INDUSTRIAL LIGHTING

HISTORY OF LIGHTING

The evolution of illumination techniques, that is, providing and utilizing visible radiation, can be considered to have three major periods. The initial period produced visible light by the ignition of combustible materials, wood, gas, oil, and so on. The second period produced light with electrical and electronic devices, (incandescent lamps and gas discharge techniques) that were operated from a central electrical supply. The third and final period was concerned with advancing lighting technologies to improve their efficacy based upon the need to conserve electrical energy. All of these sources produced both visible radiation and thermal energy; in each period the goal was to reduce the thermal component. This article will briefly describe the light sources in each period and factors that necessitated advances and emergence of new industries needed to exploit the new technologies.

Flammable Light Sources

The first source of visible light (besides sunlight and moonlight) was the combustion of wood. The primary use of burning wood was to provide heat and light was a by-product. This was followed by burning candles, oil, kerosene, and finally gas to improve light for visual tasks. The latter light source (gas lamp) was used for improving illumination in work places, outdoors, and residences. These light sources were not suited for hard visual tasks, such as reading, due to their flickering and relatively low intensity. One unique characteristic of these light sources was portability, which is still useful today. Unfortunately, these light sources were an ever-present fire hazard. Schivelbusch (1) describes, prior to any street lighting, how night-time crime prevailed and people rarely emerged from their well-secured homes. Illuminating streets with gas lights was an attempt to address this concern and is an example of a societal need spurring the advancement of technical applications.

Electric Illumination

In the late 1800s the incandescent light source was introduced and became the major illumination source over the next three decades. In these years arc lamps and mercury arc discharge lamps were also introduced but found only special applications. Unlike the previous light sources the incandescent lamp was not portable and required a centralized source of energy (electricity). This lamp was responsible for the emergence of electric utility companies as the central supply.

In 1939 the low pressure gas discharge lamp (fluorescent lamp) was demonstrated at the New York World's Fair. It was initially developed to provide colored illumination in place of incandescent lamps that delivered too little light because unwanted colors were absorbed by filters. Prior to this period, industrial growth was in full bloom and the incandescent light source was the only, if inadequate, illuminant for lighting large areas (offices, manufacturing plant, and so on). The light levels in these applications were as low as 2 fc to 5 fc, with large gradations in illuminance throughout a given space. Osterhaus (2) describes how unions voiced complaints of the poor visual working conditions and the new fluorescent light source became the answer to improve the illumination for commercial and industrial applications. The new light source was a large area source of much lower bulb wall intensity (reducing glare) and could provide more uniform illumination. In addition, its increased efficacy permitted needed increased light levels, sometimes with a decrease in electricity costs.

In a short time fluorescent lamp systems became the light source of choice for industrial and commercial applications. Over the next thirty years metal halide and sodium high in-

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tensity discharge (HID) lamps were introduced. These HID lamps, including mercury lamps, were used for outdoor and special indoor industrial applications. The HID lamps were particularly suited for lighting indoor spaces with suitably high ceilings.

During this time period technical improvements evolved but most efforts were expended in cost-reducing products, since operating cost (electrical energy) was low and the market was very competitive. Toward the end of this period worker productivity was deemed directly related to illumination levels resulting in the continual increasing of recommended light levels (reaching 200 fc to 300 fc in many commercial office buildings).

System Efficacy

The final and present period for lighting technologies started in the early 1970s after the world-wide energy crisis resulted in shortages and the increased cost of electrical energy. The cost of lighting was soon dominated by the operating cost with respect to initial product cost. In this, the electronic age, we find an increase in light source efficacies and the judicious operation of lighting systems. The most important innovation was operating fluorescent lamps at high (20 kHz to 30 kHz) frequencies using electronic ballasts. The electronic ballast (based on switching power supply technology) not only increased the fluorescent lamp efficacy by 25% but provided a simple and effective way to control light levels over very wide ranges of output. There were a host of gimmicks introduced to reduce light levels that were a popular retrofit for over-illuminated spaces, and at best these 'light reducers' marginally increased efficacy.

Lighting management systems were developed in addition to occupancy sensors. Compact fluorescent lamps (CFL) were introduced as an appropriate efficacious replacement for incandescent lamp applications. The high pressure sodium lamp replaced high pressure mercury roadway lamps. The fluorescent lamp industry introduced a more efficacious T-8 1.2 m (4 ft) lamp (25 mm (1-in.) tube diameter with new rare earth phosphors) further increasing the efficacy of the ubiquitous fluorescent lamp system.

Since 1970, increases in efficacy have been remarkable; the four-foot fluorescent lamp system efficacy has increased from 62 lm/W to well over 90 lm/W. The CFL (60 lm/W) has four times the efficacy of incandescent lamps (17.5 lm/W). The Illuminating Engineers Society's (IES) recommended light levels for many tasks have been realistically slashed, some by a factor of 2. The effect of innovations in the past twenty-plus years is reflected by newly installed lighting power densities for commercial office spaces, from 4 W/ft^2 to 6 W/ft^2 to less than 1 W/ft^2. This final period is not yet closed as further innovations are around the corner.

INCANDESCENT LAMPS

Incandescent lamps produce visible light by the passage of an electric current through a wire coil (filament) to attain a high temperature (of about 2800 K), see Ref. 3. The useful characteristics of incandescent lamps are; (1) continuous emission spectrum, (2) point light source, (3) large range of dimming by simple means, (4) the ability to operate directly from the distributed electrical power line, (5) low product cost, (6) wide distribution of product, (6) temperature independence, and (7) small size and light weight. The negative aspects of this lamp are (1) low efficacy, (2) short operating life (about 1000 h), (3) high source intensity (glare), and (4) high operating cost to product cost ratio. (A 100 W incandescent lamp costs 75 cents; with a life of 750 h, at 15 cents per kWh, its operating cost over its life is 8.4 dollars, more than 11 times the initial cost.)

There are a large range of general service lamps, 8 W to 1500 W, providing initial light output of 80 lm to 34,000 lm, respectively. These lamps have clear bulbs (used in conjunction with reflectors and lenses) to control the distribution of light from the "point" source (filament). Some incandescent lamps have their internal bulb walls frosted to provide a uniform, diffuse light distribution. There are bulbs that are elliptical or parabolic shaped (filament at the focal point) that are coated with a reflecting material that will control the output light distribution. There are low voltage lamps (12 V input) with large diameter (thick) filaments and small linear dimensions. The light from these small filament lamps is more intense and precisely controlled for critical floodlight or spotlight distributions.

Since the 1970s many low wattage incandescent applications (less than 150 W) have been replaced by fluorescent and compact fluorescent lamps, particularly in commercial and industrial spaces. High intensity discharge lamps have replaced high wattage incandescent lamps (clear bulbs) in outdoor applications (streets, parking lots, and highways). These substitutions have been mainly based on the replacement lamp's higher efficacy and longer life. Although an incandescent lamp is relatively inefficient, its small size and ability to provide the precise luminance over a desired area for decorative objectives or special visual tasks make it the more effective light source and these applications will continue to prevail in the future.

Lamp Elements

Figure 1 shows a schematic of the basic material elements of an incandescent lamp. The filament (F) is a tungsten wire having different configurations depending upon the application, straight, coiled (helical) or coiled, coil (double helical coil). Coiling the filament increases its luminous efficacy. The filament is supported (S) by sturdy conductive wires attached to a glass stem. The filament is enclosed in a glass (lime glass) bulb (B) that is hermetically sealed that is either evacuated or backfilled with an inert gas or gas mixture (argon/nitrogen). The vacuum or inert gas environment isolates the hot

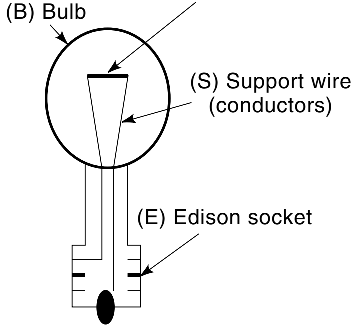

Figure 1. Basic elements of a general service incandescent lamp.

filament from reactive gases (oxygen). The support wire conducts the current to the filament and extends through the glass bulb to the lamp's base. There are different types of bases depending upon the application. The medium Edison socket (E) is most prevalent while bayonet types are used where precise position of a filament is essential (positioning the filament at the focal point of reflectors).

Lamp Efficacy/Lamp Life

Standard Service Lamps. The maximum efficacy of incandescent lamps is limited by the highest temperature to which the filament can be heated, considering its melting point, vapor pressure, and rate of evaporation. Tungsten and tungsten alloys best meet these filament criteria. Incandescent lamps have a low efficacy due primarily to the emission spectra of an incandescent filament (90% is in the nonvisible infrared region). The tungsten emission spectrum is shown in Fig. 2 where approximately only 10% of the radiant energy is in the visible region. There are also smaller secondary losses where heat is dissipated to processes other than heating the filament; (1) radiation from the filament, (2) conduction of heat through the filament supports, and (3) thermal conduction through the gas (for gas filled lamps). There is a trade-off between lamp efficacy and lamp life (higher filament temperatures and higher efficacy increases evaporation rate, which decreases filament life). For example, low wattage lamps operate at lower filament temperatures than the higher wattage lamps, for example, 10 W lamps are 8 lm/W compared to 17.5 lm/W for 100 W lamps. While the rated life of 10 W lamps are 1500 h compared to 750 h for the 100 W lamp.

End of life of an incandescent lamp is when the filament opens due to evaporation. The operating temperatures of filaments of low wattage lamps are around 2400 K and have a satisfactory evaporation rate in a vacuum. The higher wattage lamps (2800 K) require a gas fill to reduce the tungsten's vapor pressure to attain a suitable life. A heavy inert gas is preferable and an argon rich (90% AR/10% N) mixture is in general use. Krypton is still more desirable (heavier than Ar) but its scarcity and higher cost limits its use for special requirements.

High Efficiency Lamps. Techniques permitting lamps to improve efficacies and/or life of standard service lamps include reducing evaporation rates of filaments, reducing thermal losses, and reducing infrared radiation losses. The high efficacy lamps are generally more costly and are reserved for special applications.

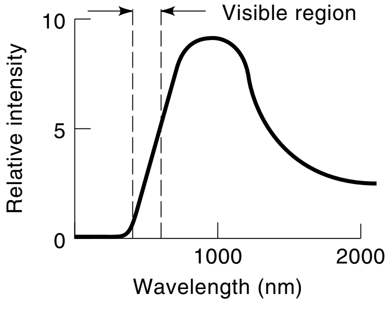

Figure 2. Emission spectra of an incandescent lamp.

Krypton Gas. The krypton (Kr) gas molecule is larger and heavier than argon and reduces thermal conduction when included in the gas mix. The evaporation rate of the filament is reduced and the lamp will have a longer operating life, have the same life by operating the filament at a higher temperature, or have a slight gain in either parameter. The maximum gain in efficacy is about 2% to 5%.

Tungsten-Halogen Lamp. These lamps employ the halogen regenerative cycle to reduce the rate of evaporation of the filament as well as enhancing the lamp's lumen maintenance. A halogen compound (iodide, bromide, and others) is added to the backfill. The lamp is operated at a higher temperature increasing the bulb wall temperature. The high operating temperature requires that the bulb wall be made of quartz. Halogen compounds dissociate at elevated temperatures; the evaporating tungsten collides with and combines with the halogen to form a tungsten–halogen molecule. This molecule diffuses through space and will only dissociate when it is in the vicinity of the hot filament, depositing free tungsten back onto the filament. The lamp wall is too cool to dissociate the molecule, thus, no tungsten deposits on the walls maintaining a clear bulbwall. There is no lamp blackening and a low rate of lumen depreciation (the filament slowly becomes higher resistance reducing light output). Reducing the effective evaporation rate extends the lamp's life and/or allows the filament to operate at a higher temperature, increasing its efficacy. The filament still has a finite life since the freed tungsten is randomly deposited back onto the filament. Caution must be exercised in the use of these lamps since the hot (400 °C) bulb wall temperatures can ignite nearby flammable materials. These lamps should not be operated in a dimmed mode as the halogen cycle is inoperative at lower operating temperatures.

Some tungsten-halogen lamps are designed to operate from a low voltage (12 V) supply. The filaments of these lamps have a lower electrical resistance, are larger in diameter, and operate at higher currents. The filament size is much smaller and approaches a more 'ideal' point source. By careful positioning of the filament, shaping the rear bulb wall of the lamp (parabolic, elliptical), and coating it with reflecting material the distribution of light is precisely controlled. Some reflective coatings are made of selective reflecting films, that is, films transparent to infrared radiation (removing heat from the lamp) and reflect visible radiation. These are used for very precise flood and spot lighting applications having little spill light.

Infrared Reflecting Lamp. In order to harness some of the wasted infrared radiation from incandescent lamps the inner bulb wall is coated with a multiple thin film dielectric material (about 17 layers). The film thicknesses are controlled such that the film is transparent to visible radiation and reflects infrared (IR) wavelengths. The bulb wall is shaped to permit the filament's emitted infrared radiation to be reflected back onto the filament. Figure 3 shows two bulb shapes for this type of lamp. Some of the previously lost IR energy is absorbed by the filament and contributes to heating the filament. The efficacy increases can be as great as 33%, for example, the efficacy of a 20+ lm/W lamp can be increased to over 30 lm/W.

Spectral Distribution

Figure 4 shows the spectral power distribution from tungsten filaments, operated at the same power (wattage) at tempera-

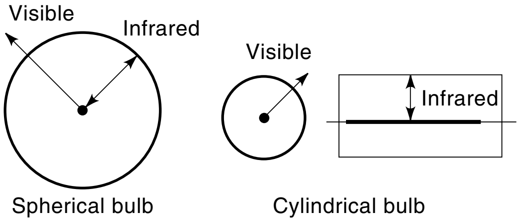

Figure 3. Two bulb shapes for efficacious incandescent lamps with infrared reflecting bulb walls.

tures of 2600 K and 3500 K, in the visible region (400 nm to 700 nm). The spectrum is continuous, that is, containing radiation for every color (wavelength) in the visible spectrum from blue to deep red. It has excellent color rendition, just slightly below a blackbody at the same temperatures, that is, a color rendition index (CRI) above 95%. The figure also shows that at low temperatures (2600 K) the color temperature (CT) is primarily yellow and red and becomes bluer at higher filament temperatures. That is, the peak of the spectral power distribution shifts toward blue (higher frequencies) at increasing filament temperatures. This shift explains why the efficacy of the incandescent lamp increases at higher filament temperatures, where the amount of energy in the visible region increases.

Electrical Supply Impacts

There are two more positive attributes of the incandescent lamp associated with the electrical power reflected back onto the line. The incandescent lamp is a simple resistive (linear) load. The current and voltage are in phase and sinusoidal (no line harmonics), that is, it has a 100% power factor. Being a resistive load the applied voltage can be readily altered allowing the light output to be varied from full light output to 0%. The voltage can be varied with rheostats (inefficient), variacs, and triac type semiconductors. However, the latter two types of control will lower power factor due to current-voltage phase shifts or distorted wave shapes (produce harmonics), respectively.

Future Advances

In this energy conscious period incandescent lamps have come under attack because of its relatively low efficacy (2 lm/W to 25 lm/W). Even with the latest incandescent lamp advances, usually reserved for special applications, it is difficult to envision lamp efficacies much greater than 30 lm/W. Compact fluorescent lamp efficacies (60+ lm/W) are being used in place of incandescent lamp sockets. Most applications are in fixtures where a diffuse, low intensity light output (less than 2000 lm) is satisfactory. Despite the rhetoric of conservation advocates, the incandescent lamp will always be a major illumination source because its unique attributes render it the most “effective” light source in applications regardless of its low efficacy.

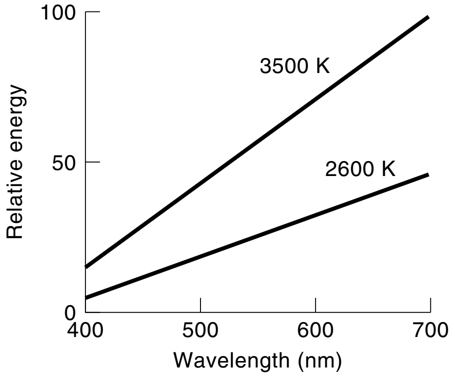

Figure 4. Visible spectra of incandescent lamp at 2600 K and 3500 K.

FLUORESCENT LAMPS

The fluorescent lamp is a low pressure mercury gas discharge in which the two most intense emission lines are in the ultraviolet (185 nm and 254 nm). The emitted ultraviolet radiation is absorbed by a phosphor which re-emits radiation in the visible region (400 nm to 700 nm) having several broad peaks. Fluorescent lamp’s useful characteristics are; (1) high efficacy, (2) low intensity light source, (3) diffuse light output, and (4) long operating life, refer to Waymouth (4) and Elenbass (5). The negative aspects of this lamp are: (1) need for auxiliary power conditioning (ballast), (2) large and bulky lamp size, (3) high initial system cost, and (4) light output is temperature sensitive.

The sizes of fluorescent lamps range from about 7 W to 110 W input power, and have linear lengths from 0.13 m (5 in.) to 2.5 m (96 in.) and diameters from less than 13 mm (0.5 in.) (T-4) to 38 mm (1.5 in.) (T-12). The most widely used lamps are 1.2 m (4 ft) to 2.4 m (8 ft) in length. There are three types of fluorescent lamps characterized by their starting and operating modes (preheat, rapid start, and instant start). Traditionally smaller lamps (<30 W) are usually preheat, the 40+ W lamps are generally rapid start, and larger lamps (eight foot) are generally instant start. Preheat lamps apply filament power during starting and operate without filament power; rapid start lamps apply filament power to the lamp during both starting and operation; and instant start lamps start and operate with no filament power. The typical operating life of the preheat and instant start lamps is about 10,000 h, while rapid start lamps have lives twice as long. The 1.2 m (4 ft) F40, 38 mm (1.5 in.) diameter (T-12), rapid start (RS) and the 2.4 m (8 ft) F96 (T-12) instant start (IS) lamps comprise over 60% of the product mix.

Since the 1980s important advances have been introduced including high frequency operation (>20 kHz) as described by Verderber and Morse (6), smaller diameter lamps and new rare earth (tristimulus) phosphors. These innovations have resulted in a 25% increase in lamp efficacy for four foot lamps and eased the techniques for safely dimming fluorescent lamps over a wide range of light outputs. In addition, by one or more 90° bends of the glass bulbs, the lamps’ long linear dimension can be greatly reduced. These smaller lamps approach the size of incandescent lamps and can be adapted to be used in Edison sockets for some applications, that is, replacing a less efficacious incandescent lamp. Compact fluorescent lamps (CFL) have over four times the efficacy of incandescent lamps and have ten times their life (10,000 h). The CFL can be integral, lamp-ballast-socket in a single package or a replaceable lamp that fits into a ballast-socket package.

Production of Visible Light

Figure 5 shows a schematic of a fluorescent lamp depicting the material elements as well as atomic processes to produce visible radiation. There are filaments (electrodes) at each end of a sealed long glass tube. The filaments are coated with a barium oxide mixture to reduce the work function of the cathode, that is, ease the emission of electrons. The tube is backfilled with an inert gas mixture (Ne/Ar) at a low pressure (1 torr to 3 torr) and includes several drops (50 mg) of liquid mercury. The inner wall of the glass bulb is coated with a fluorescent phosphor. A rapid start type lamp heats each filament via a small voltage (about 3.6 V) and ignites the discharge when a high ac voltage is applied across the two end filaments. Electrically the lamp is initially a very high impedance, after ignition it is a low negative impedance. A ballast, not shown, is required to supply the high voltage to start the discharge and limit the current when the mercury discharge is established.

In operation, electrons are injected from the cathode and accelerated by the electric field (cathode fall, positive column, and anode fall). The energetic electrons traverse the lamp, exciting mercury atoms, and are collected at the anode. The ionized mercury drifts toward the cathode. In the vicinity of the cathode the mercury ions are accelerated by the cathode fall and strike the cathode. The heavy energetic ions striking the cathode resulting in removal (sputtering) of the low work function material. Some of the ions striking the bulb wall or combining with electrons are neutralized. The large anode fall is due to the need to replace ions that combine with electrons or are lost at the bulb wall to maintain an electrical neutral plasma (electron-Hg collisions produce Hg ions). The energetic electrons collected at the anode also contribute to heating the electrodes. The excited Hg emits two major ultraviolet (UV) lines (254 nm and 185 nm) and some other sharp lines, about 2%, in the visible region. UV reaches the bulb wall and is absorbed by the fluorescent phosphor. The excited fluorescent phosphor re-emits its characteristic radiation in the visible region.

Figure 6 shows the voltage drops across a typical F40 T-12, RS lamp operated at 60 Hz that produces high electric fields at both the cathode and anode (about 1000 V/cm).

Lamp Efficacy

Power Losses. Figure 7 shows where the loss of power occurs in a rapid start fluorescent lamp. There are I^2R losses heating each of the filaments; there is a voltage drop at each of the electrodes (cathode fall and anode fall) and there is a voltage drop across the positive column. By reducing or removing filament power during operation heating losses are reduced, although this causes an increase in the cathode fall. That is, the filament temperature is reduced and an increased cathode fall is required to supply the required electrons. Operating the lamp at a high frequency (>10,000 Hz) the anode fall is reduced by about ten volts. These two techniques will increase the lamp efficacy. The most efficacious fluorescent lamp operated at 60 Hz is the hybrid lamp (85 lm/W); it starts in the rapid start mode (maintaining life) and after ignition, the filament power is removed via an electronic circuit. The most efficacious high frequency fluorescent lamp (1.2 m (4 ft) F32 T-8) operates in the instant start mode achieving an efficacy of 100 lm/W.

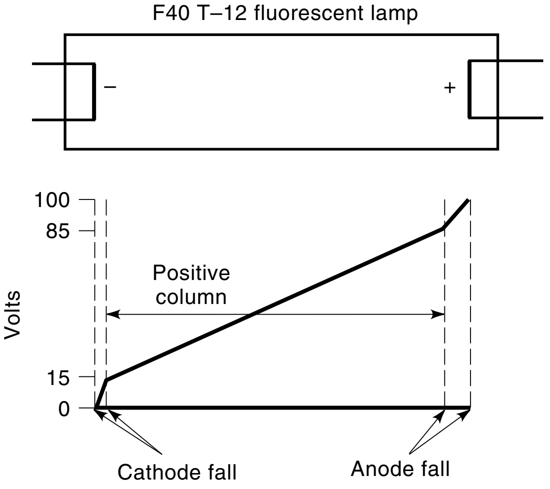

Figure 6. Voltage drops (cathode fall, positive column, anode fall) across a fluorescent lamp.

Thermal Sensitivity. The light output of fluorescent lamps is sensitive to their surrounding temperature. This is due to the increase in Hg vapor pressure with increasing temperature. After ignition the mercury density is very low and increases as the lamp temperature increases, the increasing amount of Hg vapor results in proportional increases in ionized Hg ions, UV production, and visible radiation. At a lamp wall temperature of 40°C, a competing process comes into play. UV produced is absorbed and re-emitted as it travels to the bulb wall (phosphor). While this process is reversible, with no energy loss, the excited electrons are in a higher state for a longer time increasing the probability for ions to return to a ground

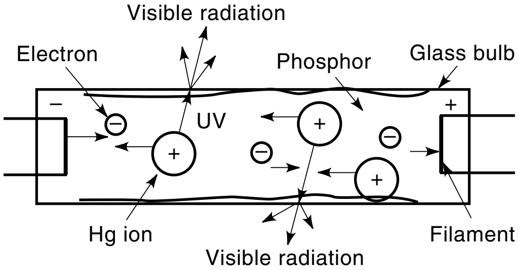

Figure 5. Atomic processes in fluorescent lamp producing visible radiation.

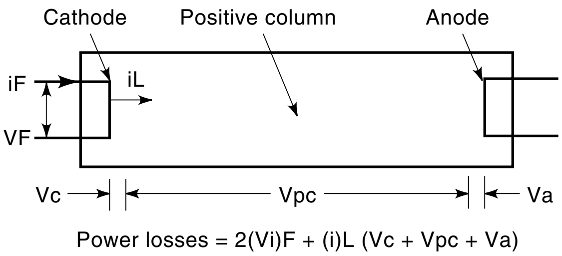

Figure 7. Where power losses occur for fluorescent lamps.

state by quenching collisions and other means by emitting phonons, effectively reducing UV radiation reaching the phosphor. Typically these transitions are made 100 to 1000 times before the initially produced UV reaches the lamp wall. At increasing temperatures above 40°C the Hg density continues to increase, further reducing light output and lamp efficacy. The latter process is called ‘radiation entrapment’ and has an adverse effect on lamp efficacy. At a 25°C ambient, the efficacy of a F40 1.2 m (4 ft) lamp reaches its maximum (lamp wall temperature of 40°C). However, most fluorescent lamps are not operated in open air but in fixtures where the lamp wall temperature are as high as 60° and lamp efficacy is 25% below its maximum.

Siminovitch (7) has shown by use of air flow fixtures, cold spot control techniques, or amalgams the efficacy of fluorescent lamps can be made to operate near their maximum light output and efficacy.

Lamp Life

Starting Cycle

Rapid Start. At start, filaments are heated and potential across the lamp is increased, and at a suitable temperature (800 °C) and voltage, electrons are emitted. The electrons gain energy from the field and collide with argon atoms (major constituent) and excite them to a metastable state; the energy is only released in a collision with a minor constituent (Hg). This process is the “Penning effect” and expedites the ignition of the Hg discharge at a suitably low voltage. (Without a Penning mixture electron collisions with the small amount of Hg vapor at room temperature is unlikely.) During the starting cycle the cathode voltage is very high (over 150 V) and energetic Hg ions bombard the cathode (sputtering) removing the low work function material. Operating fluorescent lamps on too short an operations cycle (excessive number of starts) drastically reduces their life.

Instant Start. Instant start lamps are characterized by starting and operating without a heating voltage to the filaments. Thus, the lamp starting voltage for a comparable lamp size is almost double. The initial electron emission is by a very high cathode field. Thus, the bombardment (sputtering) of the cathode is much greater for instant start lamps compared to rapid start lamps. The instant start rated lamp life is almost half that of rapid start lamps, primarily due to the severe starting sequence (high starting field at the cathode) as well as operating without filament power.

Preheat Start. Preheat start lamps are generally employed for lower wattage lamps (<30 W). The voltage is first applied across both filaments through a manual switch or a glow bottle switch. When the filaments are heated sufficiently the switch circuit is opened and the entire applied voltage appears across the lamp. Due to an inductive kick the voltage is actually higher than the applied voltage. These lamps also have a reduced operating life due to the “harder” starting, that is, high cathode field scenario compared to rapid start lamps.

Spectral Distribution

Halophosphate phosphors have been generally employed for fluorescent lamps. Their spectra consists of several broad peaks in the visible region. The widely used 4100 K “cool” white color has a high efficiency due to a major peak at about 570 nm and a smaller peak at 470 nm. The major peak corresponds closely to the peak (555 nm) of the CIE (Commision Internationale de L’Ecloirage) photopic spectral luminous efficiency curve. Since most of the emission is in the yellow-green and lesser amounts in the blue and little in the red; color rendition is just adequate (60 CRI). The sparse red radiation in the spectra renders fair skin rather pale and shallow. The color rendition can be enhanced adding red emitting phosphors to the mix [Delux Cool White (DCW), 4050 K, 89 CRI; Warm White Delux (WWD), 2940 K, 73 CRI]. Adding a blue emitting phosphor with red phosphor results in a more continuous spectra simulating daylight (daylight, 6250 K, 95 CRI). The latter improved the color rendering, but reduces lumen output due the broad blue and red peaks, where luminous efficiency (conversion of photons to lumens) is small. For example, the loss in lamp efficacy is 30% (DCW), 31% (WWD), and 18% (Daylight) compared to the 4100 K cool white lamp.

In order to improve the fluorescent lamp’s color rendering as well as its efficacy new rare earth phosphors were introduced. The emission spectra of these phosphors consisted of narrow peaks in the blue, red, and yellow portions of the visible region. The narrow intense peaks provide enhanced red and blue hues obtaining CRIs in the 70s and 80s with little loss in luminous efficiency. That is, wide range of color temperatures, 2800 K to 5000 K, can be attained maintaining an efficacy about the same as the halophosphate 4100 K cool white phosphors.

Equally important, rare earth phosphors have an improved lumen depreciation performance. They are needed for the smaller diameter CFL and the T-8 (25 mm (1 in.) diameter) 1.2 m (4 ft) fluorescent lamps to maintain the rate of lumen depreciation achieved with T-12 cool white lamps. Lumen depreciation is a function of power loading (watts per square inch) of the phosphor surface. Thus, the smaller diameter T-8 lamps have an increased power loading but with rare earth phosphors have about same rate of lumen depreciation as the T-12 lamps with halophosphate phosphors.

Fluorescent Lamp Ballasts

In order to start and safely operate a fluorescent lamp an electrical device (ballast) must be placed between the electrical line supply and the lamp. Figure 8 shows a schematic circuit for a 60 Hz two lamp F40 T-12 Rapid Start fluorescent lamp system. The primary functions of the ballast are to supply a sufficiently high voltage to initiate the discharge (initial lamp impedance very large) and to limit the current after ignition (lamp impedance negative and very small, 100+ Ω). The elements of the ballast shown are: (1) the auto trans-

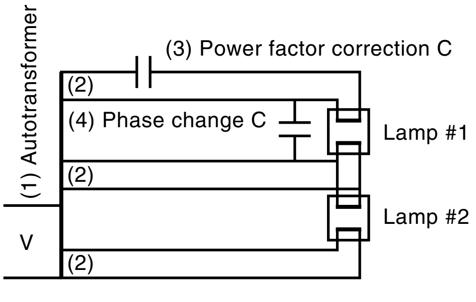

Figure 8. Schematic circuit for a two lamp fluorescent lamp system.

former, (supplies the high starting voltage, (2) the secondary taps heat the filament at start and in operation, (3) capacitor 1, corrects lagging power factor of inductor (power factor 0.90, line harmonics 20%), and (4) capacitor 2, changes phase of one of the lamps (allows the lamps to be started sequentially). The latter phase shift allows a reduced transformer output voltage to start and operate the lamps. The recommended maximum lamp current crest factor, LCCF, (peak current ÷ rms current) is 1.7. Larger crest factors require increased field emissions each half cycle increasing the sputtering of the cathode and results in a reduced lamp life.

Ballast design parameters are different for each lamp type (lamp current and starting voltage) specified by the American National Standards Institute (ANSI) (8). Magnetic (60 Hz) ballasts are designed to operate one, two, and three fluorescent lamps.

The newest fluorescent ballasts operate the lamps at a high frequency to increase the lamps efficacy. Figure 9 shows the essential features of the electronic ballast that converts the input 60 Hz to a high frequency. The 60 Hz ac voltage is converted to a dc voltage, filtered and input to a switching circuit that inverts it to a high frequency; finally, the ballasting (output circuit) employs high frequency devices (such as ferrite core transformers) to further condition the power. In addition to increasing lamp efficacy, the electronic ballast is 10% more efficient in converting the intput power to the lamp power than the 60 Hz magnetic ballast. Furthermore, the electronic ballast is much smaller and weighs less than the magnetic ballast. The conversion from ac to dc is slightly 60 Hz modulated, that is, the high frequency output (20+ kHz) is modulated with a 60 Hz envelope. The ac to dc conversion and final high frequency switching results in harmonic signals being produced and reflected to the line supply. These high harmonics (due to wave distortion) can result in a low power factor (50% to 60%). Other detrimental effects of line harmonics are; (1) possible interference with other electronic equipment on the line (via conduction or radiation), (2) distortion of the line voltage, and (3) resonant harmonic frequencies producing excess currents. Employing passive filtering at the front end can reduce the harmonics to about 20% obtaining power factors of over 90%; the use of active filters can lower harmonics to less than 10% yielding power factors approaching 100%, (there is virtually no voltage phase shifts in the electronic circuits).

Electronic ballasts have two more advantages: (1) it is possible to produce multilamp ballasts (electronic ballasts are available for one, two, three, and four lamps), and (2) electronic ballast can control the light output of fluorescent lamps over a wider range without decreasing operating lamp life. Magnetic ballast dimming systems reduce filament power as the arc current is decreased. At low light levels (<50%) the filament temperature is reduced resulting in electron emission due to an increase in the field at the cathode. Electronic ballasts can maintain or increase filament power when the light output (arc current) is lowered keeping the cathode at temperatures to assure thermal emission. Thus, electronic ballasts can dim fluorescent lamps to less than 10% of full light output without loss of lamp life.

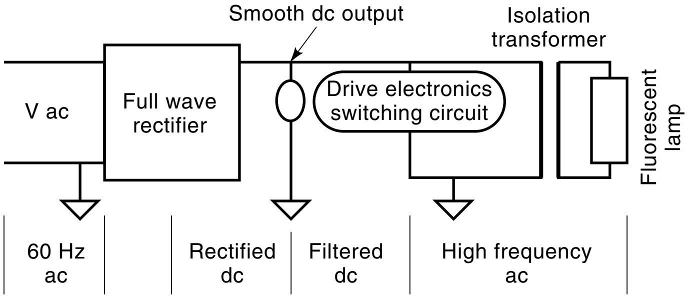

Figure 9. Schematic circuit for a high frequency electronic ballast fluorescent lamp system.

Future Advances

There are advantages to go to still higher lamp frequencies (MHz) in which the fluorescent lamp requires no filaments and the electric field is injected via a cavity to obtain free electrons. Even though there is no significant increase in lamp efficacy at megahertz frequencies, with no filaments, the lamp life is extended and limited by the lumen depreciation of the phosphor. The very high frequency lamp with a potential life of 50,000+ h makes it possible to consider sealing luminaires (lamps and ballasts) that can be replaced by another sealed luminaire when any component fails. A megahertz frequency lamp has been developed with a similar shape (globular) of standard incandescent lamps with a 60 lm/W efficacy. While this efficacy is no greater than the CFLs already on the market, megahertz lamps could find applications where very long life is required, for example, traffic lights, tunnels, and other applications where lamp replacement labor costs are high.

HIGH INTENSITY DISCHARGE LAMPS

The high intensity discharge (HID) lamp is a high pressure gas discharge lamp in which the predominant emission spectra is in the visible region, refer to Waymouth (3), and Meyer and Nienhuis (9). The positive features of HID lamps are: (1) intense light source, (2) very high light levels, (3) point light source, (4) high efficacy, (5) long operating life, and (6) temperature insensitivity. Negative aspects of HID lamps are: (1) need for power conditioning (ballast), (2) high initial system cost, (3) time delay to initiate discharge (start and restrike), (4) high temperature operation of lamp, and (5) large heavy ballast. There are three main types of HID lamps, mercury (M), metal halide (MH), and high pressure sodium (HPS). Applications of HID lamps include, (1) roadway lighting, (2) outdoor lighting, (3) industrial lighting (factories, warehouses, and other spaces with high ceilings), and (4) commercial spaces (offices, reception areas) with high ceilings.

Mercury HID Lamp

The mercury lamp is a mercury gas discharge operating at an arc tube pressure of 2 to 4 atmospheres emitting a characteristic spectra in the visible, rich in green and blues. The UV lines, prominent in the Hg low pressure discharge, are greatly reduced at high pressures. It has poor color rendering (15 CRI) and a color temperature of 5710 K. To improve color rendering the walls of the outer bulb are phosphor coated raising the CRI to 32 and reducing the color temperature to 4430 K. Lamps are available from 40 W to 1000 W having lamp efficacies from 30 lm/W to 62 lm/W, respectively. The operating life of these lamps are 24,000 h. The use of mercury lamps is declining because of its low efficacy and poor color rendering compared to MH lamps and the high efficacy HPS lamps.

Metal Halide HID Lamps

The MH lamp is a mercury high pressure discharge but includes one or more metal (sodium, thallium, indium, dysposium) halides. After the discharge is ignited and the discharge temperature increases the metal halides are vaporized and dissociated into the halogens and metals. The excited metals radiate their characteristic multiple-line spectra to enhance the lamp's color rendition. The color rendition depends upon the metal halide in the mix and CRIs above 60 are obtained with a color temperature of 3720 K. MH lamps are available from 35 W to 3500 W having lamp efficacies from 55 lm/W to 100 lm/W, respectively. The operating life of these lamps are typically 12,000 h. The color temperature of these lamps can be varied over a wide range by the choice of metal halides in the mix. These lamps have replaced many mercury lamp applications, particularly in factories and commercial applications where good color rendering is needed.

High Pressure Sodium HID Lamps

The high pressure sodium (HPS) lamp adds sodium to the Hg/argon gas mixture. The sodium spectra has a dominant doublet at about 589 nm. At high pressures there is self absorption of the doublet which broadens the two peaks. While the broadened peaks improve color rendering, its CRI is still only 21 with a color temperature of 2100 K. Lamps are available from 35 W to 1000 W with efficacies from 65 lm/W to 140 lm/W, respectively. The higher power lamps operating life is 24,000 h, similar to the mercury lamps. The HPS lamps have replaced the mercury lamps in outdoor applications (parking lots) and roadway applications where color rendition is not too important. They have also been used in factory settings but there have been complaints by occupants due to the lamps high percent flicker and highly photopic spectra. Berman (10) has measured their spectral distribution and determined their lack of scotopic content which can adversely affect visual acuity for difficult visual tasks.

"White" HPS lamps are available that have still broader peaks than standard HPS lamps. These lamps are operated at higher arc tube pressures further broadening the two peaks, rendering a whiter color with an improved CRI. These lamps are marketed for indoor applications and are usually reserved for lower wattage lamps. Since the peak is broadened the lamp efficacy and operating life are also decreased.

Lamp Construction

The arc tube of a 400 W mercury HID lamp is made of silica glass and about 70 mm (2.75 in.) long and 23 mm (0.9 in.) in diameter. The electrodes are tungsten in which a supply of barium oxide emission mix forms a continuous barium monolayer over the tungsten, reducing the filaments work function. Since some applications are at low temperature (−20°F) the arc tube includes a starting probe in the vicinity of one of the electrodes. To reach 90% of its maximum light output the lamp must heat up sufficiently, taking between 5 min to 10 min. The more serious effect is the restrike time; if the lamp is extinguished due to an interruption the lamp takes 10 min to cool down before it can be restarted, taking at least another 5 min.

The arc tube of the metal halide HID lamp is similar to the mercury lamp and also includes a starting probe. The electrodes generally employ a thorium monolayer on the tungsten since the barium oxide reacts with the added halides. The starting process is more complicated than mercury HID lamps since the halides vaporize only as the arc tube temperature increases. During this process there are several changes in the emission spectrum. The arc of a mercury–thorium iodide lamp is constricted and is no longer wall stabilized. If it is operated in a vertical position the arc wanders erratically resulting in a flickering effect that is disturbing and may even extinguish a lamp. Metal iodides (lithium, potassium, and others) have an opposite effect and broaden the arc. The arcs of MH lamps are carried up by convection, heating the top of the arc tube. Lamps to be operated in a horizontal position have curved arc tubes.

The arc tube of an HPS lamp is made of translucent alumina since the sodium at its high operating temperature strongly attacks silica glass. A 400 W HPS arc tube is 10 mm (0.375 in.) in diameter and 95 mm (3.75 in.) long, that is, longer and narrower than the M and MH arc tubes. The narrow HPS arc tube does not have space for an additional probe for starting and the HPS lamps require a high voltage pulse source to initiate the discharge. The peak of the pulse is about 2500 V, with a pulse width of about 2 μs. As the lamp ages the mercury and sodium pressures increase, and the arc voltage increases by about 70 V. At the end of life this increase is too high for a power supply and the lamps will cycle, turning off, restarting, and turning off etc.

Magnetic HID Ballasts

Mercury HID lamps have the least demand on the ballast that include (1) no cathode heat, (2) modest starting and restrike voltages, and (3) tolerating distorted current wave forms. Metal halide lamp requirements have more severe criteria for these three parameters. These ballast must be made larger than the mercury ballasts and are more costly. The HPS lamps arc voltage increases over its life and the ballast must provide operation at a lamps rated power that increases with time. They have no starting probe and require peak voltage pulses of 2000 to 3000 V, which is achieved with an electronic starter.

Future Advances

Attempts to operate HID lamps at frequencies in the 20 kHz to 30 kHz range have not resulted in any large efficacy increase but is useful for providing more constant power to lamps throughout their life.

Anderson (11) has operated HID lamps at megahertz frequencies which allows filaments to be eliminated and permits more desirable halides that previously could not be used because of reacting with the tungsten filaments. These megahertz lamps have improved color rendition and efficacy for both MH and HPS lamps. Progress in very high frequency power supplies are at hand to ballast these very high frequency lamps.

Crawford et al. (12) recently described a new light source, an HID lamp containing no mercury. The arc tube contains only sulfur and operates in the high megahertz region. The color of this lamp is very white and a point source. Lamp efficacies of 200 lm/W have been achieved for a 100 W lamp and could replace incandescent lamp applications, requiring a point source, and low power HID lamps. High output sulfur lamps (3500 W) have been installed in several locations to demonstrate their reliability.

LIGHTING MANAGEMENT/CONTROLS

The dynamic control of the light output of light sources has primarily been a functional need. Incandescent lamps (a simple resistor) have been the simplest to control over their entire light output range (0% to 100%) with rheostats, variacs, and more recently with semiconductor devices (transistors, thyristors, and triacs). Light output of gas discharge lamps has also been controlled but with more complex circuitry by limiting the duty cycle. Controlling fluorescent lamps operated at 60 Hz had a restricted dimming range (from 100% to 50%), beyond 50% the filament power was too low and adversely affects lamp life. Dimming ranges for HID lamps were also restricted due to a radical change in color at the reduced light outputs. The following sections reflect the methods and devices for controlling gas discharge lamps since they are the light sources primarily used in the commercial and industrial sectors.

The initial use of lighting controls was functional, that is, for stage lighting, in homes to create moods, conference rooms, movie theaters, and so on. It was only after the energy crisis (1970s) that the control of light was considered as a means to reduce operation costs (save energy). The five control strategies were: (1) scheduling, control of lighting upon occupants arrival, lunch periods, evenings, and cleaning hours, (2) lumen depreciation, reducing initial light levels to maintenance level and as lamps depreciate with time, power is increased appropriately to maintain the light level, (3) task tuning, in a space there are areas that require different light levels, lamps are ‘tuned’ to required light levels, (4) daylighting, certain building designs allow daylight to supply a portion of the needed illumination, electric lamps can be adjusted to supply the remainder, and (5) load shedding, generally utilities have a power demand charge, if a space is going to exceed its power demand level for a short period of time it can reduce its power demand by lowering light levels in less critical spaces for this short period of time and avert an increase in their power demand charge.

To address these needs, a wide assortment of lighting control equipment was introduced: (1) retrofits to reduce over-illuminated spaces, including centralized digital on-off relay systems that could be economically installed in the electric closets, (2) lighting management systems that employed photosensors to control lighting over several steps or by continuous dimming of lamps, and (3) occupancy sensors that allowed lighting to respond to occupants or lack of occupants in a space.

Retrofit Controls

Since there was a consensus that the existing light levels in offices and other spaces were too high (200 lm), devices were introduced that required minimum installation costs and included: (1) removal of lamps, two lamps from four lamp fixtures, (2) phantom tubes, that allowed removal of one lamp from two lamp fixtures, (3) energy reducers, a device placed in the lamp ballast circuit that reduced the light levels, (4) energy saving lamps (34 W fluorescent lamps with krypton gas fill) that could operate 40 W fluorescent ballast, reducing light output and input power. All of these methods reduced energy usage while also reducing illumination levels. They were a temporary fix since most of them lowered the efficacy of the lighting system.

Lighting management systems consisting of relays and programmable timers could also be economically installed in the electric closet. These digital controls could schedule the operation of the lighting in a space; turn lights on when occupants arrive and off at the end of the working day. This eliminated the wasted energy when lights in buildings were carelessly left on during hours of vacancy.

Occupancy Sensors

Another device was occupancy sensors that would turn light on when a space became occupied and remained on until the space was empty. The area to be controlled was scanned with a sensor (infrared or ultrasonic), sensing motion, and, if motion was sensed the lights would be activated. During periods of disuse lights would be deactivated. The sensor was most effective for single occupant offices but less effective for larger areas since zero occupancy was less likely during the working period. However, in the latter applications a greater electrical load was controlled. Since these devices were installed throughout a space, installation costs were significant since it entailed hard wiring in a ceiling plenum.There were some minor problems with a system’s sensitivity, turning lamps either on or off at inappropriate times. Effective applications were spaces that were occupied occasionally, wash rooms, copying rooms, file rooms, and the like where lamps were usually operated throughout the working period. However, these spaces required stumble lighting in case of defective operation. These devices have found a permanent place in the controls market by themselves or as an element of a lighting management system.

Dynamic Lighting Management Systems

60 Hz Systems. Continuous dimming of fluorescent lamps was accomplished by phase control, that is, reducing the duty cycle. These control systems were expensive and were economic only when controlling a large number of lamps, generally lamps on a single phase (over ten, four lamp luminaires). This meant that only strategies that were not small area sensitive were possible, for example, scheduling lumen depreciation, load shedding, and daylighting. The latter strategy, daylighting, required a specific building design and electrical distribution layout. Task tuning lighting could not be accomplished. The range of control was limited to about 50% of full light output since the filament power was reduced in proportion to the input power; dimming less than 50% could drastically reduce lamp life. Table 1 lists the energy savings that could be achieved for each strategy and their total cumulative effects. The installation of these control systems was not too expensive since the dimming controls and computers were connected in an electric closet while the photosensors, needed

Table 1. Energy Savings for 60 Hz Fluorescent Lamps for the Four Control Strategies

Control Strategy	Percent Savings
Scheduling	20 to 40
Lumen depreciation	5
Tuning	20 to 25
Daylighting	5 to 9[a]
Cumulative	42 to 62

[a] Savings considering daylighted and nondaylighted areas.

for lumen depreciation and daylighting, had to be located in the plenum above the controlled areas. The latter sensors required hard wiring throughout the working area. The controls were connected to a centrally located computer, transporting information from a timer and/or photocells, with a signal to maintain or adjust the light levels. It is evident that systems providing only scheduling were least costly and a fairly effective retrofit, while the additional strategies were most cost effective for renovations and new construction.

High Frequency Systems. High frequency control systems are based upon controlling electronic high-frequency fluorescent lamp systems. Electronic ballasts provide circuitry to maintain the proper filament power when the input power is reduced to the lower light levels of fluorescent lamps. In addition, dimming fluorescent lamps with electronic ballasts is accomplished by varying a low voltage signal (0 V to 12 V) to the ballasts output circuit. These latter two characteristics allow greater energy savings (large dimming range) for each control strategy and independent control of a lamp or group of lamps by the distribution of low voltage wiring. That is, the control of lamps need not be limited to lamps on one phase of a distribution network. The high frequency ballast systems can execute all of these lighting control strategies. For example, single offices can be controlled independently as well as different areas in an open office space that have various illumination needs.

Similar to the 60 Hz controls the auxiliary controls for high frequency systems include photosensors and a centralized computer that incorporates a timer, photocell inputs, and a means to transfer the input information via low voltage wiring to the ballasts. The high frequency system could also employ power line carrier (signals carried over the power lines) that can instruct ballast without using hard wiring. Because the frequencies of the power line carrier and the ballast may be the same they may interfere and such systems must be employed with caution. Table 2 lists the range of energy savings that have been measured by Rubinstein and Verderber (13) for high frequency lighting control systems.

Table 2. Energy Savings for High Frequency Lamps for Four Control Strategies

Control Strategy	Percent Savings
Scheduling	35 to 50
Lumen depreciation	8
Tuning	30 to 40
Daylighting	10 to 20[a]
Cumulative	62 to 78

[a] Savings considering daylighted and nondaylighted areas.

Daylighting Strategy. The use of daylighting in buildings has generally been considered useful based on aesthetics and providing a psychological benefit (in communication with outdoors) to occupants. Since the late 1970s lighting controls for supplementing electric light with daylighting has provided an economic basis as well. In the past twenty years daylighted building have been designed and built to exploit this strategy. Architects oriented buildings to face appropriate directions, used light shelves, sloped ceilings to beam light into interiors, used movable shading to limit direct sunlight, employed transparent (glass) and translucent roofs and skylights, and automatic heliostats to beam sunlight through channels to distribute light throughout a building. In any particular application, daylight distribution and intensity must be integrated with the electrical lighting system in order to maintain a desired illumination level.

The daylighting of atria in malls and commercial buildings as well as public spaces in airports has been most successful. The reasons include: (1) lack of critical visual tasks, (2) large variation in light level permissible, (3) little change in the daylight distribution, and (4) a simple low cost on-off system controlled through an electrical distribution is sufficient. The electrical energy saving for lighting would be significant since no electric lights are needed for 4 h to 5 h in winter and almost 12 h during summer months.

The use of daylighting in office buildings and other spaces where there are many difficult and/or critical visual tasks found mixed results. In general, spaces in the three major directions east, south, and west were best near the windows and at times required shading due to the direct sunlight. The north direction was ideal since the outdoor light was always diffuse. Attempts to beam light into the interiors usually produced considerable glare. Furthermore, the lighting control system had to dim lights continuously (occupants sometimes objected to any noticeable digital changes greater than 20%), and it had to be properly calibrated to follow the dynamic changes in daylighting in a particular space. Rubinstein et al. (14) showed that the electrical lights' end points must be calibrated but the rate of change response of the light must also be adjusted to the changes due to daylight on the task. The photocells, placed in the ceiling, do not sense the illumination on the task but light reflected off the task and the surrounding area and detects illumination only to some ratio to the light illuminating the task. The preferred lighting control system for daylighting uses high frequency electronic ballasts since their dimming range is over 90% of full light output and local spaces can be controlled independent of the electrical distribution.

Present Status

The lighting control systems usage has not grown as rapidly as many of the other energy efficient lighting technologies. The primary reason was the lack of design expertise in this field and the need for manufacturers to support installed product. In the late 1970s there was an economic pay-off since installed lighting systems in many commercial building were as high as 5 W/ft^2 to 6 W/ft^2. Reducing the load by 60% to 70% would save over 3 W/ft^2. Today, with the use of all the new lighting technologies (electronic ballasts, T-8 fluorescent lamps, and the recommended reduction in lighting levels) lighting designers are achieving installed lighting power densities below 1 W/ft^2. The additional cost of lighting controls and amendments to the building structure increase payback periods with savings of only 0.6 W/ft^2. The monetary saving by energy reduction is no longer as attractive.

However, the use of controls is still important to improve productivity in todays electronic office where different light levels are required in various areas and dynamically controlled in particular areas when performing a variety of different tasks (reading hard copy, writing, and viewing a video screen). The economic gains can be realized in workers' productivity which exceed any monetary savings by energy savings realized by reducing electrical lighting costs.

Future Advances

The greatest intrusion that control systems present is the required installation of wiring throughout a space, that is, the working areas. This is required since sensors (photocells, occupancy detectors) and ballasts in desired areas must be hard wired to the central control system. Power line carrier offers a means to achieve communication over the electrical distribution lines. Sophisticated powerline carrier techniques are being developed to carry more information, reliably without errors. Advanced lighting control systems shown in Fig. 10 have been introduced where sensors (occupancy, photocells, timers) emit an infrared signal which is picked up by a central receiver and processes then transmits instructions over the power lines to ballasts, altering or maintaining the light levels.

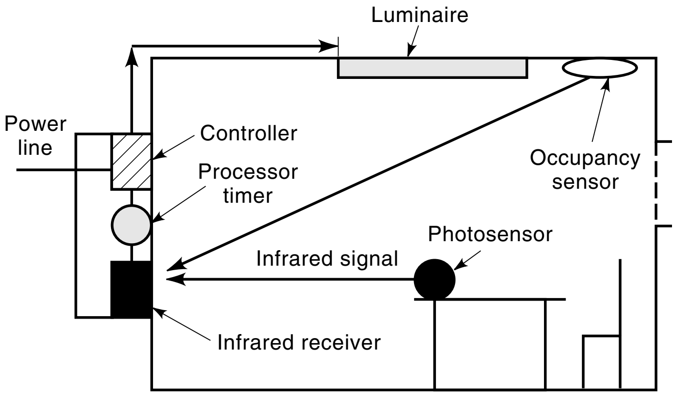

Figure 10. Advanced lighting control system requiring no hard wiring between sensors and receiver.

LIGHTING DESIGN

The basic objectives of lighting designs are to provide aesthetics, comfort, and visibility, refer to Kaufman (15). Each particular lighting task emphasizes one or more of these objectives. It is therefore possible to characterize designs into three categories: (1) markets and retail stores, illuminating inanimate objects, (2) outdoors, illuminating roads, parking lots and arenas, and (3) commercial and industrial buildings, illuminating offices and manufacturing spaces. Aesthetics is generally most important for lighting retail stores in which items for sale must be properly illuminated to attract the attention of shoppers. Depending on the type of shop the designer must provide the proper mood as well as catch the eye of shoppers inside and outside of the store. The latter lighting needs hold true for restaurants as well. The color decor is an important aspect in design of stores and shops, thus, the designer must select light sources with the proper spectral distribution that will enhance the fabrics and other colors in the space. The only important visual tasks in a restaurant would be in the kitchen preparing foods requiring suitable illumination levels (50 fc. to 100 fc.).

Outdoor lighting is generally low-level illumination. For sidewalks and parking lots the illumination level must be suitable for safety considerations. That is, for pedestrians to be aware of any hazards in their path, to be made visible to motor traffic, and be alerted to possible physical danger from intruders, and so on. The latter design goals hold true for parking lots and for identifying their parked vehicles. Roadway lightings' primary requirement is visual in nature. The important visual criteria is to limit glare (blinding, disabling, direct, or discomfort), while providing illumination that allows drivers to identify road hazards and pedestrians under low levels of illumination.

The important design criteria for lighting offices and manufacturing spaces is selecting the illumination level and minimizing glare. A particular disturbing type of glare is veiling reflections in which the contrast of a visual task is washed out (reduced) due to reflection from the immediate area of the task. Lighting these spaces is particularly difficult since different areas in the space may require different illumination levels due to differences in tasks. Some task areas might entail viewing video screens and/or reading hard copy. Tasks in a particular space may change during the work period. These latter two needs require localized lighting controls to optimize performance. Newly developed lighting equipment, such as lighting management systems, and expanded use of indirect lighting fixture allow lighting designers a means to solve these difficult problems.

The design characteristics are: (1) the types of glare, (2) illumination levels for tasks and, (3) luminous ratios and how they affect visibility and visual comfort. While they are characterized by a particular number value for each task, in essence they are at best qualitative. This difficulty is due to the large variation in visual acuity, response to various types of glare, and the color sensitivity of the human eye. Therefore, values for these metrics are statistical, empirical, or arrived at by consensus. Relations for the various metrics are obtained from experiments in laboratory conditions where parameters are varied and the response of subjects, as to their comfort or discomfort, is recorded.

Glare

Glare is unwanted or undesirable brightness (luminance) produced within the visual field of view. Usually the luminance is significantly greater than light levels to which the eyes are adapted, resulting in annoyance, discomfort, or loss in visual performance or visibility. There are six types of glare: (1) blinding, (2) direct, (3) disabling, (4) veiling, (5) discomfort, and (6) reflected.

Blinding Glare. Blinding glare is of a very high intensity that it is debilitating for even a short period of exposure.

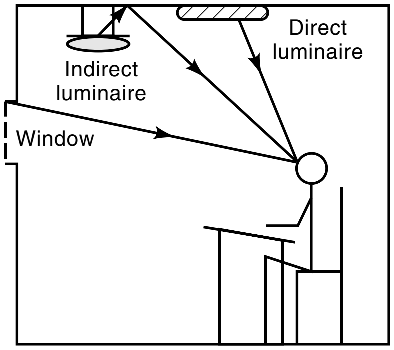

Figure 11. Illumination system showing sources of direct glare.

Direct Glare. Figure 11 shows a schematic of several sources of direct glare from an unshielded luminaire, a bright window, or a reflection from an indirect luminaire located too close to the ceiling. Spaces illuminated by indirect lighting provide good visibility but tend to be bland and uninteresting. Indirect luminaires may include some low luminance direct lighting to provide some interest without introducing discomfort. The annoyance or discomfort or direct glare manifests itself over a relatively longer time period. The time period depends upon the luminance level and the area of the glare source.

Disability Glare. Disability glare results in a reduction of visual performance by reducing the contrast of a hard paper task. While a light source illuminates a task some light rays may directly enter the eye. Any inhomogeneities in the eye may scatter this light and reduce the theoretical contrast of a perfectly focused retinal image. That is, light intended for adjacent areas are scattered onto the primary image. Another example of disability glare is the light from headlights of oncoming traffic that impairs a drivers visibility.

Veiling Glare. Figure 12 shows veiling glare (reflections) and by changing the light source occupants position a solution to this problem. The figure shows that a lamp in front of a subject can produce veiling reflections, good practice is to illuminate tasks from the side or preferably from the rear, as long as light from the rear does not produce shadows on the task to reduce contrast. Veiling reflections are caused by written tasks printed on materials with a high reflectivity. This results in a reduction of contrast that severely lowers contrast. If the lighting position cannot be changed, changing the position of the occupant or the angle of the light source-task can relieve the situation.

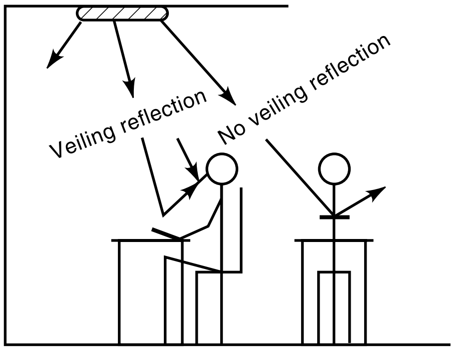

Figure 12. Lamp–occupant relationships showing the cause of veiling reflections and a solution to resolve the problem.

Discomfort Glare. Discomfort glare is an annoying, slightly excessive luminance in the field of view that does not necessarily affect accuracy in a short period of time. However, its persistence over a long period of time could adversely affect performance by causing eye fatigue and headaches. Assessment of discomfort glare is based upon the size, luminance, number of glare sources, their location in the field of view and the background luminance. Measurements determine borderline comfort and discomfort (BCD) from a single light source by increasing its luminance until a subject senses discomfort.

Reflected Glare. Reflected glare arises from specular surfaces, that is, mirrors, and highly polished surfaces that are in the field and/or within the peripheral field of view. Depending upon the intensity, direction, and area the results may be disabling (reduction in visual performance) or discomforting.

Recommended Illuminance Levels

The committee on recommendations for quality and quantity of illumination (16) (RQQ) of the Illuminating Engineers Society (IES) have been publishing single-value recommendations. In 1979 the RQQ committee recommended a new procedure established by the IES to include a weighting factor for designers to consider, providing them with a recommended range of illuminations. In the 1981 IES handbook new values of illuminance were established by a consensus of lighting experts (RQQ Committee) based upon their experience and judgement. The list of recommended illuminance levels and ranges is presented as a guide to lighting designers. It is interesting that the recommended light levels are listed in terms of illumination (light falling on a task) where the eye is responsive to luminance (light reflected from the task) and luminance contrast. However, presenting luminance levels is too impractical since it would entail consideration of the properties of a multitude of task characteristics as well as the light distribution of a lighting system. In fact, detailing the lighting distribution and illumination from a lighting system is sufficiently cumbersome.

Illumination Task Values. Many of the new 1981 published illumination values were made significantly more realistic (reduced), since previous levels were generous, based upon a philosophy “that more light is better.” Task illumination was designated by a letter, and each letter A through I provided a range of illumination levels. A partial list of levels bracketing the three reference work-planes (general lighting, illuminance on the task, and illuminance on task from both general and supplementary lighting) associated with a letter is shown in Table 3.

Table 4 lists illuminance category values for several typical tasks. The listed tasks use a letter designation for interior lighting tasks. Outdoor lighting tasks have no letter designation but are given a single illuminance value.

While lighting designers base their design on illuminance the IES does provide a means to determine the illuminance

Table 3. Generic Illuminance Categories and Illuminance Values

Activity	Illuminance Category	Illuminance Ranges (fc)	Reference Work-Plane
Dark surroundings	A	2-3-5	General lighting in space
Occasion visual tasks	C	10-15-20	
High contrast tasks	D	20-30-50	Illuminance on task
Low contrast tasks	F	100-150-200	
Low contrast for long period	G	200-300-500	Task illumination local and supplementary
Extreme low contrast task	I	1000-1500-2000	

category base on required luminance contrast. Table 5 lists the illuminance categories for measuring a few equivalent contrast values.

Weighting Factors. To provide lighting designers a means to determine the illuminance they should select within a given range three criteria were used; (1) occupants ages, (2) room surfaces reflectances, and (3) speed and/or accuracy. Table 6 lists the criteria and the method of assessing the proper illumination level. For lowest illuminance categories A through C only two criteria are required since speed and accuracy relate primarily to visual tasks. For illuminance categories D through I all three criteria are employed. For example, if the task is in category E (50 fc–75 fc–100 fc) the selected illumination for a value of −3, 0, +3 would be 50 fc, 75 fc and 100 fc, respectively. Results between 0 and 3 would be in the proper ratio between the limits, for example, 83 fc would be selected for a +1 result. Ideally these criteria make sense, but for a newly constructed building only the room surface reflectances could be well defined; it is unlikely that occupants' tasks or ages would be known. The latter problem could be resolved by 'tuning' lighting with a lighting management system after occupancy. The dynamics in most building operations (frequent changing occupants and/or tasks) would further justify these lighting controls.

Table 4. Recommended Illumination Categories for Some Specific Tasks

Type of Activity	Illuminance Category
Drafting	
Tracing paper	
High contrast	E
Low contrast	F
Reading	
Copied tasks	
Xerography	D
Micro-fiche reader	B
Offices	
Lobbies, lounges	C
Mail sorting	E
Offset printing	D
Residences	
Conversation, entertainment	B
Dining	C
Ironing	D
Laundry	D

Table 5. Illuminance Categories for Measured Equivalent Contrast Values

Equivalent Contrast	Illuminance Category
0.75–1.0	D
0.50–0.62	F
0.30–0.4	H
Under 0.30	I

Lighting Quality. Lighting quality is a term that is difficult to define precisely. One may think of it as a lighting environment in which a minimum illuminance is needed to properly perform a particular task or set of tasks. This definition is an attempt to relate performance with economics. There have been attempts to measure it quantitatively in the field with, at best, limited success. Generally, lighting quality includes three main factors; (1) visibility, (2) visual comfort, and (3) luminance ratios.

Visibility. Visibility is a measure of the ability of the eyes to distinguish contrast between an object (print) and its background. Factors that affect contrast of a specific task are veiling reflections and disability glare. Designers attempt to minimize these factors in the design process but only when the space is occupied can it be completely assessed. This would entail a visual inspection of glare and measuring the luminance contrast of tasks.

Visual Comfort. Visual comfort relates to the several types of glare produced by lighting systems. The visual comfort probability (VCP) is a metric used to assess visual comfort for ambient (general) lighting systems. The VCP is the rating of a lighting system expressed as a percent of people who, when viewing from a specific location and specific direction, will be expected to find it 'acceptable' in terms of discomfort glare. Experiments are carried out with a large number of subjects for a standard lighting layout. VCPs are also calculated for luminaires based upon their light distribution based on the standard layout. A generally accepted value of satisfaction for office lighting is 70% or greater.

Luminous Ratios. Luminous ratios between various surfaces in the visual field are important factors in a lighting environment. The three visual fields; (1) immediate area of the task, (2) general area and the task, and (3) remote areas and the task. The recommended brightness ratios are 3 : 1, 5 : 1 and 10 : 1, respectively. These ratios are based on stress

Table 6. Weighting Factor for Selecting Specific Illumination for Categories[a]

	Weighting Factor		
Characteristic	−1	0	+1
Age	under 40	40–50	over 50
Reflectances	over 70%	30% to 70%	under 30%
Speed/Accuracy	unimportant	important	critical

[a] For categories A through I.

due to eyes constantly adapting to the different luminances as they move or wander from the task to other areas in the space. Ratios higher than those recommended may affect the speed and accuracy of detection of tasks and could result in eye fatigue. These ratios are the maximum luminance differences considered good practice, therefore, designs with smaller luminance ratios are preferable.

Electronic Displays

The latest office tasks include viewing video display terminals. Some spaces have singular tasks where occupants view video terminals throughout the work day. In general, most work stations have both hard paper tasks as well as viewing a display terminal. The single most important design factor is eliminating any source of light (luminaires, windows, walls, ceilings, and so on) to be reflected from the display screen into the operator's field of view. This will cause discomfort and/or annoyance as well as reducing the tasks luminance contrast, similar to the effect of veiling reflections. One general remedy in vogue today is the use of indirect lighting or direct luminaires with small cell louvers. The object is to prevent any direct light from the luminaire to be reflected off the screen into the eyes of the operator.

Indirect luminaire design requires a wide (high angle) distribution light and a suitably high ceiling to obtain a relatively low, uniform ceiling luminance with no 'hot' spots (areas of high luminance). Direct luminaire have small cell louvers to limit the angle of distribution to less than 65°. Since the lighting from the direct luminaires will be considerably nonuniform some supplementary general lighting is required. While both will provide the lighting needed for viewing video screen these lighting systems are relatively inefficient; at least 20 to 30% of the light is lost upon the first reflection off the ceiling; fixture efficiency of fixtures with small cell louvers lose about the same percentage.

Other Sources of Discomfort. All gas discharge lamps require a ballast to condition the input power to properly operate these lamps. The ubiquitous 60 Hz magnetic ballasts source frequency operated the lamps at the same frequency. Many ballasts, particularly HID ballasts, were noted for their high 60 Hz acoustical noise. In noisy manufacturing plant the background noise negates any problem, but in an office environment the noise level could be disturbing. One solution required placing the ballasts in a remote location. In addition, the light output was not continuous but was highly modulated with 60 Hz. The resulting flicker was limited somewhat by operating neighboring lamps out-of-phase. However, there was still at least 30% flicker for fluorescent lamps and 70% for some HID lamps. A small percentage of the population are known to be affected by this flicker manifesting itself with headaches and sore eyes. It is difficult to assess those afflicted but not diagnosed. A recent double blind study by Wilkens (17) in England found that occupant complaints, (of headaches and sore eyes when working under 50 Hz fluorescent lighting), were reduced by 50% when working under high frequency fluorescent lighting. The only change in the lighting system was the lamps' operating frequency.

Advances in Design. Prior to computer aided design calculating average illuminance levels for lighting systems was cumbersome; average illumination levels could be estimated using the room cavity ratio method. Computers sped up the process and allowed advances to obtain point-by-point illumination. The next advances provided an image of an empty space. Images were made more realistic by later recreating images of furniture in the calculated images. The most recent advance developed by Ward (18) is a light tracing technique (RADIANCE) that provides illuminance and luminances for a furnished space illuminated with electric lights and/or daylighted space. The resulting computer images include the proper hues of materials and furniture in the space.

SUMMARY

Since the 1970s there have been major advances in lighting equipment and lighting design calculations. The equipment advances are evidenced by the giant leaps in equipment and system efficacies. Design calculations not only provide point-by-point illuminance and luminances in a space but can provide the metrics for a furnished space and display a colored image of the design. The most difficult aspect of illumination has been the lack of describing and quantifying glare, comfort based, illumination levels and other 'lighting quality' parameters on a sound scientific basis. It is only with a monumental research effort in this latter aspect that advances can be expected.

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