Electrical Tech Note — 341

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Lamps & Lighting Design

Introduction: Light is electromagnetic radiation that travels in the form of waves. It is visible radiant energy that travels through air or a vacuum at a speed of approximately 186,000 miles per second or 3×10^8 meters per second. It will only travel through certain materials, and it's velocity will be different through different materials. Light is a narrow band of wavelengths of electromagnetic waves that can stimulate two types of specialized receptors in the eye. The unit of measure of the wavelength of visible radiant energy is the nanometer (nm). One nanometer is one thousand-millionth of a meter (1×10^{-9} m). Electromagnetic energy that is considered visible light to humans is in the wavelength range of 380 nm to 760 nm. Wavelengths shorter or longer than this range do not stimulate receptors in the eye and the result is darkness.

Color Vision: White light to the typical human eye is a distribution of wavelengths across the visible radiant energy spectrum. Directing a beam of white light containing every wavelength of electromagnetic radiation between 380 nm and 760 nm at an angle to one surface of a glass triangular prism and the light beam will be subdivided so that each wavelength will be projected onto a different point on a white target beyond the prism as shown in Figure 1. The beam of light will bend as it passes from the air into the glass. The shortest wavelengths (violet) will bend the most. Long wavelengths (longer than 630 nm) will appear red. Short wavelengths (shorter than 490 nm will appear blue or violet). Wavelengths in the range of 490 nm to 560 nm will appear green. If the distribution of wavelengths of a light source is uneven, the eye will interpret this uneven distribution of wavelengths as a color.

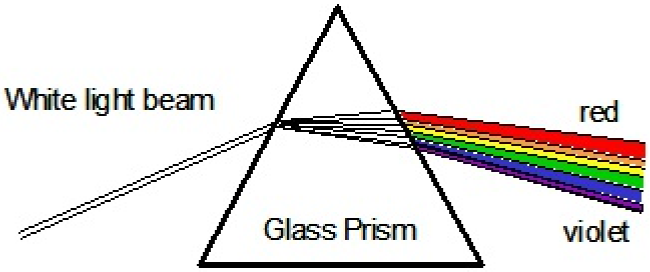

Figure 1 Light travels at different speeds through different materials such as air and glass. If light passes from one material to another at an angle, the light beam will bend with short wavelengths bending more than long wavelengths. The light will be subdivided into individual colors. The distance each color travels through a prism is different so the various colors cannot recombine to from white light again when they emerge from the prism. The result is the projection of a spectrum of colors that are in the light beam striking the prism.

If an object is illuminated by a light source that has an even distribution of all wavelengths, that object will appear white if it evenly reflects all wavelengths of light striking the surface. If some of the wavelengths of light striking an object are absorbed by the object and not reflected, the object will have a color depending upon how the eye interprets the wavelengths reflected.

An object will appear the color of light reflected. If an object transmits light it will appear a color if some of the wavelengths are absorbed by the object. In this case, the object appears the color of light transmitted. This is how color filters work. The filter absorbs all wavelengths except the color transmitted.

The eye receives all of the wavelength of light reflected or transmitted by an object and interprets the wavelengths and their intensity as a single color. If the eye sees an even distribution of all wavelengths, it will see the object as white. If the object reflects mostly red light such as for a tomato shown in Figure 2, the eye will see the tomato as red. Examination of a color picture in a newspaper using a 10X magnifier will reveal that each color is made up of color dots not necessarily the color the eye sees.

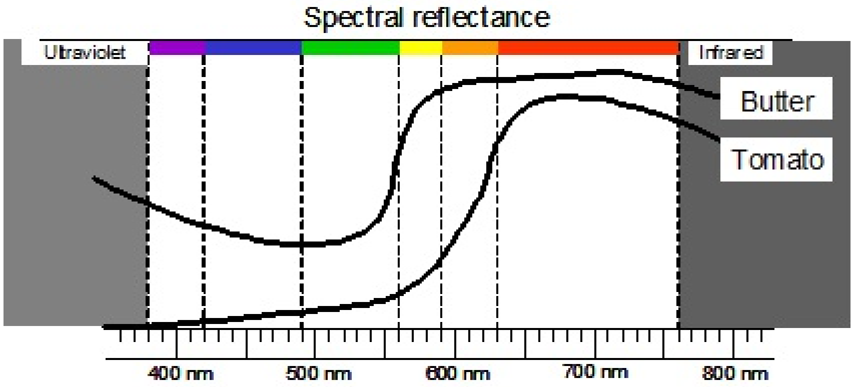

Figure 2 The light received from an object by the eye is usually a wide range of wavelengths of different intensities. The eye will interpret these wavelengths as a single color hue such as yellow for butter and red for a tomato.

How the Eye Works: Light entering the eye is projected by the lense onto the retina. The retina is a thin layer of material attached to the back of the eye and contains specialized nerves that are excited by electromagnetic radiation in the visible range of wavelengths. The radiant energy is converted to electrochemical impulses that are transmitted to the brain by means of the optical nerve. The brain interprets these electrochemical impulses as an image.

There are two types of light sensitive nerves in the retina. One type can distinguish different radiant energy wavelengths, and are responsible for seeing color. These nerve endings are called **cones** because of their shape. The central portion of the retina is made up mostly of cones. Cones are quite scarce on the outer edges of the retina. A different type of nerve is very sensitive to light levels, but cannot distinguish color. These nerve endings are called **rods** because they are long and slender. Rods are especially useful at night when light levels are low. Rods can only see black and white, but they are very sensitive so they can distinguish slight changes in light level often because an object moves. The outer portion of the retina is made up mostly of rods and there are very few in the center. A person looking at a faint object through a telescope often looks to the side of the object to direct the image onto the sensitive rod nerve endings of the retina.

The eyes of animals and other creatures cannot be assumed to be the same as humans. The eyes of various creatures will be specially adapted to perform necessary functions for survival. Some but not all insects have eyes sensitive in the ultraviolet portion of the electromagnetic spectrum. These insect are attracted to ultraviolet bug zappers. These insects are generally blind to the long wavelengths of the visible spectrum such as yellow, orange, and red. The eye of a chicken tends to be most sensitive to longer wavelengths such as red and are nearly blind to blue and violet light. Instruments designed to measure light levels for humans are probably of little value when measuring light levels for other creatures.

Color: All color hues can be created by projecting varying intensities of three primary colors onto a white background. If all three colors are projected onto the same spot with the same intensity, white is produced. Color television works by illuminating three primary colors in varying intensities. These **primary additive colors** are **red**, **green**, and **blue**. These same colors are used for lighting on a theatrical stage. In order for objects to look their natural color, the light source illuminating them must have an even distribution of these primary colors. This is why the same object will appear a different hue when lighted with different sources. Special attention must be given to the type of light source used for color television and photographic studios.

Red, green, and blue are called primary additive colors because they can be added together to form another set of primary colors called the subtractive primaries. Shining red and green on the same spot will create yellow. The eye still sees red and green, but it averages the wavelengths and the brain interprets the result as yellow. Shining red and blue on the same spot creates the color magenta. Green and blue shining on the same spot creates the color cyan. **Yellow, magenta, and cyan** are called the primary subtractive colors. The primary colors are illustrated in Figure 3. When mixing paint, or for color printing, these three subtractive primary colors can be used to create all other color hues.

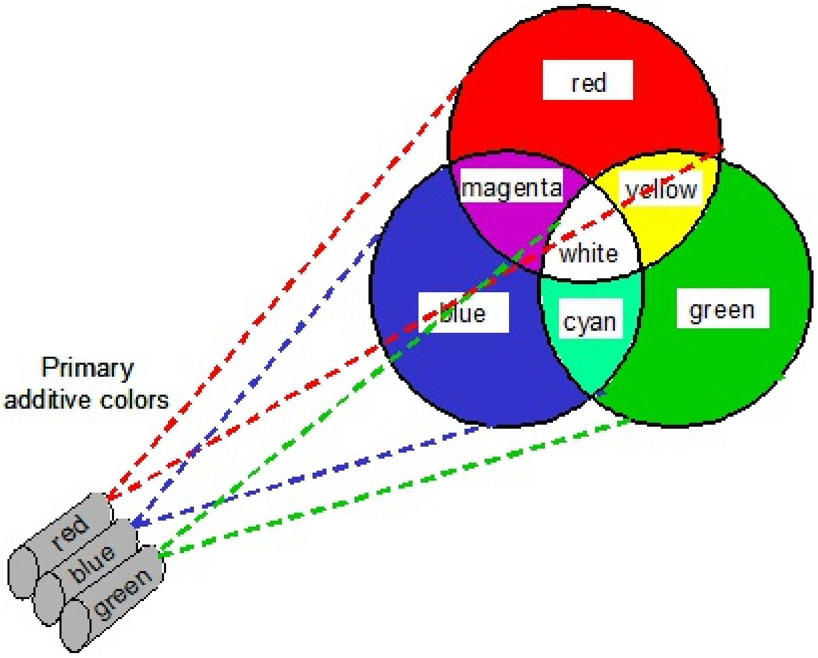

Figure 3 Any color hue can be created by projecting the three primary additive colors in varying intensities onto a white screen. The primary additive colors are red, green, and blue.

To study the primary subtractive colors, imagine a white light shining through a yellow filter. All colors are present in the white light beam, but the yellow filter will absorb all colors except red and green which are permitted to pass through the filter. Now place a cyan filter in the light beam leaving the yellow filter as shown in Figure 4. The cyan filter will allow green and blue to pass through. Since the light beam leaving the yellow filter only contains red and green light, there will only be green available to pass through the cyan filter. An observer looking at the white light through a cyan and yellow filter will see the primary additive color green. Looking at a white light through a magenta and yellow filter, the observer will see the primary additive color red. Looking at the same white light through a cyan and magenta filter, the observer will see the primary additive color blue. Theoretically mixing the three primary subtractive colors in equal quantity should result in black since all colors are absorbed. In real life this turns out to be a dirty brown, so in painting or color printing, black must be used to get true black. Color printing then involved printing four times, once with each of the three primary subtractive colors and black.

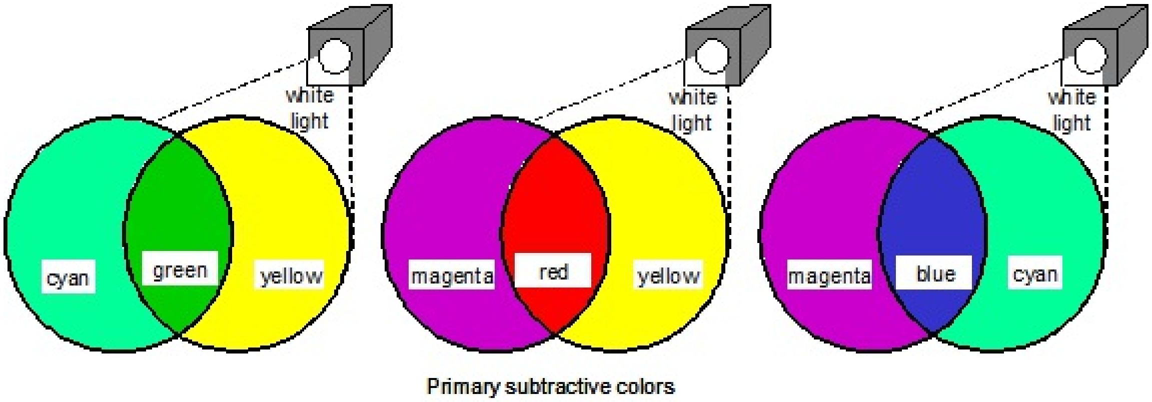

Figure 4 The primary subtractive colors are yellow, magenta, and cyan. By passing light through primary subtractive filters, the three primary additive colors can be recreated from a white light beam.

Color Temperature: All objects will produce light if heated to a sufficiently high temperature and the color will change as the temperature changes. A special type of object called a blackbody radiator will emit a specific color at a certain temperature. At 800°K (980°F) a blackbody will emit red light. At 3000°K (4940°F) the blackbody emits yellow light and at 5000°K (8540°F) it emits white light. Figure 5 shows the light produced by a typical incandescent light bulb. Note that much of the energy emitted by the light bulb is in the infrared (heat) part of the spectrum. As the temperature of the lamp filament is increased, more of the radiant energy is produced in the visible part of the spectrum with an increase of blue and violet light. The incandescent lamps in Figure 5 can be compared to blackbody emissions to see what temperature the blackbody would be to have a similar radiant output. This is called the apparent color temperature. This means the incandescent lamp on the left in Figure 5 would have a radiant output similar to a blackbody operating at 3000°K (4940°F). The filament of an incandescent lamp is made of the metal tungsten which has a melting point of 3683°K (6170°F). The melting point of the filament limits the maximum color temperature that can be achieved.

Light Sources: Light is produced in different ways and the different sources do not generally contain a even distribution of wavelengths across the visible electromagnetic spectrum. Absence of certain wavelengths in the light from a source will affect the color of an object. A tomato will not appear red if the light source does not contain wavelengths longer than 630 nm. When color is important, it is important to know the wavelengths produced by the lamp. For practical illumination, there are several basic types of light sources used. These are incandescent, fluorescent, high intensity discharge, light emitting diode (LED), and induction fluorescent lamps.

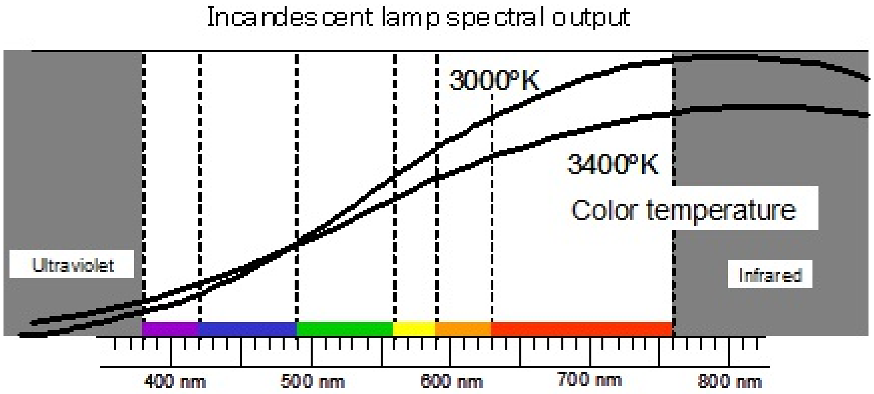

Figure 5 The radiant energy output of an incandescent lamp contains a more even distribution of light as the operating temperature of the filament increases. The apparent color temperature of a lamp means the radiant output of the lamp in the visible part of the spectrum is similar to a blackbody at that temperature.

An **incandescent lamp** has a high resistance tungsten filament that is heated to the point where the output includes all wavelengths of the visible spectrum. Typical examples are shown in Figure 5. The filament is contained within a protective transparent envelope such as a glass bulb or a quartz tube. The space within the envelope is either a vacuum or sometimes it is filled with an inert gas. Even though the filament is operating well below the melting point, it does tend to evaporate at such a high temperature and the inert gas puts pressure on the filament and tends to retard evaporation. Another way to deal with filament evaporation is to introduce iodine vapor into the envelope. The envelope will be quartz rather than glass. The iodine combines with the tungsten when it evaporates to form a substance that will not stick to the quartz envelope. The tungsten actually is redeposited back onto the filament. These lamps are called **tungsten-halogen** or **quartz-halogen** lamps. They can be operated at a higher filament temperature than an ordinary lamp which gives better color. They also have a longer life than ordinary incandescent lamps. An ordinary incandescent lamp has a life of about 1000 hours. A quartz-halogen lamp typically has a life of about 2000 hours.

Incandescent lamp life decreases as filament temperature is increased. Long life incandescent lamps will operate at a lower temperature and will produce a higher amount of red light than standard incandescent lamps. An effort to improve color output of an incandescent lamp usually results is a shortened lamp life. Increasing the operating voltage of the incandescent lamp will increase the current flow through the filament which results in a higher filament operating temperature and shorter lamp life. Light output of the lamp will also increase as well as the power use. Figure 6 shows the effect of change in voltage on life, light output, and power use for a typical incandescent lamp that is rated to operate at 120 volts. Note the dramatic change in life with only a small change in operating voltage. Many electrical systems operate at 125 volts which will decrease the operating life of incandescent lamps. A method of increasing lamp life is to use incandescent lamps with a rated voltage higher than the actual circuit voltage. This will result in the lamp operating at less than its operating voltage. Incandescent lamps are available rated for operation at 130 volts. A typical circuit providing 125 volts will be less than the lamp rated operating voltage and the result will be a significant increase in life, with some decrease in light output.

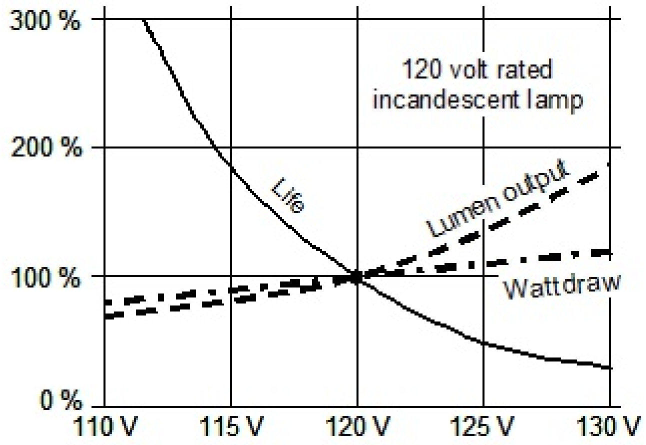

Figure 6 The graph represents the percentage change in life, power use, and light output with a change in voltage for an incandescent lamp rated 120 volts. Life is dramatically decreased when the lamp is operated with only a small over voltage, and dramatically increased with only a small under voltage.

A **fluorescent lamp** uses a completely different concept in producing light than an incandescent lamp. An electrode is placed at each end of a tubular glass envelope filled with argon gas and mercury vapor that will ionize to permit current flow when there is a sufficient voltage difference between the electrodes. The current flow energizes the mercury atoms and they produce primarily ultraviolet radiation. The inside of the glass envelope is coated with crystals of phosphor which produce visible light when energized by ultraviolet radiation. The phosphor converts the ultraviolet radiation into visible light. This process works efficiently when the ambient temperature is above 10°C (50°F). At low temperature, high voltage is required to strike the arc, and the lamp must be enclosed to trap a warm layer of air around the glass envelope.

A simple rapid start fluorescent lamp circuit is shown in Figure 7. An arc will strike between the lamp cathodes if there is sufficient voltage. By heating the electrodes the arc will strike at a lower voltage. Once the arc strikes, the resistance to current flow inside the lamp decreases and the current will increase to the point where the lamp will fail. A device called a ballast is used in a fluorescent lamp circuit to limit the current to a set level, often 350 to 400 mA. Fluorescent lamp light output can be increased by increasing the current flow, but a lowered life is the trade-off. High output lamps are designed to operate in the range of 800 to 1500 mA. The inductive reactance of the ballast coil serves as a choke to limit current flow. Most ballasts also operate as transformers to increase the voltage applied to the lamp electrodes. The ballast in Figure 7 is an autotransformer type that operates at 60 Hz. It is considered to be an electromagnetic (EM) ballast or a reactor type ballast.

Electronic ballasts are widely used that convert the 60 Hz alternating current to direct current, then produce high frequency current (20 kHz to 60 kHz) to operate the lamp. The fluorescent lamp will produce about 10% more light with the same energy consumption when operated above 20 kHz as compared to operation at 60 Hz. A heavy autotransformer is no longer required. Electronic components can respond to different operating conditions. In addition to being slightly more efficient, electronic ballasts are lighter in weight than reactor ballasts. Fluorescent lamps operated with electronic ballasts are now available that will operate at a temperature as low as -20°F, although at this low temperature they will produce little light at first until the lamp gets warm.

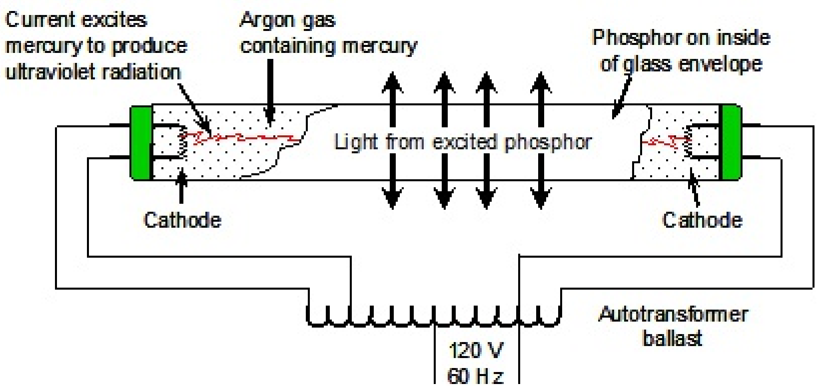

Figure 7 An autotransformer in this rapid-start fluorescent circuit heats the cathodes at each end of the lamp and an arc will strike through the argon gas and mercury vapor. The current flow, limited by the ballast to about 400 mA, energizes the mercury atoms which then emit ultraviolet radiation. The ultraviolet radiation stimulates the phosphor coating on the inside of the glass envelope which then produces visible light.

The phosphor coating on the inside of the glass envelope of a fluorescent lamp produces light at all wavelengths of the visible portion of the spectrum, but some of the light is emitted at specific wavelengths and can be seen as bright violet, blue, green, yellow, and orange lines. Cool white fluorescent is a common color designation for fluorescent lamps and its spectral energy distribution across the visible part of the spectrum is shown in Figure 8. The cool white fluorescent lamp does not emit as much red light in comparison to the other colors. Red objects and other warm colored objects will not look their normal color when illuminated with a cool white fluorescent lamp. The composition of the phosphor can be formulated to produce a range of colors. A **deluxe** cool white lamp has phosphors added that produce extra red light as illustrated in Figure 9. This color designation should be used when the lamp is illuminating warm colored objects such as red. A fluorescent lamp with a similar spectral distribution that tends to do a good job of illuminating objects that are at the red end of the spectrum is a warm white fluorescent lamp.

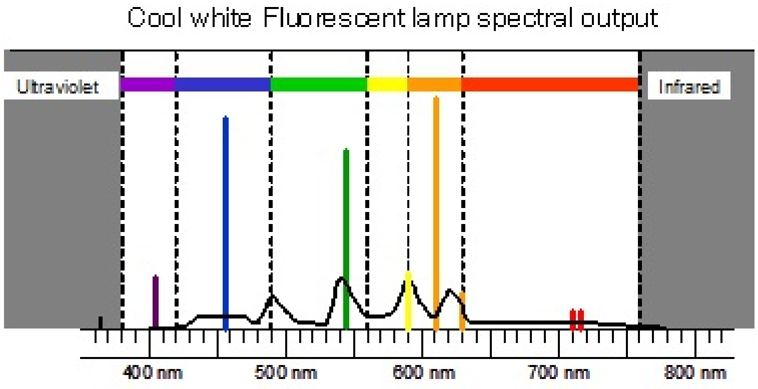

Figure 8 Spectral distribution curve for a cool white fluorescent lamp showing light emitted at specific wavelengths which is a characteristic of electric discharge lamps. In addition to a complete color spectrum, there will be a violet, blue, green, yellow, and orange bright line.

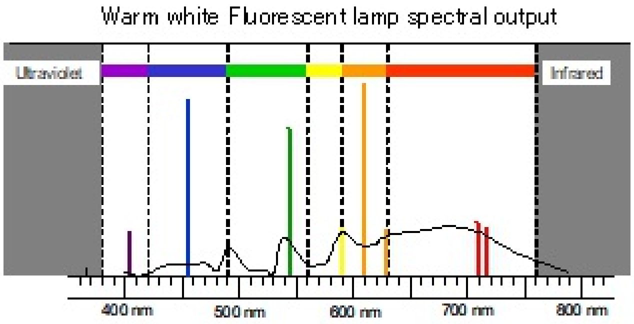

Figure 9 Spectral distribution curve for a deluxe cool white fluorescent lamp which produces an extra amount of red light compared to the output of a cool white fluorescent lamp.

A **high intensity discharge** lamp (HID) passes current through a gas containing a metal vapor such as mercury within an arc tube. This process is similar to that of the fluorescent lamp except the vapor is contained in a small arc tube, and after a warm-up period, the vapor pressure builds to a higher level than for a fluorescent lamp. Where the mercury vapor in a fluorescent lamp emits most of the energy in the non-visible ultraviolet portion of the spectrum, the higher operating pressure results in much of the radiation being emitted in the visible portion of the spectrum. Since light is produced in a small arc tube, the lamp is fitted with a glass envelope and a mogul screw shell base. A special fixture is required that produces the proper voltage for striking the arc in the lamp and limiting the current flow. The ballast must be matched to the type of HID lamp and the wattage. A major advantage of HID lamps is their compact size and ability to start and operate at low temperatures. HID lamps have a long operating life, generally in excess of 10,000 hours. Most HID lamps are highly efficient, with very high output with low power requirements. A disadvantage is the warm-up period required before they will reach full light output. They are not suited for locations where light is required immediately. Another disadvantage is the restrike problem. Once the lamp has reached full light output, the pressure in the arc tube is too high to permit the arc to restrike if there is a power interruption to the lamp. A room lighted only with HID lamps will likely be in darkness for up to several minutes until the arc tube cool enough to permit the arc to restrike. For many applications, some incandescent, LED, or fluorescent back-up lighting is required. There are several types of high intensity discharge lamps.

Mercury vapor is the least expensive type of HID lamp and fixture. Light output compared to power use for mercury vapor is good, but not as good as for fluorescent lamps. Visible light from a mercury vapor lamp is produced at specific wavelengths as shown in Figure 10 with bright emissions of violet, blue, green, and yellow. Absent in the spectral output of the mercury vapor lamp is an emission in the red portion of the spectrum. Red colored objects will tend to look brown when illuminated with a mercury vapor lamp with a clear bulb. The mercury vapor lamp emits radiation in the invisible ultraviolet portion of the spectrum. By coating the inside of the glass envelope with a phosphor, red can be added to the spectral output of the mercury vapor lamp. This is called a **deluxe** mercury vapor lamp. Because of the high mercury content in the lamp and the modest efficacy, mercury vapor lamps are no longer being produced. In a few years mercury vapor lamps will be replaced by more efficient and environmentally friendly light sources.

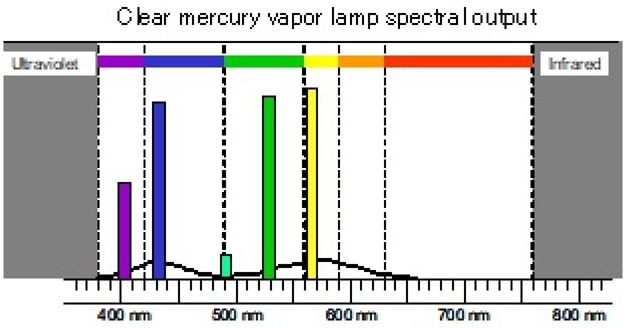

Figure 10 Spectral distribution curve for a mercury vapor lamp with a clear bulb produces light only at specific wavelengths of violet, blue, green, and yellow.

Another type of high intensity discharge lamp uses several types of metal iodide vapors in the arc tube to obtain a more even distribution of color across the visible spectrum. This **metal halide** lamp operates in a similar manner as the mercury vapor lamp. It is more expensive than a mercury vapor lamp, but it produces major emissions at specific wavelengths in the violet, blue, green, yellow, orange, and red portions of the spectrum with a broad range of smaller emissions across most of the spectrum. Objects tend to look a normal color when illuminated with this type of lamp. Light output tends to decrease with lamp life, and usually these lamps are replaced due to drop in light output rather than failure of the lamp. The spectral distribution of light over the visible part of the spectrum for a metal halide lamp is shown in Figure 11. The light output for power used is very high for metal halide lamps, usually higher than for fluorescent lamps of the same wattage. If power is interrupted after the lamp has obtained full brightness, the restrike time can be up to several minutes. Back-up fluorescent or incandescent lamps are required for some applications.

The arc-tube inside a metal halide lamp may rupture as the lamp nears end of life. This can result in rupture of the outer glass envelope and particles of broken glass showering the area below. To prevent the problem these lamps are not permitted to be installed in open fixtures unless they are rated type O which is built to prevent rupture of the glass envelope.

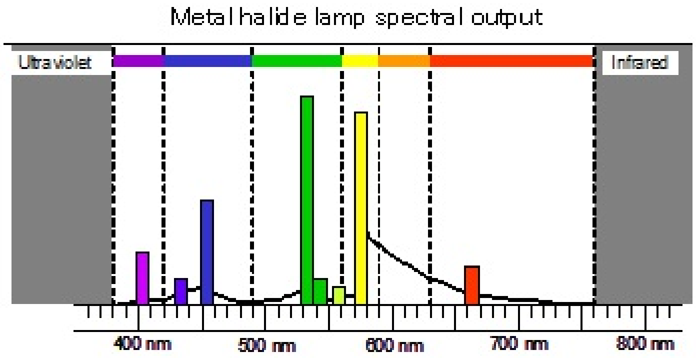

Figure 11 Spectral distribution curve for a metal halide lamp produces light at specific wavelengths in the violet, blue, green, and yellow portion of the spectrum with extra light produced in a range of wavelengths in the orange and red portion of the spectrum to give good color balance.

Sodium metal when vaporized and heated with electrical current will produce light, but only at two specific wavelengths very close together in the yellow portion of the visible spectrum. Object color will be nearly impossible to distinguish. The major advantage of this type of lamp, called **low pressure sodium**, is that it produces the highest light output of any lamp for the amount of power consumed. This type of lamp is not affected by cold weather. In the higher wattages, the lamps are quite large. A special fixture is required for low pressure sodium lamps. This type of lamp should only be used where it is not necessary to distinguish between colors. The spectral distribution for a low pressure sodium lamp is shown in Figure 12.

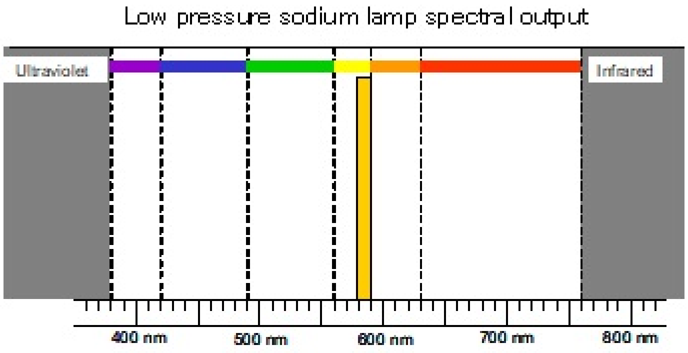

Figure 12 Spectral distribution curve for a low pressure sodium lamp with light only produced at two very close wavelengths in the yellow portion of the spectrum.

The development of a nearly transparent ceramic arc tube made it possible to energize a sodium vapor with electrical current at a higher pressure than was previously possible. The result was a wider distribution of wavelengths produced by the sodium vapor across the visible spectrum. This **high pressure sodium** lamp produces the major portion of the radiation in the orange, yellow, and green portion of the spectrum, with some light emitted in all portions of the spectrum. The color output of the high pressure sodium lamp is well enough distributed across the visible spectrum that it is suitable for a wide variety of general illumination applications. Because the lamp produces an excess of yellow and orange light, colors will be distorted to some extent, but most objects will nearly appear their natural color. The major advantage of the high pressure sodium lamp is an extremely high light output for the power used. Output is not as high as low pressure sodium lamps, but higher than any other lamp of comparable wattage used for general illumination. Restrike time is faster than any of the other HID lamps. A high pressure sodium lamp will restrike in about one minute or less when power is interrupted but back-up fluorescent, LED, or incandescent lamps are required for some applications. The spectral distribution for a high pressure sodium lamp is shown in Figure 13. If good color is important, there are high pressure sodium lamps made with what is known as a high CRI that have a better output distribution over the visible spectrum.

A **light emitting diode (LED)** is a solid state device consisting of a PN junction made of semiconducting silicon materials. When current passes across the PN junction, visible light is produced. Improvements in the LED in recent years has resulted in an ability to use it as an efficient and useful form of illumination. A device called a driver is used to convert the circuit 60 Hz ac current to direct current and to control the level of current through the LED. Efficacy is similar to that of fluorescent lamps, however, length of life is estimated at a minimum of 20,000 hours. LED sources are designed for specific purposes where the direction of light is carefully controlled by the design of the source or luminaire. This aspect of the LED as a light source results is high efficiency for task illumination. Light is directed to the area to be illuminated with minimal light lost due to scattering. It is important to prevent overheating of the actual LED source, so most LED lamps and luminaires are equipped with cooling fins that must be exposed to allow for open air movement.

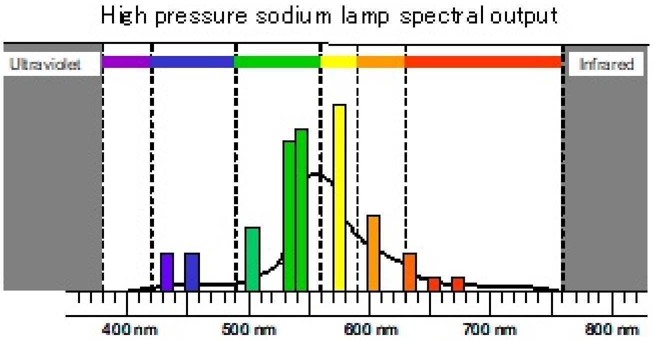

Figure 13 Spectral distribution curve for a high pressure sodium lamp with wavelengths emitted across the visible spectrum and an abundance in the yellow and orange portion of the spectrum.

LEDs produce light in specific wavelength bands depending upon their composition. Figure 14 shows the spectral distribution of light from an LED luminaire designed to replace a 2 ft by 4 ft fluorescent luminaire. There are several rows of individual LEDs that produce the light. LEDs for this type of application generally have a phosphor coating that produces light in the green, yellow, orange, and red portion of the spectrum. The LED itself produces visible light in the blue portion of the spectrum, as shown in Figure 14.

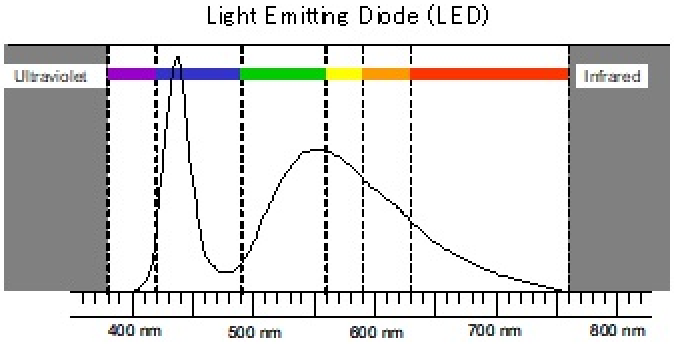

Figure 14 LEDs produce light in a narrow wavelength band and are often provided with a phosphor coating that produces light at other wavelengths. The peak to the left is produced by the LED while the emissions to the right are produced by a phosphor coating.

Fluorescent lamps can be made without electrodes, **electrodeless fluorescent**, which are usually the cause of lamp failure. The phosphor coating on the inside surface of the glass envelope of a fluorescent lamp is stimulated mainly by ultraviolet radiation to produce visible light. Common fluorescent lamps have an electrode at each end of the glass tube called cathodes. Electrical current passes directly from one cathode to the other through the filling gas. A small amount of mercury in this filling gas is stimulated by the current flow and produces the ultraviolet radiation necessary to stimulate the phosphor coating. In time these cathodes will fail and the lamp will no longer give off light. A new technique has been developed where high frequency current applied to a coil either inside or around a portion of the lamp creates the current flow in the filling gas without the need for electrodes. This type of lamp is called **induction fluorescent** or sometimes **electrodeless fluorescent**. Since there are no electrodes in the lamp that can fail, life of these lamps is estimated to be a minimum of 50,000 hours. Efficacy is claimed to be high, but not quite as high as the standard fluorescent lamp with electrodes. Light output is similar to that of ordinary fluorescent lamps as shown in Figures 8 and 9. Where fluorescent lamps are made of long tubes, these induction fluorescent lamps are more compact and generally donut shaped or oval shaped similar to that of an HID lamp. Some actually have a mogul screw shell base. Some have an external driver, although some have a self-contained driver. One caution is whether the high frequency (in the megahertz range) will have an effect in the immediate area of the lamp.

Lamp Color Quality: Color rendition index (CRI) gives an indication of how well a light source will represent colors. For example, if the light source has a high color rendition index it should be possible to distinguish the difference between two surfaces of nearly the same color hue. If the CRI is low, the colors may actually be different, but they will look like the same color. Even though incandescent lamps do not produce the different colors of light at the same intensity, they do produce every color across the spectrum and are generally considered to have a CRI of 100. The CRI scale ranges from zero to 100. A CRI of 60 to 75 is considered good, and above 75 is considered excellent. As discussed earlier in the Tech Note, other sources tend to produce light in narrow bands of wavelengths and sometimes little or no light of some wavelengths. As a result, it is difficult to distinguish between color hues when illuminated by some light sources. When proper color rendition is important it is necessary to choose a source with a high CRI. The lamp data tables at the end of this Tech Note provide the CRI as well as other important design information for typical lamps.

When selecting a light source that will properly represent colors, it is important to look both at the **correlated color temperature** (CCT) and the color rendition index (CRI). Sunlight at sunrise has a color temperature of about 2000°K, while sunlight at noon has a color temperature of about 4500°K. A bright overcast sky is at about 7000°K color temperature. A light source with a color temperature in the 4000's is best for illuminating cool colors such as green, blue, and violet, while a color temperature in the range of 3000°K to 3500°K works better for warm colors such as red, orange, and yellow. Generally fluorescent lamps use the terms "warm" and "cool" rather than giving a specific color temperature. After selecting the color temperature of the lamp, then select a source with the highest color rendition index possible at that color temperature. This will insure that different color hues are less likely to blend together so that one color hue can be distinguished from a sightly different color hue.

Terminology: The intensity of a light source in a particular direction is called **candlepower** and the unit of measure is the **candela**. An approximation of one candela is the intensity of an ordinary candle viewed from close range. Intensity decreases in proportion to the square of the distance from the source. Candlepower is not necessarily a measure of the amount of light produced by a lamp. It simply gives an indication of the intensity of light output from a lamp or luminaire in a particular direction. Figure 15 is a candlepower distribution curve for two reflector type lamps of the same wattage except one produces a narrow spot distribution and the other produces a wider angle flood distribution. Looking at the candlepower distribution curve for a lamp or luminaire is sometimes important when choosing the correct lamp or luminaire for an application.

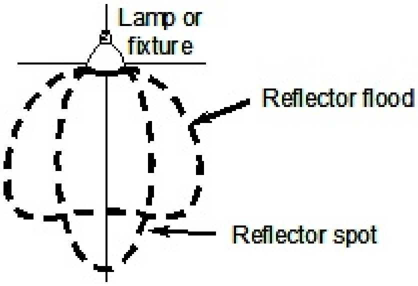

Figure 15 A candlepower distribution curve is a way of showing the direction light will be distributed from a lamp or a luminaire.

Amount of light or **luminous flux** is the time rate of flow of luminous energy or light. The unit of measure is the **lumen**. Since the lumen is a unit of time rate of flow of luminous energy, it is actually a unit of power where over the range of visible wavelengths, one lumin is approximately equal to 1.464 mW. Assume a light source is one candela and radiates light uniformly in all directions. One lumen is the amount of light flowing away from the source in a unit solid angle from the source. For example, assume a surface of one square foot is positioned such that all points on the surface are one foot from the one candela source as shown in Figure 16. The amount of light flowing within that solid angle is one lumen, and one lumen will be reaching the one square foot area. By moving out two feet from the source, the lumen will be projected onto a surface that is four square feet. If the surface is positioned one meter from the source, the lumen will be evenly distributed over a one square meter surface.

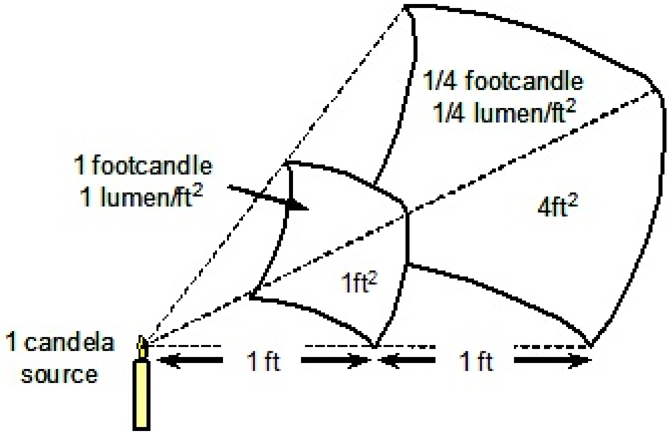

Figure 16 The luminous flux within the solid angle formed by a one square foot area located one foot from the one candela source is equal to one lumen.

Illumination is the result of a luminous flux falling upon a surface. Lamps and luminaires are installed to achieve a certain level of illumination. The conventional unit of illumination in the U.S. is the **footcandle**. A footcandle of illumination is achieved when one lumen is distributed over a one square foot surface. The metric unit of illumination is the **lux** which is one lumen per square meter. To convert footcandles to lux, multiply footcandles by 10.76.

Luminance is light leaving an area. The light may be transmitted through a material or it may be reflected from a surface. An illumination meter can be used to measure the light being received at a surface such as a wall. Aim the meter at the wall and measure the light leaving the surface. The meter is measuring the luminance of the wall. The unit of measure of luminance in the conventional measurement system is the **footlambert**. A footlambert is defined as one lumen leaving a one square foot surface. The metric unit of luminance is the **nit** which is one lumen leaving a one meter square surface. A **nit** is a much lower level of luminance than the footlambert by a factor of 0.0929.

Measuring Light: An illumination meter is needed when designing a lighting system for human applications. A light meter is placed at a location where a specific level of illumination is desired. In order to make a meaningful measurement, the light meter must be calibrated to have a wavelength response similar to the human eye. Figure 17 shows the sensitivity of the normal human eye to wavelengths of electromagnetic radiation across the visible spectrum. The normal human eye is most sensitive to light in the green and yellow portion of the spectrum. A selenium type photo cell has a sensitivity somewhat like the human eye, although it is more sensitive to violet, blue, and red than is the human eye as shown in Figure 17. If this selenium photo cell is used for making measurements it will tend to indicate higher levels of illumination than can be seen by the human eye. A filter can be added to the selenium photo cell so it will have a sensitivity nearly the same as the human eye. This is called a visual corrected photo cell. An illumination meter is calibrated to indicate the total light received in footcandles or lux. They are sometimes referred to as a footcandle or a lux meter.

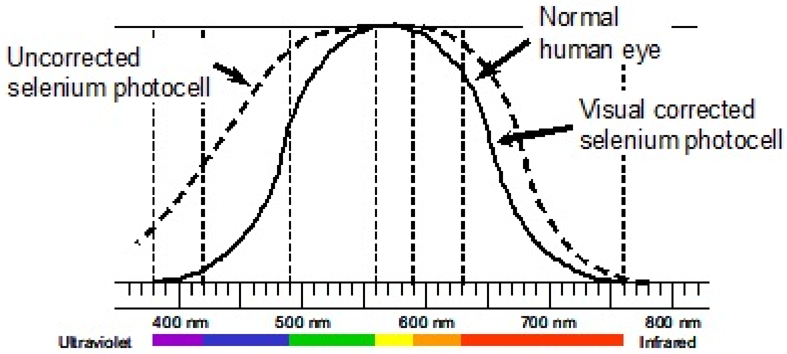

Figure 17 Spectral sensitivity curve for the normal human eye and for an uncorrected selenium type photo cell.

Light reaches a surface from all angels. Light may enter windows, or it may be reflected from light colored walls. Light reaching a surface from a wall is often being received from a low angle. The photo cell is mounted down inside a case for protection, and light coming at a low angle may be blocked from reaching the photo cell by the edge of the case. This problem can cause a significant error in the reading in some cases. A special **cosine corrected** meter can be used to avoid this problem. A cosine corrected meter will catch light being received at a work surface from a low angle.

Research has been conducted over the years to determine the optimum illumination level for different tasks. Building codes will specify a minimum illumination level for areas such as stairs. These are minimum levels found to be necessary for safety. An illumination meter is placed at the desired location, such as at a desk surface, and the person making the measurement must back away so as not to affect the reading. In all cases a significant amount of the light from a lamp is absorbed by the luminaire, or objects in the room and never reaches the work area where illumination is needed. A significant loss factor is reflectance from walls, ceiling, and floor surfaces. Light colors, such as white, on walls and ceilings will reflect rather than absorb light. A light meter can be used to make an estimate of the reflectance of a wall or ceiling surface.

Reflectance of a wall or ceiling can be estimated in percent by measuring the light being received and the light being reflected. It is best to use a visual corrected illumination meter that is not cosine corrected. Hold the illumination meter near the surface and measure the light being received. Next aim the photo cell at the surface and then slowly pull it away until the meter reading reaches a maximum. Make sure you do not stand in the light so as to affect the reading. To get the percentage reflectance, divide the light reflected by the light received using equation 341.1.

$$\text{Reflectance} = \frac{\text{Light reflected from surface}}{\text{Light received at surface}} \times 100 \qquad \textbf{Equation 341.1}$$

Transmittance of a surface can be measured in a similar manner as measuring reflectance by first measuring the level of illumination received at the top surface and then the level of illumination just below the surface. Divide the level of light transmitted by the level of illumination falling on the top surface.

Efficacy: When discussing efficacy there is a tendency to concentrate only on the light source and not the entire installation. It is important to choose a lamp with the highest efficacy that will satisfy the design criteria of the application. **Efficacy** for lamps is given in lumens per watt with typical values given in Figure 18. Efficacy varies widely for some types of lamps. Generally the higher the wattage the higher the efficacy. It is important to compare the initial cost of an installation with the cost for energy and maintenance. Lamp life is defined as the hours of operation when 50% of a group of lamps have failed when operated under specified conditions.

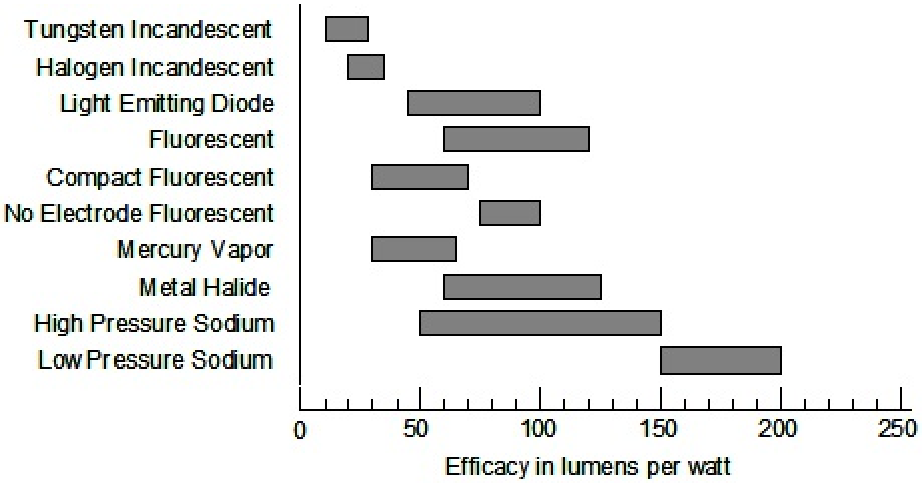

Figure 18 Lamp efficacy is given in lumens per watt. Incandescent lamps have the lowest efficacy while some fluorescent and high intensity discharge lamps have the highest efficacy.

The lumen output of a lamp is a unit of power since it is the rate at which luminous energy is being produced by the source. Efficacy is really efficiency except the units are lumens divided by power draw in watts. An approximate conversion is 1.464 mW per lumen.

Controlling Light: It is desirable to get as much of the light as possible from the lamp to the work area to be illuminated without creating negative effects. Light can be controlled and directed to the desired location using reflection and refraction. With refraction light passes through a transparent material with an irregular shaped pattern on one side to bend the light and send it in the desired direction. A refractor can have several patterns in order to obtain the desired light pattern in the work area. A disadvantage of a refraction material is that light is absorbed. Sometimes the absorption increases as the material ages.

Light can be controlled with reflection. Reflectors can be placed around a lamp that are designed to create a particular pattern in the work area. Rather than using a refractor, a reflector can be placed in front of a lamp to create the desired pattern. This technique is frequently used to reduce glare in rooms where people are working on computers. Indirect lighting uses reflection where the lamps are directed towards a wall or ceiling surface that is painted white. This is a good way to create a diffuse pattern with minimal glare.

Whatever method is used to control light, it is important to keep light absorption in mind. Getting the maximum amount of light from the lamp to the work area is a combination of the luminaire used and the room in which it is installed. Luminaires that prevent the entrance of dust is important in dirty industrial areas. If wall and ceiling surfaces cannot be used effectively as reflectors, then it is important to use luminaires that will direct the light to the work area.

Lamp Life: Typical values for lamp life are given in Figure 19. The electrodes in electric discharge lamps sustains some damage every time the lamp is started. Electric discharge lamp life is determined where the lamp is on for 10 hour periods, turned off, allowed to cool, then turned on for another 10 hours. If electric discharge lamps are turned on and off more frequently, lamp life will be shorter than the manufacturers rating.

LEDs produce light by passing electrical current through a small solid state device. Heat produced due to the current flow must be conducted away from the solid state device. LED sources must be installed according to manufacturer recommendations, or the source can fail prematurely due to lack of proper ventilation.

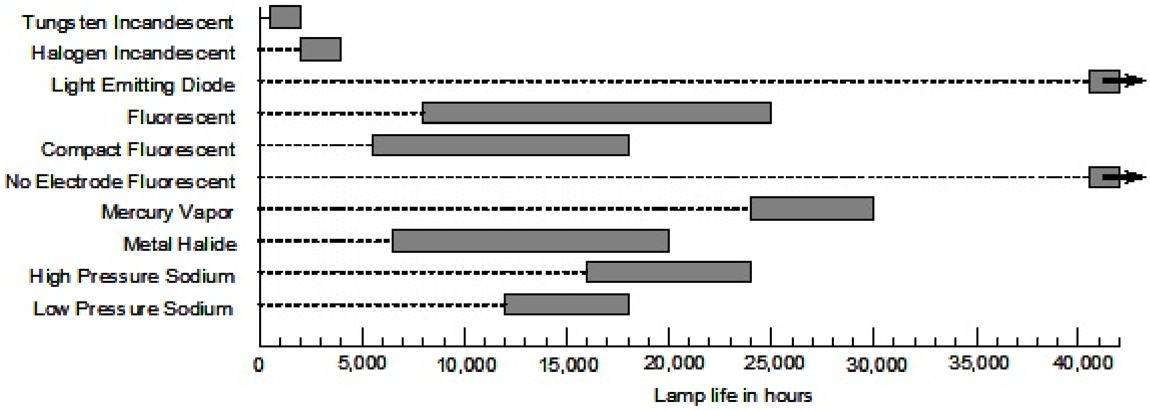

Figure 19 Lamp life is the average time until 50% of a test group of lamps fail under prescribed conditions . Incandescent lamps have the shortest lamp life. Electric discharge lamp life is reduced if the lamps are turned on and off frequently.

Quality of Light: Eye fatigue is frequently the result of poor quality light. Two important quality factors are contrast and glare. Contrast is the brightness of the object to be seen in comparison to the surrounding area within the field of vision. An example of poor contrast is looking at a dark object with a bright background such as a window. Because of the bright background, the iris of the eye closes to limit the amount of light entering the eye. The result is too little light to properly see the object. Eye strain can be caused by high contrast within the field of vision. For example, the top of a desk should be light colored rather than dark so there will be little contrast difference between the desk and papers laying on the desk. If there is considerable contrast on a work surface within the field of view, the iris of the eye will be constantly changing position due to slight head movements. This will cause eye fatigue.

Glare is a bright reflection of light in the field of view or a bright light shining in the eye within the field of view. A computer for example should be located such that light from windows, luminaires, and bright walls does not reflect from the screen into the eyes. Parabolic reflectors in ceiling luminaires will direct the light downwards rather than spreading it out across the room. This can help prevent reflection from computer screens. Luminaires with bright lamps in low ceilings can create a glare problem when a person is working at a desk. Reducing glare in the work place can help prevent eye fatigue.

Lamp Ratings: In addition to lamp wattage there are a number of other lamp ratings that are important for a design or installation. For most applications it is a good idea to accomplish the illumination level with the minimum wattage. The total wattage of the lamps in the area will be converted to heat. One watt is equal to one Joule per second or 3.14 Btu per hour. Electric discharge lamps have a ballast and the total wattage is 10% to 15% higher than the lamp wattage. Wattage will also give an indication of the number of luminaires that can be installed on a circuit. Typical circuits are rated 20 amperes and the electrical code allows the circuit to be loaded to 80% which is a maximum of 16 amperes. Electric discharge, LED, CFLs and induction luminaires will have the operating voltage and current marked on the ballast or driver. In the case of incandescent lamps and CFLs, the current draw must be calculated. Divide the total wattage of the lamp or luminaire by the circuit voltage to get the incandescent load current. For example, a luminaire that is rated for a maximum of four 60 watt lamps will have a total luminaire rating of 240 watts. Typical incandescent lamps are rated 120 volts, therefore, the luminaire will draw 2 amperes (240 watts ÷ 120 volts = 2 amperes).

Incandescent lamps will have a voltage rating marked on the lamp. Typical screw shell lamps are rated for operation on a120 volt or 240 volt circuit. Actual lamp ratings may be 120 volt, 125 volt, 130 volt, or 250 volt. A 130 volt rated lamp operated at 120 volts will give less than the rated light output, but it will have a longer than rated life. Electric discharge lamps such as fluorescent, high pressure sodium and the like will not have a voltage rating. They are made to fit a specific luminaire. The luminaire is rated to operate from circuits of various voltages. Typical circuit voltages for electric discharge lamps is 120 volts and 277 volts. A transformer in the luminaire provides the proper voltage to the lamp.

Essential for lighting design is to know the light output of the luminaire in lumens. Incandescent lamps are required to list on the package the wattage, lumen output, and average life in hours. If this information is not available on the lamp package, the distributor can provide a lamp catalog listing the light output and life of each type of lamp. This information is usually available on the web. The light output listed is generally the initial lumens. The lamp lumen depreciation is generally not a problem. Some metal halide lamps do have a high lamp lumen depreciation. It is a good idea to check lamp lumen depreciation when selecting metal halide lamps. Sometimes the manufacturer provides both the initial lumen and mean lumen output for a lamp.

Luminaire Ratings: Manufacturers will provide a considerable amount of design information about the luminaires they produce. A radiant distribution curve will give an idea of the pattern of light output from the luminaire. Another number provided for the luminaire is the coefficient of utilization. When providing luminaires for general illumination, a common method of designing the lighting is the zonal cavity method. The coefficient of utilization is the percentage of the light from the lamp that will reach the work surface for the particular type of luminaire used plus specific room factors such as wall and ceiling reflectance and luminaire mounting height.

Spacing to mounting height ratio is important when installing luminaires for general illumination. In some areas the luminaires will be required to be mounted in a specific location. In this case, for example, if the ceiling height is low, and the distance between rows is great, choose a luminaire with as high a spacing to mounting height ratio as possible to avoid dark areas between the rows of luminaires. Assume a room is to be illuminated with high pressure sodium luminaires that have a 1.2 spacing to mounting height ratio. If the distance from work surface to the bottom of the luminaire is 10 ft., the maximum luminaire spacing, center-to-center, to avoid dark areas is 12 ft.

Lighting Design: Many factors as discussed earlier must be considered in a lighting design. Assuming a type of lamp and luminaire have been selected for an installation, this section deals with the determination of the number of luminaires required to provide the desired illumination. This method assumes a relatively clean room with highly reflective ceiling and walls. Under these conditions only about one-third of the lamp lumens will reach the work surface. The minimum number of luminaires required can be determined using equation 341.2.

Equation 341.2

$$\text{Luminaires} = \frac{\text{Room Area} \times \text{Illumination Level}}{\text{Lumens per Lamp} \times \text{Lamps per Luminaire} \times \text{Light Loss Factor}}$$

Room Area	ft^2
Illumination Level	footcandles
Lumens per Lamp	lumens
Light Loss Factor	decimal number less than one

Example: An office area has a white ceiling and light colored walls and will be illuminated to a level of 50 footcandles. The room is 30 feet by 40 feet. The luminaires to be used will be four lamp fluorescent lay-in troffers in a suspended ceiling. The luminaires are 2 ft. wide and 4 ft. long. Each lamp has an output of 2800 lumens. The ceiling height from the work surface to the bottom of the luminaires is 8 ft. Assume the light loss factor to be 0.33 in this case. Determine the minimum number of luminaires required for this room.

$$\text{Number of Luminaires} = \frac{30\text{ ft.} \times 40\text{ ft.} \times 50\text{ fc}}{2800\text{ lumens} \times 4\text{ lamps} \times 0.33} = 16.2\text{ luminaires}$$

It will take 16 luminaires to achieve the desired level of illumination. Lets assume there will be two rows of 8 luminaires run end-to-end the long way of the room. If the room is 30 ft. in width, the spacing between the rows, center line to center line, should not exceed 8 to 10 ft. (1.2 × 8 ft = 9.6 ft.). Remember this is a suspended ceiling with 2 ft by 4 ft. ceiling tiles which will dictate the spacing of the luminaires. Running two rows the long way of the room will result in a row spacing of 12 ft. Consider running four rows of luminaires the short way of the room with four feet between the luminaires. This arrangement will result in a 10 ft row spacing. A sample layout of the luminaires in the 30 ft. by 40 ft. room is shown in Figure 20.

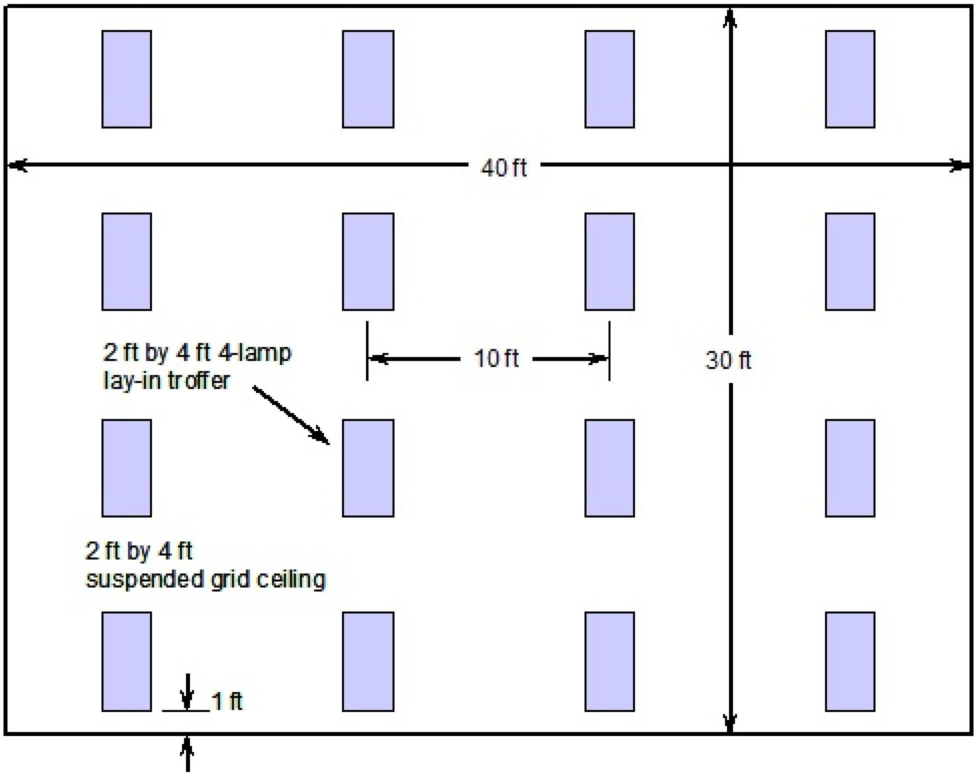

Figure 20 When laying out the luminaires for a room, consider the spacing to mounding height ratio to prevent dark areas in the room. When mounting luminaires in a suspended ceiling grid, the grid layout will be an additional constraint that must be considered in the layout.

Example Lamp Information: The following data for common lamps are averages based upon manufacturer's data. Lamp price information is only approximate and can be highly subject to change.

Table 341.1 Medium Screw Shell Base Lamps (Various color temperatures are available for compact fluorescent lamps.)

Lamp Type	Watts (W)	Mean Lumens (Lm)	Avg. Life (hrs.)	Efficacy (Lm/W)	Color Temp. (°K)(CCT)	Color Index (CRI)	Est. Cost ($)
Inc. - Tungsten	25	215	2,500	8.6	-------	100	2.26
Inc. - Tungsten	40	505	1,000	12.6	-------	100	0.65
Inc. - Tungsten	60	865	1,000	14.4	-------	100	0.63
Inc. - Tungsten	75	1190	750	15.9	-------	100	0.63
Inc. - Tungsten	100	1710	1,000	17.1	-------	100	0.63
Inc. - Tungsten	150	2780	750	18.5	-------	100	3.30
Inc. - Tungsten	200	3910	750	19.5	-------	100	3.57
Inc. - Tungsten (R30)	65	755	2,000	11.6	-------	100	5.95
Compact Fluorescent (R30)	15	750	10,000	50.0	-------	------	6.12
LED (PAR30)	12	554	35,000	46.2	2900	87	6.12
Inc. - Halogen	60	840	3,000	14.0	soft white	100	6.12
Inc. - Halogen	95	1490	3,000	15.7	soft white	100	6.56
Compact Fluorescent (25)	7	400	10,000	57.1	-------	------	4.58
Compact Fluorescent (40)	10	520	8,000	52.0	2700	------	3.77
Compact Fluorescent (60)	15	950	8,000	63.3	2700	------	5.37
Compact Fluorescent (75)	20	1260	8,000	63.0	2700	------	5.37
Compact Fluorescent (100)	26	1750	12,000	67.3	2700	------	6.45
Compact Fluorescent (150)	42	2700	10,000	64.3	2700	------	22.39
Compact Fluorescent (200)	55	3570	10,000	64.9	2700	------	11.84

Table 341.2 Double Ended Fluorescent Tube Lamps. (Add 15% to lamp wattage to account for ballast losses. T8 and T5 lamps are with electronic ballasts. Available in a variety of color temperatures.)

Lamp Type	Watts (W)	Mean Lumens (Lm)	Avg. Life (hrs.)	Efficacy (Lm/W)	Color Temp. (ºK)(CCT)	Color Index (CRI)	Est. Cost ($)
Fluorescent, T12, 48"	34	2,750	20,000	70.3			
Fluorescent, T12, 48"	40	3,200	20,000	69.6			
Fluorescent, T12, 96"	75	6,500	12,000	75.3			
Fluorescent, T12, 96", HO	95	8,000	12,000	73.2			
Fluorescent, T8, 48"	32	2,800	42,000	76.1			
Fluorescent, T8, 96",	59	5,800	20,000	85.5			
Fluorescent, T8, 96", HO	86	8,000	18,000	80.9			
Fluorescent, T5, 45"	28	2,900	36,000	90.1			
Fluorescent, T5, 45", HO	54	5,000	36,000	80.5			
Fluorescent, T5, 57"	35	3,650	36,000	90.7			
Fluorescent, T5, 57", HO	80	7,000	36,000	76.1			

Table 341.3 Low Pressure Sodium and Tubular Quartz Halogen Incandescent Lamps. (For HPS lamps, the higher value listed is the total luminaire wattage and the lower value is the rated lamp wattage. Lamps marked with * are medium base screw shell.)

Lamp Type	Watts (W)	Initial Lumens (Lm)	Avg. Life (hrs.)	Efficacy (Lm/W)	Color Temp. (ºK)(CCT)	Color Index (CRI)	Est. Cost ($)
Inc. - Quartz Halogen	300	5,950	2,000	19.8	-----	100	6.89
Inc. - Quartz Halogen	500	10,550	2,000	21.1	-----	100	8.85
*Inc. - Tungsten PAR38	75	950	2,500	12.7	-----	100	
*Inc. - Tungsten PAR38	150	1750	2,000	11.7	-----	100	
*Inc. - Halogen, PAR38	75	1050	2,500	14.0	-----	100	
*Inc. - Halogen, PAR38	100	1500	2,000	15.0	-----	100	
*CFL - PAR38	26	1300	10,000	50.0	-----	-----	
*LED - PAR38	20	1050	50,000	52.5	3,000	-----	
Low Pressure Sodium	35/60	4550	18,000	75.8	<2,000	<18	
Low Pressure Sodium	55/80	7800	18,000	97.5	<2,000	<18	
Low Pressure Sodium	90/125	14300	18,000	114.4	<2,000	<18	

Table 341.4 High Intensity Discharge Lamps. (Add 15% to lamp wattage to account for ballast losses. Mogul screw shell base. Indicates medium screw shell base *. Type O metal halide lamp permitted to be installed in an open luminaire. High pressure sodium lamps marked X have much higher CRI.)

Lamp Type	Watts (W)	Mean Lumens (Lm)	Avg. Life (hrs.)	Efficacy (Lm/W)	Color Temp. (°K)(CCT)	Color Index (CRI)	Est. Cost ($)
Mercury Vapor, clear	175	7,850	20,000	39.0	5700	15	40
Mercury Vapor, deluxe	175	7,800	20,000	38.8	3900	50	30
Metal Halide*,	50	3,000	10,000	52.2	3500	65	57
Metal Halide*, Type O	50	3,200	10,000	55.6	3500	70	77
Metal Halide*,	70	4,500	12,000	55.9	4000	75	51
Metal Halide*, Type O	70	5,300	15,000	65.8	3200	70	60
Metal Halide*,	100	7,600	15,000	66.1	4000	75	50
Metal Halide*, Type O	100	8,500	15,000	73.9	3200	70	59
Metal Halide,	150	12,800	8,000	74.2	3700	70	70
Metal Halide,	175	16,500	15,000	82.0	4000	75	58
Metal Halide, Type O	175	14,300	10,000	71.1	3800	70	74
Metal Halide,	250	21,500	15,000	74.8	3900	65	65
Metal Halide, Type O	250	19,500	10,000	67.8	3800	70	82
Metal Halide,	400	42,000	20,000	91.3	3700	82	85
Metal Halide, Type O	400	40,000	20,000	87.0	4000	70	83
Metal Halide,	750	82,000	16,000	95.1	4000	65	164
Metal Halide,	1000	115,000	12,000	100.0	3800	65	103
Metal Halide, Type O	1000	107,000	12,000	93.0	3500	65	139
High Pressure Sodium*	35	2,250	16,000	55.9	1900	22	36
High Pressure Sodium* (X)	70	3,800	10,000	47.2	2200	65	42
High Pressure Sodium*	100	9,500	24,000	82.6	2000	20	22
High Pressure Sodium (X)	150	10,500	15,000	60.9	2200	65	60
High Pressure Sodium	150	16,000	24,000	92.7	2000	22	28
High Pressure Sodium	250	28,000	24,000	87.0	2100	22	27
High Pressure Sodium (X)	250	22,500	15,000	78.3	2200	65	46
High Pressure Sodium	400	50,000	24,000	108.7	2100	22	25
High Pressure Sodium (X)	400	37,400	15,000	81.3	2200	70	56
High Pressure Sodium	1000	140,000	24,000	121.7	2100	22	96