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Germicidal:

Lamp Operation

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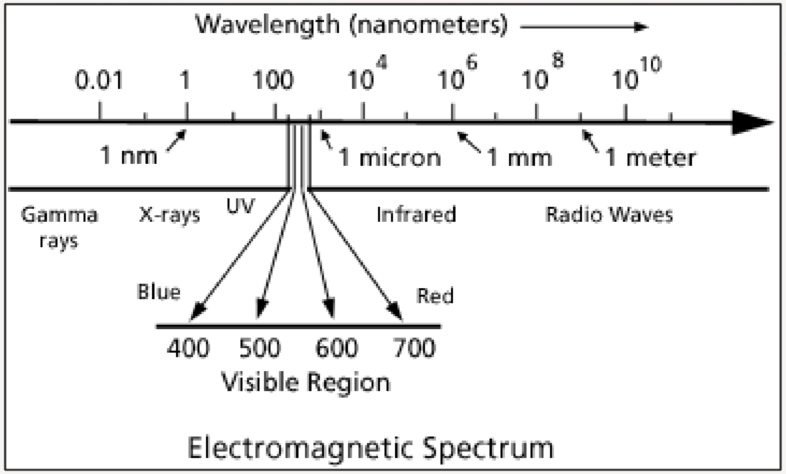
Agenda

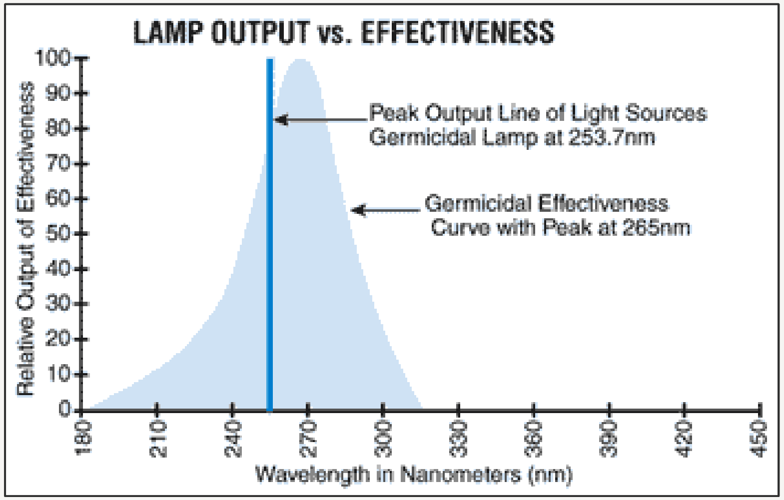
- ***Recall:*** What is a germicidal lamp?
- The lamp body
- In the beginning was the electron…
- Anatomy of the discharge
- Lamp voltage
- Power balance
- End loss
- 254nm radiation
- 185nm radiation
- Mercury vapor pressure & mercury vapor pressure control
- The cold spot

What Is A Germicidal Lamp?

Simple: It’s a device to convert electricity into ultraviolet radiation.

- Microorganisms are sensitive to a band of ultraviolet radiation peaking at 260 nanometers (nm)*.
- Low-pressure/mercury-rare gas lamps can convert up to 40% percent of the supplied electrical power into 254 nm radiation.
- However, the term *“up to”* can hide a long list of qualifications, compromises and limitations.

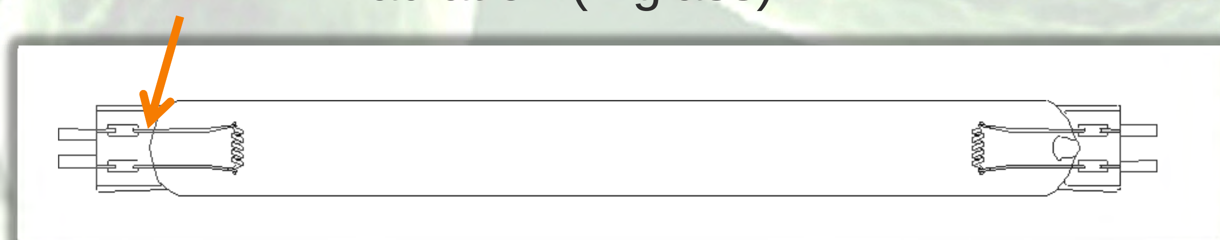




* 1 nanometer is 1 E-9 meter

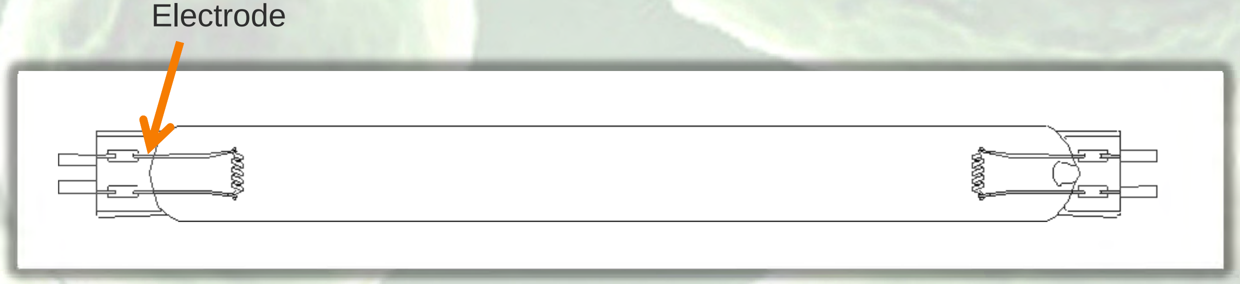
The Lamp Body

- Germicidal lamps are low-pressure, mercury/rare-gas discharge devices similar to fluorescent lamps. This is true in both operation and construction except for the lack of a phosphor coating on the inner lamp wall.
- The Lamp body may be made of pure fused-quartz that will transmit both 254 and 185nm radiation (VH glass), quartz with Titanium added to block out most of the 185nm radiation (L glass) or of a “soft” glass formulated to transmit 254nm radiation (L glass).

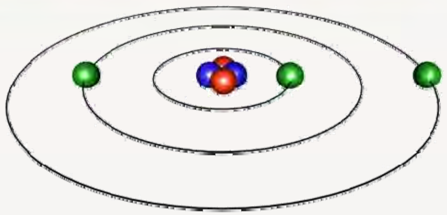


The Lamp Body

- Electrodes at each end of the lamp connect the external current source to the gas discharge itself. Each will serve alternately as anode or cathode when the lamp is run on alternating current as it is in almost every instance.
- The body may be filled either with pure Argon or with a mix of rare gasses including Argon, Neon and/or others depending on the application. There is also a small amount of mercury in the lamp necessary to provide the ultraviolet radiation.

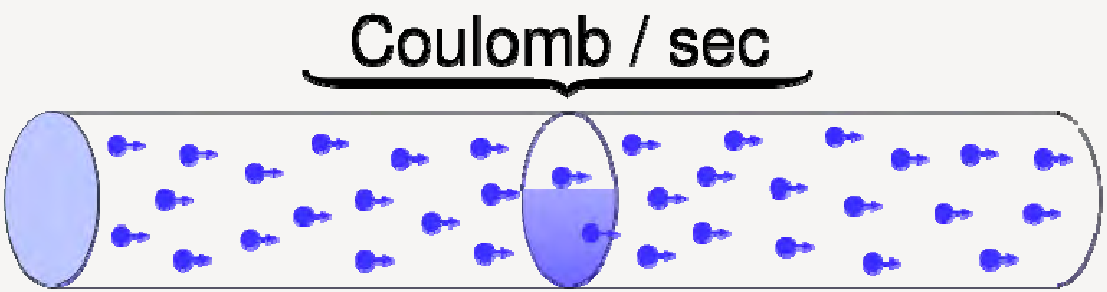


In The Beginning Was The Electron…



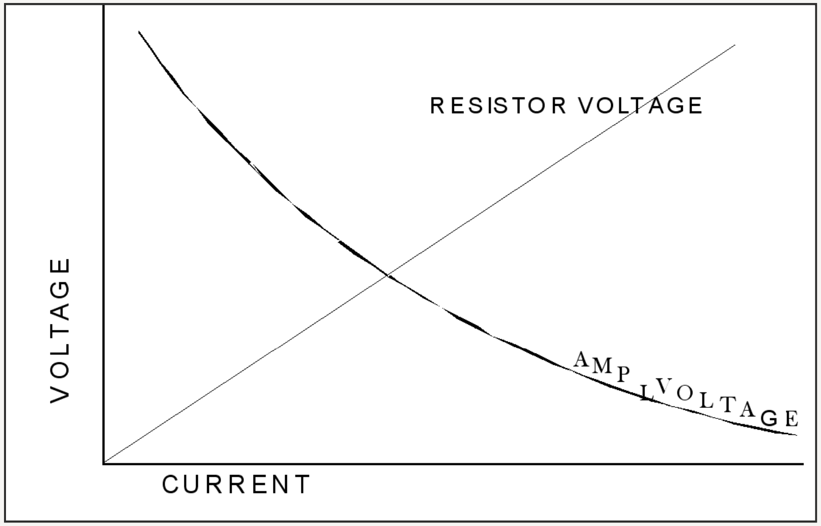
… not really but it's a good place to begin!

- The motion of electrons **(e-)** ultimately defines the familiar electrical units like Volts and Amperes. The most basic electrical unit is an unfamiliar one: the **Coulomb**.
- The **Coulomb** is the unit of electrical charge. It's defined in the number of (e-) moved to in order to plate out a specific weight of silver[1], all other units are defined in terms of the Coulomb.
- An electron flow rate of one Coulomb per second is an **Ampere**.



In The Beginning Was The Electron…

- The electrical potential difference needed to maintain a current of one Amp through a one-Ohm resistor is one Volt.
- A current of one Amp through a one-Ohm resistor will result in a potential difference of one Volt across the resistor.
- The voltage across a resistor (E) will rise with increasing current (I) according to **Ohm's law: E=IR**.
- Unfortunately, this is not true for germicidal lamps or other low-pressure lamps.



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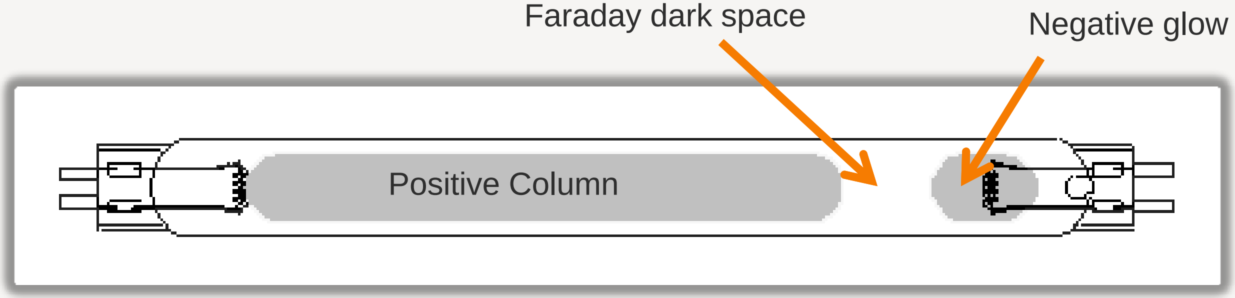
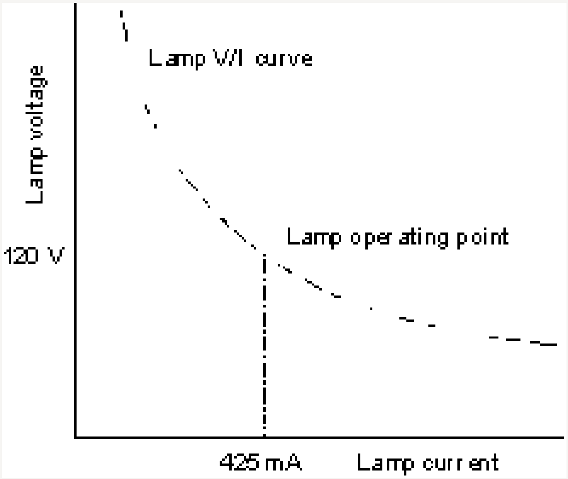
Anatomy Of The Discharge

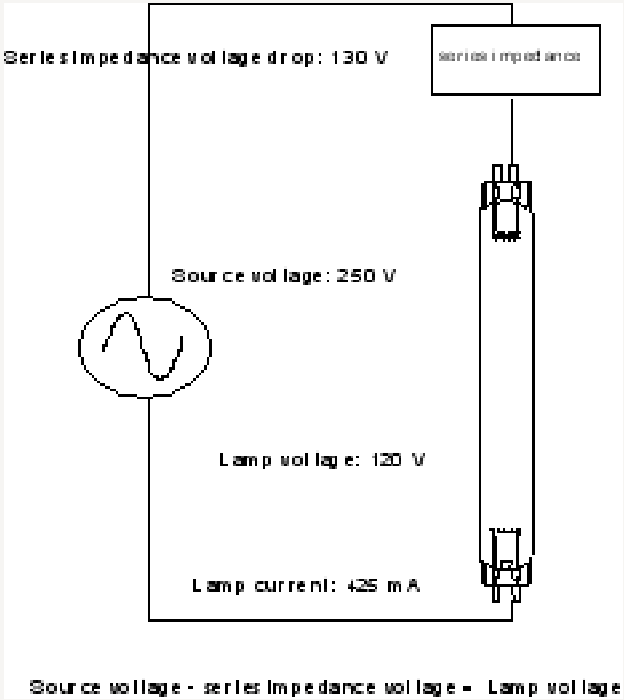
- Lamp body is filled with the positive column of the discharge. Most, if not all lamps, are operated on **alternating current**. For all practical purposes this is how the situation can be viewed.
- However, if a lamp would be operated on **direct current** it would be seen that the discharge has several distinct sections, the positions of which are dependant on the direction of current flow in the lamp.
- With **alternating current** operation either at line frequency or from a high-frequency electronic ballast, the sections switch positions faster than can be seen, giving the appearance of a **continuous discharge**.



Lamp Voltage

- Low-pressure mercury/rare-gas lamps rely on the motion of (e-).
- Like a resistor, the **voltage** across the lamp is dependant on the current flow, but unlike a resistor whose voltage rises with increasing current, the lamp voltage falls with increasing current.
- Lamps are not designated by voltage (like an incandescent lamp) but rather by operating current.
- There aren’t any 120V-rated germicidal lamps, but there are 425 mA.-rated lamps that run at 120 V.





Power Balance

- Germicidal lamps are current-driven devices. The operating voltage is determined by both the design of the lamp as well as the ballast.
- Ballasts serve two purposes:
  - to provide enough voltage to break down the rare-gas contained in the lamp
  - to limit the current flow through the lamp
- For some lamps, the ballast also needs to provide heat to the electrodes at the lamp ends.
- In order to meet various customers needs, new lamp platforms have been developed to provide **higher ultraviolet power levels** in either the same or smaller packages.
- This increase of power density comes at a price - high power density lamps are unavoidably less efficient than their lower powered relatives.

Power Balance

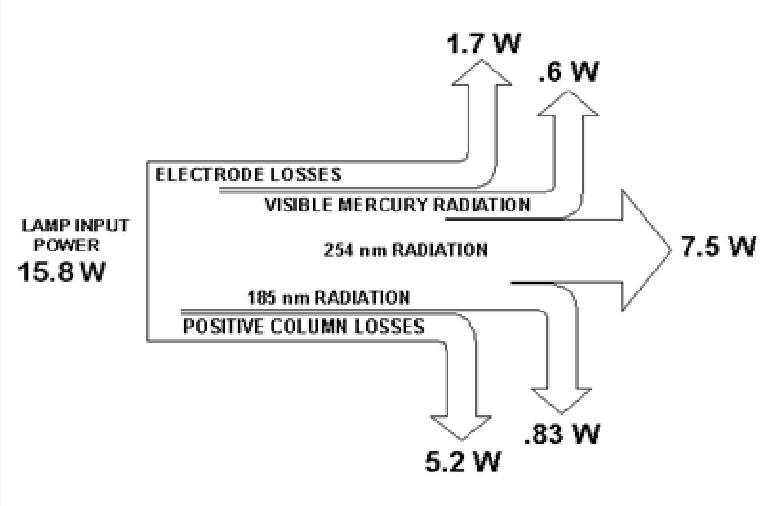
- To understand limitations of germ lamp technology we need to compare lamps on an equal basis. Hence, we need an understanding of where the electrical power goes.

***No* device is 100% efficient.**

- Within lamp, electrical power is lost through various outlets:
  - Power is turned into waste heat at the ends
  - Power is turned into waste heat in the gas discharge itself
  - Power is turned into waste heat on the inside wall

Power Balance

- Let's consider **End losses** first in lamp comparison:
  - For lamps operated in the same manner, with the same basic construction, the end losses will be the same regardless of length.
  - A 1.5 meter long lamp operated on an electronic ballast at 425 mA and consuming 65 Watts, and a .5 meter long lamp operated the same way, consuming 23 Watts will have the same end losses: about 1.7 Watts.
  - If operated on magnetic ballasts the end losses will more than double. So for a short lamp the end losses are a bigger fraction of the input power as compared to the long lamp.

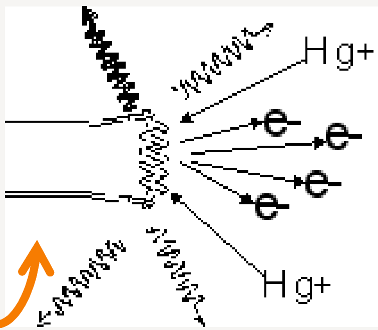


***Short* lamps are therefore less efficient than *long* lamps.**

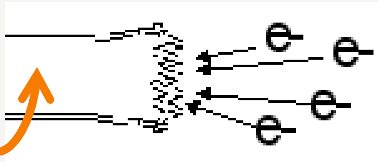
End Loss

- When electrode operates as a cathode on ½ of the current cycle, it emits $\mathbf{e}^-$ into the discharge. In a hot cathode lamp the $\mathbf{e}^-$ are effectively “boiled” out of the coil due to it’s elevated temperature. Most of the heat is from mercury ions impacting the cathode from the discharge as the $\mathbf{e}^-$ are being emitted.

Waste Heat



Cathode Half-Cycle



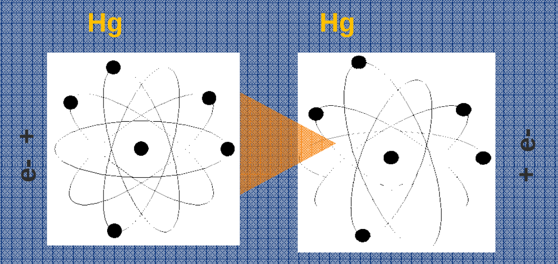
Anode Half-Cycle

- When electrode operates as anode on the other half cycle, the only happening: $\mathbf{e}^-$ are impacting the surface. At 60 Hz operation the $\mathbf{e}^-$ carry enough energy to add heat to the electrode. At high-frequency (10 KHz. And above) the $\mathbf{e}^-$ carry little energy and add negligible heat.
- None of power that ends up as cathode heat directly contributes to the generation of UV radiation. That is why **power** transferred to the electrodes is considered **“lost”.** Modern hot cathodes and high frequency ballasts are designed to minimize the end losses.

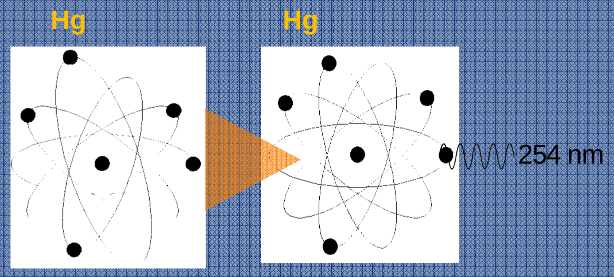
Generation Of 254nm Radiation

- The actual process of converting electricity to UV radiation takes place in the space between the electrodes, the so-called **positive column**[1].
- Mercury atoms are excited by collisions with **e⁻** flowing from the electrodes. Mercury atoms release acquired energy as **photons**.
- Increasing current will increase output – only to a point. Lamp output might stop increasing and even begin to fall.
  - Lamp is overheating, **e⁻** loose ability to effectively excite mercury atoms.
  - Excited mercury atoms are ultimate engines that transform electricity to 254 nm radiation.

e^- collision with ground-state mercury atom transfers energy to the atom exciting the atom and losing kinetic energy.



Excited atom "relaxes back to ground state emitting a photon.

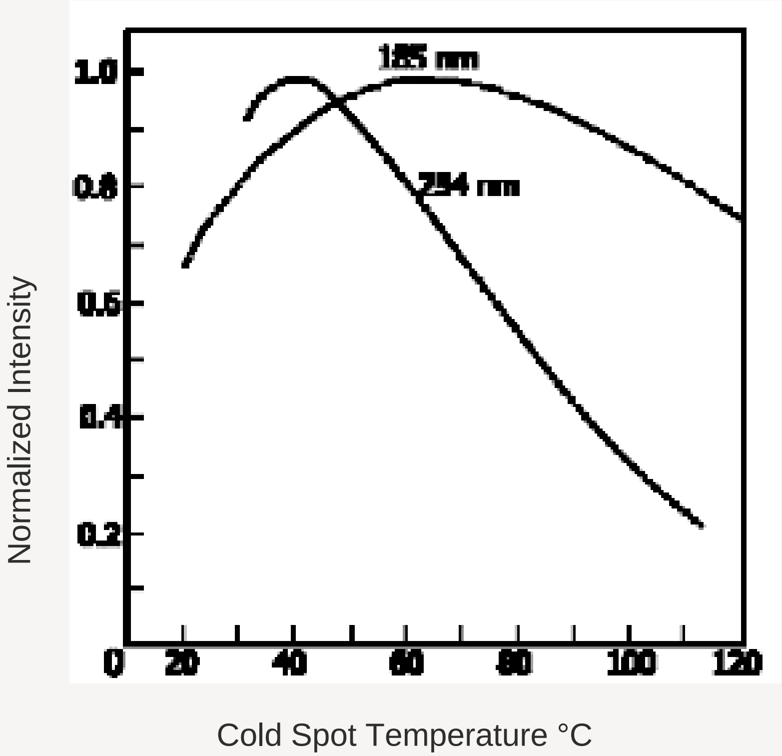


[1] Simplified explanation

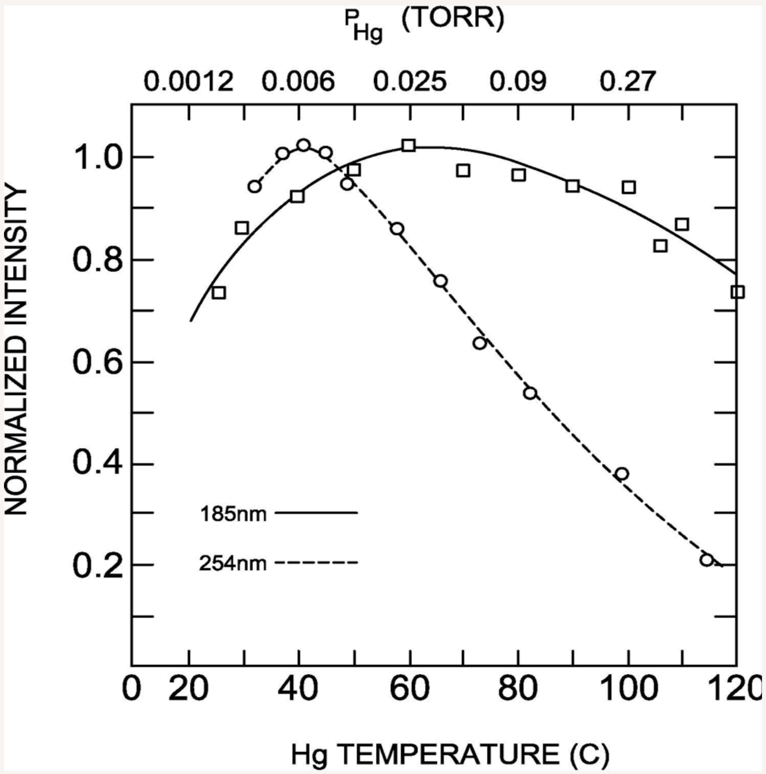
Generation Of 185nm Radiation

- In a **“nominal” germicidal lamp** (13 mm ID; Fill gas =Argon; GP = 3 Torr) operated at 425 mA, the 185nm radiation output is approximately 10% of the rated 254nm output.

- If the fill gas composition, pressure, operating current, or lamp temperature are changed this ratio can be raised or lowered.



Optimum Mercury Vapor Pressure



- The concentration of mercury atoms in the discharge (the mercury vapor pressure) must be controlled in order to optimize the conversion of electrical power to UV radiation.
- The lamp will produce its maximum output when the mercury vapor pressure is approx. 6 microns (.006 Torr).
  - At **low vapor pressures** the lamp output is low since there aren't many atoms available for the **e$^-$** to excite!
  - At **high vapor pressures**, the majority of available atoms are in the ground state (not excited) and can absorb whatever 254nm photons are produced.

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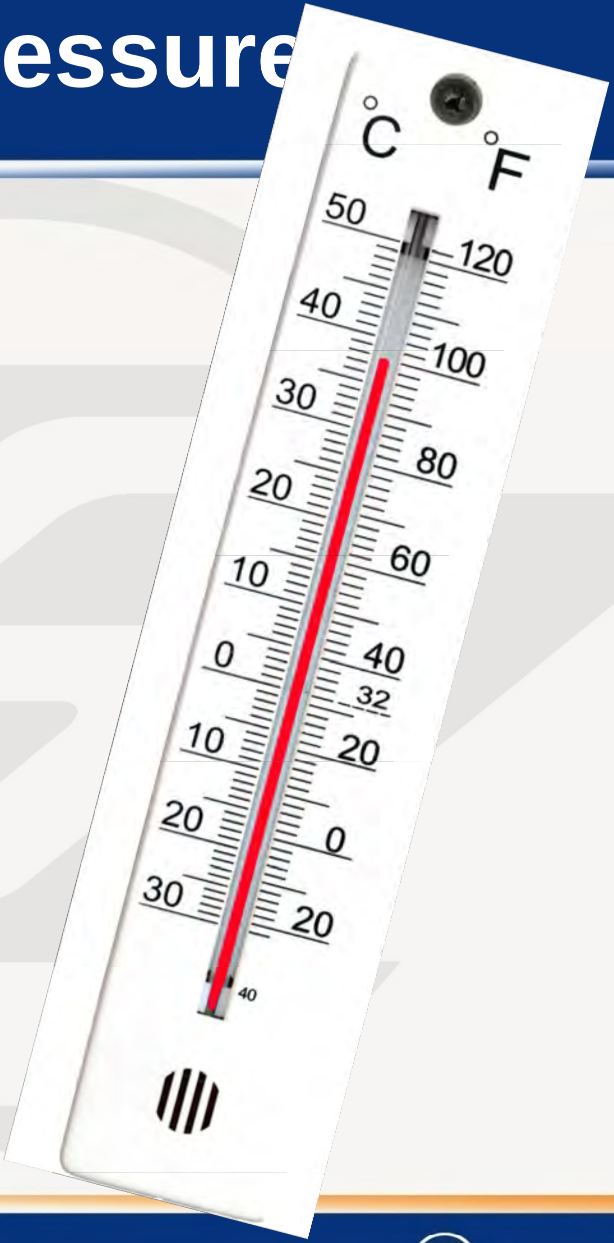
Opium Mercury Vapor Pressure

- During operation, a lamp may be **25º C** or more above ambient over most of it's surface.

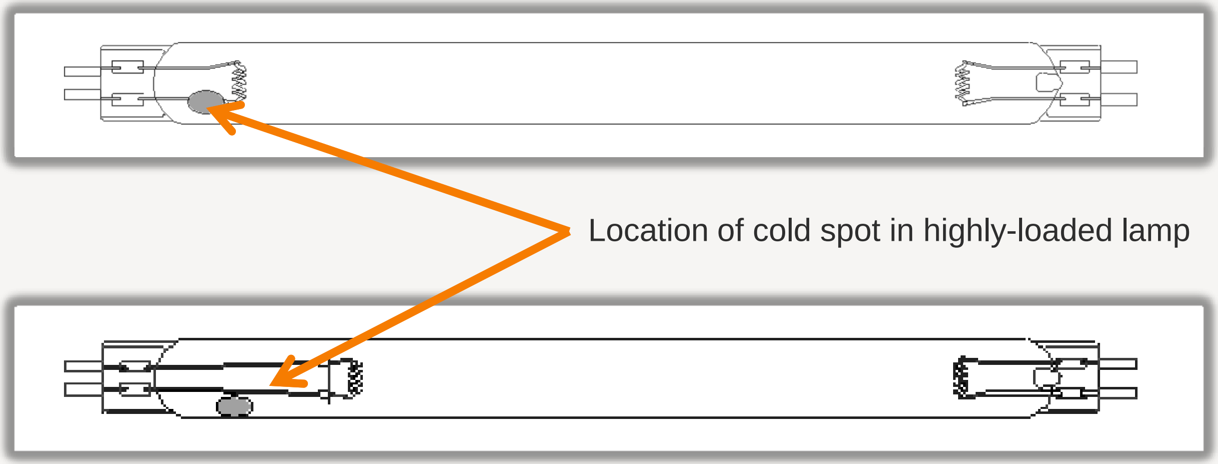
- The lamp will produce its maximum output when the mercury vapor pressure is approx. 6 microns (.006 Torr or about 8 millionths of one atmosphere). This is the pressure over liquid mercury at a temperature of **45º C**.



The Cold Spot

Only 1% of the lamp surface needs to be held at 25º C – this is when the lamp will produce it’s maximum output.

- **Lightly-loaded lamps:** no definite cold spot (still air operation)
- **Highly-loaded lamps:** Cold spot behind cathode in region shielded from positive column. Now temperature of cold spot dependant on: The infrared radiation falling on it from (1) the inner wall of the lamp, (2) the positive column directly, and (3) the filament. One filament may also be mounted on extended leads to provide for more isolation from filament heat.



Mercury Vapor Pressure Control

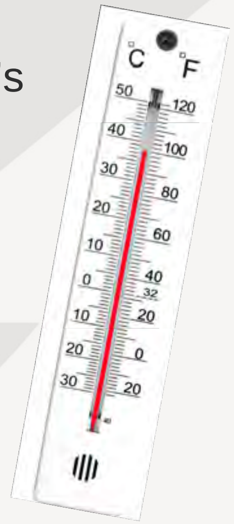
One way to **control mercury vapor pressure** is to incorporate an amalgam into the lamp structure:

- Amalgams are alloys of mercury and other metals such as indium, lead or zinc and can be formulated to act as a reservoirs for mercury
- Amalgams release only enough mercury to hold mercury vapor pressure
- Ideally, the amalgam lamp design will stabilize the lamp mercury vapor pressure in the so-called 90/90 region (optimum operation)
- The range of bulb wall temperatures where the lamp output drops to for no more than 90% of it's 20ºC value.

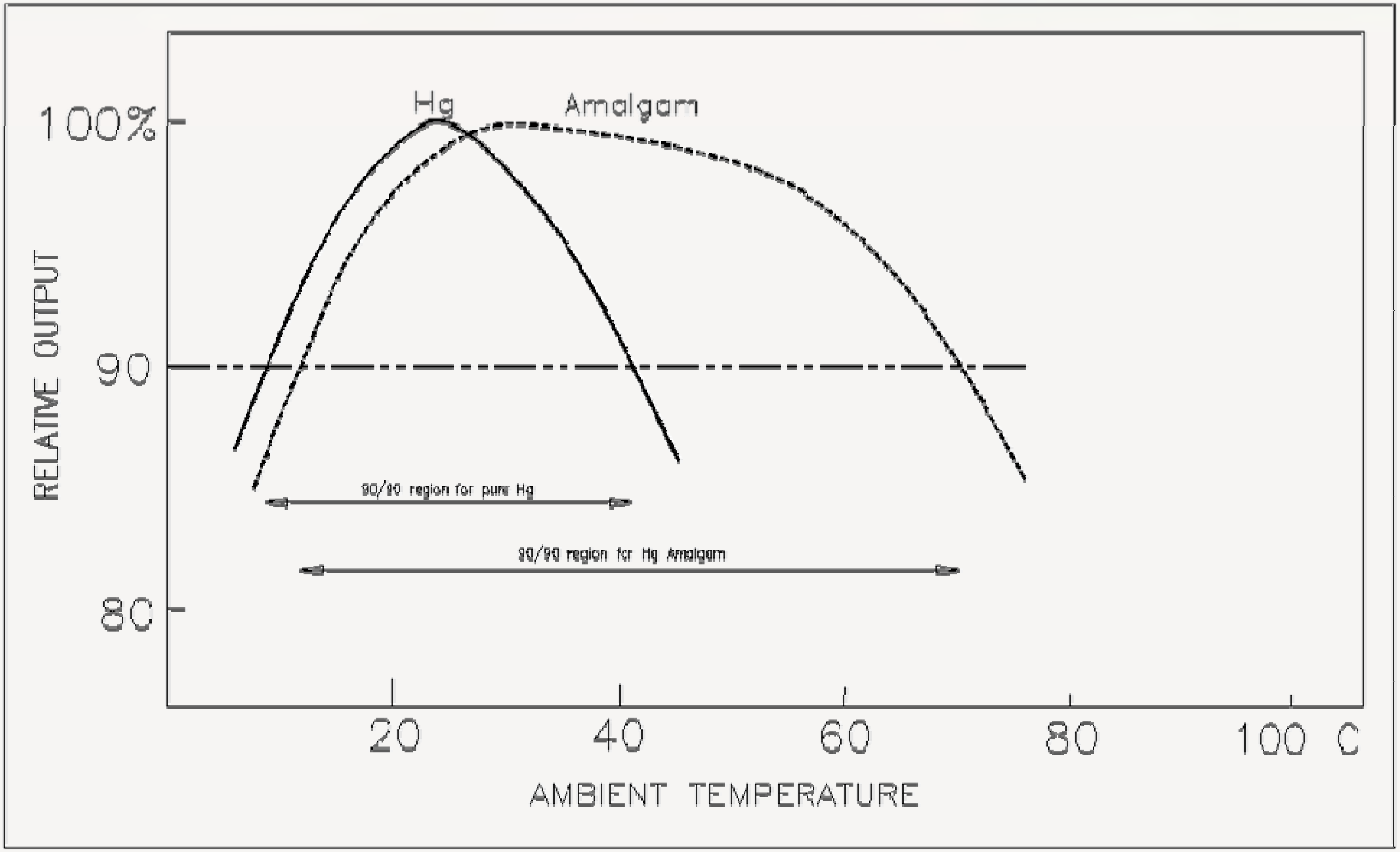
Mercury Vapor Pressure Control

- **Early amalgam germicidal lamp designs** would place the amalgam spot or spots on a location at the inside wall of the lamp fully exposed to the positive column:
  - Locations have advantage of rapid warm up and stabilization since mercury vapor can diffuse readily throughout the volume of the lamp.
  - Major disadvantage: Portions of the lamp envelope adjacent to the positive column are exposed to widest temperature variations from varying ambient and lamp operating conditions.
  - Temperature variations can overwhelm the best amalgam composition's ability to hold lamp output in the 90/90 region.

- **Newer lamp designs** shield amalgam from positive column by placing it outside discharge volume at one end of lamp:
  - Temperatures can be up to 20° C lower than on the lamp wall

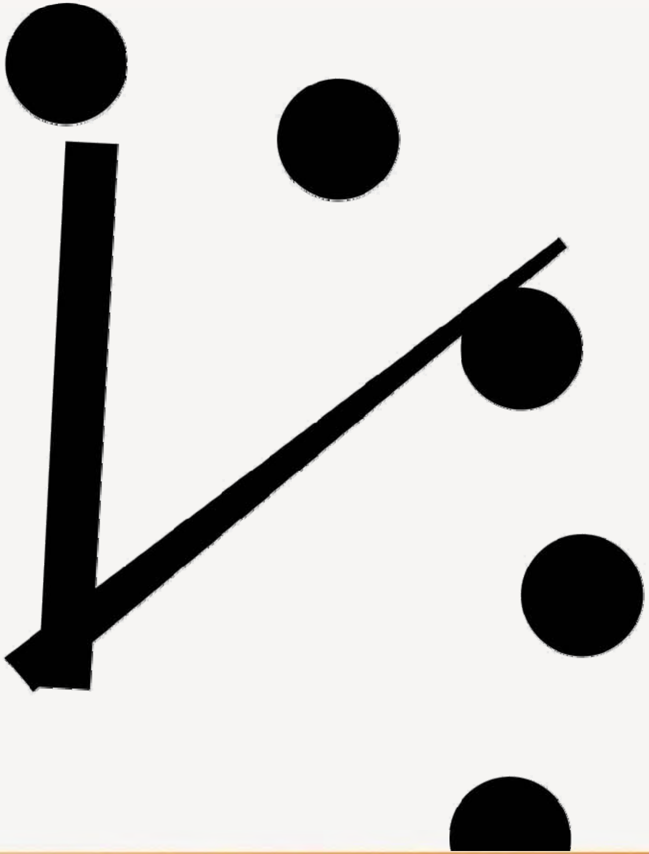


Mercury Vapor Pressure Control



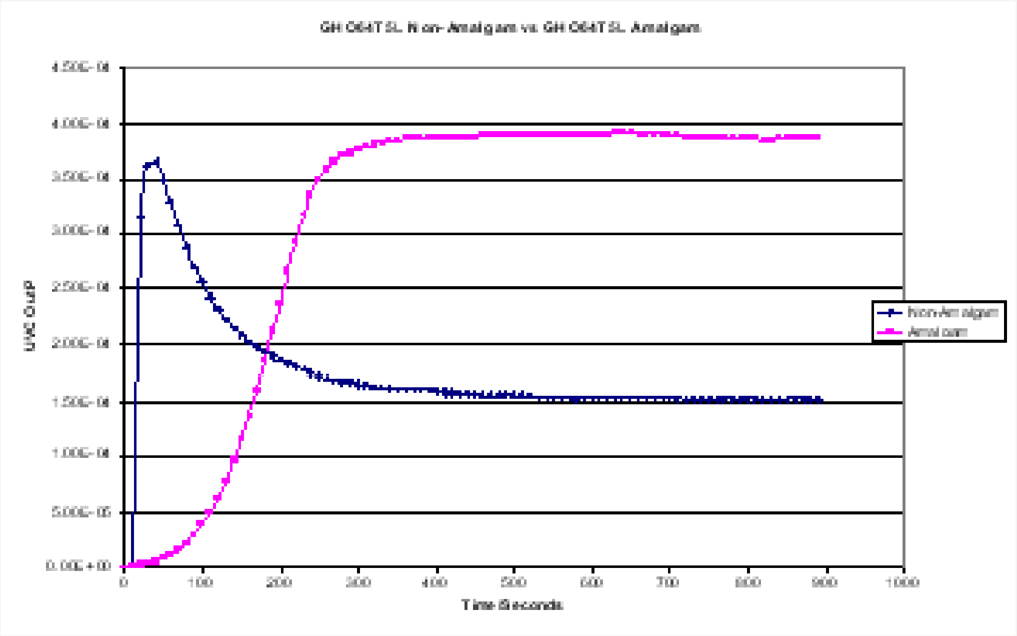
Lamp Warm-Up & Stabilization Time

- Before lamp is turned on mercury vapor pressure within is determined by ambient temperature and is essentially ZERO!
  - At ambient temperatures below 20° C mercury vapor pressure is below 1 micron.
  - When lamp turned on and power is dissipated in positive column, lamp body begins to heat raising vapor pressure to 6 microns needed for maximum output.
  - Depending on (1) the lamp design, (2) operating current, and (3) the environment, this time can be as short as 1 minute or as long as 30 minutes.
  - In most cases the lamp will warm up in 5 minutes or less.



Lamp Warm-Up & Stabilization Time

- Just because the lamp has warmed up it does not mean that the output has stabilized.

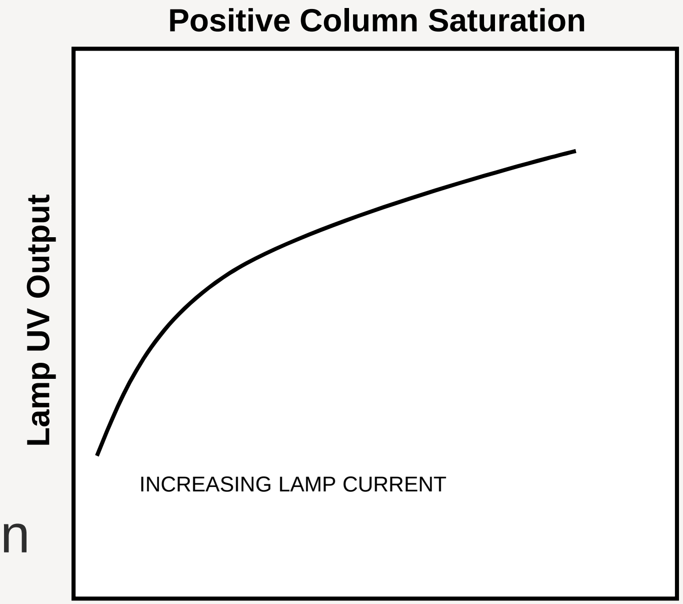


- On first lighting after installation, mercury may be partially distributed throughout lamp as randomly sized drops in equally random locations.

- As lamp operates mercury will evaporate from it's initial locations and either condense in coldest part of lamp or be absorbed into the amalgam if present.

Positive Column Saturation

- As lamp current increases, lamp temperature will rise vaporizing more mercury increasing the vapor pressure to above optimum levels resulting in loss of output.
  - If mercury vapor pressure is not stabilized at optimum point we find we have won only half the battle.
  - Lamp output will rise ever more slowly with increasing current until plateau is reached where no amount of additional current will give us more output. Positive column has reached saturation.
- Additional power supplied to lamp is going into gas losses through collisional de-excitation, wall losses mentioned previously and increased end losses.
- Some power is also converted into radiation of wavelengths useless in killing germs.



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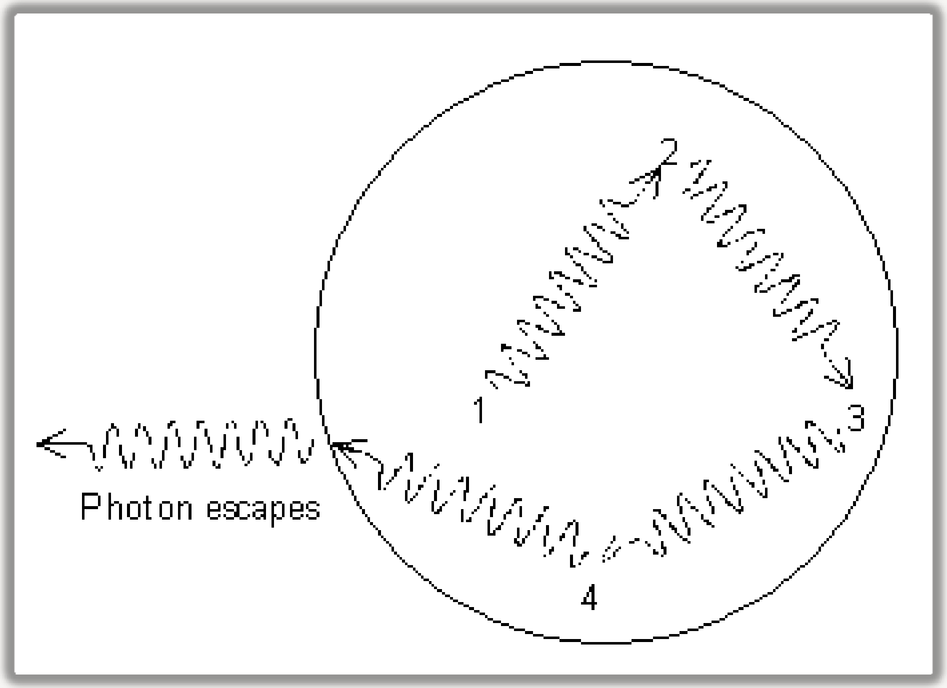
Radiation Trapping

- Any mercury atom in the discharge can collide with an **e⁻** and be excited.

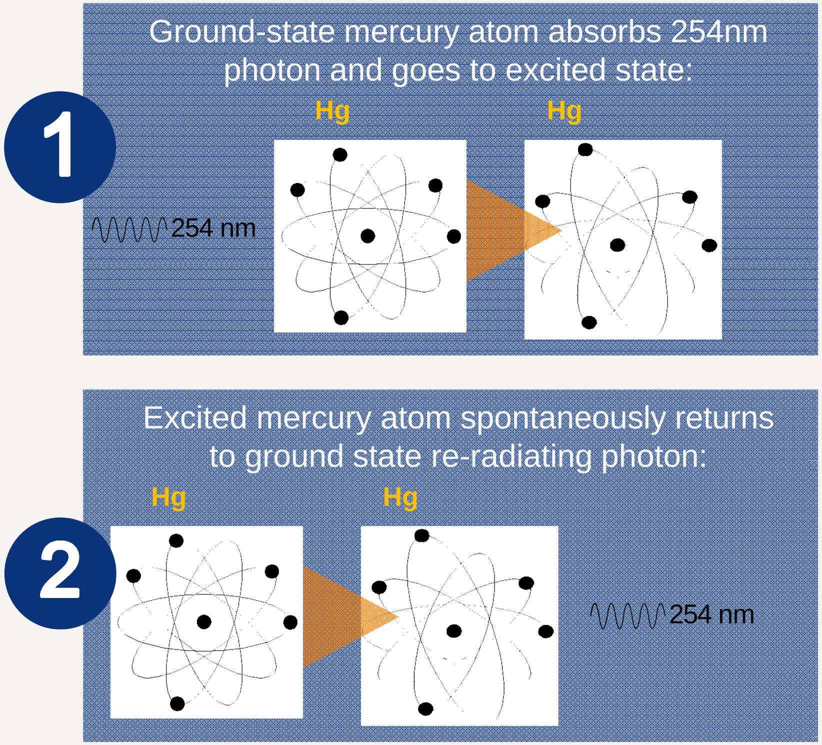
- However, the direction in which it emits a photon is entirely at random.

- The emitted photon is usually captured and re-radiated many times before it reaches the lamp wall and has a chance of escaping.



Radiation Trapping

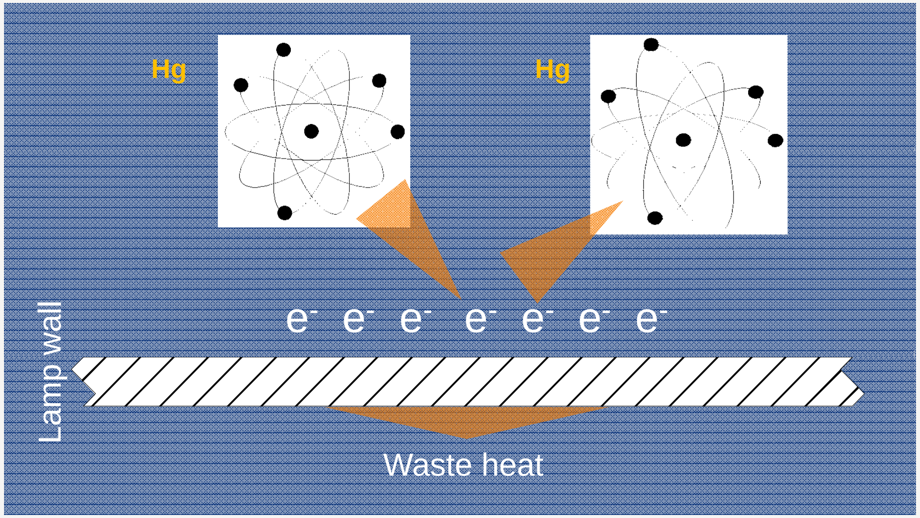
- Some photons never make it out of the lamp. They are absorbed by atoms that are subsequently involved in collisions with **e**$^-$ or other atoms. The photon's energy in this collisional de-excitation is transferred to the colliding particle and lost as heat.

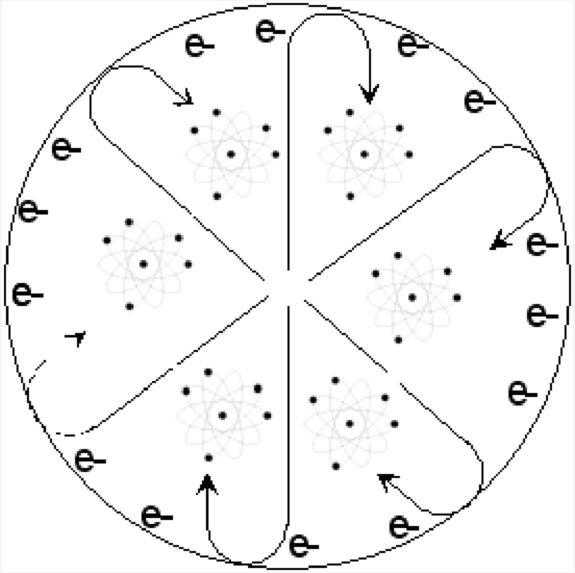


Collisional de-excitation
(loss of photon)

Wall Losses: Ambipolar Diffusion & Wall Recombination

- One factor causing the lamp wall to heat up with lost energy is **ion recombination**.
  - **e⁻** moving freely through the discharge accumulate on the lamp wall giving it a negative charge.
  - The electric field will attract ions from the positive column to the wall.
  - Ions pick up **e⁻** from wall recombining into neutral atoms, releasing energy.
  - Ion motion to wall is called ambipolar diffusion. Rate of ambipolar diffusion is one factor in determining the lamp operating voltage and output.





Lamp cross-section

Wall Loading

- Lamps with different power levels, geometries and designs are easier compared if it can be related to common lamp parameter:
  - That comparison parameter is wall loading. Wall loading is simply positive column power divided by internal surface area of the lamp wall covered by the positive column. Differences in inert-gas fill composition and pressure go away allowing lamp output and efficiency to be calculated.
  - For lamps operated at high frequency, positive column power can be calculated by multiplying lamp voltage (Vl) minus 12 volts by lamp current (Il) (at 50/60 Hz you would also need to know the lamp power factor).
- Surface area is product of lamp arc length minus .9 x I.D and the ID:

Positive column power:	P = (Vl – 12) x Il
Wall area:	A = I.D. x p x (L-.9 x I.D)
Wall loading:	Lw = P/A

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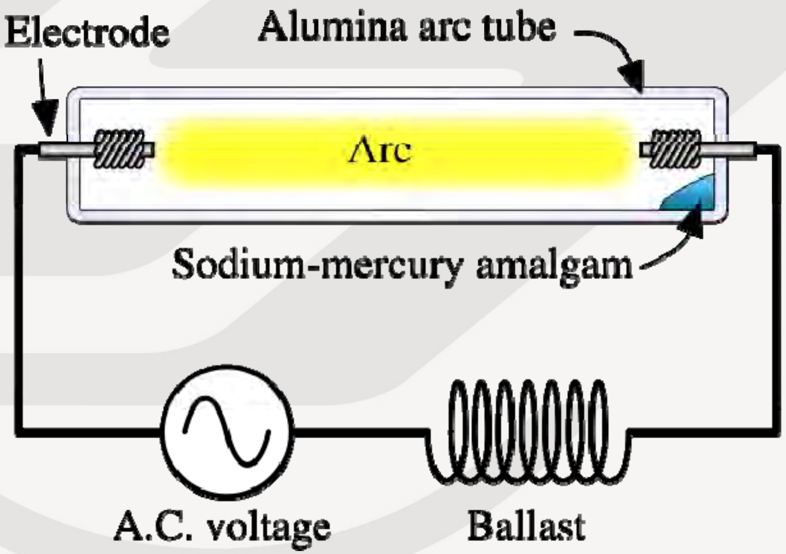
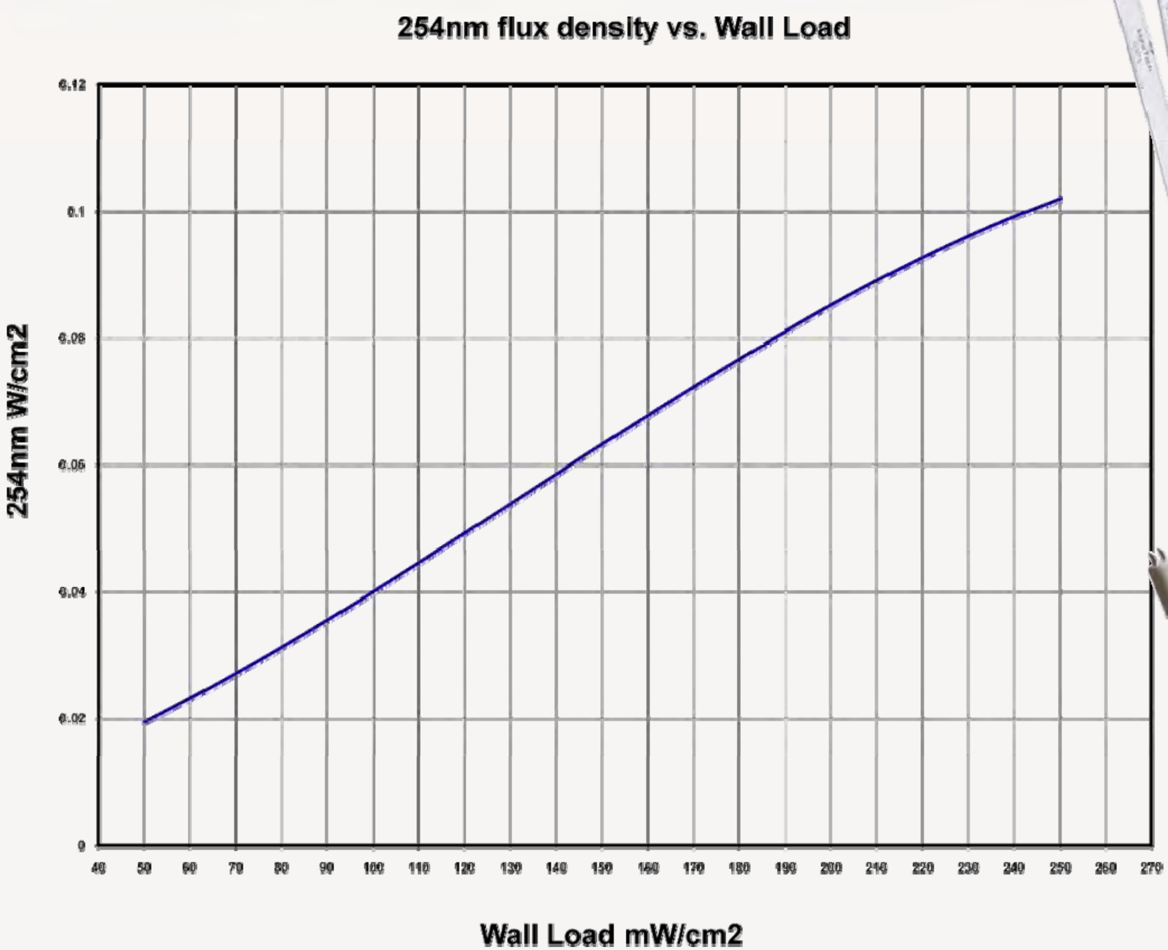
Wall Loading

Wall loading	Lamp Efficiency
Up to 100 mW/cm^2	40%+
100 to 200 mW/cm^2	37%
200 to 300 mW/cm^2	35%
300 to 450 mW/cm^2	30%



254nm Flux Density Vs. Wall Load



Any Questions?

Thank you for your attention.

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