Chapter 3

High Intensity Discharge Lamps

The previous chapter described the fluorescent lamp, which is one type of discharge lamp. Its defining characteristic is a discharge that is operated at low pressure. This chapter describes the other major type of discharge lamp called the high intensity discharge lamp or HID lamp. HID lamps, like fluorescents, produce light by sustaining an electric arc through a gas. But unlike fluorescents, which are low pressure discharges, the HID lamps operate on a high pressure discharge. This chapter discusses the various HID lamp types and their construction, as well as the features of the high pressure discharge.

3.1 HID Lamp Types and Construction

HID lamps generally have much smaller arc tubes than fluorescent lamps. While a typical fluorescent lamp will have an arc tube four feet long, HID arc tubes are usually less than several inches long. These short arc tubes operate a discharge at high temperature and pressure with high power densities. The high pressure discharge has different radiation properties than a low pressure discharge. In addition, the high operating pressures and temperatures allow different elements and gases to be used with the arc, also creating different radiating spectra. HID lamps generally have long life and good efficacy, and are compact like incandescents. Most high intensity discharge lamps operate at high power and light intensity, which makes them suitable for outdoor use more so than indoor use in general. A disadvantage of HID lamps is that once the arc is extinguished, the lamp must cool for 5 to 15 minutes before it can be reignited. There are several different types of HID lamps, including the mercury vapor, metal halide, and high pressure sodium lamps. The features and construction of these lamp types are explained in the following sections.

3.1.1 High Pressure Mercury Vapor Lamps

The construction of a mercury vapor lamp is shown in Figure 3-1. It consists of an inner and outer envelope. The inner envelope is the arc tube, which is made of quartz or fused silica, and contains the actual discharge. Fused silica can withstand temperatures of up to 800°C. The operating temperatures of mercury vapor lamps are usually within the range of 600°C to 750°C. The arc tube is filled with mercury and argon, where the argon is used primarily for starting the discharge. Operating pressures of the gas are 2–10 atm. The outer envelope is an elliptical bulb made of hard borosilicate glass (lamps with wattages less than 125 watts may use soda lime glass) and exists mainly to provide a protective environment for the arc tube. In addition to protecting the arc tube from drafts and ambient conditions, the outer bulb contains an inert gas such as nitrogen to protect internal parts from oxidation. Phosphors may also be used, in which case the outer bulb provides the surface for the phosphor coating.

The mercury vapor lamp produces light by passing an electric discharge through mercury vapor in the arc tube. Under high pressure operation, the mercury radiates in a broader spectrum of wavelengths than for low pressure operation, some of which are of visible wavelengths. This is in contrast to a low pressure mercury discharge (fluorescent) where resonance radiation occurs in an ultra-violet wavelength of 253.7 nm. There are five principle visible radiation wavelengths in mercury, 405 nm, 436 nm, 547 nm, 577 nm, and 579 nm; refer to Figure 2-5. These produce yellow, green, violet, and blue colors with a strong absence of red. Phosphors, such as vanadate phosphor, can be used to convert the ultra-violet radiation into the orange-red spectrum to improve the color of the light output. Without the color correction, red

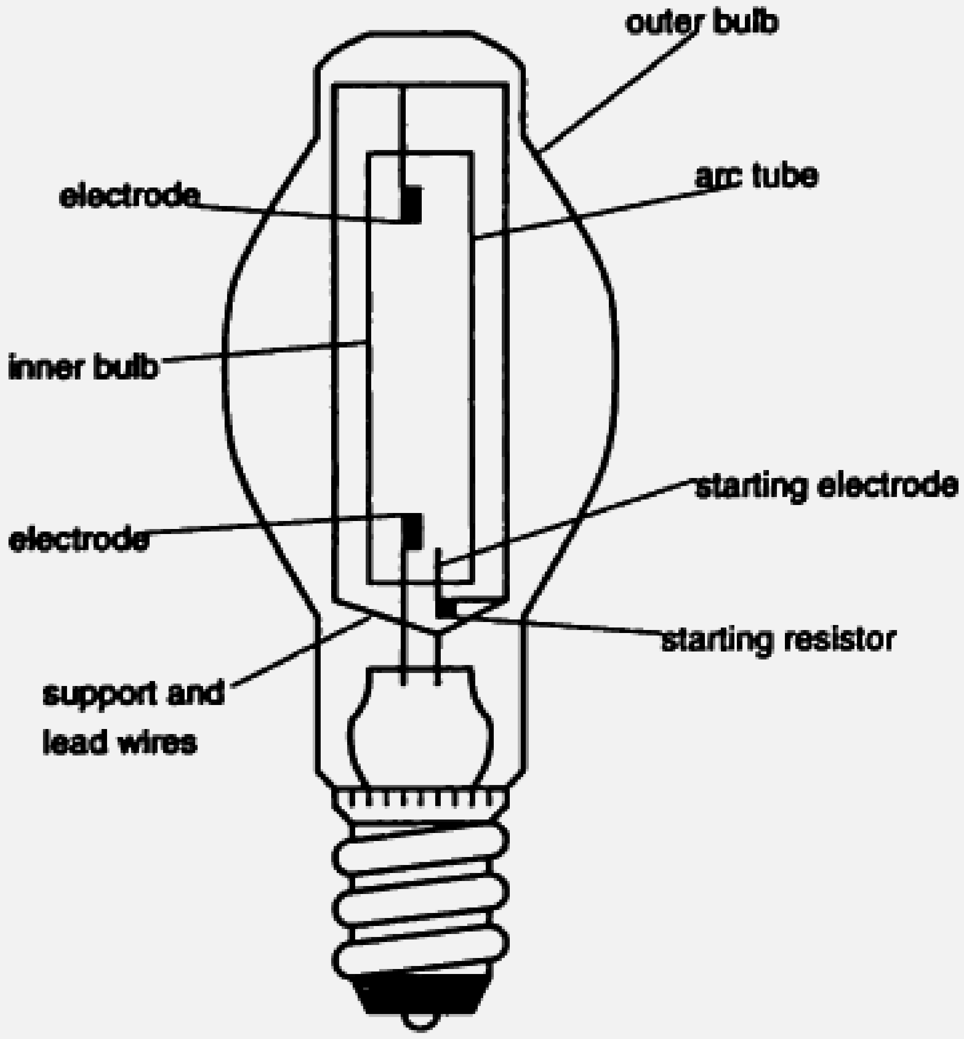

Figure 3-1: High pressure mercury vapor lamp

objects appear black or dark brown.

The electrodes are made from tungsten with an electron emissive material and are heated during operation by bombardment from the arc current. A starting electrode with a starting resistor is used to initiate the arc during ignition. The starting electrode is made of molybdenum or tungsten and is placed in close proximity to the main electrode but at the opposite polarity of voltage. The starting resistor is usually between 10 kΩ and 20 kΩ and is used to limit current during starting. The life of the lamp ends with the loss of emission material from the electrodes. Lamp lifetimes are on the order of 24,000 hours [4].

Commercial mercury vapor lamps vary in wattage from 40 to 2000 watts. Higher power lamps yield higher efficacies. For example, a 50 W mercury lamp yields efficacies around 40 lm/W, while a 1000 W mercury lamp yields efficacies around 60 lm/W [6]. These lamps generally achieve efficacies of only 30 to 65 lm/W [11, 4, 1]. Because lamp operation is not affected by ambient conditions, the mercury vapor lamp is used in outdoor and industrial plant type applications. Mercury lamps have a negative resistance characteristic and require a ballast for starting and current limiting during operation.

3.1.2 Metal Halide Lamps

Metal halide lamps are very similar to high pressure mercury lamps. The construction of a metal halide lamp is shown in Figure 3-2. The main difference is the addition of metal halides to the arc tube which alter the radiating properties of the discharge. Like the mercury vapor lamp, the inner arc tube is made of quartz or fused silica and is filled with some mercury and a rare gas such as argon for starting, along with one or more metal halides. The outer bulb is made of hard glass.

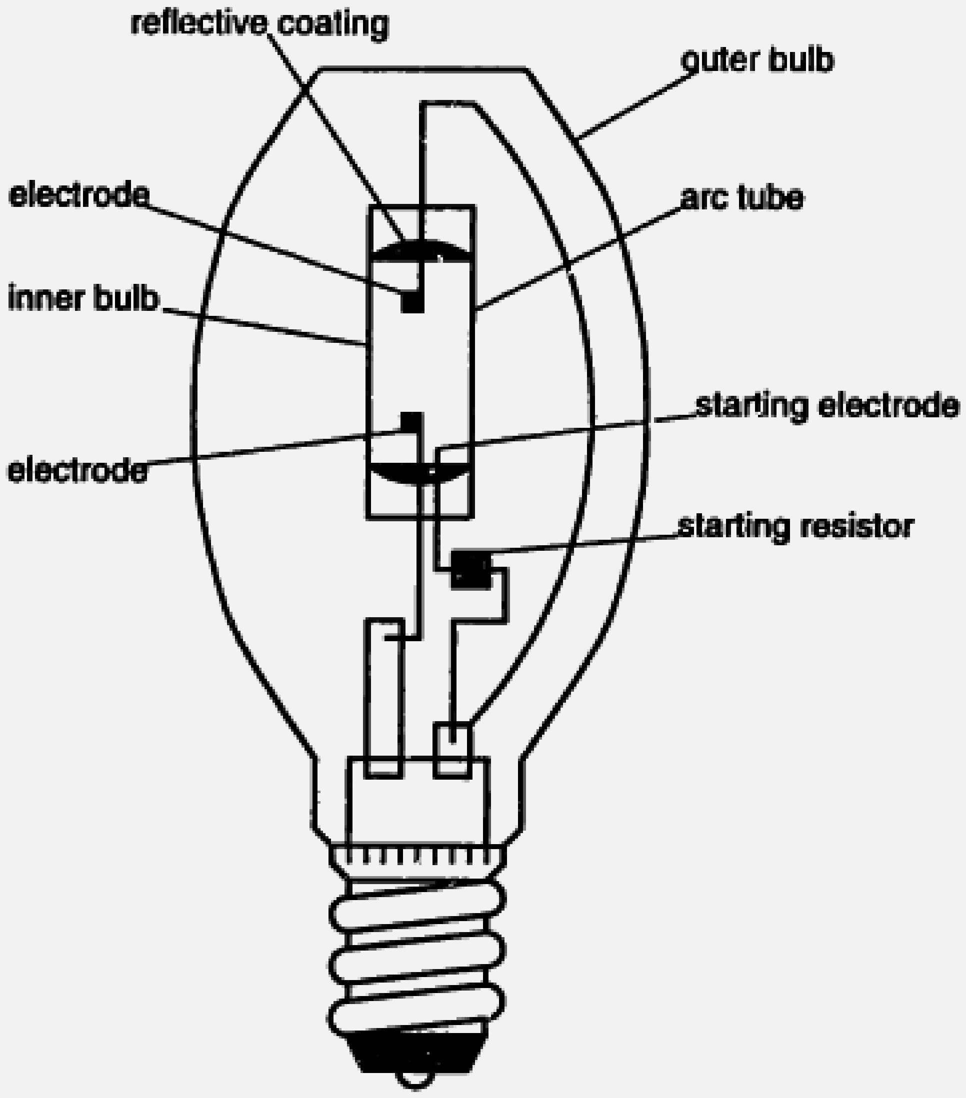

Figure 3-2: Metal halide lamp

There are two main electrodes made from thorium-tungsten. These electrodes must be designed to withstand chemical reaction with the metal halides. A heat-reflecting surface, such as zirconium dioxide, applied to the surrounding area of the electrodes prevents the condensation of the metal halides away from the arc. A starting electrode and resistor, similar to those used in the mercury lamp, are used for initiating the discharge.

Metal halides are combinations or molecules of metals and halogens. Typical metals used include sodium, thalium, indium, scandium, and dysprosium. The halogens include fluorine, chlorine, bromine, and iodine, but iodine is usually used since the others tend to react with the tube parts. Some metals in metallic form cannot be vaporized at temperatures that the arc tube can withstand. However, these problems can be overcome by using the metals in the form of a metal halide. The halides are vaporized at operating temperatures, and they do not react with the arc tube [11, 6, 5].

The halide cycle is the primary phenomenon that characterizes metal halide lamps. When the arc is ignited, the mercury in the arc tube is vaporized, while the metal halides are in solid form on the tube wall. As the arc tube wall temperature increases, the metal halides are vaporized and travel to the center of the tube by diffusion and convection. In the center of the arc, the temperature is high enough to cause the dissociation of the metal halide into metal and halogen atom The metals are then excited by bombarding electrons to produce their characteristic radiation spectrum. The metals and halogens recombine at the cooler arc tube wall, completing the halide cycle [6].

The metals are introduced to improve the color and efficacy of the lamp. The halide form of the metals must be used to achieve vaporization and dissociation at operating temperatures that the arc tube can support. There are three typical halides used.

1. Sodium, thallium, indium iodides.
2. Sodium, scandium iodides.

3. Dysprosium, thallium iodides.

The metals sodium, thallium, and indium radiate line spectra of 589 nm, 535 nm, and 435 nm respectively. Multi-line spectra are radiated by scandium and dysprosium [11]. Good color is achieved by using combinations of metal halides which emit line spectra and halides which emit multi-line spectra.

The metal halide HID lamps have good color and excellent efficacies [25]. Typical efficacies range from 75 to 125 lm/W [11, 4, 1]. Lifetimes range from 6,000 to 10,000 hours [4]. Because of the warmer color, the metal halide lamps are suitable for indoor use in addition to outdoor applications such as flood lighting, sports lighting, and street lighting. Recently, low wattage lamps have been developed which are well-suited for consumer use. A 70 watt metal halide lamp has an efficacy around 100 lm/W, using an arc tube 1.3 cm in length and 0.7 cm in diameter. A 30 watt metal halide lamp has an efficacy of 85 lm/W, using an arc tube 0.6 cm long and 0.6 cm in diameter [26]. All metal halide lamps have a negative impedance characteristic and require a ballast for starting and current limiting during steady state operation.

3.1.3 High Pressure Sodium Lamps

High pressure sodium lamps generate light by passing an electric arc through sodium vapor. This necessitates different lamp design than the previous mercury vapor and metal halide HID lamps. A sodium lamp is shown in Figure 3-3. Again there are two envelopes, an inner arc tube and an outer bulb. The inner arc tube is made from a ceramic called translucent polycrystalline alumina, or PCA, which is resistant to chemical reaction from sodium. Furthermore, it has a high melting point and has good transmission of light. The PCA allows operation at the higher temperatures and pressures necessary for the sodium vapor discharge. The outer envelope is made of borosilicate glass. The volume of the outer envelope is generally a vacuum or inert argon gas, and functions to isolate the arc tube from the ambient conditions.

The arc tube contains mercury, xenon, and sodium. The mercury and xenon gases

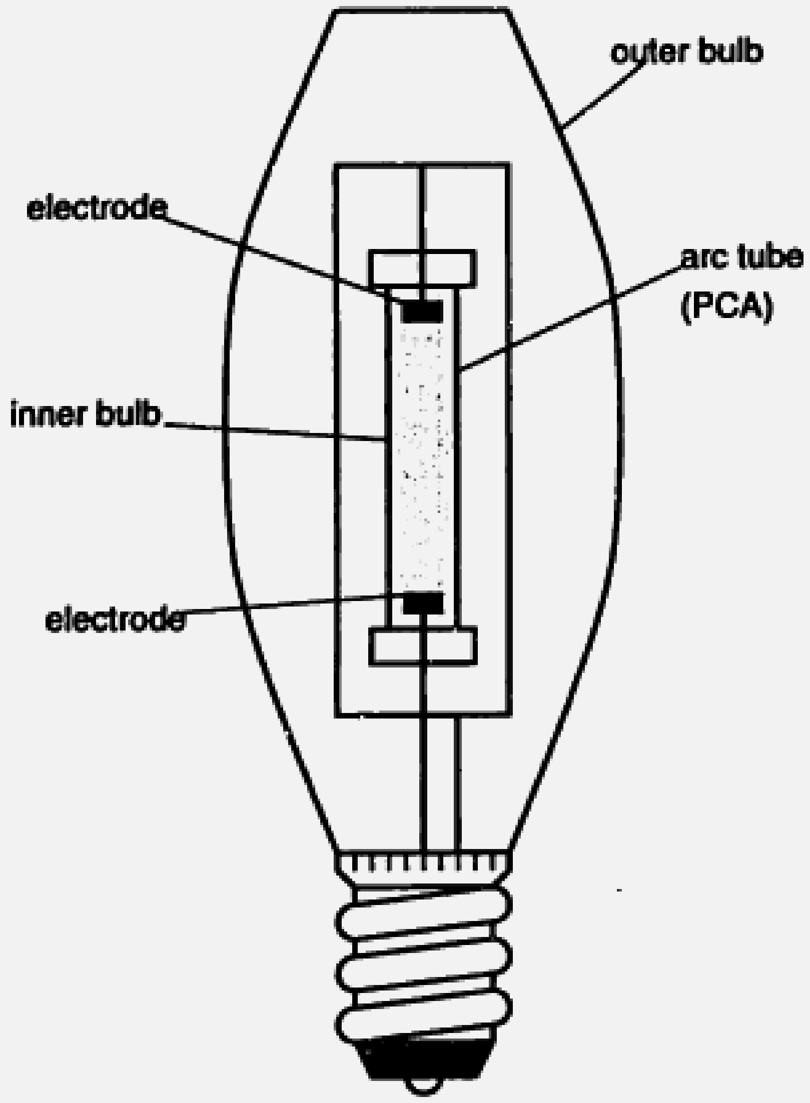

Figure 3-3: High pressure sodium lamp

function as a buffer gas, and raise the operating arc voltage and pressure. At low pressure, sodium exhibits two resonance radiation lines at 589.0 nm and 589.6 nm. By increasing the pressure to about 200 torr, these radiation lines become self-absorbed, and the radiation spectrum broadens. The emitted spectrum is largely golden-white in color.

The electrodes are tungsten with an electron emissive coating of barium and calcium oxides. The metal end cap seal makes the manufacture of a starting probe difficult [5]. The end cap seal is required because the PCA is difficult to work with and cannot be sealed conventionally. Since there is no starting electrode, the lamp is ignited by a high voltage, high frequency pulse from an electronic ignitor.

High pressure sodium lamps have efficacies of around 80 to 140 lm/W [1]. A typical 400 W lamp has an arc tube that is 3.75 inches long and 3/8 of an inch in diameter. They have long lifetimes of around 24,000 hours. High pressure sodium lamps are used mainly in street lighting and general outdoor lighting.

3.2 High Pressure Discharges

Section 2.2.2 described the principal radiation mechanisms in low pressure discharges. The majority of the radiation produced is from resonance radiation, where atoms are excited by colliding electrons and the emitted radiation occurs when exited valence electrons return to the ground state. When the pressure of the gas in a discharge tube is increased to a few atmospheres, the radiation spectrum changes and the discharge is then known as a high pressure discharge. This section describes the various characteristics of the high pressure discharge.

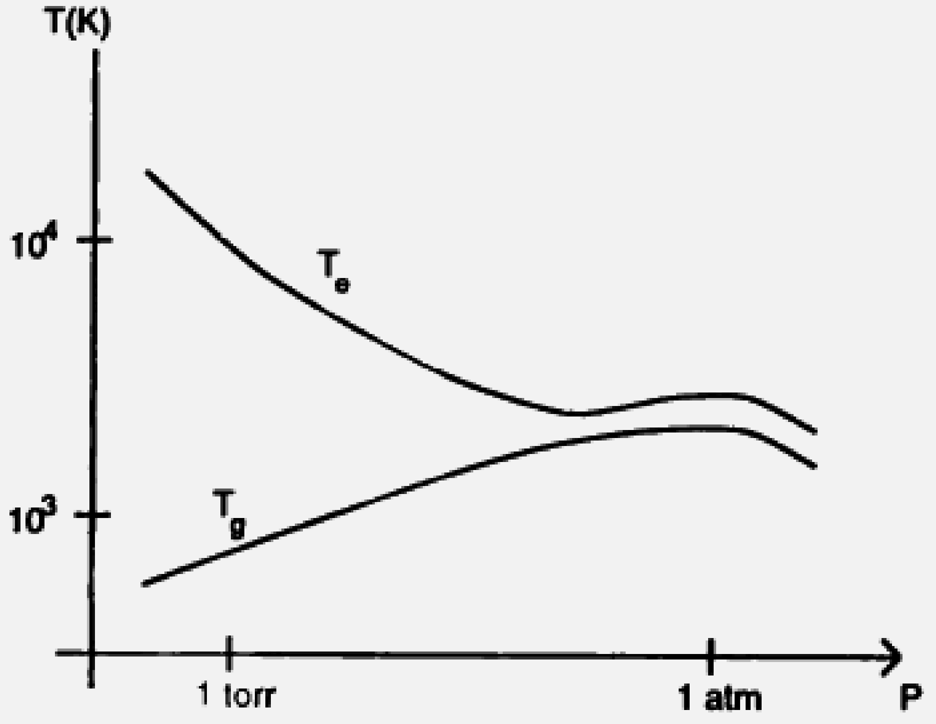

Figure 3-4: Electron temperature and gas temperature with increasing pressure

In a low pressure discharge, the electron temperature is much higher than the gas temperature. As the pressure is increased, there is an increasing number and probability of collisions between particles in the tube. The electrons lose more and more energy to the gas atoms, while the atoms in turn, gain more energy. This process continues with increasing pressure until a point is reached where the electron temperature and the gas temperature are nearly identical. Figure 3-4 illustrates this.

Because the average flow of energy is from the electrons to the gas atoms, the electron temperature is always higher than the gas temperature.

With the gas temperature increasing, there are an increasing number and variety of collision processes within the arc tube that affect the radiation spectrum of the discharge. The general effect of the increasing pressure is that the resonance radiation becomes self-absorbed or imprisoned, and any discrete spectral lines tend to broaden. At higher pressures still, spectral lines can broaden and merge, forming a continuous radiated spectrum. Discharge lamps can take advantage of this radiation broadening by radiating energy directly into the visible spectrum, eliminating the need for an intermediate conversion step of UV radiation to visible radiation.

The self-absorption of strong spectral lines is due primarily to repeated absorption and re-emission of the resonance radiation. The broadening of the emitted spectrum is due to many different collision processes. Collisions between an emitting atom and a neutral buffer gas atom can broaden the radiation and shift the line spectrum. Broadening and shifting of line spectra can occur from electric field interactions in collisions between emitting atoms and charged particles. Collisions between excited and ground state atoms of the same type also cause radiation broadening [6]. Along with broadening lines merging to form a continuous spectrum, recombining positive ions and electrons also cause the emission of a continuous spectrum [27]. All these processes are difficult to quantify, but in general there are random perturbations in energy levels resulting from collisions between radiating or excited atoms with other atoms or electrons. With increased variation in energy levels, the emitted spectrum also varies, resulting in broadening of the spectrum.

3.3 Lamp Efficacy

Less is known about quantifying the exact loss processes in HID lamps than in fluorescent lamps [5]. High pressure mercury lamps emit around 80% of the total power as radiation, where only 16% to 23% is emitted in the visible spectrum. This yields mediocre efficacies around 60 lm/W. High pressure sodium lamps radiate around 40%

of the total power in a band surrounding the 589 nm resonance lines, and therefore achieve high efficacies around 120 lm/W. Metal halide lamps radiate as much as 50% of the energy across the entire visible spectrum yielding efficacies around 100 lm/W [5].

The efficiency of HID lamps increases with increasing current density, due to the increased loading on the arc tube. In fact, the load (watts per unit length of arc tube) is the primary factor in determining the lamp efficacy [27]. Of the loss mechanisms in the lamp, which include convection, diffusion, and conduction, the conduction losses dominate. Conduction losses are roughly independent of lamp parameters, and thus can be considered to be constant [27]. With increasing power, these losses become a smaller fraction of the total and the lamp efficacy increases. At higher loading, more of the critical material is vaporized in the discharge, again yielding increased efficacy. In general, the high wattage HID lamps have higher efficacies [6, 27], because the higher arc loading and pressure results in higher light intensity [1].

As in the case of fluorescent lamps, it is desirable to operate HID lamps at high frequencies due to the reduction in size and weight of the ballast and due to the increased efficacy of the lamp itself [28]. However, the gains in efficacy at high frequency operation are not as dramatic as those in fluorescent lamps [29, 30]. More importantly, high frequency operation can excite acoustic resonances in the arc tube which can cause many problems.

3.4 Acoustic Resonance

Acoustic resonances are caused by the periodic input power giving rise to pressure perturbations within the arc tube [2, 31, 32]. If a resonant frequency is approached, a standing pressure wave mode can propagate. These pressure waves perturb the discharge path and lead to arc instabilities — the arc may move rapidly, the light output may fluctuate, the lamp voltage may increase rapidly which can lead to extinction of the arc. In the worst case, the arc may touch the tube wall causing a temperature rise which can damage or break the arc tube [6, 28, 2].

The resonant frequencies of the arc tube are a function of the gas mixture, tube dimensions, and even the electrode structure, and exist in frequency bands from as low as 500 Hz to as high as 100 kHz [2]. Several techniques are used in practice to achieve high frequency operation without exciting the acoustic resonances. It is possible to operate the lamp in a range of frequencies free of arc resonances, but these bands are usually too narrow to insure reliable operation. Furthermore, the resonant frequencies can change during the lifetime of the lamp [32, 31]. There are typically larger resonance free bands below 10 kHz, but operation there is not desirable due to noise being generated within the range of human hearing. It is possible, but not often practical, to operate the lamps at very high frequencies. Very high frequency operation (above 100 kHz or 200 kHz) can lead to significant losses in the ballast as well as radiated electromagnetic noise. It is possible to modulate the operating frequency to avoid acoustic resonances, because the arc movements due to resonances are slow and cannot be excited when the driving frequency of the lamp is changed rapidly. It is even possible to detect the onset of a resonance and then shift the operating frequency to either side of the resonating frequency [31, 30, 33, 34].

Acoustic resonances are a very troublesome problem. Troubling enough that in practice, high frequency ac operation is often avoided all together. Because the resonances are excited by ac power input fluctuations, a dc or square wave drive is very effective in avoiding resonances [31, 35, 32, 36]. As in fluorescents, dc is not practical because of the need for a resistive ballast and the need to reverse the polarity of the lamp. Square wave operation is often considered to be the ideal drive for HID lamps.