Some Bits of Discharge Lamp Theory and Other Technical Information!

Please be aware that only a few interesting and/or widely requested bits of information will appear here.

NOTE: This document will expand as time goes on.

updated slightly 8/19/2002.

Table of Contents

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1. REFERENCES!!

I highly recommend the book by W. Elenbaas, "The High Pressure Mercury Vapor Discharge", published in 1951 by North Holland Publishing Co., Amsterdam. This book has lots of basic and advanced theory on high pressure mercury lamps, some of which is applicable to other types of HID lamps.

Another is "Electric Discharge Lamps", by John F. Waymouth, available from MIT Press.

After finding these books, you may want to look into others with similar call numbers. Using the Library of Congress system, look into everything with numbers around TK4000.

2. What are low and high pressure lamps?

In a high pressure lamp, the average kinetic energy of free electrons (also known as electron temperature) is only slightly higher than the temperature of the gas in the discharge. Both temperatures are similar, and one can refer to a general temperature of the discharge. The

electron temperature is higher in order for the electrons to have the net effect of transferring energy to the gas.
It is quite fair to think of the gas or vapor as a thermal radiator, which is usually spectrally selective and radiating mainly in specific spectral lines.
Typically, the discharge diameter is over 50 times the mean free path of an electron. There is generally no non-thermal, non-optical, non-mechanical interaction between the discharge and any container it is in, except at the ends of the discharge.
In order to efficiently produce light, the power input must be much greater than the heat conduction from the discharge, which is usually near or over 10 watts per centimeter of discharge length. Therefore, power input to a high pressure lamp is usually near or over 20 watts per centimeter of discharge length.
The above can all be satisfied even if the pressure is less than 1 atmosphere. It can even be satisfied in a nearly practical lamp with a pressure of .1 atmosphere.
High pressure lamps are often referred to as High Intensity Discharge Lamps, or HID lamps.

In a low pressure lamp, the electron and gas temperatures are very different, and the pressure is generally below .05 atmosphere. Power input is generally near or less than 1 watt per centimeter.

2a. What's in a low pressure mercury or sodium lamp?

In a low pressure lamp with mercury or sodium vapor as an active ingredient, the metal vapor is mixed with an inert gas, often neon or argon. The metal vapor's pressure is usually well under 1/1000 atmosphere, or a fraction of a mm. of Hg. The mixture is generally 1 percent or even as little as .1 percent metal vapor, 99 to 99.9 percent inert gas.
The desired spectral output generally results from atomic transitions that terminate in the atom's "ground" or unexcited state. This means that most of the metal vapor atoms, since they are not excited, can easily absorb this radiation. Therefore, you don't want too much metal vapor. The inert gas largely determines electrical characteristics, mainly by controlling the mean path traveled by electrons between collisions. The gas also reduces collisions of electrons, ions, and excited metal vapor atoms into the lamp's walls.

2B. How do lamps with 1 percent or less metal vapor produce only or mainly metal spectral output?

The excited states of the metal vapor atoms are mainly, usually entirely at lower energy levels than those of the inert gas atoms. Free electrons in the lamp with enough kinetic energy to excite anything generally only have enough to excite the metal vapor atoms.

3. Negative resistance and why you need a ballast to limit current

In a high-pressure lamp, if current increases, the arc gets hotter. This tremendously increases the concentration of ions and free electrons, making the arc that much more conductive. The conductivity of the arc increases enough that the voltage across the arc usually stays about the same or even decreases if the current is increased.

In a low-pressure lamp, a variation of this causes the same thing. If you double the current, you usually roughly double the concentration of excited gas atoms and free electrons. The concentration of ions must match that of free electrons but each excited atom is bombarded twice as much by free electrons (remember, there are twice as many electrons around for an excited atom to see). The average kinetic energy of the free electrons must decrease so that ion concentration is also only roughly doubled. To get slower free electrons, the electric field in the discharge (and voltage across the discharge) must decrease.

In either case, it is not a good idea to connect the lamp directly to a voltage source. Once the lamp starts conducting, increasing current will increase the lamp's conductivity, allowing more current to flow. This process does not level off until one of the following happens:

1. A large fraction of easily ionizable atoms are ionized,

2. The concentration of ions/free electrons is so high that more of these somehow impairs mobility of free electrons,

3. The power supply's or wiring's limitations limit the current.

At this point, the current is usually around or over 100 amps or so, and will likely blow fuses/pop breakers, and is certainly not good for the lamp.

The term "negative resistance" refers to a decrease in voltage across the lamp resulting from an increase in current through the lamp.

4. Why the light from many discharge lamps makes red things look dull

Mercury lamps, most metal halide lamps, most sodium lamps, and "cool white", "white", and "warm white" fluorescent lamps have a shortage of red and green light in their spectral output. These lamps also have a surplus of yellow and/or orange-yellow. Since red plus green looks yellow, taking away red and green and adding yellow do not affect how the lamp's color looks. Nearly all yellow objects reflect red, orange, yellow, and green. Increasing yellow output and decreasing red and green does not change how yellow objects look.
However, red objects generally reflect mostly just red light. With the shortage of red light, these look darker. If they are not pure red in color, they will not only look darker but also less red in color.
Unphosphored (clear bulb) high pressure mercury lamps are especially bad at this, since they make very nearly no red light at all.
This is not a problem with most compact fluorescent lamps, most 1-inch diameter 4-foot lamps, and other fluorescent lamps that have "rare-earth" phosphors. These phosphors, unlike those in older formula fluorescent lamps, produce a strong, narrow orangish red spectral band and a strong, somewhat narrow, slightly yellowish green one, with little in between. Under these lamps, reds usually look near normal, or slightly orangish, or slightly excessively bright. Greens often also look slightly brighter under these lamps than under old formula "cool white" and "warm white" fluorescent lamps.

5. Why photos taken under discharge lamps often look blue-green

The problem here is the fact that film and human eyes have different spectral response. Human eyes are quite sensitive to the short wave end of the red range of the visible spectrum, but not to the long wave end. Most color film responds about the same to shorter and longer red wavelengths.
Most of the red light from fluorescent lamps, metal halide lamps, sodium lamps, and phosphored mercury lamps is of shorter red wavelengths. These lamps do not emit much of

the longer red wavelengths. This maximizes red sensation by the eye for a given amount of actual light. Producing less-visible longer red wavelengths detracts from maximizing luminous efficacy of the lamp, so this is minimized.
Therefore, lamps make a surplus of red wavelengths to which the eye is more sensitive than film is, and a shortage of the red wavelengths to which film is more sensitive than human eyes. This results in the film seeing red less than human eyes do, and this makes photos look blue-greenish.

6. Arc and glow discharges explained!

Electrons normally don't just move or flow from a conductor into a gas. Something has to make this happen. Explained below are ways for this to happen.

In a glow discharge, positive ions bombarding the cathode dislodge electrons from the cathode material. There is a substantial electric field near the cathode that accelerates ions toward the cathode to make this happen. The whole process tends to complicate itself, resulting in a double layer of glow around the cathode, thin dark spaces underneath and between these layers, and a more substantial dark space between all of this and either the anode or the main body of the discharge, whichever comes first. In neon glow lamps, the anode is so nearby that no main discharge body occurs.
"Neon" signs are longer, so a main discharge body occurs. Since these operate on AC, each end has a significant dark space only half the time, so these regions are a bit dim rather than dark.
There is generally a natural current density in the cathode process, generally around a milliamp to .1 amp per square centimeter, depending on the gases involved, the pressure thereof, and the cathode material. A glow discharge at this intensity is a "normal glow".
Decreasing the current causes the cathode's glowing layers to cover only part of the cathode. In this case, the glow often moves around, causing a flickering effect.
If the current is more than enough to cause the cathode to be covered with glow, (or if the glowing layers are forced into a thinner layer of space than they normally use), abnormal glow results. The voltage drop of the cathode process (this voltage is known as the "cathode fall") will be higher than normal. This causes ions to bombard the cathode harder than usual. This increases "sputtering", or dislodging of cathode material atoms. Sputtering effectively "evaporates" cathode material and often causes darkening of the lamp's inner surface.
Sputtering occurs more easily at higher cathode temperatures. It is generally recommended to neither have significantly "abnormal" glow nor significant temperature rise in the cathode, and especially not both of these combined.

The cathode fall of normal glow is usually 50 to 90 volts for neon, argon, krypton, xenon, or mixtures including significant amounts of any of these gases. Some metal vapors may have somewhat lower cathode falls. Nitrogen and some other gases have high cathode falls usually near or even well over 100 volts.

The cathode process in most HID lamps and fluorescent lamps is the thermionic arc. In this process, at the proper high temperature, some material in the cathode fails to keep a grip on its electrons. Therefore, electrons simply flow from the cathode to the gas. The cathode fall is usually around 10 volts, and the heat dissipated in this process keeps the cathode hot enough to let electrons flow from it to the gas.
The current density at the cathode process of a thermionic arc is generally in the tens or hundreds of amps per square centimeter of active cathode surface, but can occaisionally be as

low as around an amp per square centimeter if a heat source other than the arc heats the cathode.

Another arc process is the cold cathode arc. In this process, ions bombard the cathode material and dislodge electrons from it. This seems similar to the glow discharge, but the effect is quite different. The current density in the cathode process is usually hundreds or thousands of amps per square centimeter. The cathode fall is usually near the ionization potential of the cathode material or the main active gas ingredient, whichever is lower (for a minimum) to twice whichever is higher (for a maximum). Substantial sputtering may occur, especially if the cathode is hot. Cold tungsten is usually reasonably tolerant of this, permitting the use of this process in xenon flashtubes.

An arc is often not entirely thermionic nor cold-cathode, but one of these processes is usually dominant.

If a hot-cathode lamp is underpowered, the cathode is not as able to emit electrons by the thermionic process, and significant cold-cathode arc process may occur. This can cause excessive sputtering. Starting a hot-cathode lamp also results in some of this as the cathode warms up. Overpowering a hot-cathode lamp can simply overheat the cathodes.
Because of this, it is generally advised to start fluorescent and HID lamps as infrequently as practical and to neither overpower nor underpower them. This makes it difficult to dim fluorescent and HID lamps significantly without being hard on their cathodes.
There are some special dimming ballasts for some fluorescent lamps. These dissipate power into the cathodes to maintain a workable thermionic process when these lamps are dimmed. It is recommended to only dim fluorescent lamps with appropriate ballasts, and to use these dimming ballasts only with the lamps they were designed to safely dim.

7. What do high-pressure sodium lamps have?

One thing these lamps have is a mixture of mercury and sodium, rather than just sodium. If only sodium was in these, the voltage across the lamp would be excessively low. Making the arc tube longer to increase voltage drop would also increase the watt-per-centimeter loss (explained below in section 8). A higher sodium vapor pressure would also increase the voltage drop, but would broaden the sodium's emission band to the point that much of the spectral output is nearly infrared. This detracts from maximum most-visible light output.
Also, a mercury-sodium mixture conducts heat less than pure sodium vapor. This reduces thermal conduction of energy away from the arc (The watt-per-centimeter loss).
Another thing: Hot sodium is very highly chemically reactive. Some of the sodium is lost as the lamp ages, either permeating through the arc tube or chemically becoming part of it. Therefore, a surplus of sodium is included in the arc tube. The sodium vapor pressure is controlled by the temperature of the "amalgam reservoir(s)" of the arc tube, where any unevaporated mercury and sodium reside. Proper lamp operation depends on the amalgam reservoir(s) being at or near a proper temperature.

7a. Why do aging sodium lamps sometimes cycle repeatedly on and off?

The sodium vapor pressure is controlled by the temperature of the amalgam reservoirs at the ends of the arc tube. As the lamp ages, the ends of the arc tube get darkened, and they absorb light. This makes them hotter. Therefore, the amalgam reservoirs get hotter. This increases the sodium vapor pressure in the arc tube, leading to different electrical

characteristics. When this effect becomes excessive, the arc in the arc tube goes out. The arc tube must cool before the vapor in it is thin enough to restrike an arc.
Aging sodium lamps sometimes repeatedly turn on and off as the ends of the arc tubes overheat, then cool off once the arc goes out. If a high pressure sodium lamp repeatedly turns on and off, replacing the bulb with a new one is usually all that is needed.

8. Thermal Conduction from High Pressure Arcs, the Watt per Centimeter Loss

When energy is dissipated into an arc, it largely leaves the arc by three mechanisms:

1. Some is used by the cathode and anode fall mechanisms getting electrons from metal to arc and vice versa. Nearly all of the energy here ends up heating the electrodes. The anode fall is not always significant, the cathode fall usually is. 2. Thermal conduction removes energy from the main body of the arc. This ends up heating the arc's surroundings and any container or arc tube.

3. Whatever energy enters the body of the arc (not lost in electrode falls) and not thermally conducted from the arc is radiated.

Of course, it is desirable to minimize (1) and (2) and to maximize (3).

The electrode falls are generally a fairly constant voltage. Designing the main body of the arc to have more voltage across it (higher voltage drop) and use less current reduces the electrode losses.
However, there is a limit to practical arc voltages, since higher voltages may require complicated equipment to supply them, and also higher pressure.

The thermal conduction loss is a major loss in many high intensity discharge lamps, especially ones of lower wattages.
This loss varies with arc temperature, gas and vapor type, and is largely linearly proportional to the length of the arc. However, this loss usually does not vary much with the arc's diameter nor with the gas pressure. Often, especially in mercury vapor lamps, the arc temperature is surprisingly constant, and this leads to a surprisingly constant thermal conduction loss from the arc, in watts per centimeter of arc length. This loss increases if the arc tube size and/or gas pressure are great enough for convection to be significant, and the nearly constant degree of this loss applies to typical general purpose HID arcs that are many times longer than they are wide. The loss is different for the nearly spherical arcs in some special HID lamps.
For typical mercury vapor lamps, the thermal conduction loss is generally around 10 watts per centimeter. For high pressure sodium lamps, this loss is less constant but generally near 10 watts per centimeter. This loss can vary with the ratios of the mercury-sodium mix since sodium vapor conducts heat more than mercury vapor does. For metal halide lamps, this loss is less constant and generally greater (in watts per cm.) due to convection in the short, wide arc tubes that are filled to a very high pressure.
The watt/cm. loss could be reduced by:

1. Using a shorter arc. This requires a higher pressure for the same arc voltage. Also, the parts of the arc tube within one tube radius of the electrodes are subjected to being darkened by evaporated/sputtered electrode material, so it may not pay to have an arc length shorter than a few times the arc tube diameter. Reducing the arc tube diameter would help this, but a skinnier

arc tube will get hotter from the same watts of heat per centimeter. All of this combined impairs the design of economical miniaturized HID lamps.

2. Fill the arc tube with a less thermally conductive material. Such materials have larger and/or heavier molecules. Heavier molecules move more slowly, larger size ones don't go as far between collisions. This favors use of mercury and xenon as HID lamp ingredients.
Low-heat-conductivity gases and vapors should be gaseous at reasonable arc tube temperatures, chemically stable or inert at all temperatures from below freezing to the arc temperature, and not have major infrared or ultraviolet emission lines that detract from efficiently radiating visible light. This largely disqualifies polyatomic substances and the vapors of heavier alkali metals.

For more information on this, look in the Elenbaas book mentioned above.

8a. Why is the temperature of a mercury arc so constant?

The amount of energy radiated from a "blackbody" (the ideal thermal radiator) is proportional to the fourth power of the radiator's temperature. Or, the temperature is proportional to the fourth root of the amount of power being dissipated into the radiator.
Now, for two properties of high pressure mercury vapor that favor a more extreme radiation-vs.-temperature relationship.

1. Mercury has major ultraviolet lines at wavelengths shorter than those most favored by typical mercury arc temperatures. Increasing the temperature shifts the spectral output towards shorter wavelengths, causing radiation at these wavelengths to increase by more than the 4th power of the temperature.

2. Except in the shortest two major ultraviolet lines, the emissivity of mercury vapor in its spectral lines increases with temperature. This causes the mercury to radiate almost as well as a blackbody at its main emission wavelengths if the temperature is high enough, and not radiate nearly as well as a blackbody at lower temperatures. The result: radiation varying more dramatically than temperature to the 4th power.
Why emissivity in these spectral lines varying with temperature? Because the lower of the two electron orbits (energy levels) used to radiate these lines are elevated orbits, not the "ground state" (unexcited state). The mercury atom must be excited just to elevate an electron into the lower level of transitions responsible for all major spectral lines except two short-wave ultraviolet ones. This is also why mercury vapor tends to have no absorption lines except the two shortwave UV ones.

With radiation increasing very dramatically with a slight increase in arc temperature, and decreasing dramatically with a slight decrease in arc temperature, it is easy to see why mercury arcs have a nearly constant temperature in most cases. This temperature is around 5500-5900 Kelvin.

Many other substances do the same thing, but typically don't regulate the arc temperature to the degree that mercury vapor does. For example, sodium's main yellow emission line is at a wavelength slightly shorter than most favored by a typical sodium arc temperature, and high pressure sodium lamps also have significant spectral lines resulting from transitions between elevated electron orbits. High pressure sodium arcs are not as constant in temperature as mercury arcs, with arc center temperatures generally in the low to mid 4,000's degrees Kelvin.

9. Why lamp voltage cannot exceed approx. 3/4 of line/open-circuit voltage

Here's why: (Example using a simple choke or inductor or "reactor" ballast)

Suppose you have the lamp and the choke in series, powered by a variable current source, as opposed to a variable voltage source. Suppose you had optimum cathode heating regardless of current through the lamp. Due to the "negative resistance" characteristic most gas discharges have, the voltage across the tube will increase as current is decreased. In fact, there will be a point at which the combined tube-ballast voltage is minimized. This has some voltage across the choke ballast, meaning the voltage across the lamp is less than the line voltage.

The minimum line voltage to work at all is typically approx. 1.2 to 1.25 times the lamp voltage. For reasonably good, stable and reliable operation, the voltage across the lamp should generally not exceed approx. 2/3 of the line voltage.
With a "high-leakage-reactance transformer" ballast, the lamp voltage needs to be correspondingly less than the "open circuit" (no load) output voltage of the transformer.

10. What's with those aquarium metal halide lamps of extreme color temperature?

Every so often, someone gets the idea that the arc temperature in a metal halide lamp is about the same as the color temperature. That is not true. The arc temperature is almost always in the 4200 to 5400 Kelvin range. The color temperature merely indicates the temperature that a "blackbody" (ideal thermal radiator) must be to glow with the same or closest-possible color. The color of a metal halide lamp depends on what metals are used in the metal halides (usually iodides) and how much halide vaporizes. Lower color temperatures in the 3000 to 3500 Kelvin range indicate orange-yellowish shades of white, and the vapor in these lamps is rich in sodium but also has smaller traces of scandium and sometimes thallium. Most metal halide lamps contain sodium and scandium halides and have a color temperature near 4100 Kelvin (basically plain white). Some have less sodium and more scandium, and sometimes also other more blue-glowing metals like indium, and therefore have a more blue color. I have seen some metal halide lamps that seemed to have more indium than any other metal in halide form, and these were more blue in color. I have heard of metal halide lamps with color temperatures as high as 20,000 Kelvin - and this is not hard to do even with an arc temperature well below 5500 Kelvin.
Indium-rich metal halide lamps are sometimes used to illuminate aquariums that have live coral, since coral needs deep-blue wavelengths for proper health.

11. Why do some fluorescent lamp starters and neon lamps need light to start?

A few people get annoyed at fluorescent lamps that refuse to start unless some light hits the fixture. Why should there be a light that refuses to turn on when it is dark?

Here is the explanation. These fluorescent fixtures have starters. The starter is usually of the "glow switch" type. The glow switch starter is a glow lamp with a bimetal strip for one electrode. The bimetal strip changes shape as it heats up, and contacts the other electrode and temporarily becomes a short circuit. For more information on fluorescent lamp circuits, go to the Fluorescent Lamp General Info Page.

But why the light sensitivity? The glow lamp in the starter may be hard to ionize at normal line voltage. Sometimes light hitting the electrodes of the glow lamp can help via the photoelectric effect. Light hitting the electrodes can dislodge or at least loosen a few electrons of the electrode material's atoms. Some starters have holes in them, which let stray light in to help.

Some starters have been made with easier-ionizing gas in them, but have been prone to ionizing too easily. They ionized instead of the fluorescent tube at times when the tube should have struck. Other starters have had radioactive material in them to assist starting, but many people do not like radioactive things around them.

Some neon lamps do this also, normally when they have aged past their expected life. This is usually a characteristic of "high intensity" neon lamps such as NE-2H, which have a reddish orange color and are filled with pure neon. The electrodes are coated with material favorable to a glow discharge, but the electrodes wear out and either higher voltage or the photoelectric effect is needed to make them start. These lamps often flicker when there is light and stay out when it is dark. Neon lamps with a neon-argon mixture start more easily, but are dimmer. They have a non-reddish orange color. They usually work reliably until they are too dark from sputtered electrode material to be useful.

If you replace a neon lamp, be sure that the dropping resistor for an NE-2H is at least 33K ohms for use with 120 volts AC. It is common to use 22K for more light, but this compromises the life of the NE-2H. If you replace an NE-2H with an NE-2 (easier starting), be sure to use a much higher dropping resistor, at least 150K ohms and preferably at least 180K for use with 120 volts AC. Light output will be low.

Back up to Don's Main Lighting Page.

Back up to Don's Home Page.

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