PDHonline Course E418 (5 PDH)

Energy Efficiency – Fluorescent Lighting

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2020

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Energy Efficiency
Fluorescent Lighting

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Introduction

Fluorescent lamps are the mainstay of commercial lighting. Over 80% of lighting in commercial and industrial applications is created using fluorescent light sources. A fluorescent lamp or fluorescent tube is a very low pressure mercury-vapor gas-discharge lamp that uses fluorescence to produce visible light. A fluorescent lamp converts electrical power into useful light much more efficiently than incandescent lamps. Fluorescent lamps use approximately one-fourth of the energy used by incandescent lamps to provide the same amount of illumination and they also last about 10 times longer.

An electric current excites a mercury vapor gas which produces short-wave ultraviolet light that then causes a phosphor to fluoresce, producing visible light. Fluorescent lamps require a ballast to regulate operating current and provide a high start-up voltage. Electronic ballasts outperform standard and improved electromagnetic ballasts by operating at a very high frequency that eliminates flicker and noise. Electronic ballasts also are more energy-efficient. Special ballasts are needed to allow dimming of fluorescent lamps.

The two general types of fluorescent lamps are:

- Compact fluorescent lamps
- Fluorescent tube and circline lamps

Compact fluorescent lamps (CFLs) combine the energy efficiency of fluorescent lighting with the convenience and popularity of incandescent fixtures.

The luminous efficacy of a compact fluorescent light bulb is about 60 lumens per watt, four times the efficacy of a typical incandescent bulb. For conventional tube fluorescent lamps the fixture is more costly because it requires a heavy ballast to regulate the current through the lamp, but the lower energy cost typically offsets the higher initial cost. The compact fluorescent light's ballast is contained in the base of the bulb, where the frequency of the AC current is boosted electronically to 60 kilohertz. At this frequency only a very small ballast is needed.

Because they contain mercury, many fluorescent lamps are classified as hazardous waste. The United States Environmental Protection Agency recommends that fluorescent lamps be segregated from general waste for recycling or safe disposal.

History

Fluorescence of certain rocks and other substances had been observed for hundreds of years before its nature was understood. By the middle of the 19th century, experimenters had observed a radiant glow emanating from partially evacuated glass vessels through which an electric current passed.

In 1856 a German glassblower named Heinrich Geissler created a mercury vacuum pump that evacuated a glass tube to an extent not previously possible. When an electrical current passed through the *Geissler tube*, a strong green glow on the walls of the tube at the cathode end could be observed. More important, however, was its contribution to scientific research. In 1859, Becquerel observed that certain substances gave off light when they were placed in a Geissler tube. He went on to apply thin coatings of luminescent materials to the surfaces of these tubes. Fluorescence occurred, but the tubes were very inefficient and had a short operating life.

In 1895 Daniel McFarlan Moore demonstrated lamps approximately 8 feet in length that used carbon dioxide or nitrogen to emit white or pink light, respectively. Moore was able to extend the operating life of the lamps by inventing an electromagnetically controlled valve that maintained a constant gas pressure within the tube. Although Moore's lamp was complicated, expensive to install, and required very high voltages, it was considerably more efficient than incandescent lamps, and it produced a more natural light than incandescent lamps. Starting in 1904, Moore's lighting system was installed in a number of stores and offices.

At about the same time that Moore was developing his lighting system, another American was creating a means of illumination that also can be seen as a precursor to the modern fluorescent lamp. This was the mercury-vapor lamp, invented by Peter Cooper Hewitt. Hewitt's lamp luminesced when an electric current was passed through mercury vapor at a low pressure. The mercury-vapor lamp was superior to the incandescent lamps of the time in terms of energy efficiency, but the blue-green light it produced limited its applications.

All the major features of fluorescent lighting were in place at the end of the 1920s. Decades of invention and development had provided the key components of fluorescent lamps: economically manufactured glass tubing, inert gases for filling the tubes, electrical ballasts, long-lasting electrodes, mercury vapor as a source of luminescence, effective means of producing a reliable electrical discharge, and fluorescent coatings that could be energized by ultraviolet light. In 1938 General Electric entered the fluorescent light market with the sale of "fluorescent lumiline lamps". Fluorescent lighting systems spread rapidly during World War II as wartime manufacturing intensified lighting demand. By 1951 more light was produced in the United States by fluorescent lamps than by incandescent lamps.

In the early years zinc orthosilicate with varying content of beryllium was used as greenish phosphor. Small additions of magnesium tungstate improved the blue part of the spectrum yielding acceptable white. After it was discovered that beryllium was toxic, halophosphate based phosphors took over.

The spiral fluorescent lamp, which is called a compact fluorescent lamp, or CFL, was invented in 1976 by General Electric. Although the design met its goals, it would have cost GE about $25 million to build new factories to produce the lamps, and thus the invention was shelved. The design eventually was copied by others. In 1995, helical CFLs, manufactured in China, became commercially available and their sales have steadily increased.

In this course we will look at the overall lighting market in the United States, discuss the concepts of lighting in general and then cover the basics of fluorescent lighting. Finally we will cover the application of fluorescents in the marketplace.

Chapter 1
The Lighting Market

This chapter discusses the size of the U.S. lighting market, recent changes in the market and describes lighting intensities by sector (residential, commercial, industrial, and outdoor lighting).

In 2010, the total energy consumption in the United States was 97.8 quadrillion BTUs (quads) of primary energy. Roughly 40 quads (or 41 percent) of this energy was consumed for electricity use.

For the purposes of this course, the lighting industry is divided into four sections:

1. Residential
2. Commercial
3. Industrial
4. Outdoor Lighting

The total amount of electricity consumed by lighting technologies is estimated to be 700,000 GWh of site energy, or 7.5 quads of primary energy. Thus, lighting accounts for 7 percent of the total energy and 18 percent of the total electricity consumed in the U.S.

The residential sector accounts for the overwhelming majority of installed lamps, at 71 percent of installed base of lighting. However, in terms of electricity consumption, the sector only consumes 175,000 GWh, or 25 percent of the total. Due to the relatively low efficacy of residential light sources (primarily incandescent), the residential sector only accounts for 8 percent of the lumens produced.

The commercial sector is the greatest energy consumer, accounting for half of the total lighting electricity consumption. In addition, the commercial sector represents the sector in which the greatest number of lumens is produced. This is largely due to the longer operating hours found in the commercial sector as compared to the residential sector. Both the industrial and outdoor sectors make up a relatively small portion of the total installed stock of lamps, each approximately two percent. However, the use of high lumen output lamps and high operating hours result in these sectors consisting of greater shares of total electricity consumption and lumen production.

Residences account for 71 percent of all lamp installations nationwide, at 5.8 billion lamps. The commercial buildings sector is the second largest sector with 25 percent of all installations and 2.1 billion lamps. The outdoor and industrial sectors are significantly smaller, each accounting for roughly 2 percent of all lamps installed, 180 million and 140 million lamps, respectively.

With regard to average daily operating hours, while lamps in the commercial, industrial, and outdoor sectors typically are used for half the day (working hours for commercial and industrial sector lamps and night time hours for outdoor lamps) residential lamps are only used a couple hours a day on average. As for the average wattage characteristics, the residential sector average wattage of 46 watts per lamp represents the mix of low wattage, high efficacy CFLs and higher wattage, lower efficacy incandescent lamps installed in the sector. The commercial, industrial and outdoor sector's average wattages are characteristic of the high installed base of fluorescent lamps and high wattage high intensity discharge lamps. These inputs combined result in a total annual electricity use of U.S. lighting of 700,000 GWH, or approximately 18 percent of total U.S. electricity use.

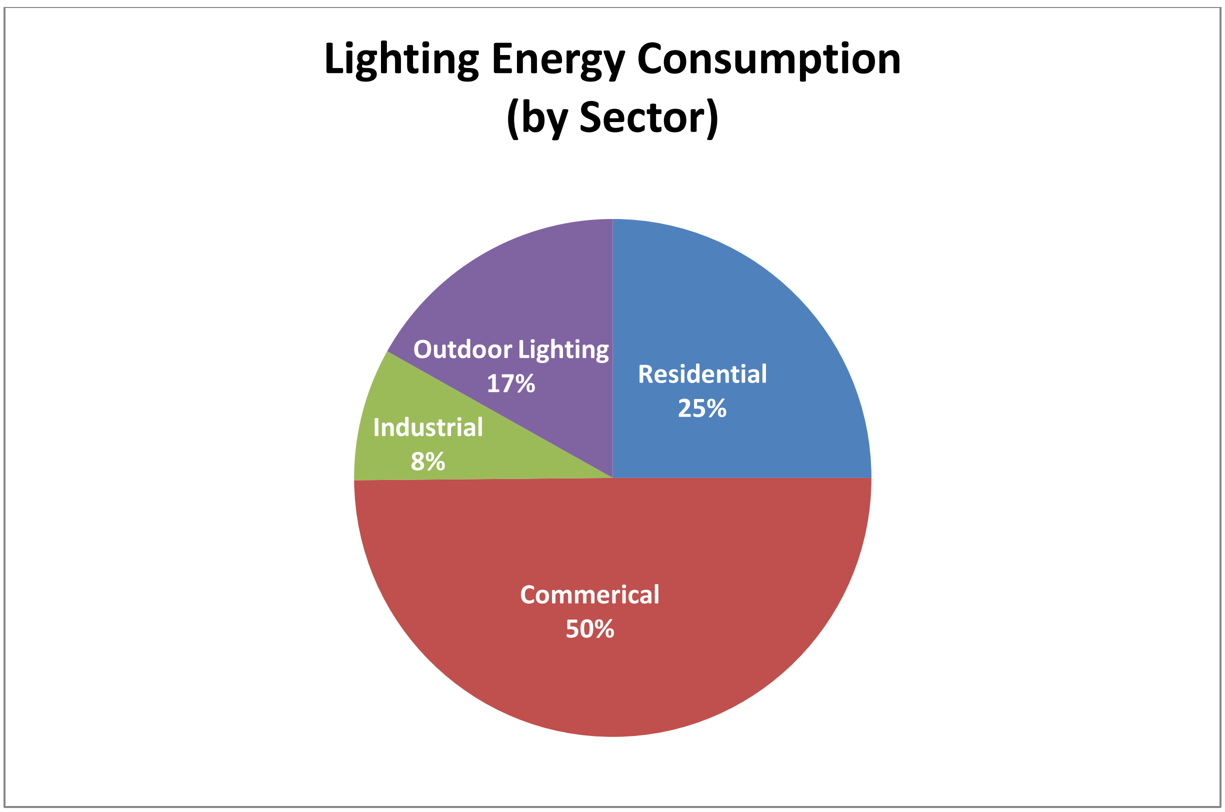


Figure 1

See Figure 1, nearly half of the lighting electricity is consumed in the commercial sector, which also represents the sector in which the majority of lumens are produced. This sector is dominated by linear fluorescent area lighting. The residential sector's large installed base of low efficacy lighting causes the sector to be the second largest lighting energy consumer, at 175,000 GWH per year or 25% of the total lighting energy consumption. Outdoor lighting follows at 17% and industrial at 8%.

The outdoor stationary sector accounts for the remainder of lamps not installed inside buildings. The outdoor subsectors are based on the application where the lamp is used. This includes lamps that may be associated with a specific commercial or industrial building but are installed on the exterior, such as parking lot lights or exterior wall packs.

Lighting Inventory and Energy Consumption Estimates

The light sources are grouped into six broad categories: incandescent, halogen, compact fluorescent, linear fluorescent, high intensity discharge, and solid state/other. Within each of these are subgroups of commonly available lighting products (e.g., reflector lamps, T8 fluorescent tubes, metal halide lamps). In total, 28 lamp types are included.

The lamp technologies have been categorized as displayed below in Figure 2.

Figure 2

There have been significant changes in the lighting stock and energy consumption characteristics during the past decade. Two notable trends include:

- Increased demand for light. The total number of lamps installed in U.S. applications grew from just under 7 billion in 2001 to over 8 billion in 2010. The majority of the growth occurred in the residential sector, primarily due to the increase in number of households and the rise in the number of sockets per household, from 43 in 2001 to 51 in 2010.

- Push towards higher efficacy lighting. Investment in more energy efficient technologies, lighting regulations, and public awareness campaigns has been effective in shifting the market towards more energy efficient lighting technologies. Across all sectors the lighting stock has become more efficient, with the average system efficacy of installed lighting increasing from 45 lumens per watt in 2001 to 58 lumens per watt in 2010. This rise in efficacy is largely due to two major technology shifts; the move from incandescent to compact fluorescent lamps (CFLs) in the residential sector, and the move from T12 to T8 and T5 fluorescent lamps in the commercial and industrial sectors.

The total installed base of lamps in 2010 was estimated to be 8.2 billion. This represents an overall growth of 17% in the past decade. In general, the bulk of lamp inventory growth has been in the residential sector, which accounts for more than double the number of lamps in the remaining sectors combined. The lamp inventory in the residential and commercial sectors have increased by 26 percent and 13 percent, respectively, largely due to an increase in number of homes and floor space. In contrast, the industrial sector lamp inventory has decreased by 54 percent over the past ten years, mostly due to a reduction in manufacturing floor space and a movement toward higher lumen output technologies, such as HID. The outdoor sector has seen a moderate decline of 16 percent relative to 2001.

In the residential sector, the most obvious trend is a transition from general service incandescent lamps (decreasing from 79 percent to 52 percent in 2010) to screw-base general service CFLs (increasing from 2 percent to 19 percent in 2010). In addition, there has been significant movement toward directional lamps (such as incandescent reflector, halogen reflector, and halogen low voltage display), which now comprise 10 percent of the residential installed base.

In the commercial sector, there has been a migration from T12 linear fluorescent lamps to T8 and T5 linear fluorescent lamps. In 2001, T8 lamps comprised less than 34 percent of the commercial installed base of linear fluorescent lamps, with the remaining base being overwhelmingly T12 lamps. In contrast, in 2010, T5s, T8s, and T12s constituted 7 percent, 61 percent, and 33 percent of the installed base of linear fluorescent lamps, respectively.

While the industrial sector depicts many of the same trends as the commercial sector, one unique trend is an increase in the prevalence of HID lamps, which doubled in share relative in the past decade. This movement from lower lumen output fluorescent lamps to higher lumen output HID lamps may also account for part of the reduction in overall number of lamps installed in the industrial sector. Although the data indicates a migration toward HID sources (likely in high bay applications), it is uncertain whether this trend will persist as fixture sales data indicates a recent increase of high lumen output linear fluorescent systems in the industrial sector, potentially replacing HID systems in low-bay applications.

The outdoor sector groups all incandescent, halogens, CFLs, and linear fluorescents in miscellaneous categories. This was done as many of the data sources used for the outdoor sector did not provide inventory detail beyond the general lamp technology level. The primary trend evident in this sector is a movement from mercury vapor lamps toward HPS, which now accounts for 32% of the installed base.

Table 1 presents the distribution of lamps by end-use sector. Linear fluorescent and incandescent lamps are estimated to comprise the majority of the installed base. While the overall shares of linear fluorescent and HID lamps have remained largely unchanged, incandescent lamp shares have decreased from 62 percent to 45 percent, while the CFL inventory shares have correspondingly increased from 3 percent to 19 percent, all in the past decade.

Table 1
Lamp Inventory by Sector
(Percent)

Lamp Category		Residential	Commercial	Industrial	Outdoor	Total
Incandescent		**62.0**	**3.7**	**0.3**	**10.0**	**45.1**
	General – A type	34.9	2.1	0.3	0.0	25.3
	General – Deco	16.9	0	0	0.0	11.9
	Reflector	7.5	0.9	0	0.0	5.5
	Miscellaneous	2.8	0.7	0	10.0	2.4
Halogen		**4.4**	**2.3**	**0.0**	**2.3**	**3.8**
	General Service	0.5	0.0	0.0	0.0	0.3
	Reflector – Other	2.9	0.9	0.0	0.0	2.3
	Reflector – Low Voltage	0.3	1.2	0.0	0.0	0.5
	Miscellaneous	0.7	0.1	0.0	2.3	0.6
CFL		**22.8**	**10.4**	**0.3**	**6.8**	**18.9**
	General – Screw	19.3	2.0	0.1	0.0	14.2
	General – Pin	0.1	6.6	0.1	0.0	1.7
	Reflector	2.0	1.9	0.1	0.0	1.9
	Miscellaneous	1.4	0.0	0.0	6.8	1.1
Fluorescent		**9.9**	**80.0**	**89.2**	**16.3**	**29.1**
	T5	0.1	5.2	6.4	0.0	1.5
	T8 < 4ft	0.1	0.7	0.5	0.0	0.2
	T8 4ft	1.1	43.9	54.4	0.0	12.8
	T8 > 4ft	0.0	1.3	2.3	0.0	0.4
	T12 < 4ft	0.1	0.4	0.0	0.0	0.2
	T12 4ft	5.7	19.8	16.6	0.0	9.3
	T12 > 4ft	0.5	5.3	7.5	0.0	1.8
	T8 U-Shaped	0.0	2.2	0.4	0.0	0.6
	T12 U-Shaped	0.0	0.5	07	0.0	0.1
	Miscellaneous	2.3	0.6	0.3	16.3	2.1

HID		**0.0**	**1.7**	**9.8**	**52.2**	**1.7**
	Mercury Vapor	0.0	0.0	1.0	2.3	0.1
	Metal Halide	0.0	1.5	6.5	16.5	0.8
	High Pressure Sodium	0.0	0.2	2.3	32.5	0.8
	Low Pressure Sodium	0.0	0.0	0.0	0.8	0.0
Other		**0.9**	**1.9**	**0.4**	**12.5**	**1.4**
	LED	0.2	1.8	0.4	10.8	0.8
	Miscellaneous	0.8	0.0	0.0	1.7	0.6
Total		**100%**	**100%**	**100%**	**100%**	**100%**

The following four sections examine the cumulative results for all lamp technologies by sector focusing on the subsector level results. Specifically, details on the installed base, average system wattage and operating hour characteristics of all lamps are evaluated by the defined subsectors within the residential, commercial, industrial and outdoor sectors.

Residential

"Intensity Rank" is a measure of how much energy is expended per year per square foot of lighted space.

In the residential sector, the number of lamps grew faster than the growth in residences due to the larger floor space and a greater number of lamps per square foot in newer homes. However the prominence of CFLs caused a large decrease in average wattage. See Table 2. Single family detached housing has the highest *intensity rank* at 0.9 kWh/yr/ft^2.

Table 2
Lighting Use by Residence Type

	Floor Space	Wattage (Watts/Ft2)	Energy Use (Kwh/yr)	Intensity (Kwh/yr/ft2)	Intensity Rank
Single Family Detached	2,178	1.1	1,922	0.9	1
Single Family Attached	1,816	1.1	1,279	0.7	2
Multifamily	1,050	1.0	679	0.6	3
Mobile Homes	1,395	1.0	975	0.7	4

Commercial

In the commercial sector, food stores have the highest intensity rank at 7.3 kWh/yr/ft^2.

The commercial sector uses more light than all the other sectors combined, largely due to its high average operating hours and large floor space. The outdoor sector produces second greatest amount of lumens, also due to the use of high lumen output lamps for long operating hours (in this case, during most of the night). The industrial sector uses the third most light. The residential sector, which houses the largest quantity of installed lighting stock predominately utilizes low lumen output lamps for relatively few hours per day and thus uses the least amount of lumens relative to the other three sectors.

Across all sectors, fluorescent lamps, responsible for approximately 55 percent of annual lumen production nationally, produce the most lumens of all the technologies. HID light sources are the second most important, producing about 34 percent of the total national light output. Because incandescent lamps are most often found in sockets that are turned on relatively infrequently, and given their characteristically low lumen outputs, the total lumen production of the technology only accounts for 5 percent of the total. See Table 3.

Table 3
Lighting Use by Commercial Building Type

	Lamps per 1,000 ft2	Wattage (Watts/Ft2)	Energy Use (kWh/yr)	Intensity (kWh/yr/ft2)	Intensity Rank
Education	17	0.6	65,100	2.5	13
Food Service	32	1.3	30,100	5.4	4
Food Store	40	1.8	40,800	7.3	1
Health Care Inpatient	26	0.8	768,100	3.2	10
Health Care Outpatient	37	1.3	55,900	5.4	5
Lodging	18	0.6	85,300	2.4	14
Offices	33	1.0	60,800	4.1	9
Public Assy	24	1.0	58,900	4.1	8
Public Safety	19	0.7	43,200	2.8	12
Churches	27	1.1	45,100	4.4	6
Retail	34	1.5	107,800	6.3	2
Services	28	1.4	37,400	5.7	3
Warehousing	17	1.1	71,900	4.3	7
Other	18	0.8	70,500	3.2	11

In the commercial sector, the installed lamp base has increased but this increase lagged the growth in commercial floor space.

Industrial Results

In the industrial sector, paper mills have the highest intensity rank at 10.8 kWh/yr/ft^2 and mineral product operations are second at 8.5 kWh/yr/ft^2. See Table 4.

Table 4
Lighting Use by Industrial Building Type

	Lamps per 1,000 ft2	Wattage (Watts/Ft2)	Energy Use (kWh/yr)	Intensity (kWh/yr/ft2)	Intensity Rank
Apparel	15	1.1	154,800	6.1	8
Beverage	11	0.7	93,600	3.9	19
Chemicals	15	1.1	58,500	5.8	11
Electronics	23	1.1	228,300	5.8	12
Appliances	20	1.6	511,000	8.4	3
Metal	10	1.2	167,000	6.5	6
Food	8	1.1	110,400	6.1	9
Furniture	10	1.0	242,500	5.2	14
Leather	15	1.1	117,100	4.1	18
Machinery	9	0.8	143,400	4.1	17
Mineral Products	10	1.5	106,700	8.5	2
Paper	8	1.7	366,400	10.8	1
Petroleum & Coal Products	7	0.6	17,300	3.5	20
Plastics & Rubber Products	14	0.9	232,200	4.4	15
Primary Metals	20	1.2	93,900	6.0	10
Printing	21	1.3	181,200	6.8	4
Textile Mills	15	1.1	440,600	6.7	5
Textile Products	5	0.3	74,300	1.6	21
Transportation	26	1.1	228,000	5.4	13
Wood Products	9	0.9	27,500	4.4	16
Misc	24	1.2	78,800	6.1	7

Outdoor Lighting

As can be seen in Table 5, parking and roadway lighting comprise the majority of outdoor lighting with metal halide and high pressure sodium being the predominate lamp types.

Table 5
Energy Use by Outdoor Lighting
(000's GWH/yr)

	Incandescent	**Halogen**	**CFL**	**Fluor. Tube**	**MV**	**MH**	**HPS**	**LPS**	**LED**	**Other**	**Total**
Bldg Ext.	3	1	1	2	1	3	2	0	0	0	**12**
Airport	0	0	0	0	0	0	0	0	0	0	**0**
Billboard	0	0	0	0	0	1	0	0	0	0	**1**
Railway	0	0	0	0	0	0	0	0	0	0	**0**
Stadium	0	0	0	0	0	1	0	0	0	0	**1**
Traffic Signals	0	1	0	0	0		0	0	0	0	**1**
Parking	1	0	0	8	1	20	20		1	1	**52**
Roadway	0	0	0	0	2	5	43	1	0	0	**51**
Total	**4**	**1**	**1**	**10**	**4**	**29**	**65**	**1**	**2**	**1**	**118**

Lighting Controls

In recent years, lighting controls have garnered increased attention as a potential method of more intelligently operating lighting systems to save energy. Lighting controls, which include various dimming and sensor technologies used separately or in conjunction with other systems such as timers and daylighting, can, if used properly, yield very significant energy savings, as they use feedback from the lit environment to provide adequate lighting levels only when needed.

Lighting controls can save energy by either reducing input wattage or limiting hours of operation. The average operating hours presented in this report account for the use of certain controls, such as timers and Energy Management Systems (EMS), because they are based on building surveys and metering data.

The following discussion provides a brief description of each of the lighting control types examined in this study:

- Dimmers allow users to manually regulate the level of lighting in a building by adjusting the voltage reaching the lamp. As voltage input is reduced, either by way of a step function or a continuous function, the lumen output of the system is proportionally decreased.

- Light sensors, or photocells, also work by dimming or by on/off cycling. In response to detected light levels, light sensors regulate the lumen output in order to supplement available natural light with an optimized level of artificial lumen output.

- Motion detectors, or occupancy sensors, switch the lamp on for a set period of time in response to detected motion and are useful in areas that are sporadically occupied. This control type saves energy by reducing hours of operation of lighting.

- Timers provide lighting service on a preset schedule, without the need for manual operation. This control type also saves energy by reducing hours of operation.

- Energy management systems are information and control systems that monitor occupancy and lighting in the built environment in order to provide centralized lighting control. They often combine several of these control technologies to reduce energy consumption.

Lighting controls are more frequently installed in the commercial sector than in the residential, with an estimated 31 percent of lamps in the commercial sector being used in conjunction with lighting controls. This is in contrast to only 14 percent of residential lamps being used with lighting controls.

In contrast to the residential sector the likelihood of finding lighting controls in the commercial sector is not greatly impacted by the lamp type. Approximately 25 percent of all lamp types are used in conjunction with lighting controls. Energy management systems, which often include multiple control types, predominate as the most often utilized controls scheme.

The choice of lighting controls also depends on the building type and how and to what extent the space is used. In the commercial sector, lighting controls are most popular in retail settings, in which 40 percent of lamps operate on an EMS and 7 percent operate on a timer. Lighting controls are also very common in non-medical office buildings and food stores (i.e., not restaurants), where they are used on 48 percent and 40 percent of lamps, respectively. Lighting controls are uncommon in public order and safety, religious worship, lodging, and restaurants.

Lighting controls equate to energy savings only if they are used. For automated control types, such as time clocks and occupancy sensors, this is a nonissue. However, dimmers, the most popular control in the residential sector, typically require users to manually adjust the level of light output. Nonetheless, if used properly, light controls can yield huge energy savings. For example, a recent study found that occupancy sensing, daylight harvesting, and individual occupant dimming control working together in an office building produce average energy savings of 47 percent.

Chapter 2
Lighting Fundamentals

In this chapter we review the fundamentals of lighting theory. There are two theories about how light travels: wave theory and particle theory. The *wave theory* is most often used to describe the physics of light. According to the wave theory, light is a form of radiant energy that travels in waves. Visible light is a form of electromagnetic energy and like all electromagnetic energy travels at the speed of light and the electromagnetic flux spreads out from its source in waves. The effect is similar to the action created by throwing a pebble in a pond. Wavelength, λ, is the distance between the waves. The number of waves during a given period is known as the frequency. Frequency is equal to the speed of light divided by the wavelength and is measured in Hertz.

Another idea – called *particle theory* - is to consider light as groups of particles emitted by the light source. A ray of light consists of a stream of particles traveling in a straight line. The particles, or photons, vibrate at the frequency of the light.

Both the wave theory and the particle theory can be used to help explain lighting principles and there are advantages to using both theories of light to help gain an understanding of how light is produced and projected.

All forms of electromagnetic energy have a characteristic frequency. Visible light is a narrow band between ultraviolet (UV) and infrared energy on the electromagnetic spectrum. Actually, ultraviolet and infrared energy are considered light because they behave like visible light and both are present when visible light is present. Electromagnetic waves in this frequency band can be focused, reflected and absorbed. See Figure 3.

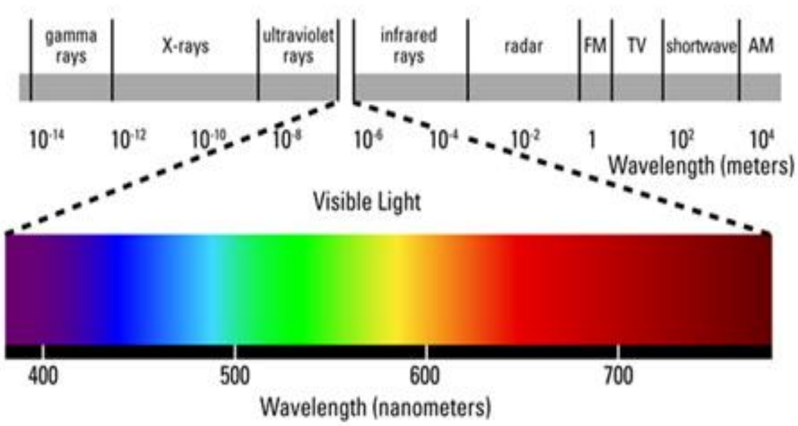


Figure 3

Light is comprised of all wavelengths within the visible portion of the electromagnetic spectrum. The relative balance of the different wavelengths, each corresponding to a distinct color, determines the tint of the light. Color temperature is the measurement used to describe the tint of light.

Measurement of Light

The measurement of light, or *Photometry*, requires knowledge of basic lighting terms. The measurement of light is based on the light output of a candle. Lumen, illumination, foot-candle, candela, exitance, inverse square law, and the cosine law are important terms in the study of lighting.

A *lumen* is the unit used to describe the quantity of light radiated from a light source. Technically, a lumen is the amount of luminous flux (light output) of light radiated into a solid angle of one steradian by a uniform light source of one candela. (A steradian is a unit solid angle subtending an area on the surface of a sphere equal to the square of the sphere radius.) See Figure 4.

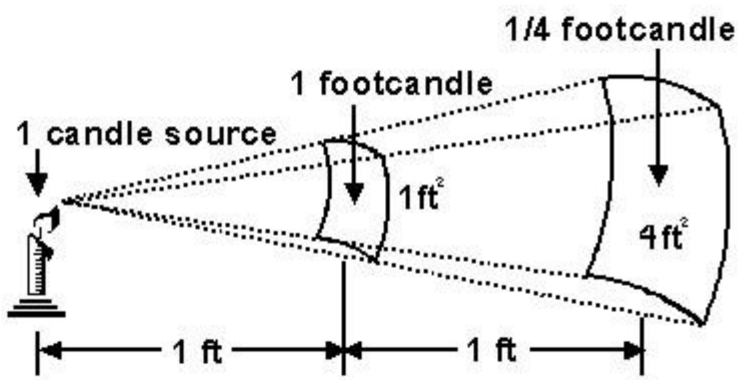


Figure 4

When luminous flux falls upon a surface, it is illuminated, and the effect is called *illumination*. This luminance is the perceived brightness of a light source. The unit of illumination is the *foot-candle* and is equal to a flux density of one lumen per square foot. Illuminance does not account for any of the reflective or transmissive properties of the surface but merely the amount of light the surface receives. One lumen uniformly distributed over 1 square foot produces an illumination of one foot-candle (fc).

$$\mathbf{FC = 1\ lumen/ft^2}$$

A *candela* is the unit of luminous intensity emitted by a light source in a given direction and is used to describe the directionality and intensity of light leaving a luminaire.

Exitance is a term that is used for relative brightness calculations. Exitance measures the total amount of light that leaves a reflective surface, measured in lumens per square foot. Exitance is determined by multiplying the Illuminance (fc) times the reflectance of a surface. Only diffuse, and no specular, reflection is assumed. For example, a 50 foot-candle illuminance on a surface of 90% reflectance will produce an exitance of 45 foot-candles.

Illumination from a single, or point, source behaves according to the inverse square law. The *inverse square law* expresses the relationship between luminous intensity (in candelas) and illumination (brightness). It states that illumination at a point on a surface is directly proportional to the luminous intensity of the light at that point and inversely proportional to the square of its distance from the source. When the point is on a surface perpendicular to the light, the following formula applies:

$$\mathbf{E = fc = Cd / D^2}$$

Where,
E = Illumination.
Fc = foot-candles.
Cd = Candela directed toward the point of interest.
D = Distance form light source to the point of interest.

Referring back to Figure 4 for a sample calculation, assume that a source has 1-candela and is 2-feet from the point of interest. The illumination is:

$Fc = 1 / 2^2$

Fc = ¼.

As can be seen from the above formula, the lumens per square foot decreases inversely with the square of the distance. At a distance of one foot from a source of one candela the illumination is one foot-candle.

A beam of light striking a surface at an angle covers a larger area than when the light strikes a surface on the perpendicular. The *cosine law* states that the illumination of a surface is proportional to the cosine of the angle of incidence of the ray of light. See Figure 5.

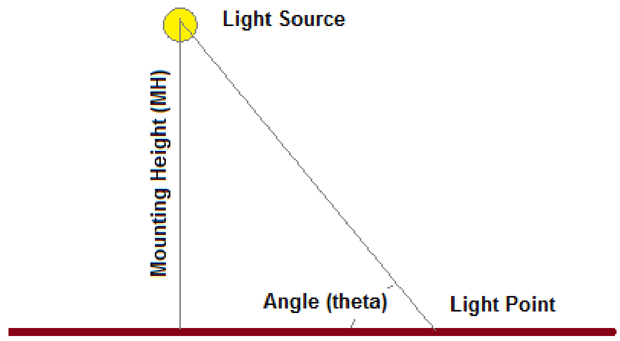


Figure 5

Considering the cosine law, the inverse square law becomes:

$$\mathbf{Fc = Cd/D^2 * \cos(\alpha)}$$

As an example, if we have 5,000 candela at a distance of 12 feet and the point of interest is 30 degrees from the source the illumination will be:

$Fc = 5,000 / 12^2 * \cos(30)$

Fc = 35 x 0.866

Fc = 30 footcandles

Table 6, shown below, has the recommended lighting levels for various work areas. As you can see in the table, work area lighting may range from a low of 5-footcandles for some warehouse space to 100-footcandles for detailed assembly work.

Table 6 **Recommend Lighting Levels**	
Area Use	**Illumination (Min Foot-candle's)**
Material Assembly	
Rough assembly, easy to see	30
Rough, difficult to see	50
Medium assembly	100

Auditoriums Social activities Assembly Exhibitions	 5 15 30
Welding	50
Warehousing Inactive Active Rough Medium Fine	 5 10 20 50
Woodworking	50
Restrooms	30
Waiting rooms	30

Optical Characteristics of Light

When light strikes a surface one of three actions will occur: the surface can absorb the light, the surface will reflect the light, or the light will be transmitted through the surface. Transmitting surfaces will exhibit all three traits. Opaque surfaces do not transmit light, but they still have absorptive and reflective properties.

The reflection and transmission of light are important in the design of lighting materials and in predicting lighting levels in a space. The term *transmission*, quantifies the amount of light passing though light fixture lenses and diffusers.

Opaque materials reflect light by both specular reflection and by diffuse reflection. *Specular reflection* occurs when light is reflected at a consistent angle from a surface. The reflected light from a mirror is a good example of specular reflection. Specular distribution is a measure of the reflected light and is expressed as a percentage of the light striking the surface. See Figure 6.

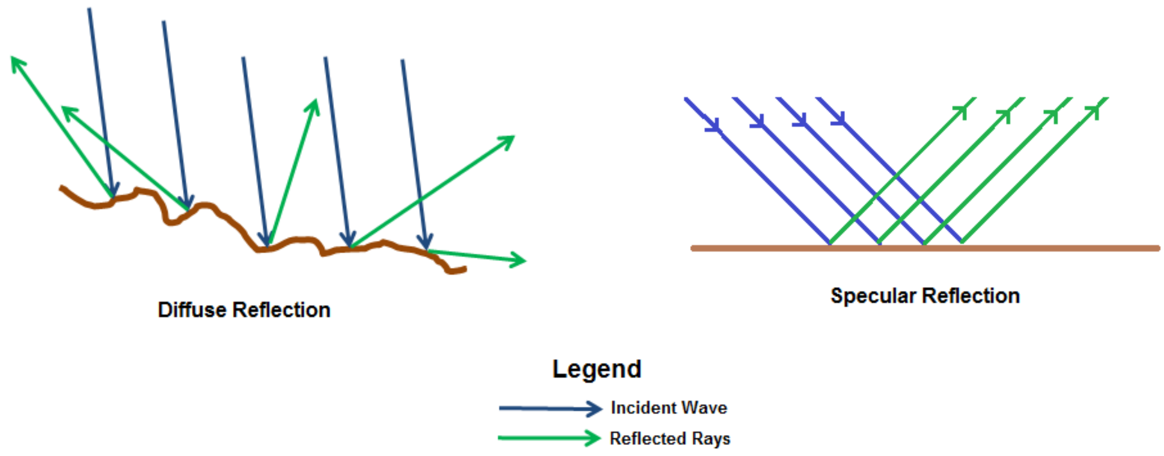


Figure 6

Diffuse reflection scatters reflected light in all directions such as when light reflects from a rough surface. Light reflecting off walls is a good example of diffuse reflection. A glossy paint on a wall is said to be a low diffuse reflector, whereas, a flat paint is said to be almost perfectly diffuse. Like specular reflection, diffuse reflection is expressed as a percentage of diffusion. White ceiling paint has about 85% diffuse reflection. Remember, a high percentage of diffusion means the surface scatters light very efficiently. Diffuse reflection is used to minimize glare, hot spots, and shadows. Most materials exhibit both specular and diffuse reflection and the total reflection is the sum of the specular and diffuse reflections.

Light can be transmitted through both transparent and translucent materials. *Transparent* materials, such as clear plate glass, allow virtually all of the light to move through the material unimpeded and, with very little bending of the light ray. Transparent materials allow objects to be viewed through the material. *Translucent* materials, such as frosted glass, also transmit light but the light is diffused or scattered. Translucent materials transmit light by diffuse transmission and objects are not seen distinctly through it because the light rays are bent as they pass through the material.

Diffuse transmission, such as occurs through frosted glass scatters incoming rays of light in all directions. This is useful in evenly distributing the output of a light source such as a frosted incandescent bulb.

The ratio of light transmitted through a material to light striking a surface is called *transmittance*. Most materials exhibit some qualities of both transparency and translucency.

Refraction causes light rays passing through one material to enter into another material at a different angle and intensity. This bending, or refraction, is important in the design of lighting fixtures.

Lenses use the principles of diffusion and refraction to cause light to travel in a desired direction. Common lens types include plano, concave, convex, fresnel, and diffusing lens. *Plano* lenses are simply flat plate lenses. *Concave* lenses allow light rays to spread while *convex* lenses focus light. A fresnel lens is a special form of either a concave or convex lens. A *fresnel* lens is specially cut to produce a desired focus or spreading of the light rays and can be manufactured to be lighter than a corresponding concave or convex lens. *Diffusing* lenses are used to broadly distribute light and to soften the intensity of the light source.

Chromaticity

Chromaticity is expressed by the Correlated Color Temperature (CCT). *Correlated Color Temperature* (CCT) is a metric that relates the appearance of a light source to the appearance of a theoretical black body heated to high temperatures. As a black body gets hotter, it turns red, orange, yellow, white, and finally blue. The CCT of a light source, given in Kelvin (K), is the temperature at which the heated black body most closely matches the color of the light source in question. It characterizes the color of the emitted light, not the color of illuminated objects. The chromaticity is measured on a Kelvin (K) temperature scale with the high temperatures representing "cooler" light sources. Color temperatures below 3,500K are considered warm, with red, yellow, and orange tints. Color temperatures above 5,000K are saturated in green and blue wavelengths lending to the "cool" designation. As a reference, a candle flame has a color temperature of 1,800K and an incandescent lamp has a color temperature of about 2,700K. Daylight has a CCT of at least 5,500K. See Table 7.

Table 7
Color Temperature Examples (CCT)

Color Temperature	Example
2,200k	High Pressure Sodium
2,700k	Incandescent Lamp
3,000k	Halogen Lamp
3,200k	Metal Halide – White
4,000k	Metal Halide – Standard

4,200k	Cool White Fluorescent
5,500k	Metal Halide – Daylight

Looking at this another way, Figure 7 shows the color temperatures on a color-continuum.

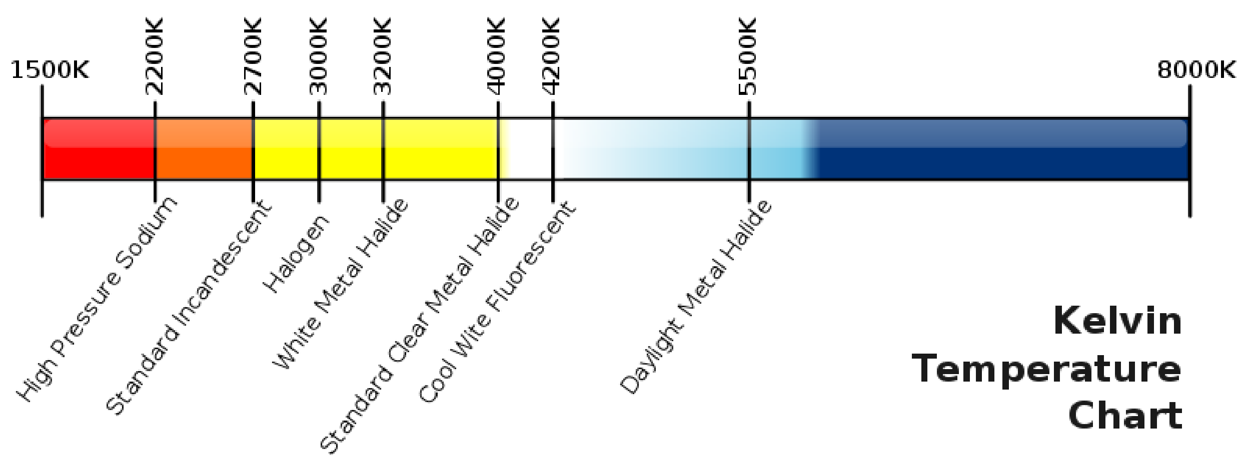


Figure 7

Like many color appearance metrics, CCT distills a complex spectral power distribution to a single number. This can create discord between numerical measurements and human perception. For example, two sources with the same CCT can look different, one appearing greenish and the other appearing pinkish. To address this issue, the American National Standards Institute (ANSI) references *Duv* - a metric that quantifies the distance between the chromaticity of a given light source and a blackbody radiator of equal CCT.

At least three aspects of color rendition are relevant to light source selection and application. These include the accurate rendition of colors so that they appear as they would under a familiar source, the rendition of colors such that objects appear more pleasing, and the ability of a source to allow for a subject to distinguish between a large variety of colors when viewed simultaneously. For simplicity, these three facets of color rendering may be called *fidelity*, *appeal*, and *discrimination*. The relative significance of these different elements of color rendition depends on the application.

Color rendition metrics attempt to characterize human perception of one or more of these elements using numerical methods, but they are not perfect. Some of the imperfections of well-established metrics have been revealed by the emergence of LED lighting products, which often have spectral power distributions that are different from those that were common when the metrics were developed.

Color rendering index (CRI) is a measure of how well colors can be perceived using light from a source, relative to light from a reference source such as daylight or a blackbody of the same color temperature. By definition, an incandescent lamp has a CRI of 100. Real-life fluorescent tubes achieve CRIs of anywhere from 50 to 99. Fluorescent lamps with low CRI have phosphors that emit too little red light. Skin appears less pink, and hence "unhealthy" compared with incandescent lighting. Colored objects appear muted. For example, a low CRI 6800 K halophosphate tube will make reds appear dull red or even brown. Since the eye is relatively less efficient at detecting red light, an improvement in color rendering index, with increased energy in the red part of the spectrum, may reduce the overall luminous efficacy.
Lighting arrangements use fluorescent tubes in an assortment of tints of white.

The International Commission on Illumination (CIE)'s *Color Rendering Index* (CRI) is a measure of fidelity (i.e., how "true" a light source is when compared to the reference source), but it does not address the other two aspects of color rendering listed above: appeal and discrimination.

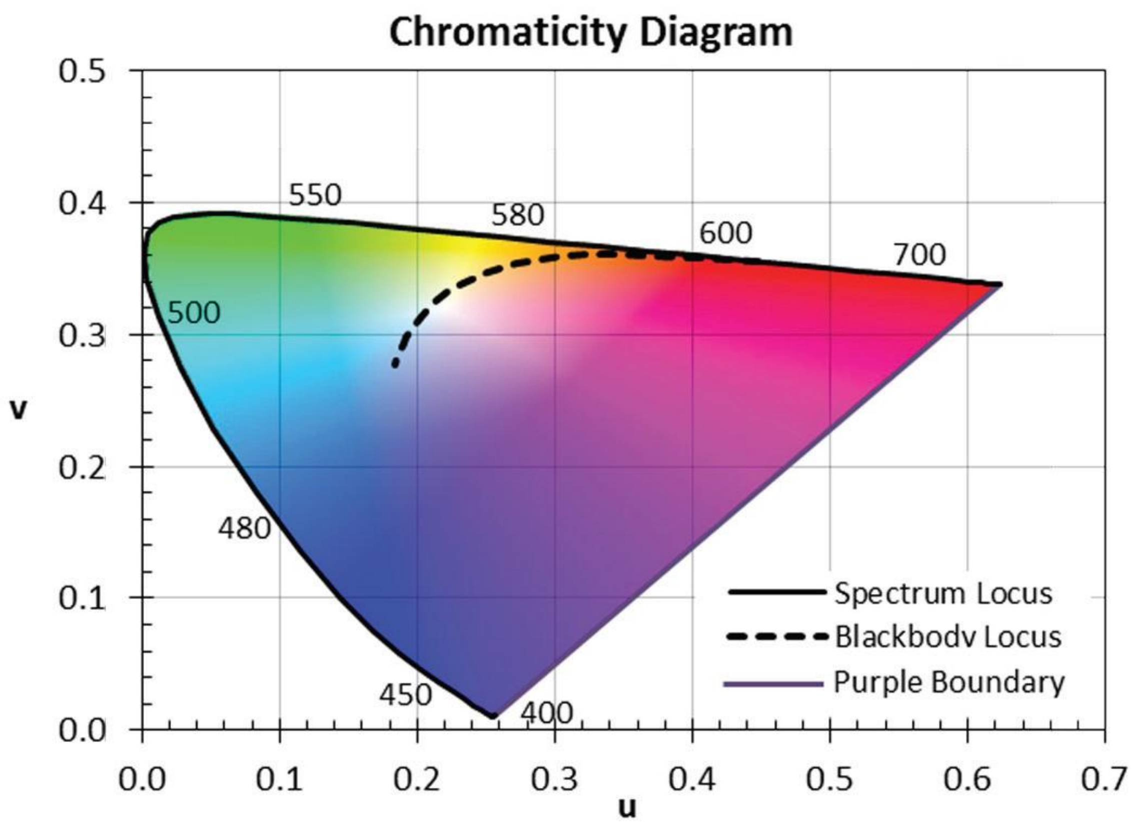


Figure 8

Figure 8, shown above is a CIE 1960 (u, v) chromaticity diagram in which CCT, CRI, and Duv are calculated. A chromaticity diagram should not be interpreted as a two-dimensional map of color, since the bright-dim dimension (lightness) is not represented. Colored backgrounds, as are shown here, are for orientation only.

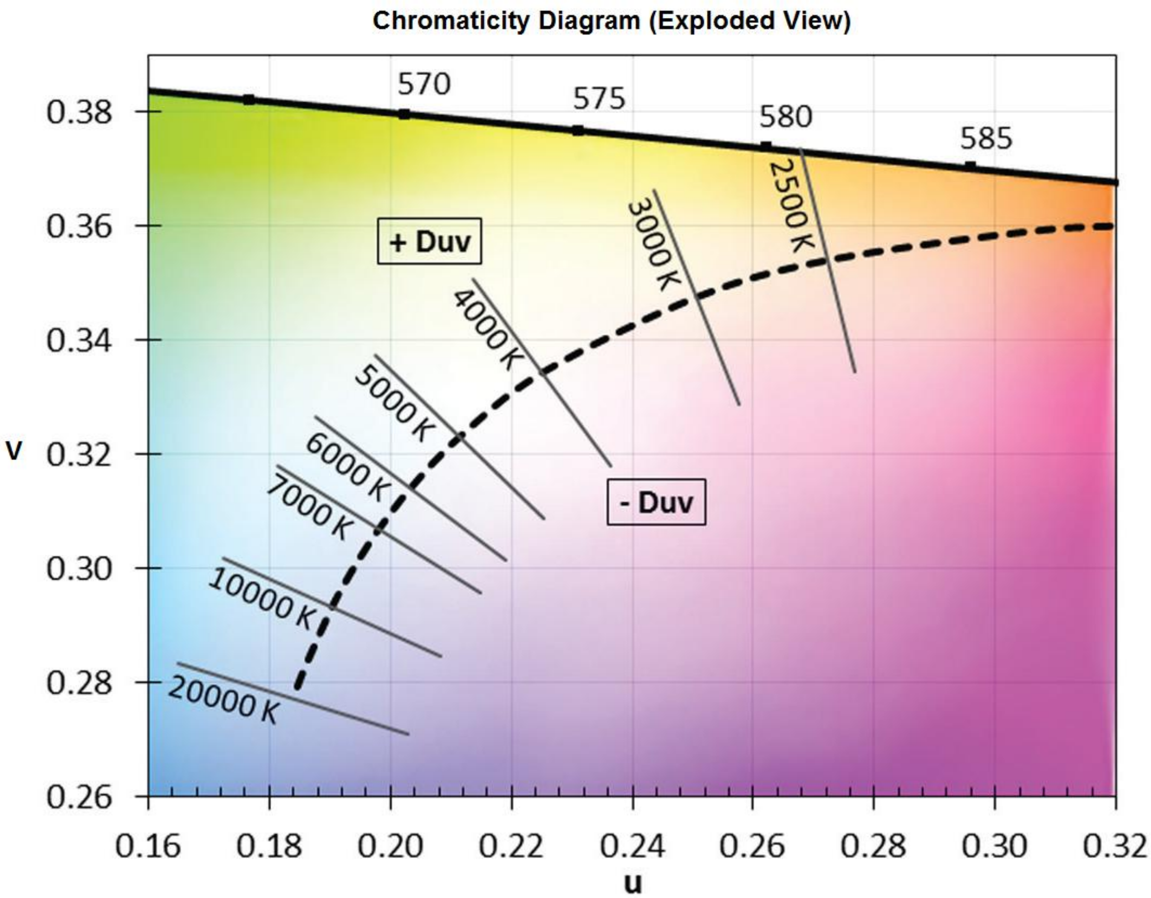


Figure 9

Figure 9, shown above is a close up of the chromaticity diagram showing lines of constant CCT, which are perpendicular to the blackbody locus. For a given CCT, a source with a positive value for Duv has a chromaticity that falls above the blackbody locus (appearing slightly greenish), whereas a source with a negative value for Duv has a chromaticity that falls below the blackbody locus (appearing slightly pinkish). The lines in this chart represent a Duv range of ± 0.02, which is much greater than ANSI tolerances for white light.

The CIE Test-Color Method, shown in Figure 10, utilizes eight standard color samples—having moderate lightness and of approximately equal difference in hue (i.e., equal spacing on a chromaticity diagram)—and six special color samples. It is an approximation of color samples used for the calculation of CRI, R9–R14, and CQS.

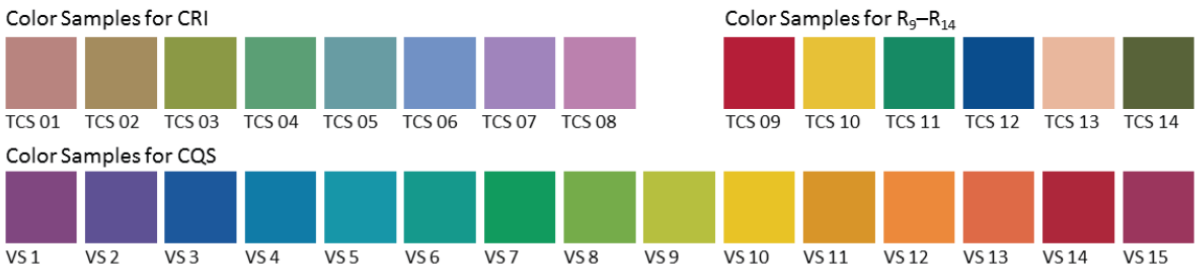


Figure 10

For each color sample, the chromaticity under a given (test) source can be compared to the chromaticity under a reference source of equal CCT, allowing for the measurement of color difference that is then mathematically adjusted and subtracted from 100 (Ri). The principal metric of the CIE system is the Color Rendering Index (CRI), which averages the Ri scores for the eight standard test colors and typically has a range from 0 to 100, though negative scores are also possible. A score of 100 indicates that the source renders colors in a manner identical to the reference. In general, a source with a CRI in the 70s would be considered acceptable for interior applications, whereas the 80s would be considered good and the 90s excellent. Because it is a reference-based metric, comparing the CRI for sources with different CCTs should only be done with great caution. Furthermore, two light sources with the same CCT and CRI may not render colors the same way (i.e., colors may still look different).

> The reference is specified as blackbody radiation for CCTs below 5000 K, or a mathematical model of daylight for higher CCTs. Because CRI is a reference based metric, it is not appropriate to compare the CRI values for sources of very different CCTs.

The special color rendering indices, referred to as R9 through R14, are each based on a single test color. They are not used for calculation of CRI but may be used for supplemental analysis when necessary. The “strong red” color sample, R9, is especially pertinent since the rendition of saturated red is particularly important for the appearance of skin tones, among other materials. An R9 score greater than zero is generally considered acceptable since the color space used in the CIE Test-Color Method often causes color shifts in the red region to be exaggerated.

While CRI is the standard for evaluating color rendering, strictly speaking it only captures the ability of a source to render colors similar to the reference source. Consequently, a source with a very low CRI may actually render objects so that they are more pleasing to an observer than a source with higher CRI. Aside from this conceptual concern, CRI has many technical limitations including the chosen color space and the limited number and type of color samples. Ultimately, subjective visual evaluation remains the most reliable means of ensuring adequate color quality.

One of the more notable recent attempts to address the imperfections of CRI is the *Color Quality Scale* (CQS), developed by researchers at the National Institute of Standards and Technology

(NIST). Although it makes significant updates based on current vision science—including a revised and expanded set of test color samples (see Figure 9)—the basic approach remains similar and the results are highly correlated with CRI. Despite significant initial interest, it has not yet been officially adopted by any standards organization and its use has yet to become widespread. Other recently developed metrics have utilized different methods in their approach, but although some offer significant advantages, none has achieved consensus support.

Many researchers have noted that evaluating color rendition based on a combination of several metrics tends to produce results more representative of human perception. Some newly proposed metrics have addressed this by including multiple numeric ratings to represent the different facets of color rendition, but there has been some reluctance to move away from a single-number metric. Despite the challenges of meeting the needs of different user groups, developing improved metrics remains imperative for improving the effectiveness of specifications and enabling manufacturers to optimize products. This is especially pertinent given the expanding market share of solid-state lighting.

Chapter 3
Principles of operation

Now that we have covered the fundamentals of lighting theory, we will discuss the basic principles of fluorescent lighting. This will include the physics of how fluorescent lamps operate construction issues, ballasts and starting aids, and failure modes.

Physics of Fluorescent Lighting

Atoms release light photons when their electrons become excited. When an atom gains or loses energy, the change is expressed by the movement of electrons. When something passes energy on to an atom an electron may be temporarily boosted to a higher orbital. This higher energy state is unstable, and the atom will emit an ultraviolet photon as the atom's electron reverts to a lower, more stable, energy level. Most of the photons that are released from the mercury atoms have wavelengths in the ultraviolet (UV) region of the spectrum, predominantly at wavelengths of 185 and 253.7 nanometers (nm). These are not visible to the human eye, so they must be converted into visible light. This is done by making use of *fluorescence*. Ultraviolet photons are absorbed by electrons in the atoms of the lamp's interior fluorescent coating, causing a similar energy jump, then drop, with emission of a further photon. The photon that is emitted from this second interaction has a lower energy than the one that caused it. The chemicals that make up the phosphor are chosen so that these emitted photons are at wavelengths visible to the human eye. The difference in energy between the absorbed ultraviolet photon and the emitted visible light photon goes toward heating up the phosphor coating.

> **Fluorescence** is the emission of light by a substance that has absorbed light or other electromagnetic radiation.

When a light is turned on, the electric power heats up the cathode enough for it to emit electrons. These electrons collide with and ionize gas atoms inside the bulb surrounding the filament to form plasma by the process of impact ionization. As a result of avalanche ionization, the conductivity of the ionized gas rapidly rises, allowing higher currents to flow through the lamp.

The type of fill gas helps determine the operating electrical characteristics of the lamp, but does not give off light itself. The fill gas effectively increases the distance that electrons travel through the tube, which allows an electron a greater chance of interacting with a mercury atom. Argon atoms, excited to a metastable state by impact of an electron, can impart this energy to a neutral mercury atom and ionize it, described as the Penning effect. This has the benefit of lowering the breakdown and operating voltage of the lamp, compared to other possible fill gases such as krypton.

Construction

A fluorescent lamp tube (see Figure 11) is filled with a gas, typically argon and low pressure mercury vapor, but it may also be, xenon, neon, or krypton. The inner surface of the lamp is coated with a fluorescent coating made of varying blends of metallic and rare-earth phosphor salts. The lamp's electrodes - or filaments - are made of coiled tungsten and usually referred to as cathodes because of their prime function of emitting electrons. For this, they are coated with a mixture of barium, strontium and calcium oxides chosen to have a low thermionic emission temperature.

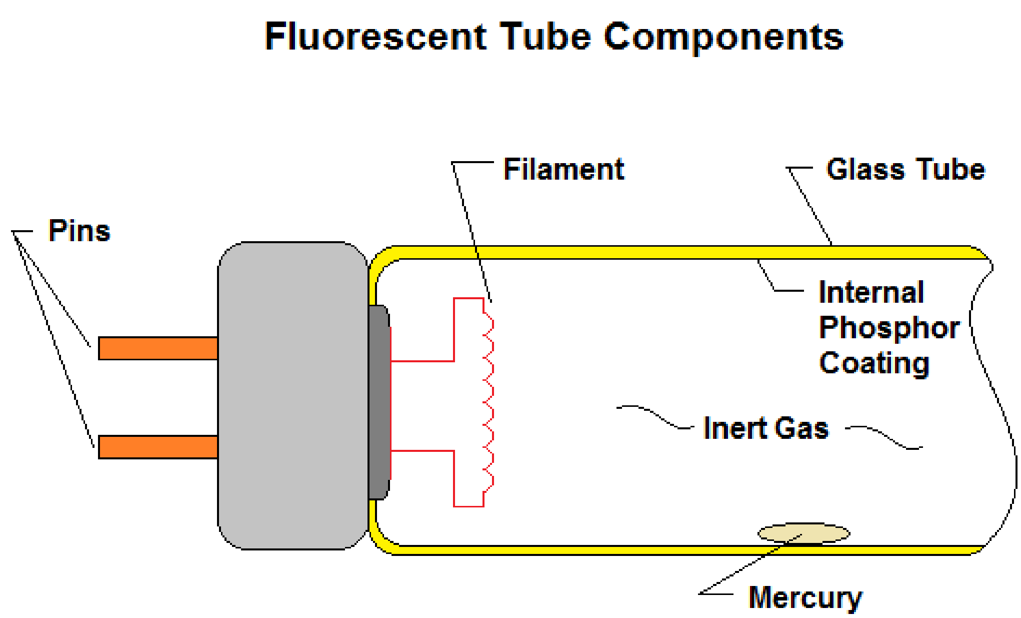


Figure 11

Traditional fluorescent lamp tubes are typically straight and range in length from less than four inches for miniature lamps, to eight feet for high-output lamps. Some lamps have the tube bent into a circle, used for table lamps or other places where a more compact light source is desired. Larger U-shaped lamps are used to provide the same amount of light in a more compact area, and are used for special architectural purposes. Compact fluorescent lamps have several small-diameter tubes joined in a bundle of two, four, or six, or a small diameter tube coiled into a spiral, to provide a high amount of light output in little volume.

Light-emitting phosphors are applied as a paint-like coating to the inside of the tube. The organic solvents are allowed to evaporate, then the tube is heated to nearly the melting point of glass to drive off remaining organic compounds and fuse the coating to the lamp tube. Careful control of the grain size of the suspended phosphors is necessary; large grains, 35 micrometers or larger, lead to weak grainy coatings, whereas too many small particles 1 or 2 micrometers or smaller leads to poor light maintenance and efficiency. Most phosphors perform best with a particle size around 10 micrometers. The coating must be thick enough to capture all the ultraviolet light produced by the mercury arc, but not so thick that the phosphor coating absorbs too much visible light.

Theory of operation

The glass tube in a fluorescent lamp contains a small bit of mercury and an inert gas, typically argon, kept under very low pressure. The inside of the tube is coated with a phosphor powder. The tube has two electrodes, one at each end, which are wired to an electrical circuit.

When the lamp is first turned on, the current flows through the electrical circuit to the electrodes. There is a considerable voltage across the electrodes, so electrons will migrate through the gas from one end of the tube to the other. This energy changes some of the mercury in the tube from a liquid to a gas. As electrons and charged atoms move through the tube, some of them will collide with the gaseous mercury atoms. These collisions excite the atoms, bumping electrons up to higher energy levels. When the electrons return to their original energy level, they release light photons. The electrons in mercury atoms are arranged in such a way that they mostly release light photons in the ultraviolet wavelength range.

Since ultraviolet light is not visible to the human eye, phosphors are used to create visible light. Phosphors are substances that give off light when they are exposed to light. When a photon hits a phosphor atom, one of the phosphor's electrons jumps to a higher energy level and the atom heats up. When the electron falls back to its normal level, it releases energy in the form of another photon. This photon has less energy than the original photon, because some energy was lost as heat.

With fluorescent lamps as more current flows through the lamp the electrical resistance of the fluorescent lamp drops, allowing even more current to flow. Connected directly to a constant-voltage power supply, a fluorescent lamp would rapidly self-destruct due to the uncontrolled current flow. To prevent this, fluorescent lamps must use a *ballast*, such as the one shown in the image on the right, to regulate the current flow through the tube.

The simplest ballast for alternating current (AC) use is an inductor placed in series, consisting of a winding on a laminated magnetic core. The inductance of this winding limits the flow of AC current. This type is still used, for example, in 120 volt operated desk lamps using relatively short lamps. Ballasts are rated for the size of lamp and power frequency. Where the AC voltage is insufficient to start long fluorescent lamps, the ballast is often a step-up autotransformer with substantial leakage inductance. Either form of inductive ballast may also include a capacitor for power factor correction.

Many different circuits have been used to operate fluorescent lamps. The choice of circuit is based on AC voltage, tube length, initial cost, long term cost, instant versus non-instant starting, temperature ranges and parts availability, etc.

Fluorescent lamps can run directly from a DC supply of sufficient voltage to strike an arc. The ballast must be resistive, and would consume about as much power as the lamp. When operated from DC, the starting switch is often arranged to reverse the polarity of the supply to the lamp each time it is started; otherwise, the mercury accumulates at one end of the tube. Fluorescent lamps are never operated directly from DC for those reasons. Instead, an inverter converts the DC into AC and provides the current-limiting function for electronic ballasts.

Starting

The mercury atoms in the fluorescent tube must be ionized before the arc can "strike" within the tube. For small lamps, it does not take much voltage to strike the arc and starting the lamp presents no problem, but larger tubes require a substantial voltage (in the range of a thousand volts). We will begin the discussion using a classic fluorescent lamp system consisting of a fluorescent tube, ballast and "starter" switch. Even though switches are not used much anymore, this will make it easier to understand the process. See Figure 12.

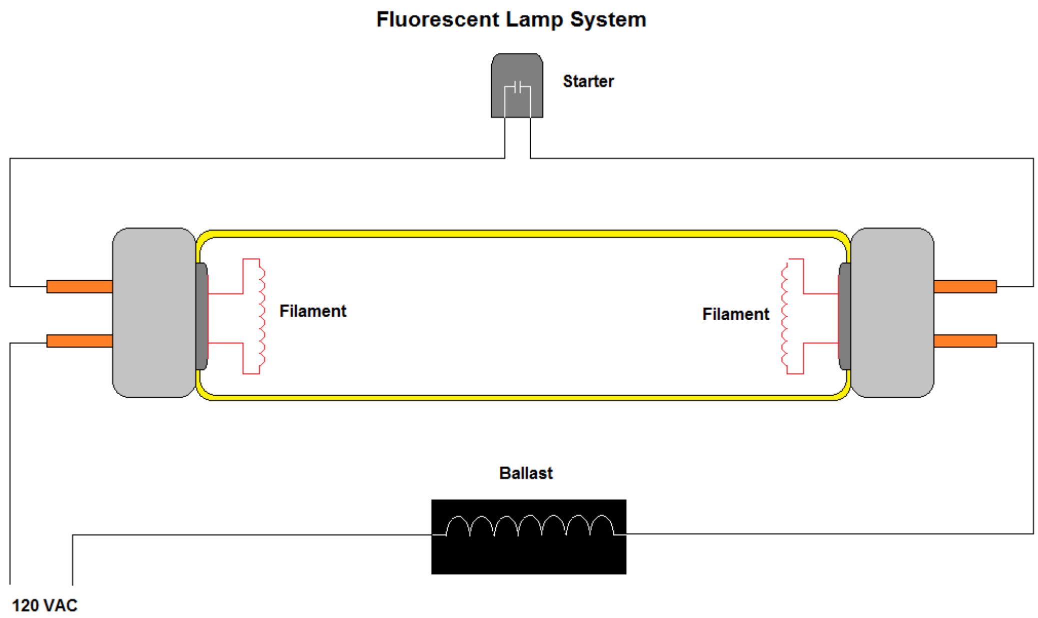


Figure 12

Starter Switch

This technique uses a combination filament–cathode at each end of the lamp in conjunction with a device called a *starter* switch that initially connect the filaments in series with the ballast to preheat them; when the arc is struck the filaments are disconnected. This system is technically known as *preheat*. A photo of a starter is shown in the adjacent photo.

When the fluorescent lamp first turns on, the path of least resistance is through the starter switch. In this circuit, the current passes through the electrodes on both ends of the tube. These electrodes are simple filaments. When the current runs through the starter circuit, electricity heats up the filaments. This sends electrons into the gas tube, ionizing the gas. The starter then "cuts out" of the circuit.

At this point, the filaments have already ionized the gas in the fluorescent tube, creating an electrically conductive medium. The tube just needs a voltage boost across the electrodes to establish an electrical arc, which is provided by the lamp's ballast.

When the current flows through the starter circuit, it establishes a magnetic field in part of the ballast. This magnetic field is maintained by the flowing current. When the starter switch is opened, the current is briefly cut off from the ballast. The magnetic field collapses, which creates a sudden jump in current and the ballast releases its stored energy.

This surge in current helps build the initial voltage needed to establish the electrical arc through the gas. Instead of flowing through the starter circuit and jumping across the gap in the starter switch, the electrical current flows through the tube. The free electrons collide with the atoms, knocking loose other electrons, which creates ions. The result is a plasma, a gas composed largely of ions and free electrons, all moving freely. This creates a path for an electrical current. The impact of colliding electrons keeps the two filaments warm, so they continue to emit new electrons into the plasma.

With automated starters such as glow starters, a failing tube will cycle endlessly, flickering as the lamp quickly goes out because the emission mix is insufficient to keep the lamp current high enough to keep the glow starter open. This runs the ballast at higher temperature. Some more advanced starters time out in this situation, and do not attempt repeated starts until power is reset. Some older systems used a thermal over-current trip to detect repeated starting attempts and disable the circuit until manually reset. The switch contacts in glow starters are subject to wear and inevitably fail eventually, so the starter is manufactured as a plug-in replaceable unit.

Electronic Starters

More recently introduced electronic starters use a different method to preheat the cathodes. They may be designed to be plug-in interchangeable with glow starters for use in standard fittings. They commonly use a purpose-designed semiconductor switch and "soft start" the lamp by preheating the cathodes before applying a controlled starting pulse which strikes the lamp first time without flickering; this dislodges a minimal amount of material from the cathodes during starting, giving longer lamp life than possible with the uncontrolled impulses to which the lamp is subjected in a preheat. This prolongs lamp life by a factor of typically three or more times for a lamp frequently switched on as in domestic use, and to reduce the blackening of the ends of the lamp typical of fluorescent tubes. Electronic starters may be optimized for fast starting, or for most reliable starting even at low temperatures and with low supply voltages, with a startup time of 2–4 seconds. The faster-start units may produce audible noise during start-up.

Electronic starters only attempt to start a lamp for a short time when power is initially applied, and do not repeatedly attempt to restrike a lamp that is dead and unable to sustain an arc; some automatically shut down a failed lamp. This eliminates the re-striking of a lamp and the continuous flickering of a failing lamp with a glow starter. Electronic starters are not subject to wear and do not need replacing periodically, although they may fail like any other electronic circuit.

Instant start

Instant start fluorescent tubes simply use a high enough voltage to break down the gas and mercury column and thereby start arc conduction. These tubes can be identified by a single pin at each end of the tube. The lamp holders have a "disconnect" socket at the low-voltage end which disconnects the ballast when the tube is removed, to prevent electric shock. Low-cost lighting fixtures with an integrated electronic ballast use instant start on lamps designed for preheating, although it shortens lamp life.

Rapid start

Newer *rapid start* ballast designs provide filament power windings within the ballast; these rapidly and continuously warm the filaments/cathodes using low-voltage AC. No inductive voltage spike is produced for starting, so the lamps must be mounted near a grounded reflector to allow the glow discharge to propagate through the tube and initiate the arc discharge. In some lamps a grounded *starting aid* strip is attached to the outside of the lamp glass.

Quick-start

Quick-start ballasts use a small auto-transformer to heat the filaments when power is first applied. When an arc strikes, the filament heating power is reduced and the tube will start within half a second. The auto-transformer is either combined with the ballast or may be a separate unit. Tubes need to be mounted near a grounded metal reflector in order for them to strike. Quick-start ballasts are more common in commercial installations because of lower maintenance costs. A quick-start ballast eliminates the need for a starter switch, a common source of lamp failures. Nonetheless, Quick-start ballasts are also used in residential installations because of the desirable feature that a Quick-start ballast light turns on nearly immediately after power is applied.

Semi-resonant start

The *semi-resonant start circuit* was invented for use with T12 fluorescent tubes. This method uses a double wound transformer and a capacitor. With no arc current, the transformer and capacitor resonate at line frequency and generate about twice the supply voltage across the tube, and a small electrode heating current. This tube voltage is too low to strike the arc with cold electrodes, but as the electrodes heat up to thermionic emission temperature, the tube striking voltage reduces below that of the ringing voltage, and the arc strikes. As the electrodes heat, the lamp slowly, over three to five seconds, reaches full brightness. As the arc current increases and tube voltage drops, the circuit provides current limiting.

Semi-resonant start circuits are mainly restricted to use in commercial installations because of the higher initial cost of circuit components. However, there are no starter switches to be replaced and cathode damage is reduced during starting making lamps last longer, reducing maintenance costs. Due to the high open circuit tube voltage, this starting method is particularly good for starting tubes in cold locations. Semi-resonant start fixtures are generally incompatible with energy saving T8 retrofit tubes, because such tubes have a higher starting voltage than T12 lamps and may not start reliably, especially in low temperatures.

Programmed start

A *programmed-start ballast* is a more advanced version of rapid start. This ballast applies power to the filaments first, then after a short delay to allow the cathodes to preheat, applies voltage to the lamps to strike an arc. This ballast gives the best life and most starts from lamps, and so is preferred for applications with very frequent power cycling such as vision examination rooms and restrooms with a motion detector switch.

Electronic ballasts

Electronic ballasts employ transistors to change the supply frequency into high-frequency AC while also regulating the current flow in the lamp. Some still use an inductance to limit the current, but the higher frequency allows a much smaller inductance to be used. Others use a capacitor-transistor combination to replace the inductor, since a transistor and capacitor working together can perfectly simulate the action of an inductor. These ballasts take advantage of the higher efficacy of lamps operated with higher-frequency current. Efficacy of a fluorescent lamp rises by almost 10% at a frequency of 10 kHz, compared to efficacy at normal power frequency.

When the AC period is shorter than the relaxation time to de-ionize mercury atoms in the discharge column, the discharge stays closer to optimum operating condition. Electronic ballasts typically work in rapid start or instant start mode. Electronic ballasts are commonly supplied with AC power, which is internally converted to DC and then back to a variable frequency AC waveform. Depending upon the capacitance and the quality of constant-current pulse-width modulation, this can largely eliminate modulation at 100 or 120 Hz.

Low cost ballasts mostly contain only a simple oscillator and series resonant LC circuit. When turned on, the oscillator starts, and resonant current causes on the LC circuit. And this resonant current directly drives the switching transistor through the ring core transformer. This principle is called the current resonant inverter circuit. After a short time the voltage across the lamp reaches about 1,000 volts and the lamp ignites. The process is too fast to preheat the cathodes, so the lamp instant-starts in cold cathode mode. The cathode filaments are still used for protection of the ballast from overheating if the lamp does not ignite. A few manufacturers use positive temperature coefficient (PTC) thermistors to disable instant starting and give some time to preheat the filaments.

More complex electronic ballasts use programmed start. The output frequency is started above the resonance frequency of the output circuit of the ballast; and after the filaments are heated, the frequency is rapidly decreased. If the frequency approaches the resonant frequency of the ballast, the output voltage will increase so much that the lamp will ignite. If the lamp does not ignite, an electronic circuit stops the operation of the ballast.

Many electronic ballasts are controlled by a microcontroller or similar, and these are sometimes called digital ballasts. *Digital ballasts* can apply quite complex logic to lamp starting and operation. This enables functions such as testing for broken electrodes and missing tubes before attempting to start, auto detect tube replacement, and auto detection of tube type, such that a single ballast can be used with several different tubes, even those that operate at different arc currents, etc. Once such fine grained control over the starting and arc current is achievable, features such as dimming, and having the ballast maintain a constant light level against changing sunlight contribution are all easily included in the embedded microcontroller software, and can be found in various manufacturers' products.

Since introduction in the 1990s, high frequency ballasts have been used in general lighting fixtures with either rapid start or pre-heat lamps. These ballasts convert the incoming power to an output frequency in excess of 20 kHz. This increases lamp efficiency. These are used in several applications, including new generation tanning lamp systems, whereby a 100 watt lamp can be lit using 90 watts of actual power while obtaining the same luminous flux as magnetic ballasts. These ballasts operate with voltages that can be almost 600 volts, requiring some consideration in housing design, and can cause a minor limitation in the length of the wire leads from the ballast to the lamp ends.

Effect of temperature

The light output and performance of fluorescent lamps is critically affected by the temperature of the bulb wall and its effect on the partial pressure of mercury vapor within the lamp. Each lamp contains a small amount of mercury, which must vaporize to support the lamp current and generate light. At low temperatures the mercury is in the form of dispersed liquid droplets. As the lamp warms, more of the mercury is in vapor form. At higher temperatures, self-absorption in the vapor reduces the yield of UV and visible light. Since mercury condenses at the coolest spot in the lamp, careful design is required to maintain that spot at the optimum temperature, around 40C.

By using an amalgam with some other metal, the vapor pressure is reduced and the optimum temperature range extended upward; however, the bulb wall "cold spot" temperature must still be controlled to prevent migration of the mercury out of the amalgam and condensing on the cold spot. Fluorescent lamps intended for higher output will have structural features such as a deformed tube or internal heat-sinks to control cold spot temperature and mercury distribution. Heavily loaded small lamps, such as compact fluorescent lamps, also include heat-sink areas in the tube to maintain mercury vapor pressure at the optimum value.

Losses

Only a fraction of the electrical energy input into a lamp is converted to useful light. The ballast dissipates some heat; however electronic ballasts may be up to 90% efficient. A fixed voltage drop occurs at the electrodes, which also produces heat. Some of the energy in the mercury vapor column is also dissipated, with about 85% is turned into visible and ultraviolet light.

The UV light is absorbed by the lamp's fluorescent coating, which re-radiates the energy at longer wavelengths to emit visible light. Not all the UV energy striking the phosphor gets converted into visible light and for every 100 incident photons of UV impacting the phosphor, only 86 visible light photons are emitted. The largest single loss is due to the lower energy of each photon of visible light, compared to the energy of the UV photons that generated them.

Cold cathode lamps

Most fluorescent lamps use electrodes that operate by *thermionic emission*, meaning they are operated at a high enough temperature for the electrode material to emit electrons into the tube by heat.

However, there are also tubes that operate in *cold cathode mode*, whereby electrons are liberated into the tube only by the large potential difference, or voltage, between the electrodes. This does not mean the electrodes are cold, but it does mean they are operating below their thermionic emission temperature. Because cold cathode lamps have no thermionic emission coating to wear out they can have much longer lives than hot cathode thermionic emission tubes. This quality makes them desirable for maintenance-free long-life applications (such as LCD backlight displays).

Cold cathode lamps are generally less efficient than thermionic emission lamps because the cathode voltage drop is much higher. The increased voltage drop results in more power dissipation at tube ends, which does not contribute to light output. However, this is less significant with longer tubes. The increased power dissipation at tube ends also usually means cold cathode tubes have to be run at a lower loading than their thermionic emission equivalents. Given the higher tube voltage required anyway, these tubes can easily be made long, and even run as series strings. They are better suited for bending into special shapes for lettering and signage, and can also be instantly switched on or off.

Phosphors and the spectrum of emitted light

The spectrum of light emitted from a fluorescent lamp is the combination of light directly emitted by the mercury vapor, and light emitted by the phosphorescent coating. The spectral lines from the mercury emission and the phosphorescence effect give a combined spectral distribution of light that is different from those produced by incandescent sources. The relative intensity of light emitted in each narrow band of wavelengths over the visible spectrum is in different proportions compared to that of an incandescent source. Colored objects are perceived differently under light sources with differing spectral distributions. For example, some people find the color rendition produced by some fluorescent lamps to be harsh and displeasing. A healthy person can sometimes appear to have an unhealthy skin tone under fluorescent lighting. The extent to which this phenomenon occurs is related to the light's spectral composition, and may be gauged by its color rendering index (CRI).

Some of the least pleasant light comes from tubes containing the older, halophosphate-type phosphors. This phosphor mainly emits yellow and blue light, and relatively little green and red. In the absence of a reference, this mixture appears white to the eye, but the light has an incomplete spectrum. The CRI of such lamps is around 60.

Since the 1990s, higher quality fluorescent lamps use either a higher CRI halophosphate coating, or a triphosphor mixture, based on europium and terbium ions, that have emission bands more evenly distributed over the spectrum of visible light. High CRI halophosphate and triphosphor tubes give a more natural color reproduction to the human eye. The CRI of such lamps is typically 82–100.

Figure 13, shows the spectral distribution of a cool white fluorescent lamp utilizing two rare earth doped phosphors, Tb3+, Ce3+:LaPO4 for green and blue emission and Eu:Y2O3 for red. Several of the spectral peaks are directly generated from the mercury arc. This is the most common type of fluorescent lamp in use today.

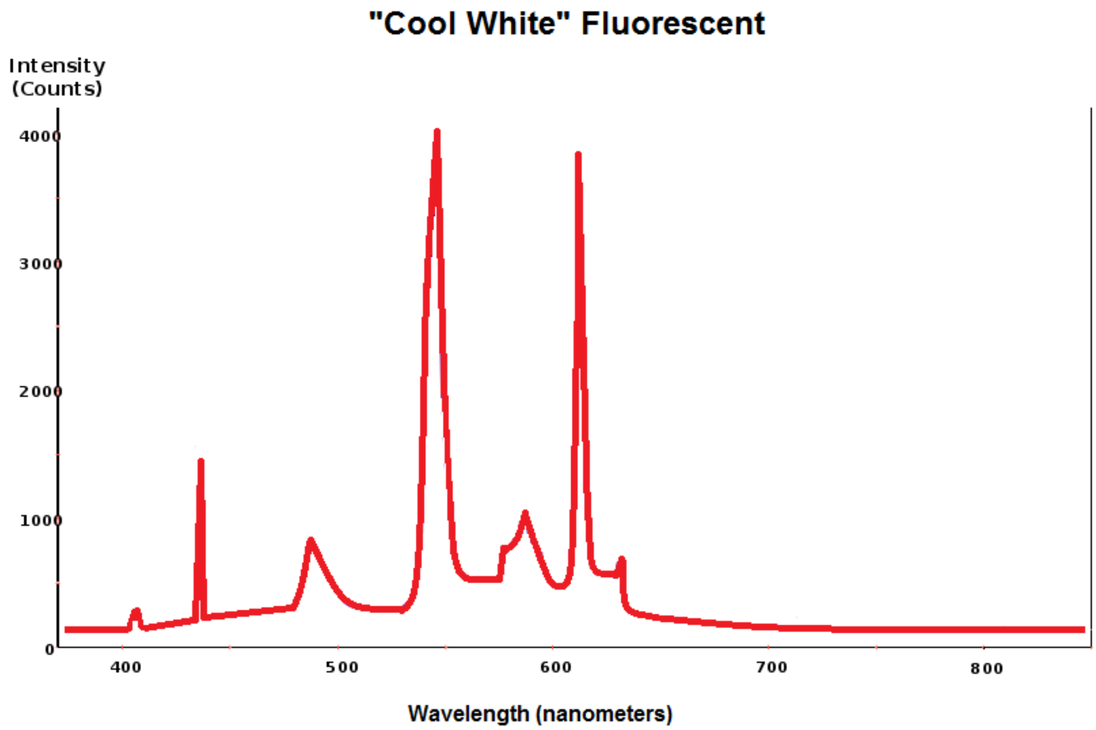


Figure 13

Figure 14 shows the spectral distribution of older style fluorescent lamps using Halophosphate phosphors. These lamps usually consist of trivalent antimony and divalent manganese doped calcium halophosphate. The color of the light output can be adjusted by altering the ratio of the blue emitting antimony dopant and orange emitting manganese dopant. The color rendering ability of these older style lamps is quite poor.

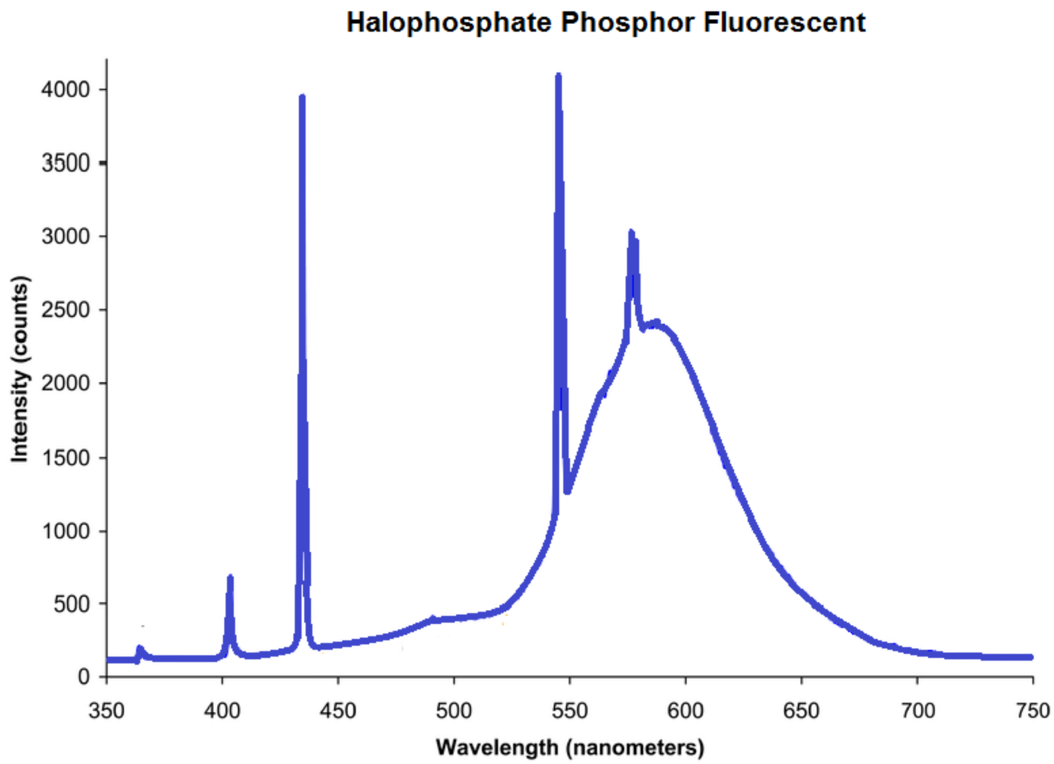


Figure 14

Failure Modes

The end of life failure mode for fluorescent lamps varies depending on how they are used and their control type. Often the light will turn pink with black burns on the ends of the lamp due to sputtering of emission mix. The lamp may also flicker at a noticeable rate. Normal tube failure modes are discussed below.

Emission mix

The *emission mix* on the tube filaments/cathodes is necessary to enable electrons to pass into the gas via thermionic emission at the tube operating voltages used. The mix is slowly 'sputtered off' by bombardment with electrons and mercury ions during operation, but a larger amount is sputtered off each time the tube is started with cold cathodes. The method of starting the lamp has a significant impact on this. Lamps operated for typically less than three hours each switch-on will normally run out of the emission mix before other parts of the lamp fail. The sputtered emission mix forms the dark marks at the tube ends seen in old tubes. When all the emission mix is gone, the cathode cannot pass sufficient electrons into the gas fill to maintain the discharge at the designed tube operating voltage. Ideally, the controls should shut down the tube when this happens. However, some controls will provide sufficient increased voltage to continue operating the tube in cold cathode mode, which will cause overheating of the tube end and rapid disintegration of the electrodes (filament goes open-circuit) and filament support wires until they are completely gone or the glass cracks, wrecking the low pressure gas fill and stopping the gas discharge.

Ballast electronics

Ballast electronics failure is a somewhat random process that follows the standard failure profile for any electronic device. There is an initial small peak of early failures, followed by a drop and steady increase over lamp life. Life of electronics is heavily dependent on operating temperature—it typically halves for each 10C temperature rise. The quoted average life of a lamp is usually at 25C ambient. The average life of the electronics at this temperature is normally greater than this, so at this temperature, not many lamps will fail due to failure of the electronics. In some fittings, the ambient temperature could be well above this, in which case failure of the electronics may become the predominant failure mechanism. Similarly, running a compact fluorescent lamp base-up will result in hotter electronics, which can cause shorter average life. Electronic ballasts should be designed to shut down the tube when the emission mix runs out as described above. In the case of integral electronic ballasts, since they never have to work again, this is sometimes done by having them deliberately burn out some component to permanently cease operation. In most CFLs the filaments are connected in series, with a small capacitor between them. The discharge, once lit, is in parallel to the capacitor and presents a lower-resistance path, effectively shorting the capacitor out.

Loss of Phosphor

The phosphor drops off in efficiency during use. By around 25,000 operating hours, it will typically be half the brightness of a new lamp. Lamps that do not suffer failures of the emission mix or integral ballast electronics will eventually develop this failure mode. They still work, but have become dim and inefficient. The process is slow, and often only becomes obvious when a new lamp is operating next to an old one.

Loss of mercury

As in all mercury-based gas-filled tubes, mercury is slowly absorbed into glass, phosphor, and tube electrodes throughout the lamp life, where it can no longer function. Newer lamps now have just enough mercury to last the expected life of the lamp. Loss of mercury will take over from failure of the phosphor in some lamps. The failure symptoms are similar, except loss of mercury initially causes an extended run-up time to full light output, and finally causes the lamp to glow a dim pink when the mercury runs out and the argon base gas takes over as the primary discharge. Subjecting the tube to asymmetric waveforms, where the total current flow through the tube does not cancel out and the tube effectively operates under a DC bias, causes asymmetric distribution of mercury ions along the tube. The localized depletion of mercury vapor pressure manifests as pink luminescence of the base gas in the vicinity of one of the electrodes, and the operating lifetime of the lamp may be dramatically shortened. The same effect can be observed with new tubes. Mercury is present in the form of an amalgam and takes some time to be liberated in sufficient amount. New lamps may initially glow pink for several seconds after startup. This period is minimized after about 100 hours of operation.

Burned filaments

The filaments can burn at the end of the lamp's lifetime, opening the circuit and losing the capability to heat up. Both filaments lose function as they are connected in series, with just a simple switch start circuit a broken filament will render the lamp completely useless. Filaments rarely burn or fail open circuit unless the filament becomes depleted of emitter and the controls are able to supply a high enough voltage across the tube to operate it in cold cathode mode. Some digital electronic ballasts are capable of detecting broken filaments and can still strike an arc with one or both filaments broken providing there is still sufficient emitter. A broken filament in a lamp attached to a magnetic ballast often causes both lamps to burn out or flicker.

Chapter 4
Applications

In residential applications, fluorescent lamps are mostly found in kitchens, basements, or garages. Fluorescent lamps are used extensively in commercial and industrial applications. In addition to general lighting, special fluorescent lights are often used in stage lighting for film and video production. They are cooler than traditional halogen light sources, and use high-frequency ballasts to prevent video flickering and high color-rendition index lamps to approximate daylight color temperatures.

Tubular fluorescent fixtures and lamps are preferred for ambient lighting in large indoor areas, such as in classrooms and meeting rooms. In these areas, their low brightness creates less direct glare than incandescent bulbs.

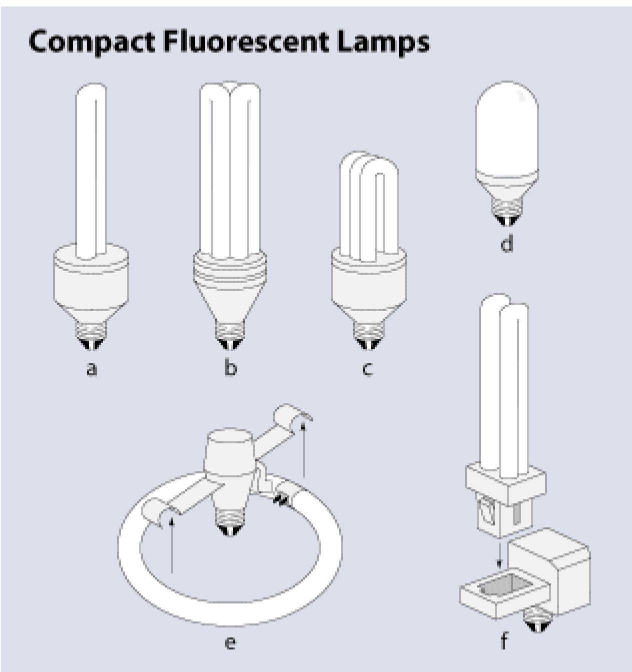


Figure 15

Fluorescent lamps come in many shapes and sizes. The compact fluorescent lamp (CFL) is becoming more popular. Many compact fluorescent lamps integrate the auxiliary electronics into the base of the lamp, allowing them to fit into a regular light bulb socket.

Figure 15 shows are few of the different sizes and shapes of CFL's, including (a) twin-tube integral, (b and c) triple-tube integral, (d) integral model with casing that reduces glare, (e) modular circline and ballast, and (f) modular quad-tube and ballast varieties.

Circular tube-type fluorescent lamps are called circline lamps. They are commonly used for portable task lighting.

Table 8 gives a comparison of various lighting technologies for an application with similar lumen outputs. This table compares an incandescent, halogen, fluorescent, and LED lamp. As you can see in the table, the LED fixture produces the most lumens per watt of energy consumed with the fluorescent being the second most energy efficient unit. Due to the cost of LED lamps, the fluorescent lamp will be the best choice for most applications.

Table 8 Comparison of Different Lamp Types				
Issue	**Incandescent**	**Halogen**	**Fluorescent**	**LED**
Energy Use	60W	42W	13W	9W
Lumen Output	860	570	660	900
Lumens/Watt	14.3	13.6	50.8	100
Color Temp	2,700K	3,100K	2,700K	3000K
CRI	100	100	82	75
Life (hours)	2,000	3,500	8,000	25,000

Lamp sizes and designations

Systematic nomenclature identifies mass-market lamps as to general shape, power rating, length, color, and other electrical and illuminating characteristics.

Tube designations
Lamps are typically identified by the following code,

FxxTy

Where,
F = Fluorescent designation.
xx = Either the power in watts or length in inches.
T = Indicates whether the shape of the bulb is tubular.
y = The diameter of the tube in eighths of an inch.

Typical diameters are T12 (1½”) for residential lamps with magnetic ballasts, T8 (1 in) for commercial energy-saving lamps with electronic ballasts, and T5 (5⁄8 in) for very small lamps, which may even operate from a battery powered device.

For example, an F96T12 lamp is 96 inches long and 1.5 inches in diameter. An F40T8 lamp is a 40-watt lamp and is 1-inch in diameter. An F13T5 is a 13-watt lamp that is 5/8-inch in diameter.

Some lamps have an internal opaque reflector. Coverage of the reflector ranges from 120° to 310° of the lamp's circumference. Often, a lamp is marked as a reflector lamp by adding the letter "R" in the model code, so a FxxTy lamp with a reflector would be coded as "FRxxTy".

Very high output (VHO) lamps with reflectors may be coded as VHOR. No such designation exists for the amount of reflector coverage. See Figure 16 for a drawing of a reflector.

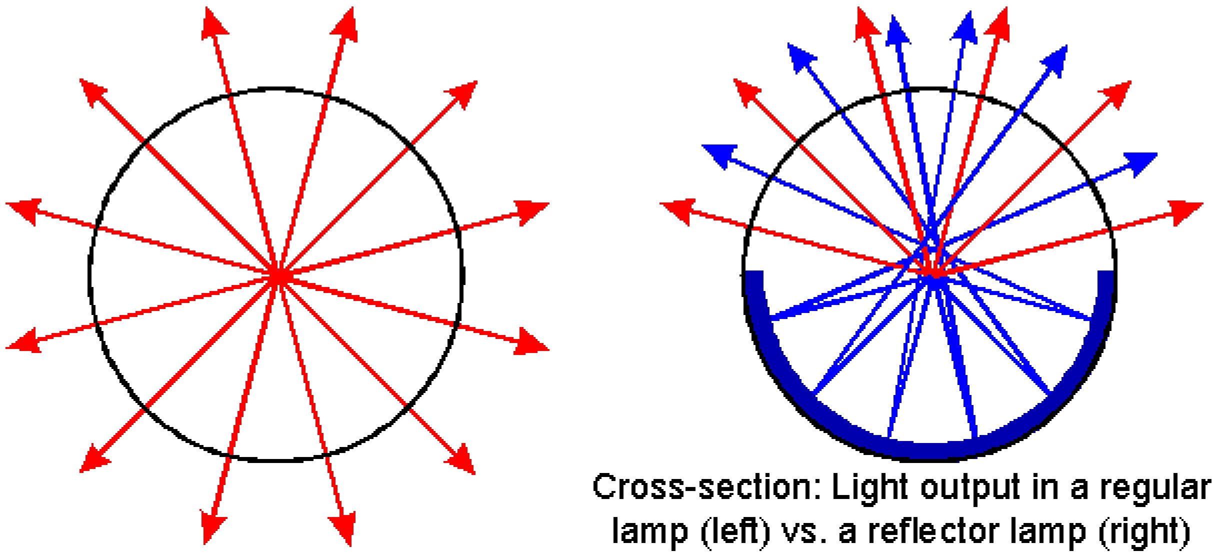


Figure 16

Reflector lamps are used when light is only desired to be emitted in a single direction, or when an application requires the maximum amount of light. For example, these lamps can be used in tanning beds or in backlighting electronic displays. An internal reflector is more efficient than standard external reflectors.

Slimline lamps operate on an instant-start ballast and are recognizable by their single-pin bases. High-output lamps are brighter and are driven at a higher electrical current, have different ends on the pins so they cannot be used in the wrong fixture, and are labeled FxxTyHO, or FxxTyVHO for very high output. U-shaped tubes are FBxxTy, with the "B" meaning "bent". Most commonly, these have the same designations as linear tubes. Circular bulbs, like the one in the adjacent photo, are FCxxTy, with the outer diameter of the circle (not circumference or watts) in centimeters being the first number and the second number referring to the tube size.

<u>Colors</u>

Based on the phosphors used, the color output of fluorescents can be manufactured to meet certain design goals. Fluorescent color designations are generally labeled as one of the following,

WW – Warm White

EW – Enhanced White, a neutral white color.
CW – Cool White, which is the most common fluorescent
DW – Daylight White, has a bluish tint
BL – Ultraviolet, Blacklight, commonly found in “bug zappers”.
BLB – Ultraviolet, Blacklight-Blue, which filters out most visible light.

In the 1990’s General Electric developed “Color Codes” to help catalog the myriad of color choices in fluorescent lamps. Many other manufacturers – but not all – have adopted the GE color coding scheme. In this scheme, the first digit is the approximate CRI in tens and the second two digits are the color temperature in hundreds. For example, consider a lamp with a color code of 530. The “5” indicates the lamp will have a CRI in the 50’s and the “30” indicates a color temperature of 3,000K. Looking the Table 9, we see that a color code of 530 equates to a warm white, Halophosphate lamp with a CRI of 54 and color temperature of 3,000k.

Table 9
Color Codes

Color Code	Color	CRI	Color Temperature
Halophosphate			
29	Warm White	54	3,000K
35	White	56	3,500K
33	Cool White	67	4,300K
25	Natural White	75	4,000K
54	Daylight	75	6,500K
Deluxe Halophosphate			
27	Deluxe Extra Warm White	95	2,700K
32	Deluxe Warm White	85	3,000K
34	Deluxe White	85	3,850K
79	Deluxe Natural	93	3,600K
38	Deluxe Cool White	92	4,000K
55	Northlight	94	6,500K
Tri-Phosphor			
827	Warm White	85	2,700K

835	White	85	3,500K
841	Cool White	85	4,100K
850	Sunlight	85	5,000K
865	Cool Daylight	85	6,500K
880	Sky White	85	8,000K
Multi-Phosphor			
927	Warm White	95	2,700K
941	Cool White	95	4,100K
950	Sunlight	98	5,000K
965	Cool Daylight	95	6,500K

T5 tubes

The use of T5 tubes rather than T8 or T12 allows the tubes to be fitted into smaller spaces, or more tubes for more light, and the smaller light source also enables more accurate control of beam direction by means of optics (reflectors and lenses in the luminaire). Each tube length is available in both a lower-power high-efficiency (HE) version, and a higher-power high-output (HO) version. The watts per unit length of the T5 HE tubes is similar to the original 13W T5 tubes, and some manufacturers produce a range of fittings spanning both these ranges of tubes. See Table 10 for a few of the common T5 lamp sizes.

Table 10
T5 Lamp Styles

Tube Diameter	Length (inches)	Nominal Power (W)	
		High Efficiency	High Output
T5	22.2 in.	14 W	24 W
T5	34.0 in.	21 W	39 W
T5	45.8 in.	28 W	54 W
T5	57.6 in.	35 W	80 W

T5 fluorescent is the first linear lamp type to be served only by electronic ballasts. It is smaller than T8 and T12 lamps, with a miniature bi-pin base. It is notable for its lumens-per-watt efficiency, due to its peak light output occurring at 35C air temperature. There are two types of ballasts available for T5 lamps: rapid start, and programmed start electronic ballasts. T5 lamps operate at frequencies greater than 20 kilohertz. Most manufacturers claim that their T5 ballasts have a total harmonic distortion (THD) of less than 15%. Most T5 ballasts are very quiet and carry class “A” sound ratings. Dimmable ballasts exist for T5 lamps.

Care must be taken when comparing efficiency of T5 and earlier technology fluorescent tubes. The apparent increased efficiency of T5 over T8 tubes is largely due to the use of electronic ballasts over magnetic ballasts. When T8 tubes are run on electronic ballasts, they are about the same efficiency as T5 HE tubes.

The T5 lamp provides peak light output at 35C air temperature as compared to the T8 and the T12 lamps which provide peak light output at a 25C ambient air temperature. The T5 lamp has a higher lumens-per-watt efficiency than a T8 lamp of about the same electric power, in a space where there is little or no air circulation.

T5 lamps are a popular energy-efficiency measure, due to their potential to cut energy use in lighting by more than 65%. See Figure 11 for a comparison of the efficacy of T5’s to T8’s and T12’s for an equivalent four-foot lamp.

Table 11
4-Foot Fluorescent Lamps

Tube Diameter	Nominal Power (Watts)	Output (Lumens)	Efficacy (Lumens/Watt)
T5	28	2,900	104
T8	25	2,200	88
T8	32	2,900	95
T12	34	2,200	65
T12	40	2,500	75

As you can see from Figure 11, the T5 has the highest efficacy of the any of the lamps shown with an equivalent light output. Since T5 are smaller than T8 bulbs, but produce roughly the same amount of light, their surface luminance is higher than T8 lamps. Glare can be an issue, especially with high output bulbs, but can be mitigated by placing the bulbs out of direct line of sight, or using louvers or diffusers.

T5 tubes operate at a higher than ideal temperature for the purposes of regulating the mercury vapor pressure in the tube. A fluorescent lamps "cold spot" is the area where the internal glass wall temperature is at its lowest. It is the temperature of the coldest spot which effectively sets

the mercury vapor pressure for the whole tube. Unlike a T8 or T12 fluorescent lamp, where the cold spot is in the middle, in T5 lamps it is at the tube end which is marked with the rating label, in the extended space behind the filament. By having this extended area outside of the discharge run cooler, this reduces the mercury vapor pressure in the whole tube to more ideal levels.
T5 lamps are generally rated for 20,000 hours, as compared to T8 lamps, which are generally rated for 24,000 hours.

T5 lamps are both electrically and physically incompatible with T8 and T12 lamps. These differences in dimension prevent T5 lamps from being used as replacements for T8 and T12 lamps.

Common tube ratings

Table 12 lists the more common tube ratings for general lighting. Many more tube ratings exist. The nominal length may not exactly match any measured dimension of the tube. For some tube sizes, the nominal length (in feet) is the required spacing between centers of the lighting fixtures to create a continuous run, so the tubes are a little shorter than the nominal length.

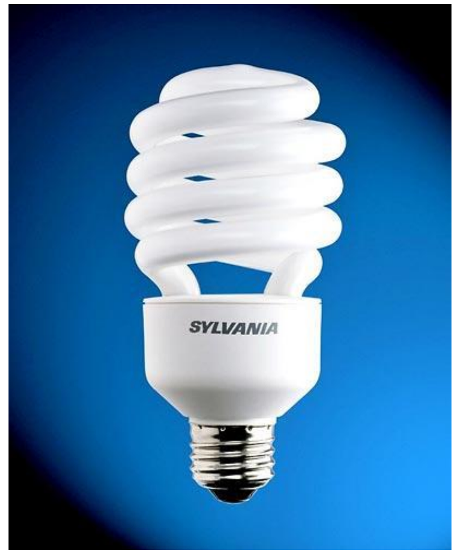
Table 12 also shows a few of the common 'energy saver' tube ratings. In the 1990s, various energy saving tubes were introduced in the US, but they are not retrofits and require new matching ballasts to drive them. Running a T8 tube with a ballast for T12 will reduce lamp life and can increase energy consumption. The tube type should always match the markings on the light fixture.

Table 12
Common Tube Ratings

Designation	Nominal Length (Inches)	Nominal Power (Watts)	
		Common Lamp	Energy Saving Lamp
T5	6 in.	4 W	-
T5	9 in.	6 W	-
T5	12 in.	8 W	-
T12	24 in.	20 W	17 W
T12	48 in.	40 W	34 W
T12	60 in.	65 W	40 W

T12	72 in.	75 W	-
T12	96 in.	125 W	59 W

Compact Fluorescent Lamps (CFLs)



A compact fluorescent lamp (CFL) works much like standard fluorescent lamps. They consist of two parts: a gas-filled tube and magnetic or electronic ballast. The gas in the tube glows with ultraviolet light when electricity from the ballast flows through it. This, in turn, excites a white phosphor coating on the inside of the tube, which emits visible light throughout the surface of the tube.

Most CFLs use electronic ballasts. Electronic ballasts are more expensive but light immediately. They are also more efficient than magnetic ballasts. A CFL with an electronic ballast should last about 10,000 hours. CFLs are designed to operate within a specific temperature range. Temperatures below the range cause reduced output. Most are for indoor use, but there are models available for outdoor use. CFLs are most cost-effective and efficient in areas where lights are on for long periods of time. Because CFLs do not need to be changed often, they are ideal for hard-to-reach areas.

CFLs are available in a variety of styles and shapes. They may have two, four, or six tubes or circular or spiral-shaped tubes. The size or total surface area of the tube determines how much light is produced. There are also types enclosed in a glass globe and look somewhat similar to conventional incandescent light bulbs. CFL light output is roughly proportional to phosphor surface area, and high output CFLs are often larger than their incandescent equivalents. This means that the CFL may not fit well in existing light fixtures.

CFLs turn on within a second, but many still take time to achieve full brightness. The light color may be slightly different immediately after being turned on. Some CFLs are marketed as "instant on" and have no noticeable warm-up period, but others can take up to a minute to reach full brightness, or longer in very cold temperatures. Some that use a mercury amalgam can take up to three minutes to reach full output.

There are two types of CFLs: integrated and non-integrated lamps. *Integrated lamps* combine the tube and ballast in a single unit. These lamps allow consumers to replace incandescent lamps easily with CFLs. Integrated CFLs work well in many standard incandescent light fixtures, reducing the cost of converting to fluorescent. Three-way lamp bulbs and dimmable models with standard bases are available.

Non-integrated CFLs have the ballast permanently installed in the luminaire, and only the lamp bulb is changed at its end of life. Since the ballasts are placed in the light fixture, they are larger and last longer compared to the integrated ones, and they don't need to be replaced when the bulb reaches its end-of-life. Non-integrated CFL housings can be both more expensive and sophisticated. They have two types of tubes: a bi-pin tube designed for conventional ballast, and a quad-pin tube designed for electronic ballast or conventional ballast with an external starter.

Electronic ballasts contain a small circuit board with rectifiers, a filter capacitor and usually two switching transistors. The incoming AC current is first rectified to DC, and then converted to high frequency AC by the transistors, connected as a resonant series DC to AC inverter. The resulting high frequency is applied to the lamp tube. Since the resonant converter tends to stabilize lamp current over a range of input voltages, standard CFLs do not respond well in dimming applications and special lamps are required for dimming service.

Some CFLs are labeled not to be run base up, since heat will shorten the ballast's life. Such CFLs are unsuitable for recessed light fixtures; however, CFLs for use in such fixtures are available. Current recommendations for fully enclosed, unventilated light fixtures (such as those recessed into insulated ceilings), are either to use "reflector CFLs" (R-CFL), cold-cathode CFLs or to replace such fixtures with those designed for CFLs. For longevity, CFL’s need good airflow, such as in a table lamp.

In addition to the wear-out failure modes common to all fluorescent lamps, the electronic ballast may fail. Ballast failures may be accompanied by discoloration or distortion of the ballast enclosure, odors, or smoke. The lamps are internally protected and are meant to fail safely at the end of their lives.

Using a dimmer with a standard CFL is ineffective and can shorten bulb life, however, some CFL lamps are designed for dimming control. A dimmer switch used in conjunction with a dimmable CFL must be matched to its power consumption range; many dimmers installed for use with incandescent bulbs do not function acceptably below 40 Watts, whereas CFL applications commonly only draw power in the range 7-20 Watts, so incandescent lamp dimmers may not effectively dim CFLs.

The dimming range of CFLs is usually between 20% and 90%. Dimmable CFLs are not a 100% replacement for incandescent fixtures that are dimmed for "mood scenes" such as wall sconces in a dining area. Below the 20% limit, the lamp may remain at 20% or flicker or the starter circuitry may stop and restart. Above 80%, the bulb may operate at 100%. Dimmable CFLs are more expensive than standard CFLs due to the additional circuitry. An advantage of dimmable CFL's is that when a CFL is dimmed, its color temperature stays the same. This is counter to most other light sources where color gets redder as the light source gets dimmer.

CFLs are generally not designed for outdoor use and some will not start in cold weather. CFLs are available with cold-weather ballasts, which may be rated to as low as minus 23C. Light output in the first few minutes drops at low temperatures. Cold-cathode CFLs will start and perform in a wide range of temperatures due to their different design.

Other fluorescent lamps

This section briefly mentions other types of specialty fluorescent lamps.

Blacklight lamps are a subset of fluorescent lamps that are used to provide near ultraviolet light (at about 360 nm wavelength). They are built in the same fashion as conventional fluorescent lamps but the glass tube is coated with a phosphor that converts the short-wave UV within the tube to long-wave UV rather than to visible light. They are used to provoke fluorescence (to provide dramatic effects using blacklight paint and to detect materials such as urine and certain dyes that would be invisible in visible light) as well as to attract insects to bug zappers.

Blacklight blue lamps are also made from more expensive deep purple glass known as *Wood's glass* rather than clear glass. The deep purple glass filters out most of the visible colors of light directly emitted by the mercury-vapor discharge, producing proportionally less visible light compared with UV light. This allows UV-induced fluorescence to be seen more easily. The blacklight lamps used in bug zappers do not require this refinement so it is usually omitted in the interest of cost; they are called simply blacklight.

Wood's glass is an optical filter glass which allows ultraviolet and infrared light to pass through while blocking most visible light.

Tanning lamps contain a different phosphor blend that emits both UVA and UVB, provoking a tanning response in most human skin. Typically, the output is rated as 3% to 10% UVB with the remaining UV as UVA. One common phosphor used in these lamps is lead-activated barium disilicate.

Grow lamps (aka Marijuana Lamps) contain phosphor blends that encourage photosynthesis, growth, or flowering in plants, algae, photosynthetic bacteria, and other light-dependent organisms. These often emit light in the red and blue color range, which is absorbed by chlorophyll and used for photosynthesis in plants.

Infrared lamps can be made with a lithium metaluminate phosphor activated with iron. This phosphor has peak emissions between 675 and 875 nanometers, with lesser emissions in the deep red part of the visible spectrum.

Bilirubin lamps generate deep blue light from a europium-activated phosphor is used in the light therapy treatment of jaundice; light of this color penetrates skin and helps in the breakup of excess bilirubin.

Germicidal lamps depend on the property that spectrum of 254 nm kills germs. Germicidal lamps contain no phosphor at all (making them mercury vapor gas discharge lamps rather than fluorescent) and their tubes are made of fused quartz that is transparent to the UV light emitted by the mercury discharge. The 254 nm UV emitted by these tubes will kill germs and ionize oxygen to ozone. In addition it can cause eye and skin damage and should not be used or observed without eye and skin protection.

Germicidal lamps have designations beginning with G (meaning 'Germicidal'), rather than F, for example G30T8 for a 30-watt, 1-inch diameter, 36-inch long germicidal lamp.

Electrode-less induction lamps are fluorescent lamps without internal electrodes. A current is induced into the gas column using electromagnetic induction. Because the electrodes are usually the life-limiting element of fluorescent lamps, such electrode-less lamps can have a very long service life, although they also have a higher purchase price.

Advantages of Fluorescent Lamps

Luminous efficacy

Fluorescent lamps convert more of the input power to visible light than incandescent lamps, though LEDs are sometimes even more efficient and are more rapidly increasing in efficiency. A typical 100 watt tungsten filament incandescent lamp may convert only 2% of its power input to visible white light, whereas typical fluorescent lamps convert about 22% of the power input to visible white light.

The efficacy of fluorescent tubes ranges from about 16 lumens per watt for a 4 watt tube with an ordinary ballast to over 100 lumens per watt with a modern electronic ballast, commonly averaging 50 to 70 lumens per watt. Most compact fluorescents above 13 watts with integral electronic ballasts achieve about 60 lumens per watt. For a given fluorescent tube, high-frequency electronic ballast gives about a 10% efficacy improvement over inductive ballast. It is necessary to include the ballast loss when evaluating the efficacy of a fluorescent lamp system; this can be about 25% of the lamp power with magnetic ballasts, and around 10% with electronic ballasts.

Fluorescent lamp efficacy is dependent on lamp temperature at the coldest part of the lamp. In T8 lamps this is in the center of the tube. In T5 lamps this is at the end of the tube with the text stamped on it. The ideal temperature for a T8 lamp is 25C while the T5 lamp is ideally at 35C.

Life
Typically a fluorescent lamp will last between 10 to 20 times as long as an equivalent incandescent lamp when operated several hours at a time. Under standard test conditions general lighting lamps have 9,000 hours or longer service life. The higher initial cost of a fluorescent lamp is usually more than compensated for by lower energy consumption over its life.

Lower luminance
Compared with an incandescent lamp, a fluorescent tube is a more diffuse and physically larger light source. In suitably designed lamps, light can be more evenly distributed without point source of glare such as seen from an undiffused incandescent filament; the lamp is large compared to the typical distance between lamp and illuminated surfaces.

Lower heat
About two-thirds to three-quarters less heat is given off by fluorescent lamps compared to an equivalent installation of incandescent lamps. This greatly reduces the size, cost, and energy consumption devoted to air conditioning for office buildings that would typically have many lights and few windows.

Disadvantages of Fluorescent Lamps

Frequent switching
If the lamp is installed where it is frequently switched on and off, it will age rapidly. Under extreme conditions, its lifespan may be much shorter than a cheap incandescent lamp. Each start cycle slightly erodes the electron-emitting surface of the cathodes; when all the emission material is gone, the lamp cannot start with the available ballast voltage. Fixtures intended for flashing of lights will use a ballast that maintains cathode temperature when the arc is off, preserving the life of the lamp. The extra energy used to start a fluorescent lamp is equivalent to a few seconds of normal operation; it is more energy-efficient to switch off lamps when not required for several minutes.

Health and safety issues
If a fluorescent lamp is broken, a very small amount of mercury can contaminate the surrounding environment. About 99% of the mercury is typically contained in the phosphor, especially on lamps that are near the end of their life.

Fluorescent lamps with magnetic ballasts flicker at a normally unnoticeable frequency of 100 or 120 Hz and this flickering can cause problems for some individuals with light sensitivity; they are listed as problematic for some individuals with autism, epilepsy, lupus, chronic fatigue syndrome, Lyme disease, and vertigo. Newer fluorescent lights without magnetic ballasts have essentially eliminated flicker.

Ultraviolet emission

Fluorescent lamps emit a small amount of ultraviolet (UV) light. A 1993 study found that ultraviolet exposure from sitting under fluorescent lights for eight hours is equivalent to only one minute of sun exposure. Very sensitive individuals may experience a variety of health problems relating to light sensitivity that is aggravated by artificial lighting.

Ultraviolet light can affect sensitive paintings, especially watercolors and many textiles. Valuable art work must be protected from light by additional glass or transparent acrylic sheets put between the lamp and the painting.

Ballast

Fluorescent lamps require a ballast to stabilize the current through the lamp, and to provide the initial striking voltage required to start the arc discharge. This increases the cost of fluorescent light fixtures, though often one ballast is shared between two or more lamps. Electromagnetic ballasts with a minor fault can produce an audible humming or buzzing noise. Magnetic ballasts are usually filled with a tar-like potting compound to reduce emitted noise. Hum is eliminated in lamps with high-frequency electronic ballast. Energy lost in magnetic ballasts is around 10% of lamp input power and electronic ballasts reduce this loss.

Power quality and radio interference

Simple inductive fluorescent lamp ballasts have a power factor of less than unity. Inductive ballasts include power factor correction capacitors. Simple electronic ballasts may also have low power factor due to their rectifier input stage.

Fluorescent lamps are a non-linear load and generate harmonic currents in the electrical power supply. The arc within the lamp may generate radio frequency noise, which can be conducted through power wiring. Suppression of radio interference is possible. Very good suppression is possible, but adds to the cost of the fluorescent fixtures.

Operating temperature

Fluorescent lamps operate best around room temperature. At much lower or higher temperatures, efficiency decreases. At below-freezing temperatures standard lamps may not start. Special lamps may be needed for reliable service outdoors in cold weather. In applications such as road and railway signaling, fluorescent lamps which do not generate as much heat as incandescent lamps may not melt snow and ice build up around the lamp, leading to reduced visibility.

Lamp shape

Fluorescent tubes are long, low-luminance sources compared with high pressure arc lamps, incandescent lamps and LEDs. However, low luminous intensity of the emitting surface is useful because it reduces glare. Lamp fixture design must control light from a long tube instead of a compact globe.

The compact fluorescent lamp (CFL) replaces regular incandescent bulbs. However, some CFLs will not fit some lamps, because the harp (heavy wire shade support bracket) is shaped for the narrow neck of an incandescent lamp, while CFLs tend to have a wide housing for their electronic ballast close to the lamp's base.

Flicker problems

Fluorescent lamps using magnetic power line frequency ballasts do not give out a steady light; instead, they flicker at twice the supply frequency. This results in fluctuations not only with light output but color temperature as well, which may pose problems for photography and people who are sensitive to the flicker. Even among persons not sensitive to light flicker, a stroboscopic effect can be noticed, where something spinning at just the right speed may appear stationary if illuminated solely by a single fluorescent lamp. This effect is eliminated by paired lamps operating on lead-lag ballast. Unlike a true strobe lamp, the light level drops in appreciable time and so substantial "blurring" of the moving part would be evident.

In some circumstances, fluorescent lamps operated at the 60 Hz power supply frequency can also produce flicker at the same frequency itself, which is noticeable by more people. This can happen in the last few hours of tube life when the cathode emission coating at one end has almost run out, and that cathode starts having difficulty emitting enough electrons into the gas fill, resulting in slight rectification and hence uneven light output in positive and negative going AC cycles. Power frequency flicker can also sometimes be emitted from the very ends of the tubes, if each tube electrode produces a slightly different light output pattern on each half-cycle. Flicker at power frequency is more noticeable in the peripheral vision than it is when viewed directly.

Near the end of life, fluorescent lamps can start flickering at a frequency lower than the power frequency. This is due to a dynamic instability inherent in the negative resistance of the plasma source, which can be from a bad lamp, bad ballast, or a bad starter; or occasionally from a poor connection to power.

The "beat effect" problem created when shooting films under standard fluorescent lighting

New fluorescent lamps may show a twisting spiral pattern of light in a part of the lamp. This effect is due to loose cathode material and usually disappears after a few hours of operation. Electromagnetic ballasts may also cause problems for video recording as there can be a "beat effect" between the periodic readings of a camera's sensor and the fluctuations in intensity of the fluorescent lamp.

Fluorescent lamps using high-frequency electronic ballasts do not produce visible light flicker, since above about 5 kHz, the excited electron state half-life is longer than a half cycle, and light production becomes continuous. Operating frequencies of electronic ballasts are selected to avoid interference with infrared remote controls. Poor quality (or failing) electronic ballasts may have insufficient reservoir capacitance or have poor regulation, thereby producing considerable 100/120 Hz modulation of the light.

Dimming

Fluorescent light fixtures cannot be connected to dimmer switches intended for incandescent lamps. Two effects are responsible for this: the waveform of the voltage emitted by a standard phase-control dimmer interacts badly with many types of ballast, and it becomes difficult to sustain an arc in the fluorescent tube at low power levels. Dimming installations require compatible dimming ballast. These systems keep the cathodes of the fluorescent tube fully heated even as the arc current is reduced, promoting easy thermionic emission of electrons into the arc stream.

Chapter 5
Environmental Issues with Fluorescent Lamps

There are several environmental issues with the materials used in fluorescent lamps. In some cases special handling and disposal is required.

Until the late 1940's fluorescent lamps used toxic beryllium compounds, which were implicated in the deaths of factory workers. Formerly, toxic materials such as beryllium, arsenic, cadmium, and thallium were used in phosphor manufacture. Modern halophosphate phosphors resemble the chemistry of tooth enamel and the rare-earth doped phosphors are not known to be harmful.

All fluorescent lamps contain mercury as vapor inside the glass tubing. Most CFLs contain 3–5 mg per bulb, with the bulbs labeled "eco-friendly" containing as little as 1 mg. Because mercury is poisonous, even these small amounts are a concern for landfills and waste incinerators where the mercury from lamps may be released and contribute to air and water pollution.

Only a few tenths of a milligram of mercury are required to maintain the vapor, but lamps must include more mercury to compensate for the part of mercury absorbed by internal parts of the lamp and no longer available to maintain the arc. Manufacturing processes have been improved to reduce the handling of liquid mercury during manufacture and improve accuracy of mercury dosing. The National Electrical Manufacturers Association (NEMA) has voluntarily capped the amount of mercury used in CFLs.

Each new generation of fluorescent lighting technology has been able to function with less mercury, but perform with the same or greater efficiency. The lamp has a coating on the inside of the glass wall that stops the glass and phosphors from absorbing mercury. This barrier coating reduces the amount of mercury needed. Since mercury absorption causes the lamp's light output to depreciate over its life, the coating helps to keep light levels much closer to initial output.

When CFLs first became a household product there were many concerns about their mercury content, however, in areas with coal-fired power stations, the use of CFLs saves on mercury emissions when compared to the use of incandescent bulbs. This is due to the reduced electrical power demand, reducing in turn the amount of mercury released by coal as it is burned. The EPA says that the net system emission of mercury for CFL lighting is lower than for incandescent lighting of comparable lumen output. This is based on the average rate of mercury emission for electricity production and average estimated escape of mercury from a CFL put into a landfill. As you can see from Figure 17, an incandescent may generate up to 5.8 milligrams of mercury from the production of the energy needed to power the lamp. In comparison, a CFL, used for the same period of time, will only generate 1.2 milligrams of mercury from the production of energy required to power the CFL. However, the CFL will add 0.6 milligrams of mercury to a landfill upon disposal. So, over the same period, a CFL will be responsible for generating 1.8 milligrams of mercury versus 5.8 milligrams for the incandescent.

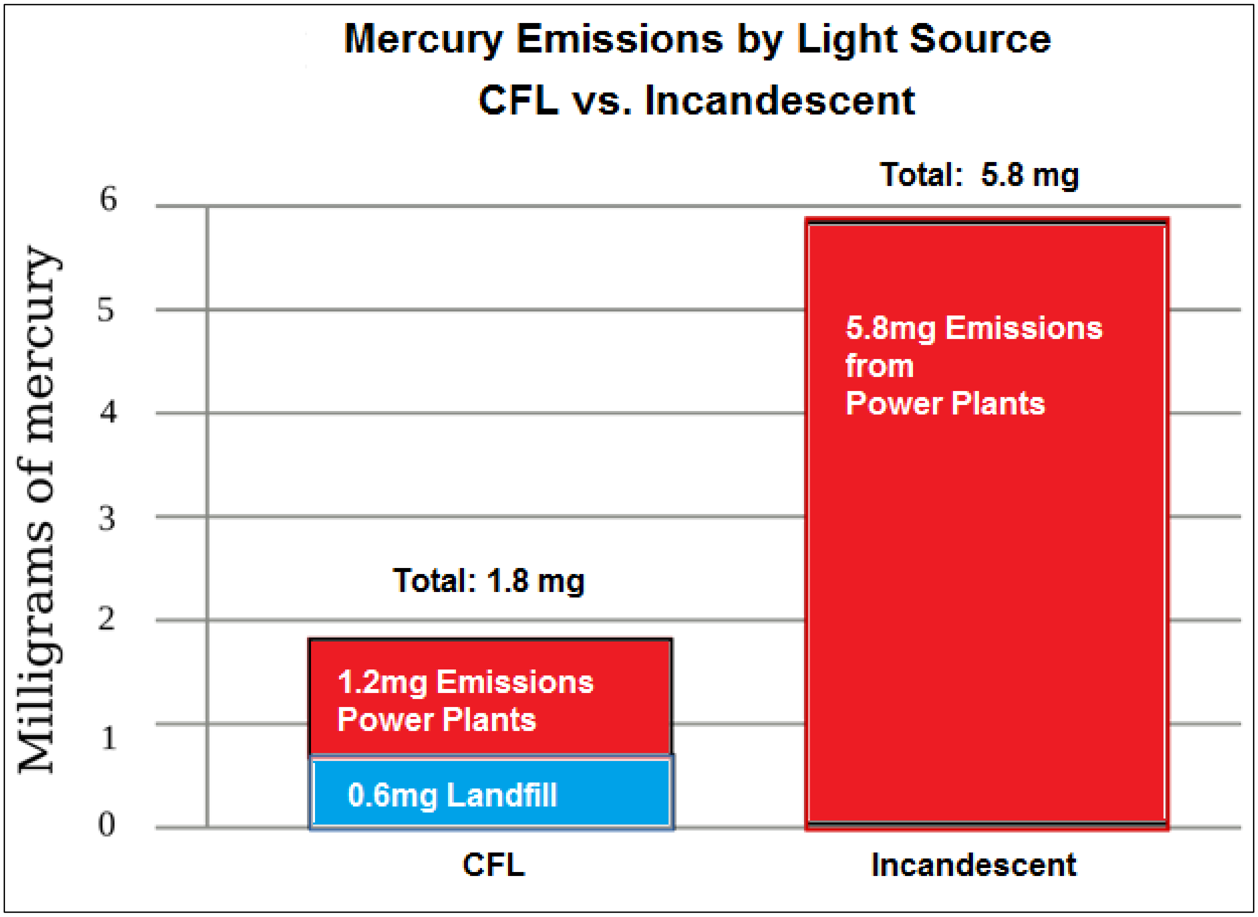


Figure 17

In the United States if all CFLs were sent to landfill sites, around 0.13 metric tons of mercury would be released, which is less than 0.1% of all U.S. emissions of mercury.

The amount of mercury released by one bulb can temporarily exceed U.S. federal guidelines for chronic exposure. Chronic, however, implies exposure for a significant time, and it remains unclear what the health risks are from short-term exposure to low levels of elemental mercury.

Estimates for the percentage of fluorescent lamps' total mercury released when they are disposed of in the following ways: municipal waste landfill 3.2%, recycling 3%, municipal waste incineration 17.55% and hazardous waste disposal 0.2%. See Figure 18.

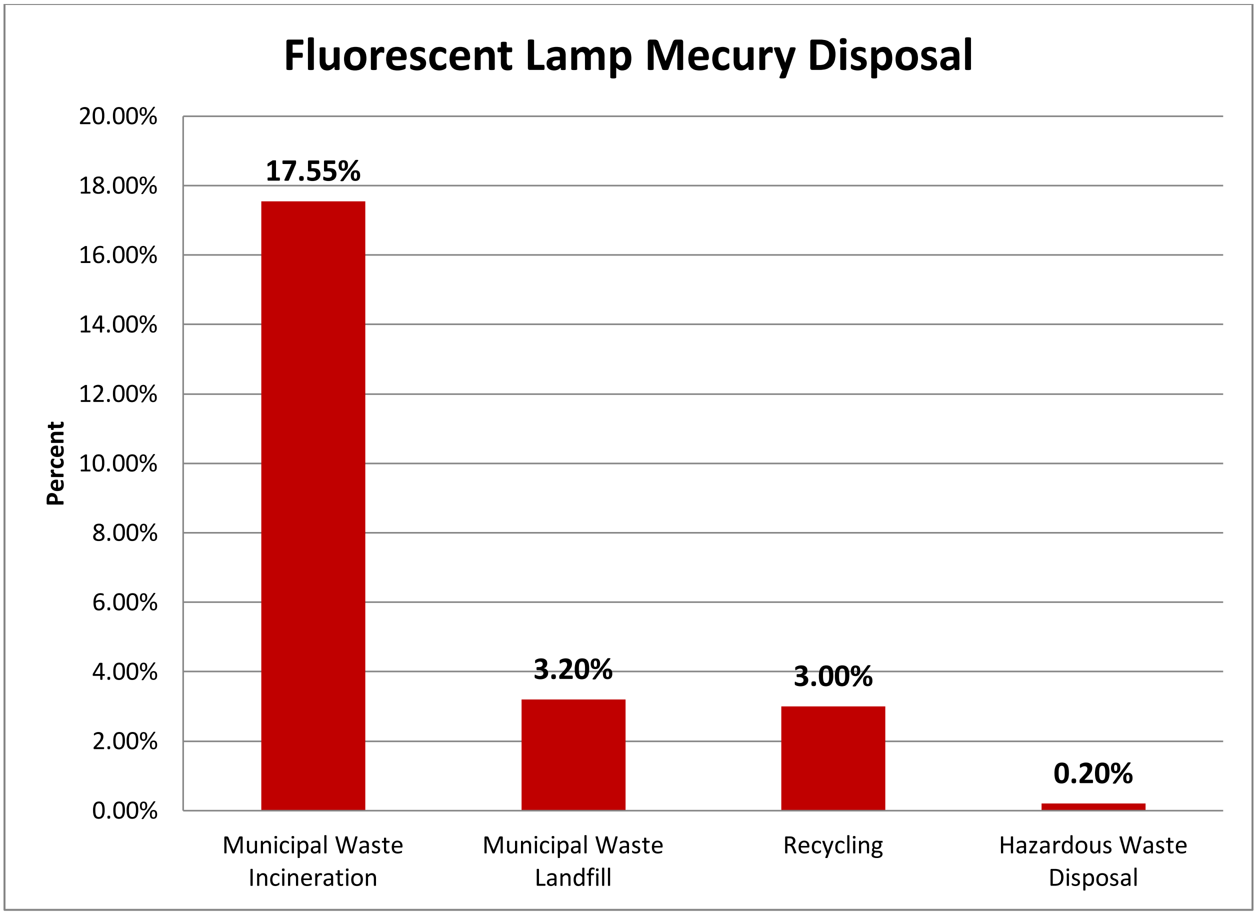


Figure 18

The disposal of phosphor and mercury toxins from spent tubes can be an environmental hazard. Regulations in many areas require special disposal of fluorescent lamps separate from general and household wastes. For large commercial or industrial users of fluorescent lights, recycling services are available and may be required by regulation. In some areas, recycling is also available to consumers.

When discarding a fluorescent tube, the main concern is the mercury, which is an important pollutant. One way to avoid releasing mercury into the environment is to combine it with sulfur to form mercury sulfide, which is insoluble in water. The easiest way to combine sulfur and mercury is to cover a group of fluorescent tubes with sulfur dust and break them; when the glass is put into a bag to continue with the reaction, the mercury will combine with sulfur without any other action. The glass can be recycled where an appropriate facility exists.

Fluorescent lamp recycling is the reclamation of the materials of a spent fluorescent lamp for the manufacture of new products. Glass tubing can be turned into new glass articles, brass and aluminum in end caps can be reused, the internal coating can be reprocessed for use in paint pigments, and the mercury contained in the lamp can be reclaimed and used in new lamps. In the United States, about 620 million fluorescent lamps are discarded annually; proper recycling of a lamp prevents emission of mercury into the environment, and is required by most states for commercial facilities. The primary advantage of recycling is diversion of mercury from landfill sites; the actual scrap value of the materials salvaged from a discarded lamp is insufficient to offset the cost of recycling.

Spent fluorescent lamps are typically packaged prior to transport to a recycling facility in one of three ways: boxed for bulk pickup, using a prepaid lamp recycling box, or crushed for pickup. A fluorescent lamp crusher can attach directly to a disposal drum and contain dust and mercury vapor.

Summary

Because of their efficiency, light out, and relatively low cost of acquisition, fluorescent lamps will remain the leading lighting source for commercial and industrial applications for many years. Even though LEDs are making inroads into this market, the economics continue to favor the fluorescent lamp.

In addition to the commercial and industrial markets, fluorescent lamps have been penetrating the residential market, especially with CFL's. Fluorescent lamps are available in a variety of styles and color outputs giving them wide latitude in meeting a lighting need.

Fluorescent lamps do create a mercury waste, though for CFL's at least, the overall impact is less than from an equivalent incandescent lamp.

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