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Energy Efficiency – HID Lighting

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Energy Efficiency High Intensity Discharge Lighting

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Introduction

Gas-discharge lamps are light sources that generate light by sending an electrical discharge through an ionized gas. The character of the gas discharge depends on the pressure of the gas as well as the frequency of the current. High-intensity discharge (HID) lighting provides the highest efficacy and longest service life of any lighting type. It can save 75%-90% of lighting energy when it replaces incandescent lighting.

Figure 1 shows a typical high-intensity discharge lamp. In a high-intensity discharge lamp, electricity arcs between two electrodes, creating an intensely bright light. Usually a gas of mercury, sodium, or metal halide acts as the conductor.

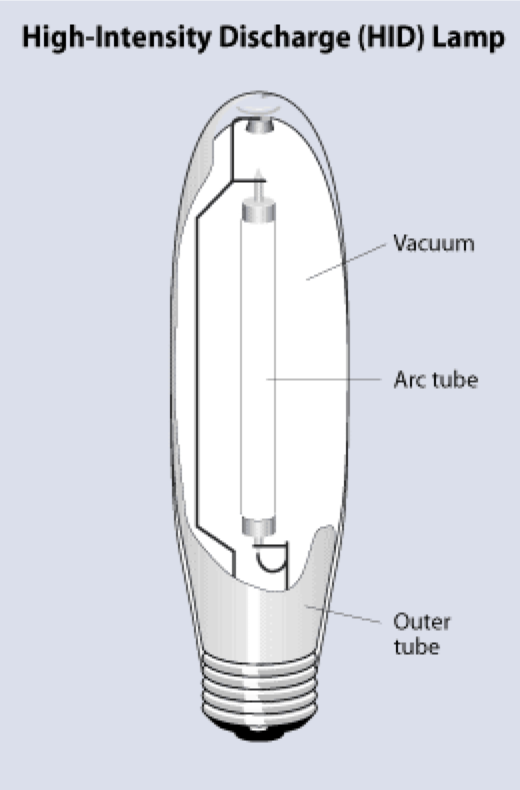

Figure 1

HID lamps use an electric arc to produce intense light. Like fluorescent lamps, they require ballasts. They also take up to 10 minutes to produce light when first turned on because the ballast needs time to establish the electric arc. Because of the intense light they produce at a high efficacy, HID lamps are commonly used for outdoor lighting and in large indoor arenas and they are most suitable for applications in which they stay on for hours at a time.

The three most common types of high-intensity discharge lamps are:

- Mercury vapor lamps
- Metal halide lamps
- High-pressure sodium lamps

Mercury vapor lamps are the oldest types of high-intensity discharge lighting and have been used primarily for street lighting. Mercury vapor lamps provide about 65 lumens per watt. They cast a very cool blue/green white light. Mercury vapor lamps have lifetimes of up to 24,000 hours.

Metal halide lamps produce a bright, white light with the best color rendition among high-intensity lighting types. They are used to light large indoor areas, such as gymnasiums and sports arenas, and outdoor areas, such as car lots. Metal halide lamps are similar in construction and appearance to mercury vapor lamps. The addition of metal halide gases to mercury gas within the lamp results in higher light output, more lumens per watt, and better color rendition than from mercury gas alone. Metal halide lamps have shorter lifetimes than mercury vapor and high-pressure sodium lamps.

High-pressure sodium lighting is the most common type of outdoor lighting. High-pressure sodium lamps have an efficacy of up to 140 lumens per watt—an efficiency exceeded only by low-pressure sodium lamps. They produce a warm white light. Like mercury vapor lamps, high-pressure sodium lamps have poorer color rendition than metal halide lamps but longer lifetimes.

The first mercury vapor lamp was invented in 1901 by American engineer Peter Cooper Hewitt. In 1903, Hewitt created an improved version that possessed higher color qualities which eventually found widespread industrial use. The Hewitt lamps used a large amount of mercury. In the 1930s, improved lamps developed by the General Electric Company and others led to widespread use of mercury vapor lamps for general lighting.

The introduction of the metal vapor lamp, including various metals within the discharge tube, was a later advance. The heat of the gas discharge vaporizes some of the metal and the discharge is then produced almost exclusively by the metal vapor. The usual metals are sodium and mercury owing to their visible spectrum emission.

In this course, starting with Chapter One, we will review the overall lighting market to get a sense of how HID lighting is participating in the marketplace. Chapter Two reviews the fundamentals of lighting and Chapter Three covers the basic characteristics of all HID lighting. In addition to the three major types of HID lighting just mentioned, there are variations and these will be discussed in more detail in Chapter Four.

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.

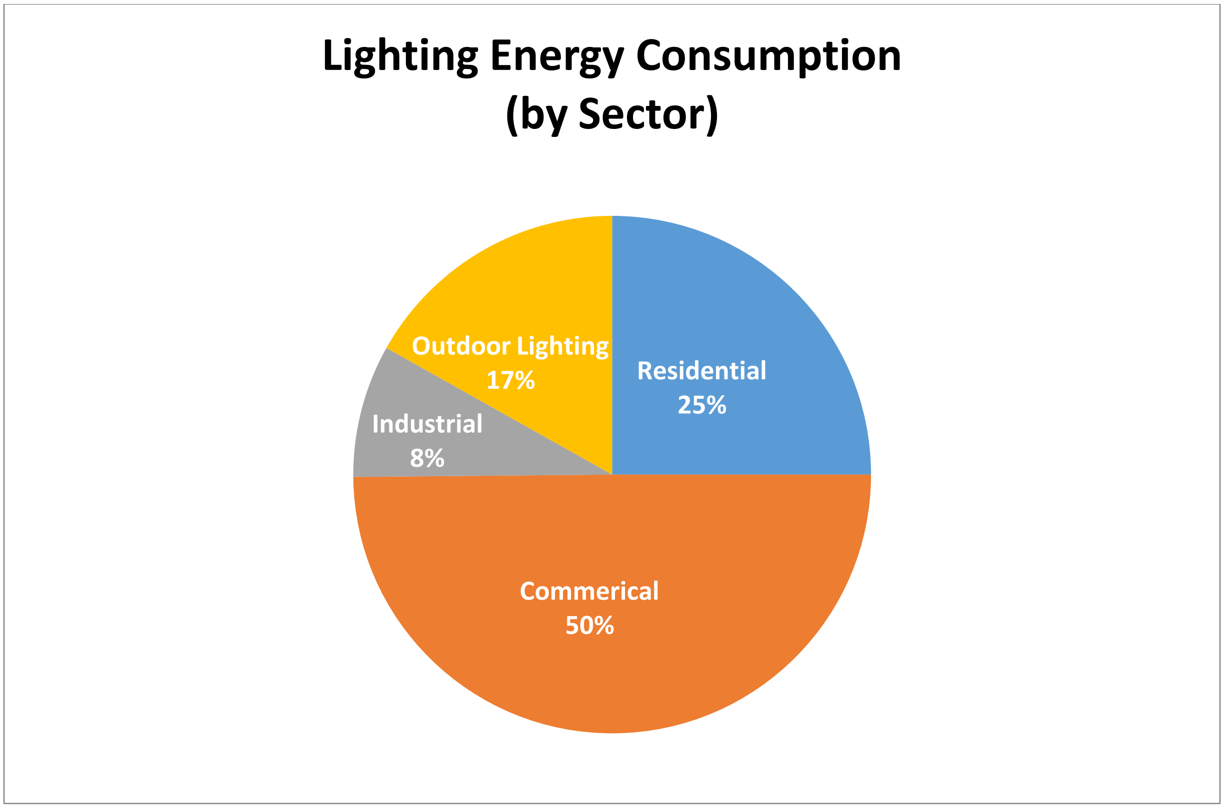

Figure 2

See Figure 2, 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 3.

Lamp Classification

Incandescent

- General Service – A Type
- General Service – Decorative
- Reflector
- Miscellaneous

Halogen

- General Service
- Reflector
- Low Voltage Display
- Miscellaneous

Compact Fluorescent

- General Service – Screw
- General Service – Pin
- Reflector
- Miscellaneous

Other

- LED Lamp
- Miscellaneous

Fluorescent

- T5
- T8 - Less than 4 ft
- T8 - 4 ft
- T8 - Greater than 4 ft
- T12 - Less than 4 ft
- T12 - 4 ft
- T12 - Greater than 4ft
- T8 - U Shaped
- T12 - U Shaped
- Miscellaneous

High Intensity Discharge

- Mercury Vapor
- Metal Halide
- High Pressure Sodium
- Low Pressure Sodium

Figure 3

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**

Approximately 84% of outdoor lighting is generated from HID lighting sources such as mercury vapor, metal halide, and sodium fixtures.

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 4.

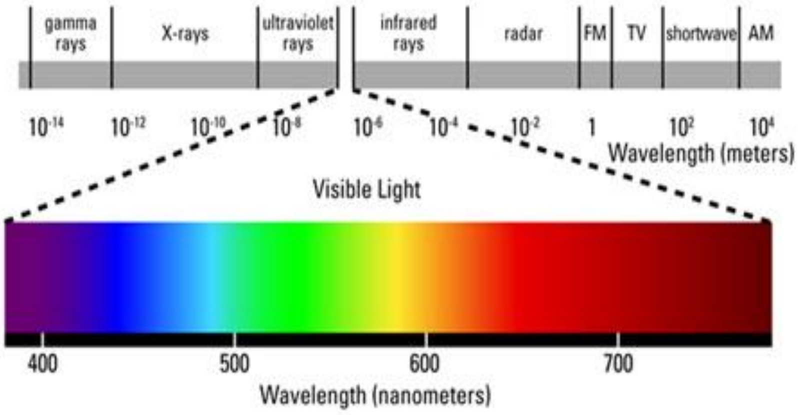

Figure 4

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 5.

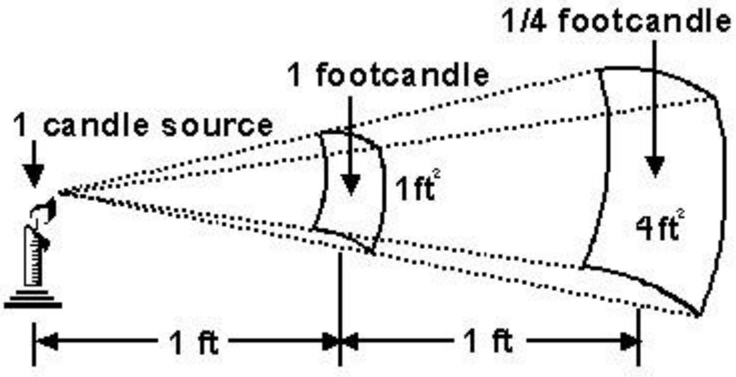

Figure 5

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 6.

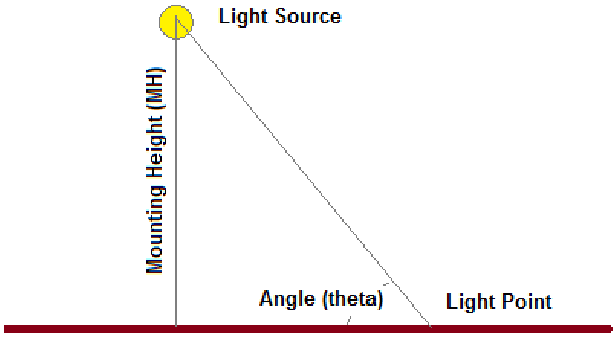

Figure 6

Considering the cosine law, the inverse square law becomes:

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

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:

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

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	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 7.

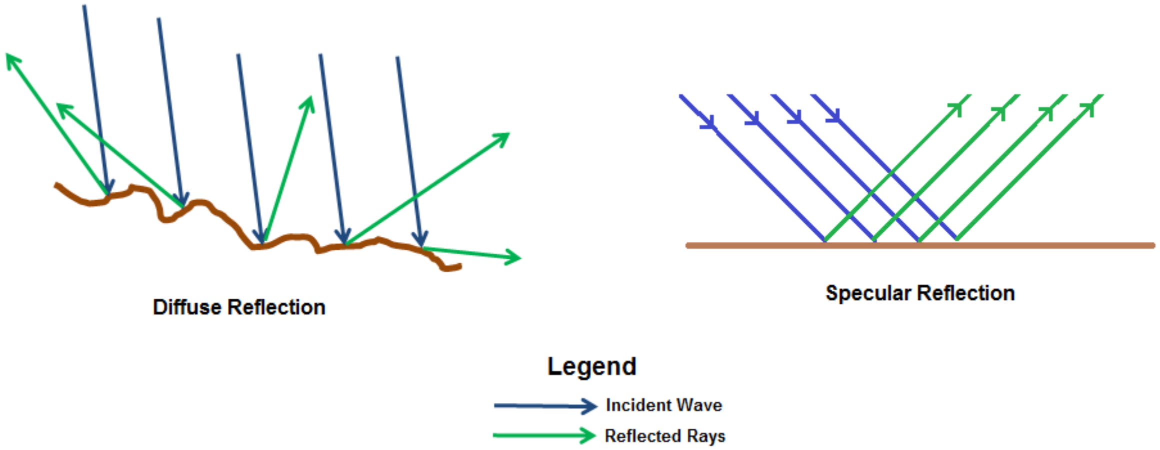

Figure 7

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 8 shows the color temperatures on a color-continuum.

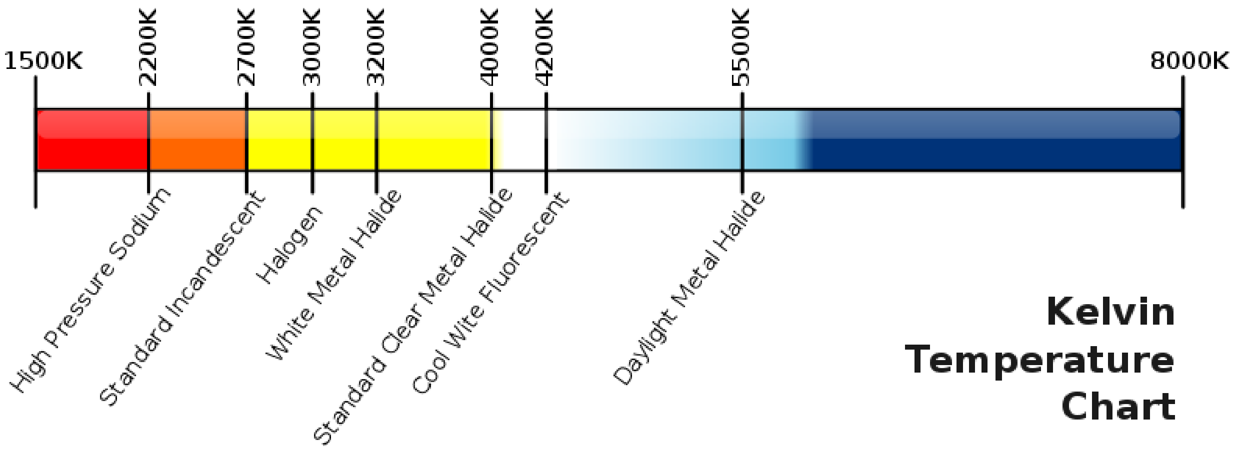

Figure 8

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.

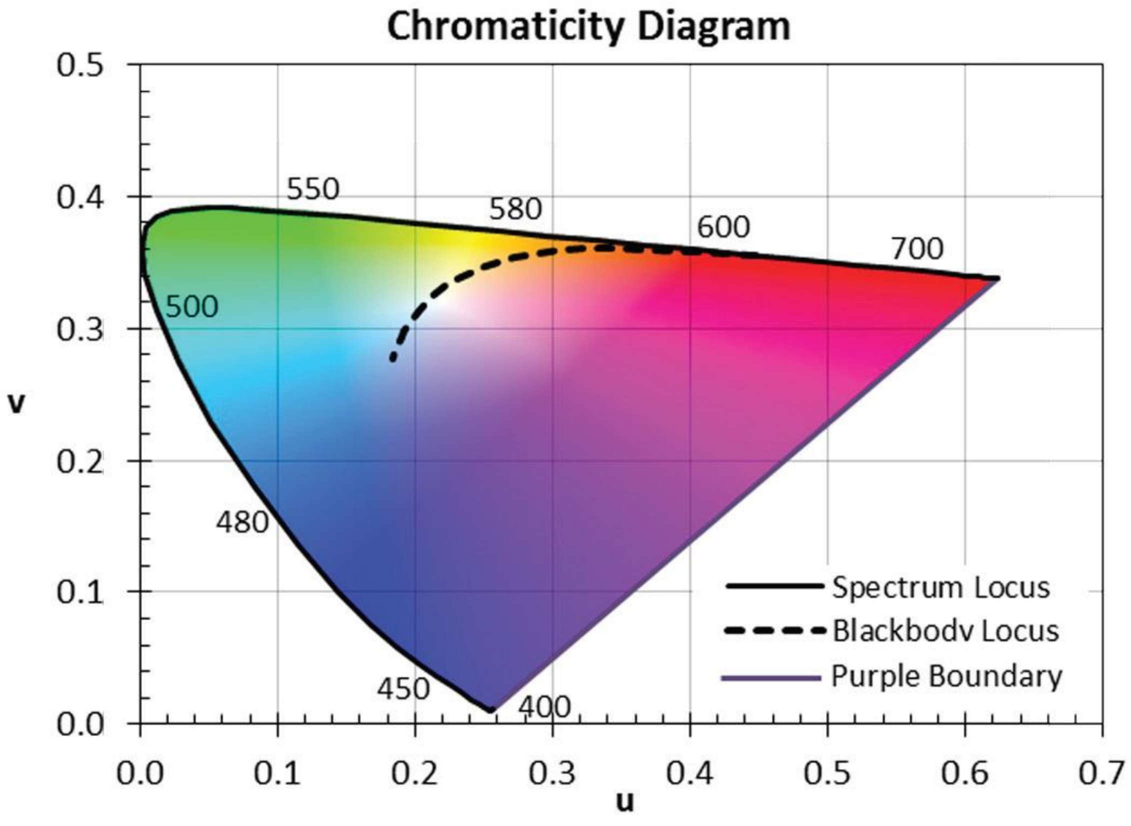

Figure 9

Figure 9, 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.

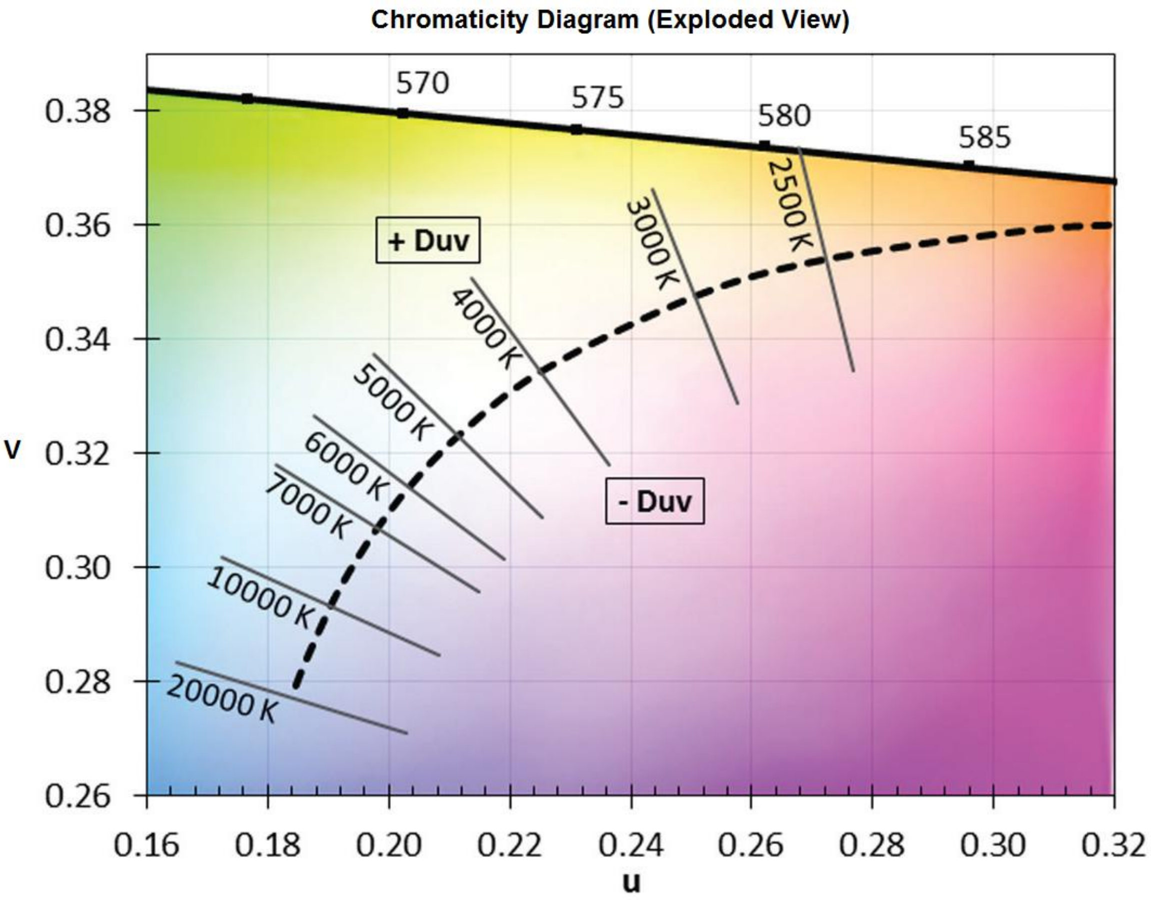

Figure 10

Figure 10, 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 11, 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.

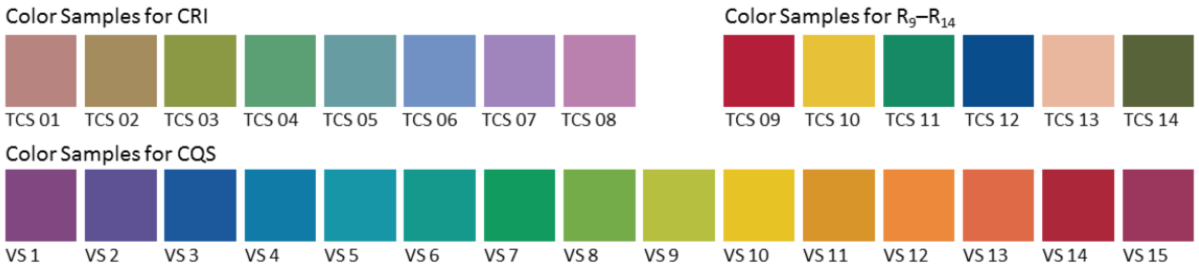

Figure 11

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
Characteristics of HID Lighting

High-intensity discharge lamps (HID lamps) are a type of electrical gas-discharge lamp which produces light by means of an electric arc between tungsten electrodes housed inside a quartz or alumina arc tube. This tube is filled with both gas and metal salts. The gas facilitates the arc's initial strike. Once the arc is started, it heats and evaporates the metal salts forming a plasma, which greatly increases the intensity of light produced by the arc and reduces its power consumption. High-intensity discharge lamps are a type of *arc lamp*.

High-intensity discharge lamps make more visible light per unit of electric power consumed than fluorescent and incandescent lamps since a greater proportion of their radiation is visible light in contrast to heat.

Construction

Most HID lamps follow the general form shown in Figure 12 below. All HID lamps contain a sealed arc tube mounted inside a glass bulb. In mercury vapor and metal halide lamps, the bulb is filled with hydrogen gas, which absorbs the ultraviolet radiation produced during operation. HPS lamps have a vacuum inside the bulb to isolate the arc tube from changes in ambient temperature. As the arc tube is manufactured, small amounts of special arc metals, such as mercury, halide compounds or sodium, are sealed inside the tube. Starting gases, such as argon, neon or xenon, are placed inside the tube. The arc tube also houses the lamp's two main electrodes, plus the separate starting electrode used in mercury vapor and metal halide lamps.

An HID lamp produces light by striking an electric arc between the lamp's two main electrodes. The striking and maintaining of this continuous arc is made possible by the starting gases and arc metals sealed inside the arc tube. The proper start-up voltage also is needed to establish the arc. Lamp start-up is not the same for all HID lamps.

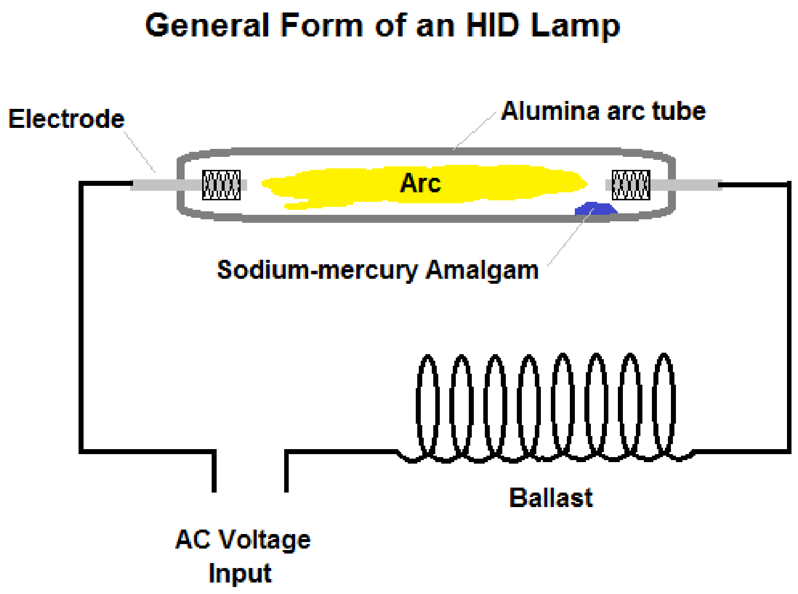

Figure 12

Various types of chemistry are used in the arc tubes of HID lamps, depending on the desired characteristics of light intensity, correlated color temperature, color rendering index (CRI), energy efficiency, and lifespan.

The light-producing element of these lamp types is a well-stabilized arc discharge contained within a refractory envelope arc tube. Mercury vapor lamps were the first commercially available HID lamps and originally they produced a bluish-green light, but more recent versions can produce light with a less pronounced color tint. However, mercury vapor lamps are falling out of favor and being replaced by sodium vapor and metal halide lamps.

Metal halide and ceramic metal halide lamps can be made to give off neutral white light useful for applications where normal color appearance is critical, such as TV and movie production, indoor or nighttime sports games, automotive headlamps, and aquarium lighting.

Low-pressure sodium vapor lamps are extremely efficient. They produce a deep yellow-orange light and have an effective CRI of nearly zero; items viewed under their light appear monochromatic. High-pressure sodium lamps tend to produce a much whiter light, but still with a characteristic orange-pink cast. New color-corrected versions producing a whiter light are now available, but some efficiency is sacrificed for the improved color.

Some HID lamps make use of radioactive substances such as krypton-85 and thorium. These isotopes help start the lamps and improve lamp operating characteristics. Krypton-85 is a gas and is found mixed in with the argon which is in the arc tube of the lamp. The thorium which is a solid is used in the electrodes. These isotopes produce ionizing radiation. It is because of their particular ionization properties that they are used in lamps. They produce alpha and beta radiation which causes high ionization inside the lamp but without being able to escape from the lamp. The amount of gamma radiation produced by the isotopes that can escape from the lamp is negligible.

Light output from all types of HID lamps gradually declines over time. Lumen maintenance depends on a number of light loss factors. These include any physical changes in the lamp, such as electrode deterioration, blackening of the arc tube or bulb, shifts in the chemical balance of the arc metals, or changes in ballast performance. Longer burning cycles result in better lumen maintenance because there is less stress on lamp components due to frequent starting. Other factors affecting lumen depreciation are lamp watts and current, and the current waveform that is a function of the lamp and luminaire circuit. Ambient temperature does not have a great effect on the maintained light output of HID lamps.

Ballasts

As shown in Figure 12, all HID lamps require the use of a ballast to assist in starting and limiting the current across the arc once the arc has been struck. Since HID lamps are negative resistance lamps, a ballast is required to prevent the arc discharge from drawing an unlimited amount of current which would destroy the lamp. The ballast performs a number of important functions in HID lamp operation. These include: Providing the correct starting current, and providing the correct starting voltage.

In addition, ballasts limit current to the lamp. The most basic function performed by a ballast is to limit the flow of current through the lamp. When the lamp starts and begins operation, it basically is operating as a short circuit across the electrodes. The ballast connected with the lamp acts to limit the current flowing to the lamp to keep it from destroying itself as resistance decreases. Without the limiting capability of the ballast, the lamp would draw more and more current and eventually explode.

Ballasts also provide the correct voltage to stabilize lamp operation. Many mercury vapor and metal halide lamps are designed to start using approximately 240 volts. If this voltage is not available, transformers are used inside the ballast to change the available voltage into the 240 volts needed for start-up. Ballasts can also be designed to produce the 2500- to 4000-volt low energy voltage spike needed to start HPS lamps.

Ballasts are needed to regulate the flow of current through the arc discharge. Since HID lamps reach a point of equilibrium several minutes after start-up, changes that affect the temperature of the arc tube, such as changes in the voltage supplied to the lamp through the ballast, can produce significant variations in the lamp's wattage and light output. Ballasts act to reduce this variation by absorbing part of this varying voltage input.

By subjecting the steel core of the ballast to high amounts of magnetic force, you also can change the ratio at which voltage is transferred between its primary and secondary coils. For example, a ballast can be designed to have a given voltage transfer ratio at a predetermined input voltage. However, if input voltage begins to increase from this value, the steel core of the ballast becomes overworked or saturated by magnetic force. The result is that increases in voltage in the primary coil are not transferred to the secondary coil, nor are they passed on to the lamp. Instead, the ballast continues to output voltage at the proper levels. This is the basic design principle used in all *regulated ballasts*. This way, the lamp is isolated from changes in the primary or power supply.

One final use of a ballast is to compensate for the low power factor characteristic of the arc discharge. Ballasts are classified as either normal or high power factor. A normal power factor ballast and HID lamp combination has a power factor of approximately 50%. This means that for a given wattage more than twice as much current is required to operate the HID lamp and ballast as would be needed to operate an ordinary incandescent lamp with the same wattage rating. Normal power factor ballasts are commonly used in reactor and high-reactance type ballast circuits for both mercury vapor and HPS lamps. They commonly are used for lower wattage lamps of 150 watts or less.

A high power factor ballast draws within 10% of the minimum line voltage for a specific power consumption. This type of ballast is described as having a power factor of 90% or greater. High power factor ballasts allow the use of a large number of luminaires and high wattage lamps on each branch circuit.

Types of ballasts used in HID lighting systems are summarized in Table 8 and are described in more detail following the table.

Table 8

Ballasts for HID Lamp Applications

Lamp	Ballast Type				
	Reactor	Lag Auto	Regulated Auto (CWA)	Constant Wattage (CW)	Mag Regulated
Mercury Vapor	✓	✓	✓	✓	n/a
Metal Halide	n/a	n/a	✓	n/a	n/a
HPS	✓	✓	✓	n/a	✓

Reactor Ballasts

Reactors are the simplest type of ballast. They consist of a single coil or wire on a core of steel. Functionally, they act as current limiters and provide some lamp wattage regulation. Reactors are normal power factor ballasts, but a capacitor can be added to provide high power factor performance. The units are designed for +/-5% input voltage variation and limit or regulate lamp wattage to a +/-12% variation within that range. Characteristically, reactor ballasts require a higher start-up current than operating current. They only are used when the available line voltage is at least two times greater than the lamp-rated operating voltage. An HPS reactor ballast contains a starting circuit that provides the proper pulse voltage for starting the lamp.

Lag Auto Ballasts

An Auto Lag Ballast is used when the line voltage is 120 volts and socket voltage is in the 240-volt range. This ballast consists of two coils on a core of steel. Together, the tap and output coils transform the line voltage into the required starting voltage. The ballast also limits lamp current. Lag auto ballasts have the same operating and performance characteristics as reactor ballasts. This type of ballast normally is used with mercury vapor and HPS lamps.

Constant Wattage Autotransformer Ballasts (CWA)

A constant wattage autotransformer (CWA) ballast consists of two coils on a core of steel and a capacitor in series with the lamp. CWA ballasts perform the basic jobs of current limiting and voltage transformation. In addition, CWA ballasts are always high power factor ballasts. They have starting currents that are less than the operating current. In regard to voltage regulation, CWA ballasts offer significant improvements over reactor and lag auto designs. CWA ballasts are designed to handle a +/-10% line voltage variation. Over this range, they will maintain lamp wattage within +/-5%, a four-fold improvement over reactor and lag auto ballasts. They also can handle sudden dips in line voltage without lamp shutdown. This type of ballast is most commonly used in area, sports and indoor HID lighting.

Constant Wattage Ballasts (CW)

The constant wattage ballast design limits current, performs voltage transformation and provides the best lamp wattage regulation available. They are designed to operate over a voltage range of +/-13%, maintaining lamp wattage to within +/-2.5%. Constant wattage (CW) ballasts have a high power factor and a lower starting current than operating current. These ballasts are similar in construction to CWA ballasts.

HPS Mag Reg

Mag Reg ballasts are used to meet HPS lamp wattage requirements on systems having a +/-10% voltage variation. These are high power factor ballasts that have lower starting than operating current requirements. The mag reg transformer consists of three isolated coils on a core of steel.

Color

Each gas, depending on its atomic structure emits certain wavelengths which translates in different colors of the lamp. As discussed in Chapter 2, as a way of evaluating the ability of a light source to reproduce the colors of various objects being lit by the source, the International Commission on Illumination (CIE) introduced the color rendering index. Some gas-discharge lamps have a relatively low CRI, which means colors they illuminate appear substantially different than they do under sunlight or other high-CRI illumination. Table 9 shows the light characteristics of the gases commonly used in HID lighting.

Table 9 **Different Gases and their Characteristics**
Helium
Color: White to Orange; under some conditions may be gray, blue, or green-blue.  *Notes: Used by artists for special purpose lighting.*
Neon

Color: Red-Orange

Notes: Intense light. Used frequently in neon signs and neon lamps.

Argon

Color: Violet to pale lavender blue

Notes: Often used together with mercury vapor.

Krypton

Color: Gray off-white to green. At high peak currents, bright blue-white.

Notes: Used by artists for special purpose lighting.

Xenon

Color: Gray or blue-gray dim white. At high peak currents, very bright green-blue.

Notes: Used in flashbulbs, xenon HID headlamps, and xenon arc lamps.

Nitrogen

Color: Similar to argon but duller, pinker; at high peak currents bright blue-white.

Oxygen

Color: Violet to lavender, dimmer than argon

Hydrogen

Color: Lavender at low currents, pink to magenta over 10 mA

Water Vapor

Color: Similar to hydrogen, dimmer

Carbon Dioxide

Color: Blue-white to pink, in lower currents brighter than xenon

Notes: Used in Carbon Dioxide Lasers.

Mercury Vapor

Color: Light blue, intense ultraviolet

Notes: In combination with phosphors used to generate many colors of light. Widely used in mercury-vapor lamps

Sodium Vapor (Low Pressure)

Color: Bright Orange-Yellow

Notes: Widely used in sodium vapor lamps.

HID Applications

HID lamps are typically used when high levels of light over large areas are required, and when energy efficiency and/or light intensity are desired. These areas include gymnasiums, large public areas, warehouses, movie theaters, football stadiums, outdoor activity areas, roadways, parking lots, and pathways. More recently, HID lamps have been used in small retail and even residential environments because of advances in reduced lumen bulbs. Ultra-High Performance (UHP) HID lamps are used in LCD or DLP projection TV sets or projection displays as well. HID lamps have made indoor gardening practical, particularly for plants that require high levels of direct sunlight in their natural habitat; HID lamps, specifically metal halide and high-pressure sodium, are a common light source for indoor gardens. They are also used to reproduce tropical intensity sunlight for indoor aquaria.

Most HID lamps produce significant UV radiation, and require UV-blocking filters to prevent UV-induced degradation of lamp fixture components and fading of dyed items illuminated by the lamp. Exposure to HID lamps operating with faulty or absent UV-blocking filters causes injury to humans and animals, such as sunburn and arc eye. Many HID lamps are designed so as to quickly extinguish if their outer UV-shielding glass envelope is broken.

Beginning in the early 1990s, HID lamps have seen applications in automotive headlamps. HID lamps are used in high-performance bicycle headlamps as well as flashlights and other portable lights, because they produce a great amount of light per unit of power. As the HID lights use less than half the power of an equivalent tungsten-halogen light, a significantly smaller and lighter-weight power supply can be used.

HID lamps have also become common on many aircraft as replacements for traditional landing and taxi lights.

HID lamps are also used in lamps for underwater diving. The higher efficacy of HID lamps compared to halogen units means longer burn times for a given battery size and light output.

More information about specific applications is included in the next chapter under the discussion of each type of HID lamp.

Chapter 4
Types of HID Lighting

All high-pressure lamps have a discharge that takes place in gas under slightly less to greater than atmospheric pressure. For a high pressure sodium lamp, the arc tube operates at approximately 25% of normal atmospheric pressure while some automotive HID headlamps have up to fifty times atmospheric pressure. Metal halide HID lamps produce almost white light, and attain 100 lumen per watt light output while High pressure sodium lamps, producing up to 140 lumens per watt and generate a yellow glow.

In this chapter we will look at five different types of HID lamps including:

- Mercury-vapor lamps
- Metal halide lamps
- Ceramic discharge metal halide lamps
- Sodium vapor lamps
- Xenon arc lamps

We will start with an overview of Mercury-vapor lamps.

MERCURY-VAPOR LAMP

Mercury Vapor Overview
Efficacy: 65 lumens/watt
Color Temp: 3,600K
CRI: 50
Life: 24,000 hours

A mercury-vapor lamp is a gas discharge lamp that uses an electric arc through vaporized mercury to produce light. The arc discharge is generally confined to a small fused quartz arc tube mounted within a larger borosilicate glass bulb. The outer bulb may be clear or coated with a phosphor; in either case, the outer bulb provides thermal insulation, protection from the ultraviolet radiation the light produces, and a convenient mounting for the fused quartz arc tube.

Mercury vapor lamps are more energy efficient than incandescent and most fluorescent lights, with luminous efficacies of up to 65 lumens/watt. Their other advantages are a long bulb lifetime in the range of 24,000 hours and a high intensity, clear white light output. For these reasons, they are used for large area overhead lighting, such as in factories, warehouses, and sports arenas as well as for streetlights. Clear mercury lamps produce white light with a bluish-green tint due to mercury's combination of spectral lines. This is not flattering to human skin color, so such lamps are typically not used in retail stores. "Color corrected" mercury bulbs overcome this problem with a phosphor on the inside of the outer bulb that emits white light.

They operate at an internal pressure of around one atmosphere and require special fixtures, as well as an electrical ballast. They also require a warm-up period of 4 - 7 minutes to reach full light output. Mercury vapor lamps are becoming obsolete due to the higher efficiency and better color balance of metal halide lamps.

Operation

The mercury in the tube is a liquid at normal temperatures. It needs to be vaporized and ionized before the tube will conduct electricity and the arc can start. So, like fluorescent tubes, mercury vapor lamps require a starter, which is usually contained within the mercury vapor lamp itself. A third electrode is mounted near one of the main electrodes and connected through a resistor to the other main electrode. In addition to the mercury, the tube is filled with argon gas at low pressure.

See Figure 13.

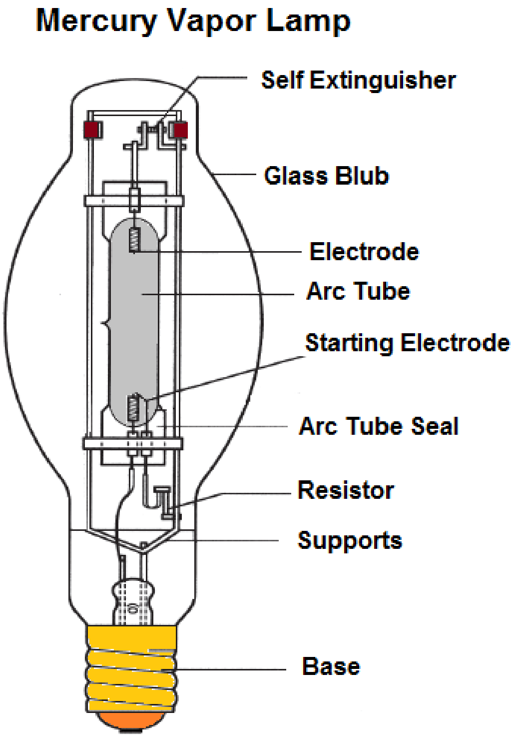

Figure 13

When a mercury vapor lamp is energized, an electrical field is generated between one of the main electrodes and the starting electrode next to it. This causes an emission of electrons that ionize the argon starting gas. The ionized argon particles create a diffused argon arc between the two main electrodes of the lamp. The heat from this argon arc gradually vaporizes the arc metals in the arc tube. These ionized arc metal particles join the arc stream between the two main electrodes. When a sufficient number of ionized particles join the arc stream, the resistance between the main electrodes drops to a point where the start-up voltage supplied by the ballast can strike a current arc across the main electrodes. The arc current continues to increase until the current rating of the lamp is reached; a process that normally takes several minutes.

Once a mercury vapor lamp starts, voltage drops to lower operating voltage levels. A resistor or thermal switch in series with the starting electrode now blocks voltage to the starting electrode so it does not arc and burn out during normal lamp operation.

The mercury vapor lamp is a *negative resistance* device. This means its resistance decreases as the current through the tube increases. So if the lamp is connected directly to the power supply, the current through it will increase until it destroys itself, therefore a ballast is needed to limit the current. Mercury vapor lamp ballasts are similar to the ballasts used with fluorescent lamps.

The HID arc consists of a very rapid flow of both electrons and charged arc metal ions. During this rapid movement, countless collisions occur between ions and electrons. As these particles collide, they release energy at a specific wavelength. This energy appears as light. Because the number of particles in the arc tube is so great and the occurrence of collisions so frequent, it appears that the entire arc path constantly generates light.

The color of the light is a characteristic of the light spectrum wavelength of the arc metals contained in the arc tube. For example, in a mercury vapor lamp, the mercury produces a distinct greenish white-blue light.

Mercury vapor arc tubes are thin-walled tubes made of high-quality quartz. The arc tubes are filled with the exact amount of arc metal needed for operation. After an initial burn-in time, mercury vapor lamps reach a stabilized operating point at which all arc metal inside the tube is ionized during start-up and operation. At this point, lamp voltage becomes relatively constant throughout the rest of the lamp's operating life. There is a very slight voltage rise, but it is not great enough to affect the life span of the lamp.

When a mercury vapor lamp is first turned on, it will produce a dark blue glow because only a small amount of the mercury is ionized and the gas pressure in the arc tube is very low, so much of the light is produced in the ultraviolet mercury bands. As the main arc strikes and the gas heats up and increases in pressure, the light shifts into the visible range and the high gas pressure causes the mercury emission bands to broaden somewhat, producing a light that appears more nearly white to the human eye, although it is still not a continuous spectrum. Even at full intensity, the light from a mercury vapor lamp with no phosphors is distinctly bluish in color.

The pressure in the quartz arc-tube rises to approximately one atmosphere once the bulb has reached its working temperature. If the discharge should be interrupted, it is not possible for the lamp to restrike until the bulb cools enough for the pressure to fall considerably. The reason for a prolonged period of time before the lamp restrikes is because mercury vapor ballasts along with other HID lamp ballasts send relatively low voltage to the lamp upon start up, but as pressure increases inside the arc-tube, higher voltage is required to keep the lamp lit so the ballast sends higher voltage to the lamp. Once the ballast is shut off and turned on again, it starts over at a low voltage but if the lamp is still hot, then high pressure inside the arc-tube prevents the lamp from striking an arc and turning on.

To correct the bluish tinge, many mercury vapor lamps are coated on the inside of the outer bulb with a phosphor that converts some portion of the ultraviolet emissions into red light. This helps to fill in the otherwise very-deficient red end of the electromagnetic spectrum. These lamps are generally called *color corrected* lamps.

One of the original complaints about mercury lights was they tended to make people look pal because of the lack of light from the red end of the spectrum. A common method of correcting this problem before phosphors were used was to operate the mercury lamp in conjunction with an incandescent lamp. There is also an increase in red color in ultra-high pressure mercury vapor lamps, which has found application in modern compact projection devices. When outside, coated or color corrected lamps can usually be identified by a blue "halo" around the light being given off.

Figure 14 shows the line spectrum of mercury vapor. The blue-green tint of mercury vapor lamps is caused by the strong violet and green lines.

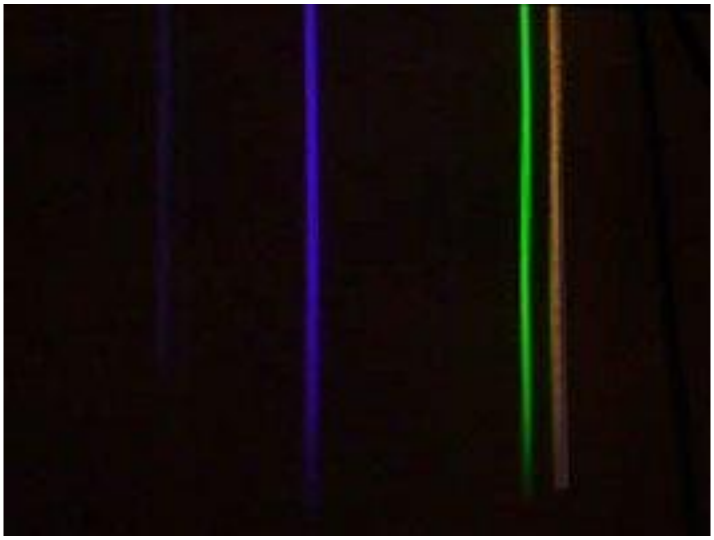

Figure 14

In *low-pressure mercury-vapor* lamps only the lines at 184 nm and 253 nm are present. Only the light at 253 nm is usable unless synthetic quartz is used to manufacture the tube as the line is otherwise absorbed. In *medium-pressure mercury-vapor* lamps, the lines from 200–600 nm are present. The lamps can be constructed to emit primarily in the UV-A (around 400 nm) or UV-C (around 250 nm). *High-pressure mercury-vapor* lamps are those lamp commonly used for general lighting purposes. They emit primarily in the blue and green. Table 10 shows the wavelengths and corresponding colors for mercury vapor lamps.

Table 10

Wavelength (nm)	**Color**
184.45	Ultraviolet (UVC)
253.7	Ultraviolet (UVC)
365.4 (I-Line)	Ultraviolet (UVA)
404.7 (H-Line)	Violet
435.8 (G-Line)	Blue
546.1	Green
578.2	Yellow- Orange

The graph in Figure 15 shows the relative spectral power distribution for a high pressure mercury vapor lamp. You can see the strong presence in the 404.7, 435.8, 546.1, and 578.2 nanometer wavelengths as mentioned in the previous table.

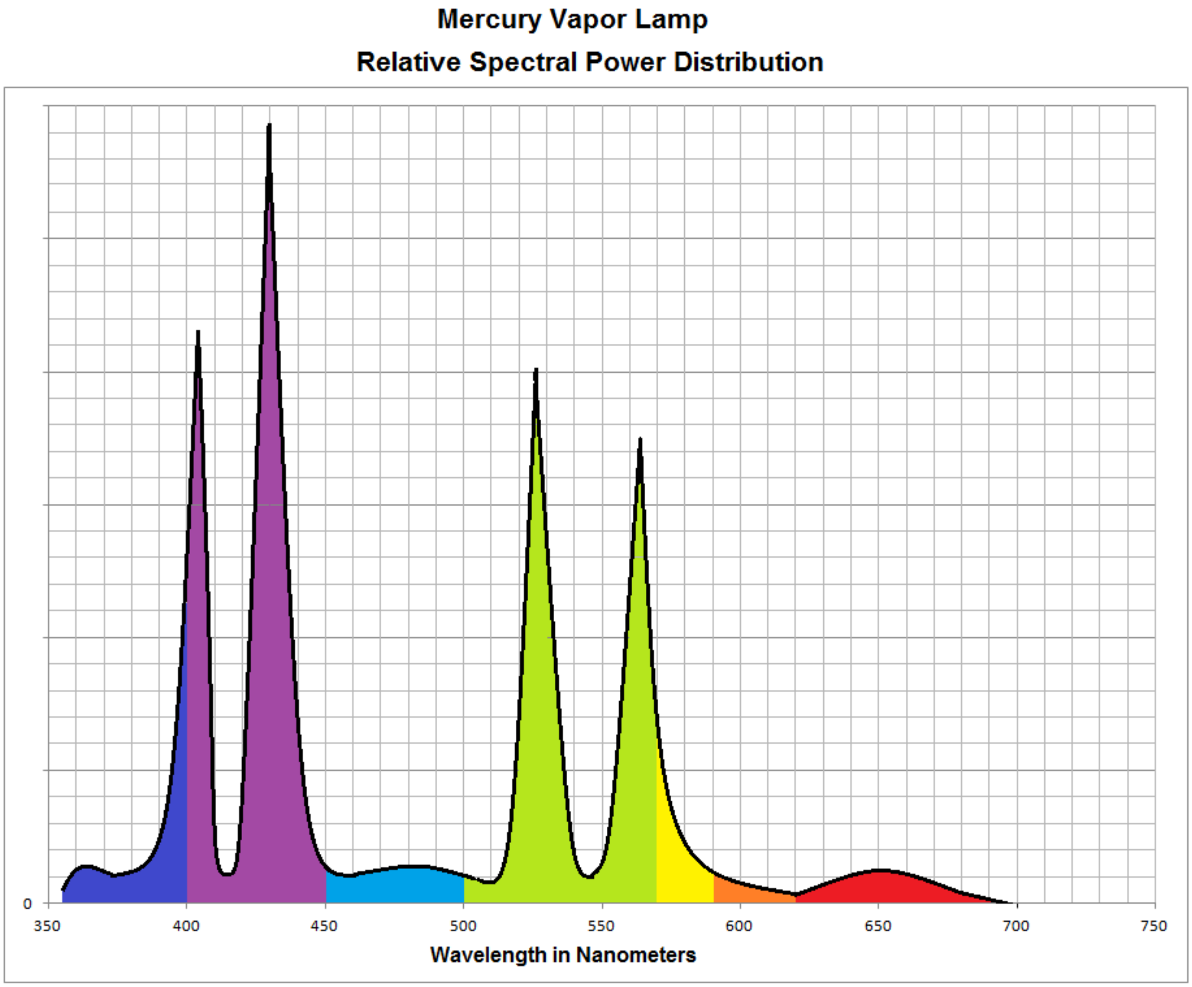

Figure 15

Mercury vapor lamps eventually burn out as the burner electrodes wear, increasing the arc gap. As the lamp nears the end of life, lumen depreciation becomes noticeable. This comes about because the emitter is deposited as a film darkening the arc tube wall and reducing light output.

Mercury vapor lamps have an extremely long-rated life, exceeding 24,000 hours. Mercury lamps should be replaced before they burn out due to decreases in lumen output. Frequent starting does not adversely affect lamp life as significantly as other HID lamps. The normal mode of failure is the inability to start.

Applications

The most common application is outdoor lighting such as street lights, parking lot lights, and residential yard lights.

Environmental Concerns

All mercury vapor lamps must contain a feature that prevents ultraviolet radiation from escaping. Usually, the borosilicate glass outer bulb of the lamp performs this function but special care must be taken if the lamp is installed in a situation where this outer envelope can become damaged. There have been cases of lamps being damaged in gymnasiums by a ball hitting it. Sun burns and eye inflammation have resulted. When used in locations like gyms, the fixture should contain a strong outer guard or an outer lens to protect the lamp's outer bulb. Also, special "safety" lamps are made that will deliberately burn out if the outer glass is broken. This is usually achieved by using a thin carbon strip, which will burn up in the presence of air, to connect one of the electrodes.

Even with these methods, some UV radiation can still pass through the outer bulb of the lamp. This causes the aging process of some plastics used in the construction of luminaires to be accelerated, leaving them significantly discolored after only a few years' service. Polycarbonate suffers particularly from this problem, and it is not uncommon to see fairly new polycarbonate surfaces positioned near the lamp to have turned a dull color after only a short time.

Mercury vapor lamps were banned from manufacture in the United States in 2008.

SODIUM-VAPOR LAMP

A sodium-vapor lamp is a gas-discharge lamp that uses sodium in an excited state to produce light. There are two varieties of such lamps: low pressure and high pressure. Low-pressure sodium lamps are the most efficient electrical light sources, but their yellow light restricts applications to outdoor lighting such as street lamps. High-pressure sodium lamps have a broader spectrum of light than the low pressure, but still poorer color rendering than other types of lamps.

HPS Overview
Efficacy: 140 lumens/watt
Color Temp: 2,800K
CRI: 80
Depreciation: 15%
Life: 24,000 hours

Low-pressure sodium (LPS) lamps have an arc tube containing solid sodium, a small amount of neon, and argon gas to start the gas discharge. When the lamp is turned on it emits a dim red/pink light to warm the sodium metal and within a few minutes it turns into the common bright yellow as the sodium metal vaporizes. These lamps produce a virtually monochromatic light averaging a 589.3 nm wavelength. As a result, the colors of illuminated objects are not easily distinguished because they are seen almost entirely by their reflection of this narrow bandwidth yellow light. See Figure 16.

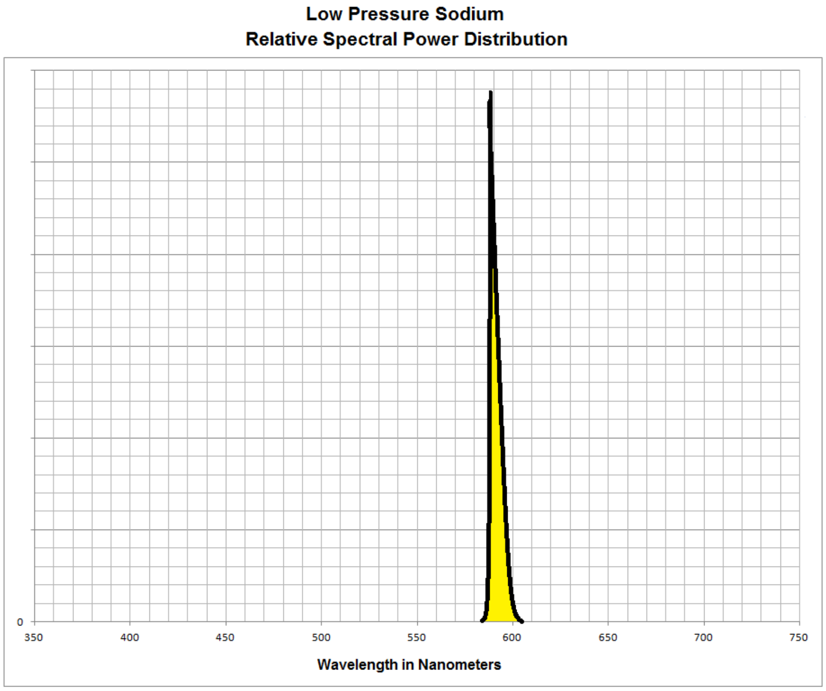

Figure 16

LPS lamps have an outer glass vacuum envelope around the inner discharge tube for thermal insulation, which improves their efficiency. Earlier types of LPS lamps had a detachable vacuum envelope jacket (SO lamps). Lamps with a permanent vacuum envelope (SOI lamps) were developed to improve thermal insulation. Further improvement was attained by coating the glass envelope with an infrared reflecting layer of indium tin oxide (SOX lamps).

LPS lamps are the most efficient electrically powered light source - up to 200 lumens per watt, primarily because the output is light at a wavelength near the peak sensitivity of the human eye. As a result they are widely used for outdoor lighting such as street lights and security lighting where faithful color rendition was once considered unimportant.

LPS lamps are more closely related to fluorescent than high intensity discharge lamps because they have a low–pressure, low–intensity discharge source and a linear lamp shape. Also like fluorescents they do not exhibit a bright arc as do other High-intensity discharge (HID) lamps; rather they emit a softer luminous glow, resulting in less glare. Unlike HID lamps, which can go out during a voltage dip, low pressure sodium lamps restrike to full brightness rapidly.

Another unique property of LPS lamps is that, unlike other lamp types, they do not decline in lumen output with age. As an example, mercury vapor HID lamps become very dull towards the end of their lives, to the point of being ineffective, while continuing to consume full rated electrical use. LPS lamps, however, increase energy usage slightly towards their end of life, which is generally around 18,000 hours.

The most popular form of sodium vapor lamp is the high pressure sodium vapor lamp. High-pressure sodium (HPS) lamps are smaller and contain additional elements such as mercury, and produce a dark pink glow when first struck, and an intense pinkish orange light when warmed.

In a high pressure sodium lamp, a compact arc tube contains a mixture of xenon, sodium and mercury. The xenon gas which is easily ionized facilitates striking the arc when voltage is applied across the electrodes. The heat generated by the arc then vaporizes the mercury and sodium. The mercury vapor raises the gas pressure and operating voltage, and the sodium vapor produces light when the pressure within the arc tube is sufficient. High pressure sodium lamps are the most efficient artificial white light source with about 30% of the energy used by the lamp producing light.

The sodium D-line is the main source of light from the HPS lamp, and it is extremely pressure broadened by the high sodium pressures in the lamp. On account of this broadening and the emissions from mercury, more colors can be distinguished compared to a low-pressure sodium lamp. This leads them to be used in areas where improved color rendering is important, or desired.

Figure 17 shows the line spectrum of high pressure sodium lamp. The yellow-red band on the left is the atomic sodium D-line emission; the turquoise line is a sodium line that is otherwise quite weak in a low pressure discharge, but becomes intense in a high pressure discharge. Most of the other green, blue and violet lines arise from mercury.

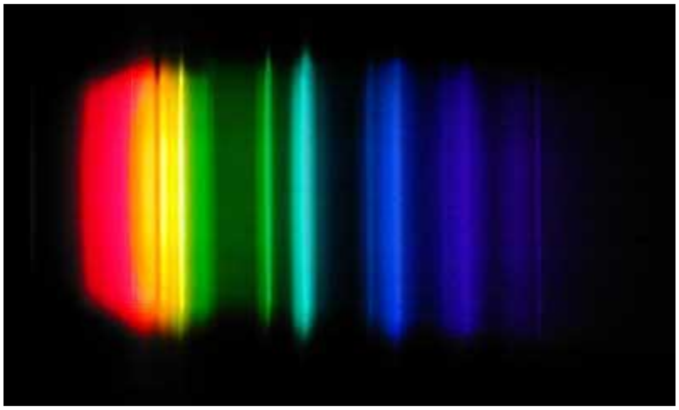

Figure 17

HPS lamps generate a sodium-based light that is strongest in the yellow and orange range of the spectrum and weakest in the blue-green wavelengths. A small amount of mercury is added to the arc tube to help strengthen blues and greens, but the overall color rendering is still golden white, with both reds and blues appearing grayed. Figure 18 has a diagram showing the spectral output of a typical high pressure sodium (HPS) lamp.

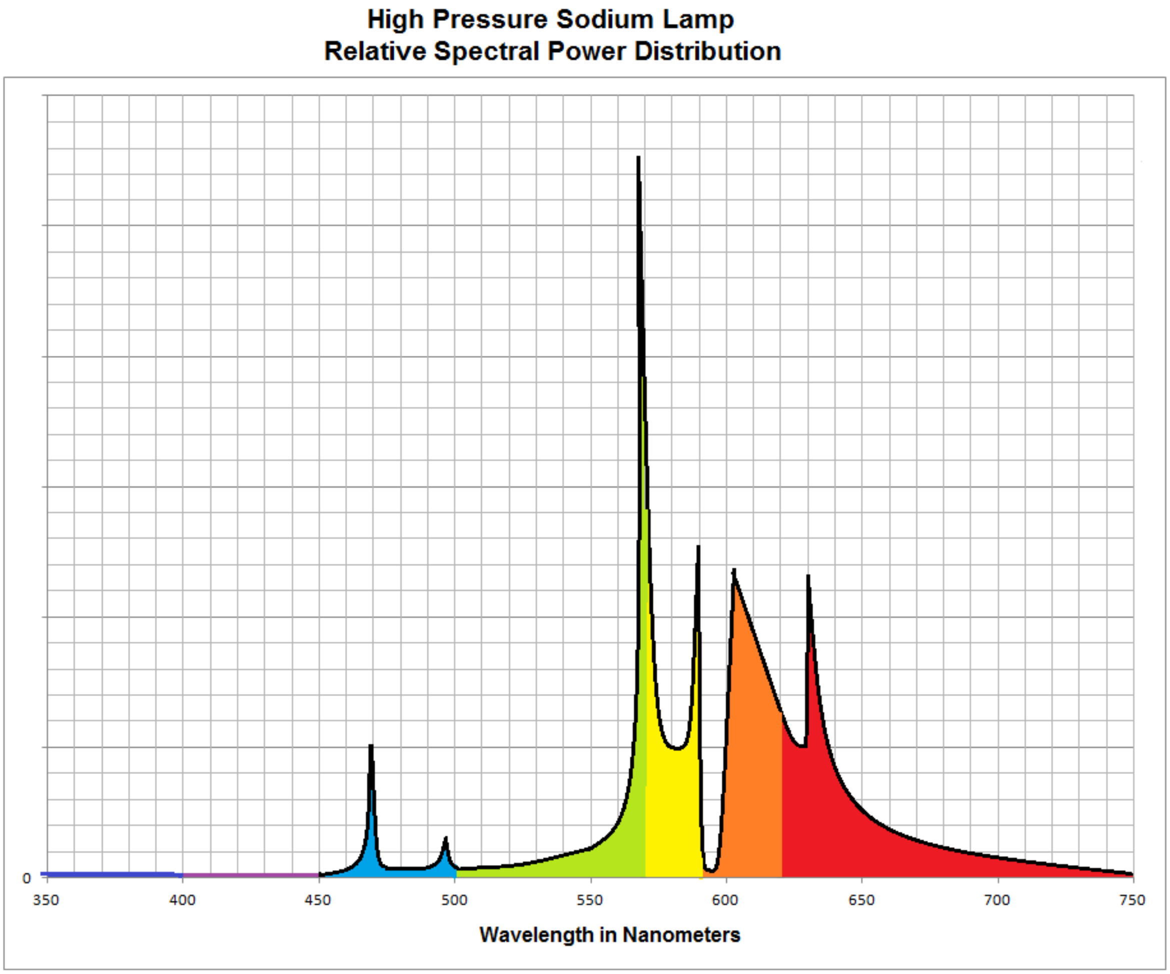

Figure 18

High pressure sodium lamps are quite efficient—about 140 lumens per watt. They have been widely used for outdoor area lighting such as streetlights and security. Because of the extremely high chemical activity of the high pressure sodium arc, the arc tube is typically made of translucent aluminum oxide.

Xenon at a low pressure is used as a *starter gas* in the HPS lamp. It has the lowest thermal conductivity and lowest ionization potential of all the non-radioactive noble gases. As a noble gas, it does not interfere with the chemical reactions occurring in the operating lamp. The low thermal conductivity minimizes thermal losses in the lamp while in the operating state, and the low ionization potential causes the breakdown voltage of the gas to be relatively low in the cold state, which allows the lamp to be easily started.

Operation

Figure 19 shows a typical HPS lamp. The basic components include:

- The arc tube contains the xenon and sodium-mercury amalgam mixture and provides the proper environment for producing light.
- The electrodes, which are made of tungsten, carry a high-voltage, high-frequency pulse to strike the arc and vaporize the mercury and sodium.
- The base of the lamp provides a means of electrical connection.
- The outer bulb shields the arc tube from drafts and changes in temperature, prevents oxidation of the internal parts, and acts as a filter for most of the UV radiation generated by the mercury vapor.

Some lamps have a phosphor coating on the inner surface of the outer bulb to diffuse the light.

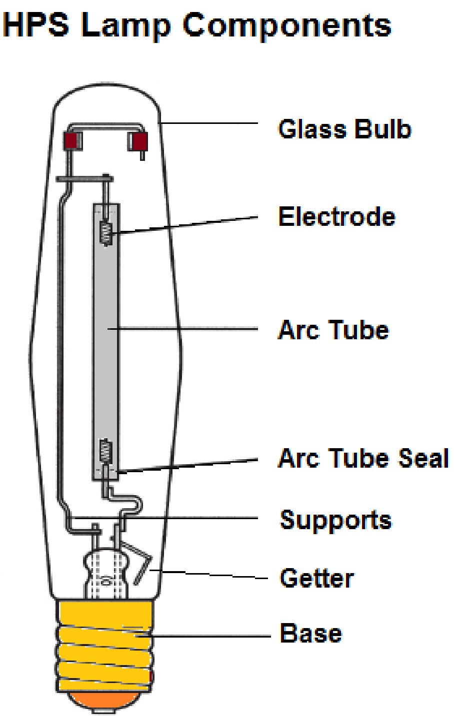

Figure 19

HPS lamps require ballasts to regulate the arc current flow and deliver the proper voltage to the arc. HPS lamps do not contain starting electrodes. Instead, an electronic starting circuit within the ballast generates a high-voltage pulse to the operating electrodes.

The arc tube of an HPS lamp is a slender cylinder approximately 3/8” in diameter. Sodium cannot be contained in a glass tube. The sodium would etch the glass and further degrade light output. Sodium must be contained in a metal container. Most lamp manufacturers use a special ceramic material known as polycrystalline alumina (PCA) to construct the HPS arc tube. PCA is basically an aluminum oxide material virtually insensitive to sodium attack.

HPS lamps are excess amalgam lamps. This means there is more sodium and mercury arc metal placed inside the tube than can be vaporized during start-up and operation. The amount of amalgam that vaporizes depends on the total energy in the arc and the temperature of the amalgam. If the lamp becomes too hot, too much amalgam will vaporize, and operating voltage will increase.

The arc tube in a HPS lamp operates under high pressure for higher efficiency. Sodium, mercury and xenon are usually used inside the arc tube. The arc tube is made of aluminum oxide ceramic which is resistant to the corrosive effects of sodium.

The most common way to start the lamp is with a *pulse start*. There is an igniter built into the ballast which sends a pulse of high voltage energy through the arc tube. This pulse starts an arc through the xenon gas. The lamp turns sky blue as the xenon lights. The arc then heats up the mercury and the mercury vapor then lights, giving the lamp a bluish color. The lamp heats and the sodium is the last material to vaporize. The sodium is mixed with other impurities to create a more "white" light. The mercury helps add a blue spectrum light to the pure yellow of the sodium.

Maintaining a vacuum is difficult, oxygen and other gasses can seep in over time. The *getter* keeps a stable vacuum by sucking out remaining oxygen and unwanted gasses. The sodium is stored often stored in the amalgam reservoirs on the ends of the arc tube when it is cool unlike the LPS lamp where the sodium is stored in the bumps on the side of the tube.

HPS lamps do not have a starting electrode so a much higher start-up voltage is required to establish an arc between the wide gaps of the main electrodes. This low-power, high voltage spike is around 4,000 volts. This voltage spike or pulse is provided by a starter pulse circuit board separate from the ballast.

When an HPS lamp is energized, the high-voltage pulse ionizes the xenon gas in the arc tube, and an arc is established between the main electrodes. As soon as this arc is established, the voltage pulse is switched off. Sodium and mercury arc metals quickly vaporize and join this arc stream, and the arc current increases and stabilizes.

An amalgam of metallic sodium and mercury lies at the coolest part of the lamp and provides the sodium and mercury vapor that is needed to draw an arc. The temperature of the amalgam is determined to a great extent by lamp power. The higher the lamp power, the higher will be the amalgam temperature. The higher the temperature of the amalgam, the higher will be the mercury and sodium vapor pressures in the lamp and the higher will be the terminal voltage. As the temperature rises, the constant current and increasing voltage result in increased power until the nominal power is reached and the lamp is operating with liquid amalgam in the tube. This is the desired operating state of the lamp, because a slow loss of the amalgam over time from a reservoir.

An HPS lamp is powered by an AC voltage source in series with an inductive ballast in order to supply a nearly constant current to the lamp, rather than a constant voltage, thus assuring stable operation. The ballast is usually inductive rather than simply being resistive to minimize resistive losses. Because the lamp effectively extinguishes at each zero-current point in the AC cycle, the inductive ballast assists in the re-ignition by providing a voltage spike at the zero-current point.

HPS lamps have a long average life span of 24,000 plus hours. Normal end of life occurs when the lamp begins to cycle on and off due to excessive lamp voltage rise. More frequent starts will cause voltage to rise faster, as will over-wattage operation. Slight under-wattage operation will have no adverse effect on lamp life.

At the end of life, high-pressure sodium lamps exhibit a phenomenon known as *cycling*, which is caused by a loss of sodium in the arc. Sodium is a highly reactive element and is easily lost by reacting with the arc tube, made of aluminum oxide. As a result, these lamps can be started at a relatively low voltage, but, as they heat up during operation, the internal gas pressure within the arc tube rises, and more and more voltage is required to maintain the arc discharge. As a lamp gets older, the maintaining voltage for the arc eventually rises to exceed the maximum voltage output by the electrical ballast. As the lamp heats to this point, the arc fails, and the lamp goes out. Eventually, with the arc extinguished, the lamp cools down again, the gas pressure in the arc tube is reduced, and the ballast can once again cause the arc to strike. The effect of this is that the lamp glows for a while and then goes out, typically starting at a pure or bluish white then moving to a red-orange before going out.

More sophisticated ballast designs detect cycling and give up attempting to start the lamp after a few cycles, as the repeated high-voltage ignitions needed to restart the arc reduce the lifetime of the ballast. If power is removed and reapplied, the ballast will make a new series of startup attempts.

Applications

HPS lamps, unlike most metal halides, do not require enclosure except to prevent moisture from accumulating on the lamp. This makes HPS lamps especially easy to use in many fixture types. Moreover, the virtual insensitivity of HPS lamps to burning position means that fewer lamp types are needed as compared to metal halide.

PAR type HPS lamps are useful for compact directional light sources, such as track lighting and outdoor lighting luminaires. The poor color rendition of these lamps, however, limits the usefulness to specific industrial and security floodlighting and general lighting

The double-ended HPS lamp was designed to take advantage of luminaires and lighting installations originally designed for the double-ended metal halide lamp. The double-ended HPS lamp offers comparable lumen output, as well as HPS' longer lamp life and excellent lumen maintenance characteristics. These lamps, however, are relatively uncommon at this time.

White HPS lamps use ballast designs with electronic circuits that increase system color temperature and CRI, making them suitable for many interior spaces. The color temperature of white sodium lamps, at 2,600 K to 2,800 K, closely resembles incandescent lighting. During the lamp's stable color-life, the color performance is more consistent and appealing than most metal halide lamps. Although efficacy is a relatively low 45 lumens per watt, the white sodium lamp is in many ways the best high-efficacy substitute for incandescent lamps.

The sodium in these lamps is a highly volatile substance. When exposed to air the sodium may explode. The sodium lamp should not be disposed of in normal the normal garbage disposal. There have been many cases of garbage trucks catching fire when the bulbs in the back broke. Sodium lamps also contain mercury.

METAL-HALIDE LAMP

Metal Halide Overview
Efficacy: 100 lumens/watt
Color Temp: 4,200K
CRI: 85
Life: 20,000 hours

A metal-halide lamp is an electric light that produces light by an electric arc through a gaseous mixture of vaporized mercury and metal halides (compounds of metals with bromine or iodine). It is a type of high-intensity discharge (HID) gas discharge lamp. Developed in the 1960s, they are similar to mercury vapor lamps, but contain additional metal halide compounds in the arc tube, which improve the efficacy and color rendition of the light.

Metal-halide lamps have high luminous efficacy of around up to 100 lumens per watt, which is about twice that of mercury vapor lights and 3 to 5 times that of incandescent lights. Lamp life is in the range of 20,000 hours and produces an intense white light. As one of the most efficient sources of high CRI white light, metal halides are the fastest growing segment of the lighting industry. They are used for wide area overhead lighting of commercial, industrial, and public spaces, such as parking lots, sports arenas, factories, and retail stores, as well as residential security lighting and automotive headlamps.

The lamps consist of a small fused quartz or ceramic arc tube which contains the gases and the arc, enclosed inside a larger glass bulb which has a coating to filter out the ultraviolet light produced. Metal atoms produce most of the light output. They require a warm-up period of several minutes to reach full light output.

Figure 20 shows the output spectrum of a typical metal-halide lamp which has its highest peak occurring at 583nm.

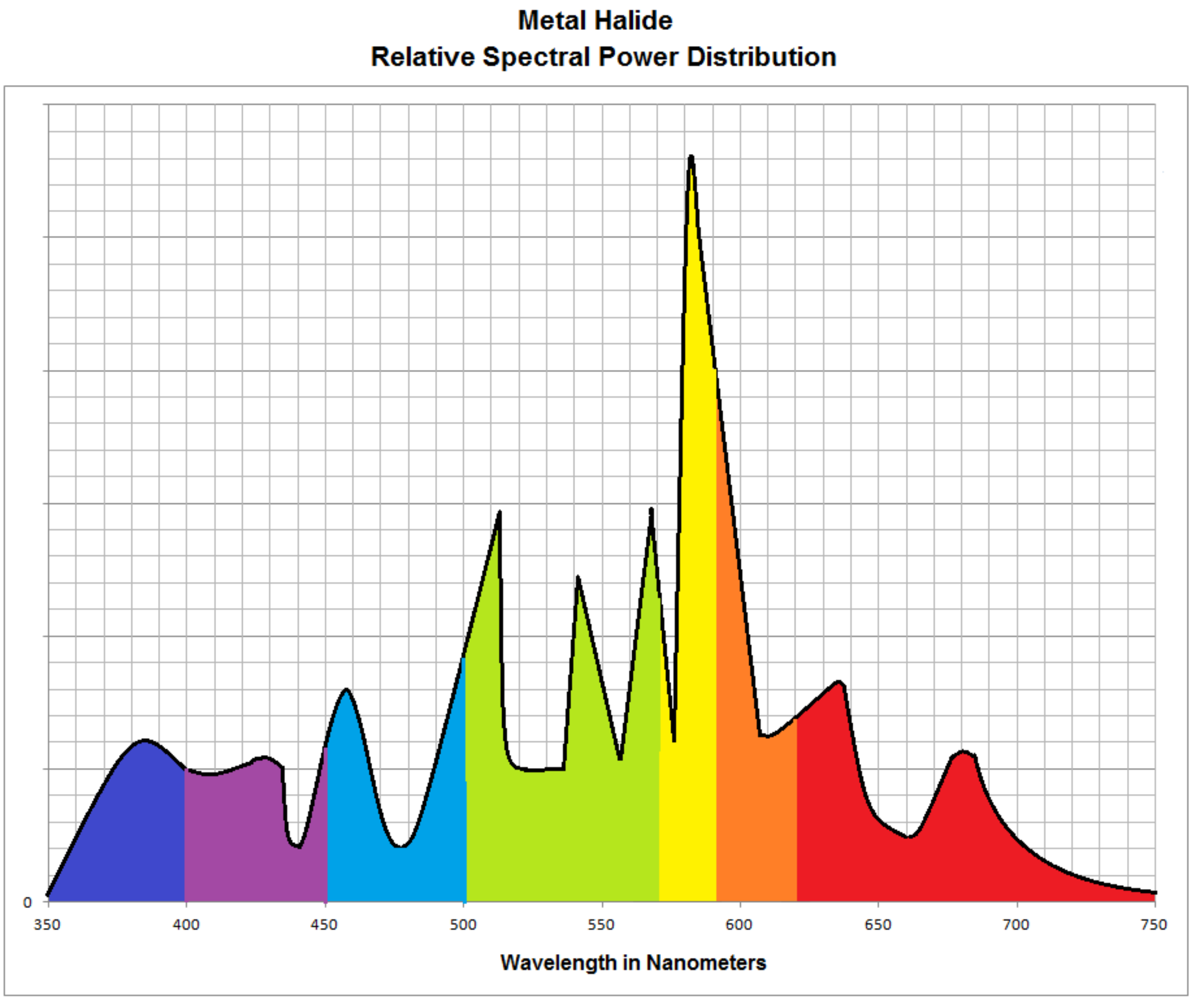

Figure 20

Metal-halide mixtures, metal-halide lamps are available with a correlated color temperature from 3,000 K to over 20,000 K. Color temperature can vary slightly from lamp to lamp, and this effect is noticeable in places where many lamps are used. Because the lamp's color characteristics tend to change during lamp's life, color is measured after the bulb has been burned for 100 hours according to ANSI standards. Newer metal-halide technology, referred to as *pulse start*, has improved color rendering and a more controlled Kelvin variance.

The color temperature of a metal-halide lamp can also be affected by the electrical characteristics of the electrical system powering the bulb and manufacturing variances in the bulb itself. If a metal-halide bulb is underpowered, because of the lower operating temperature, its light output will be bluish because of the evaporation of mercury alone. This phenomenon can be seen during warm-up, when the arc tube has not yet reached full operating temperature and the halides have not fully vaporized. It is also very apparent with dimming ballasts. The inverse is true for an overpowered bulb, but this condition can be hazardous, leading possibly to arc-tube explosion because of overheating and overpressure.

Operation

Like other gas-discharge lamps such as the very-similar mercury-vapor lamps, metal-halide lamps produce light by making an electric arc in a mixture of gases. In a metal-halide lamp, the compact arc tube contains a high-pressure mixture of argon or xenon, mercury, and a variety of metal halides, such as sodium iodide and scandium iodide. The particular mixture of halides influences the correlated color temperature and intensity. The argon gas in the lamp is easily ionized, which facilitates striking the arc across the two electrodes when voltage is first applied to the lamp. The heat generated by the arc then vaporizes the mercury and metal halides, which produce light as the temperature and pressure increases.

Common operating conditions inside the arc tube are 5-50 atm or more and up to 3,000C. Like all other gas-discharge lamps, metal-halide lamps have negative resistance and require a ballast to provide proper starting and operating voltages and regulate the current flow in the lamp. About 25% of the energy used by metal-halide lamps produces light, making them substantially more efficient than incandescent bulbs, which typically have efficiencies of less than 5%.

As shown in Figure 21, a Metal-halide lamp consists of an arc tube with electrodes, an outer bulb, and a base.

Traditional metal halide (MH) lamps use *probe-start* technology. Three electrodes are present in the arc tube of a probe-start MH lamp: a starting electrode and two operating electrodes. To start the lamp, a discharge is created across a small gap between the starter electrode and the operating electrode. Electrons then jump across the arc tube to the other operating electrode to help start the lamp. Once the lamp is started, a bi-metal switch removes the starter electrode from the circuit.

Each time a MH lamp is turned on, tungsten sputters from the electrodes. Over the lamp life, this tungsten can cause the arc tube wall to blacken, thus reducing performance of the lamp.

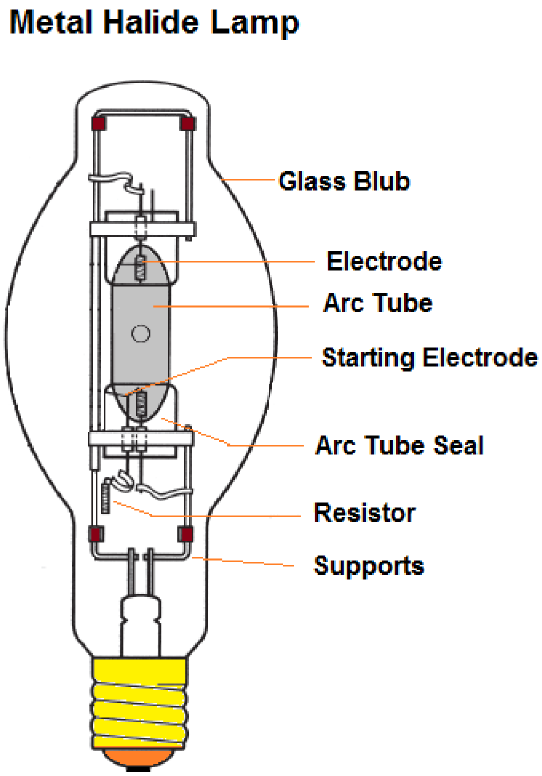

Figure 21

Another starting method is known as *pulse start*. Pulse-start MH lamps do not have the starting probe electrode. Instead they have a high-voltage igniter that works with the ballast to start the lamp using a series of high-voltage pulses. Using an igniter with a lamp reduces the tungsten sputtering by heating up the electrodes faster during starting. Warm-up time is also reduced. Pulse-start technology was developed to increase lamp life.

Pulse-start technology can:

- Provide longer lamp life of up to 50% over traditional MH lamps,
- Increase lumen maintenance by up to 33%,
- Provide better cold starting capability, and
- Allow faster starting when cold, shorter warm-up times, and a faster restrike.

A "cold" (below operating temperature) metal-halide lamp cannot immediately begin producing its full light capacity because the temperature and pressure in the inner arc chamber require time to reach full operating levels. Starting the initial argon arc sometimes takes a few seconds, and the warm up period can be as long as five minutes. During this time the lamp exhibits different colors as the various metal halides vaporize in the arc chamber.

If power is interrupted, even briefly, the lamp's arc will extinguish, and the high pressure that exists in the hot arc tube will prevent re-striking the arc; with a normal igniter a cool-down period of 5–10 minutes will be required before the lamp can be restarted, but with special igniters with specially designed lamps, the arc can be immediately re-established. On fixtures without instant restrike capability, a momentary loss of power can mean no light for several minutes. For safety reasons, many metal-halide fixtures have a backup tungsten-halogen incandescent lamp that operates during cool-down and restrike. Once the metal halide restrikes and warms up, the incandescent safety light is switched off. A warm lamp also tends to take more time to reach its full brightness than a lamp that is started completely cold.

The ends of the arc tube are often externally coated with white infrared–reflective zirconium silicate or zirconium oxide to reflect heat back onto the electrodes to keep them hot and thermionically emitting. Some bulbs have a phosphor coating on the inner side of the outer bulb to improve the spectrum and diffuse the light.

Most types are fitted with an outer glass bulb to protect the inner components and prevent heat loss. The outer bulb can also be used to block some or all of the UV light generated by the mercury vapor discharge, and can be composed of specially doped "UV stop" fused silica. Ultraviolet protection is commonly employed in single base models and double ended models that provide illumination for nearby human use. Some high powered models, particularly the lead-gallium UV printing models and models used for some types of sports stadium lighting do not have an outer bulb. The use of a bare arc tube can allow transmission of UV or precise positioning within the optical system of a luminaire. The cover glass of the luminaire can be used to block the UV, and can also protect people or equipment if the lamp should fail by exploding.

The electric arc in metal-halide lamps, as in all gas discharge lamps has a negative resistance property; meaning that as the current through the bulb increases, the voltage across it decreases.

In MH lamps, ballasts provide the starting voltage and ignition pulses necessary to ignite the lamp. Probe-start MH ballasts, however, can take as long as 10 to 20 minutes to restrike a lamp. Pulse-start MH ballasts can restrike the lamp within 2 to 8 minutes of an interruption in current, because they provide high-voltage pulses to start these lamps.

The ballast regulates the lamp operating current flowing through the lamp after the lamp has been started. The ballast is set to deliver relatively stable power to the lamp while regulating the lamp current despite typical line voltage fluctuations. This maximizes lamp life and ensures other performance characteristics such as color and light output.

MH ballasts must maintain suitable voltage and current wave shape to the lamp. MH lamp voltage typically increases over time, and the ballast must continue to provide sufficient voltage to the lamp as it ages.

Several companies now offer self-ballasted metal-halide lamps as a direct replacement for incandescent and self-ballasted mercury-vapor lamps. These lamps include an arc tube with a starting electrode as well as a tubular halogen lamp which is connected in series and used to regulate the current in the arc tube. A resistor provides the current limiting for the starting electrode. Like self-ballasted mercury-vapor lamps, self-ballasted metal-halide lamps are connected directly to mains power and do not require an external ballast. In contrast to the former, these lamps usually have a clear outer bulb without a coating, making the arc tube and the halogen lamp tube clearly visible from the outside.

Like HPS lamps, metal-halide lamps exhibit a phenomenon known as *cycling* at the end of life. These lamps can be started at a relatively low voltage but as they heat up during operation, the internal gas pressure within the arc tube rises and more and more voltage is required to maintain the arc discharge. As a lamp gets older, the maintaining voltage for the arc eventually rises to exceed the voltage provided by the electrical ballast. As the lamp heats to this point, the arc fails and the lamp goes out. Eventually, with the arc extinguished, the lamp cools down again, the gas pressure in the arc tube is reduced, and the ballast once again causes the arc to strike. This causes the lamp to glow for a while and then goes out, repeatedly. In rare occurrences the lamp explodes at the end of its useful life. Modern electronic ballast designs detect cycling and give up attempting to start the lamp after a few cycles. If power is removed and reapplied, the ballast will make a new series of startup attempts.

All HID arc tubes deteriorate in strength over their lifetime because of various factors, such as chemical attack, thermal stress and mechanical vibration. As the lamp ages the arc tube becomes discolored, absorbing light and getting hotter. The tube will continue to become weaker until it eventually fails, causing the breakup of the tube.

Since a metal-halide lamp contains gases at a significant high pressure, failure of the arc tube is inevitably a violent event. Fragments of arc tube are launched, at high velocity, in all directions, striking the outer bulb of the lamp with enough force to cause it to break. If the fixture has no secondary containment then the extremely hot pieces of debris will fall down onto people and property below the light, likely resulting in serious injury, damage, and possibly causing a major building fire if flammable material is present.

Lamps that require an enclosed fixture are rated "/E". Lamps that do not require an enclosed fixture are rated "/O" (for open). Sockets for "/O" rated fixtures are deeper. "/E" rated bulbs flare at the base, preventing them from fully screwing into a "/O" socket. "/O" bulbs are narrow at the base allowing them to fully screw in. "/O" bulbs will also fit in an "/E" fixture.

Metal halide lamps have an average-rated life span of 3,000 to 20,000 hours, depending on lamp wattage. Lamp life generally is much shorter than HPS and mercury vapor due to poorer lumen maintenance and the presence of iodine compounds in the arc tube. The normal failure mode is the inability to start because of increased starting voltage requirements. Frequent starting also will adversely affect lamp life, as will over-wattage operation.

Applications

Metal-halide lamps are used both for general lighting purposes both indoors and outdoors, automotive and specialty applications. Because of their wide spectrum, they are used for indoor growing applications and in athletic facilities.

Metal-halide lamps are used in automobile headlights, where they are commonly known as "xenon headlamps" due to the use of xenon gas in the bulb instead of the argon typically used in other halide lamps. They produce a more intense light than incandescent headlights.

Another widespread use for such lamps is in photographic lighting and stage lighting fixtures, where they are commonly known as MSD lamps.

CERAMIC DISCHARGE METAL-HALIDE LAMP

Several years ago, Ceramic Metal Halide (CMH) technology was introduced, which, instead of a quartz arc tube as used in mercury vapor lamps and previous metal-halide lamp designs, use a sintered alumina arc tube similar to those used in the high pressure sodium lamp. This development reduces the effects of *ion creep* that plagues quartz arc tubes. During their life, sodium and other elements tends to migrate into the quartz tube, because of high UV radiation and gas ionization, resulting in depletion of light emitting material that causes cycling. The sintered alumina arc tube does not allow the ions to creep through, maintaining a more constant color over the life of the lamp. These are usually referred as ceramic metal-halide lamps or CMH lamps.

Ceramic Metal Halide Overview

Efficacy: 117 lumens/watt
Color Temp: 5,400K
CRI: 96
Life: 20,000 hours

During operation, the temperature of the ceramic tube can exceed 1,200K. The ceramic tube is filled with mercury, argon and metal-halide salts. Because of the high wall temperature, the metal halide salts are partly vaporized. Inside the hot plasma, these salts are dissociated into metallic atoms and iodine.

The ceramic tube is an advantage in comparison to earlier quartz tube. During operation, at high temperature and radiant flux, metal ions tend to penetrate the silica, depleting the inside of the tube. Alumina is not prone to this effect.

Ceramic Metal Halide tubes are more resistant than standard Metal Halide tubes to the corrosion metal halide salts create within the arc tube. This allows CMH tubes to operate at higher temperatures than traditional Metal Halide tubes, boosting performance and quality of light characteristics as lumen maintenance, lamp color-shift, CRI, and dimming.

The metallic atoms are the main source of light in these lamps, creating a bluish light that is close to daylight with a CRI of up to 96. The exact correlated color temperature and CRI depend on the specific mixture of metal halide salts. There are also warm-white CMH lamps, with somewhat lower CRI which still give a more clear and natural-looking light than the old mercury-vapor and sodium-vapor lamps when used as street lights, besides being more economical to use.

Figure 22 shows the spectral power distribution of a CMH lamp.

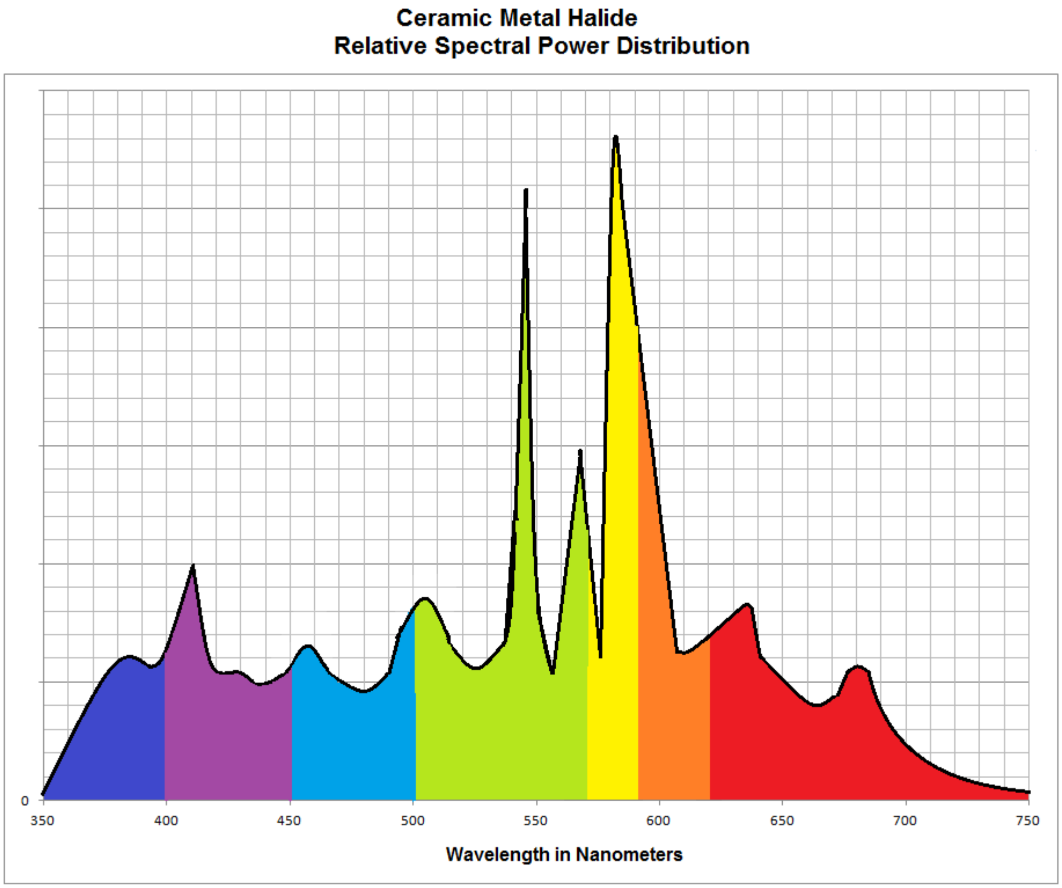
Ceramic Metal Halide
Relative Spectral Power Distribution

Figure 22

CMH lamps use one fifth of the power of comparable tungsten incandescent light bulbs for the same light output and retain color stability better than most other gas discharge lamps. Like other high-intensity discharge lamps, they require a correctly rated electrical ballast in order to operate.

They also have improved lumen maintenance characteristics. CMH lamps are available in ranges from 20 watts through 400 watts, and in most standard configurations. One of the newest types is designed specifically as a direct lamp retrofit for 400 watt High Pressure Sodium lamps. This retrofit offers far better color quality without requiring the replacement of existing ballasts.

The advantages of CMH lamps include:

- More efficient than halogen
- Better color quality than Standard MH
- Better lumen maintenance
- Better color consistency than Standard MH
- Lower operating cost

The disadvantages are:

- Higher initial cost
- Requires a ballast
- Not easily dimmable
- Requires re-strike time

Applications

Accent lighting has traditionally been dominated by incandescent and halogen sources due mainly to excellent color quality, source flexibility, and good optical control. Standard Metal Halide and color corrected High Pressure Sodium lamps have been used as energy efficient replacements for some accent lighting applications with mixed success. Problems with color quality and consistency have been limitations of these lamp technologies. CMH lamps overcome most of the problems of the older style energy efficient lamps while producing crisp light with excellent color rendition and optical control that is almost identical to halogen sources. In fact, many of the available CMH lamp types have been specifically designed to be optically equivalent to the halogen sources they are designed to replace.

The best opportunity for the use of CMH lamps is in retail spaces. Retail lighting generally requires point source accent lighting and high contrast ratios. Most retail lighting in the United States is still delivered by inefficient halogen track heads or recessed accent adjustable luminaires. Many retailers throughout the country are moving to these sources to save electricity and radically reduce maintenance costs.

While the color rendition of CMH lamps is excellent, spaces like museums or galleries have specific requirements. While the light that is being delivered is perceived as “white,” the spectral distribution of the source is not truly continuous like sunlight or halogen light. Some colors may be slightly muted while others are enhanced changing the perception of art.

XENON ARC LAMP

A xenon arc lamp is a specialized type of gas discharge lamp, an electric light that produces light by passing electricity through ionized xenon gas at high pressure. It produces a bright white light that closely mimics natural sunlight.

Xenon Arc Lamp Overview

Efficacy: 000 lumens/watt
Color Temp: 6,200K
CRI: ~100
Life: 2,000 hours

Xenon lamps exhibit the highest luminance and radiance output of any operating light source and very closely approach the ideal model for a point source of light. In contrast to mercury and metal halide illumination sources, the xenon arc lamp is distinct in that it produces a largely continuous and uniform spectrum across the entire visible spectral region. Because the xenon lamp emission profile features a color temperature of approximately 6,200 K and lacks prominent emission lines, this illumination source is more advantageous than mercury arc lamps for many applications.

The exceedingly high pressure of xenon lamps during operation broadens spectral lines to yield far more uniformly distributed excitation of fluorophores when compared to the narrow and discrete emission lines produced by mercury lamps.

Xenon arc lamps are used in movie projectors in theaters, in searchlights, and for specialized uses in industry and research to simulate sunlight. Xenon headlamps in automobiles actually use metal-halide lamps where xenon arc is only used during start-up.

Xenon arc lamps can be roughly divided into two categories:

- Continuous-output xenon short-arc lamps
- Continuous-output xenon long-arc lamps

Each form consists of quartz or other heat resistant glass arc tube, with a tungsten metal electrode at each end. The glass tube is first evacuated and then re-filled with xenon gas. For xenon flashtubes, a third "trigger" electrode usually surrounds the exterior of the arc tube. The lamp has a lifetime of around 2,000 hours.

The most common form of xenon lamps is the *short-arc lamp*. The white, continuous light generated by the xenon arc is spectrally similar to daylight, but the lamp has a rather low efficiency in terms of lumens of visible light output per watt of input power.

Operation

Xenon short-arc lamps use a fused quartz envelope with thoriated tungsten electrodes. Fused quartz is the only economically feasible material currently available that can withstand the high pressure and high temperature present in an operating lamp, while still being optically clear. The thorium dopant in the electrodes greatly enhances their electron emission characteristics. Because tungsten and quartz have different coefficients of thermal expansion, the tungsten electrodes are welded to strips of pure molybdenum metal or *Invar* alloy, which are then melted into the quartz to form the envelope seal.

Invar is a nickel–iron alloy notable for its uniquely low coefficient of thermal expansion.

Xenon short-arc lamps also are manufactured with a ceramic body and an integral reflector. They are available in many output power ratings with either UV transmitting or blocking windows. Xenon arc lamps are manufactured with spherical or ellipsoidal envelopes composed of fused silica quartz, one of the few optically transparent materials that will withstand the excessive thermal loads and high internal pressures imposed on materials used in the fabrication of these lamps.

The anode and cathode electrodes in xenon arc lamps are fabricated from forged tungsten or specialized tungsten alloys doped with thorium oxide or barium compounds to reduce the work function and increase the efficiency of electron emission. The high grade tungsten used in Xenon lamps has a very low vapor pressure and ensures that xenon lamp electrodes are able to withstand the extremely high arc temperatures (over 2,000C for the anode) encountered during operation and helps to minimize the buildup of envelope deposits.

The design of xenon lamp cathodes has received a considerable amount of attention aimed at increasing stability of the arc during operation. In conventional lamps using thorium-doped tungsten electrodes, the arc emission point on the cathode intermittently shifts due to localized variations in electron emission from the surface. This artifact, which increases in severity as the tip wears, leads to momentary fluctuations in lamp brightness when the arc relocates to a new region on the cathode. In addition, the sharp tips of thorium-doped cathodes tend to wear at an accelerated rate compared to cathodes fabricated with advanced rare-earth oxide alloys. Lamps featuring advanced cathode technology are often referred to as *super-quiet* and have demonstrated high short-term arc stability of less than one-half percent, as well as reduced drift rates of less than 0.05 percent per operating hour. Long term analysis of high performance cathode operation indicates that wear is significantly reduced, and shifting of the arc point over the average lamp lifetime is virtually eliminated.

Xenon short-arc lamps have a negative temperature coefficient like other gas discharge lamps. They're operated at low-voltage, high-current, DC and started with a high voltage pulse of 20 to 50kV. They are also inherently unstable, prone to phenomena such as plasma oscillation and thermal runaway.

Because of the very high power levels involved, large lamps are water-cooled. In those used in IMAX projectors, the electrode bodies are made from solid Invar and tipped with thoriated tungsten. An O-ring seals off the tube, so that the naked electrodes do not contact the water. In low power applications the electrodes are too cold for efficient electron emission and are not cooled; in high power applications an additional water cooling circuit for each electrode is necessary. To save costs, the water circuits are often not separated and the water needs to be deionized to make it electrically non-conductive, which, in turn, lets the quartz or some laser media dissolve into the water.

Xenon *short-arc lamps* come in two distinct varieties: pure xenon, which contain only xenon gas; and xenon-mercury, which contain xenon gas and a small amount of mercury metal. In a pure xenon lamp, the majority of the light is generated within a tiny, pinpoint-sized cloud of plasma situated where the electron stream leaves the face of the cathode. The light generation volume is cone-shaped, and the luminous intensity falls off exponentially moving from cathode to anode. Electrons passing through the plasma cloud strike the anode, causing it to heat. As a result, the anode in a xenon short-arc lamp either has to be much larger than the cathode or be water-cooled, to dissipate the heat. The output of a pure xenon short-arc lamp offers fairly continuous spectral power distribution with a color temperature of about 6,200K and CRI close to 100.

Even though xenon lamps produce broadband, almost continuous emission having a color temperature approximating sunlight in the visible wavelengths, several lower energy lines exist around 475 nanometers in the visible region. Between 400 and 700 nanometers, approximately 85 percent of the total energy emitted by a xenon lamp resides in the continuum whereas about 15 percent arises from the line spectrum. The spectral output of a xenon lamp is not altered as the device ages and, unlike mercury arc lamps, the complete emission profile occurs instantaneously upon ignition. The xenon lamp output remains linear as a function of applied current and can be modulated for specialized applications. Furthermore, the spectral radiance is not altered by variations in lamp current. Figure 23 shows the spectral power distribution for a Xenon lamp.

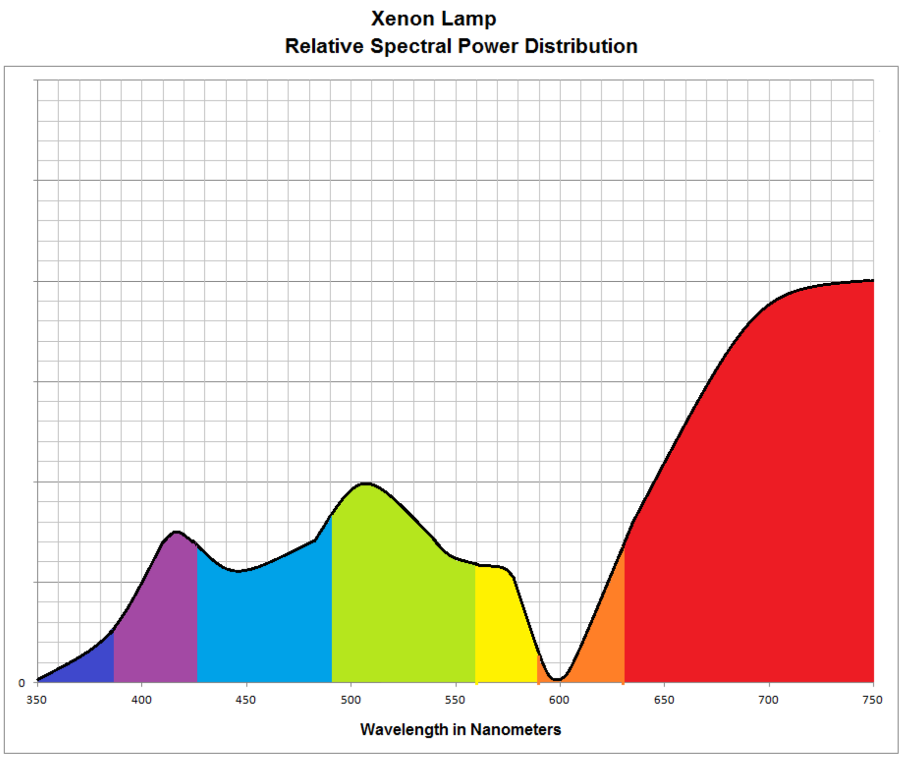

Figure 23

Many lamps have a shortwave UV blocking coating on the envelope and are sold as "Ozone Free" lamps. Some lamps have envelopes made out of ultra-pure synthetic fused silica, which roughly doubles the cost, but which allows them to emit useful light into the vacuum UV region. These lamps are normally operated in a pure nitrogen atmosphere.

In order to achieve maximum efficiency, the xenon gas inside short-arc lamps is maintained at an extremely high pressure — up to 30 atmospheres — which poses safety concerns. If a lamp is dropped, or ruptures while in service, pieces of the lamp envelope can be thrown at high speed. To mitigate this, large xenon short-arc lamps are normally shipped in protective shields, which will contain the envelope fragments, should breakage occur. Normally, the shield is removed once the lamp is installed in the lamp housing. When the lamp reaches the end of its useful life, the protective shield is put back on the lamp, and the spent lamp is then removed from the equipment and discarded. As lamps age, the risk of failure increases, so bulbs being replaced are at the greatest risk of explosion. Because of the safety concerns, lamp manufacturers recommend the use of eye protection when handling xenon short-arc lamps. Because of the danger, some lamps, especially those used in IMAX projectors, require the use of full-body protective clothing.

Xenon long-arc lamps are structurally similar to short-arc lamps except that the arc-containing portion of the glass tube is greatly elongated. When mounted within an elliptical reflector, these lamps are frequently used to simulate sunlight.

Applications

Xenon lamps are used in a wide variety of applications, such as video projectors, fiber optic illuminators, endoscope and headlamp lighting, dental lighting, and search lights.

The very small size of the arc makes it possible to focus the light from the lamp with moderate precision. For this reason, xenon arc lamps of smaller sizes are used in optics. Larger lamps are employed in searchlights where narrow beams of light are generated, or in film production lighting where daylight simulation is required.

In 1991 "xenon headlamps" were introduced for vehicles. These are actually metal-halide lamps; the xenon gas is used only to provide some light immediately upon lamp startup, as required for safety in an automotive headlamp application. Full intensity is reached 20 to 30 seconds later once the salts of sodium and scandium are vaporized by the heat of the xenon arc. The lamp envelope is small and the arc spans only a few millimeters. An outer hard glass tube blocks the escape of ultraviolet radiation that would tend to damage plastic headlamp components.

The useful life span of a xenon arc lamp is primarily determined by the decrease in luminous flux that occurs as a consequence of evaporated tungsten that is deposited on the inner wall of the envelope over time. Decay of the cathode tip and solarization effects of ultraviolet radiation on the quartz envelope also contribute to lamp ageing, as well as stability. Frequent lamp ignitions tend to accelerate electrode wear and lead to premature blackening of the envelope. The blackening gradually reduces light output and shifts the spectral characteristics to a lower color temperature. Lamp blackening, which increases the envelope operating temperature due to absorption of energy from radiated light, occurs slowly during the early stages of the lamp lifetime, but increases rapidly in later stages. Other factors that negatively impact xenon lamp life span include overheating, low current, power supply ripple, incorrect burning position, excessive current, and uneven envelope blackening. Xenon lamps should be replaced (even if they are still able to ignite) when the average lifetime has been exceeded by 25 percent.

Summary

High-intensity discharge (HID) lighting provides the highest efficacy and longest service life of any lighting type. It can save up to 90% of lighting energy when it replaces incandescent lighting. High-intensity discharge lamps make more visible light per unit of electric power consumed than fluorescent and incandescent lamps since a greater proportion of their radiation is visible light in contrast to heat.

HID lamps use an electric arc to produce intense light. Like fluorescent lamps, they require ballasts. They also take up to 10 minutes to produce light when first turned on because the ballast needs time to establish the electric arc. Because of the intense light they produce at a high efficacy, HID lamps are commonly used for outdoor lighting and in large indoor arenas and they are most suitable for applications in which they stay on for hours at a time.

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