



ISBN 3 900 734 47 X

COMMISSION INTERNATIONALE DE L'ÉCLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

TECHNICAL REPORT

LIGHT AS A TRUE VISUAL QUANTITY: PRINCIPLES OF MEASUREMENT

Pub. N° CIE 41

1st Edition 1978/Reprint 1994

UDC: 612.843.3
535.242

Light sense
Photometry, subjective

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Ce rapport a été préparé par le Comité Technique CIE 1.4 « Vision ». Il a été approuvé par la majorité du Comité, dans lequel sont représentés la plupart des pays membres de la CIE, et il est recommandé pour une future étude. Il n'est pas une recommandation officielle de la CIE approuvée par les Comités Nationaux des pays membres. Il faut noter que toutes les recommandations de ce rapport sont conseillées et non obligatoires.

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Summary

There are many methods available to photometrists by which visually meaningful assessments of light may be made. All are somewhat more complicated than the simple use of a physical photometer corrected to $V(\lambda)$. In addition, all require some understanding of the visual system and how it works. However the advantages are sizeable : the assessment of light bears a logical relationship to how we perceive the light. The methods are summarized below.

For photopic vision, luminances of several $\text{cd}\cdot\text{m}^{-2}$ or higher, ordinary physical photometers corrected to $V(\lambda)$ give visually accurate measures for small, centrally fixated lights of broad spectral composition. For all other applications a different luminous efficiency function should be employed. In order to utilize the appropriate function, one must either measure the spectral distribution of radiant power directly or correct the photocell's existing $V(\lambda)$ curve to the appropriate luminous efficiency.

An alternate solution is to calculate a new quantity from ordinary luminance values and from CIE colorimetric measures according to mathematical formulae specifically developed for this purpose. This method is potentially the most useful since different formulae can be developed for different applications (for example, two degree or ten degree fields); at the same time it rests on established CIE quantities and no new measures need be developed.

For scotopic vision, assessment of radiant power is made with respect to the scotopic luminous efficiency function $V'(\lambda)$, either with a physical photometer appropriately corrected or by radiance measurement or visual photometry.

For mesopic photometry, the light should be assessed for both its photopic and its scotopic contributions. An estimate can be obtained by combining the simple photopic and scotopic luminances non-linearly or a more precise measure by utilizing three, or even better, four quantities, based on X_{10} , Y_{10} , Z_{10} and $V'(\lambda)$, in the final assessment.

Résumé

Les photométristes disposent d'un grand nombre de méthodes pour évaluer les effets visuels de la lumière. Elles sont toutes passablement plus compliquées que le simple usage d'un instrument de photométrie énergétique dont la réponse est corrigée pour tenir compte de la fonction $V(\lambda)$. D'autre part, elles requièrent toutes une certaine compréhension du système visuel et de son fonctionnement. Toutefois, les avantages sont appréciables : il existe une relation logique entre l'évaluation ainsi obtenue et la façon dont nous percevons la lumière. Voici comment on peut résumer ces méthodes.

Pour la vision photopique (luminances supérieures ou égales à quelques cd m^{-2}) les photomètres énergétiques corrigés selon $V(\lambda)$ donnent des mesures précises du point de vue visuel lorsqu'il s'agit de stimuli de petite dimension, observés en vision centrale et dont le spectre est largement étalé. Dans tous les autres cas, il convient d'avoir recours à une fonction d'efficacité lumineuse différente. Pour appliquer celle-ci il faut, soit déterminer directement la répartition spectrale du flux énergétique, soit appliquer une correction à la courbe $V(\lambda)$ utilisée dans la cellule photo-électrique afin de tenir compte de l'efficacité lumineuse qui convient.

Une autre solution consiste à calculer une quantité nouvelle à partir des valeurs ordinaires de la luminance et des mesures colorimétriques de la CIE, en appliquant des formules mathématiques établies à cet effet. Cette méthode est celle qui offre le plus de possibilités puisque des formules appropriées peuvent être mises au point pour chacune des applications (par exemple, une pour les champs de 2° et une pour les champs de 10°) et que, néanmoins, elle reste basée sur les grandeurs CIE déjà établies sans qu'il soit nécessaire d'en introduire de nouvelles.

Pour la vision scotopique, l'évaluation est faite, soit à partir du flux énergétique en tenant compte de la fonction d'efficacité lumineuse scotopique $V'(\lambda)$, soit avec un photomètre énergétique convenablement corrigé, soit encore au moyen d'une mesure de luminance énergétique ou par photométrie visuelle.

Pour la photométrie mésopique, la lumière doit être évaluée tant en ce qui concerne ses effets photopiques que ses effets scotopiques. Il est alors possible d'obtenir une estimation, soit en combinant d'une façon non linéaire les luminances photopique et scotopique, soit, si l'on désire une évaluation plus précise, en combinant dans la formule finale trois ou, mieux encore, quatre quantités basées sur X_{10} , Y_{10} , Z_{10} et $V'(\lambda)$.

Zusammenfassung

Dem Photometriker stehen viele Methoden zur Verfügung, nach denen eine visuell sinnvolle Bewertung des Lichtes vorgenommen werden kann. Alle Methoden sind etwas komplizierter als nur die Anwendung eines $V(\lambda)$ korrigierten physikalischen Photometers. Darüberhinaus erfordern alle einiges Verständnis des visuellen Systems und seiner Funktionsweise. Die Vorteile sind jedoch erheblich : Die Messung des Lichtes steht in logischem Zusammenhang mit der Augenphysiologie, d.h., wie wir das Licht wahrnehmen. Die Methoden sind unten zusammengestellt.

Für photopisches Sehen (Tagessehen), Leuchtdichten von mehreren cd/m^2 oder höher, liefern gewöhnliche $V(\lambda)$ korrigierte physikalische Photometer visuell richtige Meßergebnisse für kleine zentral fixierte Lichter breiter spektraler Zusammensetzung. Für alle anderen Anwendungen sollte eine verschiedene spektrale Helligkeitsfunktion angewendet werden. Zur Anordnung der geeigneten Funktion muß man entweder die spektrale Verteilung der Strahlungsquelle direkt messen, oder die bestehende $V(\lambda)$ -Kurve der Photozelle an die gültige spektrale Empfindlichkeit anpassen.

Eine andere Lösung besteht darin, eine neue Größe aus den gewöhnlichen Leuchtdichtewerten und farbmtrischen Größen der CIE nach speziell für diesen Zweck entwickelten Formeln zu berechnen.

Diese Methode ist möglicherweise die nützlichste, da verschiedene Formeln für verschiedene Anwendungszwecke entwickelt werden können (z.B. zwei Grad oder zehn Grad Felder); gleichzeitig ist sie auf den von der CIE aufgestellten Größen aufgebaut und es brauchen keine neuen entwickelt zu werden.

Für scotopisches Sehen (Nachtsehen) wird die Bewertung der Strahlungsleistung auf die spektrale Empfindlichkeitsfunktion $V'(\lambda)$ bezogen, entweder mit einem physikalischen Photometer, der entsprechend korrigiert ist oder durch Strahlungsmessung oder visueller Photometrie.

Für die mesopische Photometrie (Messungen im Dämmerungssehbereich) sollte das Licht nach beiden Arten, sowohl photopisch ($V(\lambda)$) als auch scotopisch ($V'(\lambda)$) bewertet werden. Eine Abschätzung erhält man durch nichtlineare Addition der photopischen und scotopischen Leuchtdichteanteile oder zur endgültigen Bewertung durch Verwenden von drei oder noch besser vier Größen, die auf X_{10} , Y_{10} , Z_{10} und $V'(\lambda)$ basieren.

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Chapter 1

Problems in photometry

1.1. INTRODUCTION

This report is dedicated to the measurement of light. To many who have been making light measurements for years, it may seem superfluous, and indeed it is for the vast majority of the applications around the world. However, there are many instances in which light is measured in the routine way, with light meters and photometers, and the values yielded bear little or no relationship to the visual impression.

The definition of light itself lies behind the problems encountered in photometry. The CIE provides two similar definitions¹ appropriate to the problem at hand: 1. Any radiation capable of causing a visual sensation directly. 2. Radiation capable of stimulating the organ of vision. In this document we will use a concept consistent with those defined by the CIE but somewhat more general. Light is radiant power weighted according to the spectral sensitivity of the human eye. The word weighted implies measurement and indeed photometry concerns the measurement of light. The mathematical expression associated with photometric measures of light is

$$L_v = K_m \int_{360}^{830} L_{e,\lambda} V(\lambda) d\lambda \quad (1)$$

where L_v = luminance (*) in $\text{cd} \cdot \text{m}^{-2}$

$L_{e,\lambda}$ = spectral radiance in $\text{W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1} \cdot \text{nm}^{-1}$

$V(\lambda)$ = spectral luminous efficiency for photopic vision (**)

K_m = maximum spectral luminous efficacy (683 lumens per watt) (***)

The two definitions and this equation represent major and far-reaching accomplishments of the CIE. Without such a definition, the only means of specifying the physical stimulus for vision would be to give the entire radiant power distribution for the source in question.

This definition of light makes it an unusual quantity, something not completely physical, not psychological, but psychophysical. Its introduction was somewhat of an historical accident. Humans were using light and measuring it long before physicists learned that light was part of the radiant energy spectrum. The unit of measurement was the most common source — the candle — and the means of measuring was a visual brightness match using a standard candle. Since there was always a human doing the measuring, the spectral sensitivity of the human eye was already built into the procedure of measuring light. The CIE $V(\lambda)$ curve thus became a bridge tying the existing art of photometry to the physicist's newly discovered science of electromagnetic energy.

Unfortunately, this definition of light brings disadvantages as well as advantages. Discrepancies occur in the assessment of light for a wide variety of reasons. This report will list these problems for which routine light measurement may vary; it gives the reasons for the error, discusses possible alternative means of assessing the light, and makes recommendations as to the proper procedure for each case.

(*) Luminance is the fundamental quantity considered throughout this document because it is the basic visual stimulus. It represents the "light-emitting" ability of an element of a surface, whether this be self-luminous or reflective. In the International System of Units (SI), it is measured in candelas per square metre, somewhat as if that number of standard candle flames were spread uniformly over a unit area containing the element in question. However, the considerations of this report apply to other measures of light as well, such as intensity and illuminance, since all are related to luminance by simple mathematical equations.

(**) Values are listed in Table 2.1 and depicted graphically in Figure 1.1.

(***) New value approved by The International Committee for Weights and Measures, Sept., 1977.

1.2. THE PROBLEMS OF PHOTOMETRY

The problems are roughly categorized below into three groups. First the $V(\lambda)$ curve itself may be in error, not representing adequately the average observer. Second, the $V(\lambda)$ curve may be used in situations for which it is inappropriate. (The most obvious example is the use of the photopic or daylight $V(\lambda)$ curve for night vision, but there are many other instances of its misuse as well.) Finally, the assumption of linear additivity of the contributions of different wavelengths as expressed by equation (1) may be wrong. This problem arises because of the physiology of the visual system and requires understanding of when and why the additivity assumption fails.

1.2.1. Inadequacies in the original determination of $V(\lambda)$.

It has been realized for many years that the weighting of the short wavelengths is too low; in 1951, Judd² published his correction and this has been used extensively where needed. Since the eye is so insensitive in general to the shorter wavelengths, and since they do not contribute heavily to the spectral powers of many light sources, most notably tungsten, the error involved is usually of slight importance. However, in measuring the luminance of monochromatic lights from 400 to around 450 nm or so, of bluish lights, or of sources with a larger proportion of short wavelengths, the contribution of these short wavelengths will be undervalued and the measurement in error.

1.2.2. Inappropriate uses of $V(\lambda)$.

Since the $V(\lambda)$ curve is an integral part of the measurement of light, adequate measurement of light demands that the $V(\lambda)$ curve is a reasonable assessment of the spectral sensitivity of human beings in the light being measured. In many situations, such as photopic levels of illumination, $V(\lambda)$ does provide a reasonable assessment. This is particularly true of light from tungsten lamps. There are however many situations in which $V(\lambda)$ values are *not* sufficiently representative of the luminous efficiency of the viewer and the following sections will enumerate these and the reasons for them.

a) *Problems introduced because an individual's luminous efficiency function differs from $V(\lambda)$.*

There are, of course, a number of organisms, which, for genetic reasons, possess luminous efficiencies different from the standard CIE curve. Such a statement probably applies to most infrahuman animals, invalidating the use of $V(\lambda)$ units for many experimental purposes with animals. However, this fact seems to be rather generally recognized; numerous investigators attempt to determine brightness equivalents behaviorally for their animal subjects before using light as an experimental variable.

Certain human beings are likewise equipped constitutionally with luminous efficiencies different from $V(\lambda)$. Most notable are the protanopes, color defective individuals seriously insensitive to the longer wavelengths of radiation. Other color defective individuals, deuteranopes and tritanopes, may also display sensitivities distinct from the CIE function, but to a lesser extent³. Deviations from $V(\lambda)$ may be also found among the elderly and in certain highly pigmented races.

Variations are also found in individuals with normal color vision. Because the CIE curve is an average of the data for a large number of individuals, it will rarely apply precisely to a given individual. This variation in the normal population is of little importance in most practical situations. There are, however, some instances requiring precise measurement for which it is necessary to specify the subject's own luminous efficiency function rather than use $V(\lambda)$. [See ch. 3 for methods].

b) *Problems due to a change of luminous efficiency function with luminance level.*

There are many ways in which light units may be used inappropriately but by far the gravest problems are introduced when the level of illumination is not in the range of daylight or photopic vision (*). Under this condition, the photopic luminous efficiency function or $V(\lambda)$ is usually employed even though the spectral sensitivity of the human eye has shifted toward the shorter wavelengths (Purkinje shift). The shorter wavelengths appear brighter than they are given credit for, while the long wavelengths are being overestimated for their light producing capabilities. The use of $V(\lambda)$ values, when scotopic or night vision values apply,

(*) The lower level of photopic vision can only be approximated since many conditions, such as adaptation level, size and position of visual field, and the task of the individual, affect it. This approximation is indicated in the CIE definition of "at least several $\text{cd}\cdot\text{m}^{-2}$ ".

results in sizeable errors. For example, Illuminant C will be underestimated by some 2.5 times, while the measurement of a monochromatic light of 450 nm is too low by a factor of 30⁴.

Fortunately, these problems were recognized a long time ago and a scotopic standard observer, $V'(\lambda)$, was standardized by the CIE in 1951^{5, 6}. This curve should be used to evaluate the energy distributions at scotopic levels; the formula is completely analogous to that used for photopic luminance.

$$L'_v = K'_m \int_{360}^{780} L_{e,\lambda} V'(\lambda) d\lambda \quad (2)$$

where L'_v = scotopic luminance in $\text{cd} \cdot \text{m}^{-2}$

$L_{e,\lambda}$ = spectral radiance in $\text{W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1} \cdot \text{nm}^{-1}$

$V'(\lambda)$ = spectral luminous efficiency for scotopic vision (*)

K'_m = maximum spectral luminous efficacy (1,699 lumens per watt).

The technique is completely analogous to the use of $V(\lambda)$ at high levels; physical photometers can be built with a spectral sensitivity curve matching the $V'(\lambda)$ values; and the result is, of course, in *scotopic* photometric units.

Between photopic and scotopic levels of luminance, there is a wide range, covering several log units, for which neither the $V(\lambda)$ nor the $V'(\lambda)$ values are really suitable.

One possible solution to the question of mesopic photometry would be a series of standard luminous efficiency curves, each applicable to a different level. There are, however, many problems which accrue to this solution, since the range in between photopic and scotopic levels is characterized by a series of curves which shift irregularly from one extreme to the other. The amount of shift at a given luminance depends upon a large number of factors, such as the size and retinal position of the field and the adaptation level of the eye⁷⁻¹³. For example, as the luminance is raised above scotopic threshold the first change to take place is heightened sensitivity to the longer wavelengths. While this increase continues regularly for several log units, relative sensitivity to the short wavelengths remains essentially unchanged; the result is a progressive broadening of the luminous efficiency curves, until finally the shift in short wavelength sensitivity toward the photopic curve is realized at much higher luminances. Furthermore, the rate of change will depend markedly on the retinal area stimulated. If the foveal area is included, the changeover will be much more rapid than if only peripheral areas are stimulated.

c) Problems due to inappropriate viewing conditions.

Since the luminous efficiency function of the human eye is known to vary with a wide variety of viewing conditions, the assessment of radiant power can give accurate values only when the measured light corresponds to the conditions under which $V(\lambda)$ was obtained. These conditions are, specifically, photopic levels of illumination, a small field size (2 to 3 degrees), a neutral background, and central fixation. One troublesome problem in this category is field size; frequently one wishes to measure large fields rather than small spots of light. Luminous efficiency functions for large fields show the eye to be more sensitive to short wavelengths than is indicated by $V(\lambda)$; this means of course that the more short wavelength energy in a source, the greater will be the error in measuring a large field. The CIE has recognized this and provided a provisional $V(\lambda)$ curve for a 10 degree field¹⁴. Fortunately beyond ten degrees, the luminous efficiency for a centrally fixated target does not change much with area.

Another troublesome problem is measuring point sources of light; here too, spectral sensitivity differs somewhat from $V(\lambda)$ but no CIE standard currently exists.

1.2.3. Criteria for establishing $V(\lambda)$.

A much more insidious problem arises from the fact that luminous efficiency functions depend upon the method of assessment. The goal of the CIE in defining light was to have a means of assessing the visual effects of radiation. Thus, the measurement of light should predict its brightness and its efficiency for seeing. The method used in the assessment of sensitivity to radiant power should be immaterial: the amount of radiant power necessary at each wavelength for some constant response could be determined and the constant response might be equal brightness to some standard, absolute threshold, equal visual acuity, etc. In fact, the results obtained depend markedly on the constant response selected to assess the monochromatic radiations.

(*) $V'(\lambda)$ values can be found in Table 2.1 and Figure 1.1.

Since luminous efficiency does vary with the method it is of considerable interest to know how the $V(\lambda)$ function was obtained. The 1924 $V(\lambda)$ (2°) was derived primarily from flicker photometry although some step-by-step brightness matching was involved also¹⁵⁻¹⁷.

Flicker photometry requires the observer to adjust the quantity of a chromatic light which temporally alternates with a reference light, until minimum flicker is obtained. In the step-by-step brightness matching method the observer makes brightness matches between two wavelengths in a bipartite field. The two wavelengths are selected to be only a few nanometers apart so that the colors almost look alike and the observer can concentrate on making a brightness match without appreciable color differences to complicate the task. These methods were used to determine the CIE $V(\lambda)$ instead of heterochromatic brightness matching method for two main reasons. The first is that heterochromatic brightness matching yields generally much more variable data than does the step-by-step or minimum flicker method. Furthermore, it has been determined that the additivity law is not obeyed with heterochromatic brightness matching but is obeyed with flicker photometry (see below).

As noted above (Equation (1)), the CIE defines luminance of non-monochromatic light as the summation of the weighted spectral radiance of the component wavelengths. If, for example, one had a light which appeared yellow but indeed was made up of a mixture of red and green light, the luminance of the yellow light is defined as equal to the sum of the luminances of the red and green lights. Whether or not this additivity reflects its appearance to the eye depends upon how the weighting of the radiances to derive luminance is achieved¹⁸⁻²⁵. If the weightings are achieved by means of the flicker method then additivity will be obtained. If the weightings are obtained by means of heterochromatic brightness matching then additivity will not be obtained.

This adherence or lack of adherence to the additivity law (Abney's law) can be described in another way. If, for example, one matched for brightness a green light to a given white light and then matched for brightness a red light to that same white light and finally mixed these two quantities of red and green light together one would find that the resulting yellow light would not match twice the amount of the original white light. Similar additivity failures are obtained when the experiment is performed using an absolute threshold criterion²⁶.

On the other hand, if one were to take the green light and adjust its radiance in order to obtain minimum flicker with an alternating reference white light and then take a red light and adjust its radiance for minimum flicker with that same reference white light, it would be found that when these amounts of red and green lights are mixed and then the white light is adjusted in order to obtain a minimum flicker with this mixture of red and green light one would require twice the amount of the original white light. That is to say the additivity law would hold for minimum flicker as a criterion²⁷.

It has also been determined that the additivity law holds for at least two other psychophysical criteria. Boynton and Kaiser²⁸ have shown that additivity holds when using the criterion of minimally distinct border. In this criterion the observer adjusts the brightness of a chromatic field which is precisely juxtaposed with a reference white field until the border between these two fields is minimally distinct. This would be done first with, for example, a red light and then a green and then when the quantities of the red and green lights are halved and mixed it would be found that the minimally distinct border would be maintained. Similarly, additivity is found to hold if luminous efficiency is measured with visual acuity as the criterion²⁹⁻³¹.

The conclusion from all these studies is that the method used to obtain luminous efficiency functions unfortunately influences the function that is obtained. Other possible measures as pupil size, reaction time, electroretinograms, cortical evoked responses, and increment thresholds, etc., are described in Chapter 3. One type of curve is obtained from flicker photometry, step-by-step matches, minimally distinct border and acuity. This curve is narrow, the weightings obtained are additive, and it is very similar in shape to Judd's modification of $V(\lambda)$. Another type of curve with greater sensitivity at both the blue and red ends of the spectrum, particularly the blue, is obtained from direct heterochromatic brightness matching and threshold criteria; values obtained from these techniques are not additive.

Most of these effects have been recognized for years; in fact, the non-additivity problem has been named the Helmholtz-Kohlrausch effect³². The causes are only recently beginning to be understood. A possible explanation and the data supporting it are described in some detail in Chapter 2. Briefly, however, this explanation states that the output from cones feeds into two systems, one spectrally opponent or chromatic and the other one achromatic. Signals from the cones to the non-opponent achromatic system are combined linearly and activity at higher neural levels can be accurately predicted from the sum of the inputs. Signals from the cones to the opponent or chromatic system however are antagonistic in that activity within the red-green system (or the blue-yellow) is subtracted from one another. Thus, the specific

luminous efficiency function obtained in a given experiment depends upon whether the method used taps the output of the achromatic system (flicker, minimum border, etc.) or the outputs of both the chromatic and achromatic systems (heterochromatic brightness matching, absolute foveal threshold, etc.)^{26, 31, 33-36}.

What this means for photometry is that the results based upon $V(\lambda)$, the additive system, will not always be representative of the perceived brightness of the light. Generally speaking, neutral sources will appear equally bright when their luminances are the same; this occurs because the additional activity in the chromatic systems tends to cancel. Colors of equal luminance lying close to each other on the spectral locus will also appear equally bright. But, if two highly saturated lights relatively far apart in wavelength are of equal luminance they will rarely be equally bright. Since a relative luminous efficiency function obtained by heterochromatic brightness matching is broader than even Judd's modification of the CIE $V(\lambda)$, equally luminous lights (using Judd's correction) would not always be equally bright. Similarly they may not be equally visible, using a threshold criterion.

1.3. THE SIZE OF THE DISCREPANCIES INTRODUCED

The preceding discussion has shown the many ways in which discrepancies are introduced into the measurement of light by using CIE $V(\lambda)$ when some other luminous efficiency curve more appropriately assesses vision in a specific situation. In order to give the reader some idea of the magnitude of the problem, tables have been prepared for a variety of the problem areas³⁷. In each case, the standard luminance, based on $V(\lambda)$, is used as the norm and the "true" luminance is calculated using an appropriate luminous efficiency curve for the given conditions. The ratio of the latter value to this norm is given in the tables. The difference introduced through these various misapplications of $V(\lambda)$ obviously varies from an infinitesimal amount to a sizeable quantity depending upon the specific conditions. For neutral sources, all differences are small, regardless of their cause; for monochromatic radiances, most differences are large. Thus most of the problems apply to the measurement of colored lights.

The readers can judge for themselves whether or not a given difference marks a significant departure from reality for his given application. For example, it may or may not be important to the user that a large field of 6,486 K has 1.1 times more light when assessed by a curve known to be more appropriate than CIE $V(\lambda)$. However, the fact that a blue light emitting diode was underestimated by a factor of two compared with a yellow of equal luminance would be undoubtedly a problem for many applications. Chapter 2 is devoted to recommended techniques to circumvent each of these errors.

1.4. SUMMARY TABLES OF SOME EXAMPLES OF DISCREPANCIES INTRODUCED BY IMPROPER MEASURING TECHNIQUES

The values in these tables are ratios, calculated from

$$\frac{\int L_{e,\lambda} V^*(\lambda) d\lambda}{\int L_{e,\lambda} V(\lambda) d\lambda}$$

where V^* refers to the curve, appropriate to the condition, found in the Tables at the end of Chapter 2.