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ADVISORY CIRCULAR

AIRCRAFT POSITION AND ANTICOLLISION LIGHT MEASUREMENTS

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

Initiated by: FS-130

FOREWORD

1. PURPOSE. This advisory circular contains useful information concerning measurements for intensity, covering and color of aircraft position and anticollision lights.

2. REFERENCES. Federal Aviation Regulations FAR 23.1385 through 23.1397 and 23.1401. FAR 25.1385 through 25.1397 and 25.1401. FAR 27.1385 through 27.1397 and 27.1401. FAR 29.1385 through 29.1397 and 29.1401. Advisory Circular AC 20-30A.

3. BACKGROUND.

   a. This advisory circular has been developed as a reference for those concerned with data on measurements of aircraft position and anti-collision lights. Light measurement is quite complex, and users of this advisory circular will have various degrees of experience and training. For these reasons, chapter one contains educational and reference material on the properties of light. It includes a description of light and discusses the general parameters.

   b. Chapter two includes information on types of measurements and descriptions of the equipment used to make them.

   c. Chapter three is devoted to discussions on measurement data. First, the Federal Aviation Regulations are shown by pictorial representations. Following this, measurement data considerations are given including the precautions which should be observed when making measurements.

   d. The appendices include a glossary of terms, a conversion table, a bibliography and a discussion of tristimulus colorimetry as applied to aircraft position and anticollision light measurements.

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TABLE OF CONTENTS

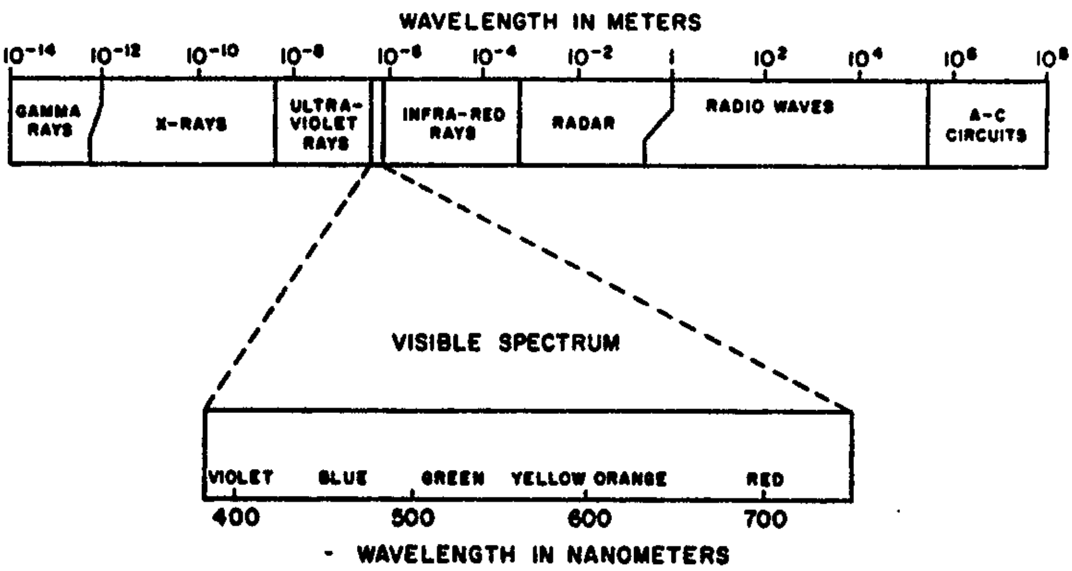
LIST OF ILLUSTRATIONS

LIST OF TABLES

CHAPTER 1

PROPERTIES OF LIGHT

1. GENERAL. Light is visually evaluated radiant energy. Like other forms of radiant energy, light travels through space at a constant velocity of 300,000,000 meters per second. Light energy may be considered as having a sinusoidal wave form, stimulating vision only over a narrow band of wavelengths (Fig. 1.1). Within this band, the amplitude affects the visual sensation of brightness and the wavelength, the visual sensation of hue. The longest waves produce a sensation of red, and the shortest a sensation of violet. By definition, white occurs when all visible wavelengths are combined in equal amounts. The appearance of white, however, may be produced when certain critical ones are combined. If the light covers a narrow band of wavelengths, a certain hue is seen. Black is usually treated as the absence of stimulation. The wavelength of light may be expressed in micrometers (μm), equal to 10^{-6} meters, in nanometers (nm), equal to 10^{-9} meters, or in angstroms (Å), equal to 10^{-10} meters.



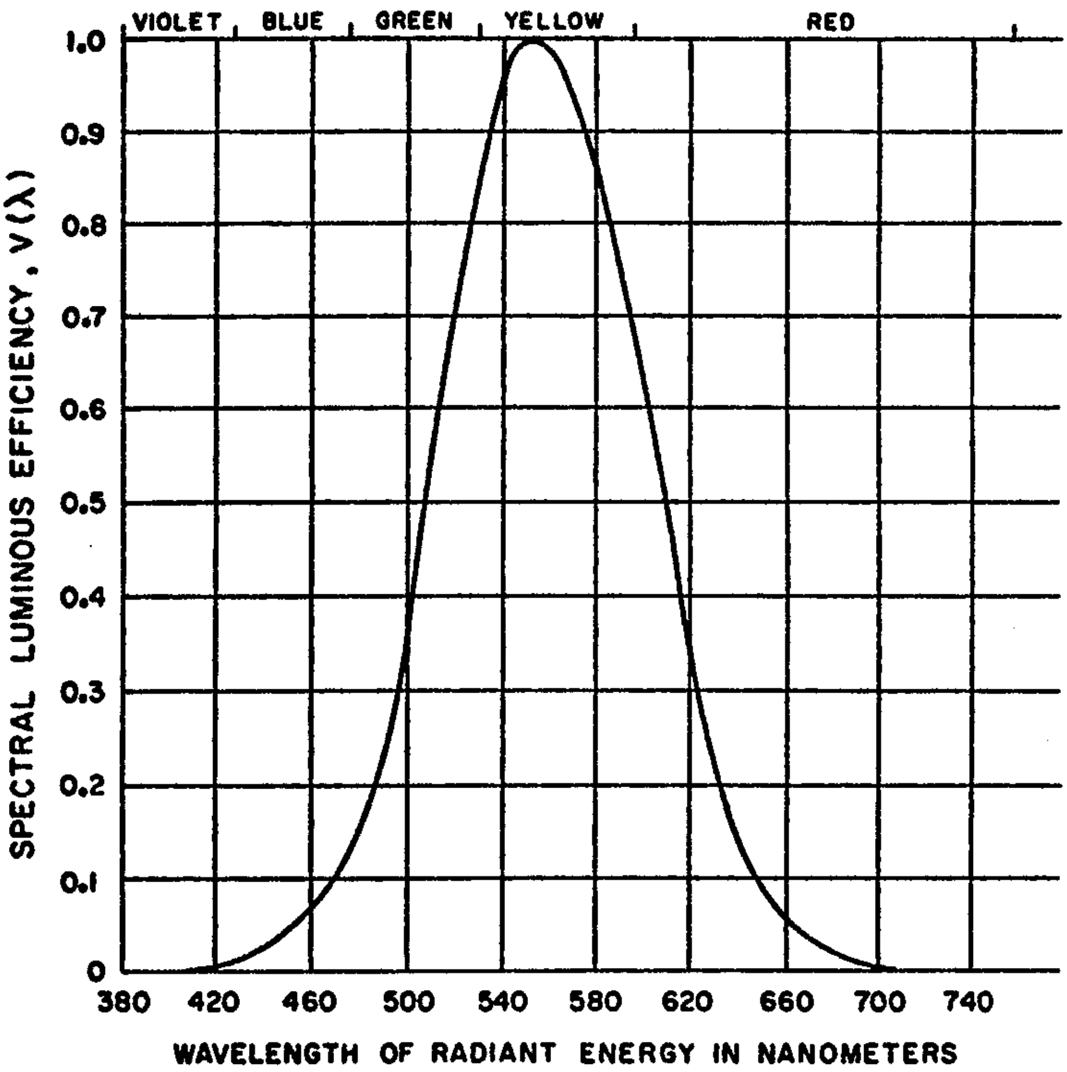
THE VISIBLE SPECTRUM

Figure 1.1

The sensitivity of the eye, however, varies within this visible spectrum. Radiant energy at different wavelengths produces varying sensations of brightness even though the amount of energy received is the same at each wavelength. Figure 1.2 and Table 1.1 show that the eye is twice as sensitive to a yellow-green of 555 nanometers, as it is to a green of 510 nm. This curve is referred to as "spectral sensitivity of the human eye" or "luminous efficiency". When the intensity of colored lights is measured, this variable sensitivity of the eye must be taken into consideration. In other words, a red light must be much higher in power to appear equally as bright as a green light. The detecting device, therefore, must be corrected for the response of the standard observer if the reading is to indicate luminous (visual) output. The numbers associated with Figure 1.2 and Table 1.1 are referred to as "spectral luminous efficiencies". It should be remembered that lumens and candelas are associated with visible light, and as the sensitivity of the eye decreases, so does the amount of lumens for the same radiant power. This is evidenced in the conversion from watts to lumens: luminous flux in lumens = 680 $V(\lambda)$ times the radiant flux in watts.

2. INTENSITY. The luminous flux being emitted from a point source, if the light is emitted equally in all directions, may be represented by a sphere. Light flux is rate of flow of visible energy. The basic unit of flux is the lumen which by definition is equal to $1/4\pi$ times the total flux emitted by a uniform point source of one candela. The flux emitted by a point source per unit solid angle (steradian) is called intensity. A steradian is defined as that solid angle originating at the center of a sphere and subtending an area on the sphere surface equal to the square of the sphere radius. Intensity is measured in lumens per steradian, and a uniform point source equal to one candela has an intensity in every direction of one lumen per steradian. Intensity in a given direction is usually expressed in candelas and is often called candlepower.

The luminous flux density received on a surface (illuminance) varies with the intensity of the source, and inversely as the square of the distance from the source to the surface. Illuminance is expressed in lumens per unit area or footcandles. Figure 1.3 shows that as the distance from a source increases, one lumen is spread over increasing areas, and the illuminance decreases. The relation of illuminance to distance from the source is referred to as the "inverse square law". The illuminance from a given source varies inversely as the square of the distance from that source. Doubling the distance causes the illuminance to decrease to one fourth. As measurements of a light source are usually done with instruments which measure illuminance, the distance must be known before the intensity of the source can be determined. In other words, footcandles times the distance squared gives candelas. For example, if a footcandle reading of 10 is measured at 10 feet from the source, the intensity is 1000 candelas.



STANDARD-OBSERVER LUMINOUS EFFICIENCY CURVE (C.I.E.)

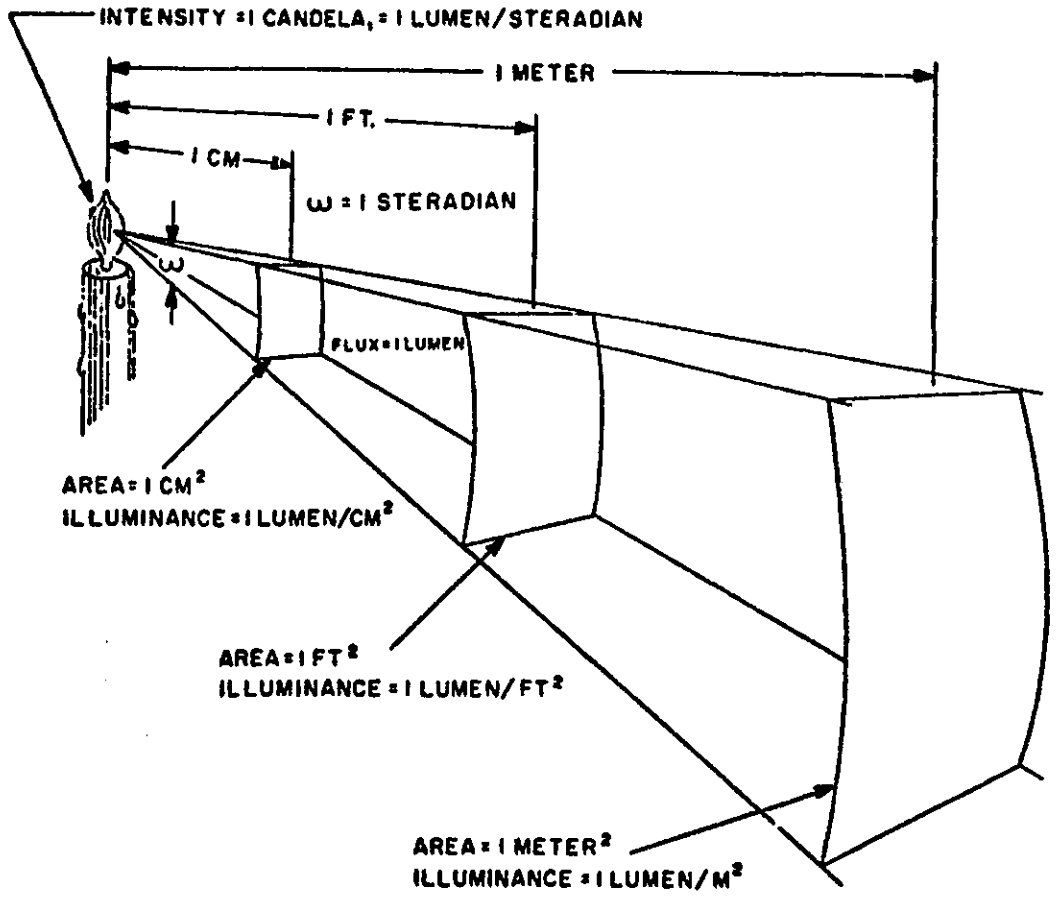
Figure 1.2

1931 C.I.E. STANDARD OBSERVER

WAVELENGTH NANOMETERS	SPECTRAL LUMINOUS EFFICIENCY, V(λ)	WAVELENGTH NANOMETERS	SPECTRAL LUMINOUS EFFICIENCY, V(λ)
380	0.0000	580	0.8700
390	0.0001	590	0.7570
400	0.0004	600	0.6310
410	0.0012	610	0.5030
420	0.0040	620	0.3810
430	0.1116	630	0.2650
440	0.0230	640	0.1750
450	0.0380	650	0.1070
460	0.0600	660	0.0610
470	0.0910	670	0.0320
480	0.1390	680	0.0170
490	0.2080	690	0.0082
500	0.3230	700	0.0041
510	0.5030	710	0.0021
520	0.7100	720	0.0010
530	0.8620	730	0.0005
540	0.9540	740	0.0003
550	0.9950	750	0.0001
560	0.9950	760	0.0001
570	0.9520	770	0.0000

SPECTRAL LUMINOUS EFFICIENCY, V(λ)

Table 1.1



INTENSITY AND ILLUMINATION

Figure 1.3

Flashing lights are used extensively as signals and warnings because of their superiority in attracting attention. Because of this characteristic, flashing beacons were established as the required lighting for anticollision lights. These beacons are of several types: rotating, flashing incandescent, oscillating and gas discharge (strobe).

When a light signal consists of separate flashes, the maximum intensity during the flash must be greater than the intensity of a steady light to have the same apparent intensity. It is convenient to evaluate flashing lights in terms of their EFFECTIVE INTENSITY, I_e or EFI, the intensity of a steady light which will appear equally bright when viewed at threshold, and is expressed in candelas.

Current airworthiness requirements for aircraft anticollision lights specify the following equation (known as the Blondel Rey equation) for the computation of effective intensity:

$$I_e = \frac{\int_{t_1}^{t_2} I(t)\,dt}{0.2 + (t_2 - t_1)};$$

where: I_e = effective intensity

$I(t)$ = instantaneous intensity as a function of time

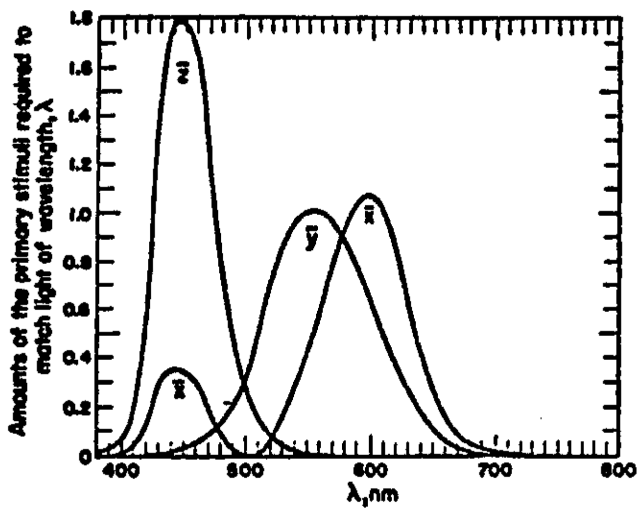
$t_2 - t_1$ = flash time interval (seconds)

The maximum computed value of effective intensity is obtained when t_2 and t_1 are chosen so that the effective intensity is equal to the instantaneous intensity at t_2 and t_1. For short time flashes, $t_2 - t_1$ becomes insignificant compared to 0.2 seconds, and the total flash is integrated.

Short-duration flashtube lights have been used primarily as supplementary lights. Since flashtubes in general produce relatively small proportions of red light, about 90 percent of the light is lost in passing it through a red filter. Therefore, in order to use this source for an anti-collision light, it is necessary to operate them at higher energy levels than has been common in the small supplementary lights.

3. COLOR. The sensation of color is closely related to the wavelength of light and varies with the individual and the conditions of viewing. Usually a color is said to have three psychological components: hue (red, blue, orange, etc.), brightness, and saturation (the amount a color differs from a grey of the same brightness). A measure of hue, sufficiently reliable for signal-color specification, is the wavelength of the part of the spectrum required to be mixed with the equal-energy (white) source to produce the color; this wavelength is called the dominant wavelength of the color. Saturation is satisfactorily specified by the ratio of the distance on the CIE chromaticity diagram (See Figure 1.5) from the equal-energy point to the color point, to the distance from equal-energy point, in the same direction, to the spectrum locus. This ratio is called purity.

It can be shown that any color can be matched by combining three properly chosen colors called primary colors. If a colored sample is placed in one half of a photometric field, a mixture of three primary colors such as red, green, and blue, in the other half of the field can be made to match the colored sample to the satisfaction of the eye. This is done by varying the relative brightness of the three primary colors. A problem with this method is that the matching judgment of one observer cannot be taken as representative of the average person. Only when a large number of observers are used in each experiment can consistent values be obtained for the relative brightness of primary colors required to match any given color. In order to avoid this difficulty, the tristimulus method was revised and standardized. Three primary colors were agreed upon; then, by experiments with a number of normal observers, standard values for the relative amounts of each primary color were established to match each wavelength in the visible spectrum. These numbers were associated with a "standard observer". With these values made available in 1931 by the Commission Internationale de L'Eclairage (CIE), a more objective and economical technique is available to specify color. Figure 1.4 is a graphical presentation of the relative amounts of each primary color required to match any wavelength. Standard notation for these functions is: $\bar{x}$ for the red primary, $\bar{y}$ for the green primary, and $\bar{z}$ for the blue primary. It should be noted that the $\bar{y}$ function has been adjusted to correspond to the luminous-efficiency function (Figure 1.2). Table 1.2 shows the values of these functions in tabular form.



SPECTRAL TRISTIMULUS VALUES ACCORDING TO THE 1931 CIE STANDARD OBSERVER

Figure 1.4

The 1931 CIE standard observer

Wave-length, nm	Spectral tristimulus values of equal-energy spectrum			Wave-length, nm	Spectral tristimulus values of equal-energy spectrum		
	$\bar{x}$	$\bar{y}$	$\bar{z}$		$\bar{x}$	$\bar{y}$	$\bar{z}$
380	0.0014	0.0000	0.0065	580	0.9163	0.8700	0.0017
385	.0022	.0001	.0105	585	.9786	.8163	.0014
390	.0042	.0001	.0201	590	1.0263	.7570	.0011
395	.0076	.0002	.0362	595	1.0567	.6949	.0010
400	.0143	.0004	.0679	600	1.0622	.6310	.0008
405	.0232	.0006	.1102	605	1.0456	.5668	.0006
410	.0435	.0012	.2074	610	1.0026	.5030	.0003
415	.0776	.0022	.3713	615	0.9384	.4412	.0002
420	.1344	.0040	.6456	620	.8544	.3810	.0002
425	.2148	.0073	1.0391	625	.7514	.3210	.0001
430	.2839	.0116	1.3856	630	.6424	.2650	.0000
435	.3285	.0168	1.6230	635	.5419	.2170	.0000
440	.3483	.0230	1.7471	640	.4479	.1750	.0000
445	.3481	.0298	1.7826	645	.3608	.1382	.0000
450	.3362	.0380	1.7721	650	.2835	.1070	.0000
455	.3187	.0480	1.7441	655	.2187	.0816	.0000
460	.2908	.0600	1.6692	660	.1649	.0610	.0000
465	.2511	.0739	1.5281	665	.1212	.0446	.0000
470	.1954	.0910	1.2876	670	.0874	.0320	.0000
475	.1421	.1126	1.0419	675	.0636	.0232	.0000
480	.0956	.1390	0.8130	680	.0468	.0170	.0000
485	.0580	.1693	.6162	685	.0329	.0119	.0000
490	.0320	.2080	.4652	690	.0227	.0082	.0000
495	.0147	.2586	.3533	695	.0158	.0057	.0000
500	.0049	.3230	.2720	700	.0114	.0041	.0000
505	.0024	.4073	.2123	705	.0081	.0029	.0000
510	.0093	.5030	.1582	710	.0058	.0021	.0000
515	.0291	.6082	.1117	715	.0041	.0015	.0000
520	.0633	.7100	.0782	720	.0029	.0010	.0000
525	.1096	.7932	.0573	725	.0020	.0007	.0000
530	.1655	.8620	.0422	730	.0014	.0005	.0000
535	.2257	.9149	.0298	735	.0010	.0004	.0000
540	.2904	.9540	.0203	740	.0007	.0003	.0000
545	.3597	.9803	.0134	745	.0005	.0002	.0000
550	.4334	.9950	.0087	750	.0003	.0001	.0000
555	.5121	1.0002	.0057	755	.0002	.0001	.0000
560	.5945	0.9950	.0039	760	.0002	.0001	.0000
565	.6784	.9786	.0027	765	.0001	.0000	.0000
570	.7621	.9520	.0021	770	.0001	.0000	.0000
575	.8425	.9154	.0018	775	.0000	.0000	.0000
580	.9163	.8700	.0017	780	.0000	.0000	.0000
				Totals	21.3713	21.3714	21.3715

SPECTRAL TRISTIMULUS VALUES

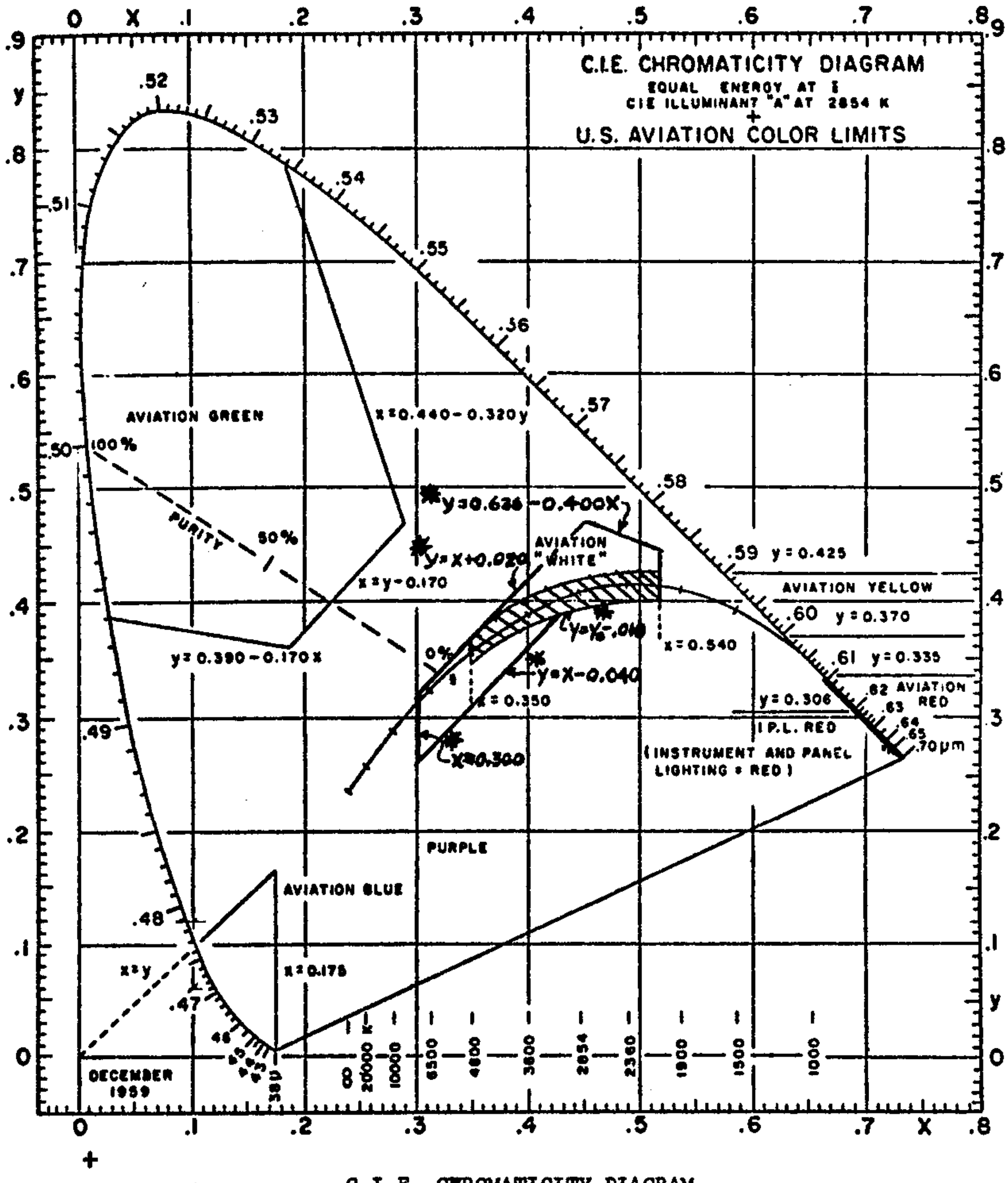
Table 1.2

Capital letters X, Y, and Z have been assigned as notation for the amounts of the three primaries required to visually match a color containing multiple wavelengths. These values can be plotted graphically if the following transformations are made:

$$x = \frac{X}{X + Y + Z} \quad (2) \qquad y = \frac{Y}{X + Y + Z} \quad (3) \qquad z = \frac{Z}{X + Y + Z} \quad (4)$$

where X, Y, and Z are the amounts of the three primaries and x, y, and z are the "chromaticity coordinates" in the CIE system. The horizontal of the graph becomes x and the vertical becomes y; z may be obtained from the relationship $x + y + z = 1$. Such a graph, shown in Figure 1.5, is called a chromaticity diagram. Any color may be located on the diagram by specifying its chromaticity coordinates. The colors used for lighting of aircraft are shown with the limits as established by the airworthiness regulations. On this diagram, there is a central white point marked E, where $X = Y = Z$ corresponding to the color of a source having an equal-energy spectrum. As $x + y + z = 1$, this white point appears graphically at $x = .333$; $y = .333$ and represents a position of zero purity. The outer periphery of this diagram is a locus of points of 100% purity for visible wavelengths. A line drawn from any point on this periphery to the point of equal energy (E) represents all purities between 100% and 0 for that dominant wavelength. For example, a line is shown for a light of dominant wavelength 0.5 micrometers with the 0%, 50%, and 100% purity points indicated. An aviation green light of this dominant wavelength would have to have a purity of only 32% to meet the regulatory requirements. Aviation red, however, would require a purity of nearly 100%.

The temperature scale along the bottom of the diagram, showing a range from 1000 K to infinity, contains calibrations for source color temperatures. Note that each temperature has a calibration mark on the curved line above. The curved line is called the "Planckian locus," and represents the chromaticities of blackbodies at different temperatures. In practical applications, it is accepted as representing the chromaticities of incandescent bodies such as lamp filaments. The numbers along this curve on the CIE diagram indicate the color temperature in Kelvins. CIE illuminant "A" can be represented on this curve at the 2854 K point, illuminant "B" at about 5000 K and "C" at about 6800 K. Illuminant A represents the spectral distribution of typical tungsten-filament incandescent lamps, illuminant B represents the spectral distribution of average noon sunlight, and illuminant C represents the spectral distribution of average daylight.



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*EFFECTIVE 11 AUGUST 1971
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C.I.E. CHROMATICITY DIAGRAM

Figure 1.5

The color of an object depends on the spectral characteristics of the illuminant as well as the nature of the object. For example, fabrics change color when moved from the light of ordinary tungsten-filament bulbs to fluorescent light. Any accurate system of color specification must account for this fact by relating the color to a specified light source. In specifying a color that is going to be used under known conditions of illumination, the tristimulus values for the standard illuminant conforming most closely to those conditions should be used. For example, in coloring an aviation red light cover, the color temperature of the light-source must be considered.

Some red glass filters change color as their temperatures change. As the temperature increases, the light passing through some red filters becomes more red (longer wavelength) and less intense. For this reason, red filters are generally designed to be near the yellow limit (shortest wavelength) at room temperature. Then, if the operating glass temperature is consistently higher than room temperature, aviation red light will be produced under all operating conditions. By designing to this yellow limit, the maximum intensity will also be obtained. Glass of other colors changes slightly with temperature, but not enough to be a problem.

CHAPTER 2

MEASUREMENT CONSIDERATIONS

4. GENERAL. The measurement of visible radiated energy is called photometry. Instruments for measurement of the amount of a light, regardless of their calibration, measure only flux, and care must be taken when converting to various photometric units. An additional precaution is necessary because photosensitive devices, unless properly filtered, do not have the same characteristics as the human eye.

There are four general types of light measurements:

a. Luminous Intensity - The luminous flux emitted per unit solid angle in a given direction (candelas).

b. Illuminance - The luminous flux incident per unit area on a surface at some distance from the source (footcandles).

c. Luminance - Luminous intensity per unit projected area of surface (candelas per square foot).

d. Chromaticity - The color quality of light determined by its chromaticity coordinates.

In addition to the above light measurements, the efficiency of light covers is sometimes measured. There are two terms associated with such efficiency measurements; spectral transmittance (τ) which refers to the ratio of transmitted to incident power at one wavelength or a very narrow band of wavelengths, and luminous transmittance (T) which is the ratio of transmitted to incident total light power. The transmittance of a light cover indicates the decrease in light due to material and color, and can be used to adjust luminous intensity values measured without the cover. The filtered light may be measured directly provided the photometer is equipped with filters which accurately match the luminous-efficiency function.

5. INTENSITY. The instrument used to measure the luminous intensity of lights is called a photometer. Photometers can be placed in two general classes; "visual" and "direct-reading photoelectric".

a. Visual Photometers. Before the invention of photoelectric cells, most instruments for measuring intensity employed the principle of balancing two adjacent fields visually. With these photometers, a test light and a standard light of known intensity were viewed simultaneously. By adjusting the relative distances from the viewing point, a balance was obtained, and by applying the inverse square law, the intensity of the test light could be determined. Although visual photometers have generally been superseded by direct-reading photoelectric type instruments, many are still being used.

b. Direct-Reading Photoelectric Photometers. Photoelectric devices are now being used to detect and convert light energy to electrical energy for measurement. A photometric system for precisely measuring the magnitude and coverage of aircraft lights usually consists of the following:

(1) Goniometer. This device includes an attachment position for the light unit which can be moved around two axes of freedom. The vertical and horizontal positions are calibrated, and in some cases the information is remoted to recorders so that a plot of intensity vs. direction can be made directly. A goniometer of this type is installed in the photometric laboratory of the National Bureau of Standards in Washington, D. C.

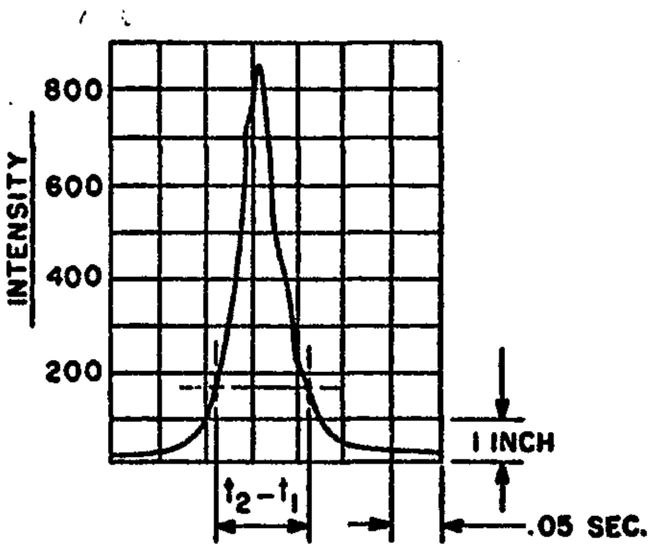
(2) Tunnel and Track. A dark tunnel, including baffles to eliminate stray light, is located in line with the goniometer. A photodetector is placed on a carrier which can be moved on a track to vary the distance between the goniometer and the photodetector. Position information is usually remoted to a recorder.

(3) Photodetector. Photodetectors are of several types, and read-out in units such as milliwatts, microamperes, etc. By conversion factors, footcandles (illuminance) can be computed from the read-out. Then, by means of the distance information, a calculation of intensity can be made. For steady lights, measurements are concerned with rate of flow of light entering the eye, analogous to gallons per minute into a container. For flashing lights, however, the measurements are concerned with the quantity of light per flash entering the eye, analogous to gallons. The quantities are proportional to footcandles and footcandle-seconds respectively. Since the instantaneous illuminance varies during exposure to flashing lights, integration is necessary to determine the footcandle-seconds. As discussed in paragraph 2 of Chapter 1, the computation of effective intensity requires a candela-second measurement. Candela-seconds

can be computed from footcandle seconds by multiplying by the distance (in feet) squared. Care must be taken not to overload a photodetector by too much light as it can saturate and its response become non linear.

Integrating photometers are available which electronically perform the integration and read out the total exposure in microcoulombs. These photometers are used only on short duration strobes where the entire flash is integrated. A microcoulomb is a microampere-second, and a calibration factor is used to convert a microcoulomb reading to footcandle-seconds. Then, multiplying by the distance squared gives candela-seconds corresponding to the numerator of the equation for effective intensity.

Strip recorders or recording oscilloscopes are generally used for longer duration flashes, such as rotating beacons, and mechanical integration is then performed.



STRIP RECORDING OF FLASH

Figure 2.1

Figure 2.1 shows an example of a recording made by a strip recorder. The paper is moved horizontally at a linear rate so that each division represents approximately .05 seconds. The recorder is calibrated so that each vertical division represents 100 candelas. After the flash is recorded, a mechanical integrator (planimeter) is used to trace the recording and obtain the area, in candela-seconds, between the limits of t_2 and t_1. This area divided by $0.2 + t_2 - t_1$ gives the effective intensity. The values of t_2 and t_1 are determined by experimentation, and are selected to maximize the computed effective intensity. In the example of figure 2.1 the flash has an area between t_2 and t_1 of approximately 51 candela-seconds. When divided by 0.3 seconds (0.2 + 0.1) the effective intensity is 170 candelas. The peak intensity of 850 candelas, therefore, has an effective intensity of only 170 candelas. A method for selecting t_2 and t_1 is given in Chapter 3.

When measuring colored flashing lights, the photodetector cannot always be relied upon to give accurate results, even with luminous-efficiency-correction filters. The alternative is to measure the effective intensity with a clear cover, and then with a spectrophotometer, determine the relative luminous transmittances of the two covers. The effective intensity value measured through the clear cover is then reduced by this luminous transmittance factor. Spectrophotometers are discussed in paragraph 3., Color.

3. COLOR. Color can be evaluated with a visual photometer by comparing a sample against a filter of known color. In such comparisons, the same, correct color temperature should be used for both sources. However, there has been increasing interest in the use of photoelectric instruments for the measurement of chromaticity of colored lights. The following is a discussion of some of these instruments:

a. Spectrophotometer. Spectrophotometers break up a self-contained light source into a spectrum by prisms or gratings, so that narrow bands within the visible spectrum can be individually applied to a test ware (such as a light cover). Although these are not single wavelengths, they are very narrow bands approximately five nanometers wide. Determining either luminous transmittance (T), or chromaticity coordinates (x, y, and z) with a spectrophotometer involves the measurement of 40 transmittances (τ), spaced 10 nanometers apart, throughout the visible spectrum. Mathematically, these transmittances are used as follows:

$$X = \Sigma_{380}^{770} \bar{x}E\tau\Delta\lambda \quad (5) \qquad Y = \Sigma_{380}^{770} \bar{y}E\tau\Delta\lambda \quad (6) \qquad Z = \Sigma_{380}^{770} \bar{z}E\tau\Delta\lambda \quad (7)$$

The values for $\bar{x}$, $\bar{y}$, and $\bar{z}$ are found in Table 1.2, and represent the relative amounts of primaries required at each wavelength. The E in the equations represents the spectral distribution of the light source, and is published for certain illuminants such as C.I.E. Source A. Tables are available which list the products $\bar{x}E$, $\bar{y}E$, and $\bar{z}E$ for certain illuminants (NBS Monograph 104). These numbers are sometimes found on a computation form as shown in table 2.1. If the light is not a standard source, a table must be developed from measurements of the energy distribution. When each of the 40 lines have measured values for τ logged, the remainder of the sheet can be filled out with data computed by hand, calculating machine, or computer. For example, assume a measured value for τ at 380 nanometers of 0.078. Then $\bar{x}E\tau$ would be 0.078, $\bar{y}E\tau$ would be 0.000, and $\bar{z}E\tau$ would be 0.468.

Guide for Computation of x, y, z, and T
Observer: C.I.E. Standard 1931
Basic Stimulus: Equal Energy
Illuminant: Planck 2856 K
(C.I.E. Standard A)

Sample____________________

Wave Length Nanometers	τ	$\bar{x}E$	$\bar{y}E$	$\bar{z}E$	$\bar{x}E\tau$	$\bar{y}E\tau$	$\bar{z}E\tau$
380	0.	1	0	6			
390	0.	5	0	23			
400	0.	19	1	93			
410	0.	71	2	340			
420	0.	262	8	1256			
430	0.	649	27	3167			
440	0.	926	61	4647			
450	0.	1031	117	5435			
460	0.	1019	210	5851			
470	0.	776	362	5116			
480	0.	428	622	3636			
490	0.	160	1039	2324			
500	0.	27	1792	1509			
510	0.	57	3080	969			
520	0.	425	4771	525			
530	0.	1214	6322	309			
540	0.	2313	7600	162			
550	0.	3732	8568	75			
560	0.	5510	9222	36			
570	0.	7571	9457	21			
580	0.	9719	9228	18			
590	0.	11579	8540	12			
600	0.	12704	7547	10			
610	0.	12669	6356	4			
620	0.	11373	5071	3			
630	0.	8980	3704				
640	0.	6558	2562				
650	0.	4336	1637				
660	0.	2628	972				
670	0.	1448	530				
680	0.	804	292				
690	0.	404	146				
700	0.	209	75				
710	0.	110	40				
720	0.	57	19				
730	0.	28	10				
740	0.	14	6				
750	0.	-6	2				
760	0.	4	2				
770	0.	2					
SUMS		109828	100000	35547	X=	Y=	Z=

$x = \frac{X}{X+Y+Z}$ $\quad y = \frac{Y}{X+Y+Z}$ $\quad z = \frac{Z}{X+Y+Z}$

x, y, and z
COMPUTATION FORM

Table 2.1

Summing the column for $\bar{x}E\tau$ would yield X which is the relative amount of red primary required for the match. Y and Z can be found with the other two columns. Then, the chromaticity coordinates for representing the sample on a chromaticity diagram, or evaluation against regulatory requirements is found as follows:

$$x = \frac{X}{X + Y + Z} \qquad y = \frac{Y}{X + Y + Z} \qquad z = \frac{Z}{X + Y + Z}$$

The luminous transmittance T of the ware can be found from the same computation sheet as follows: The sum of the $\bar{y}E\tau$ column (Y) is divided by the sum of the $\bar{y}E$ column. This is possible because $\bar{y}$ and $V(\lambda)$ values (luminous-efficiencies) are identical. For example, if the sum of the $\bar{y}E\tau$ column is 24407, dividing by 100,000 gives .24407 or 24.4%. The values given in this table have been adjusted so that the sum of the $\bar{y}E$ column is a power of ten to simplify computations. This means that only 24.4% of the light incident on the ware is being transmitted through it. A more detailed explanation is given in the Appendix as "Tristimulus Colorimetry and Aviation Lights."

b. Spectroradiometer. Spectroradiometers are similar to spectrophotometers, but can be used to measure the spectral distribution of external sources over a wider range of wavelengths than just the visible spectrum.

c. Brightness Meters. When evaluating the color of ware with these instruments, a standard filter is used for comparison. The results are not chromaticity coordinates (x, y, and z), but are in or out of tolerance indications. Such procedures, due to filter limitations, are used only on highly saturated red glass (sharp cut-off).

One method of determining whether a color meets a specific requirement, by using a brightness meter and a NBS filter, is given in MIL-L-25467C. The filter specified in this procedure has a yellow limit corresponding to instrument and panel lighting red (National Bureau of Standards Filter No. 3215). However, the procedure has been used with an aviation red filter (NBS Filter No. 3647A). The procedure is a Go/No-Go measurement with the NBS filter used as a measurement standard. A brightness reading is taken of a colored aviation light at 10 ft. distance. A second reading is taken after a NBS filter is added in the light path. The ratio of these 2 readings must approximate a similar ratio obtained using a white light source in place of the colored aviation light. In the second case, a first reading is made with one NBS filter and the second reading is made with two NBS filters. In this way, the aviation light color is compared to the NBS filter color. The two ratios must not differ over 3% (in the yellow direction) to qualify the test light color.

d. Tristimulus Colorimeters. If the response of three photocells could be adjusted by glass filters, so their responses follow the curves of the C.I.E. Standard Observer, $\bar{x}$, $\bar{y}$, and $\bar{z}$ (see Figure 1.4), they could be made to yield direct measurements of tristimulus values X, Y, and Z. Complete success of these colorimeters depends on the ability to duplicate the C.I.E. Standard Observer System. Acceptable instruments could simplify the measurements and reduce the required data processing. Presently, such instruments have more application to production line measurements than for showing initial compliance.

7. TEMPERATURE EFFECTS. All glass filtering elements have their color and transmittance affected in varying degrees by increased temperature. The change is more pronounced for red than for other colors. One manufacturer of glass has published data such that different red glasses are identified by their percent transmittance at room temperature. For example, red glasses are identified as 12.6%, 25.3%, etc., at 78° F. For each number, the color and transmittance at any temperature up to 500° F is charted and plotted. Most red glass colors are reversible up to the softening temperature(over 800°F). Reversibility means that after heating, when the temperature is returned to 78° F, the original color will return. Glasses that have transmittances of 25% or more at 78° F have transmittance vs temperature curves which are essentially linear up to 300° F, and transmittances change approximately 0.5% for each 10° F change in temperature.

In application of these filters, proper evaluation of their color characteristic at elevated temperatures requires knowing the following:

a. The initial glass temperature, color and transmission.

b. The range of glass temperatures found in operation.

c. The type glass used in the filter and its characteristics. Generally, an increase in red glass temperature makes its color more red and decreases its transmission. The amount of such changes is determined by the temperature range of the glass in operation and the characteristics of the glass.

CHAPTER 3

MEASUREMENT DATA

8. GENERAL. Aircraft exterior lights, on which measurements are required, include position and anticollision lights. Measurements include intensity (coverage and overlap) and color.

   a. Position Lights. The airworthiness requirements for aircraft position lights are given in FAR 23.1385 through 23.1397, FAR 25.1385 through 25.1397, FAR 27.1385 through 27.1397 and FAR 29.1385 through 29.1397.

      (1) Intensities.

         (a) Horizontal Coverage. Figure 3.1 shows the minimum intensity requirements for the horizontal plane at 0° vertical. Overlap limits are not shown as they vary when intensities exceed 100 candelas.

         (b) Vertical Coverage. Figure 3.2 shows the minimum intensities for any vertical plane. The value of "I" indicates the maximum required candelas for a given horizontal position.

      (2) Color. A graphical presentation of the chromaticity coordinate limits for aviation red (left), aviation green (right), and aviation white (rear), is shown in figure 1.5.

   b. Anticollision Lights. The airworthiness requirements for aircraft anticollision lights are given in FARs 23.1401, 25.1401, 27.1401 and 29.1401.

      (1) Intensity & Coverage: Figure 3.3.

      (2) Color: Each anticollision light must be either aviation red or aviation white.

9. POSITION LIGHT DATA.

   a. Intensity. Measurement of position light intensity requires photometric equipment such as that described in Chapter 2, paragraph 2. Figure 3.4 and 3.5 show typical recordings as made in a photometric laboratory. The data should include enough distribution plots to adequately substantiate coverage. The following data should be sufficient:

   Forward Red and Green Position Lights. A horizontal distribution curve in the zero degree vertical plane from directly forward outboard through 110 degrees (figure 3.4). Vertical distribution curves from 90 degrees up to 90 degrees down at 0, 10, 20, and 110 degree horizontal points (figure 3.5). In addition to these distribution curves, a visual inspection through the entire area should be made to determine whether or not there are any noticeable shadows or areas where visual observation would indicate questionable conformance. If any such questionable areas are noted, further measurements should be made in those areas to demonstrate satisfactory coverage.

Rear White Position Light. A horizontal distribution from 70 degrees right to 70 degrees left of directly to the rear. Three vertical distribution curves from 90 degrees up to 90 degrees down through the following horizontal points: directly astern, 70 degrees left of directly to the rear, and 70 degrees right of directly to the rear. Laboratory reports of such measurements should also include at least the following:

(1) A list of the test equipment and calibration dates for light standards which should show calibration against the lab working standard within the past 30 days, and the working standard against the lab primary standard within the last 180 days. The laboratory primary standard should be traceable to the National Bureau of Standards.

(2) If a luminous-efficiency-correction filter is included, data adjustment for filter errors should be shown and substantiated.

(3) If transmittance measurements are used, the data should show adjustment for the comparison in transmittance between any clear filter used during the intensity measurements and the transmittance of the colored filter. If a clear cover is used, it should have the identical shape as the colored cover. Transmittance data should be shown on a computation sheet such as shown in Table 2.1. Also, if a spectrophotometer is used it should be substantiated that the sample used in the measurements is representative of the actual light cover.

(4) When red glass is used, the data should show the temperature of light covers during measurements and data on the transmittance characteristics relative to temperature. Measured intensity values should be adjusted as follows:

(a) For measurements made with the red cover in place, adjust the intensity values to those corresponding to an ambient temperature of 100°F. If no actual measurement is made with an ambient temperature of 100°F, extrapolation should be supported by data.

(b) When transmittance data is used, values should be adjusted to correspond to a glass temperature equivalent to that of the outside surface of the light cover. Glass temperature measurements should be made after the glass has stabilized with an ambient temperature of at least 100°F. Optionally, a temperature of 130°F should be allowed in lieu of measured temperature.

(5) A description of the procedure used to obtain intensity and transmittance data, including the calculations. A diagram of the test set-up is desirable. This description and diagram should show:

(a) Intensity measurements made from a distance sufficient to give accurate results with the linear operating range of the photocell of prime consideration. The distance should always be at least 10 times the diameter of the light source and preferably greater. (See IES Lighting Handbook, 4th Edition, page 4-18)

(b) Voltage measurements made as near the light source as possible, using a suitable meter when considering accuracy and loading. Current readings should also be recorded and data supplied to show where the lamp falls with respect to the manufacturing tolerance limits.

b. Color. Position light color measurements require equipment such as described in Chapter 2, paragraph 3. Aviation green conformance should be shown with data in chromaticity-coordinate form (x, y, and z). Aviation red conformance should be shown by the same type data, or by the optional brightness meter and filter method. When spectrophotometric procedures are used, the data should include a computation sheet such as shown in Table 2.1. Laboratory reports which accompany the data should include at least the following:

(1) A list of the test equipment with, when applicable, calibration dates.

(2) When red glass is used, the data should include the temperature of light covers during color measurements, and data on the color characteristics relative to temperature. Red glass data should also include the following:

(a) For measurements made with the red cover in place, substantiating data to show that the color will be within limits when the outside temperature of the glass is 78°F.

(b) If chromaticity-coordinate measurements are made, measured values should be adjusted to those corresponding to an outside cover glass temperature of 78°F.

(3) A description of the procedure used to obtain the color data. A diagram of the test set-up is desirable.

3. ANTICOLLISION LIGHT DATA.

a. Intensity. Measurements for "effective intensity" require techniques as described in Chapter 2, paragraph 2.b.(3). The light may be measured as a white light, and the intensity values adjusted according to the transmittance of the red cover. The computation sheet used to determine the chromaticity-coordinates contains the data for determining the luminous transmittance of the red cover. If a clear cover is used in the intensity measurements, the ratio of the transmittances of the two covers must be used to correct the data.

To show field of coverage, a combination of vertical and horizontal measurements is necessary. Figure 3.6 is a typical presentation of vertical effective intensity distribution and is shown with the FAA minimum intensity requirements. Such curves are constructed from points representing separate effective intensity measurements. To assure sufficient points to accurately draw the vertical distribution curve, measurements are usually made at vertical angles of ±30°, ±20°, ±10°, ±5° and 0. Three of nine such points are shown in Figure 3.6. To obtain the values for the three points, individual intensity vs time curves are recorded and processed. The processing for long duration type lights can be done from a paper recording, using a planimeter for area measurements. Horizontal coverage must also be substantiated. As the curve of Figure 3.6 represents a single horizontal direction, there should be enough measurements to assure complete field of coverage. In other words, it should be substantiated that any variations in vertical patterns around the light will not result in an out of tolerance condition at any horizontal position.

When using the Blondel-Rey equation, the maximum value of effective intensity is obtained when t_2 and t_1 are chosen so that the effective intensity is equal to the instantaneous intensity at t_2 and t_1. To compute the highest possible effective intensity value for a given curve, estimates should be made until the proper values for t_2 and t_1 have been determined. When the instantaneous intensity at the t_2 and t_1 points approximate the effective intensity value computed from the Blondel-Rey equation, the maximum computed value has been found. Figures 3.7 and 3.8 have examples of data and include the mechanics for determining maximum computable intensity for points A, B, and C of Figure 3.6. The heat correction factors used in Figures 3.7 and 3.8 are used because the light cover is at a higher temperature in the laboratory than in actual operation. For rotating beacon measurements, the motor is stopped and the light is concentrated on a particular area of the glass. As mentioned before, red glass decreases in transmittance with heat.

For short time flashes such as those produced by flashtube units, an integrating type photometer is generally used. These instruments integrate the whole flash rather than between specific limits. If an integrating photometer is used, the manufacturers' calibration and operation procedures should be followed. For typical flashtube measurements, the value of $t_2 - t_1$ is negligible compared to 0.2 seconds. Computed effective intensity for these lights is therefore maximum when the entire flash is included. Effective intensity for short time flashes can be found by the following relation:

Footcandle-seconds (meter reading) x distance squared ÷ 0.2 seconds

To improve the accuracy, several flashes are integrated and an average is taken. Figure 3.9 is an example of typical flashtube measurement data. Information furnished usually includes the charge voltage, flash capacity, electrical energy stored (watt-sec), flash rate, and the plane of measurement. In the example, the 15.6 watt-seconds results from the equation:

$$\text{Energy} = 1/2\ E^2C = 1/2\ (420)^2\ (177\text{X}10^{-6})$$

The 15.6 watt-seconds of electrical energy is partially converted to light energy. If reflectors and gas conversion efficiency are considered, the watt-second number can be used to estimate possible candelas. The test distance is given so that the meter reading is convertible to candelas. The multiplier (125) in the example results from $D^2/0.2$. In the tabled data, therefore, the single flash footcandle-second reading times 125 gives effective intensity.

Laboratory reports of such measurements should include at least the following:

(1) A list of test equipment and calibration dates as discussed in paragraph 2.a.(1).

(2) Luminous-efficiency-correction filter data as discussed in paragraph 2.a.(2).

(3) Transmittance data as discussed in paragraph 2.a.(3).

(4) Temperature corrections as discussed in paragraph 2.a.(4). If a heat correction factor is used, it should be substantiated by data.

(5) Procedure information as discussed in paragraph 2.a.(5). For anticollision lights, this information should also include the method used to determine "effective intensity."

443-481 O - 71 - 3

(6) For strobe sources, the spectral distribution data used in transmittance computations should be substantiated by data showing spectroradiometer measurements, or published data which can be shown to be applicable.

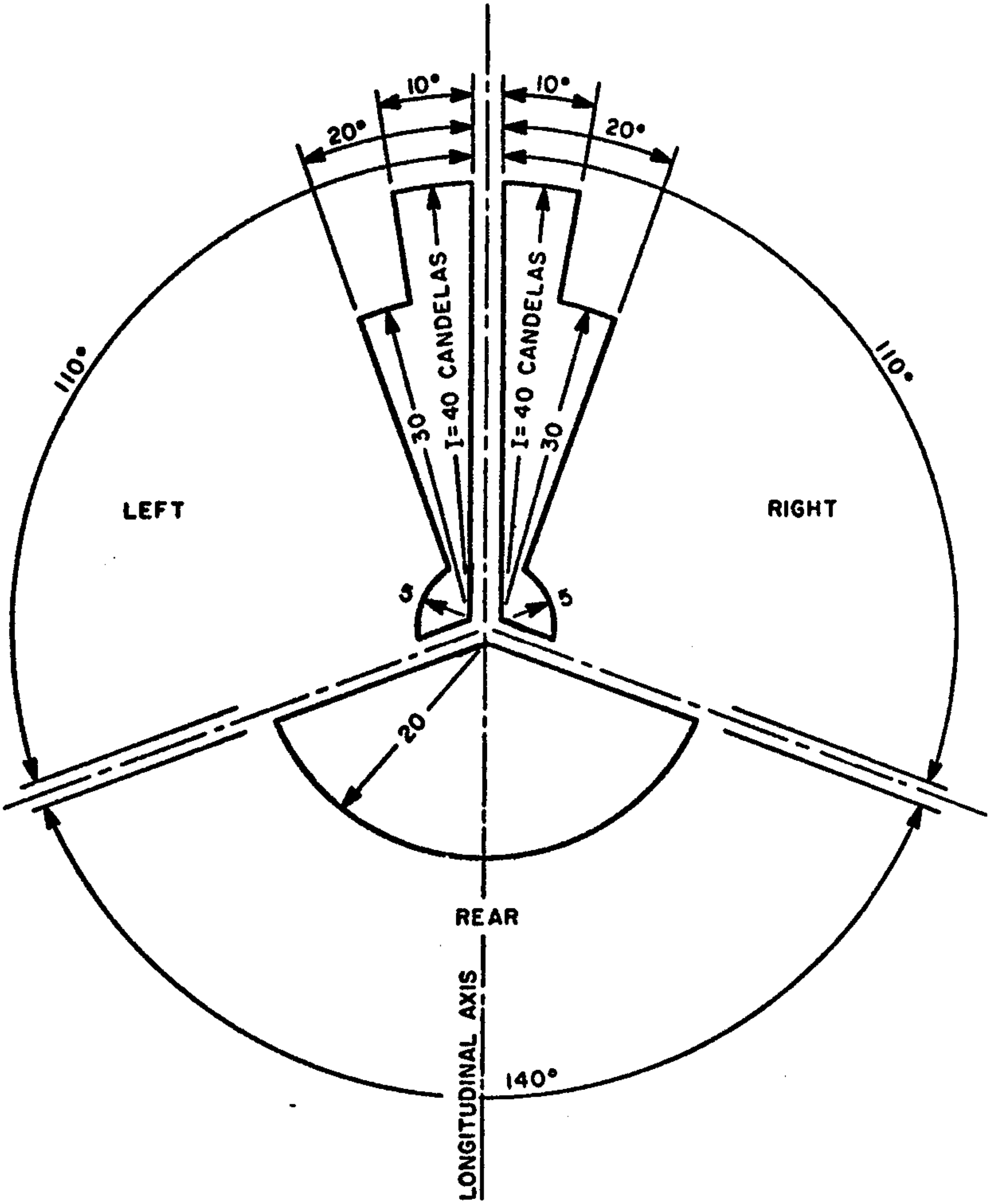
h. Color. The measurement for color of an anticollision light red cover is usually made with a spectrophotometer. In this measurement, the computation sheet (Table 2.1) should contain values for spectral distribution which are representative of the light source being used. Pre-computed values for $E\bar{x}$, $E\bar{y}$, and $E\bar{z}$ are available for many type sources and are identified by color temperature. NBS Monograph 104 has several examples. The color temperature and the values for $E\bar{x}$, $E\bar{y}$, and $E\bar{z}$ must be accurately known if the results are to be dependable.

Laboratory reports which accompany the data should show at least the following:

(1) A list of the test equipment with, when applicable, calibration dates.

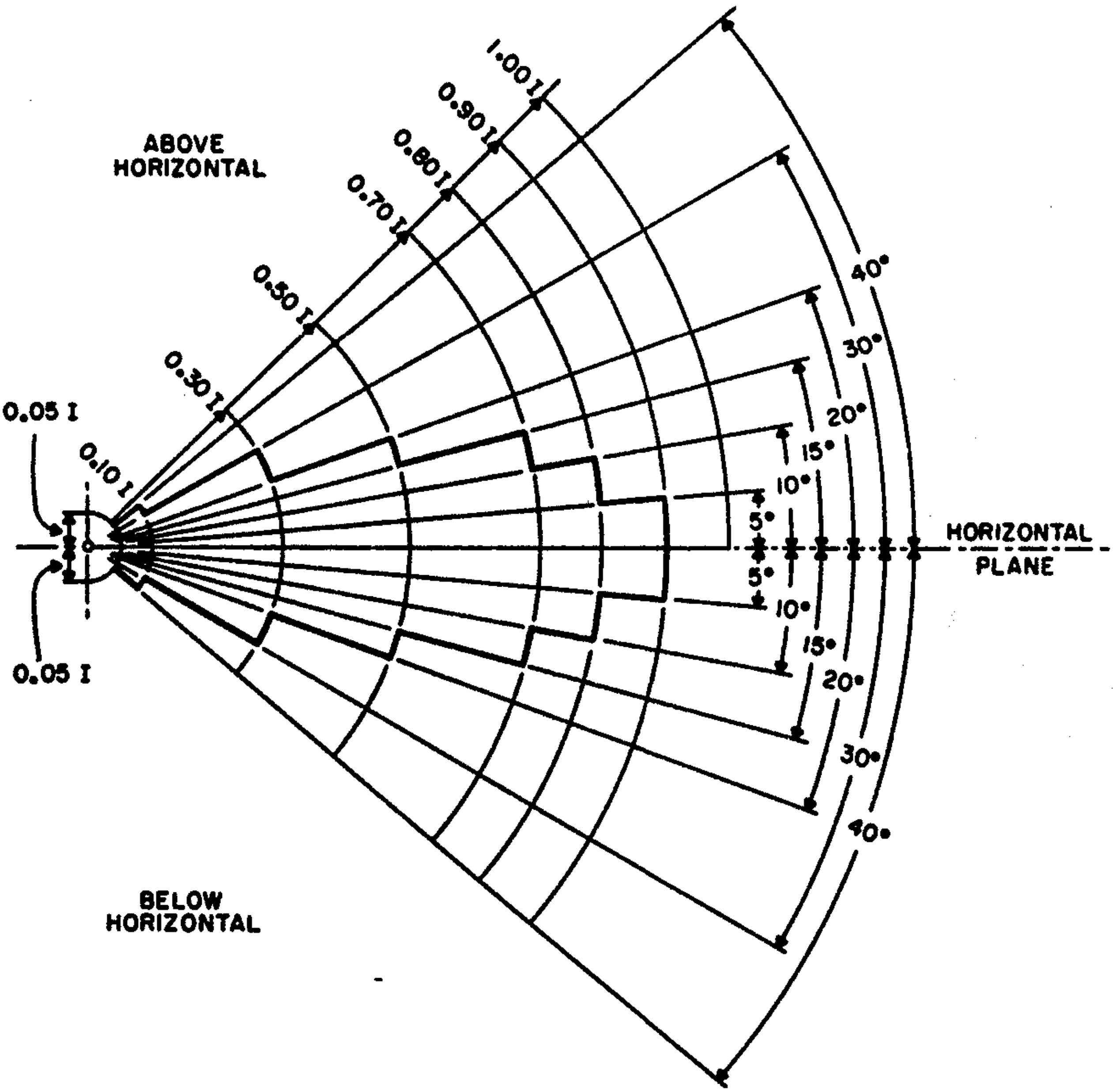
(2) Temperature data as discussed in paragraph 2.b.(2).

(3) Procedure information as discussed in paragraph 2.b.(3).



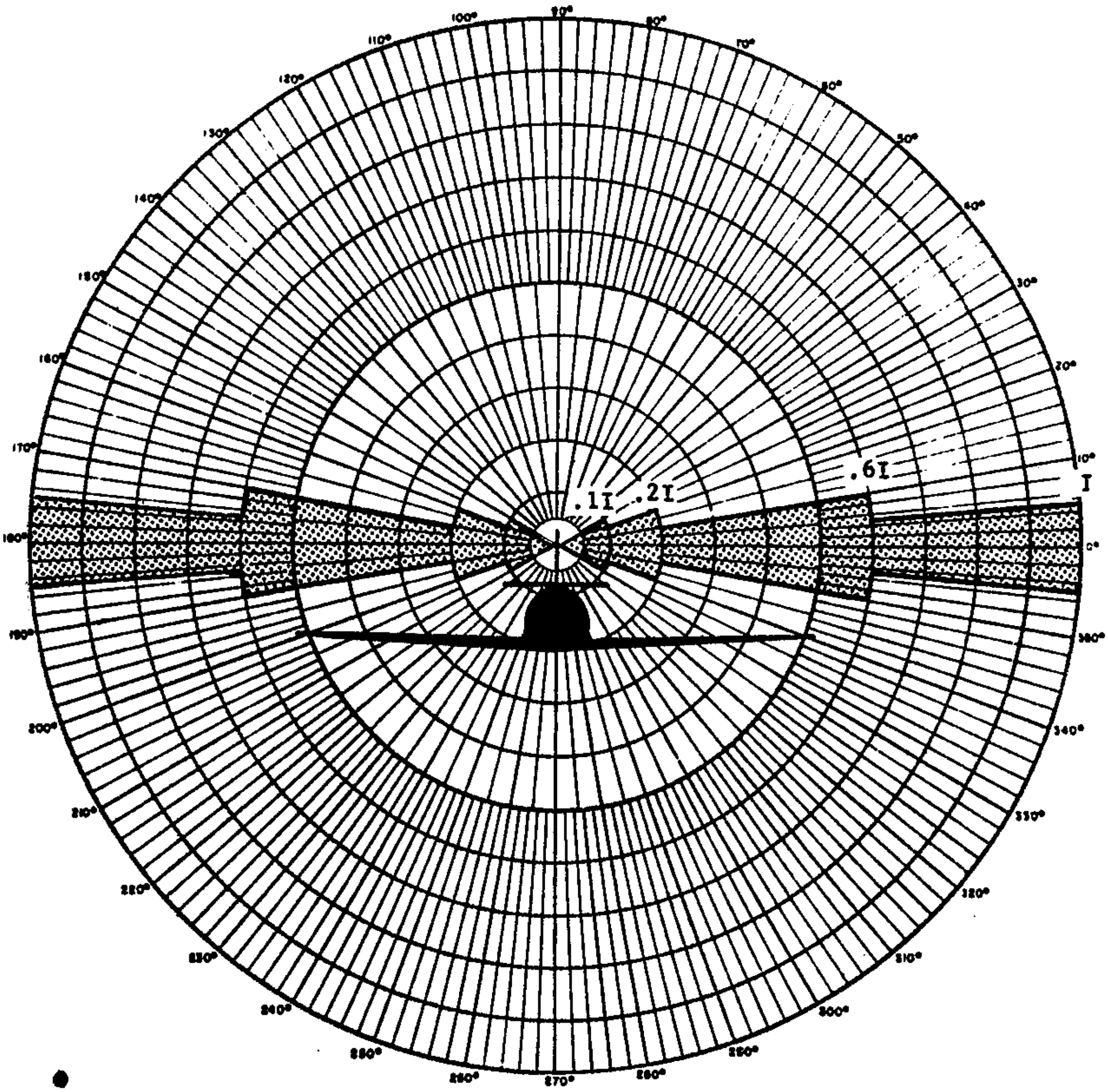
POSITION LIGHTS, MINIMUM INTENSITY IN THE HORIZONTAL PLANE

Figure 3.1



POSITION LIGHTS, MINUMUM INTENSITIES IN VERTICAL PLANES

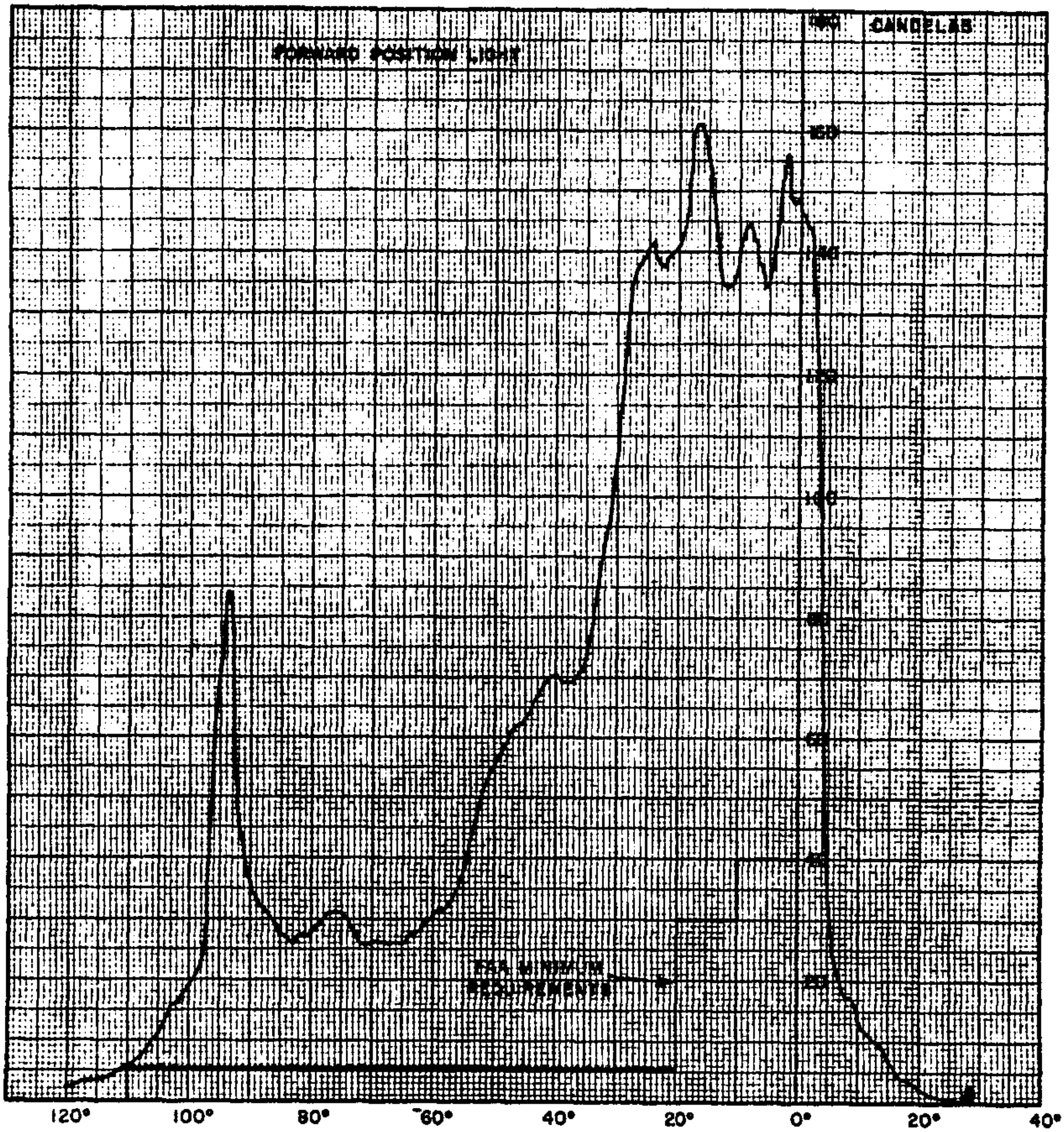
Figure 3.2



ANTICOLLISION LIGHTS, MINIMUM INTENSITY IN VERTICAL PLANE

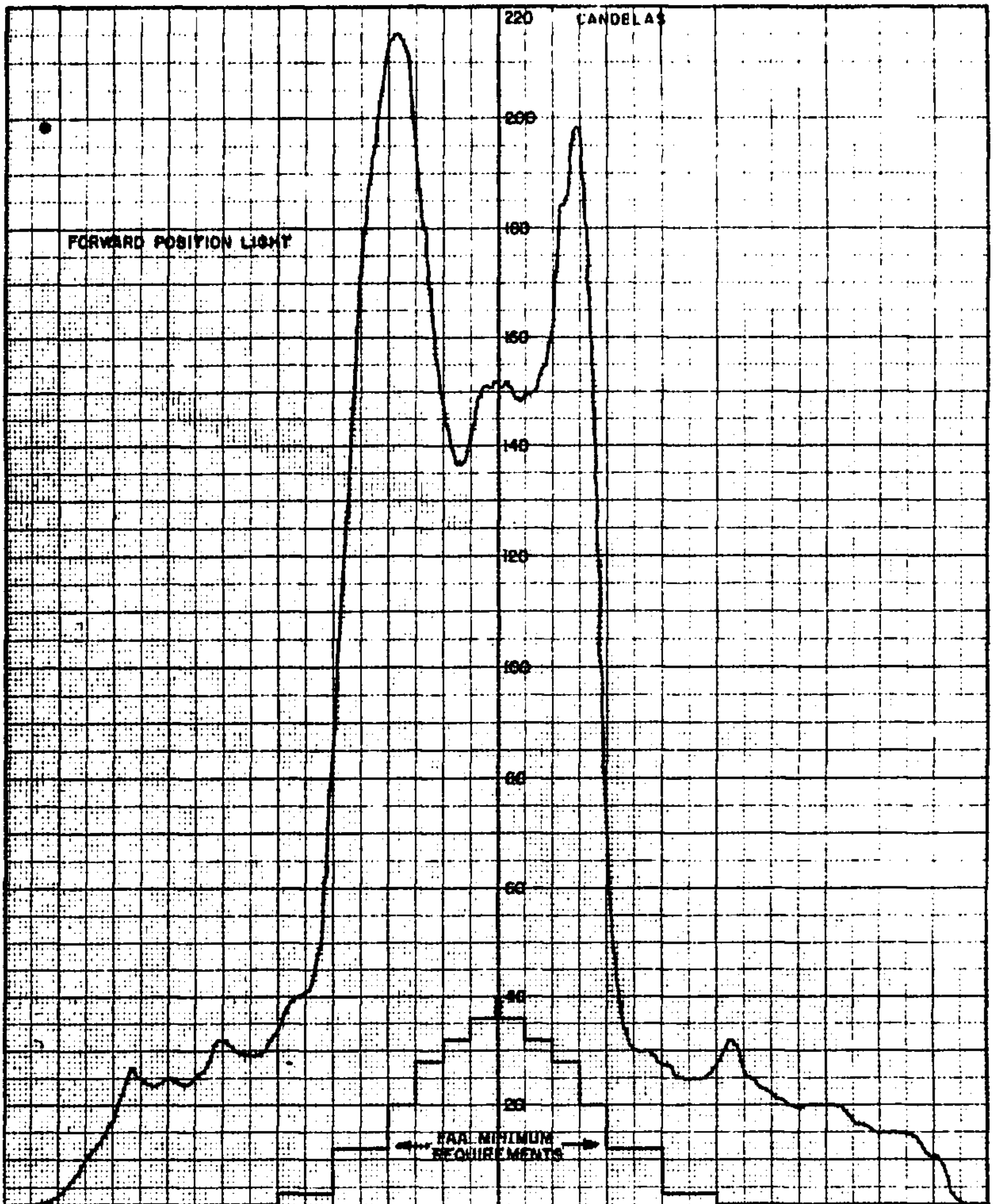
Figure 3.3

Date of T. C. Application:	I
Prior to 8/11/71	100
On or after 8/11/71	400



TYPICAL HORIZONTAL INTENSITY DISTRIBUTION–POSITION LIGHT

FIGURE 3.4



TYPICAL VERTICAL INTENSITY DISTRIBUTION—POSITION LIGHT

FIGURE 3.5

ROTATING BEACON

EFFECTIVE INTENSITY DISTRIBUTION

28.0 VOLTS 1.67 AMPERES 50 RPM

AVIATION RED LENS

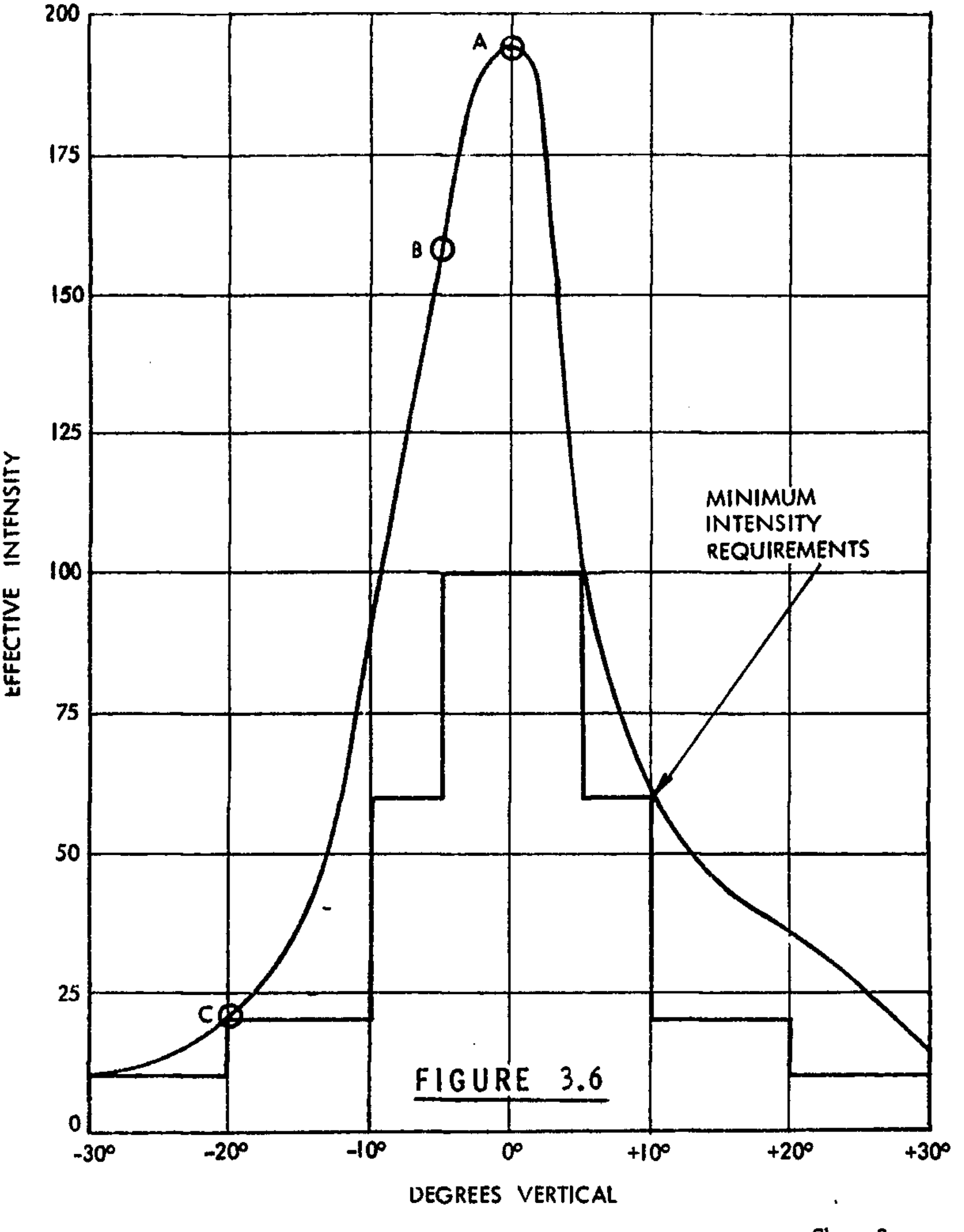


FIGURE 3.6

EXAMPLES OF TYPICAL TIME-INTENSITY CURVES
SHOWING EFFECTIVE INTENSITY CALCULATIONS
SECONDS PER INCH = .0666
CANDELAS PER INCH = 200

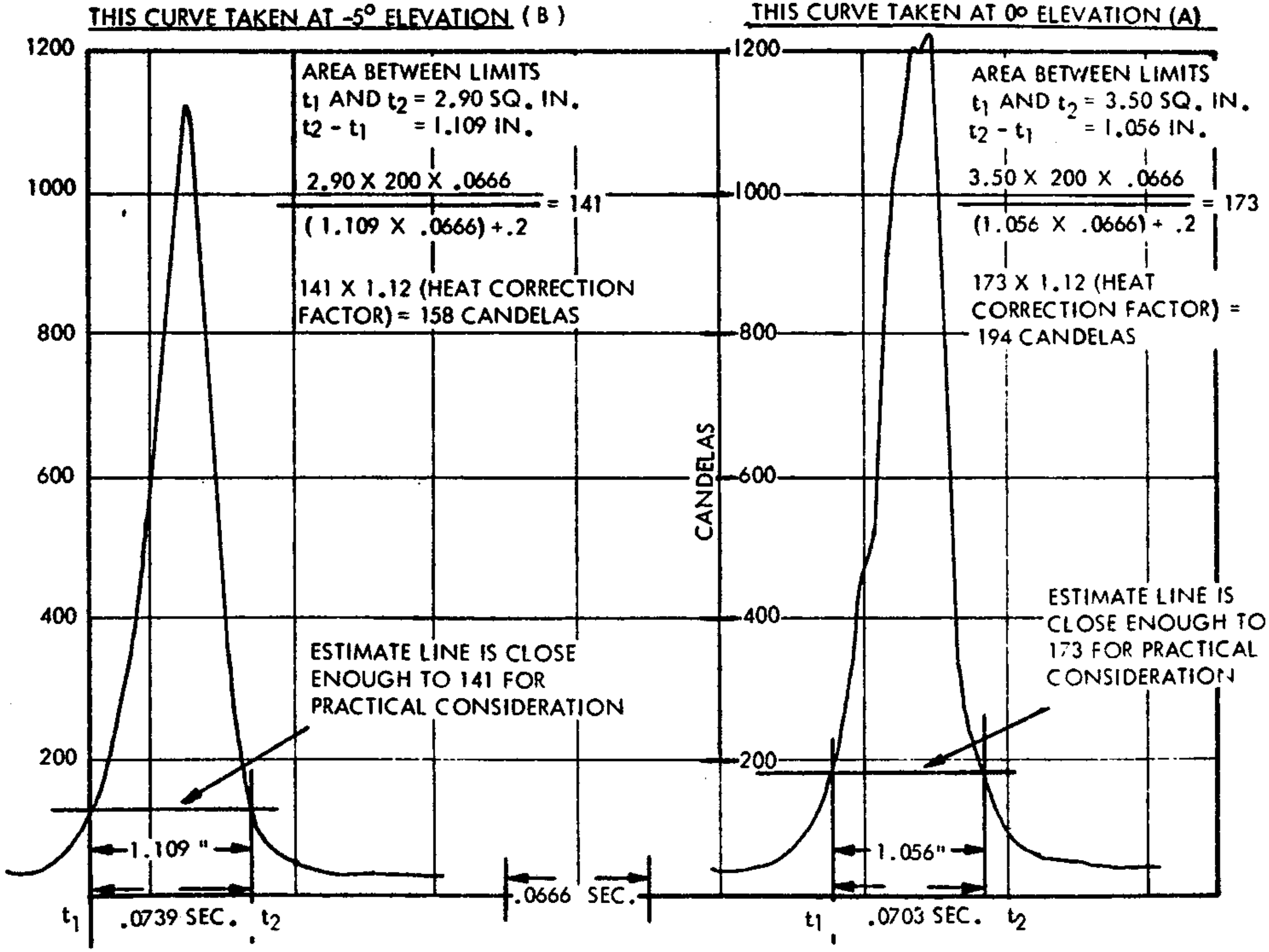


FIGURE 3.7

EXAMPLE OF TYPICAL EFFECTIVE INTENSITY CALCULATION

$$\text{BASED ON } I_e \text{ MAX.} = \frac{\text{AREA IN SQ. IN. X SEC. PER IN. X CANDELAS PER IN.}}{(t_2 - t_1 \text{ IN INCHES X SECONDS PER IN.}) + .2}$$

1ST ESTIMATE (a) SEC. PER IN. = .0666

AREA BETWEEN LIMITS t_1a and t_2a = 9.0 SQ. IN.

DISTANCE FROM t_1a TO t_2a = 7.04 IN.

$$\frac{9.00 \times .0666 \times 20}{(7.04 \times .0666) + .2} = 17.9 \text{ CANDELAS}$$

2ND ESTIMATE (b) SEC. PER IN. = .0666

AREA BETWEEN LIMITS t_1b and t_2b = 4.60 SQ. IN.

DISTANCE FROM t_1b TO t_2b = 2.165 IN.

$$\frac{4.60 \times .0666 \times 20}{(2.165 \times .0666) + .2} = 17.8 \text{ CANDELAS}$$

3RD ESTIMATE (c) SEC. PER IN. = .0666

AREA BETWEEN LIMITS t_1c AND t_2c = 7.13 SQ. IN.

DISTANCE FROM t_1c TO t_2c = 4.765 IN.

$$\frac{4.60 \times .0666 \times 20}{(4.765 \times .0666) + .2} = 18.4 \text{ CANDELAS}$$

18.4 X 1.12 (HEAT CORRECTION FACTOR) = 20.6 CANDELAS

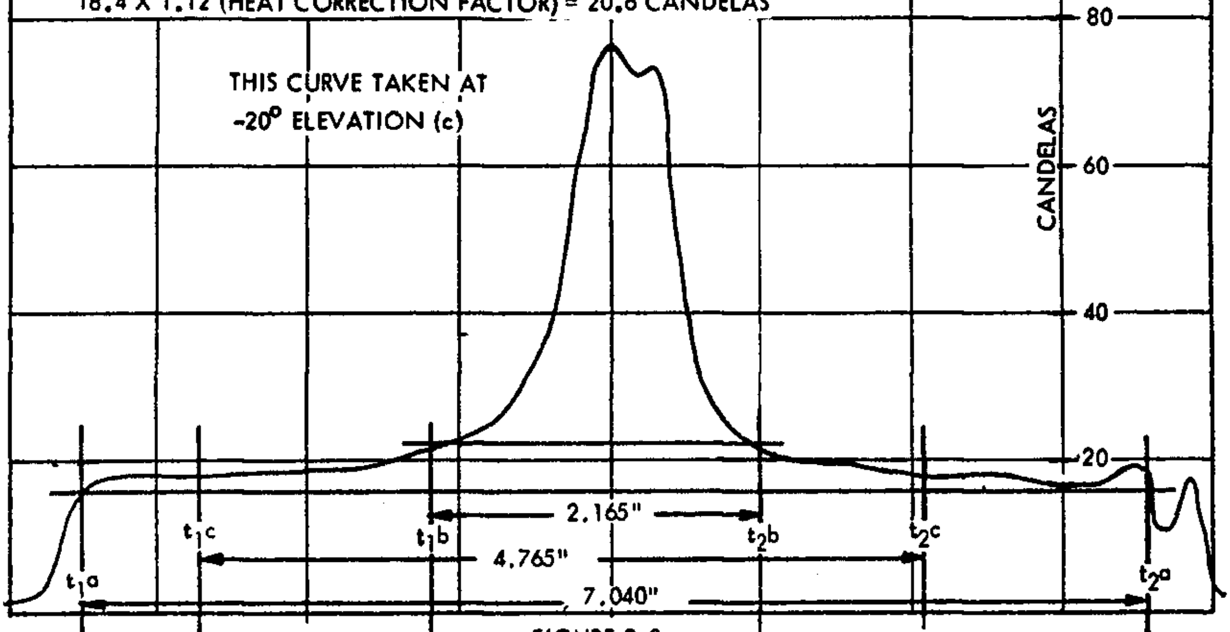


FIGURE 3.8

TYPICAL FLASHTUBE MEASUREMENT DATA SHEET

Input Voltage - 14.0, Flash Capacitor 177 MFD.
Charge Voltage - 420 V., 15.6 Watt-Seconds
Flash Rate - 1 per second.
Vertical Angle - 0°

Test Distance - 5.0 ft.
EFI = Single flash reading x D^2 x 5, (Multiplier = 125)

Horizontal Distribution Data

HOR. DEG.	METER READING	NO. OF FLASHES INTEGRATED	AVG. READING FOR SINGLE FLASH	EFI
0°	19.8	10	1.98	248.0
10°	22.0	10	2.20	275.0
20°	22.0	10	2.20	275.0
30°	19.8	10	1.98	248.0
40°	20.4	10	2.04	255.0
50°	17.1	10	1.70	212.0
60°	13.7	10	1.37	171.0
70°	11.0	10	1.10	137.0
80°	11.0	10	1.10	137.0
90°	11.5	10	1.15	144.0
100°	12.1	10	1.20	150.0
110°	11.5	10	1.15	144.0
120°	11.0	10	1.10	137.0
130°	8.8	10	.88	110.0

TYPICAL FLASHTUBE MEASUREMENT
DATA SHEET

Figure 3.9

APPENDIX 1

GLOSSARY OF TERMS

1. CANDELA - Unit of intensity. Produces one lumen per unit solid angle (steradian). At a distance of one foot, one candela produces an illuminance of one footcandle.

2. CHROMATICITY - The color quality of light determined by its chromaticity coordinates.

3. COLORIMETRY - A method for measuring colors and specifying them in numerical or definite symbolic terms.

4. COLOR TEMPERATURE - The temperature at which a blackbody must be operated to give the same color as the source, usually expressed in Kelvins (K).

5. DOMINANT WAVELENGTH - That wavelength of spectrum light which, when combined with neutral light in suitable proportions, matches the color. Neutral light is light for which the chromaticity coordinates are $x = .333$ and $y = .333$.

6. EXPOSURE - The product of the illuminance and the time during which the material is exposed to this illuminance, or $E = it$. The unit of measure is the footcandle-second, which represents an exposure of 1 second to a source having a light intensity of 1 candela at a distance of 1 foot.

7. HUE - The attribute of color determined primarily by the wavelength of light entering the eye.

8. ILLUMINANCE - The areal density of luminous flux incident on a surface, in lumens per unit area or footcandles.

9. INTENSITY - Flux per unit solid angle from a point source measured in lumens per steradian or in candelas; often called candlepower.

10. LIGHT - Radiant energy that produces visual sensations.

11. LUMEN - Unit of luminous (visible) flux. Luminous energy emitted per second by a uniform point source of one candela intensity through a solid angle of one steradian.

12. LUMINANCE - Luminous intensity of a surface in a given direction per unit of projected area of the surface as viewed from that direction; measured in candelas per unit area.

13. LUMINOUS FLUX - The time rate of flow of light, sometimes called light power.

14. PHOTOMETER- An optical device that utilizes equations of brightness or flux to permit the measurement of a photometric quantity, such as intensity, illuminance or brightness.

15. PHOTOMETRY - The measurement of visible radiation on the basis of its effect upon the eye under standard conditions. Visual photometry involves the adjustment of two parts of the visual field, in order to identify or to determine a minimal difference. Photoelectric photometry involves the measurement of the flux incident on a receiver from a test and a standard source at known distances.

16. SATURATION - The extent to which a chromatic color differs from grey of the same brightness, measured on an arbitrary scale from 0% to 100% (where grey is 0%). Also called "purity".

17. SPECTROPHOTOMETER - An instrument designed to measure the spectral transmittance or reflectance of objects. Used primarily for comparing, at each wavelength, the flux leaving the object with the flux incident upon it. It usually has a built-in light source.

18. SPECTRORADIOMETER - An instrument used to measure the spectral distribution of radiant energy.

19. SPECTRAL LUMINOUS EFFICIENCY $V(\lambda)$ - Quotient of the luminous flux at a given wavelength by the radiant flux at that wavelength normalized by dividing by the maximum value of that quotient, formally called luminosity factor.

20. STERADIAN - The unit solid angle. That solid angle originating at the center of a sphere which subtends an area on the surface of that sphere equal to the square of its sphere radius. A sphere contains 4π steradians (see Figure 1.3).

PHOTOMETRIC TERMS

QUANTITY	SYMBOL	DESCRIPTION	UNIT	EQUIVALENT	CONVERSIONS
Flux	ϕ	Rate of Flow of Light	lumen		lumens = watts x 680 x $V(\lambda)$
Intensity	I	Point Source Light Power	candela	1 lumen/steradian	candelas = footcandles x distance squared
Luminance (brightness)	L	Concentration of Intensity from Surface Source	footlambert	$(1/\pi)$ candelas/ft^2 1/452 candelas/in^2	
			lambert	1 lumen/cm^2 2.054 candelas/in^2	
Illuminance	E	Surface Received Light Density	footcandle	1 lumen/ft^2	footcandles = candelas/distance squared
Wavelength	λ	Distance Traveled During a Cycle	meter	Ratio of velocity to frequency of radiation	meter = 10^6 micrometers (μm) = 10^9 nanometers (nm) = 10^{10} angstroms (A°)
Solid Angle	ω	Two Dimension Angles	steradian	Total Solid Angles/4π (Sphere)	steradians = surface area/distance squared
Power	W	Electrical Energy Rate	watt	joules/Sec	
Luminous Efficiency	$V(\lambda)$	Eye Response to Varying Wavelengths (Table 1.1)		$\bar{y}$	

APPENDIX 3

TRISTIMULUS COLORIMETRY AND AVIATION LIGHTS

Although the energy distribution of a colored light may extend throughout the visible spectrum, the characteristics of vision are such that a combination of three primary colors can match the light to the satisfaction of the eye. The apparent match of two colors of different spectral content is called "metamerism," and the two colors are called a "metameric pair." This method of matching or reproducing a color is the basis for tristimulus colorimetry. The tristimulus method is to measure the energy distribution and then to convert this information into the tristimulus values which form a metameric match. Figure 1.4 of this circular shows how to mix the three CIE primary colors in order to match any wavelength. If we have energy distribution throughout the visible spectrum, we simply multiply the relative power amplitude at each wavelength by the corresponding tristimulus values $\bar{x}$, $\bar{y}$, and $\bar{z}$ for that wavelength. Then, by adding up all the measurements a total amount for each of the primaries is found. Mixing these amounts of X (red), Y (green), and Z (blue), we accomplished a metameric match. Thus,

$$X = \Sigma_{380}^{770} E\bar{x}\ \Delta\lambda$$

where E is the power, and $\bar{x}$ is the proportion of red primary required for that wavelength; Y and Z are found similarly.

In this way, we can determine the required amounts of primaries to match the color of a source or in the case of lights, the lamp. C.I.E. standard illuminant "A" (incandescent) has a published power distribution, as have several other sources, and tables of $E\bar{x}$, $E\bar{y}$, and $E\bar{z}$ are available. If the source is non-standard, the E values must be measured, and by computation, the tables developed. The significance of this information is that the color of the light transmitted by the filter depends not only on the filter but also on the spectral distribution of the light incident on it.

After tabled values for $E\bar{x}$, etc., are developed, they must be modified by the filter effect. Usually, this is done by measuring the filters' transmittances throughout the visible spectrum. This gives a new column labeled "τ". Then, to obtain the X, Y, and Z required to form a match of the overall system, we must combine the data. Combining the source and filter data we solve the equations:

$$\bar{X} = \Sigma_{380}^{770} E\bar{x}\ \tau\Delta\lambda \quad \text{etc.}$$

Mechanically this is done as follows:

1. Measure the power distribution of the light source (E) in 10 nanometer steps from 380 to 770 nanometers (40 measurements).

2. For each step, combine (by multiplication) $\bar{x}$, $\bar{y}$, and $\bar{z}$ information from tabled values to obtain $E\bar{x}$, $E\bar{y}$, and $E\bar{z}$ (40 values).

3. Measure the transmittance (τ) of the filter at these same 40 points. Combine these numbers with previously computed values to obtain 40 values for $E\bar{x}\tau$, $E\bar{y}\tau$, $E\bar{z}\tau$.

4. Add the 40 values for $E\bar{x}\tau$ to obtain X; the amount of red primary required for a match. Repeat for $E\bar{y}\tau$ and $E\bar{z}\tau$ to obtain Y and Z.

5. Compute $x = \dfrac{X}{X + Y + Z}$, $y = \dfrac{Y}{X + Y + Z}$, and $z = \dfrac{Z}{X + Y + Z}$. This gives the chromaticity coordinates which will form a metameric match of the light color.

The transmittance of a light filter is, by definition, the ratio of transmitted to incident light power. The transmittances (τ) measured at the 40 sample points do not consider eye response, nor the power distribution of the illuminant. Therefore, when we evaluate a filter for overall transmittance, we must combine the following data:

1. Power distribution of source . . . . E
2. Eye response luminous-efficiency function . . . $\bar{y}$ [$\bar{y}$ was adjusted to correspond to $V(\lambda)$]
3. Filter transmittance distribution . . . . τ

These three variables were combined when developing Y as $\Sigma_{380}^{770} E\bar{y}\,\tau\Delta\lambda$. As this is also a measurement of visible transmitted light magnitude, dividing by the incident light will give the transmittance of the filter. The incident light is the same as the transmitted light if we omit the filter transmittances. Therefore, the incident light is $\Sigma_{380}^{770} E\bar{y}\,\Delta\lambda$ and the transmittance $T = \dfrac{\Sigma_{380}^{770} E\bar{y}\,\tau\Delta\lambda}{\Sigma_{380}^{770} E\bar{y}\,\Delta\lambda}$.

APPENDIX 4

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