PDHonline Course E442 (4 PDH)

Energy Efficiency – Halogen Lighting

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2020

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Energy Efficiency
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Introduction

In traditional incandescent lamps, vaporized gaseous tungsten from the filament is transported through the vapor phase and continuously deposited on the inside walls of the glass bulb. This artifact serves to blacken the inner walls of the bulb and gradually reduces light output. In order to maintain light loss at the lowest possible levels, conventional tungsten lamp filaments are housed in large bulbs having sufficient surface area to minimize the thickness of deposited tungsten that builds up over the life span of the lamp. Eventually, when a sufficient amount of tungsten is depleted, the lamp fails.

A halogen lamp, also known as a tungsten halogen or quartz lamp, is a form of incandescent lamp that has a small amount of a halogen such as iodine or bromine added. The combination of the halogen gas and the tungsten filament produces a halogen cycle chemical reaction which re-deposits evaporated tungsten back onto the filament, increasing its life and maintaining the clarity of the envelope. In order for the chemical reaction to take place, the filament needs to be hotter than that needed for incandescent bulbs. This hotter filament produces a brilliant white light and is more efficient than an incandescent lamp.

The filament is composed of ductile tungsten and located in a gas filled bulb just like a standard tungsten bulb, however the gas in a halogen bulb is at a higher pressure. The bulb must be stronger than standard glass in order to contain the high pressure. The glass bulb is typically made of fused quartz or some other special compound.

The first halogen type lamp was developed by General Electric in the 1950's. Previously, others had tried to build halogen lamps, however they could not determine how to stop the blackening of the lamp. General Electric determined that using a small amount of iodine surrounding the tungsten filament, would allow the lamp to burn at elevated temperatures. Philips Lighting developed a lamp that used halogen bromine instead of iodine. This lamp was more efficient than iodine at the time and became the standard form of halogen lamp.

In this course, starting with Chapter One, we will review the overall lighting market to get a sense of how halogen lamps are participating in the marketplace. Chapter Two reviews the fundamentals of lighting and Chapter Three covers the basic characteristics of all halogen lamps, including construction and operation. Chapter Four explains the predominate uses of halogen lighting.

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.

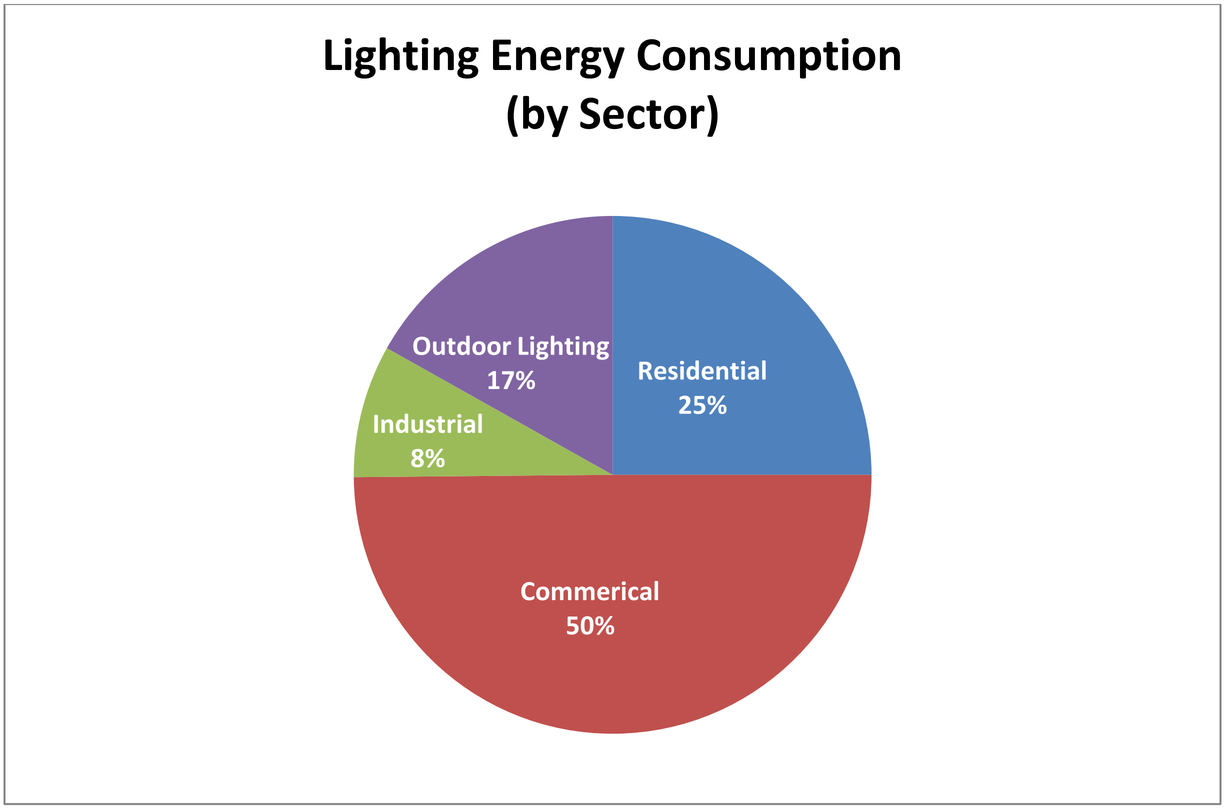


Figure 1

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

While LED lighting has experienced significant growth over the past decade, the impact of this technology has been limited, as of 2010, to mostly niche applications, such as traffic signal lighting and exit lights. LEDs penetration into general illumination applications in the building sectors is still significantly below one percent and the technology will need continued research and marketing support to realize its high potential penetration and energy savings.

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		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

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.

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

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 ft^2	**Wattage (Watts/Ft^2)**	**Energy Use (kWh/yr)**	**Intensity (kWh/yr/ft^2)**	**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 ft^2	Wattage (Watts/Ft^2)	Energy Use (kWh/yr)	Intensity (kWh/yr/ft^2)	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**

Solid-State Lighting

Solid-state lighting is one of the most efficacious lighting technologies available. In 2001 SSL, specifically LEDs, was found in approximately 1.6 million lamps or installations, or less than 0.1 percent of the total installed base of lighting. The majority, nearly 90 percent, were exit signs in the commercial and industrial sectors. The remainder of the LED installations was in outdoor traffic signal applications. Over the last decade the installed base of LED lighting has grown to over 67 million lamps, luminaires, and exit signs. While this represents a 40 fold increase in installed lamps, LEDs still only represented approximately 1 percent of the total installed base of lighting. This section details several characteristics of the LED installations in the residential, commercial, industrial, and outdoor sectors.

It was estimated that in 2010 approximately 9.2 million LED lamps were installed in the residential sector, accounting for 0.2 percent of the installed inventory of residential lighting. Approximately one-third of these residential LED lamps were screw based lamps. These lamps were most often found in common replacement applications such as torchieres and table lamps. Screw-based LEDs represent less than 0.1 percent of the installed stock of all residential screw based lamps.

The remainder, non-screw based, of the residential LEDs were installed in specialty applications such as under cabinet and landscape applications.

Although only 20 percent of LED lamps in the commercial sector are in non-exit sign applications, this represents significant growth from 37,000 non-exit sign LED lamps in 2001 to nearly 7.5 million non-exit sign LED lamps in 2010. These lamps range in wattages from 2 to 57, and are installed in applications ranging from display, track, task, and area lighting. Overall, non-exit sign LED lamps represent less than one percent of non-exit lighting in the commercial and industrial sectors.

The outdoor sector has seen the greatest penetration and growth in LED lamps due largely to their long lifetime (low maintenance cost) and high efficacy (low operating cost). While in 2001 it was estimated that 97,000 LED lamps or luminaires were installed in the outdoor sector, this report estimates that in 2010 the outdoor installed base of LED lamps or luminaires grew to 19 million. Across the entire outdoor sector, LEDs comprised 10 percent of the installed stock and experienced far greater shares in certain individual subsectors, as depicted by Figure 4-1. Similar to the 2001 analysis, traffic signals still represent the outdoor application in which LEDs have both the greatest percentage penetration (95 percent) and absolute number of installations. LEDs in parking and roadway applications have the next highest number of installed LED lamps or luminaires, representing three to four percent of lighting inventory in those applications.

Overall LED lamps consume approximately 3,000 GWh of electricity per year, constituting less than 0.5 percent of national lighting energy use.

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, □, 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.

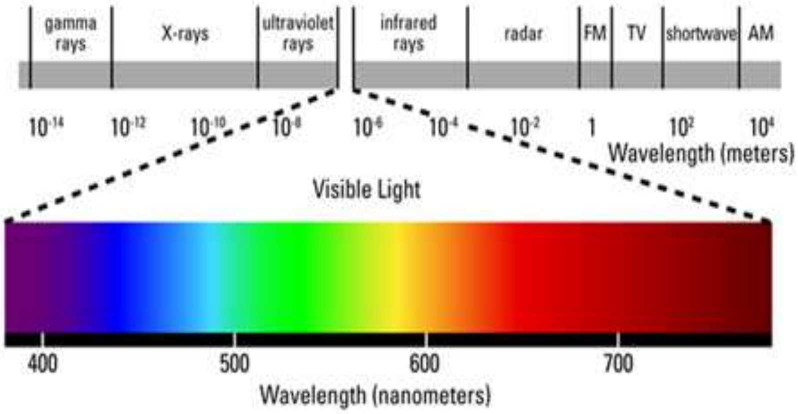


Figure 3

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.

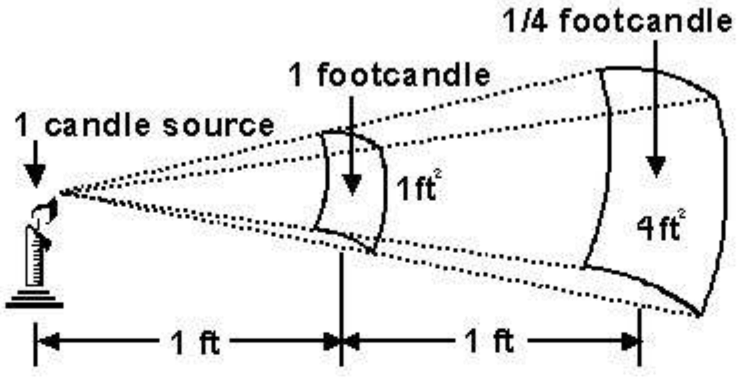


Figure 4

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).

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.

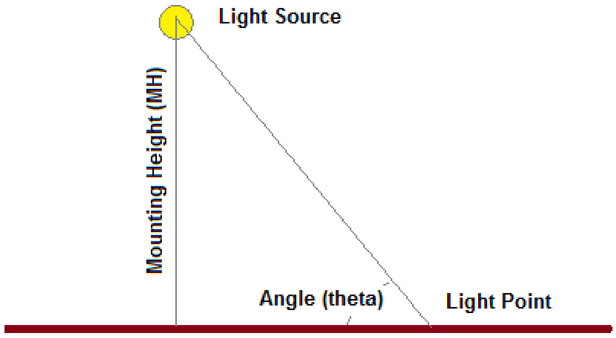


Figure 5

Considering the cosine law, the inverse square law becomes:

$Fc = Cd/D^2 \times \cos(\alpha)$

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:

$Fc = 5{,}000 / 12^2 \times \cos(30)$

$Fc = 35 \times 0.866$

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	5
Assembly	15
Exhibitions	30
Welding	50
Warehousing	
Inactive	5
Active	
Rough	10
Medium	20
Fine	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.

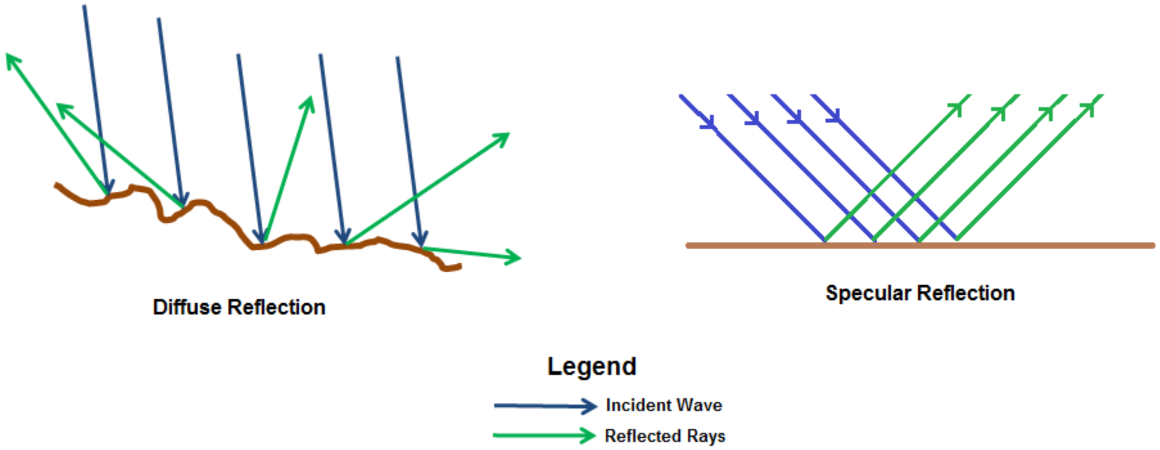


Figure 6

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 is 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.

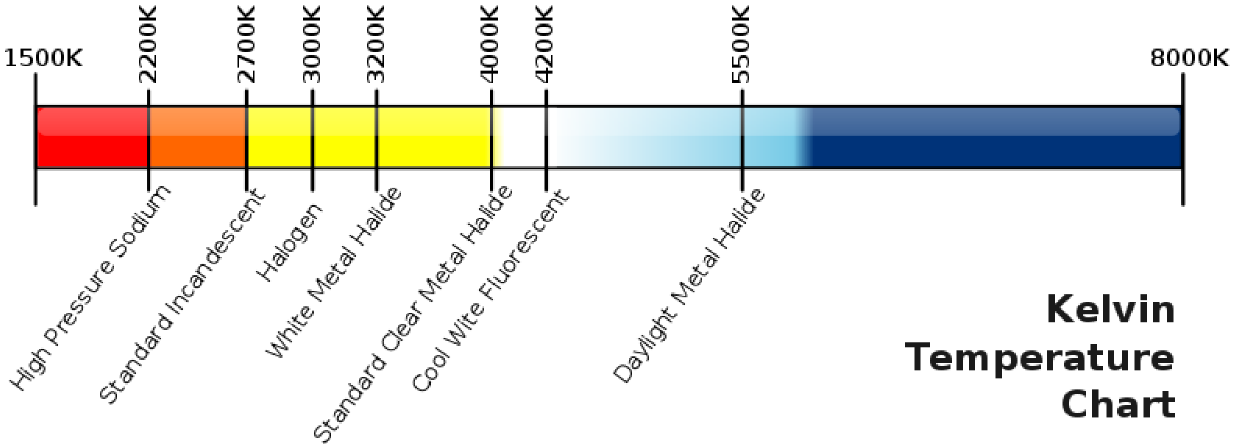


Figure 7

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.

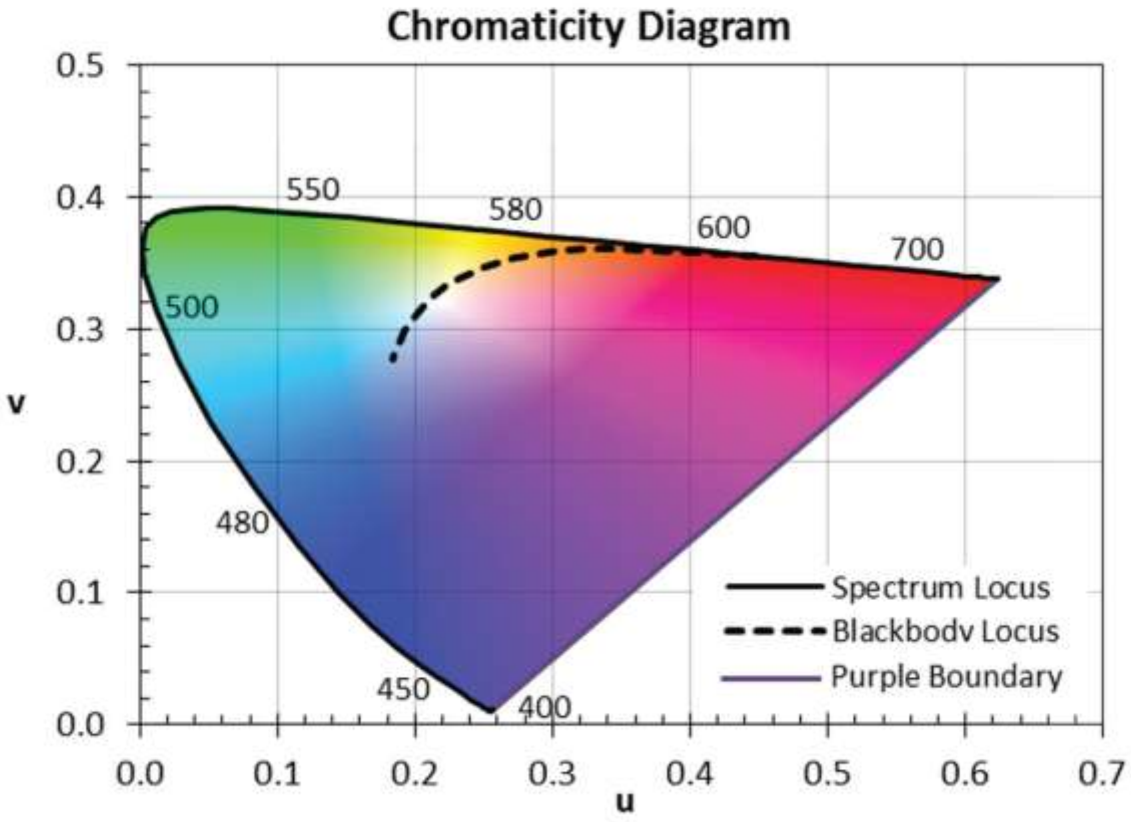


Figure 8

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.

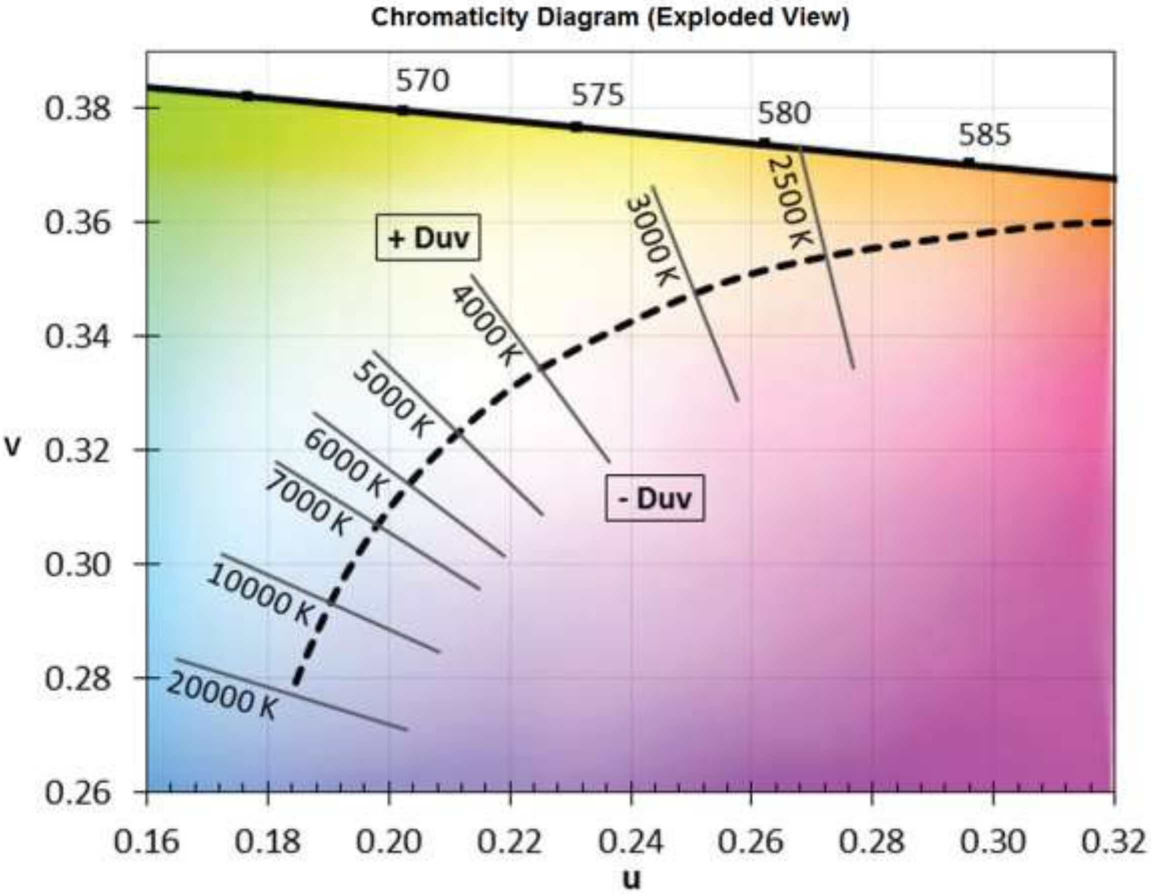


Figure 9

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.

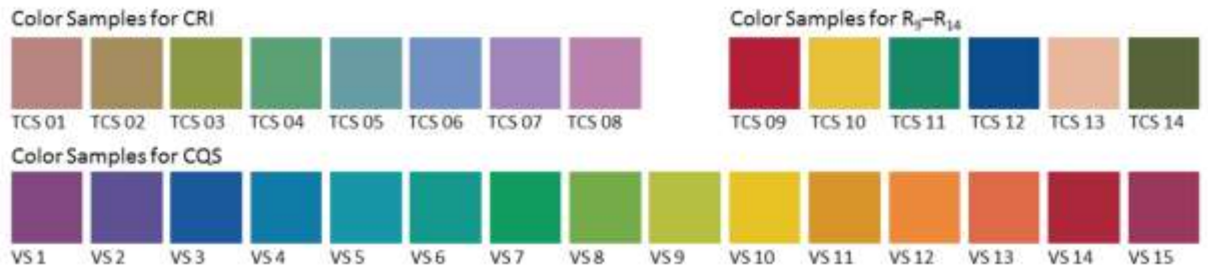


Figure 10

For each color sample, the chromaticity under a given 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
Operation of Halogen Lamps

In ordinary incandescent lamps, evaporated tungsten mostly deposits onto the inner surface of the bulb. A halogen lamp also uses a tungsten filament, but it is encased inside a much smaller quartz envelope. The gas inside the envelope is also different -- it consists of a gas from the halogen group which will combine with tungsten vapor. If the temperature is high enough, the halogen gas will combine with tungsten atoms as they evaporate and redeposit them on the filament. This recycling process gives the filament a longer life and it will generate more light output as a result of the higher operating temperature.

The halogen sets up a reversible chemical reaction cycle with the tungsten evaporated from the filament. The halogen cycle keeps the bulb clean and the light output remains almost constant throughout life. At moderate temperatures the halogen reacts with the evaporating tungsten, the halide formed being moved around in the inert gas filling. At some time it will reach higher temperature regions, where it dissociates, releasing tungsten and freeing the halogen to repeat the process. The overall bulb envelope temperature must be higher than in conventional incandescent lamps for the reaction to work.

The bulb must be made of fused quartz or a high-melting-point glass (such as aluminosilicate glass). Since quartz is very strong, the gas pressure can be higher, which reduces the rate of evaporation of the filament, permitting it to run a higher temperature (and so luminous efficacy) for the same average life. The tungsten released in hotter regions does not generally redeposit where it came from, so the hotter parts of the filament eventually thin out and fail.

High temperature filaments emit some energy in the UV region. Small amounts of other elements can be mixed into the quartz, so that the doped quartz blocks harmful UV radiation. Hard glass blocks UV and has been used extensively for the bulbs of car headlights. Alternatively, the halogen lamp can be mounted inside an outer bulb, similar to an ordinary incandescent lamp, which also reduces the risks from the high bulb temperature. Undoped quartz halogen lamps are used in some scientific, medical and dental instruments as a UV-B source.

Operation

As previously mentioned, the halogen lamp has a tungsten filament similar to the standard incandescent lamp, however the lamp is much smaller for the same wattage, and contains a halogen gas in the bulb. The halogen is important in that is stops the blackening and slows the thinning of the tungsten filament. This lengthens the life of the bulb and allows the tungsten to safely reach higher temperatures and therefore generate more light. The bulb must be able to stand higher temperatures so fused quartz is often used instead of normal silica glass.

Normally tungsten atoms evaporate off of the filament and deposit on the inside of the bulb, this blackens normal incandescent lamps. As atoms leave the filament the filament gets thinner. Eventually the filament breaks. In a halogen tungsten lamp the tungsten atoms chemically unite with the halogen gas molecules and when the halogen cools, the tungsten is re-deposited back on the filament. This process is called the *halogen regenerative cycle*.

A halogen is a monovalent element which readily forms negative ions. There are 5 halogens: fluorine, chlorine, bromine, iodine, and astatine. Only Iodine and Bromine are used in halogen tungsten lamps. Quartz iodine lamps, using elemental iodine, were the first commercial halogen lamps marketed in the 1950's by General Electric. Soon after, bromine was found to have advantages, but was not used in elemental form. Certain hydrocarbon bromine compounds gave good results. Regeneration of the filament is also possible with fluorine, but its chemical reactivity is so great that other parts of the lamp are attacked. The halogen is normally mixed with a noble gas, often krypton or xenon.

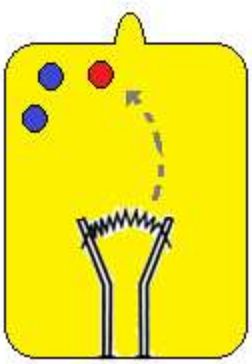
The major concern with tungsten lamps is that, during normal operation, the filament continuously vaporizes to produce gaseous tungsten that slowly reduces the filament diameter and eventually solidifies on the inside of the glass envelope as a blackened, sooty deposit. Over time, the lamp output diminishes as the residue of deposited tungsten on the inner envelope walls grows thicker and absorbs increasing amounts of the shorter visible wavelengths. Likewise, the loss of tungsten from the filament reduces the diameter, leaving it so thin that it ultimately fails.

Replacement of the lower-melting glass by quartz is necessary because the halogen regenerative cycle of the lamp requires the envelope to be maintained at a high temperature to prevent tungsten halogen compounds from solidifying on the inside surface. Although lamps containing halogens represented a significant improvement over the plain tungsten bulbs they replaced, the lamps feature a slight pinkish tinge that is characteristic of iodine vapor. In addition, quartz is readily attacked by the mild alkalis formed during operation, leading to premature failure of the envelope itself. Bromine compounds have replaced iodine and the envelope is now fabricated with borosilicate glass alloys to produce tungsten-halogen lamps having even longer life spans and higher radiant output than the earlier iodine lamps.

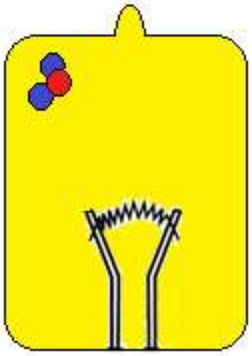
The envelope in tungsten-halogen lamps is filled with an inert gas (either nitrogen, argon, krypton, or xenon) that is mixed during assembly with a minute amount of a halogen compound and trace levels of molecular oxygen. The halogen compound serves to initiate a reversible chemical reaction with tungsten evaporated from the filament to yield gaseous tungsten halide molecules in the vapor phase. Thermal gradients formed as a result of the temperature differential between the hot filament and the cooler envelope contributes to interception and recycling of tungsten to the lamp filament through the *halogen regenerative cycle*. Thus, vaporized tungsten reacts with hydrogen bromide to form gaseous halides that are subsequently re-deposited onto cooler areas of the filament rather than being slowly accumulated on the inner walls of the envelope.

The following is a step-by-step explanation of the halogen regenerative cycle.

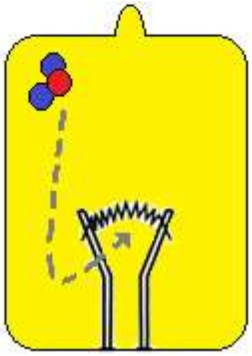
Step 1. At the start of operation, the lamp's envelope, fill gas, vaporous halogen, and filament are initially in equilibrium at room temperature. When power is applied to the lamp, the filament temperature rises rapidly to its operating temperature of around 3,000C, a sequence of events that also heats the gas and the envelope. Eventually, the envelope achieves its stable operating temperature of up to 1,000C. The temperature differential between the filament and the envelope creates thermal gradients and convection currents in the fill gas. Once the envelope reaches a temperature of approximately 250C the halogen regenerative cycle begins. At this point, tungsten particles evaporate from filament and attach on to bulb wall. At the same time, halogen is decomposed and becomes atomic halogen.



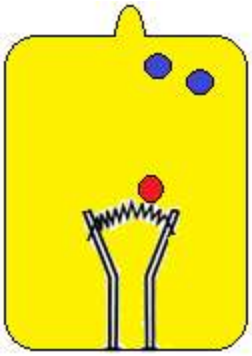
Step 2. Tungsten atoms evaporated from the filament react with gaseous halogen vapor and the trace levels of molecular oxygen to form tungsten halides.



Step 3. Due to the high temperature on the bulb wall, instead of condensing on the hot inner walls of the envelope, the halide compounds are circulated by convection currents back to the region surrounding the filament where they decompose, leaving elemental tungsten re-deposited on the cooler regions of the filament.



Step 4. Once free of combined tungsten, the oxygen and halide compounds diffuse back into the vapor to repeat the regenerative cycle. Continuous recycling of metallic tungsten back and forth between the vapor phase and the filament maintains a more uniform wire thickness than would otherwise be possible.



The halogen lamp's envelope is made of quartz glass because of the high operating temperature and pressure required to permit the halogen regenerative cycle process. Quartz also renders the lamp extremely resistant to heat impact. The small dimensions of halogen lamps allow accurate control over the light beam for a better focused and precise light.

The benefits of the halogen regenerative cycle include the ability to use smaller envelopes that are maintained in a clean, deposit-free condition during the life span of the lamp. Because the envelope is smaller than those used in conventional tungsten lamps, expensive quartz and related glass alloys can be more economically employed during fabrication. The stronger quartz envelopes enable higher internal gas pressure to be used to assist in suppression of filament vaporization, thus allowing increased filament temperatures that produce more luminous output and shift emission profiles to feature a greater proportion of the more desirable visible wavelengths. As a result, tungsten-halogen lamps retain their original brightness throughout their life span and also convert electric current to light more efficiently than traditional incandescent lamps. On the downside, the tungsten vaporized and re-deposited by the halogen regenerative cycle is not returned to its original location, but rather winds up on the coolest regions of the filament, resulting in uneven thickness. Eventually the lamps fail due to decreased filament thickness in the hottest regions. Otherwise, tungsten-halogen lamps might feature almost infinite life spans.

Spectrum

Like all incandescent light bulbs, a halogen lamp produces a continuous spectrum of light, from near ultraviolet to deep into the infrared. Since the lamp filament can operate at a higher temperature than a non-halogen lamp, the spectrum is shifted toward blue, producing light with a higher effective color temperature.

Tungsten-halogen lamps generate a continuous distribution of light across the visible spectrum, although most of the energy emitted by these lamps is dissipated as heat in the infrared wavelengths (see Figure 11). Due to their relatively weak emission in the ultraviolet portion of the spectrum, tungsten-halogen lamps are not as useful as arc lamps and lasers applications that require illumination in wavelengths below 400 nanometers.

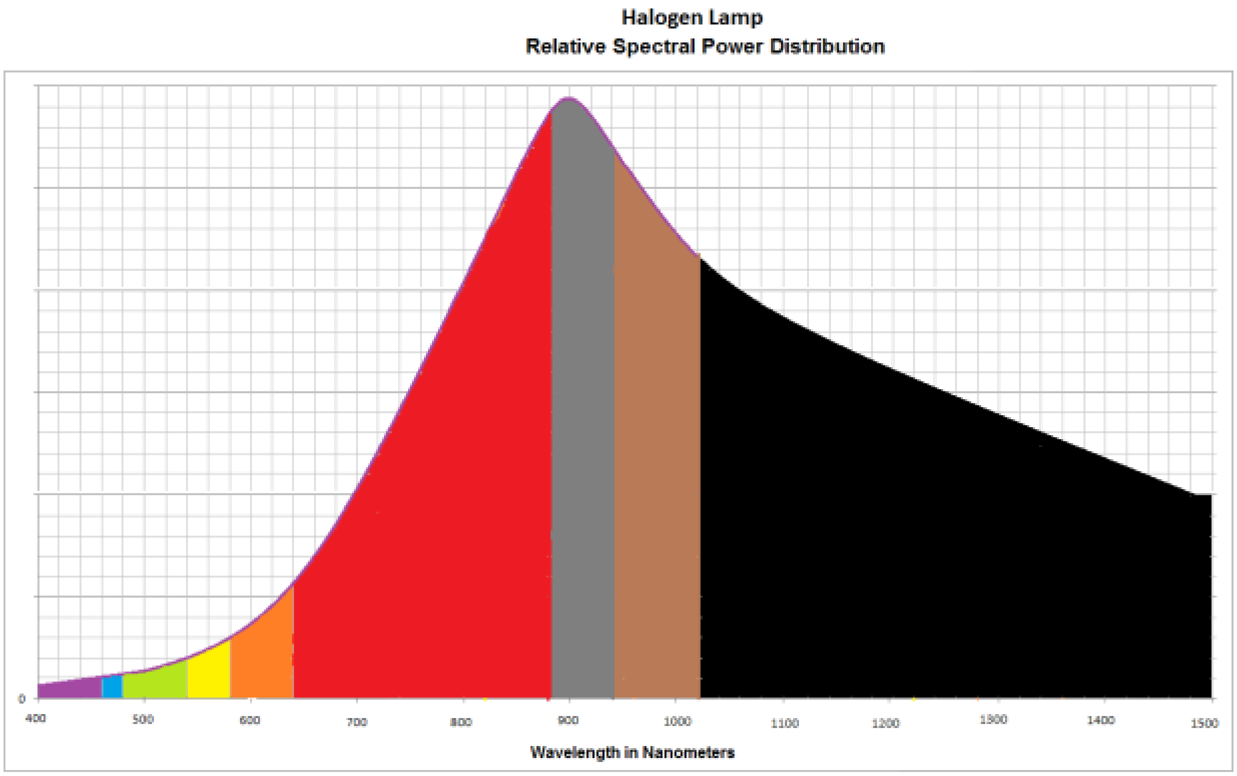


Figure 11

Tungsten-halogen incandescent lamps operate as *thermal radiators*, meaning that light is generated by heating a solid body (the filament) to a very high temperature. Thus, the higher the operating temperature, the brighter the light will be. All tungsten-based lamps exhibit emission spectral profiles resembling that of a *blackbody radiator*, and the spectral output profile of tungsten-halogen lamps is similar to those of incandescent lamps. The majority of the emitted energy (up to 85 percent) lies in the infrared and near-infrared regions of the spectrum, with 15-20 percent falling into the visible (400 to 700 nanometers), and less and 1 percent in the ultraviolet wavelengths (below 400 nanometers).

A ***Blackbody Radiator*** is an idealized physical body that has a spectrum that is determined by temperature alone, not by the body's shape or composition.

Construction

The basic anatomy of a single-ended tungsten-halogen lamp is illustrated in Figure 12. The total length is measured from the end of the base pin to the point of the sealed exhaust tube. Important parameters are the bulb diameter (thickest portion of the envelope), the *pinch width* of the base (usually slightly greater than the bulb diameter), and the dimensions of the filament. The effective size of the illumination source used in designing the output optical system is determined by the height and width of the filament.

The excessively high operating temperatures of tungsten-halogen lamps require substantially stronger and thicker transparent envelopes than conventional tungsten and carbon lamps. Fused silica quartz glass is the standard material used in the fabrication of tungsten-halogen lamps because this material can withstand envelope temperatures up to 1,000C and operating pressures approaching 50 atmospheres. In general, the optical quality of quartz lamp envelopes is considerably lower than that of the blown glass bulbs used to manufacture conventional incandescent lamps. The quartz targeted for lamp envelopes starts as a cylindrical tube that is first cut to the proper length before a smaller exhaust tube is attached.

Later in the manufacturing process, after the filament and lead pins are inserted and pinched, the envelope is filled with the appropriate gas and halogen compound before the exhaust tube is removed and sealed in a process referred to as *tip-off*, which leaves a visible blemish in the envelope. The prefabricated internal lamp structural elements (filament, foil connector, and pins) are inserted into the tubular quartz before the lead pins are hermetically sealed into the envelope by pinching. The outer surface of the pinch is shaped to ensure maximum mechanical strength.

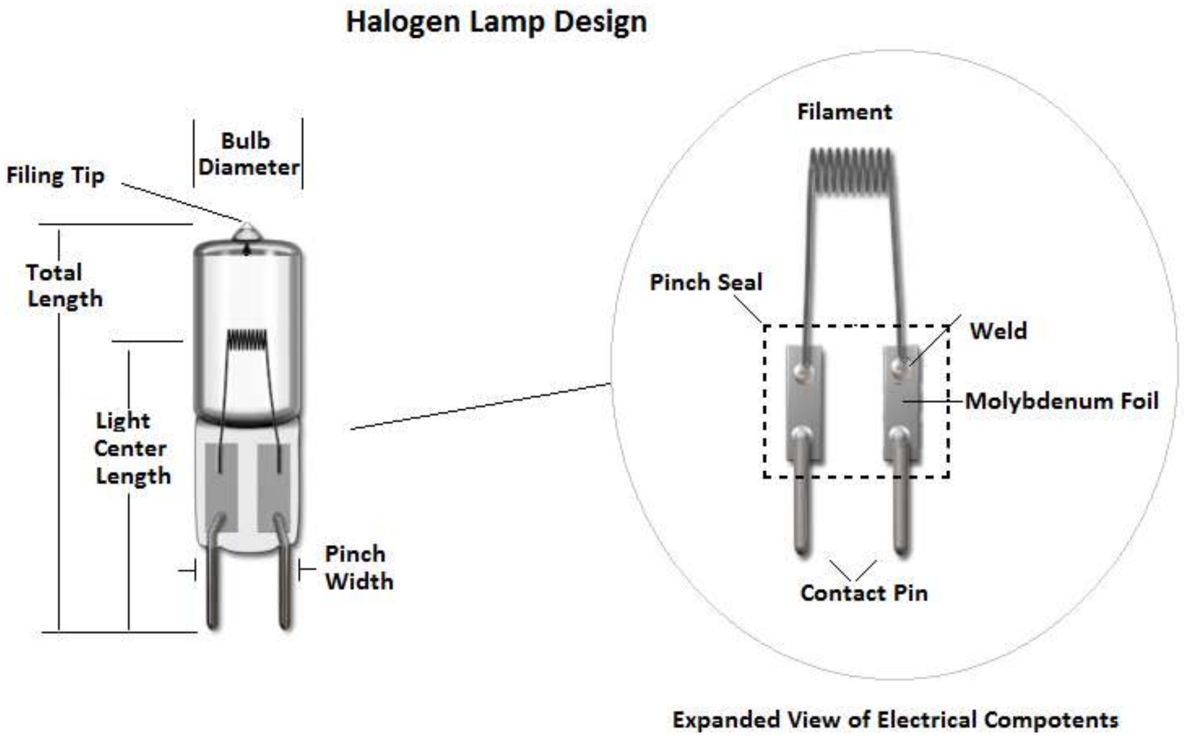


Figure 12

After the pin leads are pinched the bulb is filled through the exhaust tube with the appropriate gas containing 0.1 to 1.0 percent of a halogen compound. The inert fill gas can be either xenon, krypton, argon, or nitrogen, as well as a mixture of these gases having the highest average atomic weight consistent with the desired arc resistance. The high internal lamp pressure is achieved by filling the envelope to the desired pressure and immersing the lamp in liquid nitrogen to condense the fill gas. After sealing the exhaust tube at tip-off, the fill gas expands as it warms to ambient temperature. High performance tungsten-halogen lamps feature xenon, which has a higher atomic mass than krypton and the other fill gasses. Xenon provides better suppression of tungsten vaporization, enables higher filament temperatures, and increases the luminous efficacy.

Tungsten is always used to fabricate wire filaments in modern incandescent lamps. In order to be suitable for tungsten-halogen lamps, the raw tungsten wire must undergo a complex doping and heat treatment process to bestow the ductility necessary for processing and to ensure that the filament does not distort over extended periods of high temperature during lamp operation. The wire must also be rigorously cleaned to prevent harmful gases from being emitted after the lamp has been sealed. The filament wire length is determined by the operating voltage, with higher voltages requiring longer lengths. The diameter is dictated by lamp power levels and the desired life span. High power levels require thicker filaments, which are also mechanically stronger. Filament geometry is largely responsible for the photometric properties of tungsten-halogen lamps.

One of the critical factors in the fabrication of tungsten-halogen lamps is sealing the internal elements to isolate them from the external atmosphere. Lead-in wires protrude from the lamp base, through the seal, to position and secure the lamp in a socket that is wired to a power source. The most important aspect of creating a seal is the difference in thermal expansion coefficients between quartz and the tungsten filament leads. Quartz has a very low expansion coefficient whereas that of tungsten is much higher. Without a proper seal, the lead-in wires would rapidly expand when the lamp became hot and shatter the surrounding glass. In modern tungsten-halogen lamps, a very thin molybdenum foil is embedded in the quartz and each end of the foil is welded to short molybdenum connecting wires that are in turn welded to the filament and lead-in pin wires. Molybdenum is used in the seal because the razor-sharp edges enable it to be safely embedded into the quartz during the pinch operation.

The life of a typical lamp ends suddenly, usually upon powering up a cold lamp filament. During the course of an average life span, advanced tungsten-halogen lamps do not blacken and undergo only minor changes in photometric output characteristics. Similar to other incandescent lamps, tungsten-halogen lamp lifetimes are determined by the vaporization rate of tungsten from the filament. If the filament does not have a constant temperature along the entire length of the wire, but instead has regions of much higher temperature produced by uneven thickness or internal structural variations, then the filament will usually fail due to premature breakage in these regions. Even though vaporized tungsten is returned to the filament by the halogen regenerative cycle, the material is unfortunately deposited on cooler regions of the filament and not those critical hot spots where thinning usually occurs. As a result, it is virtually impossible to predict when any particular filament will fail in lamps that are operated continuously. In those lamps that are switched on and off frequently, it is safe to assume that they will fail at some point when being switched on.

Filament Designations

The filament is the most important element that produces light in a light bulb and, as for incandescent lamps, its design is crucial to ensuring the lamp will operate as intended. Tungsten filaments are used in the construction of the halogen lamps because of their high flexibility, high melting points and slow evaporation properties at high operating temperatures. They produce light by operating at about 3,000C temperature in an atmosphere of inert gases with added halogen gases (Iodine and/or bromine). Because halogen lamps are usually very compact in size, the filaments are also extremely small which, enables them to concentrate a high light energy inside the lamp. Some halogen lamps feature axial filament as shown if Figure 13 as opposed to standard horizontal mounting of the filament. An axial filament offers better light distribution and higher lamp efficacy.

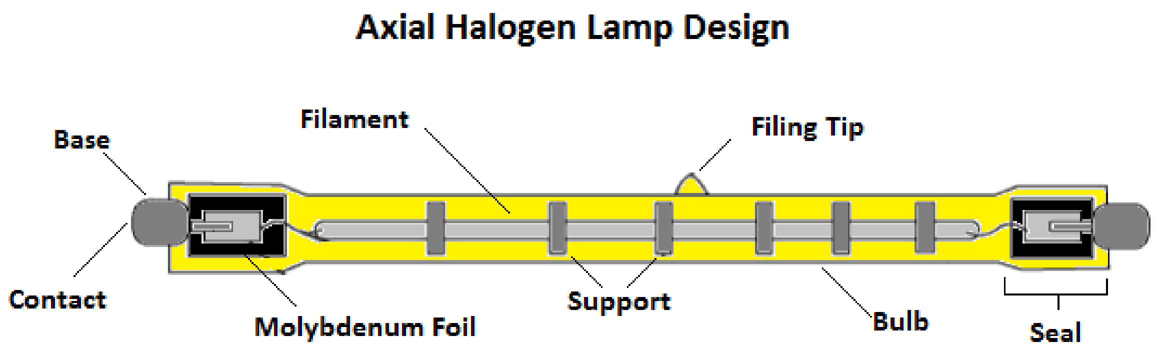


Figure 13

Filaments come in various shapes for many different applications. The length of the filament wire is largely determined by the lamp operating voltage whereas the diameter of the wire is dependent on the lamp wattage and the required lamp life. A 24-volt lamp filament is around 5-inches in length.

Besides the obvious issue that a 5-inch filament will not fit into a typical lamp, the efficacy of the lamp increases if the wire filament is wound into a core. The individual turns will heat up the adjacent turns and increase the wire temperature for a given wattage, thereby increasing the light output.

In addition to just coiling the wire filament, it may also be double wound or may include a flattened wire filament wound into a core. Similar to the incandescent filament designations, halogen lamp filaments are identified by a letter or letters which indicates a coiled wire (C) or double coiled wire (CC), followed by a number to indicate the shape of the filament. Figure 14 shows a few of the typical filament designs.

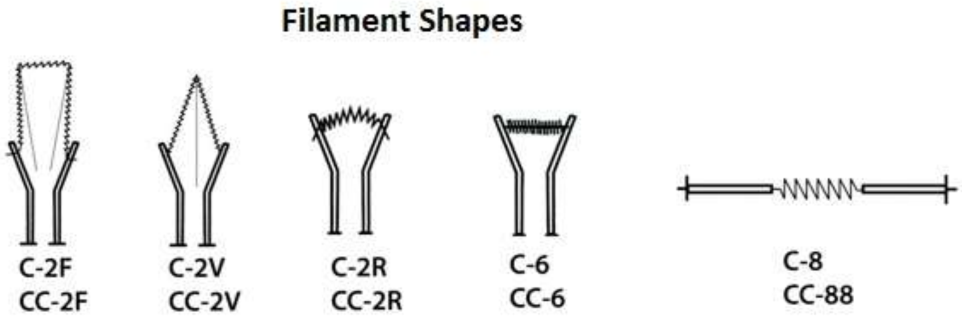


Figure 14

Effect of voltage on performance

Tungsten halogen lamps behave in a similar manner to other incandescent lamps when run on a different voltage. However the light output is proportional to the voltage cubed (V^3), and the luminous efficacy proportional to the voltage to the 1.3 power ($V^{1.3}$). The life of the lamp is inversely proportional to the voltage and is $V^{-1.4}$. For example, a bulb operated at 5% higher than its design voltage would produce about 15% more light, and the luminous efficacy would be about 6.5% higher, but would be expected to have only half the rated life.

Halogen lamps are manufactured with enough halogen to match the rate of tungsten evaporation at their design voltage. Increasing the applied voltage increases the rate of evaporation, so at some point there may be insufficient halogen and the lamp goes black. Over-voltage operation is not generally recommended. With a reduced voltage the evaporation is lower and there may be too much halogen, which can lead to abnormal failure. At much lower voltages, the bulb temperature may be too low to support the halogen cycle, but by this time the evaporation rate is too low for the bulb to blacken significantly. There are many situations where halogen lamps are dimmed successfully. However, lamp life may not be extended as much as predicted. The life span on dimming depends on lamp construction, the halogen additive used and whether dimming is normally expected for this type.

Since halogen lamps are designed with a tungsten filament, lamp life is proportional to the rate at which the filament evaporates, which means the filament temperature determines the nominal life of a given halogen light source. A slight change in voltage will increase or decrease the filament temperature and may cause deterioration in lamp life. Rated lamp life represents average life under laboratory conditions, where 50% of the lamps will continue burning at the end of their nominal rated life, while 50% will burn out.

Halogen lamps are designed to operate at very high temperatures to ensure optimal performance. Dimming to approximately 60% of the rated voltage is possible. However, dimming below 60% of the rated volts can cause blackening and alter the tungsten halogen regenerative cycle process thus reducing brightness and lamp life.

Chapter 4
Applications of Halogen Lighting

A common halogen fixture is the MR-16 reflector lamp. These are widely used for display lighting and in residential applications. Halogen lamps for home and commercial lighting has grown in recent years. The halogen track light is a popular way to provide quality light to specific areas for food preparation, paintings/wall hangings, and general mood lighting. The MR-16 lamp is used in many modern track lighting fixtures. We will discuss the ubiquitous MR-16 in more detail later.

There are many other applications for halogen lamps such as,

- Halogen headlamps in automobiles,
- Halogen floodlights for outdoor lighting systems,
- Infrared spectroscopy as a near-infrared light source,
- Heating element in a halogen oven,
- Tubular lamps in standalone lamps and household fixtures,
- Theatrical and studio fixtures, including Ellipsoidal Reflector Spotlights and Fresnels,
- Projection lamps in motion-picture and slide projectors for homes and school use, and
- Inspection lights and microscope illuminators.

The halogen lamp has "instant on" ability unlike mercury vapor or high pressure sodium, therefore they work well for security lamps that are activated by motion sensors. However, the life of a halogen lamp is shortened by frequent on and off cycles.

Advantages and Disadvantages of Halogen Lamps

Like any lighting source, halogen lamps have advantages and disadvantages. Generally, they are more efficient than traditional incandescent lamps and produce better light. They get very hot though and can be dangerous when they fail. Here are few of the advantages and disadvantages,

Advantages:
- Small,
- Lightweight,
- Lamps do not blacken over time,
- Does not use mercury like CFLs or mercury vapor lights,
- Have a high color temperature,
- Longer life than a traditional incandescent lamp, and
- No warm up time.

Disadvantages:

- Extremely hot during operation,
- The lamp is sensitive to oils left on the bulb by the human skin contact, which will cause premature failure of the bulb,
- The lamp can fail explosively, projecting glass shards, and
- Though more efficient than incandescent lamps, they are not nearly as efficient as efficient as HID and LED lamps.

Lamp Designations

Lamps have codes that define their shape and the type of base used with the lamp. The following is a brief explanation of the codes and a few of the lamp shapes and bases types. This list is not all-inclusive each type shown is not necessarily applicable to halogen lamps.

Light Bulb Shapes

Light bulbs are described by a shape, diameter, and length designation. This normally is in the form of letters followed by a number followed by an optional letter. The first letters indicate the shape, the numbers indicate the diameter and the final, optional letter can designate the length. The number that follows the shape designation to indicate the maximum diameter is in eighths of an inch.

The first letter is defined in Table 8 below,

Table 8

Shape Designator

Designation	Description
A	Standard household incandescent light bulb shape
B	Bulged bulb shape
BT	Bulged or Blown Tubular bulb shape
BR	Short reflector style light bulb
C	Candle shape
CA	Candle Angular shape
CW	Candle Twisted

CP	Crystalline Pear bulb shape
E	Ellipsoidal bulb shape
ER	Extended reflector light bulb shape
F	Flame style candelabra bulb shape
G	Globe bulb or circular bulb
GA	Decorator
HX	Hexagonal Candle
K	Krypton or narrow reflector light bulb shape
P	Pear bulb shape
PAR	Parabolic Aluminized Reflector (PAR) lamp
PS	Elongated standard incandescent bulb
R	Reflector light bulb style
S	Straight Sided bulb style
T	Tube lamp shape

The second digit is a number and is in eights of an inch. If a third digit exists it will describe the length of the bulb and will be either “S” for short, or “L” for long. See the explanation of an “A19” lamp in Figure 14 below.

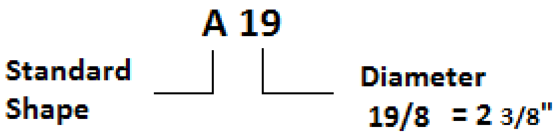


Figure 14

As you can see, this is a standard household type lamp that is 2 3/8” in diameter.

Figure 15 shows the different types of lamp shapes.

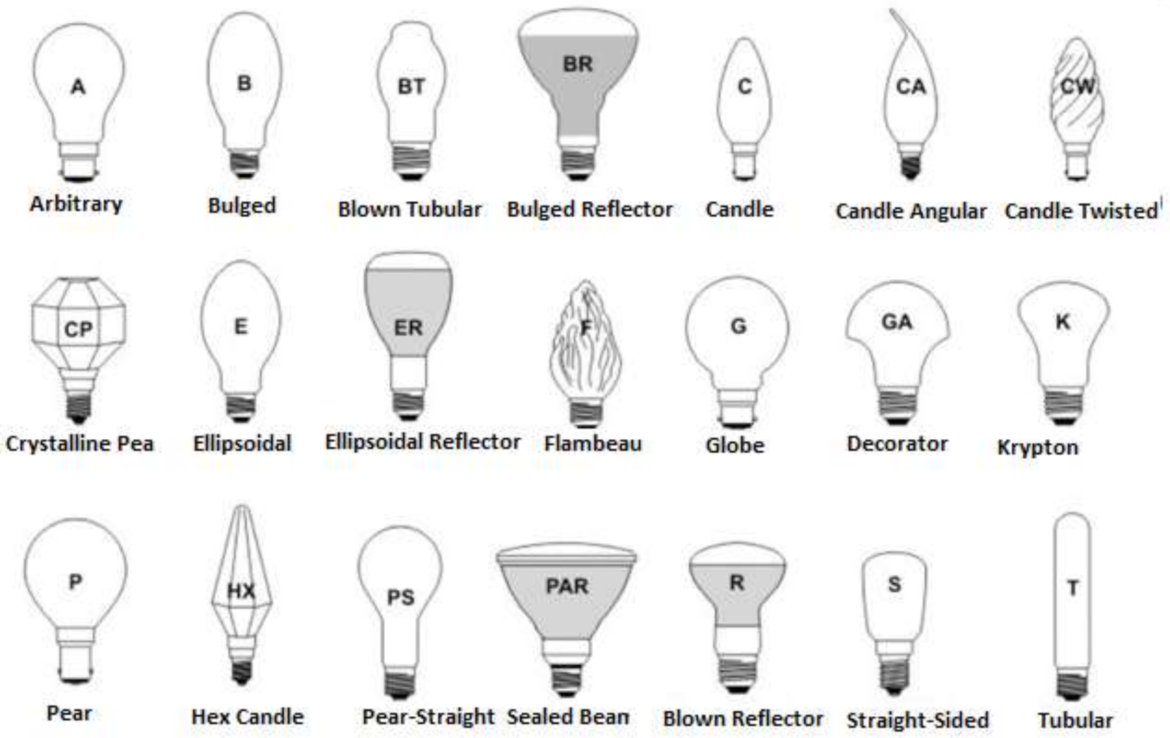


Figure 15

Base Types

Halogen lamps come with a variety of bases, some of which are common to both incandescent and halogen lamps. Some are single-pin or bi-pin and are particular to halogen lamps and infrared quartz. Light bulb bases and sockets are normally defined by a letter-number-letter format, with the last letter optional. The first letter designates the shape of the base, the numbers represent either the width of the base or the distance between the pins. The second letter designates the number of pins or contacts on the lamp. The numbers are normally in millimeters.

The first letter may be is defined in Table 9 below,

Table 9

Lamp Base Designators

Designation	Description
B	Bayonet Base
E	Edison Screw Base
F	Single Pin Type Base
G	Multiple Pin Type Bulb Base

K	Cable Connections
P	Pre-focused Light Base
R	Recessed Contact(s) Base
S	Shell-type Bulb Base
T	Telephone Slide Base
W	Wedge Base
X	Special Base

Table 10 shows the third position, which is a letter (if used),

Table 10

Lamp Base Pin Designator

Designation	Description
s	Single Pin
d	Double or 2-Pin Base Type
t	Triple Pin Base or 3-Pin Base
q	Quadruple Pin Base or 4-Pin Base
p	Penta- or 5-Pin Base

For example a “G5.3d” base is a multi-pin base with a pin-to-pin distance of 5.3mm and it has two pins (“d” means double.) See Figure 16.

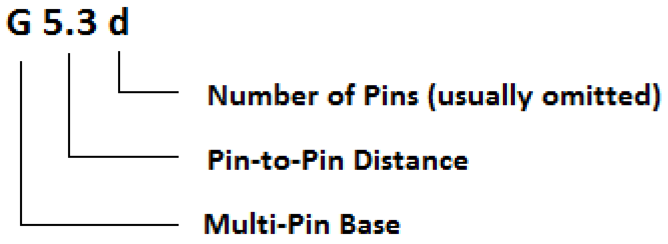


Figure 16

For another example a standard screw-in incandescent bulb has a base type of E26. The “E” stands for Edison screw-in and the “26” means that the base is 26mm.

Table 11 shows several “E” style bases while Table 12 shows several “G” style bases.

Table 11
“E” Style Bases

Base	Description
E5	Lilliput Edison Screw Base
E10	Miniature Edison Screw Base
E12	Candelabra Edison Screw Base
E17	Intermediate Edison Screw Base
E26	Medium Edison Screw Base
E40	Mogul or Giant Edison Screw Base

Table 12
“G” Style Bases

Base	Pin-to-Pin Distance	Application
G4	4mm	MR11
G5.3 GU5.3	5.33 mm	MR16
GU10	10mm	Twist-lock bi-pin base

Figure 17 is a graphical representative of a sampling of base types.

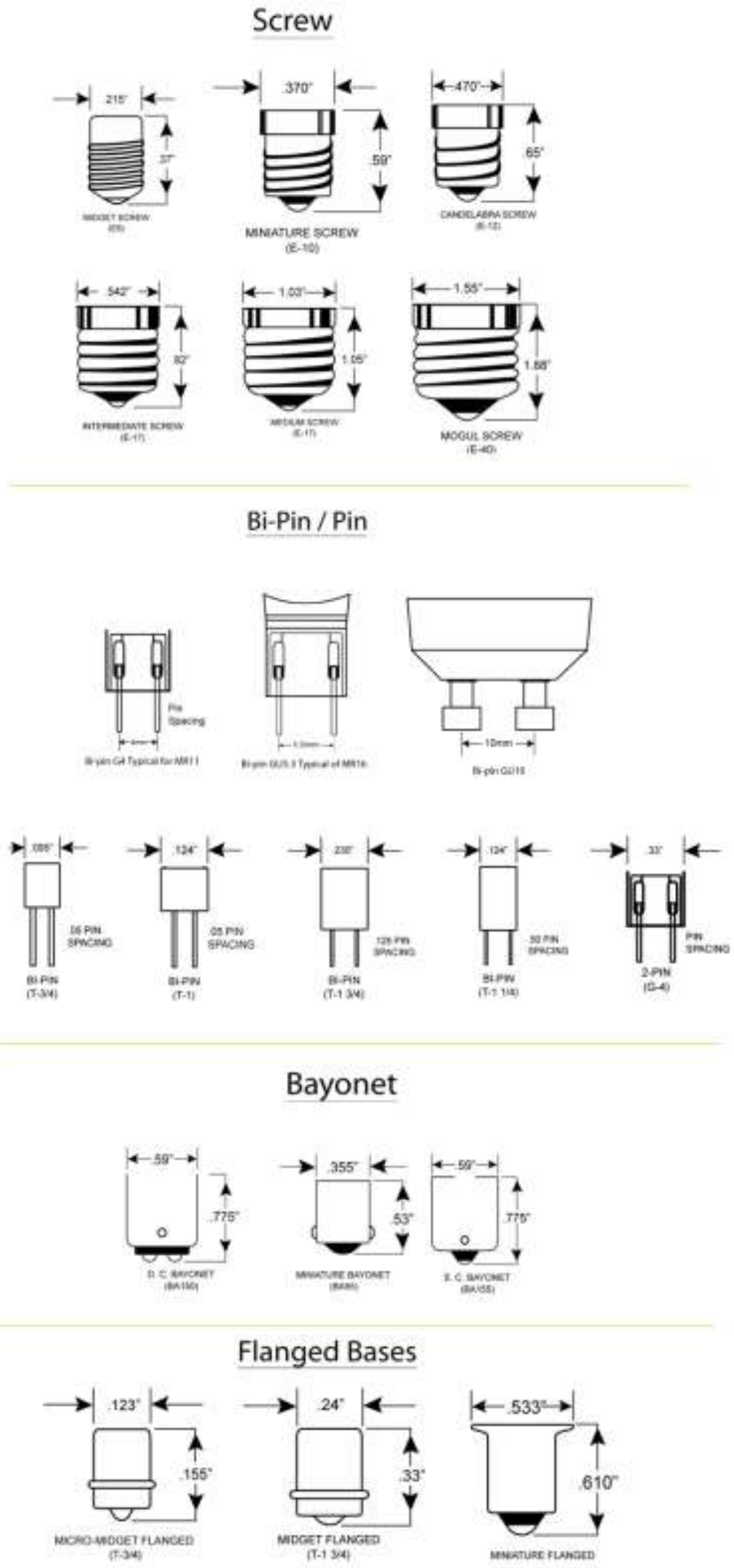

Screw
.215"
.37"
MIDGET SCREW
(E5)
.370"
.59"
MINIATURE SCREW
(E-10)
.470"
.65"
CANDELABRA SCREW
(E-12)
.542"
.82"
INTERMEDIATE SCREW
(E-17)
1.03"
1.05"
MEDIUM SCREW
(E-17)
1.55"
1.88"
MOGUL SCREW
(E-40)
Bi-Pin / Pin
Pin Spacing
4mm
Bi-pin G4 Typical for MR11
5.33mm
Bi-pin GU5.3 Typical of MR16
10mm
Bi-pin GU10
.085"
.05 PIN SPACING
BI-PIN
(T-3/4)
.124"
.05 PIN SPACING
BI-PIN
(T-1)
.230"
.125 PIN SPACING
BI-PIN
(T-1 3/4)
.124"
.50 PIN SPACING
BI-PIN
(T-1 1/4)
.33"
PIN SPACING
2-PIN
(G-4)
Bayonet
.59"
.775"
D. C. BAYONET
(BA15D)
.355"
.53"
MINIATURE BAYONET
(BA9S)
.59"
.775"
S. C. BAYONET
(BA15S)
Flanged Bases
.123"
.155"
MICRO-MIDGET FLANGED
(T-3/4)
.24"
.33"
MIDGET FLANGED
(T-1 3/4)
.533"
.610"
MINIATURE FLANGED

Figure 17

Reflector Lamps

As mentioned at the beginning of this chapter, the MR-16 reflector lamp is one of the most common halogen lamps for residential and commercial lighting. MR-16 lamps are commonly used for highlighting display objects and for accenting architectural and landscape features. The MR16 is a reflector lamp originally used in slide projectors. Its small size, durable construction, and wide range of intensities and beam spreads have since made the MR-16 a useful tool in lighting design as well.

A wide variety of halogen lamp designs incorporate integral reflectors that serve to efficiently gather light wavefronts emitted by the lamp and direct them into the illumination system in an organized manner. Termed *reflector lamps*, these pre-assembled units have found widespread use in a variety of applications.

Reflector lamps vary widely in design with regards to reflector features and geometry, as well as alignment of the lamp within the reflector. However, all reflector lamps incorporate single-ended lamps, which are mounted in the center of the reflector optical axis with the base cemented into the reflector apex. Filament configuration is generally determined by the beam characteristics required by the particular optical system for which the lamp is targeted. All filament designs, including transverse, axial, and flat-core, are used in reflector lamps.

Halogen reflectors are designed to either focus or collimate light emitted by the lamp, as illustrated in Figure 18. *Focusing reflectors* concentrate the light on a small spot in the central optical axis at a defined distance from the reflector. This type of reflector is designed with an elliptical geometry, which requires that the lamp filament be placed in the first focal point of the ellipsoid so that the projected light spot is concentrated at the second focal point. *Collimating reflectors* have a parabolic geometry in order to generate a parallel beam of light having beam characteristics that are defined by the lamp parameters and reflector size. The emerging beam angle is primarily determined by the size of the lamp filament and the free aperture of the reflector. In most cases, a round-core axial filament ensures a rotationally symmetrical beam.

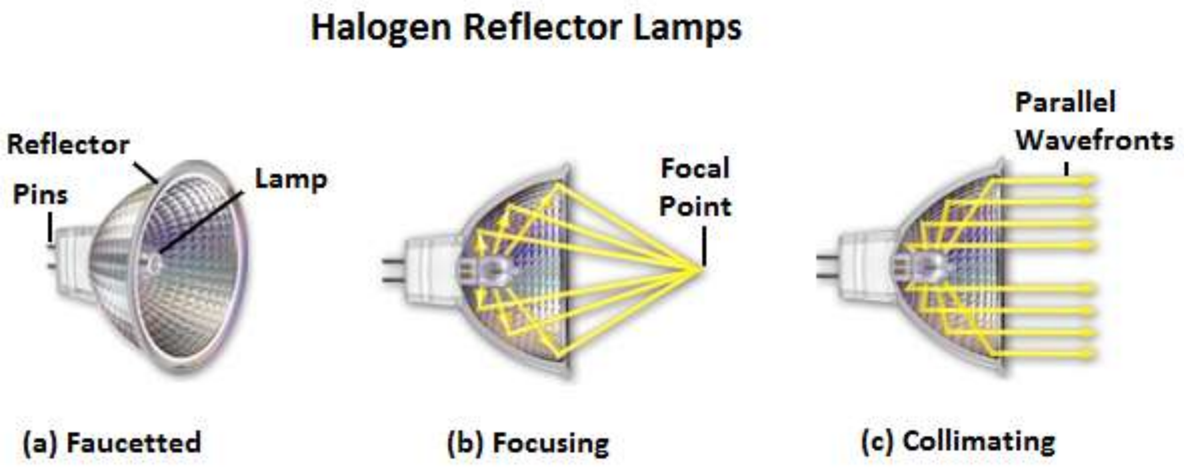


Figure 18

Reflectors are generally fabricated from glass, but some are also made with aluminum. Their inner walls can be either smooth or structured with facets to control light distribution. Internal structure ranges from fine, barely visible grains to large, tiled facets. In glass reflectors, the inner domed reflector surface is coated to obtain the required reflective properties. The dimensional stability of glass reflectors is superior to that of metal reflectors and the ability to choose specific coating materials, including those that can change the spectral character of reflected light, renders these reflectors far more versatile. Metal reflectors are far easier and cheaper to fabricate, but they are limited in spectral output control and are more prone to fluctuations in geometric tolerances during operation.

Because the capsule can rupture under certain end-of-life conditions (referred to in the lighting industry as *non-passive failure*), MR16 lamps must either have an integrated cover glass or be used in an enclosed fixture. The quartz capsule transmits ultraviolet (UV) radiation from the filament; however, this undesirable effect is mitigated by the lamp cover glass and/or fixture shields and filters.

The majority of MR16 lamps are designed for low-voltage operation. Filaments in low-voltage MR16 lamps are shorter, thicker, and more robust than their line-voltage counterparts. The thick filament provides increased resistance to current flow, which allows the low-voltage MR16—with its inherently higher operating current—to generate greater luminous intensity than line-voltage lamps of equal wattage. In combination with lamp reflector design, the small filament also allows more precise control of light distribution and beam appearance.

MR16 reflectors generally use either a dichroic or aluminum coating. *Dichroic coatings* reflect light from the filament through the front of the lamp and transmit infrared radiation (IR) through the back of the reflector along with some colored light. In contrast, aluminum coatings are opaque, reflecting all light and IR forward. Many manufacturers provide different quality grades for MR16 reflector coatings and optics, allowing the user to match lamp performance and cost with application requirements.

The MR16 lamp is commonly characterized by its beam spread. Small beam angles for highlighting individual objects or features and wide angles are used for general accent lighting. For directional lamps, intensity rather than total lumen output is the prevalent metric. Figure 19 illustrates the relationship between *center beam candlepower* (CBCP) and beam angle:

- CBCP is the intensity in candelas (cd) emitted at the center of a directional lamp beam (0°, or nadir). CBCP values for halogen MR16 lamps range from 230 to 16,000 cd and are affected by both the lamp wattage and the beam angle of the lamp. A lamp with a large beam angle will have a lower CBCP than a lamp with narrow distribution.

- *Beam angle* is the angle at which the beam intensity is 50% of the CBCP. Beam angles for halogen MR16 lamps range from less than 10° (narrow spot) to greater than 50° (wide flood).

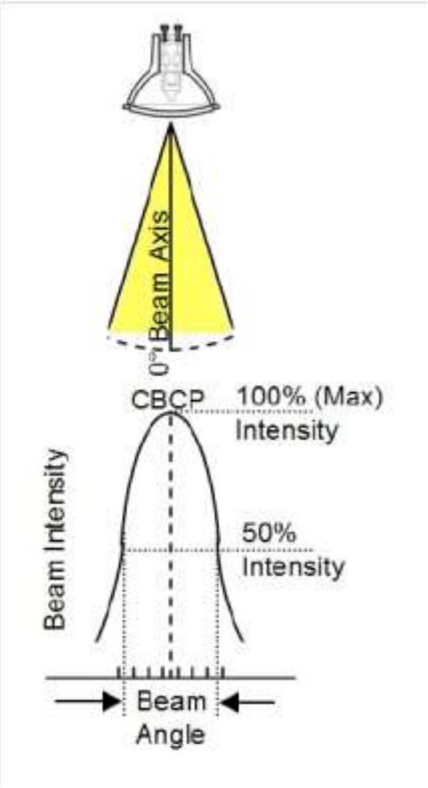


Figure 19

Table 13 presents a summary of data for a typical low-voltage 20-W halogen MR16 lamp.

Table 13

Performance Characteristics of Low-Voltage Halogen MR16 Lamps

Characteristic	Ratings
Input power	20 Watts
Light output	400 Lumens
CBCP by beam angle	
Spot (<20°)	7,400 cd
Narrow flood (20–35°)	2,300 cd
Wide flood (>35°)	1,000 cd

Efficacy	20 lumens/watt
CCT	23,000 K
CRI	99

Halogen Lamp Environmental Concerns

Halogen lamps are may create fire hazards explosions, and unwanted, UV exposure. In addition, special handling is required during installation to prevent premature failure of the lamp.

Halogen lamps get hotter than regular incandescent lamps because the heat is concentrated on a smaller envelope surface, and because the surface is closer to the filament. This high temperature is essential to their operation. Because the halogen lamp operates at very high temperatures, it can pose fire and burn hazards. Numerous house fires each year are attributed to ceiling-mounted halogen downlights. Some safety codes now require halogen bulbs to be protected by a grid or grille, especially for high power bulbs used in theatre, or by the glass and metal housing of the fixture to prevent ignition of draperies or flammable objects in contact with the lamp.

To reduce unintentional ultraviolet (UV) exposure, and to contain hot bulb fragments in the event of explosive bulb failure, general-purpose lamps usually have a UV-absorbing glass filter over or around the bulb. Alternatively, lamp bulbs may be doped or coated to filter out the UV radiation. With adequate filtering, a halogen lamp exposes users to less UV than a standard incandescent lamp producing the same effective level of illumination without filtering.
Handling precautions

Any surface contamination, notably the oil from human fingertips, can damage the quartz envelope when it is heated. Contaminants will create a hot spot on the bulb surface when the lamp is turned on. This extreme, localized heat causes the quartz to change from its vitreous form into a weaker, crystalline form that leaks gas. This weakening may also cause the bulb to form a bubble, weakening it and leading to its explosion. Consequently, manufacturers recommend that quartz lamps should be handled without touching the clear quartz, either by using a clean paper towel or carefully holding the porcelain base. If the quartz is contaminated in any way, it must be thoroughly cleaned with alcohol and dried before use.

Halogen lamps do not contain mercury and manufactures say that none of the materials used in halogen lamps are classified as hazardous waste.

Summary

Halogen lamps have the advantage of being more efficient and having longer life than the incandescent bulb. They are relatively small in size and are dimmable. The disadvantages are that they are more expensive, and burn at a much higher temperature, which could possibly be a fire hazard in certain areas.

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