

#### 4.5.2 Radiometry - Units and Definitions

Radiometry deals with the measurement of amounts of light. In radiometric terms the characteristics of a light source can be specified in several ways.

Radiant power,  $W$ , measured in watts, is the total amount of energy emitted by a light source per second. The spectral variation of radiant power can be specified in terms of the radiant power density per unit wavelength interval,  $W_\lambda$ . Clearly,

$$W = \int_0^\infty W_\lambda d\lambda. \quad (125)$$

If a light source emits radiation only for some specific duration - which may be quite short in the case of a flashlamp - it is more useful to specify the source in terms of its radiant energy output,  $Q_e$ , measured in joules. If the source emits radiation for a time  $T$ , we can write

$$Q_e = \int_0^T W(t) dt. \quad (126)$$

The amount of power emitted by a source in a particular direction per unit solid angle, is called radiant intensity,  $I_e$ , measured in units of watts per steradian. In general,

$$W = \oint I_e(\omega) d\omega, \quad (127)$$

where the integral is taken over a closed surface surrounding the source. If  $I_e$  is the same in all directions, the source is said to be an isotropic radiator. At a distance  $r$  from such a source, where we will assume that  $r$  is much greater than the dimensions of the source, the radiant flux crossing a small area  $\Delta S$  is

$$\phi_e = \frac{I_e \Delta S}{r^2}. \quad (128)$$

The irradiance at this point, measured in Watts  $\text{cm}^{-2}$  is

$$E_e = \frac{I_e}{r^2}, \quad (129)$$

which is equal to the average value of the Poynting vector measured at the point. The radiant flux emitted per unit area of a surface, whether this be the surface of a source itself or a surface which is reflecting and scattering radiation, is called the radiant emittance,  $M_e$ , measured in units of watts  $\text{m}^{-2}$ .

For an extended source, the radiant flux emitted per unit solid angle per unit area of the source is called its radiance,  $L_e$ .

$$L_e = \frac{\delta I_e}{\delta S_n}, \quad (130)$$

where the area  $\delta S_n$  is the projection of the surface element of the source in the direction being considered. When the light emitted from a source or scattered from a surface has a radiance that is independent of viewing angle the source or scatterer is called a perfectly diffuse or Lambertian radiator. Clearly, for such a source, the radiant intensity at an angle  $\theta$  to the normal to the surface is

$$I_e(\theta) = I_e(0) \cos \theta. \quad (131)$$

The total flux emitted per unit area of such a surface is its radiant emittance, which in this case is

$$M_e = \pi I_e(0). \quad (132)$$

Illuminated diffusing surfaces made of finely ground glass or finely powdered magnesium oxide will behave as Lambertian radiators.

For plane waves, since all the energy in the wave is transported in the same direction, the concepts of radiant intensity or emittance are not useful. It is customary to specify the radiant flux crossing unit area normal to the direction of propagation, and call this the intensity,  $I$ , of the plane wave. Because lasers emit radiation into an extremely small solid angle, they have very high radiant intensity and it is once again more usual to refer to the intensity of the laser beam at a point as the energy flux per second per unit area. The total power output of a laser is

$$W = \int_{\text{Beam}} I dS . \quad (133)$$

### 4.5.3 Photometry

The response of the human eye gives rise to a non-linear and wavelength-dependent subjective impression of radiometric quantities. Because of the wavelength-dependent response of the human eye, which extends roughly from 400 nm to 700 nm with a peak at 555 nm for the photopic (light-adapted) eye, measures in photometry take into account this so-called relative spectral luminous efficiency  $V(\lambda)$ . Thus, for example, in physiological photometry the luminous flux  $F$  is related to radiant flux  $\phi_e(\lambda)$  by

$$F = K \int_0^{\infty} V(\lambda) \phi_e(\lambda) d\lambda, \quad (134)$$

where  $K$  is a constant. When  $F$  is measured in lumens and  $\phi_e(\lambda)$  is measured in watts,  $K \equiv 679.6 \text{ lumen watt}^{-1}$ . Other photometric quantities which may be encountered in specifications of light sources are: the luminous intensity measured in candela, where

$$1 \text{ candela} = 1 \text{ lumen str}^{-1},$$

the illumination, measured in units of candela  $\text{cm}^{-2}$ , which is a measure of the amount of light reaching an area, and the luminance, also measured in candela  $\text{cm}^{-2}$  which is a measure of the amount of light leaving a surface in a given direction. A Lambertian source has a luminance which is independent of observation direction. Photometric description of the characteristics of light sources should be avoided in strict scientific work, although some catalogs of light sources may use photometric units to describe lamp performance. For further details of photometry, and other concepts such as color in physiological optics, the reader should consult Applied Optics by Levi<sup>17</sup>, or Fry.<sup>34</sup>

#### 4.5.4 Line Sources

Line sources are used as wavelength standards for calibrating spectrometers and interferometers, as sources in atomic absorption spectrometers, in interferometric arrangements for testing optical components, such as Twyman-Green interferometers (Section 4.7.6(a)), in a few special cases for optically pumping solid state and gas lasers, and for illumination purposes.

##### (a) Line Shapes

The emission lines from a line source are not infinitely sharp. The variation of the radiant intensity with frequency across a line whose center frequency is  $\nu_0$  is described by its lineshape function  $g(\nu, \nu_0)$ , where

$$\int_{-\infty}^{\infty} g(\nu, \nu_0) d\nu = 1. \quad (135)$$

The extension of the lower limit of this integral to negative frequencies is done for formal theoretical reasons connected with Fourier theory and need not cause any practical problems, since for a sharp line the major contribution to the integral in Eq. (135) comes from frequencies close to the center frequency  $\nu_0$ . There are three main types of lineshape function which are worthy of note<sup>35</sup>:

The Lorentzian lineshape function

$$g_L(\nu, \nu_0) = \frac{2}{\pi \Delta \nu} \frac{1}{1 + [(\nu - \nu_0) / \Delta \nu]^2}, \quad (136)$$

where  $\Delta \nu$  is the frequency spacing between the half-intensity points of the line (the full width at half maximum height or FWHM). Spectral lines at long wavelengths (in the middle and far-infrared) and lines emitted by heavy atoms at high pressures and/or low temperatures frequently show this type of lineshape.

The Gaussian lineshape function

$$g_D(\nu, \nu_0) = \frac{2}{\Delta \nu_D} \left( \frac{\ln 2}{\pi} \right)^{\frac{1}{2}} \exp \left\{ -[2(\nu - \nu_0) / \Delta \nu_D]^2 \ln 2 \right\} \quad (137)$$

where  $\Delta \nu_D$  is the FWHM. Gaussian lineshapes are usually associated with visible and near-infrared lines emitted by relatively light atoms in discharge tube sources at moderate pressures. In this case, the broadening comes from the varying Doppler shifts of emitting species whose velocity distribution in the gas is Maxwellian. However, emitting ions in real crystals sometimes have this type of lineshape because of the random variations of ion environment within a real crystal produced by dislocations, impurities and other lattice defects. A Lorentzian and Gaussian lineshape are compared in Fig. (4.74). Frequently, the broadening processes responsible for Lorentzian and Gaussian broadening are simultaneously operative, in which case the resultant lineshape is a convolution of the two, and is called a Voigt profile.

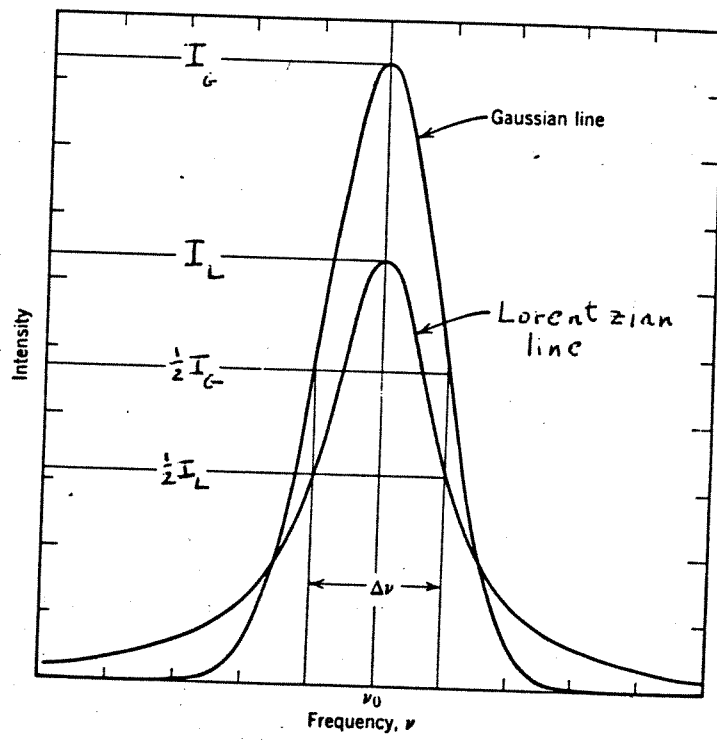


Fig. (4.74)

The low pressure mercury lamp is the most commonly used narrow line source, these lamps actually operate with a mercury-argon or mercury-neon mixture. The principle lines from a mercury-argon lamp are listed in Table (4.3). Numerous other line sources are also available, notably hollow cathode lamps which emit the strongest spectral line of any element desired for use in atomic absorption spectrometry. Such lamps are available from Oriel and Baird Atomic, among others.

TABLE 4.4

Wavelengths of Characteristic lines from a Mercury Lamp ( $\mu\text{m}$ )\* (vac.)

0.253652  
0.313156  
0.313184  
0.365015  
0.365483  
0.366328  
0.404656  
0.435835  
0.546074  
0.576960  
0.579066  
0.69075  
0.70820  
0.77292  
1.0140  
1.1287  
3.9425

\* Extensive listings of calibration lines from other sources can be found in references 126 and 127.

#### 4.5.5 Continuum Sources

A continuum source in conjunction with a monochromator can be used to obtain radiation whose wavelength is tunable throughout the emission range of the source. However, if the wavelength region transmitted by the monochromator is made very small, not very much energy will be available in the wavelength region selected. Even so, continuum sources find extensive use in this way in absorption and fluorescence spectrometers. Certain continuum sources called black-body sources have very well characterized radiance as a function of wavelength and are used for calibrating both the absolute sensitivity of detectors and the absolute radiance of other sources.

##### (a) Black-Body Sources

All objects are continuously emitting and absorbing radiation. When an object is in thermal equilibrium with its surroundings, it emits and absorbs radiation in any spectral interval at equal rates. An object which absorbs all radiation incident on it is called a black-body - its absorbivity  $\alpha$  is equal to unity. Such a body is also the most efficient of all emitters - its emissivity  $\epsilon$  is also unity. In general, for any object emitting and absorbing radiation at wavelength  $\lambda$ ,  $\epsilon_{\lambda} = \alpha_{\lambda}$ . Highly reflecting, opaque objects, such as polished metal surfaces, do not absorb radiation efficiently, nor when heated do they emit radiation efficiently.

The simplest picture of a black-body source is a heated-hollow object with a small hole in it. Any radiation entering the hole has minimal chance of re-emerging. Consequently, the radiation leaving the hole will be characteristic of the

interior temperature of the object. The energy density distribution of this black-body radiation is

$$\rho(\nu) = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{h\nu/kT} - 1} \quad (138)$$

where  $\rho(\nu)d\nu$  is the energy stored ( $\text{J m}^{-3}$ ) in a small frequency band  $d\nu$  at  $\nu$

The energy density distribution with wavelength is

$$\rho(\lambda) = \frac{8\pi hc}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} \quad (137)$$

This translates into a spectral emittance  $M_{e\lambda}$  (the total power emitted per unit wavelength interval into a solid angle of  $2\pi$  by unit area of the black-body) of

$$M_{e\lambda} = \frac{C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} \quad (140)$$

where  $C_1 = 2\pi hc^2$ , called the first radiation constant, has the value  $3.7405 \times 10^{16} \text{ Wm}^2$  and  $C_2 = hc/k$ , called the second radiation constant, has the value  $= 1.43878 \times 10^{-2} \text{ m}^\circ\text{K}$ .

A true black-body is also a diffuse (Lambertian) radiator. Its radiance is independent of the viewing angle. For such a source

$$M_{e\lambda} = \pi L_{e\lambda} \quad (141)$$

The variation of  $L_{e\lambda}$  with wavelength for various values of the temperature is shown in Fig. (4.75). The wavelength of maximum emittance  $\lambda_m$  at temperature  $T$  obeys Wien's displacement law

$$\lambda_m T = 2.8978 \times 10^{-3} \text{ m } ^\circ\text{K} . \quad (142)$$

The total radiant emittance of a black-body at temperature  $T$  is

$$M_e = \int_0^\infty M_{e\lambda} d\lambda = \frac{2\pi^5 k^4}{15c^2 h^3} T^4 = \sigma T^4 . \quad (143)$$

Eq. (131) is a statement of the Stefan-Boltzmann law.  $\sigma$ , called the Stefan-Boltzmann constant, has a value of  $5.6697 \times 10^{-8} \text{ Wm}^{-2} (\text{ }^\circ\text{K})^{-4}$ . The known parameters  $M_{e\lambda}$  and  $M_e$  of a black-body allow it to be used as an absolute calibration source in radiometry. If a detector responds to photons the spectral emittance in terms of photons,  $N_\lambda$ , may be useful

$$N_\lambda = \frac{M_{e\lambda}}{(hc/\lambda)} . \quad (144)$$

Curves of  $N_\lambda$  are given by Kruse, McGlauchlin and McQuistan.<sup>36</sup>

A source whose spectral emittance is identical to a black-body, apart from a constant multiplicative factor, is called a gray-body. The constant of proportionality,  $\epsilon$ , is called the emissivity. Several continuum sources such as tungsten filament lamps, carbon arcs and flash lamps are approximately gray-body emitters within certain wavelength regions.

#### (b) Practical Black-Body Sources

The radiant emittance of a black-body increases at all wavelengths as the temperature of the black-body is raised, so a practical black-body should, ideally, be a heated body with a small emitting aperture which is kept as hot as possible. Kruse,

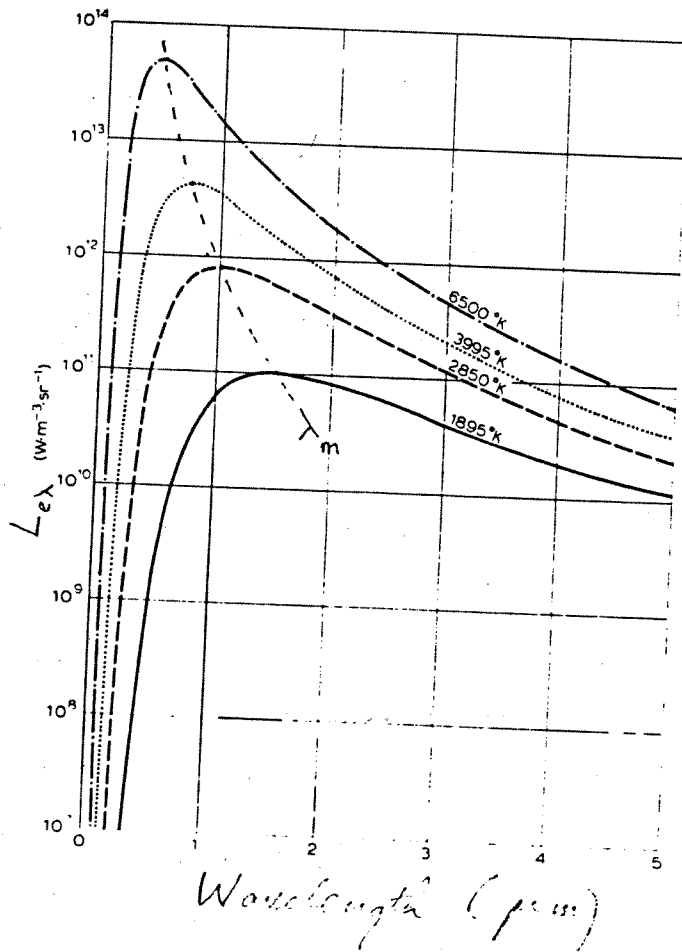


Fig. (4.75)

McGlauchlin and McQuistan<sup>36</sup> describe such a source, illustrated in Fig. (4.76), that can be operated at temperatures as high as 3000°K. 25µm thick tungsten ribbon 2 cm wide is rolled on a 3mm diameter copper mandrel and seamed with a series of overlapping spot welds. A hole about 0.75mm in diameter is made in the foil and the copper dissolved out with nitric acid under a fume-hood. The resulting cylinder is mounted on 1mm diameter Kovar or tungsten rod feed-throughs in a glass envelope and heated from a high-current, low-voltage power supply. The glass envelope should be fitted with a window that is transmissive to the wavelength region desired from the source.

Another design of black-body source is shown in Fig. (4.77). This design is based on a heated copper cylinder which contains a conical cavity of 15° semi-vertical angle which is allowed to oxidize during operation (so that it becomes non-reflective and consequently of high emissivity). The cylinder is heated by an insulated heater wire wrapped around its circumference. If nichrome wire is used, the cylinder can be heated to about 1400°K. This assembly is mounted in a ceramic tube, alumina is quite satisfactory, or potted in high temperature ceramic cement. For high temperature operation the whole assembly can be mounted inside a water cooled block.

The most popular black-body source available commercially is the Globar, a rod of bonded silicon carbide available from Carborundum, Perkin-Elmer, and Oriel. For further details of the advantages and disadvantages of this and various other black-body sources, the reader is referred to Hudson.<sup>37</sup>

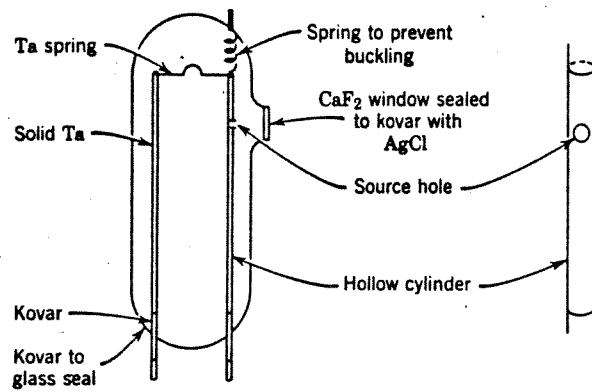


Fig. (4.76)

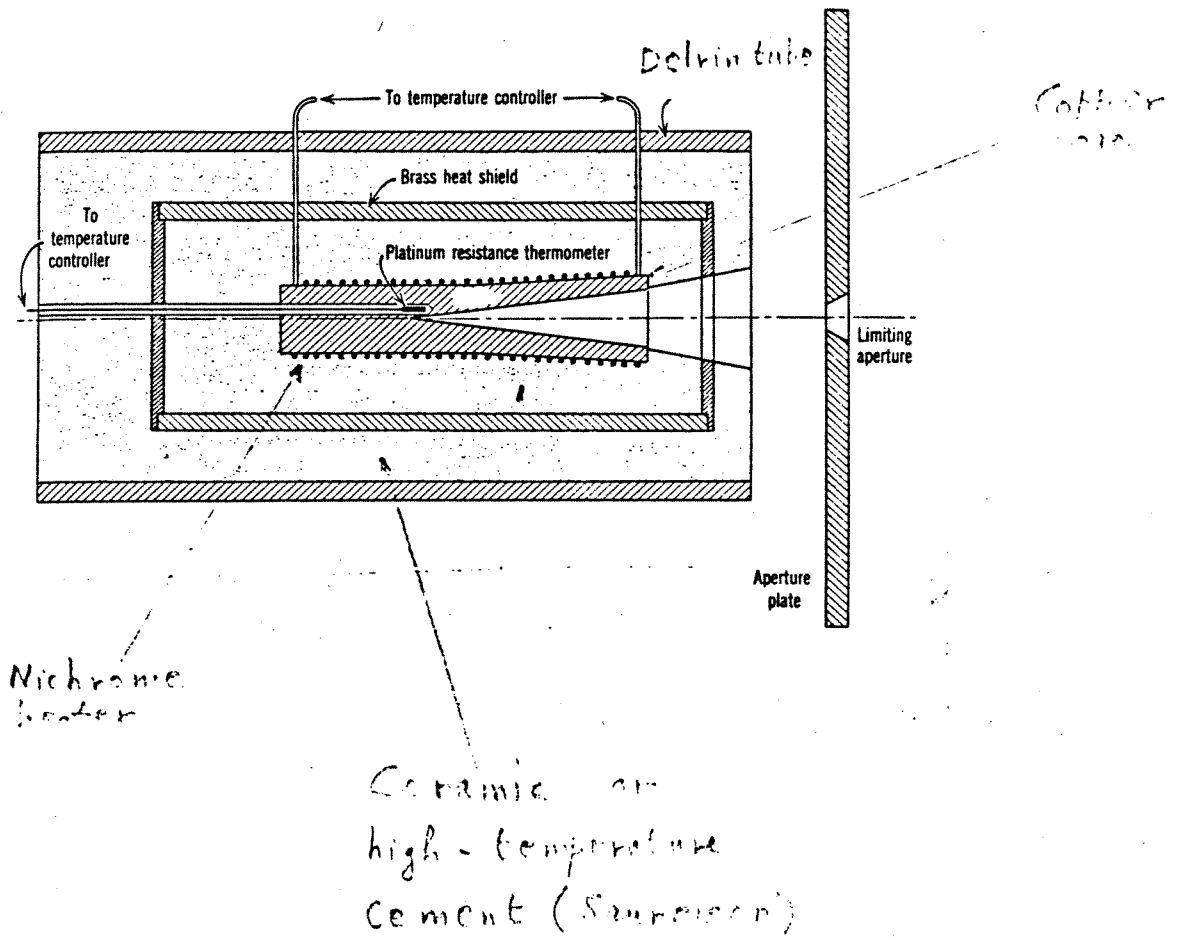
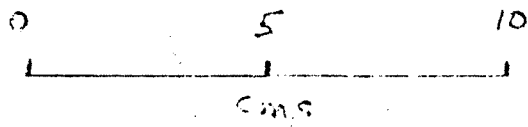


Fig. (4.77)

(c) Tungsten Filament Lamps

Tungsten filament lamps are approximately gray-bodies in the visible with an emittance between 0.45 and 0.5. Such lamps are frequently described in terms of their color temperature,  $T_c$ , which is the temperature at which a black-body would have a spectral emittance closest in shape to the lamp. The color temperature will depend on the operating conditions of the lamp.

Lamps with calibrations of color temperature versus operating current are available from EG&G and GE. Tungsten filament lamps can most conveniently be operated in the laboratory with a Variac, however, for best stability and freedom from ripple on their output, they should be operated from a stabilized dc supply. Typical supply requirements range up to few hundred volts. Lamps with wattage ratings up to 1kW are readily available. Small size tungsten filament lamps which can be used as point sources are available from Oriel. Very-long-life and constant efficiency tungsten-halogen lamps are available in which the lamp envelope usually contains a small amount of iodine. In operation, the iodine vaporizes and recombines with tungsten that has evaporated from the filament and deposited on the inside of the lamp envelope. The tungsten iodate thus formed diffuses to the hot filament where it decomposes redepositing tungsten on the filament. The constant replacement of the filament in this way allows the filament to be operated at very high temperature and radiant emittance. Because the lamp envelope must withstand the chemical action of hot iodine vapor and high temperatures, it is made of quartz, hence such lamps are frequently called quartz-iodine lamps. Such lamps can be quite compact, a 1kW lamp will have a filament length of about 1 cm.

The N.B.S. standard of spectral irradiance consists of a quartz iodine lamp with a coiled-coil tungsten filament operating at about  $3000^{\circ}\text{K}$  and calibrated from 250nm to  $2.6\mu\text{m}$  against a black-body source.

Such calibrated lamps are available from E.G.&G. Because they are intense sources of radiant energy, these lamps can be used for heating purposes. They are particularly useful when placed inside complex vacuum systems to bake out internal components which are otherwise well insulated thermally from the chamber walls.

#### (d) Continuous Arc Lamps

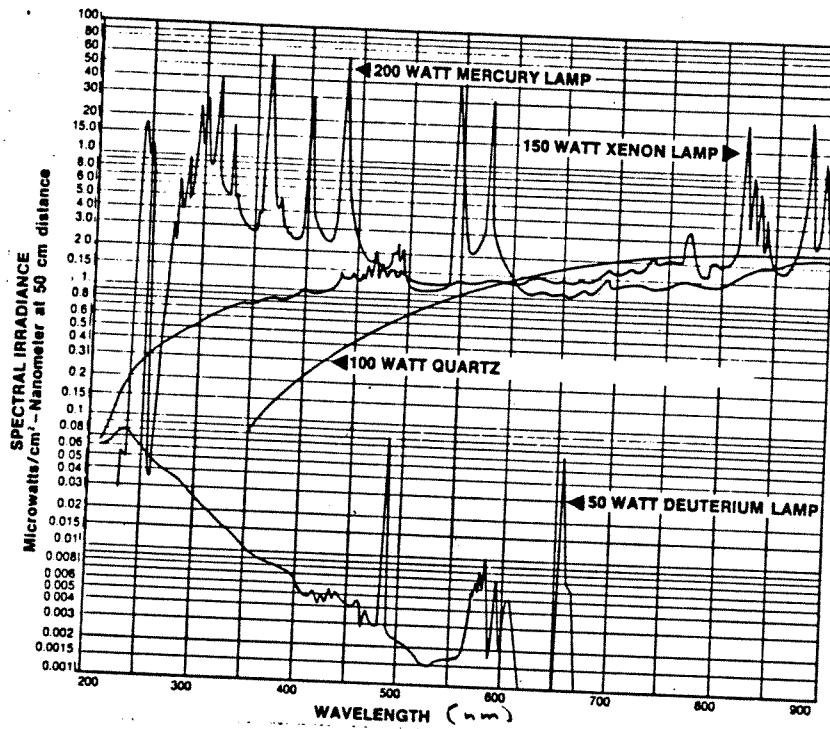
High current electrical discharges in gases, with currents that typically range from 1-100 amps, can be intense sources of continuum or line emission and sometimes both at the same time. For substantial continuum emission the most popular such lamps are the high pressure xenon, high pressure mercury and high pressure mercury-xenon lamps. The arc size in these lamps typically ranges up to about 5cm long and 6.2mm diameter (for a 10kW lamp - 100V, 100A input). Because of their small size, arc lamps have much higher spectral radiance (brightness) than quartz iodine lamps of comparable wattage. In the visible region at 500nm a typical xenon arc lamp shows 1.9 times the output of a quartz-iodine lamp, at 350nm 14 times and at 250nm, 200 times. In addition, because of their small size, high pressure arc lamps lend themselves well to the illumination of monochromator slits in spectroscopic applications. Lower wattage arc lamps come close to being point sources and are ideal for use in projection systems and for obtaining well collimated beams.

There are two different kinds of high pressure arc lamps, those where the discharge is confined to a narrow quartz capillary - which

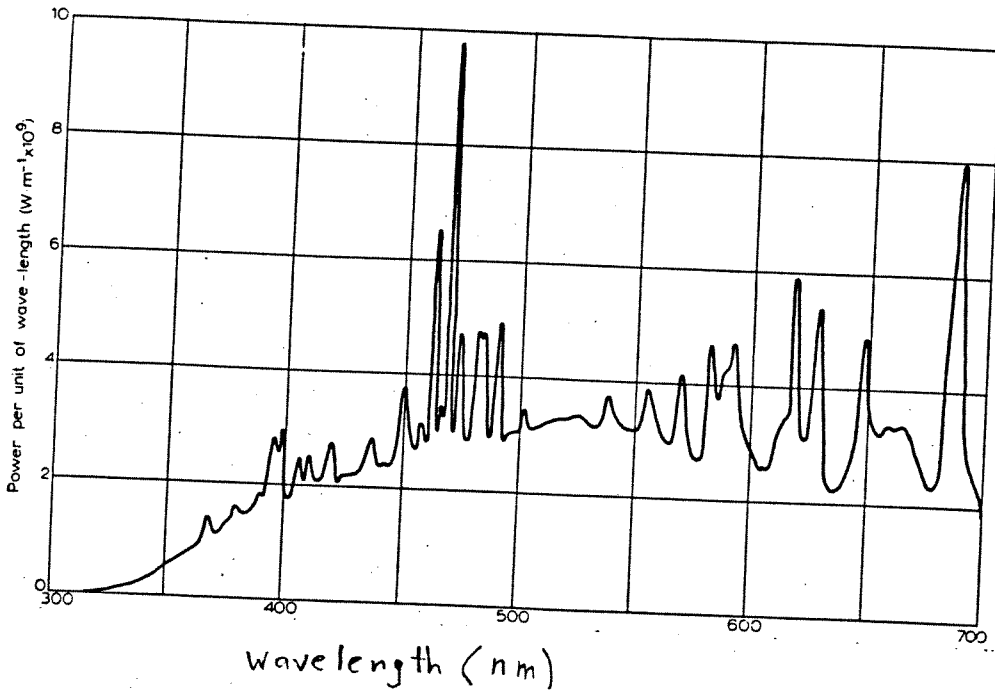
must be water cooled - and those where the discharge is not confined and which usually operate with forced air cooling. The former are available from Illumination Industries/PEK and are used for pumping CW solid state lasers (krypton arc lamps are better than xenon arc lamps for pumping  $\text{Nd}^{3+}$  lasers as their emission is better matched to the absorption spectrum of  $\text{Nd}^{3+}$  ions.)

Because high pressure arc lamps operate at very high pressures when hot - up to 200 bars they must be housed in a rugged metal enclosure to contain a possible lamp explosion. The mounting must be such as to allow stress-free expansion during warmup. Generally speaking, commercial lamp assemblies should be used. Power supplies requirements are somewhat unusual, a high voltage pulse is necessary initially to strike the arc and then a voltage, typically in the range 70-120V, to establish the arc. When the arc is fully established, the operating voltage will drop to perhaps as low as 10V. Arcs containing mercury need a further increase in operating voltage as they warmup and their internal mercury pressure increases. Complete lamp assemblies and power supplies are available from several companies: for example, Oriel and Conrad-Hanovi

High pressure arc lamps give substantial continuum emission with superimposed line structure as can be seen in Fig. (4.78). These lamps are not efficient sources of infrared radiation. However, they give substantial UV emission and care should be taken in their use to avoid eye or skin exposure. Their UV output will also generate ozone and provision should be made for venting this safely from the lamp housing. Deuterium lamps are efficient sources of ultraviolet emission with very little emission at longer wavelengths as shown in Fig. (4.78a). They are available from Oriel.



(a)



(b)

Fig. (4.78)

# Photometry

Spectral response of the normal human eye with luminous to radiometric conversion.

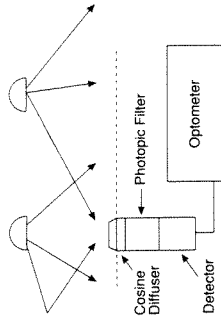
Wavelength (nm)	V <sub>λ</sub> CIE Photopic Luminous Efficiency Coefficient	Photopic Lumen/Watt Conversion Factor
380	0.0000	0.05
390	0.0001	0.13
400	0.0004	0.27
410	0.0012	0.82
420	0.0040	2.73
430	0.0116	7.91
440	0.0230	15.7
450	0.0380	25.9
460	0.0600	40.9
470	0.0910	62.1
480	0.1390	94.8
490	0.2080	142.0
500	0.3230	220.0
510	0.5030	343.0
520	0.7100	484.0
530	0.8620	586.0
540	0.9540	650.0
550	0.9950	679.0
555	1.0000	683.0
560	0.9950	679.0
570	0.9520	649.0
580	0.8700	593.0
590	0.7570	516.0
600	0.6310	430.0
610	0.5030	343.0
620	0.3810	260.0
630	0.2650	181.0
640	0.1750	119.0
650	0.1070	73.0
660	0.0610	41.4
670	0.0320	21.8
680	0.0170	11.6
690	0.0082	5.59
700	0.0041	2.78
710	0.0021	1.43
720	0.0010	0.716
730	0.0005	0.355
740	0.0003	0.170
750	0.0001	0.820
760	0.0001	0.041

# Photometric Quantities and Units

Quantity	Symbol	Units	Abbreviations
Luminous energy	Q <sub>v</sub>	lumen-second = talbot	lm·s = talbot
Luminous density	U <sub>v</sub>	lumen·second/m <sup>3</sup>	lm·s/m <sup>3</sup>
Luminous flux	F <sub>v</sub>	lumen	lm
Illuminance	E <sub>v</sub>	lumen/m <sup>2</sup> = lux	lm/m <sup>2</sup> = lx
		lumen/cm <sup>2</sup> = phot	lm/cm <sup>2</sup> = ph
		lumen/ft <sup>2</sup> = footcandle	lm/ft <sup>2</sup> = fc
		same units as illuminance	
Luminous exitance	M <sub>v</sub>	candela/m <sup>2</sup> = nit	cd/m <sup>2</sup> = nit
Luminance (brightness)	L <sub>v</sub>	candela/cm <sup>2</sup> = stilb	cd/cm <sup>2</sup> = sb
		candela/π m <sup>2</sup> = apostilb	cd/π ft <sup>2</sup> = fl
		candela/π m <sup>2</sup> = lambert	cd/π m <sup>2</sup> = asb
		candela/steradian = candela	cd/π cm <sup>2</sup> = L
Luminous intensity	I <sub>v</sub>	lumen/steradian = candela	lm/st = cd

# Graseby Optronics Guide to Optical Units

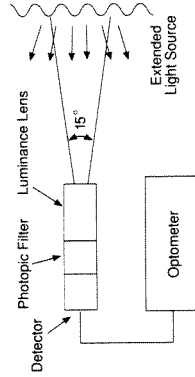
## Typical Illumination Measurement



## Illumination Conversion Factors

Multiply Number > To Obtain Number of	By	Footcandles		Lux		Phot		Milliphot	
		Footcandles	Lux	Phot	Milliphot				
Footcandles	1	10.76	0.0929	929	0.929	10,000	10	10,000	10
Lux	0.00108	0.00108	0.0001	1	0.001	1	0.001	1	0.001
Phot	1.076	1.076	0.1	1,000	1,000	1,000	1	1,000	1
Milliphot									

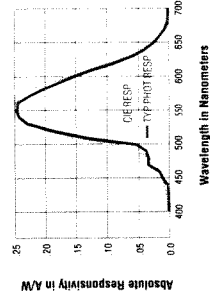
## Typical Luminance Measurement



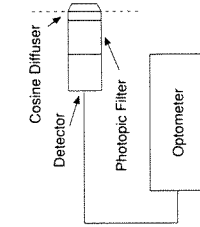
## Luminance (Photometric Brightness) Conversion Factors

Multiply Number > To Obtain Number of	By	Footlambert		Nit		Millilambert		Candela/in <sup>2</sup>		Candela/ft <sup>2</sup>		Stilb	
		Footlambert	Nit	Millilambert	Candela/in <sup>2</sup>	Candela/ft <sup>2</sup>	Stilb						
Footlambert	1	3.426	0.2919	0.929	452	3.142	2,919	10,76	10,000	10,000	10,000	10,000	10,000
Nit	1.076	1.076	0.3142	1	487	3.382	3,142	1	1	1	1	1	1
Millilambert	0.00221	0.00221	0.000645	0.00205	1	0.00694	6.45	0.00221	0.00221	0.00221	0.00221	0.00221	0.00221
Candela/in <sup>2</sup>	0.3183	0.3183	0.0929	0.2919	1	0.00032	0.155	0.3183	0.3183	0.3183	0.3183	0.3183	0.3183
Candela/ft <sup>2</sup>	0.00034	0.00034	0.0001	0.00032	0.155	0.00108	0.00108	0.00034	0.00034	0.00034	0.00034	0.00034	0.00034
Stilb													

## Typical Photometric Detector Response



## Photometric Energy Measurement



## Photographic Terms

Speed of Photographic Materials

E = Exposure measured in Lux-sec

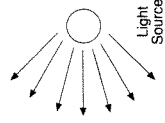
ASA index = 5/E

DIN index = (10 log E) - 5

Illumination of Camera Image Plane  
B = Brightness of object measured in candelas/sq. ft.

I = Illumination on image plane = πB/4 (f#)<sup>2</sup>

Where illumination at object plane = πB

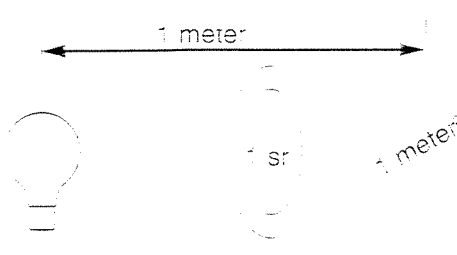
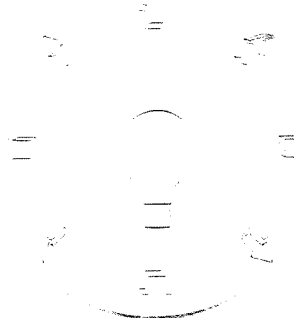
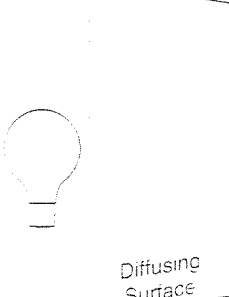



**PHOTOMETRIC UNITS**

- LUMINOUS FLUX: (Visible Flux)**  
 1 lumen (lm) = 1.464 x 10<sup>-3</sup> watts at 555 nm  
 = 7.958 x 10<sup>-2</sup> candela (isotropic)
- ENERGY: (Visible Flux \* Time)**  
 1 lm\*s = 1 talbot (T)  
 = 1.464 x 10<sup>-3</sup> joules at 555 nm
- LUMINOUS INTENSITY: (Vis. Flux per Solid Angle)**  
 1 lm/sr = 1 candela (cd)  
 = 12.566 lumens (isotropic)  
 = 1.464 x 10<sup>-3</sup> watts/sr at 555 nm
- ILLUMINANCE: (Visible Flux Density)**  
 1 lm/m<sup>2</sup> = 1 lux (lx)  
 = 10<sup>-4</sup> lm/cm<sup>2</sup>  
 = 10<sup>-4</sup> phot (ph)  
 = 9.290 x 10<sup>-2</sup> lm/ft<sup>2</sup>  
 = 9.290 x 10<sup>-2</sup> foot-candles (fc)
- LUMINANCE: (Visible Flux Density per Solid Angle)**  
 1 lm/m<sup>2</sup>/sr = 1 candela/m<sup>2</sup> (cd/m<sup>2</sup>)  
 = 1 nit  
 = 10<sup>-4</sup> lm/cm<sup>2</sup>/sr  
 = 10<sup>-4</sup> cd/cm<sup>2</sup>  
 = 10<sup>-4</sup> stilb (sb)  
 = 9.290 x 10<sup>-2</sup> cd/ft<sup>2</sup>  
 = 9.290 x 10<sup>-2</sup> lm/ft<sup>2</sup>/sr  
 = 3.142 apostilbs (asb)  
 = 3.142 x 10<sup>-4</sup> lamberts (L)  
 = 2.919 x 10<sup>-1</sup> foot-lamberts (fL)

**RADIANT UNITS**

- RADIANT FLUX: (Flux)**  
 1 watt (W) = 1 joule/second  
 = 10<sup>7</sup> erg/second  
 = 0.27 lm at 400 nm  
 = 25.9 lm at 450 nm (blue)  
 = 220.0 lm at 500 nm  
 = 679.0 lm at 550 nm (green)  
 = 683.0 lm at 555 nm (CIE peak)  
 = 430.0 lm at 600 nm  
 = 73.0 lm at 650 nm (red)  
 = 2.78 lm at 700 nm  
 = 14,330 gram\*calorie/min
- ENERGY: (Flux \* Time)**  
 1 joule (J) = 10<sup>7</sup> erg  
 = 1 watt\*second  
 = 0.2388 gram\*calories
- RADIANT INTENSITY: (Flux per Solid Angle)**  
 1 W/sr = 12.566 watts (isotropic)  
 = 683 candela at 555 nm
- IRRADIANCE: (Flux Density)**  
 1 W/cm<sup>2</sup> = 10<sup>4</sup> watts/m<sup>2</sup>  
 = 6.83 x 10<sup>6</sup> lux at 555 nm  
 = 14,330 gram\*calories/cm<sup>2</sup>/min  
 = 14,330 langley/min
- RADIANCE: (Flux Density per Solid Angle)**  
 1 W/cm<sup>2</sup>/sr = 6.83 x 10<sup>6</sup> lm/m<sup>2</sup>/sr at 555 nm  
 = 683 cd/cm<sup>2</sup> at 555 nm

<p><b>IRRADIANCE &amp; ILLUMINANCE</b>  <i>(Density of light incident upon a surface)</i></p>  <p>A 1 watt/steradian source produces 1 W/m<sup>2</sup> at 1 m.          A 1 candela (1 lumen/steradian) source produces 1 lm/m<sup>2</sup> (1 lux) at 1 m. and 1 lm/ft<sup>2</sup> (1 fc) at 1 ft.</p>	<p><b>RADIANT &amp; LUMINOUS FLUX</b>  <i>(Total light output in all directions)</i></p>  <p>Flux is typically measured in lumens or watts, using an integrating sphere to collect light emitted in all directions. Beam power can be measured directly as long as the beam underfills the detector.</p> <p>1 watt = 683.0 lumens at 555 nm.          1 watt = 1 joule per second.</p>
<p><b>RADIANCE &amp; LUMINANCE</b>  <i>(Light scattered or emitted by a surface)</i></p>  <p>The sampled area increases with distance, cancelling inverse square losses to make radiance independent of distance. Typically measured in W/cm<sup>2</sup>/sr, lm/m<sup>2</sup>/sr, or fL.</p> <p>1 footcandle illumination on a perfectly diffusing surface produces 1 footlambert of brightness.</p>	<p><b>RADIANT &amp; LUMINOUS INTENSITY</b>  <i>(Flux per solid angle of an isotropic source)</i></p>  <p>Mean spherical measurements can be made in a calibrated integrating sphere. Beam intensity measurements sample only the peak of a beam.</p> <p>A 12.6 watt isotropic source produces 1 watt/sr.          A 12.6 lumen isotropic source produces 1 lm/sr.</p>