply general illumination with good overall visibility and minimal glare. At each bench a row of fluorescent under-shelf fixtures will provide supplemental task illumination.

Lighting Calculations

General lighting design calculations determine how much light produced by luminaries eventually reach the work surface. According to the Fluorescent Lighting Manual (p.169), lighting design consists of five principles:

1. Decision as to lux level required for the application.
2. Layout of luminaries to provide uniform illumination throughout the room.
3. Ensuring adequate electrical wiring for future capacity, convenient switching, and control.
4. Selection of reflecting equipment from the standpoint of efficiency, flexibility, and ease of maintenance.
5. Computation of luminary size (in lux) necessary to provide the desired illumination.

The overhead ambient lighting with a 20' ceiling height in the 30' x 50' lab will support the tasks that are going to be performed in the area. The majority of the detailed work area is located in the center of the room, occupying about a quarter of the available space. The IES Lighting Handbook recommended levels of illumination are 1,000–2,000 lux. Company standards for lab lighting are derived from the IES Lighting Handbook.

Company design practice would be to design the entire room to the 2,000 lux level, which would require 60 *evenly-spaced* 2'x4' fixtures with four 32WT8 lamps in each fixture. This standard design assumes reflectance of 80 percent from a white ceiling, 50 percent from the walls, and 30 percent from the floors. This standard layout will provide the required 2,000 lux; the luminance range will average195 fc ≈ 2,090 lux and have a minimum level of approximately 85 fc ≈ 920 lux.

Calculation of Uniform Ceiling Lighting for Lab

32WT8 with 4-light electronic ballast = 27.5 watts (including ballast loss)

60 fixtures with 4 lamps each = 240 lamps (6 rows, 10 fixtures/row, 5' separation)

240 lamps x 27.5 watts = 6,600 watts

Room size 30 x 50 = 1,500 sq/ft

Energy density of space = 4.4 watts per sq/ft (6,600 watts/1,500 sq/ft)

If a lighting designer decided to use the task-concentrated lighting approach, the layout would be much different. Placing six 4'x 4' fixtures, each with eight 32WT8 lamps, over the center area of the lab would provide the luminance desired for manufacturing and test operations being performed. There would be an average of 2,050 lux delivered to the work surface over the task area, meeting the needs of the space. The light levels would drop off around the center area to an average of about 300 lux. But the company wants the entire lab to be illuminated evenly and completely.

Calculation of Task-Concentrated Lighting for Lab

32WT8 with 4-light electronic ballast = 27.5 watts (including ballast loss)

Ten fixtures with 8 lamps each = 80 lamps

80 lamps x 27.5 watts = 2,200 watts

Room size 30' x 50' = 1,500 sq/ft

Energy density = 1.47 watts per sq/ft (2,200 watts/1,500sq/ft)

Average Brightness Calculations

Brightness in addition to illumination is another important consideration in lighting design. The following procedure developed by IES is given to permit the prediction of approximate brightness values for interior lighting. First, determine the average illumination level in the room. Then, calculate the room coefficient, K_r which equals:

$$[height \times (length + width)] / 2 \times length \times width$$

Once the room coefficient has been calculated, refer to the IES lighting Handbook tables for the lighting method involved and the room surface for which a brightness prediction is desired. Select the brightness factor corresponding to the room reflectances and the Kr calculated. Then multiply the factor that was obtained by the illumination level to get the average brightness.

Predicted Results Defined

The new lab lighting has been installed in order to process space hardware manufacturing and testing. The new lighting is significantly brighter than the previous lighting. However the lighting is not so bright as to cause those who enter to turn away, but with the additional level of brightness, there is greater chance for glare when working on assemblies or parts with high-gloss surfaces.

The luminaires (light fixtures) have been evenly-spaced making illumination more uniform throughout the lab. Luminaries spacing is important to ensure that there is a proper amount of overlap. The goal of lighting the lab more uniformly has been accomplished. There is little difference in brightness no matter where one stands in the lab. Shadows are at a minimum, and the illumination is vivid, yet pleasing.

Due to the uniformity of the lab lighting, it is now possible to work in any part of the lab. There is negligible difference in lighting throughout the lab. The added task lighting at workstations provide the illumination necessary for engineers and technicians to perform delicate or detailed work.

Changes in adaptation for those individuals working in the lab will be minimal no matter which part of the lab one is working in. Because of the nature of diffuse illumination only very soft shadows will be present. There will be some reflection of light off the walls (50%) because by design, they have been painted with white, semi-gloss paint. The added workstation lighting will allow technicians to perform more close-up work and inspections.

In conclusion, the scope of illumination theory is broad and goes far beyond the scope of this paper. So much so, that this paper presents an overview and touches on the key points of illumination theory. Like Human Factors Engineering and Ergonomics, Illumination Engineering is a separate discipline. What the two disciplines share are the goal of providing illumination that overall best serves people performing a particular task or tasks. Like most things in life, the nature of engineering disciplines require some trade-offs and compromise in the final design. One of the key trade-offs that will always be a consideration of any lighting system are the costs of design, implementation, operation, and maintenance. These tangible costs should be considered against the less tangible human factors costs.

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