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VII. ELECTRIC LIGHTING

A. PREPARATION

1. Introduction

One of the earliest uses to which widely distributed electricity was put was electric lighting. And electric lighting remains today one of the most important uses of power line electricity even though the total energy consumed therein is small compared to that consumed by electric motors. In recognition of this importance, your forward-looking Department long had an offering on Illumination. Beginning as a course in building lighting for architecture students, Illumination fell about the time of World War One under the guidance of Professor Harry Gray Hake with whom it was associated for some thirty years. Unfortunately, as with so many other courses of real practical importance (such as Electric Railways and Telephone Transmission), EE46 (a.k.a. 346 or 446) succumbed to the relentless advance of more recent material and burned out with the 53/54 academic year. Today, though many electrical engineers are concerned with electrically based illumination*, few electrical engineers encounter the topic in their schooling.

*To verify this, one need only visit the annual exposition of the St. Louis Electrical Board of Trade and observe what products are being displayed.
Illumination is however more than just the physical and engineering aspects of devices which send out photons in the visible or near-visible spectrum, it is also the science of such radiation as perceived and employed: a full appreciation of artificial illumination must also embrace a good deal of fundamental biology and photochemistry and include much of the science of color. Clearly that is well beyond the scope of this course and of its instructors, and we shall have to be content with a brief introduction to the notions of "irradiance" and generalized "luminance"; without these notions it is impossible to speak scientifically about illumination.

As for artificial sources of light themselves, they are diverse almost beyond imagining and, in the time available, we shall be able to cover only three: the incandescent and fluorescent lamps because of their ubiquity and the low-pressure sodium-vapor because of its conspicuously efficient use of input energy.

2. Irradiance

In classical electromagnetic field theory the fundamental descriptor of energy propagation many wavelengths from a source (i.e., in the so-called far zone) is the Poynting vector* \( \vec{S}(x,y,z;t) = \vec{E} \times \vec{H} \). The units of \( \vec{S} \) are [watts/square meter] and the vectorial direction defined by \( \vec{S} \) is along the straight line between the source and the point of observation.

*Named after the British physicist J.H. Poynting who first defined it in 1884.
In most discussions of illumination the vectorial nature of \( \vec{S} \) is ignored as are the field vectors \( \vec{E} \) and \( \vec{H} \) which give rise to \( \vec{S} \), and instead one is concerned solely with the energy transferred along a particular pencil of light rays. In fact, however, the energy passing by some point in space may be the consequence of emission by many point sources or even many extended areas with the result that it is more useful to speak of a total average vectorial flux \( \vec{S}_T \) [W/m\(^2\)] and to define a radiant flux \( P \) [W] such that \( P = \int_{\Sigma} \vec{S}_T \cdot \hat{n} \, d\sigma \) where \( \Sigma [m^2] \) is a surface a small element of which is \( d\sigma \) and where \( \hat{n} \) is a unit normal to the element \( d\sigma \). The quantity of practical interest however is not \( P \) but rather \( P/\int_{\Sigma} d\sigma \). This ratio of integrals, which may itself be a function of position, is called the irradiance and given the symbol \( H \) [W/m\(^2\)]. Most commonly \( H \) is defined by letting \( \Sigma \to 0 \) and is thus a function of position over some larger surface of which \( \Sigma \) is a subset. The irradiance is thus a measure of the total electromagnetic energy striking a surface in a unit time. It is independent of wavelength since it represents all the electromagnetic energy. Since, however, the incident radiation will have a spectral distribution, it is common to define an irradiance per unit increment of spectrum \( H_\lambda (\lambda) \) (W/m\(^3\)) where \( \lambda [m] \) is the wavelength and say

\[
H = \int_0^\infty H_\lambda (\lambda) \, d\lambda ; \tag{7.1}
\]

\( H_\lambda \) is sometimes referred to as the spectral irradiance.

\( ^5 \)The average is taken over a time long compared to the period of the lowest Fourier component of the radiation but short compared to the temporal resolution of the measuring equipment.
3. **Black Bodies and Lasers**

To understand the nature of a particular light source it is necessary to appreciate first that a given emitter will distribute its energy over a range of wavelengths and over a range of spatial directions. Of the huge number of possible emitters, two serve as paradigms for the illustration of these properties:

a. The perfect black body. Here the emissivity is continuous with wavelength and distributed over a wide region while the radiation pattern of an element of black surface is such as to favor no particular direction.

b. The perfect laser. Here the emissivity is concentrated at a single wavelength, the spectral emittance being a delta-function in $\lambda$. The radiation pattern is likewise of delta-function form, the emitted energy being confined to a single direction.

Many light sources can be approximated either as a perfect black body, or as a perfect laser, or as a linear combination of such perfect sources.

A perfectly black body is one which absorbs all of the radiant energy incident upon it, reflecting none and transmitting none. However, the perfect black body at a temperature $T$ [K] also radiates; and the spectral emittance of a unit area of surface within a small range of wavelengths is given by the Planck formula (Sears, 1949)

$$w_{\lambda}^{(bb)} = \frac{2\pi c^2 h}{hc} \frac{\lambda^{-5}}{e^{\frac{k\lambda T}{\lambda}} - 1}, \quad (7.2)$$
where \( c [= 2.997 \ldots \times 10^8 \text{ m/s}] \) is the speed of light in vacuum, \\
h \( [= 6.625 \ldots \times 10^{-34} \text{ J} \cdot \text{s}] \) is Planck's constant, and \\
k \( [= 1.380 \ldots \times 10^{-23} \text{ J/K}] \) is Boltzmann's constant. Note that the \\
integral \( \int_0^\infty W^{(bb)}_\lambda d\lambda \) yields the radiant emittance \( W_{bb} [\text{W/m}^2] \) of a \\
black surface.

Several valuable formulas follow at once from Eq. (7.2). 
First, by differentiation with respect to wavelength, it can be 
shown that the wavelength of maximum emittance is given by 
\[
\lambda_{\text{max}} T = 2.897 \ldots \times 10^{-3};
\]
this is known as Wien's displacement law. Second, by simple 
integration,
\[
W_{bb} = \frac{2\pi^5}{15} \frac{k^4}{h^3 c^2} T^4 = \sigma T^4,
\]
where \( \sigma [= 5.669 \ldots \times 10^{-8} \text{ W/(m}^2 \cdot \text{K}^4)] \) is the Stefan-Boltzmann 
constant. The upshot of these results is that, as the temperature 
of an incandescent light source is increased, its most characteristic 
wave length falls slowly as \( 1/T \) while its output rises 
sharply as \( T^4 \).

Of course, ideal black bodies do not exist and an incandescent 
source's spectral emittance is generally specified as 
\( W^{(i)}_\lambda = e_\lambda W^{(bb)}_\lambda \), where \( e_\lambda \) [dimensionless] is the spectral emis-
sivity of the source and where the integral measure of radiation 
output becomes
\[
W_i = e W_{bb} = e \sigma T^4.
\]
The spectral emittance from our sun crudely approximates a black body in the 6000-7000 K range and, since it was background to all our seeing, is psychophysical white even though its spectrum is not flat over the 400-700 nm band.

The laser is not a typical light source since its output is temporally coherent (that is, is of predictable phase), is highly monochromatic, and is almost ideally pencil beam. However, it is typical of light sources based upon simple atomic emission processes in general since these tend to possess sharply peaked spectral emittances and are therefore perceived as colored rather than white. Because colored illumination is not especially pleasant to work in, the output of a laser or other simple atomic source is generally processed through a phosphor which absorbs the spectral lines and reemits radiant energy smeared over a broad range of longer wavelengths, thereby yielding quasi-white illumination.
4. Luminous Flux and Related Quantities

Visible light, of course, is electromagnetic radiation and conventional electrical units such as watts, watts/m², joules, etc., may be used for its description. The human eye is a light detector but it does not have a uniform, or flat, response over the frequency spectrum to which the eye responds. Figure 7.1 shows how the eye responds to light at various wavelengths. A standard curve of this type has been constructed as an average of a large number of human observers. This curve actually depends on the illumination level and is shifted about 50 nm. to the left at low light levels (the boundary between low light levels and high light levels is in the range 0.034 - 3.4 candelas/m²). This shift is known as the Purkinje effect and illustrates the increased sensitivity of the eye in the blue at low light levels.

Light as perceived by the eye is described in different units

![Figure 7.1](image-url)
than are used to describe light as electromagnetic radiation. These units are a result of early light generation methods (e.g. the candle) and studies made by researchers over the years (the Lambert is a unit named after J. H. Lambert who made many contributions to photometry). The original standard for visible light intensity was the 'candle' and a spermaceti candle, later a gas flame, was used for its realization until the early 1900's. From 1909 to 1937 the U. S. and Europe redefined the candle in terms of carbon filament incandescent lamps heated by electric current, but this was not entirely satisfactory and in 1937 the luminosity of a black body radiator at the temperature of freezing platinum (2042 K.) was defined to be 60 candles/cm².

In 1948 the General Conference on Weights and Measures (CGPM) decided that the unit of luminous intensity should be called the 'candela' (cd.) and should be defined such that the surface of a blackbody radiator at the temperature of freezing platinum would have a luminosity of 60 cd/cm². In 1979 the CGPM redefined the standard to give it a direct relation to electromagnetic or radiometric units and decreed that 'the candela is the luminous intensity in a given direction of a source which is emitting monochromatic radiation of frequency 540(10)^12 Hz. (555 nm.) and whose radiant intensity in that direction is 1/683 watts/steradian.'

We can visualize the candela as the intensity of a standard point source emitting about the same amount of light as a candle would. This is a fairly satisfactory definition, physically. Of course the candle flame is a lot cooler than the temperature of freezing platinum, nevertheless, its surface area is sufficiently large that the light emitted is the same as that emitted from the much smaller
standard source (\(1/60 \text{ cm}^2\)) at a much higher temperature (2042 K.)

The candela is a primary unit that relates visible light to other physical units. Other photometric units are derived from the candela. One of the most important is the 'lumen'. The lumen is the amount of light emitted from a uniform point source of 1 candela intensity that passes through a solid angle of 1 steradian of a sphere centered at the point source. As is clear from this definition the candela and the lumen are dimensionally equivalent and 1 candela = \(4\pi \text{ lumens}\). The candela is a unit of quantitative brightness or 'luminance' appropriate to a light emitter, be it a point or an extended surface. Thus the luminance of a diffusing panel through which light shines is specified in terms of candelas/m\(^2\). On the other hand, as light travels it ultimately impinges on another surface. The amount of light impinging or illuminating the surface is the 'illuminance' and is measured in lumens/m\(^2\). We should avoid confusing brightness, which is a subjective term, with luminance, a quantitative term. An object might appear bright in a dark environment but might not appear so in a lighter environment. Its luminance would be the same, however.

In discussing visible light it is helpful to consider the light as a flow of particles streaming from the source. The density of the flow is the 'flux'. If the emitter is a point source, then the flux is given as the number of lumens per solid angle, where the solid angle is centered on the emitter. We note that the flux may not necessarily be distributed uniformly over the \(4\pi\) steradians surrounding the point source. The illumination on a plane area, A, at a distance R from a uniform point source, as in figure 7-2a, would be
\[ E = \frac{\Phi (\cos \theta)}{R^2} \text{ lumens/m}^2. \]

where \( \Phi \) is the intensity of the source in candelas and \( E \) is the illuminance of the surface in lumens/m\(^2\).

In another example, suppose that we have a plane, light-emitting surface of infinite extent where each small element of area, \( dS \), of
the emitting surface can be considered to be a uniform point source emitting \( L(dS) \) candelas of light. For a small element of area, \( dA \), situated a distance, \( d \), from the emitting surface, the illumination would be (see figure 7.2b)

\[
\frac{dE}{dA} = \frac{I(2\pi RdR)}{d^2 + R^2} \left( \frac{d}{\sqrt{d^2 + R^2}} \right)
\]

Integrating this gives

\[
E = 2\pi L \quad \text{lumens/m}^2
\]
or the illumination is independent of the distance from the plane.

A case of more practical interest is a 'perfectly diffusing' plane, circular light emitting surface of finite radius, as in figure 7.2c. Here, the intensity, \( L \), varies as \( L_0\cos(\theta) \), where \( \theta \) is the angle at which the light emitting surface is viewed. For such a surface, the previous integral becomes

\[
E = \int_{R=0}^{R=a} \frac{L_0(2\pi Rd^2)}{(d^2 + R^2)^2} dR
\]
and the result is
\[ E = \frac{L_0 a^2}{a^2 + d^2}. \]

As is evident, if \( d > 10a \), the illumination falls off as the square of the distance, and even though the source is not a point source, it obeys the inverse square law if the distance, \( d \), is large enough.

Although they introduce no new concepts, several other alternate names exist for the photometric quantities previously described. As we have noted, the candela unit was derived from the candle and so an alternate unit of luminous intensity, although its use is not encouraged, is the 'candlepower'. Other units of illuminance are the 'footcandle' and the 'lux', which are lumens/square foot and lumens/square meter, respectively.
5. Photometric and Quantum Measures

There are two common weighting factors in use with the generalized luminous flux. One is the so-called photopic relative luminosity curve for a standard human observer in normal daylight. This nearly symmetrical curve, which peaks at about 556 nm and has fallen 60 dB at 410 and at 720 nm, forms the basis for the photometric units defined within SI and, when used in Eq. (7.6) defines luminous flux in ordinary lumens*. The precise shape of photopic relative luminosity curve (cf. Barrows, 1951, Wright, 1969) will not of itself suffice to define \( d\Phi \) or the ordinary photometric lumen precisely because \( T \) has not as yet been precisely specified. To get at this note that the photometric generalized flux emitted by a surface element in some direction is

\[
d(\Delta\Phi) = [\Delta I](d\Omega) = [B(\theta, \phi)\Delta\text{Acos}\theta](\sin\theta d\theta d\phi) . \tag{7.18}
\]

Hence the photometric luminous emittance \([lx]\) of the patch is

\[
L = \frac{\Delta\Phi}{\Delta A} = \int_0^{2\pi} \int_0^{\pi/2} B(\theta, \phi)\sin\theta\cos\theta d\theta d\phi . \tag{7.19}
\]

*Under low levels of illumination, the sensitivity of the human eye is perhaps ten-fold greater and peaks near 510 nm. This so-called scotopic relative luminosity curve is of negligible use in illumination engineering since illuminated scenes are photopic.
For a Lambert's law (i.e., perfectly diffuse) source of constant brightness B, Eq. (7.19) reduces to

$$L = \pi B . \quad (7.20)$$

But, by Eq. (7.6) and numerical integration using the photopic sensitivity curve and $H_\lambda(\lambda)$ for a black body at 2042 K (the freezing point of platinum)

$$L = 2750 T . \quad (7.21)$$

But, by definition, photometric luminance (or luminance) of the surface of freezing platinum is precisely 600,000 cd/m$^2$ so that $T = 685.4...$. Since different observers have slightly different relative sensitivities and since there is some minor uncertainty in the physical constants which describe blackbody radiation, one commonly says

$$T = 685 \text{ lm/W} ; \quad (7.22)$$

this is quite accurate enough for all practical purposes.

The implications of these choices for $f(\lambda)$ and $T$ are manifold, but we shall describe only a few here. First, the greatest efficacy possible under photometric conditions is $\varepsilon = 685 \text{ lm/W}$; under subdued illumination where the eye is much more sensitive, $\varepsilon$ remains unchanged even though the real physiological utility of the incident photons may be much greater. Second, the ideal black body is not an especially efficient radiator, being approximately (Sears, 1949) 15 lm/W at incandescent lightbulb temperatures,
59 lm/W at the melting point of tungsten (\(\approx 3680\) K), and 93 lm/W at its peak at approximately 6500 K.

While it is true that the eye is a photochemical transducer, it is not the only important photochemical transducer in biology or even the most important one. From the viewpoint of a photosynthesizing plant, it is the number of photons absorbed in the 400-700 nm band rather than their wavelength which is important*. Hence the variable of interest is the photoynthetic photon flux density (PPFD) the preferred unit of which is \([\text{mol/s\cdot m}^2]\). One mole of photons is commonly called an einstein, a term which does not enjoy SI approval. Of course, a mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilograms of carbon-12, that is, Avogadro's number \(N_A; N_A = 6.022\ldots\times 10^{23}\) entities/mole. Now \(c = \lambda\nu\) and \(e_\nu = h\nu\), where \(\nu\) [Hz] is the frequency of a photon and \(e_\nu\) [J] is its energy. Therefore, for photosynthetic radiation we can define (Shibler, 1976) an \(\hat{F}\) [mol/(s\cdot m²)] based upon (photon/joule) = \(1/e_\nu = \lambda/hc\) so that, from Eqs. (7.6) and (7.7),

\[
\hat{E} = \frac{\Delta\hat{F}}{\Delta A} = \frac{1}{N_Ahc} \int_{\lambda<}^{\lambda>} \lambda H_\lambda(\lambda) d\lambda
\]

(7.23)

and

\[
\hat{e} = \frac{\lambda>}{N_Ahc} \frac{\int_{\lambda<}^{\lambda>} \frac{\lambda}{\hat{H}_\lambda(\lambda)} d\lambda}{\int_{\lambda<}^{\lambda>} \hat{H}_\lambda(\lambda) d\lambda},
\]

(7.24)

Of course, this rule is only approximate as anyone who has ever tried to grow plants under artificial light knows.
where \( \lambda_\wedge = 400 \times 10^{-9} \) and \( \lambda_\vee = 700 \times 10^{-9} \). A device which measures \( \hat{E} \) is called a quantum sensor or quantum radiometer and \( \hat{E} \) may be termed the quantum efficacy*. Obviously the units of \( \hat{E} \) are \([\text{mol}/\text{J}]\), and \( \hat{E} \leq \lambda_\vee / N_A h c \approx 5.85 \times 10^{-6} \). The quantum efficacy of direct sunlight is very roughly 75% of this maximum.

6. Flicker and Color Temperature

If a light source is to be used to illuminate a scene for visual observation by people, it should not be psychologically disturbing to them. That is, it should appear to be of steady luminosity and it should color match ordinary daylight.

Flicker is a complex psychophysical phenomenon which arises from the persistence of vision. That is, if the photometric luminance is a periodic function of time \( B(t) \) of period \( \tau \) [s], then the propensity of the human visual system to take annoyance at this temporal variation will be a complicated function of the mean luminance \( B_{\text{avg}} \) (or the mean illuminance provided by it), of the ratio of maximum to minimum luminance \( B_{\text{max}}/B_{\text{min}} \), and of the period \( \tau \). With early incandescent bulbs operated at 25 Hz

*The term "quantum efficacy" does not enjoy currency. And the term "quantum illuminance" for \( \hat{E} \) is never employed; instead PPFD is called things like "irradiance", "light intensity", etc. in more modern literature while older literature may use almost anything in any units. Moreover, even within photobiology there is rampant revisionism (e.g., Rupert and Latarjet, 1978) and nomenclature is almost certain to change.
flicker was a problem. At 60 Hz, $\tau$ is so short (8 1/3 ms) and $B_{\text{max}}/B_{\text{min}}$ so small that it is not. However, $B_{\text{max}}/B_{\text{min}}$ may still be of the order of 1.05 (Anonymous, 1980) for a 100 W incandescent or 1.4 (Barrows, 1951) for a fluorescent. For non-incandescent lamps luminance variations can sometimes be detected through stroboscopic effects on moving objects (e.g., the blades of an electric fan), but this could scarcely be called flicker.

A blackbody operated at a given temperature will evoke a certain color sensation from the human visual system. An arbitrary light source which evokes a sensation similar or identical to a blackbody at temperature $T_\lambda \ [\text{K}]$ is said to have the color temperature $T_\lambda$. There obviously are limitations to this scheme: greens, for example, will be hard to match, and the color temperature of the source (e.g., blue sky) may bear little relation to its output of radiant flux. Moreover, there is no guarantee that sources which from visual observation seem to have the same color temperature will have even remotely similar $H_\lambda(\lambda)$; and experiments with non-human observers, green plants for example, can be counted upon to drive home this point with depressing regularity.

The sun, as viewed from the surface of the earth, has a color temperature of perhaps 5000 K as contrasted (cf. Wright, 1969) to a candle at about 1900 K or average daylight at 6500 K. Fluorescent lamps are as often as not not rated by a color temperature since their $H_\lambda(\lambda)$ is commonly bimodal and very different from that of a blackbody. Tungsten filament lamps are normally
specified in \( \text{lm/W} \) and the color temperature read from a standard graph; for example, an ordinary soft-white 100 W bulb is about 2900 K.

7. Desirable Levels of Illumination

The general levels of illumination which are needed for a task vary with the age and physical condition of the worker and also with the task. The Illuminating Engineering Society has recommendations, but much depends upon individual taste and also upon what you can afford.

Some whimsically selected recommendations are (cf. Nuckolls, 1976, Table 14.12)*

- Statuary display in art gallery: 1100 lx
- Barber shops: 1100 lx
- Art glass windows (dark glass, illuminated from behind): 5400 lx
- Platforms in depots: 220 lx
- Subdued restaurant lighting: 160 lx
- Autopsy tables: 11000 lx
- Stacks in library: 320 lx
- Auditorium during movie: 1.1 lx
- Lecture rooms (student areas): 750 lx
- Lecture rooms (demonstration areas): 1600 lx
- Laboratories: 1100 lx

*The photometric illuminance \( E \), though properly specified in \( \text{lm/m}^2 = \text{lx} \) is frequently specified in \( \text{lm/ft}^2 = \text{footcandles} \). 1 footcandle = 10.76391 lx.
There is a general rule that the greater the difficulty of a visual task, the more illuminance it requires. However, one must note that the retina does accommodate so that, as the illuminance rises, the sensitivity of the retina slowly decreases. Hence, at latitude 42°N on a clear June 21, the noontime illumination from sun and sky exceeds $10^5$ lx; but the retina is so desensitized that one is visually handicapped immediately upon coming indoors to a well lighted room. The precise psychophysics of this phenomenon are beyond the scope of this course; yet the effect is worth remembering.

8. **Principal Lamp Types**

   a) **Introduction.** The variety of light sources is astounding. For example, the monograph by Elenbaas (1972) devotes two pages to a taxonomic breakdown by physical principles. However, despite the richness of phenomena available and the intrinsic interest of flashing fireflies or winking LED displays, the lumens which brighten our lives are almost all obtained either from solids heated white hot or from electrical discharges which occur in gas. What can also be said by way of overview is that the trend in photometric efficacy has been toward ever higher levels as Table 7.1 indicates.

   b) **Incandescent.** The oldest known artificial light sources are incandescent; and, until well into the nineteenth century, the only practical light sources were incandescent. In the beginning incandescence (i.e., emission from heated solids) was achieved
### PHOTOMETRIC EFFICACIES*

<table>
<thead>
<tr>
<th>Source</th>
<th>lm/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paraffin candle</td>
<td>0.1</td>
</tr>
<tr>
<td>Acetylene lamp</td>
<td>0.7</td>
</tr>
<tr>
<td>Edison's first lamp</td>
<td>1.6</td>
</tr>
<tr>
<td>Cellulose filament incandescent</td>
<td>2.6</td>
</tr>
<tr>
<td>Tungsten filament incandescent</td>
<td></td>
</tr>
<tr>
<td>(early high vacuum)</td>
<td>10</td>
</tr>
<tr>
<td>Tungsten filament incandescent</td>
<td></td>
</tr>
<tr>
<td>(early gas filled)</td>
<td>20</td>
</tr>
<tr>
<td>Tungsten filament incandescent</td>
<td></td>
</tr>
<tr>
<td>(modern $10^2$W)</td>
<td>15</td>
</tr>
<tr>
<td>Tungsten filament incandescent</td>
<td></td>
</tr>
<tr>
<td>(modern $10^4$W)</td>
<td>33</td>
</tr>
<tr>
<td>Early sodium lamp</td>
<td>20</td>
</tr>
<tr>
<td>Modern sodium lamp</td>
<td>150</td>
</tr>
<tr>
<td>Early mercury lamp</td>
<td>40</td>
</tr>
<tr>
<td>Early fluorescent lamp</td>
<td>55</td>
</tr>
<tr>
<td>Modern fluorescent lamp</td>
<td></td>
</tr>
<tr>
<td>(general purpose)</td>
<td>70</td>
</tr>
<tr>
<td>Gallium arsenide diode</td>
<td>180</td>
</tr>
<tr>
<td>&quot;Ideal&quot; source</td>
<td>685</td>
</tr>
</tbody>
</table>

*These data were taken in part from Table A3-6 of J.P. Martino, Technological Forecasting for Decisionmaking. New York, American Elsevier (1972).
chemically as the carbon particles in a flame were raised to a temperature high enough to radiate in a somewhat blackbody fashion. However, the efficacy of these sources was low; and, while a candle may be suitable for romance, it can cause strained eyes when used for reading fine print.

Eventually it was realized that the chemical reaction could be used to heat a nonvolatile solid to incandescence at a high temperature, thereby avoiding the convective loss of chemical energy in medium temperature infrared emitting gas (cf. Gaster and Dow, 1915). The prototypic illuminant of this variety was the limelight of Thomas Drummond (1826) which so revolutionized theatre illumination; it was a simple oxyhydrogen flame which imprinted on a piece of limestone. But the most famous was the mantle of Auer von Welsbach who discovered that a suitable fiber mesh impregnated with thorium dioxide (with a 0.9% CeO₂ dopant) would incandesce brilliantly and in a somewhat nonblackbody fashion which favored the visible; this so revolutionized gas lighting when it was discovered about 1890 that the gaslight entered its heyday only at the turn of the century!

However, oil lamps, candles, mantles, and the like all had their drawbacks and none could compare with a good light bulb. The problem was with the "good" for it proved very difficult to combine long life with a reasonable color temperature, acceptable photometric efficacy, and simplicity of operation. Color temperature and efficacy forced operating temperatures upwards which meant that carbon or tungsten were the filaments of choice.
Carbon had the higher melting point; but this could not effective- 
ly be exploited fully because of its high vapor pressure 
(\sim 5000-fold that of tungsten in the popular 2800 K range). 
Tungsten could not however be used effectively until 1911 after 
Coolidge figured out how to make it ductile. And it was not un- 
til 1913, when GE adopted Langmuir's* notion of putting an inert 
gas in the formerly evacuated bulb to reduce tungsten evaporation, 
that the electric light really took off and beat out the gas 
mantle.

c) **Glow Discharge.** When the incandescent bulb is subtracted, 
the sources which light up our lives are primarily those which in- 
volve electric discharge in gases and vapors. Of these, the one 
with historical primacy is the carbon arc studied first by Davy 
about 1809; but, searchlights and movie projectors aside, they are 
not terribly important in the present day. Others are; and, in 
order to understand them, one must first understand something 
about gas discharges, that is, the passage of current between two 
electrodes in a gas. Leaving aside questions of the influence of 
gas pressure, a \( v [V] \) versus \( i [A] \) curve will have the canonical 
form shown in Fig. 7.2. As one might have expected, a desire to 
operate at low voltages and nontrivial currents and to avoid run- 
away instability under constant voltage drive has lead to a 
concentration on the regions labelled IV and VII (cf. Elenbaas, 
1972). Moreover, even within these two regions, there can be

*There was a time when scientists of note worked on practical 
problems!
considerable variation as to where there is emission of useful radiation:

(i) In IV (especially at its right-hand end) a space in front of the cathode can be highly luminous and is called the negative glow because the net charge of the gas is negative there and the gas glows.

(ii) In IV and VII there may be a long, highly luminous, positively charged region in front of the anode; it is called the positive column.

(iii) In addition to the atomic emission processes which characterize the negative glow and the positive column, there may be sufficiently intense heating of the electrodes to cause them to emit significant blackbody radiation.

We shall not in this course do any experiments on sources which operate in region IV. However, two such glow discharges are familiar to you. First, the so-called indicating glow-lamp is often used to signal whether or not the voltage is on or to be an ornament in a child's bedroom; it has negative glow but no positive column. Second, the famous neon sign is a lamp in which the light is produced almost exclusively in a long positive column.

Neon signs come in two basic colors and a variety of secondary colors. The basics are the red which characterizes tubes filled with pure neon and the blue of tubes with an argon-mercury filling. The secondaries are derived from the short wavelength emissions of argon-mercury which normally are absorbed by a
phosphor and re-emitted at longer wavelengths but which may be filtered through yellow glass to emphasize the green spectral line of mercury.

d) **Arc Discharge.** Whereas glow-lamps are almost always operated at gas pressures well below atmospheric (low-pressure discharge lamps), lamps which utilize the arc discharge of region VII may be operated either well below atmospheric pressure (low-pressure discharge lamps) or closer to or even at atmospheric pressure (high-pressure discharge lamps). All suffer from the drawbacks (i) that ignition of the discharge requires that a considerable quantity of recondite engineering lore be available to the lamp designer and (ii) that the lamp be ballasted to control the positioning of the operating point along the negative slope of the $v(i)$ curve. There are three types of arc discharge lamps frequently seen: the fluorescent and the low-pressure sodium, both of which we shall study in the laboratory and will consider in detail later, and the high-pressure mercury which we shall not see in the laboratory.

The high-pressure mercury vapor lamp is a glass envelope containing two electrodes, a small amount of liquid mercury and a little argon. At turnon, the lamp gives a low-pressure arc discharge similar to that of a fluorescent lamp. However, the initial discharge heats the mercury so that more is vaporized and soon the partial pressure of the mercury rises shifting the resonance radiation of the tube from the far UV lines at 185 and 254 nm toward the lines at 405/408 nm, at 436 nm,
at 546 nm (the celebrated mercury green line so much used in experimental optics prior to the advent of the laser), and at 577/579 nm. Further, at still higher temperatures, resonance radiation becomes supplemented by the continuous spectra of temperature radiation and ion-electron recombination. In addition, the color balance may be enhanced by the judicious use of phosphors since the tendency for shorter wavelengths to predominate in the unaltered spectrum of the discharge gives rise to an undesirable color balance and the infamous "liver lips" effect.

9. The Ordinary Incandescent Lamp

The common incandescent lamp consists of a doubly coiled\textsuperscript{§} tungsten\textsuperscript{*} filament inside a

\textsuperscript{*}The process by which tungsten is made ductile was invented in 1910 by William D. Coolidge and, with minor modifications, is still in use today. Imparting non-sag to the filaments was found by A. Pacz (1917) to require the addition of small amounts of potassium, silicon and aluminum to the tungsten.

\textsuperscript{§}Single coiling stems from the work of Irving Langmuir (1912) on the rate of heat dissipation from heated filaments in a gaseous atmosphere. The coiled-coil, which increases efficacy still more, was introduced about 1936 by B. L. Benbow, J. Force and J. Flaws.
gas-filled* glass bulb with a diffusing surface§. Since the resistivity of tungsten rises roughly (Elenbaas, 1972) as \( T^{1.21} \), turn-on of an incandescent lamp is accompanied by a surge of current known as the \textit{inrush current}; the rise time of

*The idea of using an inert filling gas to lower the evaporation rate of the tungsten and thereby enable higher temperature higher efficacy operation is due to Irving Langmuir (1913). Reducing filament evaporation serves the dual purpose of lengthening filament life and reducing bulb blackening due to deposited tungsten. The normal filling gas is a nitrogen-argon mixture. However, the lower thermal conductivity of krypton does result in higher efficacy, and krypton is therefore being used in certain premium bulbs these days. The gas pressure at normal operating temperature is roughly atmospheric.

§In a clear glass bulb, the apparent source of light is the filament. This was superseded after 1925 by the inside frosted bulb, an invention of the unjustly unknown Marvin Pipkin. Inside frosting caused the apparent source of light to become a sphere inside the bulb; the luminance of this sphere is only about \( 1/30 \) that of the filament while the efficacy is dropped about \( 2\% \). Pipkin went on to invent in 1949 the silica powder coating which, with only a slight \( (\sim 2\%) \) loss in efficacy, made the apparent source of lumens become the surface of the bulb itself.
the luminous output is roughly 100 ms, and the rise in resistance as the bulb warms up is roughly fifteen-fold. Key operating characteristics of the typical bulb are normally described allometrically (Anonymous, 1980):

\[ \varepsilon \propto V_{\text{rms}}^a \quad (a \approx 1.84) \]  

\[ W_{\text{rms}} \propto V_{\text{rms}}^b \quad (b \approx 1.54) \]  

\[ I_{\text{rms}} \propto V_{\text{rms}}^c \quad (c \approx 0.54) \]  

\[ \text{(bulb life)} \propto V_{\text{rms}}^d \quad (d \approx -13.1) \]  

\[ F \propto V_{\text{rms}}^e \quad (e \approx 3.38) \quad \]

where \( V_{\text{rms}} \) [V] is the voltage at which the bulb is operated while \( W_{\text{rms}} \) [W] and \( I_{\text{rms}} \) [A] are the power dissipation and current which obtain at that voltage. Typical values vary greatly, but for a new 60 W silica coated lamp one might expect an efficacy of 14.5 lm/W and a lifetime of 1000 h.

10. The Ordinary Fluorescent Lamp

There is a startling number of different 48" long 40 W fluorescent lamps: for example, the current General Electric catalogue lists roughly ten different varieties of white, three different starting options, and three different pin configurations; and of course this does not include premium energy saving
options. In addition, the fluorescent lamp, since it utilizes a low pressure mercury arc discharge, operates in a negative resistance region of the $v(i)$ characteristic and will experience current run away followed by self destruction unless suitably \textit{ballasted}. We shall discuss here only the questions of color, start-up, and ballasting.

First (Elenbaas, 1972), a low pressure arc discharge in mercury produces radiation primarily in the far ultraviolet (85\% at 254 nm and 15\% at 185 nm) but with some near UV and visible at 577/579, 546, 435, 405/408, 365/366, 334, and 313/313 nm. The interior of a bulb is therefore coated with a \textit{phosphor} which absorbs the far UV (and possibly also the lines at 334 and 313/313) and emits longer wavelengths; for example, zinc silicate is most sensitive at 254 nm and emits over 460-640 nm with its peak in the green at 525 nm. The radiation from a fluorescent tube in consequence contains the unabsorbed longer mercury lines and the continuous spectrum from the phosphor. Fig. 7.3 (Anonymous, undated) shows such a spectrum for the General Electric "Cool White" lamp. The spectrum is comparatively weak.
in red, but the efficacy of a new lamp is about 79 lm/W. To bring up the red and get a more natural color balance one would use a phosphor mix such as "Chroma 75" whose perceived color balance approximates north skylight but whose efficacy is only 50 lm/W. Other useful phosphor mixes are "Gro and Sho" (a decidedly pinkish light for plant culture with a 21 lm/W efficacy), "Green" (sharply peaked near 560 nm with an 109 lm/W efficacy), and the ever popular "Black Light" (with a barium silicate phosphor which peaks near 350 nm and yields a negligible efficacy).

All fluorescent lamps require some special provision to get the arc discharge going. In the preheat lamp (seen now for example in home aquaria or small desk lamps) a starter initially completes the circuit (as shown in Fig. 7.4A) and allows the two lamp cathodes to heat; when the starter switch opens, an inductive "kick" from the ballast produces a big enough voltage
transient to strike the arc through the partially ionized pre-heated gases in the tube. In an instant start lamp (shown in Fig. 7.4B) the ballast contains a transformer which provides sufficient open circuit voltage to strike the arc; in operation, a few turns of each cathode coil became hot enough to emit a copious supply of thermionic electrons. The rapid start lamp (used today in the vast majority of new fluorescent installations) features immediate heating of the cathodes (cf. Fig. 7.4C) which greatly reduces the voltage necessary to strike the arc. However, rapid start lamps do need an external starting aid in the form of a grounded metal strip running the length of the lamp not more than a centimeter or so from the lamp.

The ballast is an inductive impedance whose function is to limit the current through a fluorescent lamp. The lamp of course will, since it operates in a negative resistance regime, experience current runaway unless current is limited in a fashion such as this. The ballast normally consists of a core of laminated steel about which a coil has been wound; as Fig. 7.4 shows, core and coils may also have transformer-like properties. Additionally, the ballast must (under the provisions of the National Electrical Code) contain a thermal protector to interrupt power if the ballast overheats. The ballast will also generally contain a capacitor to increase the power factor. And, of late, there has been a tendency to view efficacy as a property of the system and not just the lamp so that some effort has been expended to minimize dissipation in the ballast itself.
Fig. 7.4
11. *The Low-Pressure Sodium-Vapor Lamp*

It seemed appropriate to discuss this arc discharge for three reasons. First, at least one source used for outdoor illumination should be considered. Second, its efficacy (about 150 lm/W) is higher than that of any other powerful commercial light source. Third, a name luminous in its history is that of Washington University's very own Arthur Holly Compton who (Elenbaas, 1972) developed the sodium resistant glass which made it practical.

What is remarkable about it is that roughly 85% of the emission from an excited sodium atom occurs in just two lines at 589.0 and 589.6 nm. The low-pressure sodium-vapor lamp gives off essentially no energy anywhere else in the visible. This is responsible for its very high efficacy but yields a very unusual color balance. Therefore these lamps are used primarily when one wishes to see the geometrical forms within a certain space and is unconcerned with their color or reflectivity.

Naturally, since it operates in a negative resistance region, this lamp must be ballasted.

12. *Considerations of Waveform and Power*

With respect to the puny demands of the lamps considered here, the power company's infinite busbar can be considered a rock which can not be moved: the supply voltage to the luminaire will be sinusoidal. However, because the resistivity of tungsten is a pronounced function of temperature (incandescent) and because striking, maintaining, and quenching an arc is an inherently
nonlinear phenomenon (fluorescent or sodium-vapor), a voltage

\[ v(t) = \sqrt{2} V_1 \cos \omega t \tag{7.26a} \]

will cause to flow a system current (lamp plus ballast) of

\[ i(t) = \sum_{p=1}^{\infty} \sqrt{2} I_p \cos (p \omega t - \theta_p) \tag{7.26b} \]

so that

\[ P = V_1 I_1 \cos \theta_1 \tag{7.27a} \]

\[ Q = V_1 I_1 \sin \theta_1 \tag{7.27b} \]

while

\[ I_{\text{rms}} = \sqrt{I_1^2 + \sum_{p=2}^{\infty} I_p^2} \tag{7.28} \]

and the distortion voltamperes are given by (cf. Chapter I)

\[ D = V_1 \left[ \sum_{p=2}^{\infty} I_p^2 \right]^{1/2} = \sqrt{S^2 - (P^2 + Q^2)} \tag{7.29} \]

\( Q \) can of course be reduced considerably by putting a suitable capacitor across the terminals of the ballast/lamp system. \( D \) however can not be removed and is simply with us for better or for worse. "Worse" is sometimes the case, for the higher harmonics can give rise to a variety of electrical interference phenomena if sensitive electronic equipment is present.
The legacy of Marvin Pipkin looms large in the history of electric lighting. But only for his luminous technical achievements. About Pipkin the man we know virtually nothing§.

In the early years of incandescent lamps, the bulb was of clear glass and the apparent source of light the filament itself. This caused severe glare and eye-strain and led to the development of lampshades which, in addition to reducing glare by diffusing the light, also reduced the reduced the intensity of illumination.

Then, about 1925, Marvin Pipkin of General Electric discovered the secret of inside-frosting light bulbs. For many years people had recognized the utility of frosting since it reduced the brilliance of the filament by a factor of roughly a hundred. And originally the frosting was achieved either by acid etching or spraying a mineral paint onto the exterior surface: both methods tended to absorb rather more light than one would wish; and the acid etched surface had a tendency to collect dirt and inhibit the removal thereof. However, inside etching weakened the bulb and enhance breakage (Howell and Schroeder, 1927). The problem was that the acid etch cut tiny sharp crevices in the glass, from which larger crevices were wont to grow when pressure was applied to the external surface (either by lowering the pressure inside the bulb or by incautious handling). Pipkin’s brilliant solution was to apply a second etch which rounded out the bottoms of the crevices and greatly inhibited stress-cracking of the bulb. The resultant bulb caused the apparent source of the light to expand from the filament to a sphere of much reduced luminance inside the bulb; the resulting loss in efficacy was about 2%, roughly three-fold less than with outside-frosting. With this advance, GE introduced the familiar “standard” bulb shape in the familiar 15, 25, 40, 50, 60, 100 sequence.

Not content to rest on his laurels, Pipkin went on in 1949 to invent the Q-coat process in which the inside of the lamp is “smoked” with minute particles of pure silica. This resulted in only a slight loss of efficacy (~2%) while making the apparent source of light the surface of the bulb itself. This breakthrough is familiar to you as the Soft White light bulb.

Let us now praise famous men, and our fathers that begat us. The Lord hath wrought great glory by them through his great power from the beginning ... Leaders of the people by their counsels, and by their knowledge of learning meet for the people, wise and eloquent are their instructions ... All these were honoured in their generations, and were the glory of their times. There be of them, that have left a name behind them, that their praises might be reported. And some there be, which have no memorial; who are perished, as though they had never been; and are become as though they had never been born; and their children after them. But these were merciful men, whose righteousness hath not been forgotten ... and their glory shall not be blotted out.

Ecclesiasticus 44: 1-13

§ If you can discover items of interest for the Pipkin Pages, please submit them to the instructor together with complete bibliographical details.
14. **Glossary and Manufacturers’ Data Sheets**

There are many specialized terms associated with lighting, as can be seen by examining the following glossary taken from a recent Graybar catalogue. On several following pages you will find interesting illustrations of items of interest and a Data Sheet on the photometric sensor.

15. **References Cited & Recent Monographs Worth Examining.**


**MONOGRAPHS**


ENERGY-SAVING TIPS ON LIGHTING PROBLEMS

The table below is a partial listing of recommended minimum footcandle levels established by the Illuminating Engineering Society (IES) for various commercial, industrial, institutional, and recreational tasks.

Three primary considerations when designing and specifying a lighting system are:
1. Selection of the most efficient light source possible in order to minimize power costs and energy consumption.
2. Matching the proper lamp type to the intended work task or aesthetic application, commensurate with color, brightness control and other requirements.
3. Establishing adequate light to maintain productivity, improve security and increase safety.

Note: Shaded areas denote outdoor task or application.

<table>
<thead>
<tr>
<th>Footcandles</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 fc</td>
<td>Reading Handwriting, Hard pencil, Active Filing</td>
</tr>
<tr>
<td>30 lc</td>
<td>Rough Assembly, difficult seeing, Rough Bench and machine work, Bank Tellers, Ordinary Inspection</td>
</tr>
<tr>
<td>20 lc</td>
<td>Corridors, Stairways, Elevator, Reading Glass, Printed Matter, Ship Fabricating</td>
</tr>
<tr>
<td>15 lc</td>
<td>Concourse, Freight Cars</td>
</tr>
<tr>
<td>10 lc</td>
<td>Service Station, entrance drive, Football Field (indoor), Ballfield, Dugout (indoor)</td>
</tr>
</tbody>
</table>

ENERGY SAVING LIGHTING—NOW!
Start saving energy and dollars now with GE Aircraft lamp types. Simply take out your old lamps and replace them with Energy-saving retrofits and get more light immediately, with no capital investment.

WHERE YOU NOW USE

<table>
<thead>
<tr>
<th>F40</th>
<th>F40 WATT-MISSER</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 WATT</td>
<td>7500</td>
</tr>
<tr>
<td>400 WATT</td>
<td>400 LINES M-V</td>
</tr>
</tbody>
</table>

CHARGE TO THIS

<table>
<thead>
<tr>
<th>GET THIS MUCH LIGHT</th>
<th>SAVE THIS MANY WATTS PER LAMP</th>
<th>GET THIS SAVING PER LAMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 WATT FLOOD</td>
<td>SAME OR MORE **</td>
<td>7 $5.60</td>
</tr>
<tr>
<td>400 WATT MERCURY</td>
<td>SAME OR MORE **</td>
<td>75 $6.00</td>
</tr>
</tbody>
</table>

*Based on 50% less energy rate over average rated lamp life. **Based on ECE light output where you need it. ***Based on equal value. Typically when older standard lamps are group installed with Watt-Missers and fixtures changed.

BASIC LIGHTING TERMS

ACCENT LIGHTING: directional lighting to emphasize a particular object or draw attention to a specific area.

AMBIENT TEMPERATURE: temperature surrounding the lamp, including lamp socket, wire, etc.

ANODIZING: any electrolytic or chemical process by which a protective or decorative film is realized on a metal surface.

ASYMMETRIC: unequal distribution about one or more axes.

BALLAST: an auxiliary electrical device for fluorescent and discharge light sources.

CANDLESPOWER OR CANDELA: basic unit for measuring luminous intensity from a light source in a given direction.

COEFFICIENT OF UTILIZATION: C.U.: the amount of light (lumen) delivered on a workplane or a percent of the rated lumen of the lamp or lamps.

COLOR VIEW: an electric-discharge lamp whose mode of operation is that of a glow discharge.

COVE LIGHTING: distributes light over the ceiling and upper walls.

DIFFUSER: a device to redirect or scatter the light from a source.

FOOTCANDLE: the unit of illumination when the foot (as taken as the unit of length) is the illumination on a surface one square foot in area on which there is a uniformly distributed flux of one lumen.

FOOTLAMBERT: a unit of luminance (photometric brightness) equal to one candela per square foot.

HAZARDOUS LOCATIONS: an area where ignitable vapors or dust may cause a fire or explosion created by energy emitted from lighting or other sources.

HIGH INTENSITY DISCHARGE LAMPS: a general group of lamps consisting of mercury, metal halide, high-pressure sodium and low-pressure sodium.

HIGH-PRESSURE SODIUM LAMP: a sodium vapor lamp in which the partial pressure of the vapor during operation is of the order of 0.1 atmospheres.

HIGH-PRESSURE LAMP: an electric-discharge lamp whose mode of operation is that of an arc discharge.

ILLUMINATION: the density of the light flow incident on a surface.

INCANDESCENT FILAMENT LAMP: a lamp in which light is produced by a filament heated to incandescence by an electric current.

KILOWATT HOUR:KWH: a measure of electrical energy.

LUMEN: the basic unit of light.

LUMINARIE: a complete lighting unit consisting of lamps, with parts for positioning and protecting the lamps, distributed the light, and to connect the lamps to the power supply.

MERCURY LAMP: an electric-discharge lamp in which the mean power of the radiation is produced by the emission from a mixture of metallic vapor and the products of the dissociation of helium.

NFC: National Electrical Code.

RACeway: any channel for holding wires, cables or bus bars designed and used solely for this purpose.

REFLECTOR: a device used to redirect the light from a source by reflecting it off the surface.

REFRACTOR: a device used to redirect the light from a source, primarily by bending the way of the light.

STREET LIGHTING UNIT: the assembly of a pole or lamppost with a bracket and luminaires.

SYMMETRIC: equal distribution about one or more axes.

TRIPOFF: a recessed lighting unit installed with a protective glass block or other shield.

TUNGSTEN-BULB-RATED LAMP: a gas-filled tungsten bulb-discharge lamp containing a certain proportion of halogen.

UNDERWATER LABORATORY: lights and fixtures meeting fire, safety, and electrical standards.
**ELECTRIC LIGHTING**

Electromagnetic Spectrum, Visible Spectrum, Color versus Wavelength, Illuminance

![Graph of Electromagnetic Spectrum]

**TABLE 1-1 Color Versus Wavelength**

<table>
<thead>
<tr>
<th>Color</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>760-630</td>
</tr>
<tr>
<td>Orange</td>
<td>630-590</td>
</tr>
<tr>
<td>Yellow</td>
<td>590-580</td>
</tr>
<tr>
<td>Green</td>
<td>560-490</td>
</tr>
<tr>
<td>Blue</td>
<td>490-440</td>
</tr>
<tr>
<td>Indigo</td>
<td>440-420</td>
</tr>
<tr>
<td>Violet</td>
<td>420-380</td>
</tr>
<tr>
<td>Purple</td>
<td>Not a pure spectral color</td>
</tr>
</tbody>
</table>

![Graph of Color Correction]

**Figure 1-6. Illuminance (1 lm/ft² = 1 footcandle).**
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Figure 4-1. Incandescent Lamp. (Courtesy of GTE Products Corp.)

Incandescent Sources

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 2400 2500 2600 2700 2800 2900 3000</td>
</tr>
</tbody>
</table>

Radiation power:
- 2600°C
- 3400°C

- Ultra violet
- Violet
- Indigo
- Blue
- Green
- Yellow
- Orange
- Red
ELECTRIC LIGHTING

Fluorescent Lamps

Compact fluorescent
Tubular
circle
U-Lamp

Figure 4-9. Fluorescent Lamp Shapes. (Courtesy of GE Lighting.)

Figure 4-11. Spectral Power Distribution for the Standard Fluorescent Lamps. (Courtesy of GE Lighting.)
ELECTRIC LIGHTING

Low Pressure Sodium-Vapor Lamps

![Diagram of Low Pressure Sodium-Vapor Lamp](image)

**Table 4-3. Low-Pressure Sodium Lamp (Only) Efficacy**

<table>
<thead>
<tr>
<th>Nominal Watts</th>
<th>Actual Lamp Watts (100 hr)</th>
<th>Lamp Efficacy (100 hr)</th>
<th>Actual Lamp Watts (18,000 hr)</th>
<th>Lamp Efficacy (18,000 hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18*</td>
<td>1,800 17</td>
<td>105.9 18</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>4,800 35</td>
<td>137.1 39</td>
<td>123.1</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>8,000 55</td>
<td>145.5 61</td>
<td>135.9</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>13,500 90</td>
<td>150.0 98</td>
<td>137.5</td>
<td></td>
</tr>
<tr>
<td>135</td>
<td>22,500 130</td>
<td>173.1 142</td>
<td>142</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>33,000 176</td>
<td>187.5 192</td>
<td>172</td>
<td></td>
</tr>
<tr>
<td>34,000†</td>
<td>192</td>
<td>177.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 18 W rated at 14,000 hr.
† Lumens at end of life.

**Table 4-2. Low-Pressure Sodium Lamps—Shape and Burning Position**

<table>
<thead>
<tr>
<th>Nominal Watts</th>
<th>MOL*</th>
<th>Lamp Shape</th>
<th>Burning Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>8.50</td>
<td>T17</td>
<td>UPH/OR</td>
</tr>
<tr>
<td>35</td>
<td>12.19</td>
<td>T17</td>
<td>UPH/OR</td>
</tr>
<tr>
<td>55</td>
<td>16.75</td>
<td>T17</td>
<td>UPH/OR</td>
</tr>
<tr>
<td>90</td>
<td>20.79</td>
<td>T21</td>
<td>HOR only</td>
</tr>
<tr>
<td>135</td>
<td>30.50</td>
<td>T21</td>
<td>HOR only</td>
</tr>
<tr>
<td>180</td>
<td>44.33</td>
<td>T21</td>
<td>HOR only</td>
</tr>
</tbody>
</table>

* Maximum Overall Length, in inches.

**Table 4-4. Low-Pressure Sodium Lamp (Lamp plus Ballast) Characteristics**

<table>
<thead>
<tr>
<th>Nominal Watts</th>
<th>Input Watts (100 hr)</th>
<th>System* Efficacy (100 hr)</th>
<th>Input Watts (18,000 hr)</th>
<th>System* Efficacy (18,000 hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>1,800</td>
<td>60.0 33</td>
<td>54.5</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>4,800</td>
<td>80.0 68</td>
<td>70.6</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>8,000</td>
<td>100.0 96</td>
<td>88.9</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>13,500</td>
<td>108.0 149</td>
<td>90.6</td>
<td></td>
</tr>
<tr>
<td>135</td>
<td>22,500</td>
<td>126.4 226</td>
<td>99.5</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>33,000</td>
<td>150.0 286</td>
<td>115.4</td>
<td></td>
</tr>
<tr>
<td>34,000†</td>
<td>286</td>
<td>118.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* System efficacy is lamp + ballast (ballast is a high-power-factor, high-reactance type).
† Lumens at end of life.

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LI-210SA Photometric Sensor

Use of the Photometric Sensor

The LI-210SA Photometric Sensor is designed to measure illumination in terms of lux (1 footcandle = 10.764 lux). This is radiation as the human eye sees it. The spectral response is shown in Figure 6.

This sensor may be handheld or mounted at any angle. In its most frequent application, the sensor is set on a level surface. It is most conveniently leveled by using the 2003S Mounting and Leveling Fixture.

Keep the sensor clean and treat it as a scientific instrument in order to maintain the accuracy of its calibration. The vertical edge of the diffuser must be kept clean in order to maintain appropriate cosine correction.

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Photometric Terms

Although characteristics of the human eye vary from person to person, standard luminosity coefficients for the eye were defined by the Commission Internationale de Eclairage (C.I.E., International Commission on Illumination) in 1931. An absolute "sensitivity" figure established for the standard eye relates photometric units and radiant power units. At 5550 angstroms (555 nm) the wavelength of the maximum sensitivity of the eye, one watt of radiant power corresponds to 680 lumens.

The sensitivity of the eye outside the wavelength limits defined by the C.I.E. is very low but not actually zero. Studies with intense infrared sources have shown that the eye is sensitive to radiation of wavelength at least as long as 10500 angstroms. According to Goodeve\(^5\) the ultraviolet sensitivity of the eye extends to between 3125 and 3023 angstroms. Below this level the absorption of radiation by the proteins of the eye lens apparently limits further extension of vision into the ultraviolet. Radiation having a wavelength of 3023 angstroms is detected by its fluorescent effect in the front part of the eye.

Photometry deals with the measurement of radiation in reference to the effect produced on the theoretical standard C.I.E. observer. Measurements are made by visual comparison, or by some equivalent photoclectric method. Units, standards, and systems of measurement have been developed to correspond to the effect as observed by the eye.

Luminous intensity (or candle-power) is a measure of a light source which describes its luminous flux per unit solid angle in a particular direction. For many years, the standard measure of luminous intensity was the international candle established by a group of carbon-filament lamps at the Bureau of Standards. In 1948 the International Commission of Illumination agreed on the introduction of a new standard of luminous intensity and recommended the adoption of the name candela to distinguish it from the international candle. The term candela is now widely used abroad and in general use in the United States; the older term candela is sometimes used but refers to the new candle or candela.

The candela is defined by the radiation from a black body at the temperature of solidification of platinum. A candela is one-sixtieth of the luminous intensity of one square centimeter of such a radiator. The major advantage of the new standard is that it may be reproduced in any laboratory. The effective change in the value of the candle as a result of the 1948 agreement is of the order of tenths of one percent and, therefore, is negligible in practical measurements.

Luminous flux is the time rate of flow of light energy that is characteristic of radiant energy which produces visual sensation. The unit of luminous
flux is the lumen, which is the flux emitted in units per solid angle by a uniform point of source of one candela. Such a source produces a total luminous flux of 4π lumens.

A radiant source may be evaluated in terms of luminous flux if the radiant energy distribution of the source is known. If \( W(\lambda) \) is the total radiant power in watts per unit wavelength, total radiant power over all wavelengths is

\[
\int_\lambda W(\lambda) \, d\lambda
\]

and the total luminous flux \( L \) in lumens can be expressed as

\[
L = \int_\lambda \left[ 680 W(\lambda) \right] \left[ y(\lambda) \right] \, d\lambda
\]

where \( y(\lambda) \) represents the luminosity coefficient as a function of wavelength and \( d\lambda \) is a differential of wavelength.

Illuminance is the density of luminous flux incident on a surface. A common unit of illuminance is the lux, which is the illumination produced by one lumen uniformly distributed over an area of one square meter. It follows that a source of one candela produces an illuminance of one lux at a distance of one meter. A footcandle is one candela at a distance of one foot.

**Spectral Response**

The spectral response of a typical LI-COR LI-210SA Photometric Sensor compared to the C.I.E. standard observer curve is presented in Figure 6. In 1976, LI-COR had sensor calibration data verified by the National Research Council of Canada (NRC), one of the major standards laboratories in the world. Information concerning these tests is available from LI-COR.

**Calibration**

The LI-210SA Photometric Sensor has been calibrated against a standard lamp. The uncertainty of the calibration is \( \pm 5\% \).

Beginning June 1, 1978, all LI-COR photometric sensors have been calibrated using 683 lumens per watt as the value of spectral luminous efficacy at a wavelength of 555 nm, rather than the previously accepted C.I.E. standard value of 680 lumens per watt.

This change was made to conform to the recommendations of the International Committee for Weights and Measures (CIPM) adopted at their September, 1977, meeting. The new value is considered to be the one that best relates the photometric and radiometric units currently maintained by the major national laboratories. It was adopted after considering the preferred values submitted by the national laboratories of nine countries. Therefore, measurements taken with LI-COR sensors calibrated after the above date will give illuminance values of 0.4% higher than would be obtained with the sensors calibrated at the old standards.

**LI-210SA Specifications**

- **Absolute Calibration:** \( \pm 5\% \) traceable to NBS.
- **Sensitivity:** Typically 20 µA per 100 klux.
- **Linearity:** Maximum deviation of 1% up to 100 klux.
- **Stability:** \( < \pm 2\% \) change over a 1 year period.
- **Response Time:** 10 µs.
- **Temperature Dependence:** \( \pm 0.15\% \) per °C maximum.
- **Cosine Correction:** Cosine corrected up to 80° angle of incidence.
- **Azimuth:** \( < \pm 1\% \) error over 360° at 45° elevation.
- **Tilt:** No error induced from orientation.
- **Detector:** High stability silicon photovoltaic detector (blue enhanced).
- **Sensor Housing:** Weatherproof anodized aluminum case with acrylic diffuser and stainless steel hardware.
- **Size:** 2.38 Dia. x 2.54 cm H (0.94" x 1.0").
- **Weight:** 28 g (1 oz.).
- **Cable Length:** 3.0 m (10 ft.).
- **Accessories:** 2003S Mounting and Leveling Fixture, 2222SB Extension Cable.
B. EXPERIMENT

1. Equipment List
   1 relay rack containing the usual test equipment
   1 Electrical Energy Monitor chassis
   1 stroboscopic light source (1 group at a time)
   1 single-phase wattmeter
   1 variable autotransformer
   1 quantum/radiometer/photometer (Li-Cor model Li-189)
   1 incandescent lamp test fixture
   1 60-W soft-white incandescent lamp
   1 60-W compact fluorescent lamp
   1 40-W warm-white rapid-start fluorescent lamp GE model F40WW-R5-WM
   1 LED lamp
   1 55-W low-pressure sodium-vapor lamp mounted in a test fixture
   Such other equipment as may prove useful

2. Flicker

   WARNING: Students with known or suspected epileptic tendencies must omit the flicker experiments.

   Step into the equipment storage room where the lab's only stroboscope has been set up#. Fiddle with the unit until you learn how it operates. Then turn off the room lights and adjust the flash frequency until the flicker ceases to be noticeable. Make a note of this frequency, converting the rpm readout to frequency in Hertz.

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# Obviously, since there is only one such device, not all groups can do this portion of the experiment first. Take turns!
3. **The Photometer and Its Use**

The photometers are durable, but still use care with this instrument. Attach a photometric head to the Li-189, and calibrate as follows: keep sensor cover on, turn on, press CAL, select proper units, and then adjust screw until the reading matches the value on the tag. Then press CAL to exit the calibration mode. Remove cover, measure and record ambient light.

4. **The 60-W Incandescent Lamp**

The 60-W incandescent lamp comes mounted in a test fixture whose block diagram is given in Fig. 7.5A. The overall experimental arrangement is shown in Fig. 7.5B. Fig. 7.6 shows a small chassis (the Electrical Energy Monitor) that is uncommonly useful for interconnecting various meters and parts. Observe that provision has been made for determining current and voltage waveforms *differentially* (Neutral cannot be assumed to be at ground until proven to be there beyond a reasonable doubt!), for determining rms voltage differentially, and for determining rms current.

(a) Measure the low-voltage dc resistance of the lamp when its filament is at room temperature.

(b) For this part only, employ **120 VDC**. Using your well-honed experimental arts, capture and print out the inrush current.

(c) Attach the wattmeter to measure power absorbed by the lamp. Set the lamp voltage to **120 VAC**. Measure and record the lamp current and the measured power and make a copy of the current waveform.

(d) Simultaneously display and then copy the lamp voltage and current waveforms at **120 VAC** using CH1 and CH2 of the scope and the FFT of the current. Measure any observable phase shift between the two waveforms. The measurement is simple, but normally requires a bit of thought in advance.

(e) Measure, as a function of AC lamp voltage, the lamp's current, wattage, and luminance. Cover the range of 0-120 VAC.

5. **The 60-W Compact Fluorescent Lamp**

Repeat (c), (d), and (e) above using the 60-W compact fluorescent lamp.

6. **The LED Lamp**

Repeat (c), (d), and (e) above using the LED lamp.
B.

Fig. 7.5
Electric Lighting - 48

Fig. 7.6
The 40-W Rapid-Start Fluorescent Lamp

The 40-W fluorescent lamp comes mounted in a test fixture whose block diagram is given in Fig. 7.7. The overall experimental arrangement is akin to Fig. 7.5B. The details of measurement are similar to those for the incandescent lamp.

(a) Set the luminaire voltage driving the ballast to 120 VAC; and simultaneously display and then copy the voltage and current waveforms and the FFT of the current waveform. Measure observable phase shift.

(b) Over the luminaire voltage range 100-125 V, measure system wattage, rms current, and luminance as a function of voltage.

(c) Observe and record the trans-electrode voltage when the rms input voltage to the luminaire is 120 V.

8. The 55-W Low-Pressure Sodium-Vapor Lamp

This lamp, together with its ballast comes mounted in a luminaire to which a cord with a three-prong plug is attached. Connect it to the wall by way of the arrangement shown in Fig. 7.5B.

(a) Set the luminaire voltage to 120 V and simultaneously display and then copy the voltage and current waveforms and the FFT of the current waveform. Measure observable phase shift.

(b) Over the luminaire voltage range 90-120 V, obtain system voltage, system wattage, rms current, and luminance as a function of voltage. Beware of device hysteresis #!

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# In particular, do not momentarily turn off the luminaire because it won't restart until it has cooled down! Note also that, by long standing tradition, at least one group always falls into this trap: Just don’t let it be you.
C. Report

(a) Flicker

At what frequency in Hertz did flicker cease to be annoying to you? What does this imply about the design of an AC power system for lighting use? For that matter, what does it imply about the refresh rate that you employ for your TV or PC Monitor?

(b) The 60-W incandescent lamp.

(i) Provide a hardcopy of the inrush current. Comment cogently. At a lamp voltage of 120 V, what are the voltage drops at the neutral return and across the 1.00-Ω resistor? Comment as to their magnitude compared to lamp voltage.

(ii) Present the hardcopy of the lamp voltage and current waveforms and the FFT of the current at 120 VAC. What is the observed phase shift between the two waveforms? And approximate power factor?

(iii) Tabulate lamp voltage, current, wattage and luminance. Normalize (e.g. use 120VAC values as base) the current, wattage, and luminance relative to their values at 120VAC and include these normalized values in the table.

(iv) On the same graph sheet, plot (as a function of lamp voltage) lamp current, system wattage, and luminance (each normalized relative to its value at 120 V)\(^*\). Comment cogently.

(v) On a separate graph sheet, plot system wattage versus the product (rms lamp voltage) x (rms lamp current). Comment cogently. Present in suitable fashion a comparison of the power factors derived in this graph. Comment cogently.

(vi) From your measurements, calculate the inferred filament temperature versus lamp voltage. Be very explicit about how you do this. Now tabulate this data and plot filament temperature versus voltage. Comment cogently on this result.

\(^*\) This process of plotting relative values is known as ‘normalization’.
(c) The 40-W fluorescent lamp.

(i) Present the hardcopy of the lamp voltage and current waveforms and the FFT of the current at 120 VAC. Determine the approximate power factor and comment.

(ii) Tabulate lamp voltage, current, wattage and luminance. Normalize the current, wattage, and luminance relative to their values at 120VAC and plot versus voltage on the same graph sheet. Comment.

(iii) On a separate graph sheet, plot system wattage versus the product (rms ballast voltage) x (rms system current). Comment cogently. In particular, what (if anything) do these data tell you about system power factor?

(iv) Present, in suitable form, your data on the trans-electrode voltage. Comment cogently.

(d) The 60-W Compact Fluorescent Lamp

(i) Present the hardcopy of the lamp voltage and current waveforms and the FFT of the current at 120 VAC. Determine the approximate power factor and comment.

(ii) Tabulate lamp voltage, current, wattage and luminance. Normalize the current, wattage, and luminance relative to their values at 120VAC and plot versus voltage on the same graph sheet. Comment.

(iii) On a separate graph sheet, plot system wattage versus the product (rms ballast voltage) x (rms system current). Comment cogently. In particular, what (if anything) do these data tell you about system power factor?

(e) The LED Lamp

(i) Present the hardcopy of the lamp voltage and current waveforms and the FFT of the current at 120 VAC. Determine the approximate power factor and comment.

(ii) Tabulate lamp voltage, current, wattage and luminance. Normalize the current, wattage, and luminance relative to their values at
120VAC and plot versus voltage on the same graph sheet. Comment.

(iii) On a separate graph sheet, plot system wattage versus the product (rms ballast voltage) x (rms system current). Comment cogently. In particular, what (if anything) do these data tell you about system power factor?

(f) Discuss the following issues for the sodium vapor lamp.

(i) Present the hardcopy of the lamp voltage and current waveforms and the FFT of the current at 120 VAC. Determine the approximate power factor and comment.

(ii) Tabulate lamp voltage, current, wattage and luminance. Normalize the current, wattage, and luminance relative to their values at 120VAC and plot versus voltage on the same graph sheet. Comment.

(iii) On a separate graph sheet, plot system wattage versus the product (rms ballast voltage) x (rms system current). Comment cogently. In particular, what (if anything) do these data tell you about system power factor?