A SunCam online continuing education course

Interior Lighting Design
The Fundamentals

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THE BASICS OF LIGHT AND COLOR

In order to understand the principles involved in performing a lighting design, it would be beneficial to begin with an understanding of light and color. This course will touch on a few of these important concepts, as there are numerous books and reports that can be consulted which go into greater detail of the physics and theories of light and color.

The three most common types of radiant energy given off from the sun are ultraviolet radiation, light and radiant heat. Light is similar to ultraviolet and heat since it is radiant energy, but it is capable of creating a sensation in the human eye that results in a visual image. Many proposed theories over the past few centuries attempted to explain the nature of light. One of the earliest theories was Maxwell's Electromagnetic Wave Theory, which states that light travels in the form of electromagnetic waves, as shown in Figure 1. A later theory, known as Planck's Quantum Theory, states that light travels in the form of discrete packages (quanta), and that higher frequency waves (shorter wavelengths) contain more energy than lower frequency waves (longer wavelengths). A recognized theory today is that light behaves as quanta at the points of emission and absorption, but travels in the form of electromagnetic waves.

Figure 1 - Typical Light Wave

The length of individual electromagnetic waves can vary from 10^{-16} meters to approximately 10^{7} meters. The wavelength of an electromagnetic wave classifies it as a Gamma ray, X-ray, Infrared or any of the other areas indicated in the electromagnetic spectrum. Light, the visible portion of the electromagnetic spectrum, contains all colors and appears as the color white. By diffracting white light through a prism, the individual colors that make up the white light will appear. It is interesting to note that blending only red, green and blue light in the correct proportions results in white light. For this reason, the primary colors of light are red, green and blue, while white light has come to mean the absence of color.

The wavelengths of the individual colors that make up white light will typically range from 380 nanometers to about 750 nanometers. A wave 380 nanometers long will be violet, while a wave of green may be 530 nanometers. Yellow light is about 580 nanometers and red ranges from 680 to 750 nanometers. As indicated in the Quantum

Theory, a wave of violet light contains more energy than a wave of green light, and a wave of green light contains more energy than a wave of red light. Figure 2 shows the electromagnetic spectrum and the corresponding relationships between the different wavelengths, and the wavelengths of colors in the visible light region.

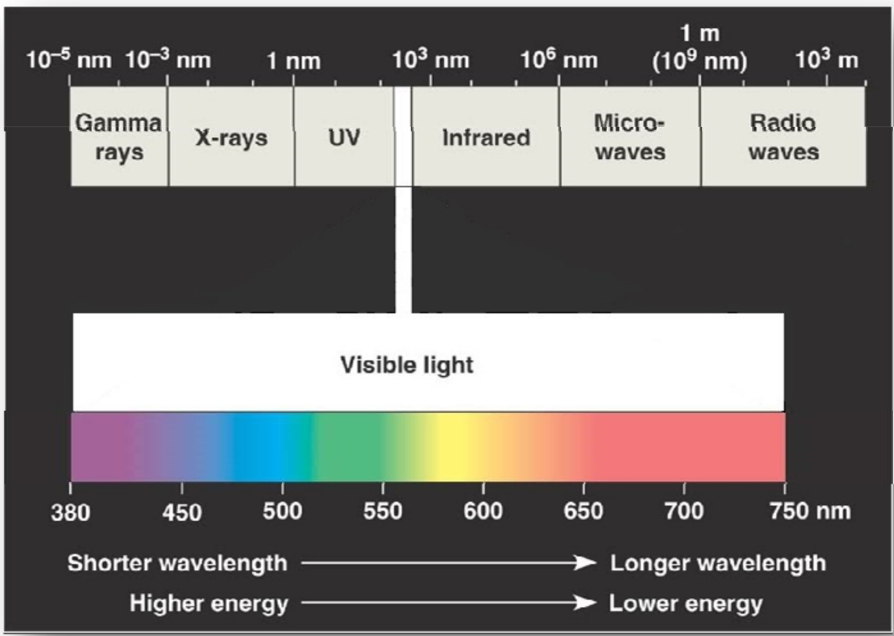


Figure 2 – Electromagnetic Spectrum

When light strikes an object, it will either be reflected or absorbed by the object. Objects with colored surfaces will absorb all contrasting colors of light, while reflecting all similar colors. For example, when white light strikes a green object, only green light will be relected and all other colors will be absorbed. However, a pure white surface will reflect all colors of light, while a black surface will absorb all colors of light.

The apparent color of an object is therefore dependent upon the available light source. When viewing an object, a color must be present in both the object and the light source in order to see that color on the object. If a color is missing from either the object or the light source, then that color will not be seen on the object. It has also been found that many different combinations of wavelengths can produce the same perceived color. If you have two light sources which appear to be equally white, they could be obtained by adding two distinctly different combinations of colors. If you then use these two sources to light an object, this object may look very different when viewed under these two separate light sources. This would be due to the object reflecting different colors present in the light sources. It is important to remember that light waves travelling through space are not visible, and that what is seen by the human eye is only the reflection or emission of light from a surface.

LIGHT AND THE HUMAN EYE

The eye is a very complex organ that must take in reflected light, have this light converted to electrical impulses, have the impulses tranmitted to the brain, and then have the brain process the information to create a perceived visual image of what is being viewed. These processes are detailed as follows:

- The outermost layer of the eye, called the sclera, is a tough composition that helps maintain the shape of the eye. All light must first pass through the front section of the sclera, which is called the cornea, in order to enter the eye.
- The choroid is the second layer of the eye, and it contains the blood vessels that supply blood to the stuctures of the eye. The front part of the choroid has two structures, the ciliary body and the iris.
- The ciliary body is a muscular area that contracts and relaxes to control the size of the lens for focusing light rays on the retina. The ciliary body also produces a watery material called aqueous humor, which is contained in two areas called the anterior chamber (located in front of the iris) and the posterior chamber (located behind the iris).
- The iris is the colored part of the eye. It is an adjustable diaphragm that surrounds an opening called the pupil. The dilator muscle makes the iris smaller and the pupil larger, allowing more light into the eye; the sphincter muscle makes the iris larger and the pupil smaller, allowing less light into the eye. The pupil size can change from 2 millimeters to 8 millimenters, thereby allowing 30 times more light to enter the eye.
- The innermost layer at the back of the eye is a membrane called the retina. It is the light sensing portion of the eye that contains the photoreceptors, known as cones and rods. In the center of the retina is the macula, which is responsible

for the central vision. In the center 10% of the macula is an area called the fovea centralis. This area is responsible for being able to see very fine detail.

- The retina contains a chemical called rhodopsin that converts light into electrical impulses. The retinal nerve fibers assemble at the back of the eye and form the optic nerve, which consists of approximately one million nerve fibers. These fibers then direct the impulses to the brain for processing. Once in the brain, the electical impulses are transformed into a visual image.

Figure 3 shows a section cut of the human eye that indicates the locations of some of the major parts of the eye.

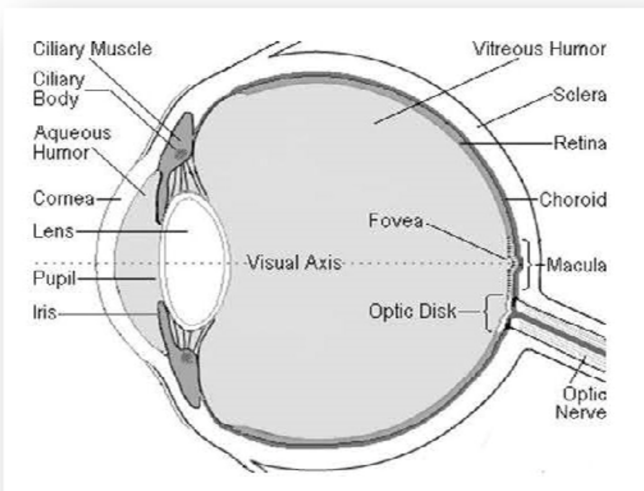


Figure 3 – Section of the Human Eye

The part of the eye that is concerned with color and vision is the retina, which is responsible for transforming incoming light rays into vision. There are two types of photoreceptors in the retina, called cones and rods. There are approximately 6 million cones which provide color sensitivity for the eye and are centrally located in the macula. The center of this area, called the fovea centralis, is rod-free, densely packed with very thin cones and provides the highest visual acuity. The rods are more numerous, approximately 120 million, are more sensitive than the cones, but are absent from the fovea. A short distance from the fovea the rods increase in density to a peak value and then spread out and decrease in density towards the edges of the retina. The rods are responsible for night vision, motion detection and peripheral vision. See Figure 4 for a picture of the concentration of cones and rods in the retina.

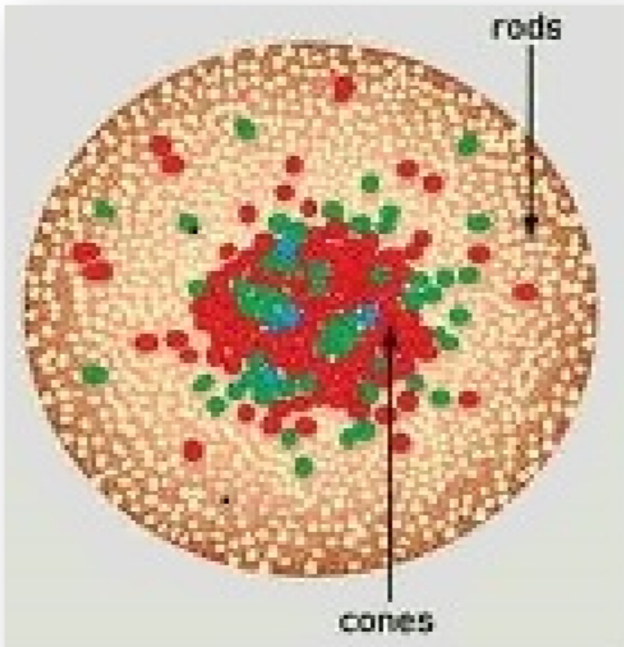


Figure 4 – The Retina indicating Photosensor Concentration

CONES, RODS AND VISION

Research has shown that the cone photoreceptors are divided into red cones (64%), green cones (32%), and blue cones (2%), with the red and green cones being densely packed into the fovea centralis, and the blue cones found mostly outside the fovea. The three colored cones are what provide the color sensitivity for the eye. The blue cones, although low in number, have been found to have the highest sensitivity of the cones. Response curves for the three cones indicate that the red cones are most sensitive to wavelengths of 565 to 575 nanometers, green cones are most sensitive to wavelengths of 534 to 535 nanometers, and blue cones are most sensitive to wavelengths of 420 to 445 nanomenters. The maximum efficacy (the power to produce the effect of vision) over the wavelengths for the three cones has been found to be 683 lumens/watt at a wavelength of 555 nanometers. This wavelength is in the yellow/green region, and is a major reason why the new safety vests worn by highway workers are this color. The rods are very efficient photoreceptors, more than one thousand times as sensitive as the cones. The response curve for rods indicates that over the range of wavelengths from 400nm to 600nm, they are most sensitive to a wavelength of 507nm, with a maximum efficacy of 1700 lumens/watt. See Figure 6 for the response curves for the three different cones and the rods.

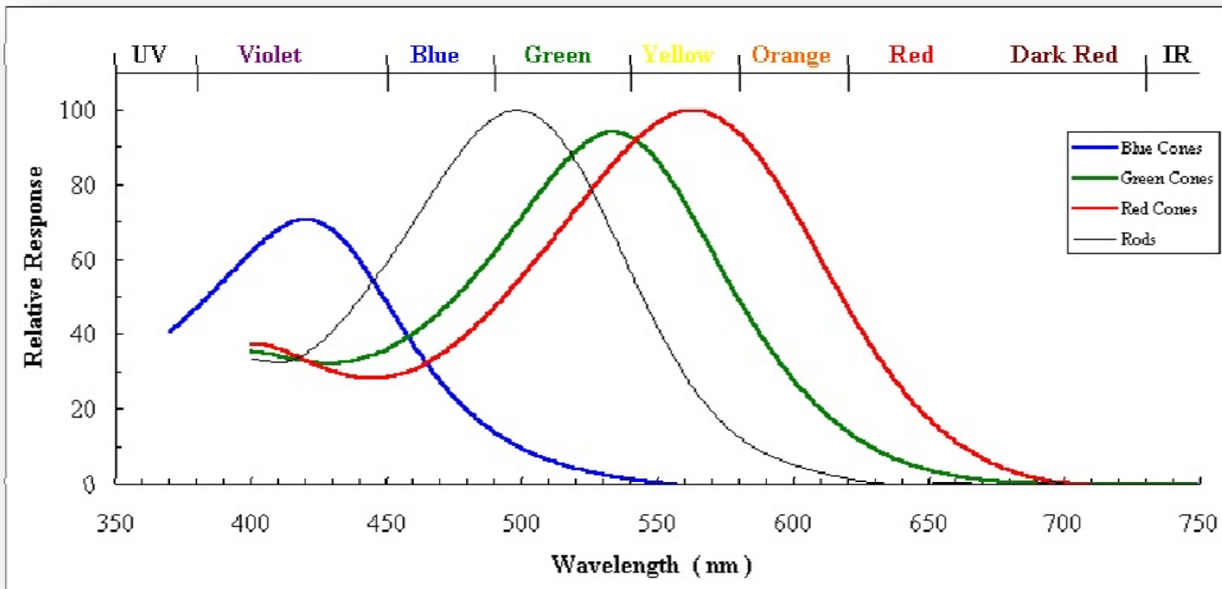


Figure 5 – Response Curves for the Photosensors

Some colors which are a single wavelength, such as yellow, will initiate a response from the red and green cones. These signals will be combined in the brain such that we experience the color of yellow. However, it is not possible through our perception to determine if the yellow color is a single wavelength or the combination of red and green wavelengths. The magenta colors located between the red and blue-violet regions have no single wavelength and are always a mixture of wavelengths. The secondary colors (yellow, cyan, and magenta) will be perceived to be brighter than the primary colors because there will be at least two sets of cones sensitive to these colors in an object.

The response curve for the rods also indicates a sharp peak in the blue region, with very little response to red. This is the reason a captain's boat instruments are red in color; they will not be picked up by the rods and will not interfere with night vision.

Another phenomenon with night vision is that when looking at a dimly lit star, it can be seen when using your peripheral vision, but when you look directly at it, it will disappear since the image is moved into the fovea centralis region and less sensitive to light.

Humans can see images due to three distinct types of vision known as photopic vision, mesopic vision, and scotopic vision. Photopic vision takes place under medium and well-lit conditions and provides for color perception and visual acuity. This term usually refers to cone vision and covers adaption levels of three footcandles (30 lux) or higher. Adaption is very responsive when transitioning from a low light level to a high light level.

Mesopic vision refers to a range where rods and cones are both active and accepting light signals. There is not a hard and fast transition point between photopic and mesopic vision, and between mesopic and scotopic vision. It is generally accepted that the mesopic range occurs from 3 footcandles down to about 0.01 footcandles.

The third type of vision is called scotopic vision, sometimes called rod vision. This vision corresponds to an adaptation level below 0.01 footcandles. There will be very little cone activity at this footcandle level, and when it drops further to 0.001 footcandles, cone activity has ceased and only rods are active. This is also the point where distinguishing colors is no longer available, and visual acuity is non-existent. See Figure 6 for a graph of the three types of vision in refence to different luminance levels.

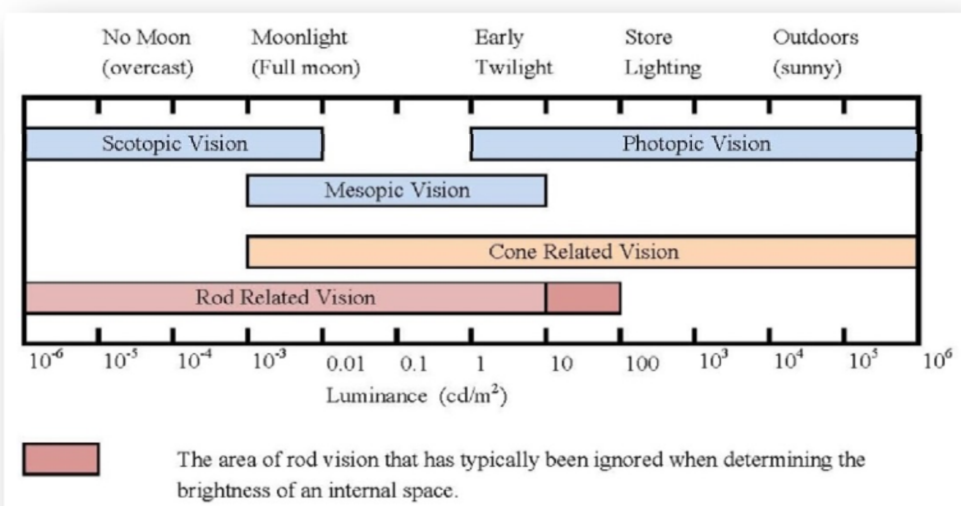


Figure 6 – The Three Types of Vision at Various Light Levels

As shown in Figure 6, there is a small, but significant region in Rod Related Vision purposely overlooked and ignored due to the assumption that rods do not contribute to photopic vision. This assumption carries over into the use of industry standard light meters, which only measure lighting levels of Cone Related Vision, completely ignoring the effects of Rod Related Vision. Likewise, lighting tests performed on lamps and lighting fixtures in order to determine brightness, light distribution angles, and efficacy, only take into account photopic lumens.

Two scientists, Dr. Sam Berman and Dr. Don Jewett, have performed much research in this area of vision and have discovered some intuitive and new developments involving human vision. The two scientists found that rods have more control of the opening and closing of the pupil and that the functioning of the rods influences the perception of room brightness. They found that vision improves if the functioning rods were actively responsive to the light provided in a workplace setting. They also found that the pupil size influences vision; smaller pupils will improve the depth of view and provide better acuity at certain light levels and color temperatures. Standard practice has always been to increase the lighting levels in order to reduce the size of the pupil, but this typically leads to glare, headaches and wasted energy. This new research, identified as scotopically enhanced lighting, significantly improves the quality of lighting for a space.

GETTING STARTED IN LIGHTING DESIGN

When beginning a project, the ultimate goal for the Lighting Designer is to specify a particular lamp with an appropriate color to achieve a desired visual effect. The way a fixture looks and performs, although important, is secondary to the selection of the proper lamp. It is the understanding of these properties and characteristics that can make the selection of a lamp somewhat confusing. There are metrics that are available to aid the Lighting Designer to predict the probable affect a particular lamp will have on color and the visual warmth or coolness imparted on a lighted environment. These metrics include the Correlated Color Temperature, the Color Rendering Index, and the Spectral Power Distribution. It is important to remember that these metrics provide only general guidelines, and it takes a visual examination and past experience to make the final determination if a particular lamp is suited for a particular space.

In many manufacturers' data sheets of lamp characteristics, there is typically a column heading indicated as "Color Temperature". For discharge lamps, such as fluorescent and HID types, the correct terminology should be "Correlated Color Temperature" or "Apparent Color Temperature". This is due to discharge lamps not exhibiting radiation characteristics which coincide with a blackbody radiator. A blackbody radiator is a theoretical object that absorbs all of the energy which strkes it and then perfectly re-radiates that energy. "Color Temperature" more directly relates to incandescent sources that do exhibit the radiation characteristics of a blackbody radiator. For the remainder of this course, the term "CCT" will be used throughout and is intended to be interpreted as "Correlated Color Temperature" when dealing with discharge lamps.

The visual color of a light source can be described by its color temperature, which is expressed in units of degrees Kelvin. Lower temperatures refer to lamps with a large red component (wavelengths of 680nm to 750nm in the electromagnetic spectrum) which create a feeling of warmth. Higher temperatures refer to lamps with a large blue component (wavelengths of 380nm to 410nm in the electromagnetic spectrum) which create a space that becomes progressively cooler. While there is no industry standard for the cutoff temperatures between warm, neutral, cool or daylight classifications of color temperature, the following ranges are generally acceptable to describe effects of the lamp source on the lighted environment:

Less than 3500^{o}K – Warm	3500^{o}K to 4000^{o}K – Neutral
4100^{o}K to 5000^{o}K – Cool	Above 5000^{o}K - Daylight

It is important to understand that the color temperature only describes the apparent color of the source and the degree of warmth or coolness that projects into the space, but nothing about the quality of the light.

The "Color Rendering Index" (CRI) for a particular lamp provides a means for comparing the color shift of a test object under a test lamp, as compared to the color when viewed under a reference lamp. It is imperative that the test lamp and reference lamp have the same color temperature, or the tests will be meaningless. Eight specific colors used in a comparison test between the test lamp and the reference lamp develop the correlation between the two lamps. A test lamp with a CRI of 100 perfectly correlates to the reference lamp, meaning that there is no color shift between the eight colors when viewed under the test or reference lamps. The CRI will progressively drop as the differences widen between the two lamps at the eight colors. For this reason, lamps with high CRI's provide better color rendering than lamps with low CRI's. Unfortunately, the CRI does not indicate the extent of the color differences at the specific colors, nor does it indicate the direction of the color shift. An evaluation of the color temperature and the CRI will provide only general guidelines. A visual evaluation will be required to make the final determination if color rendering and the visual warmth or coolness of the environment is acceptable.

Most lamp manufacturers publish curves for the "Spectral Power Distribution" (SPD) of their lamps. The SPD curves indicate the radiant power emitted by the source at each wavelength over the visible region of 380nm to 750nm. Typical SPD curves for halo-phosphate lamps (used between the 1970's and 1990's) indicate a blending of the phosphors to create different hues of light. This blending is evident in the SPD curves shown in Figure 7 for a warm white and cool white fluorescent lamp.

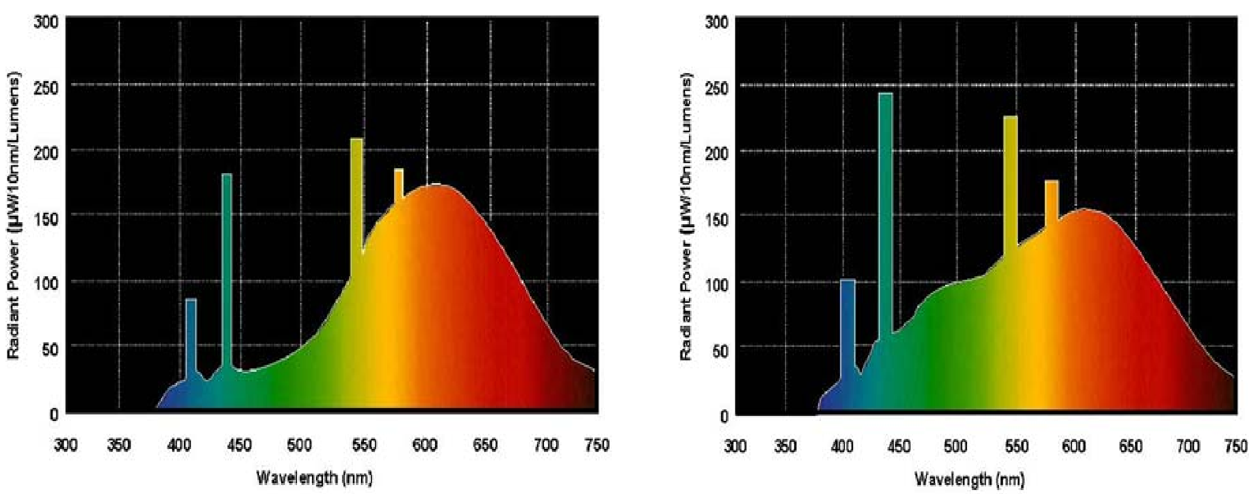


Figure 7 – Comparison of a warm white and cool white fluorescent lamp
(*Images courtesy of General Electric Company*)

Observing the SPD for the warm white fluorescent lamp shows that the blended wavelengths are shaped like a bell curve, with the peak in the red/orange region at a wavelength of 600nm, and the peak of the orange spike at 580nm. These two values are very close to the red cone response curve of 575nm, and with the high radiant energy, the eyes will be very sensitive to red colors. The yellow/green peak wavelength occurs at 550nm, which is very close to the wavelength of maximum efficacy at 555nm, and very close to the green cone response curve of 535nm, which indicates the eyes will be very sensitive to yellow/green colors. The blended green region on the downside of the bell curve has a lower radiant energy, and objects in this region will not be as pronounced as compared to those in the red/orange region. The blended blue/violet region has very limited radiant energy and the eyes will not be very sensitive to these colors. However, the two wavelengths in the blue region that peak at 410nm and 440nm are very close to the blue cone response curve of 445nm, and with the blue cones being more sensitive, the eyes will be somewhat sensitive to colors at these wavelengths. From the SPD curve, it is evident that the majority of the radiant energy falls in the red region of the spectrum, and therefore justifies the lamp's description as being listed as a warm white lamp.

Looking at the SPD curve for the cool white fluorescent lamp, the blended bell curve has begun to flatten out, with the peak of the red/orange region dropping in radiant energy. The yellow/green blended area has also substantially increased in radiant energy and the two peak curves in this region have maintained their radiant energy. The blended blue/violet area has maintained its radiant energy, but the two peak wavelengths in this region have substantially increased their radiant energy. This results in the eyes becoming more sensitive to these dominant colors in the cooler region of the spectrum. These observations justify the lamp's description as being listed as a cool white lamp.

As fluorescent lamp technology evolved even further through the 80's and 90's, research found that the eyes could not in fact see all of the wavelengths shown in the blended areas of the SPD curve. Since this was a substantial amount of light, researchers began looking into phosphors that would emit maximum radiant energy that coincided with the wavelengths of the red, green and blue cone response curves. What developed out of this research was the use of rare earth phosphors for coating the lamps that improved both efficacy and color rendering. The earth phosphors produce high concentrations of light at the peak sensitivity regions of the eye, and then the eyes blend these colors to produce other colors. These new lamps, called tri-phosphor lamps, have their spectral power distribution accentuate the three primary colors of light. Lamps with strong components and peaks of the primary colors will accentuate those colors, while low energy in the other colors will soften those colors. The SPD curves of Figure 8 clearly indicate the tri-phosphor peaks.

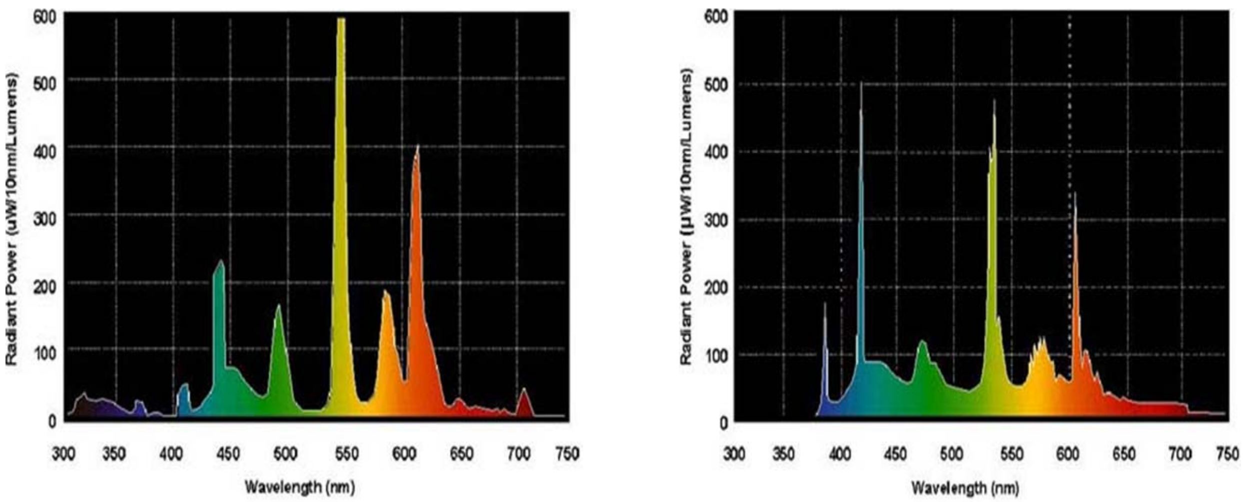


Figure 8 – Comparison of a SPX41 lamp and an SP65 fluorescent lamp
(*Images courtesy of General Electric Company*)

It is easy to determine the three peak wavelengths for the SPX41 lamp by examining the SPD curve. The peak in the red/orange region occurs at a wavelength of 610nm, which is very close to the red cone response curve of 575nm, and with the high radiant energy, the eyes will be sensitive to red colors. The yellow/green peak wavelength occurs at 550nm, which is very close to the wavelength of maximum efficacy at 555nm, and very close to the green cone response curve of 535nm, which indicates the eyes will be sensitive to these colors as well. The peak wavelength in the blue region occurs at 440nm and is very close to the blue cone response curve of 445nm, and the eyes will be sensitive to colors at these wavelengths. From the SPD curve, it is evident that the majority of the radiant energy falls in the yellow/green region of the spectrum, and therefore justifies the lamp's description as being listed as a neutral lamp at 4100^{o}K.

Looking at the SPD curve for the SP65 lamp in comparison to the SPX41 fluorescent lamp, the peak of the red/orange region has dropped in radiant energy. The peak of the yellow/green region has also substantially dropped in radiant energy, while the peak curve in the blue region has substantially increased in radiant energy. In addition, since the blue cones are more sensitive than the red or green cones, this SPD curve clearly shows that this lamp operates in the cooler part of the spectrum. All of these factors justify the lamp's description as being listed as a daylight lamp at 6500^{o}K.

UNDERSTANDING FLUORESCENT LAMPS

Fluorescent lighting has become the most trusted and widely used lamp source in the world. Due to its popularity, this report will focus primarily on the 2-foot to 4-foot linear T8 fluorescent sources, lamps, ballasts and operation. These gaseous discharge lamps produce light by discharging an electric arc through a tube filled with a low-pressure gas and a small amount of mercury vapor. Upon generating the electric arc, the electrons in the arc collide with the electrons in the mercury atoms, and the mercury electrons will absorb this excess energy and jump to the next highest energy level in the atom. Since the mercury electrons do not like to function in this unstable state, they almost immediately return to their normal orbit and will give off the excess energy they previously absorbed as ultraviolet light.

These ultraviolet emissions are not visible, but they stimulate fluorescent powders which coat the inside surface of the tube. The powders, called phosphors, convert the ultraviolet light into visible light for emission from the tube. The color of the emitted light is dependent on the precise composition of the phosphors. Some phosphors will radiate broadly across many different wavelengths, while others produce a narrow band emission of just one color. By applying these phosphors to the inside of the tube in isolation or blended together, it is possible to achieve almost any desired color or shade of white.

The most commonly found types of fluorescent lamps (i.e. warm white, warm white deluxe, cool white) use an internal coating of a calcium halo-phosphate material. This phosphor is a blend of two different materials, which radiate broadly in the blue and orange regions of the SPD curve. By changing the ratio of the two components, a full range of warm to cool white hues is possible. The CRI for this lamp is typically 50 to 70 and the lamp efficacy is approximately 60 to 70 lumens per watt.

Traditional thinking believes that to achieve good color rendering, the lamp has to produce a full spectrum of light with all wavelengths present. However, the human eye is not equally sensitive to all colors. Therefore, a lamp built to radiate all wavelengths will have most of the wavelengths occur in regions where the eye is less sensitive. New research into color perception found that it is possible to achieve a very high CRI from a light source that has a very narrow tri-band system. The tri-band spectrum corresponds to the red, green and blue photoreceptors in the eye. Blending the red, green and blue components in the correct proportions generates a net white output of various hues. The peaks of these components correspond to the color receptors in the eye thereby creating CRI values of 85 or greater. In addition, a tri-phosphor lamp at 4100^{o}K is much stronger in the red region than a halo-phosphate lamp at 4100^{o}K. Another advantage of a tri-phosphor lamp is its high efficiency of converting ultraviolet waves into visible light, which boosts the lamp efficacy for these lamps to levels of 80 to 90 lumens per watt.

The biggest drawback of tri-phosphor lamps is the price. One of the main reasons for the extremely high prices for these lamps is that China controls over 95% of the rare earth phosphors, and they are instituting limits on the mining of these phosphors. See the report at the web address below for further information on the availability of rare earth phosphors and the effect China has on global prices.

Assets.sylvania.com/assets/Documents/Sylvania-presentation-rare-earth-crisis.0e64cc05-e1a4-4419-8f60-95ae0d35ae71.pdf

While research was progressing on the use of tri-phosphors, studies began on using different CCTs for the lamps. This uncovered many questions, as this new information appeared to contradict the age-old theories of light. One of the biggest changes in the theory of light deals with scotopic lighting and its absence from the contribution to interior lighting levels. Current research in the new theory of scotopic enhanced lighting will help the understanding of how rod activated vision affects the perception of light in an office environment. Studies now show that rod activated vision is not only active in dim lighting, but is also active in typical interior lighting levels. It is a fact that rods are more sensitive than cones to bluish-white light sources, characteristically found in the higher color temperature lamp sources. In addition, the higher the color temperature, the more the rods are activated and the higher the perceived brightness in a space. Numerous studies show where individuals have chosen scotopically enhanced lighting (higher color temperature) to be brighter than photopic lighting, even though measured lighting levels were 30% lower for the scotopically enhanced lighting. It would therefore be reasonable to combine the photopic and scotopic lumens of a particular lamp in order to get a more complete evaluation of how the human eye perceives light. See Figure 9 for a comparison of standard fluorescent lamps with scotopically enhanced lamps, and the SPD curve for a 7500^{o}K lamp.

Figure 9a – Space lit with two (2) 4100°K fluorescent lamps per fixture

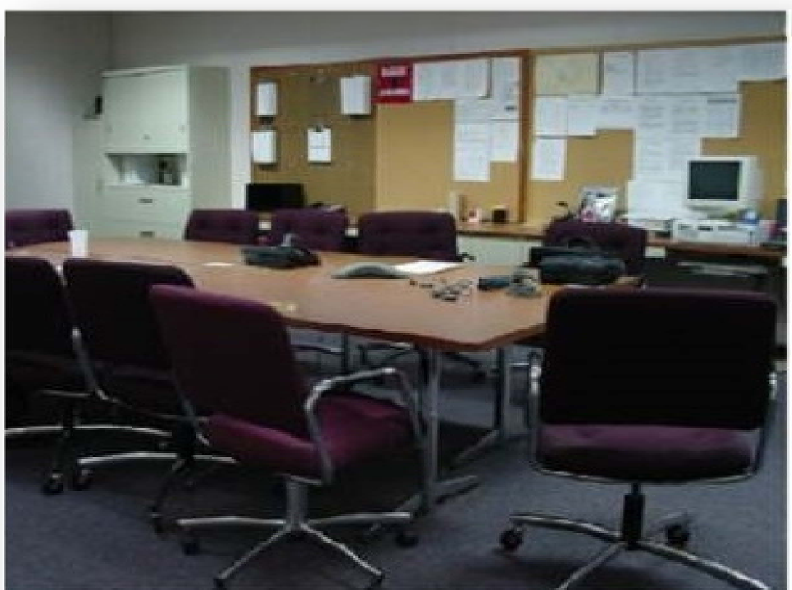


Figure 9b – Space lit with one (1) 7500°K fluorescent lamp per fixture

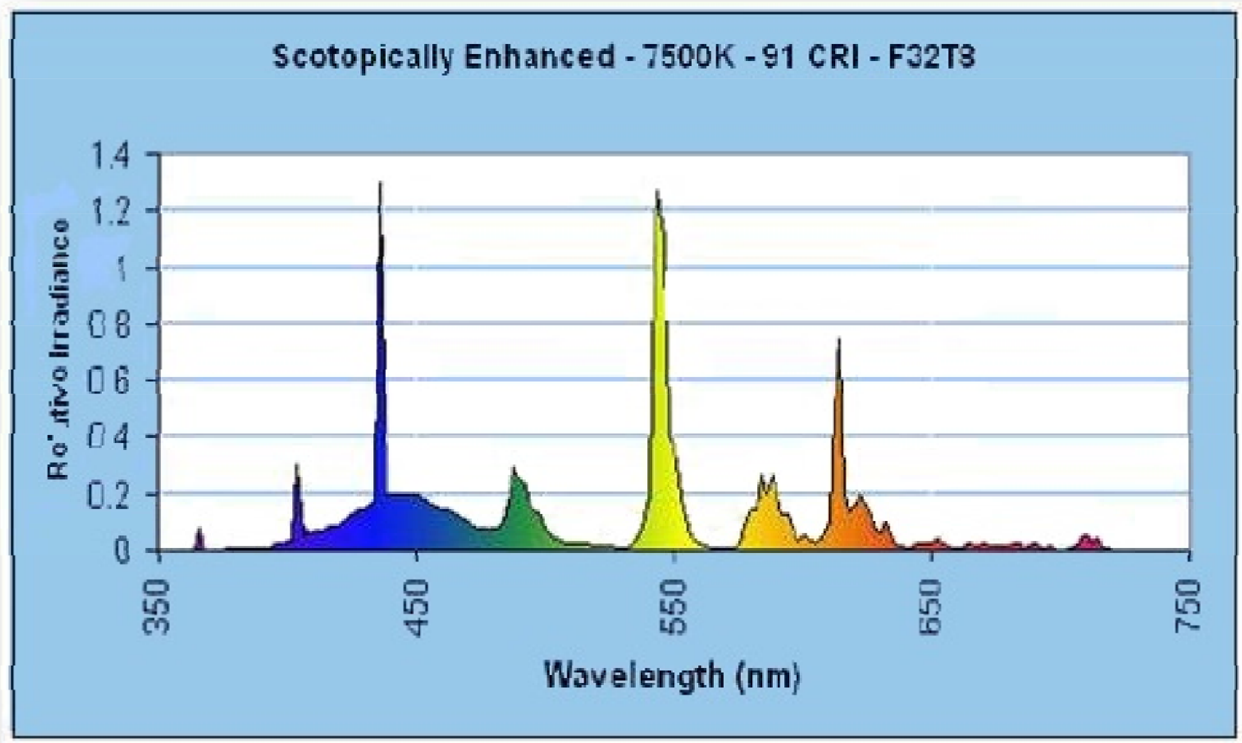


Figure 9c – 7500^{o}K SPD Curve

Additional studies show that general lighting with high scotopic to photopic ratios (S/P), representative of high color temperature lamps, provides better visual acuity. They also contribute to faster reading time, reduced visual fatigue, reduced glare, and a reduction in task-oriented errors. Some lamp manufacturers have started including the S/P ratios with the published data for their lamps. The addition of this ratio is an attempt to capture the relative strengths of the responses of the cones (photopic vision) and rods (scotopic vision). Measurements of these ratios are as indicated below and will be discussed in the Basic Lighting Calculations.

F32T8/SP30 – 1.3	F32T8/SPX30 – 1.3
F32T8/SP35 – 1.4	F32T8/SPX35 – 1.5
F32T8/SP41 – 1.6	F32T8/SPX41 – 1.8
F32T8/SP50 – 1.9	F32T8/SPX50 – 2.0
F32T8/SP65 – 2.1	F32T8/SPX65 – 2.3

SPECIFYING FLUORESCENT LAMPS

There are literally hundreds of different types and sizes of fluorescent lamps available today. Fortunately, there is a standard lamp identification protocol that is somewhat universal in describing the characteristics for each individual lamp. Since there are subtle differences in the catalog description code between various manufacturers, this report will discuss identification codes based on the most popular linear T8 lamps from General Electric.

The format for 2-foot to 4-foot, linear T8 fluorescent lamps is as follows:

<u>F</u> <u>17</u> <u>T</u> <u>8</u> / <u>SXL</u> / <u>SPX</u> <u>30</u> / <u>HL</u> / <u>IS</u> / <u>WM</u> / <u>ECO</u>

“F” indicates a Fluorescent lamp

“17” indicates a 2-foot, 17-watt lamp
“25” indicates a 3-foot, 25-watt lamp
“28” indicates a 4-foot, 28-watt lamp
“32” indicates a 4-foot, 32-watt lamp

“T” indicates a Tube lamp shape

“8” indicates lamp diameter in eighths of an inch (T8 = 1-inch diameter)

“XL” when used, indicates extra life

for F17 lamp	(20,000 hours @ 3 hours/start)
	(24,000 hours @ 12 hours/start)
for F17/XL lamp	(24,000 hours @ 3 hours/start)
	(29,000 hours @ 12 hours/start)
for F25/XL lamp	(24,000 hours @ 3 hours/start)
	(29,000 hours @ 12 hours/start)
for F28/XL lamp	(36,000 hours @ 3 hours/start)
	(42,000 hours @ 12 hours/start)
for F32/XL lamp	(36,000 hours @ 3 hours/start)
	(42,000 hours @ 12 hours/start)

“SXL” when used, indicates super long life
for F32/SXL lamp (40,000 hours @ 3 hours/start)
(46,000 hours @ 12 hours/start)

“SP” or “SPX” indicates the lamp’s lumen and CRI performance
for F17/SP lamps (1325 initial lumens, 1260 mean lumens, CRI = 78)
for F17/SPX lamps (1350 initial lumens, 1280 mean lumens, CRI = 86)
for F17/SPX50 lamp (1300 initial lumens, 1235 mean lumens, CRI = 86)
for F17/SPX65 lamp (1250 initial lumens, 1125 mean lumens, CRI = 85)
for F25/SP lamps (2080 initial lumens, 1970 mean lumens, CRI = 78)
for F25/SPX lamps (2150 initial lumens, 2040 mean lumens, CRI = 86)
for F25/SPX50 lamp (2050 initial lumens, 1950 mean lumens, CRI = 86)
for F25/SPX65 lamp (1950 initial lumens, 1755 mean lumens, CRI = 85)
for F28/SPX lamps (2725 initial lumens, 2562 mean lumens, CRI = 85)
for F28/SPX50 lamp (2625 initial lumens, 2463 mean lumens, CRI = 80)
for F32/SP lamps (2800 initial lumens, 2660 mean lumens, CRI = 78)
for F32/SP50 lamp (2750 initial lumens, 2610 mean lumens, CRI = 78)
for F32/SP65 lamp (2700 initial lumens, 2565 mean lumens, CRI = 78)
for F32/SPX lamps (2950 initial lumens, 2800 mean lumens, CRI = 86)
for F32/SPX50 lamp (2800 initial lumens, 2660 mean lumens, CRI = 86)
for F32/SPX65 lamp (2750 initial lumens, 2475 mean lumens, CRI = 86)

“30” indicates the lamp’s CCT of 3000^{o}K
“35” indicates the lamp’s CCT of 3500^{o}K
“41” indicates the lamp’s CCT of 4100^{o}K
“50” indicates the lamp’s CCT of 5000^{o}K
“65” indicates the lamp’s CCT of 6500^{o}K

“HL” when used, indicates a high lumen lamp
for F32/SPX** lamps (3100 initial lumens, 2915 mean lumens, CRI = 85)
for F32/SPX50 lamp (3000 initial lumens, 2820 mean lumens, CRI = 80)

“IS” when used, indicates a lamp to be used with an instant start ballast
for F32/SP**/IS/WM lamps (30-watt lamp)
for F32/SP50/IS/WM lamp (30-watt lamp)

"WM" when used, indicates a Watt-Miser energy saving lamp
for F17/SPX**/WM lamps (15-watt lamp)
(1200 initial lumens, 1130 mean lumens, CRI = 85)
for F17/SPX50/WM lamp (15-watt lamp)
(1175 initial lumens, 1105 mean lumens, CRI = 80)
for F25/SPX**/WM lamps (22-watt lamp)
(1925 initial lumens, 1810 mean lumens, CRI = 85)
for F25/SPX50/WM lamp (22-watt lamp)
(1900 initial lumens, 1785 mean lumens, CRI = 80)
for F32/SP**/WM lamps (30-watt lamp)
(2800 initial lumens, 2635 mean lumens, CRI = 83)
for F32/SP50/WM lamp (30-watt lamp)
(2700 initial lumens, 2540 mean lumens, CRI = 80)

"ECO" indicates the lamp has passed toxicity TCLP tests as outlined by the EPA

For the most up-to-date information, see www.gelighting.com.

It is important to understand that changing just one entity in the lamp description could substantially affect the performance of the lamp. In a simplistic example, an office space of 5000 square feet requires 50 footcandles at desk height using 2' x 4' recessed lighting fixtures. Since 50 footcandles is the target lighting level, and using the equation footcandles = lumens / square foot, the space would require 250,000 lumens. If the designer uses two F32T8/SP35 lamps per fixture, the total number of lamps would be 250,000 lumens / 2660 lumens per lamp = 94 lamps, resulting in 47 fixtures. If the designer uses two F32T8/SPX35 lamps per fixture, the total number of lamps would be 250,000 lumens / 2800 lumens per lamp = 90 lamps, resulting in 45 fixtures. Therefore, by using the SP lamps, additional lamps and fixtures would be required, and the color rendering would not be as sensitive as the SPX lamp.

This example brings to light the required attention to detail when performing lighting calculations. Performing lighting calculations using an SPX lamp will require the installation of an SPX lamp for the calculations to be meaningful. Installing an SP lamp will make the calculations meaningless, and the visual evaluation of the perceived colors in the space will not be as sensitive as that of the SPX lamp. It is therefore imperative that a complete and comprehensive description of the lamp be included in the lamp description column on the Luminaire Schedule that matches the type used in the lighting calculations. If a 4-foot linear lamp specification calls for an "F32T8", there are over forty different types of lamps that can satisfy this requirement. It could be very likely that the lamps delivered to the project site with this specification will be the cheapest available, or overstocked in inventory at the supply house. In addition, the Lighting Designer should always verify the installation of the correct lamp type at the project site, so that the visual results will agree with the calculations.

UNDERSTANDING FLUORESCENT BALLASTS

The most common fluorescent ballast is the instant start ballast, mostly used in 3 to 12-hour applications of continuous lighting. The instant start ballast ignites the lamp by applying a very large and significant voltage across the cathodes (>550 volts), which are located at each end of the lamp. The cathodes act as terminals for the electric arc, and contain a special "emission" material of barium, strontium or calcium oxide that has free electrons. These electrons help initiate the electric arc, and then collide with the electrons in the mercury atoms. There is no heating of the cathodes, which results in lamp ignition within 50 milliseconds. After ignition, the voltage drops to a level to keep the lamp energized. Due to the high impressed ignition voltage, there is a significant amount of emissive material released with the formation of the electric arc. Once the emission material has depleted from the cathodes, the lamp will ultimately fail. Instant start ballasts provide about 7,000 to 13,000 starts before 50% lamp failure. For this reason, T8 lamps that operate on instant start ballasts should not have occupancy sensors or electronic controls switching the lamps on and off. The frequent switching will significantly affect lamp life and void the lamp warranties. The manufacturer's recommendation is to use program start ballasts where sensor switching occurs more than three times in a 12-hour period.

The rapid start ballast will ignite lamps typically around 500 milliseconds, and at a lower voltage than instant start ballasts. Heating of the cathodes takes place continuously while the lamp is in operation, thereby stabilizing the rate of emission of material from the cathode and improving lamp life. When the circuit is energized, about 3.5-volts is applied across each cathode which evaporates the emission material, and then the material circulates through the tube and ionizes the gas. When sufficient ionization has occurred, a high voltage of about 250-volts is impressed across the cathodes to start the arc ignition. Once establishing the arc, the voltage drops to a lower value for normal lamp operation. This helped improve lamp life, and the rapid start ballast became the most popular ballast through the 1980's and up to the time of the electronic ballast.

With the release of the electronic ballast, research began utilizing electronics to control the operation of the rapid start ballast to help improve overall operation. The program start ballast works in unique well-defined steps that eliminate the problems associated with the instant start and rapid start ballasts. The first step controls the heating of the cathodes and reduces the voltage across the cathodes in order to minimize the release of emission material. The time duration of this preprogrammed step in the ballast circuitry allows the temperature of the cathodes to reach 700^{o}C, when the program proceeds to the next step. The second step applies an instant starting voltage across the cathodes, igniting them with minimal loss of emission material. This period takes approximately 30 milliseconds, which prohibits further loss of emission material. Once the lamps have ignited, the cathode heat drops to a predetermined level that saves additional energy, while rapid start ballast will continue heating the cathodes with no additional benefit. By using this process, program start ballasts provide more than 100,000 starts before 50% lamp failure. Other characteristics of the ballast include similar energy savings and efficiencies compared to instant start ballasts.

SPECIFYING FLUORESCENT LAMP BALLASTS

The ballast is the device that provides the proper voltage for lamp starting and operation, as well as limiting the current to keep the heat from destroying the lamp. For this report, the focus will be on GE electronic program start lighting ballasts, which are compatible with the lamps previously discussed. The format for an electonic ballast for linear T8 fluorescent lamps is as follows:

GE – 1 32 - MV PS – N

"GE" indicates an LFL (linear fluorescent lamp)
"GEC" indicates a CFL (compact fluorescent lamp)

"1" indicates 1 lamp supported by this ballast
"2'" indicates 2 lamps supported by this ballast
"3" indicates 3 lamps supported by this ballast
"4" indicates 4 lamps supported by this ballast
"6" indicates 6 lamps supported by this ballast

"17"	indicates a 2-foot T8 lamp
"25"	indicates a 3-foot T8 lamp
"32"	indicates a 4-foot T8 lamp
"59"	indicates an 8-foot T8 lamp

"IS"	indicates Instant Start ballast
"RS"	indicates Rapid Start ballast
"PS"	indicates Program Start ballast

"XL"	indicates ultra low ballast factor (0.60)
"L"	indicates low ballast factor (0.71)
"N"	indicates normal ballast factor (0.87)
"N+"	indicates normal-high ballast factor (1.00)
"H"	indicates high ballast factor (1.18)

The other important imformation required from the ballast is the system watts, or the amount of power drawn by the lamp/ballast combination. This information for some of the popular lamp types using program start ballasts is shown below. Information for additional lamp types can be found at www.gelighting.com.

Lamp/Ballast	1-Lamp	2-Lamp	3-Lamp	4-Lamp
F32T8 (.60 BF)	n/a	45W	67W	n/a
F32T8 (.71 BF)	25W	47W	69W	90W
F32T8 (.87 BF)	30W	59W	86W	114W
F32T8 (1.18 BF)	39W	75W	110W	147W
F28T8 (.71 BF)	22W	41W	58W	77W
F28T8 (.87 BF)	26W	51W	73W	96W
F28T8 (1.18 BF)	33W	63W	92W	125W
F25T8 (.71 BF)	20W	38W	58W	NA
F25T8 (.87 BF)	24W	51W	66W	87W
F25T8 (1.18W)	30W	59W	86W	117W

BASIC LIGHTING CALCULATIONS

Although there are numerous software packages available to perform lighting calculations, it is important to understand how the room geometry, the workplane height and the light loss factors for ballast/lamp systems play important roles in determining the exact number of fixtures required to meet a specific footcandle level in a space. The basic lighting calculation used in this report is the average illuminance calculation, also known as the Zonal Cavity Method, to determine the average footcandles in a space.

Footcandles are defined as lumens of light per square foot of area. If 2000 lumens are evenly distributed over 100 square feet (2000 lm / 100 sq ft), this provides a result of 20 lm/sq ft, or an average of 20 footcandles in the space. This equation only works for the actual amount of lumens that reach the work surface, not the total number of lumens produced by the lighting system. The actual number of lumens that reach the work surface will typically be 40% to 70% less than the total number of lumens, and is referred to as the coefficient of utilization (CU). For our previous example, if the CU is equal to 0.50, then the total lighting system will need to produce at least 4000 lumens in order to provide the 20 footcandles at the work surface. The CU is a dynamic value, that changes with the room dimensions and surface reflectances, and is also dependent on the characteristics of the luminaire itself.

In order for light to reach the work surface, it must first be projected out of the fixture. If a fixture has dark interior surfaces, such as a dark multigrooved baffle, this surface will absorb more light than a fixture with a smooth, highly reflective surface, and will result in a smaller CU. Fixtures that have lenses or diffusers to direct light in a specific direction will also reduce the amount of light that exits the fixture. Since all surfaces within a fixture absorb some light, the number of lamps in a fixture will also influence the CU; fixtures with several lamps will have a lower CU than fixtures with fewer lamps.

Once light has been emitted from the fixture, some travels to the work surface, some to the walls, some to the floor, and in certain cases, some to the ceiling. The light which does not directly strike the work surface will either be re-reflected by surfaces that it strikes or absorbed by these surfaces. If there is a small percentage of wall surface area in the room, then this will allow more of the light to be projected to the work surface. It can be concluded that a room with a low percentage of its total surface area in walls will have a higher CU, whereas a higher pecentage of wall surface area will result in a lower CU. In addition, the reflectances of the wall as well as the other surfaces will affect the CU. As the amount of re-reflected light within a room increases, a higher percentage of the light will reach the work surface, resulting in a higher CU. Dark colored room surfaces will absorb more light, with a resultant reduction in the CU. This leads to the conclusion that the CU will change due to the influence of three factors: the physical characteristics of the luminaire, the room geometry, and the percentage of light that is reflected by room surfaces.

Manufacturers perform photometric tests on their most widely used fixtures, which aid Lighting Designers when performing calculations. Technical literature shows only portions of the test report, which includes the CU table and the type of lamp used during testing. This table can also be derived from the luminaire IES data file, also available from the manufacturer, through Photometric Viewer software (free online software from Acuity Brands). The values in the table are decimal numbers, and are accessed using the appropriate columns and rows which depict the room surface reflectances and the room size. The use of the CU tables for other lamps, not used in the original tests, provides accurate results if the lamp and ballast information are modified in the calculations. See Figure 10 for a photometric report, which provides technical data for a Lithonia 2 ’x 4’, 2-lamp volumetric troffer using FO32, 2800 lumen lamps.

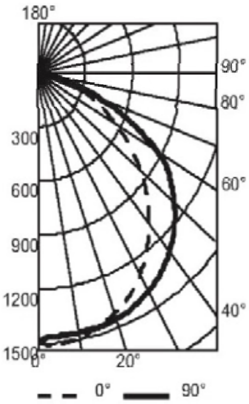
The first item shown on the report is the Candela Distribution Curve which indicates the intensities of light at various angles. Two curves are shown, one representing the intensities parallel to the fixture axis, and the other representing intensities perpendicular to the axis. The primary use of this curve is for determining the illuminance at a specific point in space.

The second item is the CP Summary which presents the data used to plot the Candela Distribution Curves. This table provides more accurate information than the curves when determing the illuminance of a point in space.

The fourth item is the Zonal Lumen Summary which shows the lumens in the listed conic zones around the fixture. Looking at the zone 90^o – 180^o for example, it is shown that there are zero lumens emitted from the fixture at the sides to the top, indicating a cutoff type of distribution. This will eliminate any hot spots on the ceiling, and all light on the ceiling will be by reflection, resulting in little to no glare.

PHOTOMETRICS

2RT8S 2 32, F032 lamps, 2800 lumens per lamp, s/m 1.28 (along) 1.4 (across), test no. LTL18481



CP Summary

	0°	90
0°	1490	1490
5°	1507	1464
15°	1459	1461
25°	1362	1430
35°	1198	1352
45°	975	1215
55°	707	1017
65°	438	648
75°	205	208
85°	35	20
90	0	0

Coefficients of Utilization

pf	20%								
pc	80%			70%			50%		
pw (RCR)	70%	50%	30%	50%	30%	10%	50%	30%	10%
0	96	96	96	94	94	94	90	90	90
1	88	84	81	82	79	77	79	77	74
2	80	73	68	72	67	63	69	65	61
3	73	64	58	63	57	52	61	56	51
4	67	57	50	56	49	44	54	48	44
5	61	51	43	50	43	38	48	42	37
6	56	46	38	45	38	33	43	37	33
7	52	41	34	41	34	29	39	33	29
8	49	38	31	37	30	26	36	30	26
9	45	34	28	34	28	23	33	27	23
10	42	32	25	31	25	21	30	25	21

Zonal Lumen Summary

Zone	Lumens	% Lamp	% Fixture
0° - 30°	1198	21.4	26.5
0° - 40°	1997	35.7	44.2
0° - 60°	3630	64.8	80.4
0° - 90°	4515	80.6	100.0
90° - 180°	0	0.0	0.0
0° - 180°	4515	80.6	100.0

Efficiency: 80.6%

*The LER (Luminaire Efficacy Rating) is the lumens per watt rating for this fixture. It is used to compare the energy efficiency of various products. This photometric report is based upon IES testing procedures, as stated in LM-41-1998.

Figure 10 – CU Table for Lithonia #2RT8S-232 Luminaire
(The Acuity Brands logo is a registered trademark of Acuity Brands)

The third item is the actual CU Table. The first item in the CU Table is "pf", which indicates the reflectance of the floor when the work surface is on the floor, or the effective reflectance of the floor cavity if the work surface is above the floor. This value is based on 20% reflectance.

The next item is "pc", which indicates the reflectance of the ceiling for recessed fixtures, or the effective reflectance of the ceiling cavity if the light fixtures are suspended. This value is based on an 80%, 70% or 50% reflectance.

The following item is "pw", which indicates the reflectance of the walls, and are based on 70%, 50% or 30% when the ceiling reflectance is 80%; and 50%, 30% or 10% when the ceiling reflectance is 70% or 50%.

The first column on the left is called RCR, or Room Cavity Ratio. The RCR represents a modified ratio of wall area to the horizontal surface area in a room. It is important to note that the physical size of a room does not affect the percentage of light directed to the walls and the workplane, only the ratio of wall area to horizontal surface area is significant. A room that has dimensions of 10'x10'x10' will have the same percentages of light directed to walls and floors as a room with dimensions of 20'x20'x20'.

The Zonal Cavity Method of lighting calculations is a design tool that allows the Lighting Designer to examine how the characteristics of a particular room or space will impact the CU for a specific fixture. The major goal of this calculation method is to determine the actual reflectances of the ceiling and floor cavities so that a proper value for the CU can be determined based on the actual room characteristics.

A room is divided into three separate vertical zones, referred to as the ceiling cavity, the room cavity and the floor cavity. When luminaires are suspended from the ceiling, the height of the ceiling cavity is measured from the centerline of the lamps up to the structural ceiling. The height of the room cavity is measured from the centerline of the lamps down to the work plane. If luminaires are recessed into the ceiling, then the height of the ceiling cavity is equal to zero and the height of the room cavity is measured from the ceiling down to the work plane. If the work plane is located above the floor, the height of the floor cavity is measured from the work plane down to the floor. If the work plane is on the floor then the floor cavity height is equal to zero.

In each cavity, there will be reflectance percentages that will also factor into the determination of the CU for a given fixture. For the ceiling cavity, "pc" indicates the percentage reflectance for the structural ceiling if the fixtures are suspended, or the false ceiling if using recessed fixtures. If the fixtures are suspended, then the value "pwc" is used as the percentage reflectance for the wall area above the centerline of the lamps. If recessed fixtures are used, then the ceiling cavity ratio will equal zero.

For the room cavity, "pw"indicates the percentage reflectance for the walls down from the centerline of the lamps to the workplane if fixtures are suspended, or the percentage reflectance for the walls from the false ceiling down to the workplane for recessed fixtures.

For the floor cavity, "pf" indicates the percentage reflectance for the floor. If the workplane is located above the floor, then the value "pwf" is used as the percentage reflectance for the wall area from the floor to the workplane. If the workplane is on the floor, then the floor cavity ratio will equal zero. See Figure 11 for a view of the three cavities used in determination of the CU.

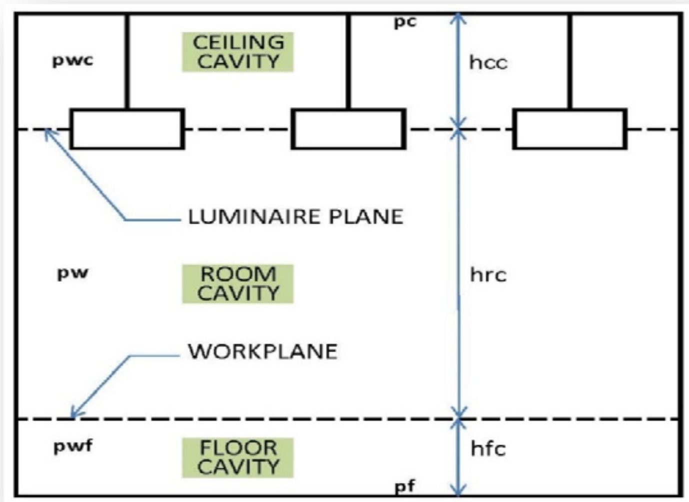


Figure 11 – The three Cavities for lighting calculations

Now that the basics of the CU Table and the room characteristics have been examined, these criteria can now be applied to a practical and realistic situation. A Restoration Room in a Museum will have room dimensions approximately 18-feet in length, 12-feet in width and 11-feet in height. The ceiling is a dropped white acoustical tile ceiling at 8-feet with a reflectance of 90%. The walls will be painted with an eggshell white color and matte finish with a reflectance of 50%. A light colored tan carpet will be installed on the floor with a reflectance of 20%. The lighting fixtures installed in this room will be the Lithonia 2RT8S-232 recessed, volumetric luminaires with two F32T8/SP lamps at 2800 initial lumens, 3500^{o}K color temperature and a normal power factor instant start ballast. An average lighting level of 50 footcandles on the workplane is the desired outcome. See Figure 12 for the technical data for the fixture.

Since there is a dropped ceiling in the room, the ceiling cavity height is zero, and the ceiling cavity ratio will be zero. The workplane will be at desk height of 2.5-feet, resulting in a room cavity height of 5.5-feet, and a floor cavity height of 2.5-feet. The base ceiling reflectance is assumed to be 80%, the wall reflectance is assumed to be 50%, the wall reflectance below the work plane is assumed to be 30%, and the base floor reflectance is assumed to be 20%. See Figure 13 for the room characteristics for the this space which will be used in the lighting calculations.

LITHONIA LIGHTING®

Catalog Number	
Notes	
Type	

FEATURES & SPECIFICATIONS

INTENDED USE — RT8S is designed for applications that require the extremely energy efficient delivery of comfortable volumetric light from a lay-in fixture that is appealing and shallow in depth and where room-side ballast access is required. Ideal for offices, schools, hospitals and numerous other commercial applications. **Certain airborne contaminants can diminish integrity of acrylic.**

Click here for Acrylic Environmental Compatibility table for suitable uses.

OPTICAL SYSTEM — Delivers volumetric lighting by filling the entire volume of space with light, providing the ideal amount to walls, cubicles, work surfaces and people.

Luminous characteristics are carefully managed at high angles, distributing just enough intensity to deliver the volumetric effect.

98% reflective Alanod MIRO® silver optical assembly efficiently redirects lamp output to the refractor.

Regressed refractive system obscures and softens the lamp and smoothly washes the reflector with light.

Linear faceted reflector softens and distributes light into the space and minimizes the luminance ratio between the fixture and the ceiling.

Mechanical cut-off across the reflector and fresnel refraction along the refractor provide high angle shielding and a quiet ceiling.

Sloped endplates provide a balanced fixture to ceiling ratio while enhancing the perception of fixture depth.

CONSTRUCTION — Rugged, steel reflector with embossed facets. Painted after fabrication.

Fixtures may be mounted end-to-end.

ELECTRICAL SYSTEM — High-efficiency, CEE qualified, instant-start, ≤ 10% THD, universal voltage and sound rated A are available as quick-ship items.

Optional program-start and step-dimming ballasts available.

Designed and optimized for use with CEE (Consortium for Energy Efficiency) qualified, high-lumen, long life T8 lamps and energy-efficient electronic ballasts.

MAINTENANCE — Lamps accessed by unlatching trim and allowing it to hinge open for easy maintenance. Ballast is accessed from below by removing channel cover.

LISTING — UL Listed to U.S. and Canadian standards.

WARRANTY — 1-year limited warranty. Complete warranty terms located at www.acuitybrands.com/CustomerResources/Terms and conditions.aspx

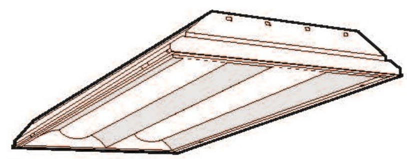
Protected by one or more of US Patents Nos. 7,229,192; D541,467; D541,468; D544,633; D544,634; D544,992; D544,933 and additional patent pending.

Actual performance may differ as a result of end-user environment and application.

Note: Specifications subject to change without notice.

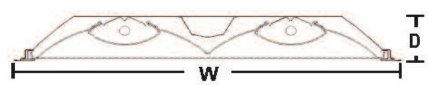
RT5

2RT8S



2 X 4
2 Lamps T8

Specifications
Length: 48 (121.8)
Width: 24 (61.0)
Depth: 3-3/16 (8.1)



All dimensions are inches (centimeters) unless otherwise specified.

ORDERING INFORMATION For shortest lead times, configure products using **bolded options**.

Example: 2RT8S 2 32 MVOLT BINP L835HT8

2RT8S		2	32				
Series	**Trim type**	**Number of lamps**	**Wattage**	**Voltage**	**Ballast**	**Lamp**	**Options**
2RT8S	(blank) **Lay-in grid** F Overlapping flanged	2	32 **32W T8 (48")**	**MVOLT**[1] 347	**BILP IS, high efficiency, .78 bf (low)**[2] **BINP IS, high efficiency, .88 bf (normal)**[2] **GEB10IS IS, .88 ballast factor** BIHP IS, high efficiency, 120 bf (high)[2] BSNP PS, step-dimming, high efficiency, .88 bf (normal)[2,3]	**L835HT8 3100 lumen long life, 3500° K** LP735 2800 lumen, 3500°K	GLR Fast-blow fuse[4] EL Emergency battery pack (see Life Safety section) **EL14 Emergency battery pack (see Life Safety section)** PWS1836 6' prewire, 3/8" diameter, 18 gauge, 3-wires[5] PWS1846 6' prewire, 3/8" diameter, 18 gauge, 4-wires[6] QFC_ Quick-flex fixture cable, factory installed prewired cable (RELOC®)[4]

T8 Energy Comparison

System	*Lamp Type*	*Ballast Factor*	*Input Watts*	*Watts Saved Compared to 3 lamp T8*
3-lamp T8 Parabolic	F32T8	0.88	85	–
2RT8B 2-lamp BINP T8	F32T8	0.88	55	30
2RT8B 2-lamp BILP T8	F32T8	0.78	48	37

Figure 12 – Technical Data Sheet for the Luminaire used in the Example

(The Acuity Brands logo is a registered trademark of Acuity Brands)

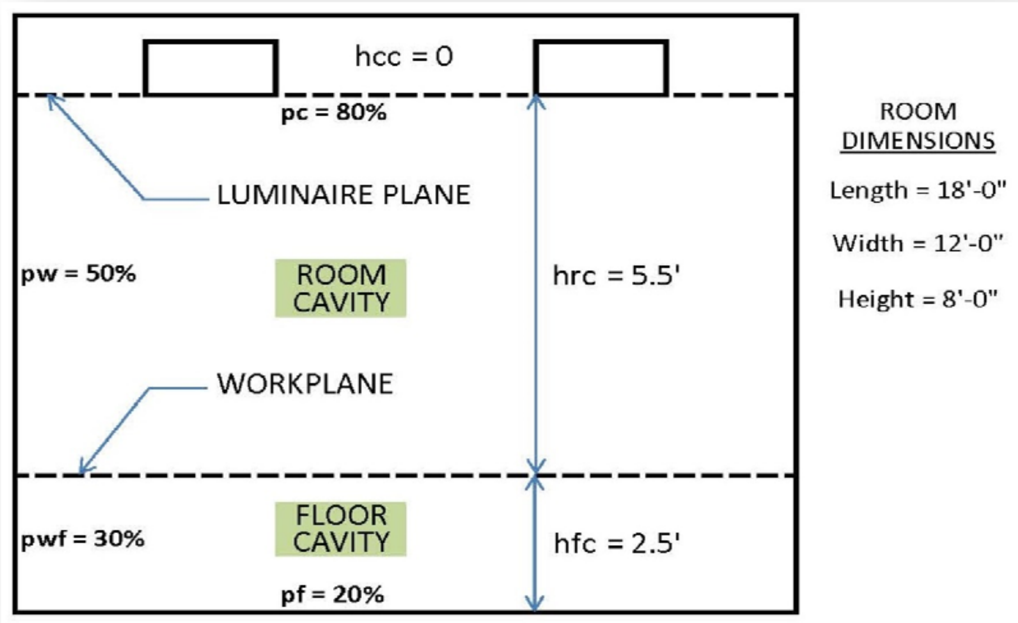


Figure 13 – Room characteristics for the Restoration Room

The following steps can now be performed in order to perform lighting calculations for the Restoration Room using the Zonal Cavity Method:

Step 1: Determine the three Cavity Ratios

Cavity Ratio = [(5 x hc)(L + W)] / [L x W]
CCR = [(5 x 0.0)(18 + 12)] / [18 x 12] = 0.0
RCR = [(5 x 5.5)(18 + 12)] / [18 x 12] = 3.82
FCR = [(5 x 2.5)(18 + 12)] / [18 x 12] = 1.74

For a room that is not a perfect square or rectangle, the three Cavity Ratios can also be calculated by the following:

Cavity Ratio = [(5 x hc)(0.5 x perimeter)] / [area]
CCR = [(5 x 0.0)(0.5 x (18 + 12 + 18 +12))] / [18 x 12] = 0.0
RCR = [(5 x 5.5)(0.5 x (18 + 12 + 18 +12))] / [18 x 12] = 3.82
FCR = [(5 x 2.5)(0.5 x (18 + 12 + 18 +12))] / [18 x 12] = 1.74

Step 2: Determine the Effective Ceiling Cavity Reflectance

Since the dropped acoustical tile ceiling will be treated as the ceiling, the value hcc is equal to zero, as well as the Ceiling Cavity Ratio, and the Effective Ceiling Cavity Reflectance remains 80%. If suspended fixtures had been used, then the Effective Ceiling Cavity Reflectance would be determined by the same method that is used for the Effective Floor Cavity Reflectance calculated below. These calculations can also be found in the 8th Edition of the IES Lighting Handbook.

% CR or % FR		90				80				70			50			30				10		
%CWR or %FWR		90	70	50	30	80	70	50	30	70	50	30	70	50	30	70	50	30	10	50	30	10
CCR	0	90	90	90	90	80	80	80	80	70	70	70	50	50	50	30	30	30	30	10	10	10
Or	0.1	90	89	88	87	79	79	78	78	69	69	68	49	49	48	30	30	29	29	10	10	10
	0.2	89	88	86	85	79	78	77	76	68	67	66	49	48	47	30	29	29	28	10	10	9
FCR	0.3	89	87	85	83	78	77	75	74	68	66	64	49	47	46	30	29	28	27	10	10	9
	0.4	88	86	83	81	78	76	74	72	67	65	63	48	46	45	30	29	27	26	11	10	9
	0.5	88	85	81	78	77	75	73	70	66	64	61	48	46	44	29	28	27	25	11	10	9
CCR	0.6	88	84	80	76	77	75	71	68	65	62	59	47	45	43	29	28	26	25	11	10	9
Or	0.7	88	83	78	74	76	74	70	66	65	61	58	47	44	42	29	28	26	24	11	10	8
	0.8	87	82	77	73	75	73	69	65	64	60	56	47	43	41	29	27	25	23	11	10	8
FCR	0.9	87	81	76	71	75	72	68	63	63	59	55	46	43	40	29	27	25	22	11	9	8
	1.0	86	80	74	69	74	71	66	61	63	58	53	46	42	39	29	27	24	22	11	9	8
CCR	1.1	86	79	73	67	74	71	65	60	62	57	52	46	41	38	29	26	24	21	11	9	8
Or	1.2	86	78	72	65	73	70	64	58	61	56	50	45	41	37	29	26	23	20	12	9	7
	1.3	85	78	70	64	73	69	63	57	61	55	49	45	40	36	29	26	23	20	12	9	7
FCR	1.4	85	77	69	62	72	68	62	55	60	54	48	45	40	35	28	26	22	19	12	9	7
	1.5	85	76	68	61	72	68	61	54	59	53	47	44	39	34	28	25	22	18	12	9	7
CCR	1.6	85	75	66	59	71	67	60	53	59	52	45	44	39	33	28	25	21	18	12	9	7
Or	1.7	84	74	65	58	71	66	59	52	58	51	44	44	38	32	28	25	21	17	12	9	7
	1.8	84	73	64	56	70	65	58	50	57	50	43	43	37	32	28	25	21	17	12	9	6
FCR	1.9	84	73	63	55	70	65	57	49	57	49	42	43	37	31	28	25	20	16	12	9	6
	2.0	83	72	62	53	69	64	56	48	56	48	41	43	37	30	28	24	20	16	12	9	6

Figure 14 – Table of Effective Cavity Reflectances

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Step 3: Determine the Effective Floor Cavity Reflectance

Refer to the Table of Effective Cavity Reflectances, shown in Figure 14, to determine the Effective Floor Cavity Reflectance. The vaues shown below will be used in the Table:

Base Floor Reflectance = 20%

Wall Reflectance = 30%

FCR = 1.74

Since the FCR falls between 1.7 and 1.8, and there is no column for 20% Base Floor Reflectance, interpolation will be used to determine the final value for the Effective Floor Cavity Reflectance. The first interpolation occurs between the FCR of 1.7 and 1.8, while the second interpolation occurs between a wall reflectance of 10% and 30%.

- Interpolate for FCR = 1.74
- Locate the column under the %FR heading of 30%
  - Locate the column under the %FWR heading of 30%, which is under the %FR column of 30%
- Locate the Cavity Ratio value of 1.7 under the FCR column
  - Floor Cavity Reflectance for FCR 1.7 = .21
- Locate the Cavity Ratio value of 1.8 under the FCR column
  - Floor Cavity Reflectance for FCR 1.8 = .21
- Floor Cavity Reflectance for FCR 1.74 = .21
- Locate the column under the %FR heading of 10%
  - Locate the column under the %FWR heading of 30%, which is under the %FR column of 10%
- Locate the Cavity Ratio value of 1.7 under the FCR column
  - Floor Cavity Reflectance for FCR 1.7 = .09
- Locate the Cavity Ratio value of 1.8 under the FCR column
  - Floor Cavity Reflectance for FCR 1.8 = .09
- Floor Cavity Reflectance for FCR 1.74 = .09
- Interpolate to 20% Base Reflectance
  - [(30 - 20) / (30 – 10)] = [(.21 – Eff. Fl. Cav. Ref.) / (.21 - .09)]
- Effective Floor Cavity Reflectance = 0.15, or 15%

Step 4: Determine the CU from the CU Table of Figure 10

- Locate the column under the pc heading of 80%
  - Locate the column under the pw heading of 50%, which is under the pc column of 80%
- Locate the RCR value of 3 under the RCR column
  - CU for RCR 3 = .64
- Locate the RCR value of 4 under the RCR column
  - CU for RCR 4 = .57

- Subtract the smaller CU from the larger
  .64 - .57 = .07
- Multiply the result by the decimal portion of the RCR
  (.07) x (.82) = .06
- Subtract the result from the larger CU
  .64 - .06 = .58
- CU for RCR 3.82 = 0.58

The calculated CU of 0.58 is based on a 20% Floor Reflectance, while the Effective Floor Cavity Reflectance has been calculated as 15%. Since the Effective Floor Cavity Reflectance is not 20%, perform a calculation to determine if an adjustment should be applied to the original CU value. See Figure 15 for the Multiplying Factors for a CU and the calculations in Step 5.

Multiplying Factors for Other than 20 Per Cent Effective Floor Cavity Reflectance

% ECCR	80				70				50			30			10		
% WR	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10
For 10 Per Cent Effective Floor Cavity Reflectance (20 Per Cent = 1.00)																	
RCR																	
1	0.923	0.929	0.935	0.940	0.933	0.939	0.943	0.948	0.956	0.960	0.963	0.973	0.976	0.979	0.989	0.991	0.993
2	0.931	0.942	0.950	0.958	0.940	0.949	0.957	0.963	0.962	0.968	0.974	0.976	0.980	0.985	0.988	0.991	0.995
3	0.939	0.951	0.961	0.969	0.945	0.957	0.966	0.973	0.967	0.975	0.981	0.978	0.983	0.988	0.988	0.992	0.996
4	0.944	0.958	0.969	0.978	0.950	0.963	0.973	0.980	0.972	0.980	0.986	0.980	0.986	0.991	0.987	0.992	0.996
5	0.949	0.964	0.976	0.983	0.954	0.968	0.978	0.985	0.975	0.983	0.989	0.981	0.988	0.993	0.987	0.992	0.997
6	0.953	0.969	0.980	0.986	0.958	0.972	0.982	0.989	0.977	0.985	0.992	0.982	0.989	0.995	0.987	0.993	0.997
7	0.957	0.973	0.983	0.991	0.961	0.975	0.985	0.991	0.979	0.987	0.994	0.983	0.990	0.996	0.987	0.993	0.998
8	0.960	0.976	0.986	0.993	0.963	0.977	0.987	0.993	0.981	0.988	0.995	0.984	0.991	0.997	0.987	0.994	0.998
9	0.963	0.978	0.987	0.994	0.965	0.979	0.989	0.994	0.983	0.990	0.996	0.985	0.992	0.998	0.988	0.994	0.999
10	0.965	0.980	0.989	0.995	0.967	0.981	0.990	0.995	0.984	0.991	0.997	0.986	0.993	0.998	0.988	0.994	0.999

ECCR Effective Ceiling Cavity Reflectance
WR Wall Reflectance

Figure 15 – Table of Multiplying Factors
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Step 5: Determine if a correction factor is required for the CU value
The values shown below will be used for Table 15:
Effective Ceiling Cavity Reflectance = 80%
Wall Reflectance = 50%
RCR = 3.82

- Locate the column under the %ECCR heading of 80%
  Locate the column under the %WR heading of 50%, which is under the %ECCR column of 80%
- Locate the RCR value of 3 under the RCR column
  Value for RCR 3 = 0.951
- Locate the RCR value of 4 under the RCR column
  Value for RCR 4 = 0.958
- Subtract the smaller Value from the larger
  0.958 – 0.951 = .07
- Multiply the result by the decimal portion of the RCR
  (.07) x (.82) = .06
- Add the result to the smaller Value
  0.951 + .06 = 0.957
- Value for RCR 3.82 = 0.957

To determine the adjusted CU, multiply the previously determined CU, 0.58, by the adjustment factor, 0.957.

(0.58) x (0.957) = 0.56

(0.56) represents the CU value to be used in the design calculations.

Step 6: Determine the Lamp Loss Factors (LLF)
There have been many different types of light loss factors used over the years to help determine an adequate light loss value to be included in lighting calculations. Even lighting software packages allow the user to modify these values because there is no exact science to determining all light losses. In addition, there have been vast improvements made in lighting which have rendered some of the old light loss factors as obsolete. For these reasons, and for the sake of simplicity, the light loss factors for this report will be as follows:

- Lamp Lumen Depreciation (LLD) is the depreciation of the lumen output of the lamp, determined by dividing the mean lamp lumens by the initial lamp lumens.

From the CU Table of Figure 10, an F32T8 lamp was the test lamp in the photometric report having an initial value of 2800 lumens. Based on the information in the Specifying Fluorescent Lamps section, the F32T8/SP lamp has a mean value of 2660 lumens.

LLD = 2660 lumens / 2800 lumens = 0.95

- Luminaire Dirt Depreciation (LDD) is the factor relating to how dirty an environment is, and how much it affects the performance of a luminaire. The process for determining the LDD as defined by IES can be complicated and subjective. The recommendation is to use one of the following categories to simplify the calculations.

  Clean Areas (Offices, schools, retail, etc.) = 0.95
  Medium Areas (Warehouses, light manufacturing, etc.) = 0.90
  Dirty Areas (Machine shops, heavy manufacturing, etc.) = 0.85

- Ballast Factor (BF) – the percentage of rated lumens that a lamp can be expected to produce when operated on a specific ballast. Up to date information is available from the Manufacturer's technical literature and ballast catalogs. Typical ballast factors are given in the Specifying Fluorescent Ballasts section, and are shown below:

  Low BF = 0.71
  Normal BF = 0.87
  High BF = 1.18

- LLF = (LLD)(LDD)(BF) = (.95)(.95)(.87) = 0.80

Step 7: Perform the Lighting Calculation
The values we have obtained thus far are:

- Required FC = 50 footcandles
- Area = 216 square feet
- Lumens / Fixture = (2-lamps x 2800) = 5600 lumens/fixture
- CU = 0.56
- LLF = 0.80
- Luminaire wattage = 55 watts

\# Fixtures = (FC x Area) / [(lumens/fixture)(CU)(LLF)]
\# Fixtures = (50 x 216) / [(5600)(0.56)(0.80)] = 4.3, say 4 Fixtures
FC = [(# Fixtures)(lumens/fixture)(CU)(LLF)] / (Area) = 47 FC

Lighting Power Density = (LPD) in watts / sq. ft.
LPD = total watts / square feet = (55 x 4) / 216 = 1.01 watts/sq. ft.

Step 8: Analysis of the Calculations
The lighting calculations used the exact fixture, lamp and ballast in the photometric report, and this arrangement is shown to adequately meet the required footcandle levels, as well as the ASHRAE 90.1 LPD of 1.02 watts/sq. ft. If the intent is to fully meet the energy code, the requirement to turn off the lights 30 minutes after a space has been vacated must also be met. The easiest way to do this is to install a wall mounted occupancy sensor by the door in lieu of a standard wall switch. So now the system has been calculated and designed to meet the required footcandle levels and ASHRAE 90.1. The Lighting Designer is still required to perform due dilligence on this design to verify if the results are in the Owner's best interests.

If the "Understanding Fluorescent Ballasts" section is revisited, it is found that using occupancy sensors with instant start ballasts is not recommended since it seriously degrades lamp life, and voids all warranties on the lamps. This would be a major flaw in the design, as manufacturer's recommendations for operation have not been followed. To correct the situation, a normal ballast factor program start ballast will be introduced into the calculations to determine if the lighting design is still acceptable. Since only the ballast type is changing, all design values will remain the same, except the wattage.

- Required FC = 50 footcandles
- Area = 216 square feet
- Lumens / Fixture = (2-lamps x 2800) = 5600 lumens/fixture
- CU = 0.56
- LLF = 0.80
- Luminaire wattage = 59 watts

\# Fixtures = (FC x Area) / [(lumens/fixture)(CU)(LLF)]

# Fixtures = (50 x 216) / [(5600)(0.56)(0.80)] = 4.3, say 4 Fixtures
FC = [(# Fixtures)(lumens/fixture)(CU)(LLF)] / (Area) = 47 FC

LPD = total watts / square feet = (59 x 4) / 216 = 1.10 watts/sq. ft.

By changing the ballast type to program start, the system watts increased to where the maximum allowed LPD has been exceeded and the results do not comply with the ASHRAE LPD of 1.02 watts/sq. ft. In order to reduce the system wattage for the luminaire, a low ballast factor program start ballast will be introduced into the design.

- Required FC = 50 footcandles
- Area = 216 square feet
- Lumens / Fixture = (2-lamps x 2800) = 5600 lumens/fixture
- CU = 0.56
- LLF = (0.95)(0.95)(0.71) = 0.64
- Luminaire wattage = 47 watts

# Fixtures = (FC x Area) / [(lumens/fixture)(CU)(LLF)]
# Fixtures = (50 x 216) / [(5600)(0.56)(0.64)] = 5.4, say 4 Fixtures
FC = [(# Fixtures)(lumens/fixture)(CU)(LLF)] / (Area) = 37 FC

LPD = total watts / square feet = (47 x 4) / 216 = 0.87 watts/sq. ft.

The implemented change has the system meeting the requirements of the energy code at 0.87 watts/sq. ft., but now the lighting level has dropped significantly below the required level of 50 footcandles. In order to raise the system lumens, 3500^{o}K, high lumen lamps will be introduced into the design.

- Required FC = 50 footcandles
- Area = 216 square feet
- Lumens / Fixture = (2-lamps x 3100) = 6200 lumens/fixture
- CU = 0.56
- LLF = (2915/3100)(0.95)(0.71) = 0.63
- Luminaire wattage = 47 watts

# Fixtures = (FC x Area) / [(lumens/fixture)(CU)(LLF)]
# Fixtures = (50 x 216) / [(6200)(0.56)(0.63)] = 4.9, say 4 Fixtures
FC = [(# Fixtures)(lumens/fixture)(CU)(LLF)] / (Area) = 44 FC

LPD = total watts / square feet = (47 x 4) / 216 = 0.87 watts/sq. ft.

This ballast/lamp combination now provides an acceptable result for meeting the energy codes, but the Lighting Designer must now make the decision of whether to accept the 44 FC, or to make further design changes to meet the required level of 50 FC.

Step 9: Analysis of the Scotopic effect to lighting levels (Optional)
When looking into the effects of scotopic lighting, the major goal is to determine the actual amount of light useful to human vision that is available in a given situation. This amount of light is referred to as the Visually Effective Lumens (VEL), or Pupil Lumens. As stated previously in the report, this is relatively new research taking place in lighting labs across the country. At this moment, the effects of scotopic lighting have not been endorsed by the IESNA, and have not been approved to be inclusive to any type of calculations or measurements. There is much to be said though for the many tests and actual installations that have shown there is possibly some merit to the scotopic effects. The following calculations have been included for informational and educational purposes only, in an effort to increase the awareness of this new research.

Scotopic / Photopic ratio (S/P) = 1.5 for a 3500^{o}K, High Lumen lamp
from Understanding Fluorescent Lamps, page 18

- Required FC = 50 footcandles
- Area = 216 square feet
- Photopic Lumens / Fixture = (2 x 3100) = 6200 lumens/fixture
- Scotopic Lumens / Fixture = (6200 x 1.5) = 9300 lumens/fixture
- CU = 0.56
- LLF = (2915/3100)(0.95)(0.71) = 0.63
- Luminaire wattage = 47 watts

Fixtures = (FC x Area) / [(lumens/fixture)(CU)(LLF)]
Fixtures = (50 x 216) / [(9300)(0.56)(0.63)] = 3.3, say 3 Fixtures

VEL = [(# Fixtures)(lumens/fixture)(CU)(LLF)] / (Area) = 46 FC
LPD = total watts / square feet = (47 x 3) / 216 = 0.65 watts/sq. ft.

Taking another step further, if two F32T8/SPX, 5000^{o}K lamps with (S/P) = 2.0 were used in the fixtures:

FC = [(3)(2 x 2800 x 2)(.56)(2660/2800)(.95)(.71)] / (216) = 56 FC
LPD = total watts / square feet = (47 x 3) / 216 = 0.65 watts/sq. ft.

And taking one final step, if two F32T8/SPX, 6500^{o}K lamps with (S/P) = 2.3 were used in ***only two*** fixtures:

FC = [(2)(2 x 2700 x 2.3)(.56)(2475/2700)(.95)(.71)] / (216) = 40 FC
LPD = total watts / square feet = (47 x 2) / 216 = 0.44 watts/sq. ft.

Jumping to a normal power factor ballast will provide the final results of:

FC = [(2)(2 x 2700 x 2.3)(.56)(2475/2700)(.95)(.87)] / (216) = 49 FC
LPD = total watts / square feet = (59 x 2) / 216 = 0.55 watts/sq. ft.

The lighting level has increased from a photopic level of 44 FC to a VEL level of 49 FC, and the number of fixtures has decreased by two, representing a 50% reduction in energy. In addition, even though two fixtures have been deleted from the original layout, the Space/Mounting Height Ratios indicated on the photometric report of Figure 10 will not be exceeded.

As the calculations indicate, there are substantial footcandle levels available using this technique, but this is strictly for informational purposes only. It is recommended that if this technique is used, a mock-up of a typical space be built to test the validity of the calculations. Using a light meter in this situation will be meaningless, as the meter will only pick up the photopic lumens. If a light meter is used, it should bring up questions as to how a particular space can look just as bright using two less fixtures as the same space using four fixtures, and the meter reading indicating less lumens. It all comes down to the perceived brightness, past experience, knowing the room characteristics and reflectances of the surface areas, and then performing due dilligence to come up with a design that meets the Owner's requirements and applicable codes and standards.

AVOID THE PITFALLS IN LIGHTING DESIGNS

The following is a checklist of items to verify or keep in mind when performing lighting calculations, as they can seriously affect the desired outcome or correct operation of the lighting system. Several quotes have been taken from the report and a brief recommendation follows each item for further explanation.

1. The apparent color of an object is dependent upon the available light source.
   Be aware of the CCT of the lamp, the colors in the space, and how you want the brightness to be perceived. Also, do not use high CCT lamps at low light levels, and do not use low CCT lamps at high light levels.

2. The secondary colors (yellow, cyan, and magenta) will be perceived to be brighter than the primary colors because there will be at least two sets of cones sensitive to these colors in an object.
   Use a primary color and a secondary color together to create a high sensitivity in the cones. For example, a red color object located adjacent to a yellow color object viewed under a 3000^{o}K lamp can create a dramatic effect. Similarly, use a blue object and cyan, or magenta, object under a 4100^{o}K lamp. High contrast ratios should also be avoided; do not have light materials adjacent to dark materials.

3. The maximum efficacy (the power to produce the effect of vision) over the wavelengths for the three cones has been found to be 683 lumens/watt at a wavelength of 555 nanometers. This wavelength is in the yellow/green region, and is a major reason why the new safety vests worn by highway workers are this color.
   If you are trying to make a statement, incorporate this color wavelength into your objects to definitely be noticed.

4. It is a fact that rods are more sensitive than cones to bluish-white light sources, characteristically found in the higher color temperature lamp sources. In addition, the higher the color temperature, the more the rods are activated and the higher the perceived brightness in a space.
   Remember that spaces lit with higher color temperature lamps are perceived to be brighter, even though there will be less footcandles. Areas with daylighting should use 5000^{o}K lamps, minimum.

5. Obtain actual reflectances from manufacturers for ceiling tiles, paints, floors, carpets, etc. so they can be incorporated into the lighting calculations.
   It is critical to obtain the actual reflectances of materials, so the calculated lighting levels will be close to the actual levels.

6. General Electric T8 Watt-Miser lamps and F28UMX lamps are intended for use only with instant start ballasts. They can be used on program start ballasts, but only if using the GE Ultrastart ballasts, but no other manufacturer. Watt-Miser, F28T8, F32T8/25W and energy efficient lamps are intended for use where ambient temperatures are 60^{o}F or higher. Lower temperatures could result in reduced life, poor starting and erratic behaviour. These same lamps are also not recommended for dimming systems.
   The GE energy efficient lamps will work on any instant start ballasts, but are fine tuned to operate correctly only on the GE program start ballasts. Due to these and other nuances, the Lighting Designer may find it more beneficial to specify standard type T8 lamps and adjust the type of ballast and the lumen output of the lamp in order to meet lighting levels and energy requirements, instead of using energy saving lamps. There are several issues with the energy saving lamps; they could cause more problems than they solve in certain situations.

7. It is imperative that a complete and comprehensive description of the lamp be included in the lamp description column on the Luminaire Schedule that matches the type used in the lighting calculations.
   In order to avoid issues as listed above, include a complete description of the lamp on the drawings and in the specifications, and verify the final lamp installed against the approved shop drawings.

8. If a ballast is not specified on the drawings or the specifications, then the instant start ballast will typically be provided since it is the least costly.

Same issue with the ballast as the lamp, include a complete description to match what was included in the lighting calculations. With the stricter requirements for lighting controls coming out in the new energy codes, there are now fewer places where instant start ballasts can be used. It may be in the Lighting Designer's best interests to avoid using instant start ballasts at all (except for those areas listed in the energy codes that do not require automatic switching), so that this type of ballast does not have to be stocked by the Owner.

9. Instant start ballasts provide about 7,000 to 13,000 starts before 50% lamp failure. For this reason, T8 lamps that operate on instant start ballasts should not have occupancy sensors or electronic controls switching the lamps. The frequent switching will significantly affect lamp life and void the lamp warranties. *This is perhaps the biggest reason to avoid using instant start ballasts.*

10. Use the different combinations of lamps and ballasts in order to obtain the desired footcandle levels and the required watts / square foot. This could involve using high lumen lamps with low ballast factor lamps to meet high footcandle levels with low energy requirements.
As stated previously, using this method will allow the Lighting Designer to fine tune the design using standard lamp/ballast combinations to achieve the desired outcome for lighting levels and lighting power densities. Make every attempt to standardize on one type of ballast and one type of lamp. This will result in less lamps and ballasts the Owner will have to stock.

To improve the lighting quality of a system, perform the following:

- Select fixtures that hide the lamp and distribute light by reflection, refraction or diffusion.
- Place light sources in coves, valences or troughs.
- Use indirect lighting fixtures; 10' ceiling height is ideal, 9' is acceptable.
- For 8' ceiling height, use recessed direct/indirect fixtures, or integrate indirect fixtures into the furniture.
- Use lamps with a focused beam spread for accent lighting.
- Limit the use of recessed fixtures that direct a majority of light to the floor, which include troffers and can downlights.

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