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

CIE COLLECTION IN PHOTOBIOLOGY AND PHOTOCHEMISTRY 2000

Contents:

- 138/1 CIE TC 6-14 report: Blue-light photochemical retinal hazard
- 138/2 CIE TC 6-32 report: Action spectrum for photocarcinogenesis (non - melanoma skin cancers)
- 138/3 CIE TC 6-34 report: Standardized protocols for photocarcinogenesis safety testing
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CIE 138 - 2000

UDC: 612.014.481-06 Descriptor: Optical radiation effects on humans

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The International Commission on Illumination (CIE) is an organisation devoted to international co-operation and exchange of information among its member countries on all matters relating to the art and science of lighting. Its membership consists of the National Committees in 37 countries and one geographical area and of 10 associate members.

The objectives of the CIE are :

1. To provide an international forum for the discussion of all matters relating to the science, technology and art in the fields of light and lighting and for the interchange of information in these fields between countries.
2. To develop basic standards and procedures of metrology in the fields of light and lighting.
3. To provide guidance in the application of principles and procedures in the development of international and national standards in the fields of light and lighting.
4. To prepare and publish standards, reports and other publications concerned with all matters relating to the science, technology and art in the fields of light and lighting.
5. To maintain liaison and technical interaction with other international organisations concerned with matters related to the science, technology, standardisation and art in the fields of light and lighting.

The work of the CIE is carried on by seven Divisions each with about 20 Technical Committees. This work covers subjects ranging from fundamental matters to all types of lighting applications. The standards and technical reports developed by these international Divisions of the CIE are accepted throughout the world.

A plenary session is held every four years at which the work of the Divisions and Technical Committees is reviewed, reported and plans are made for the future. The CIE is recognised as the authority on all aspects of light and lighting. As such it occupies an important position among international organisations.

LA COMMISSION INTERNATIONALE DE L'ÉCLAIRAGE

La Commission Internationale de l'Éclairage (CIE) est une organisation qui se donne pour but la coopération internationale et l'échange d'informations entre les Pays membres sur toutes les questions relatives à l'art et à la science de l'éclairage. Elle est composée de Comités Nationaux représentant 37 pays plus un territoire géographique, et de 10 membres associés.

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6. De constituer un centre d'étude international pour toute matière relevant de la science, de la technologie et de l'art de la lumière et de l'éclairage et pour l'échange entre pays d'informations dans ces domaines.
7. D'élaborer des normes et des méthodes de base pour la métrologie dans les domaines de la lumière et de l'éclairage.
8. De donner des directives pour l'application des principes et des méthodes d'élaboration de normes internationales et nationales dans les domaines de la lumière et de l'éclairage.
9. De préparer et publier des normes, rapports et autres textes, concernant toutes matières relatives à la science, la technologie et l'art dans les domaines de la lumière et de l'éclairage.
10. De maintenir une liaison et une collaboration technique avec les autres organisations internationales concernées par des sujets relatifs à la science, la technologie, la normalisation et l'art dans les domaines de la lumière et de l'éclairage.

Les travaux de la CIE sont effectués par 7 Divisions, ayant chacune environ 20 Comités Techniques. Les sujets d'études s'étendent des questions fondamentales, à tous les types d'applications de l'éclairage. Les normes et les rapports techniques élaborés par ces Divisions Internationales de la CIE sont reconnus dans le monde entier.

Tous les quatre ans, une Session plénière passe en revue le travail des Divisions et des Comités Techniques, en fait rapport et établit les projets de travaux pour l'avenir. La CIE est reconnue comme la plus haute autorité en ce qui concerne tous les aspects de la lumière et de l'éclairage. Elle occupe comme telle une position importante parmi les organisations internationales.

DIE INTERNATIONALE BELEUCHTUNGSKOMMISSION

Die Internationale Beleuchtungskommission (CIE) ist eine Organisation, die sich der internationalen Zusammenarbeit und dem Austausch von Informationen zwischen ihren Mitgliedsländern bezüglich der Kunst und Wissenschaft der Lichttechnik widmet. Die Mitgliedschaft besteht aus den Nationalen Komitees in 37 Ländern und einem geographischen Gebiet und aus 10 assoziierten Mitgliedern.

Die Ziele der CIE sind :

11. Ein internationaler Mittelpunkt für Diskussionen aller Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik und für den Informationsaustausch auf diesen Gebieten zwischen den einzelnen Ländern zu sein.
12. Grundnormen und Verfahren der Meßtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
13. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
14. Normen, Berichte und andere Publikationen zu erstellen und zu veröffentlichen, die alle Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik betreffen.
15. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

Die Arbeit der CIE wird in 7 Divisionen, jede mit etwa 20 Technischen Komitees, geleistet. Diese Arbeit betrifft Gebiete mit grundlegendem Inhalt bis zu allen Arten der Lichtanwendung. Die Normen und Technischen Berichte, die von diesen international zusammengesetzten Divisionen ausgearbeitet werden, sind von der ganzen Welt anerkannt.

Tagungen werden alle vier Jahre abgehalten, in der die Arbeiten der Divisionen überprüft und berichtet und neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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COMMISSION INTERNATIONALE DE L'ECLAIRAGE

CIE Central Bureau

Kegelgasse 27, A-1030 Vienna, AUSTRIA

Tel: +43(0)1714 31 87 0, Fax: +43(0)1713 08 38 18

e-mail: ciecb@ping.at

WWW: <http://www.cie.co.at/cie/>

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The Reports in this publication have been prepared by various CIE Technical Committees within Division 6 "Photobiology and Photochemistry". The reports draw on current knowledge and experience within the specific field of light and lighting described, and are intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of the reports is advisory and not mandatory. The latest CIE proceedings, CIE NEWS, future issues in the "CIE Collection" Series or publication listing should be consulted regarding possible subsequent amendments.

Les rapports ont été préparés par différents Comités Techniques de la Division 6 "Photobiologie et Photochimie" de la CIE. Les rapports traitent des connaissances et de l'expérience courantes dans le domaine spécifique décrit de la lumière et de l'éclairage, et ils sont destinés à être utilisés par les membres de la CIE et autres parties intéressées. Il faut cependant noter que les rapports sont indicatifs et non obligatoires. Les derniers comptes rendus de la CIE, le CIE NEWS, éditions futures de la série "CIE Collection" ou la dernière liste de publications de la CIE devront être consultés pour connaître d'éventuels et récents amendements.

Die Berichte wurden von verschiedenen Technischen Komitees der CIE in Division 6 "Photobiologie und Photochemie" erarbeitet. Die Berichte behandeln den derzeitigen Stand des Wissens und der Erfahrung auf dem Gebiet Licht und Beleuchtung; sie sind zur Verwendung durch CIE-Mitglieder und durch andere Interessierte bestimmt. Es sollte jedoch beachtet werden, daß die Berichte Empfehlungen und keine Vorschriften sind. Die neuesten CIE-Tagungsberichte, das CIE NEWS, zukünftige Ausgaben in der Serie "CIE Collection" oder die Publikationsliste sollten im Hinblick auf mögliche spätere Änderungen zu Rate gezogen werden.

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CIE TC 6-14 REPORT

BLUE-LIGHT PHOTOCHEMICAL RETINAL HAZARD

FORWORD

This technical report was prepared as a result of activities of CIE Technical Committee TC 6-14, The Blue-Light Hazard. The TC 6-14 was organized after discussions at the full meeting of Division 6, Photobiology and Photochemistry which was held during the term of the CIE session which began in Venice, 1987.

The following members and consulting experts of TC 6-14 "The Blue-Light Hazard" took part in the preparation of this technical report. TC 6-14 comes under CIE Division 6 "Photobiology and Photochemistry".

Members:

Césarini, J. P.	France
Crabbe, P. J.	United Kingdom
DiDomenico, S.	USA
Feigusch, G.	Italy
Kohmoto, K.	Japan, Chairman
McKinlay, A. F.	United Kingdom
Meulemans, C. C. E	The Netherlands
Mutzhass, M.(†)	Germany
van Norren, D.	The Netherlands
Ronchi, L. R.	Italy
Sliney, D. H.	USA
Sperling, G.	USA
Suga, S.	Japan

Consulting experts:

Aoki, T.	Japan	Okuno, T.	Japan
Azuma, T.	Japan	Osakabe, T.	Japan
Beede, C.	USA	Seki, R.	Japan
Chaki, K.	Japan	Tanaka, G.	Japan
Inukai, H.	Japan	Tokuyama, I.	Japan
Koshi, S.	Japan	Tsuji, S.	Japan
Mike, Y.	Japan	Yagami, T.	Japan
Misu, K.	Japan	Yamaguchi, H.	Japan
Naitoh, E.	Japan	Yamamoto, T.	Japan
Ohzu, H.	Japan	Yonemoto, S.	Japan

BLUE-LIGHT PHOTOCHEMICAL RETINAL HAZARD

SUMMARY

The results of studies of acute photochemical retinal injury, frequently referred to as the "blue light hazard (BLH)" are described in this technical report. The BLH results from a photochemical injury to the human retina and is termed by ophthalmologists "photoreinitis". The original biological research relating to photoreinitis included the determination of the action spectra for this effect. Studies were performed by a number of scientists, but two series of fundamental studies were performed by the group led by Dr. William T. Ham¹⁻³ of the Medical College of Virginia, Richmond, Virginia, and Dr. Harry G. Sperling⁴ of the University of Texas, Houston, Texas. Their pioneering work provided the basis for threshold limit values (TLV) and the BLH action spectrum recommended by the American Conference of Governmental Industrial Hygienists⁵ (ACGIH) in the 1970's, and more recently, after completion of the work of TC 6-14, by the International Commission on Non-Ionizing Radiation Protection⁶ (ICNIRP).

The potential for photoreinitis resulting from viewing the sun, tungsten-halogen lamps, high intensity discharge lamps, xenon short-arc lamps, welding arcs, etc., is provided in this report. Means and methods to evaluate potential BLH were studied by the CIE committee and one technique employing the ACGIH TLV⁵ is proposed for general use.

As a result of evaluating a number of light sources used for general lighting applications or in photocopiers and overhead projectors, it is concluded that there is an insignificant risk from blue-light photoreinitis during ordinary viewing conditions. Tungsten-halogen lamps used for desk illumination may pose the greatest possibility for blue-light photoreinitis. Under the worst-case condition, direct staring at a bare tungsten-halogen filament for 13 seconds within one day will exceed the BLH TLV. Because of the natural

aversion response to bright light, individuals would never be expected to stare at such a source for such a lengthy period.

Blue-light photoreinitis does occur, but rarely, to unprotected welders, typically young welders, who fixate on the welding arc for a period of minutes. Normally welders are obliged to wear suitable eye protectors while engaged in arc welding. In addition such eye protection also protects against potential eye injury from ultraviolet and infrared radiation. The most frequently reported clinical cases of acute photoreinitis occur when individuals stare at the sun, as during a solar eclipse.

Both national and international standards for eye protectors exist (e.g., in the USA, UK, Canada, Germany, Japan). The recognized international standard (ISO 4850: Personal Eye Protectors for Welding and Related Techniques - Filters - Utilization and Transmittance Requirements)⁷ is followed internationally. These eye protection filter standards were not developed based upon knowledge of the BLH, but were developed empirically to provide comfortable viewing for open arc processes and welding arcs. It has since been shown clearly that such filters provided adequate protection against the BLH.⁸

It is concluded that actual specifications for maximal blue-light transmittance may be a desirable addition to future editions of eye protection standards. A proposal to ISO will also be prepared under the scope of activities of TC 6-14. And this proposal will be presented to the ISO TC 94 through the CIE in accordance with the Memorandum of Understanding between the CIE, the IEC and the ISO.

DANGER PHOTOCHIMIQUE RETINIENNE DE LA LUMIERE BLEUE

RESUME

Les résultats des études sur l'agression photochimique aiguë rétinienne, fréquemment désignée sous le terme "Blue Light Hazard (BLH)" soit, "Danger de la Lumière Bleue (DLB)" sont réunis dans ce rapport technique. Le DLB résulte de l'agression photochimique de la rétine chez l'homme et il est communément identifié par les ophtalmologistes sous le terme de "phototraumatisme rétinien". La recherche biologique originale en rapport avec le phototraumatisme rétinien a permis la détermination du spectre d'efficacité de cet effet. Des études ont été menées par un certain nombre de scientifiques, cependant, deux séries de travaux fondamentaux ont été exécutées par l'équipe menée par le Dr. William T. Ham¹⁻³ du Medical College of Virginia, Richmond, Virginie, et le Dr. Harry G. Sterling⁴ de l'University of Texas, Houston, Texas. Leur travail de pionniers a fourni les bases du calcul des "Threshold Limit Values (TLV)" ou "Valeurs Limites de Seuil (VLS)" et le spectre d'efficacité du DLB, recommandés par l'American Conference of Governmental Industrial Hygienists⁵ (ACGIH) dans les années 1970, et plus récemment, après l'aboutissement du travail du TC 6-14, par l'International Commission on Non-Ionizing Radiation Protection⁶ (ICNIRP).

Les probabilités du risque d'induire un phototraumatisme rétinien résultant de l'observation du soleil, de sources tungstène-halogènes, de lampes à décharge d'intensité élevée, de lampes xénon à arc court et d'arcs générés par la soudure électrique, etc., sont indiquées dans ce rapport. Les moyens et les méthodes pour évaluer le risque de DLB ont été étudiés par le comité ad hoc de la CIE et une technique utilisant les VLS définies par l'ACGIH⁵ est proposée pour application générale.

Après l'évaluation d'un certain nombre de sources lumineuses utilisées pour l'éclairage en général ou dans les appareils à photocopie et dans les rétro-projecteurs de documents, on peut conclure que, en conditions habituelles d'usage, le risque de photoagression rétinienne par la lumière bleue est insignifiant. Les sources tungstène-halogènes utilisées pour l'éclairage de bureau peuvent présenter un risque important de phototraumatisme rétinien. Dans le pire des cas, regarder directement un filament tungstène-halogène nu pendant 13 secondes par jour, dépassera le VLS du DLB. En fait, en raison du réflexe d'aversion naturelle à la lumière brillante, les sujets ne devraient pas être se trouver dans de telles conditions pendant une telle durée.

Le phototraumatisme rétinien survient, quoique rarement, chez les soudeurs non protégés, typiquement de jeunes soudeurs, qui regardent l'arc de soudure pendant une durée de plusieurs minutes. Normalement les soudeurs sont dans l'obligation de porter des

protections oculaires adaptées quand ils effectuent une soudure à l'arc. De plus, cette protection oculaire protège également contre les risques résultant de l'agression induite par les radiations ultraviolettes et infrarouges. Les observations cliniques de phototraumatisme rétinien le plus fréquemment rapportées surviennent quand les sujets regardent directement le soleil, comme par exemple, lors d'une éclipse solaire.

Des normes nationales et internationales pour la protection oculaire existent (exemples: aux Etats-Unis, Grande Bretagne, Canada, Allemagne, Japon). La norme internationalement reconnue (ISO 4850: Protection individuelle oculaire pour soudure à l'arc et technologies associées - filtres - utilisation et conditions requises de transmission)⁷ est habituellement appliquée. Les normes fixant la qualité de protection des filtres oculaires n'ont pas été basées sur les connaissances du DLB mais ont été développées, empiriquement, pour procurer une vision confortable lors de l'utilisation d'arcs ouverts ou de soudure à l'arc. Depuis, il a été clairement démontré que de tels filtres procuraient une protection adéquate également contre le DLB.⁸ On peut conclure que les spécifications actuelles pour la transmission maximale de la lumière bleue sont une addition souhaitable aux futures éditions de normes pour la protection oculaire. Une proposition sera faite à l'ISO dans le cadre des activités du TC 6-14. Cette proposition sera présentée à l'ISO TC 94 par le canal de la CIE selon le "Memorandum of understanding", accord passé entre la CIE, l'IEC et l'ISO.

PHOTOCHEMISCHE RISIKEN FÜR DIE NETZHAUT DURCH BLAULICHT

ZUSAMMENFASSUNG

Dieser technische Bericht beschreibt die Ergebnisse von Studien über die akute photochemische Verletzung der Netzhaut, häufig als "blue light hazard" (BLH) bezeichnet. BLH resultiert aus einer photochemischen Verletzung der menschlichen Netzhaut und wird von Augenärzten "Photoretininitis" genannt. Die ursprüngliche biologische Forschung über die Photoretininitis beinhaltete die Bestimmung der Wirkungsfunktion dieser Störung. Viele Studien verschiedener Wissenschaftler wurden durchgeführt; zwei Serien grundlegender Studien stammen von Experten um Dr. William T. Ham¹⁻³ (Medical College of Virginia, Richmond, Virginia) und Dr. Harry G. Sperling⁴ (University of Texas, Houston, Texas). Ihre bahnbrechende Arbeit lieferte die Grundlagen der Schwellengrenzwerte (TVL) und der BLH-Wirkungsfunktion. Die letztere wurde in der 70er Jahren durch die American Conference of Governmental Industrial Hygienists⁵ (ACGIH) und später, nach dem Abschluß der Arbeit von TC 6-14, durch die International Commission on Non-Ionizing Radiation Protection⁶ (ICNIRP) empfohlen.

Dieser Bericht behandelt das Risiko für die Entstehung einer Photoretininitis durch Blicken in die Sonne, Glühlampen, Hochdruckentladungslampen, Xenon Kurzbogenlampen, Schweißbogen usw. Mittel und Methoden zur Beurteilung des eventuellen BLH wurden im CIE Komitee untersucht. Eine Technik, die den ACGIH Schwellengrenzwert⁵ verwendet, wird zur allgemeinen Verwendung empfohlen.

Nach der Beurteilung einiger Lichtquellen, die für allgemeine Beleuchtungsanwendungen oder in Fotokopierern und Overheadprojektoren verwendet werden, wurde festgestellt, daß unter normalen Bedingungen nur ein unbedeutendes Risiko für die Photoretininitis durch Blaulicht besteht. Halogenglühlampen, die für Schreibtischbeleuchtungen benutzt werden, können das größte Risiko für die Photoretininitis durch Blaulicht darstellen. Im schlimmsten Fall wird durch 13 Sekunden langes direktes Starren auf den Faden einer Halogenglühlampe binnen eines Tages der BLH-Schwellengrenzwert überschritten. Infolge der natürlichen Abwehrreaktion gegen grelles Licht ist jedoch nicht zu erwarten, daß eine Person eine solche Quelle über eine solch lange Zeit anstarrt.

Die Photoretininitis durch Blaulicht kommt, wenn auch selten, bei ungeschützten, meist jungen Schweißern vor, die über eine Zeitdauer von Minuten den Blick auf den Schweißbogen fixieren. Normalerweise sind Schweißer dazu verpflichtet, während des Schweißprozesses einen geeigneten Augenschutz zu tragen. Dieser Augenschutz schützt auch vor möglichen Augenverletzungen durch Ultraviolett- und Infrarotstrahlung. Die häufigsten klinischen Fälle von akuter Photoretininitis kommen vor, wenn Personen, z.B. während einer Sonnenfinsternis, direkt in die Sonne schauen.

Es existieren nationale und internationale Normen für den Augenschutz (z.B. in den USA, Großbritannien, Kanada, Deutschland, Japan). Die anerkannte internationale Norm (ISO 4850: Personal Eye Protectors for Welding and Related Techniques - Filters - Utilization and Transmittance Requirements)⁷ wird weltweit eingehalten. Diese Augenschutz-Normen wurden nicht aufgrund des Wissen über BLH entwickelt, sondern empirisch ermittelt, um bequeme Sicht auf offene Bogenprozesse und Schweißbögen zu ermöglichen. Es hat sich seitdem erwiesen, daß solche Filter ausreichenden Schutz gegen BLH bieten.⁸

Es wurde festgestellt, daß es wünschenswert wäre, wenn die aktuellen Spezifikationen für maximale Transmission von Blaulicht in zukünftigen Ausgaben der Augenschutz-Normen erscheinen würden. Im Rahmen der Aktivitäten von TC 6-14 wird auch ein Vorschlag an die ISO fertiggestellt. Dieser Vorschlag wird dem ISO TC 94 durch die CIE, in Übereinstimmung mit dem zwischen der CIE, IEC und ISO geschlossenen "Memorandum of Understanding" vorgelegt werden.

1. INTRODUCTION

The aim of CIE TC 6-14 was to investigate the current state of knowledge regarding the so called "Blue-Light Hazard" and if necessary, to recommend proposals to protect the human eye from this hazard.

There are basically five separate types of optical radiation hazards to the human eye that require consideration when evaluating the potential risk of exposure to any light source:

- (1) Photokeratoconjunctivitis, i.e. photochemical injury to the cornea and the conjunctiva from UV radiation (principally UV-B and UV-C).
- (2) Ultraviolet radiation injury to the lens which may result in cataract.
- (3) Infrared radiation (thermal) injury hazard to the cornea and lens.
- (4) Thermal retinal injury resulting from exposure to very intense visible and near-infrared (IR-A) radiant energy.
- (5) The blue-light photochemical hazard to the retina (photoreinitis).

With regard to the biological effects listed in (1)-(4) the interaction mechanism and the spectral weighting functions have been investigated and threshold limit values (TLVs) published. Protective measures, and suitable eye protection have been established. International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines have been published.

Throughout the discussion leading up to the publications of ISO standards for eye protection, a blue-light photochemical hazard (BLH) was not considered. To complete new specifications during the revision of current ISO standards, consideration of the BLH appeared to be an important new activity. With this background, the technical committee TC 6-14 was established at the CIE session held in Venice in 1987. The terms of reference for TC 6-14 were:

- (1) To summarize and evaluate a spectral weighting function and an exposure limit value for BLH exposure of the human eye.
- (2) To investigate and recommend practical protective measures for the BLH.
- (3) To propose a new standard for eye protection or for future revision of current ISO standards for eye protectors.

The recommendation for practical protective measures with the BLH should be closely related to the following ISO Standards:

- ISO 4007-1977 Personal eye-protectors - Vocabulary
- ISO 4849-1981 Personal eye-protectors - Specifications
- ISO 4850-1979 Personal eye-protectors for welding and related techniques - Filters - Utilization and transmittance requirements
- ISO 4851-1979 Personal eye-protectors - Ultraviolet filters - Utilization and transmittance requirements
- ISO 4852-1978 Personal eye-protectors - Infrared filters - Utilization and transmittance requirements
- ISO 4854-1981 Personal eye-protectors - Optical test methods

ISO 4856-1982 Personal eye-protectors - Synoptic tables of requirements for ocular and eye-protectors

It was considered that the studies and conclusions of TC 6-14 should be communicated through a liaison activity to appropriate ISO committees. This liaison activity should be undertaken with the full recognition of the Memorandum of Understanding between the CIE, IEC, and ISO relating to future standardization at the international level.

2. BLUE-LIGHT PHOTOCHEMICAL RETINAL HAZARD (BLH)

2.1 Interaction mechanism

Visible light interacts with the photoreceptors of the retina, producing a nerve-signal (visual transduction), communicated to the brain for vision. The action spectrum of this process, in daylight environments, is the CIE photopic luminous efficiency curve, $V(\lambda)$. In addition to visual stimuli, intense optical radiation may cause photochemical or thermal injury if retinal irradiance levels are sufficiently high.

A retinal thermal injury ("retinal burn or photocoagulation") is produced when the eye images an extremely bright, normally pulsed, light source, such as a laser. Higher irradiances are required to produce thermal injuries, as compared to a photochemical injury to the retina. Photochemical injury is produced by exposures of lengthy duration at relatively lower irradiance levels than are required to cause thermal injury. The resulting temperature rise produced at the retina will be typically less than one degree C to produce a photochemical injury.¹ Current evidence supports the theory that photochemical injury requires a threshold radiant exposure dose (approximately 22 J/cm^2 or $2.2 \cdot 10^5 \text{ J/m}^2$ at 446 nm) and is independent of spot size (save for the effect of eye movements).

Phototoxicity (photochemical) injury mechanisms are subdivided into at least two different types of injuries:

- (A) Low retinal irradiance lengthy exposures of several hours duration (generally repeated over several days).⁹
- (B) High retinal irradiance shorter exposures (generally one exposure lasting for minutes to a few hours).^{1, 3, 10}

The action spectrum to produce the former type of hazard appears to coincide with the spectral absorption properties of rhodopsin (i.e. the visual pigment of rod photoreceptors), and it is therefore theorized that this type of injury occurs as a result of the direct absorption of rhodopsin.⁹ The spectral absorption properties of rhodopsin are provided in Figure 2.1.1.

The action spectrum for the higher irradiance phototoxicity peaks at the short-wavelength region in either the blue or the ultraviolet region (the BLH). There is some debate amongst experts as to whether more than one photochemical photoreinitis action spectrum exists. The author of the primary research studies in this area, Professor Ham, argued that there is one action spectrum which peaks in the ultraviolet region if the crystalline lens is not present, however, because of the strong absorption of the crystalline lens in the near-ultraviolet region (300 nm-400 nm), little ultraviolet radiation reaches the retina. The primary photoreinitis action spectrum in a normal eye peaks in the 440-450 nm region. It is this injury mechanism for photoreinitis which is typically referred to as the BLH. The chromophore, or reacting pigment, responsible for the BLH is not known. It has been theorized that it may be melanin or mitochondria such as cytochrome C or riboflavin or it may even be a secondary product of the photo-oxidized visual pigment (rhodopsin) such as retinal, retinol or 3 hydroxy retinol.^{3, 8, 9, 10} The spectral absorption properties of melanin and related bleach products are also shown in Figure 2.1.1.

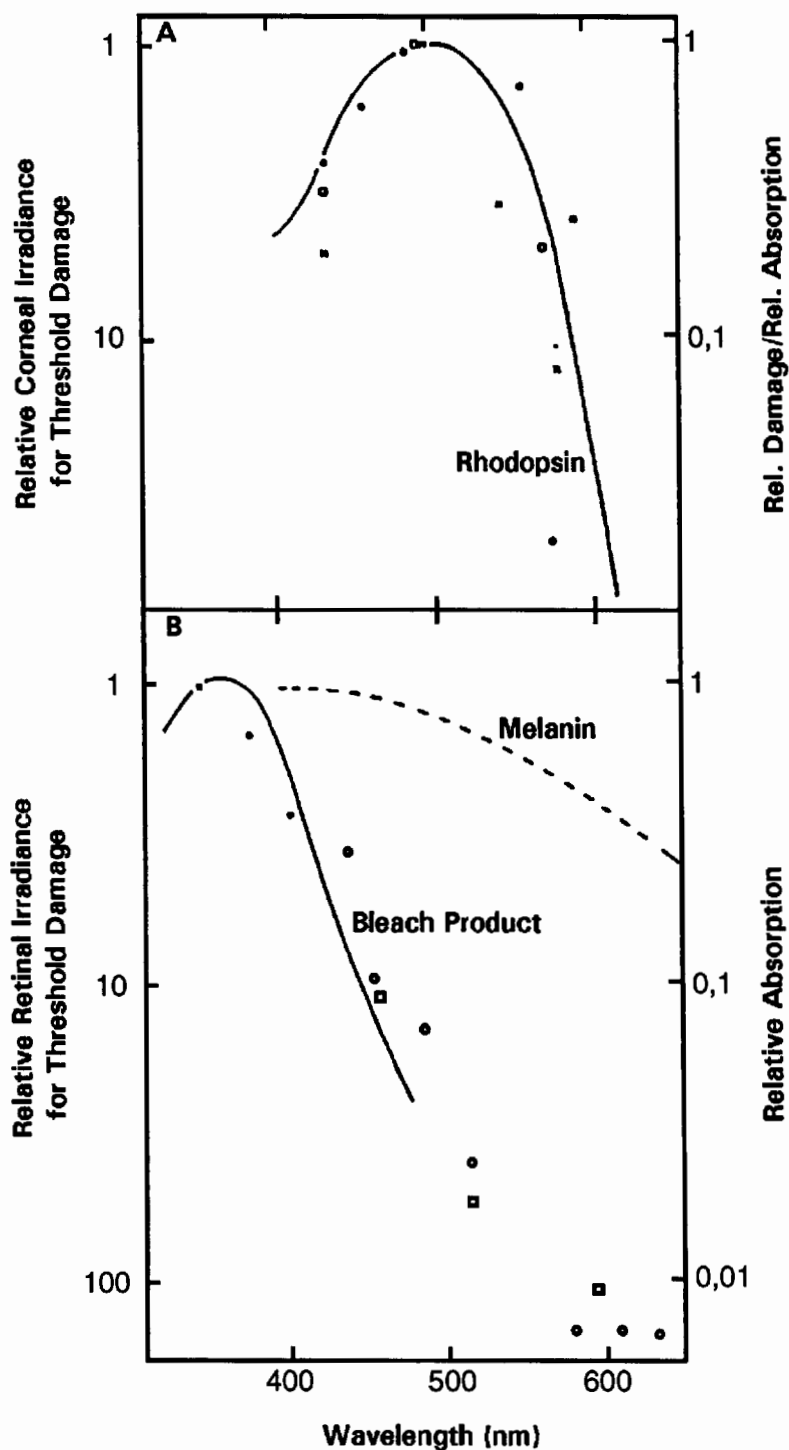


Figure 2.1.1 Spectral absorption properties of rhodopsin melanin and related rhodopsin bleach products.

2.2 Spectral weighting function of BLH and its standardization

The standard weighting function $B(\lambda)$ was first recommended by David Sliney of the U.S. Army Center for Health Promotion and Preventive Medicine (formerly known as the U.S. Army Environmental Hygiene Agency). He based this weighting function on the experimental results of Ham, et. al. which were obtained from research studies employing the rhesus monkeys as determined by the observation of a fundusoscopically apparent lesion of the retina (see Table 2.2.1). Subsequently, this function has been adopted by the American Conference of

Governmental Industrial Hygienists (ACGIH). ACGIH used this function to establish a threshold limit value (TLV) for human exposure.

Table 2.2.1 Spectral weighting functions for assessing retinal hazards from broad-band optical radiation sources.

Wavelength (nm)	Aphakic hazard function A_λ	Blue-light hazard function B_λ	Burn hazard function R_λ
305	6,00	0,01	—
310	6,00	0,01	—
315	6,00	0,01	—
320	6,00	0,01	—
325	6,00	0,01	—
330	6,00	0,01	—
335	6,00	0,01	—
340	5,88	0,01	—
345	5,71	0,01	—
350	5,46	0,01	—
355	5,22	0,01	—
360	4,62	0,01	—
365	4,29	0,01	—
370	3,75	0,01	—
375	3,56	0,01	—
380	3,19	0,01	—
385	2,31	0,0125	—
390	1,88	0,025	—
395	1,58	0,050	—
400	1,43	0,100	1,0
405	1,30	0,200	2,0
410	1,25	0,400	4,0
415	1,20	0,800	8,0
420	1,15	0,900	9,0
425	1,11	0,950	9,5
430	1,07	0,980	9,8
435	1,03	1,000	10,0
440	1,000	1,000	10,0
445	0,970	0,970	9,7
450	0,940	0,940	9,4
455	0,900	0,900	9,0
460	0,800	0,800	8,0
465	0,700	0,700	7,0
470	0,620	0,620	6,2
475	0,550	0,550	5,5
480	0,450	0,450	4,5
485	0,400	0,400	4,0
490	0,220	0,220	2,2
495	0,160	0,160	1,6
500-600	$10^{[(450-\lambda)/50]}$	$10^{[(450-\lambda)/50]}$	1,0
600-700	0,001	0,001	1,0
700-1049	NA*	NA*	$10^{[(700-\lambda)/500]}$
1050-1400	NA*	NA*	0,2

* NA = Not Applicable

In addition to the function $B(\lambda)$ for the normal eye an additional function $A(\lambda)$ was later developed based on studies of Ham in rhesus monkeys with the crystalline lens surgically removed.² This was to simulate the viewing condition which could occur when a cataract patient having an intraocular lens without UV-A absorption, or with no lens (aphake), viewed an intense light source. The values for this newer function, the aphake hazard function, $A(\lambda)$

are provided in Table 2.2.1. The function $A(\lambda)$ should be applied for persons who do not have an intraocular lens which absorbs ultraviolet radiant energy in the UV-A spectral region; this condition is becoming rare.

2.3 Threshold limit value of BLH – Recommendation of ACGIH

2.3.1 TLV of ACGIH

The ACGIH has recommended TLVs for many physical agents, among them for light and near-infrared radiation. These guidelines for the BLH are as follows:

The TLV for occupational exposure to broad-band light and near-infrared radiation for the eye apply to exposure in any 8-hour workday and require knowledge of the spectral radiance (L_λ) and total irradiance (E) of the source as measured at the position(s) of the eye of the worker. Such detailed spectral data of a white light source are generally only required if the luminance of the source exceeds $1 \text{ cd}\cdot\text{cm}^{-2}$ ($10^4 \text{ cd}\cdot\text{m}^{-2}$). At luminances less than this value, the TLV would not be exceeded.

To protect against the retinal photochemical hazard from chronic blue-light, the spectral radiance L_λ weighted against the blue-light hazard function $B(\lambda)$ should not exceed:

$$\sum_{400}^{700} L_\lambda \cdot B(\lambda) \cdot \Delta\lambda \leq 10^{-2} \text{ W}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1} \quad (t > 10^4 \text{ s}) \quad [1]$$

$$\text{or } \leq 10^2 \text{ W}\cdot\text{m}^{-2}\cdot\text{sr}^{-1}$$

$$\sum_{400}^{700} L_\lambda \cdot t \cdot B(\lambda) \cdot \Delta\lambda \leq 100 \text{ J}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1} \quad (t \leq 10^4 \text{ s}) \quad [2]$$

$$\text{or } \leq 10^6 \text{ J}\cdot\text{m}^{-2}\cdot\text{sr}^{-1}$$

The weighted product of L_λ and $B(\lambda)$ is termed L_{blue} . For a source radiance L weighted against the blue-light hazard function ($B(\lambda)$) which exceeds $10 \text{ mW}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1}$ ($10^2 \text{ W}\cdot\text{m}^{-2}\cdot\text{sr}^{-1}$) in the blue spectral region, the permissible exposure duration t_{max} in seconds is simply.

$$t_{\text{max}} = 100 (\text{J}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1})/L_{\text{blue}} \text{ or } 10^6 (\text{J}\cdot\text{m}^{-2}\cdot\text{sr}^{-1})/L_{\text{blue}} \quad [3]$$

The latter limits are greater than the maximum permissible exposure limits for 400-440 nm laser radiation, because the laser TLV has an added safety factor to account for potential, undiscovered, narrow-band action spectra. A constricted, 2-3 mm pupil was assumed in the derivation of both types of exposure limits. However, because of eye and head movements, measurements need not be taken with such very small entrance apertures. For example, laser guidelines recommend a 7 mm aperture, but blue-light exposure limits can be averaged over larger aperture sizes.

Measurements of spectral radiance or blue-light radiance (with blue-light safety filter radiometer) for hazard assessment are carefully specified in health protection guidelines.⁶ The entrance aperture of the instrument should be small enough to account for significant "hot-spots" of high irradiance. The measurement cone angle of acceptance (field-of-view) is specified as 11 mrad for durations of 100 s or less, and to simulate ever increasing eye movements, this cone angle increases as the square-root of time to 0,1 radian at 10000 s. This measurement cone angle is fixed, regardless of source size (whether the source subtends an angle less than or greater than the measurement cone angle of acceptance).^{6, 11}

For a light source subtending an angle α less than 11 mrad (0,011 radian), the above limits on radiance can actually be expressed as irradiance limits such that the spectral irradiance weighted against the blue-light hazard function $B(\lambda)$ should not exceed E_{blue} .

$$H_{\text{blue}} = \sum_{400}^{700} E_\lambda \cdot t \cdot B(\lambda) \cdot \Delta\lambda \leq 10^{-2} \text{ J}\cdot\text{cm}^{-2} \quad (t < 100 \text{ s}) \quad [4]$$

$$\text{or } \leq 10^2 \text{ J}\cdot\text{m}^{-2}$$

$$E_{\text{blue}} = \sum_{400}^{700} E_{\lambda} \cdot B(\lambda) \cdot \Delta\lambda \leq 0,1 \text{ mW} \cdot \text{cm}^{-2} \quad (t > 100 \text{ s}) \quad [5]$$

$$\text{or } \leq 1 \text{ W} \cdot \text{m}^{-2}$$

For a source where the blue-light weighted irradiance E_{blue} exceeds $0,1 \text{ mW} \cdot \text{cm}^{-2}$ ($1 \text{ W} \cdot \text{m}^{-2}$) the maximum permissible exposure duration t_{max} in seconds is:

$$t_{\text{max}} = 10^{-2} \text{ J} \cdot \text{cm}^{-2} / E_{\text{blue}} \quad \text{or} \quad 10^2 \text{ J} \cdot \text{m}^{-2} / E_{\text{blue}} \quad [6]$$

For the worker having a lens surgically removed (cataract surgery), there will be an increased blue-light hazard. Unless a UV-absorbing intraocular lens has been surgically inserted into the human eye, an adjusted $B(\lambda)$ function should be applied in equations mentioned above, and the function summed from 300 nm to 700 nm. This alternative $B(\lambda)$ function is termed the Aphakic hazard function $A(\lambda)$.

3. OPTICAL RADIATION SOURCES RELATING TO THE BLH

3.1 Optical properties of some radiation sources

Various optical radiation sources, including the sun, may be directly viewed. However, safe viewing of such intense light sources depends upon the viewing duration. Some sources are spectrally rich in the blue-light region of the spectrum. For this reason these sources were studied to determine the potential BLH. Table 2.1.1 shows the spectral weighting functions for assessing a retinal hazard from broad-band optical radiation sources. Table 3.1.1 provides the optical properties relating to the BLH for the sources which were thought to pose a relatively high risk for BLH. Characteristics and details of individual light sources are shown in Table 4.2.1 and from Figure 3.1.1 to Figure 3.1.3.

Table 3.1.1 Optical radiation sources relating to the Blue-light hazard.

Sources	Lamp (W)	Radiation (W)	Radiance ($\text{W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}$)	Wavelength range (nm)	% of Blue-Light
solar radiation	—	(1 $\text{kW} \cdot \text{m}^{-2}$)	$2,2 \cdot 10^7$	300-2 500	5-10
incandescent lamp	10-2 000	9-1 800	$1,0 \cdot 10^2$	300-2 500	0,5-2,0
tungsten halogen	500-10 000	450-9 000	$1,0 \cdot 10^4$	270-2 500	1,0-4,0
short arc xenon	500-20 000	250-10 000	10^6 - 10^8	250-3 500	6-10
high pressure mercury	40-2 000	25-1 200	10^3 - 10^5	300-1 000	8-20
metal halide lamp	100-2 000	80-1 500	10^3 - 10^5	300-1 000	8-22
welding arc spot	—	—	10^8 - 10^{10}	200-1 000	5-40
(reference) laser	—	1-10 mW	10^9 - 10^{14}	300-10 000	—

Notes: (1) Wavelength range of blue-light: 400-500 nm

(2) Laser: just for reference

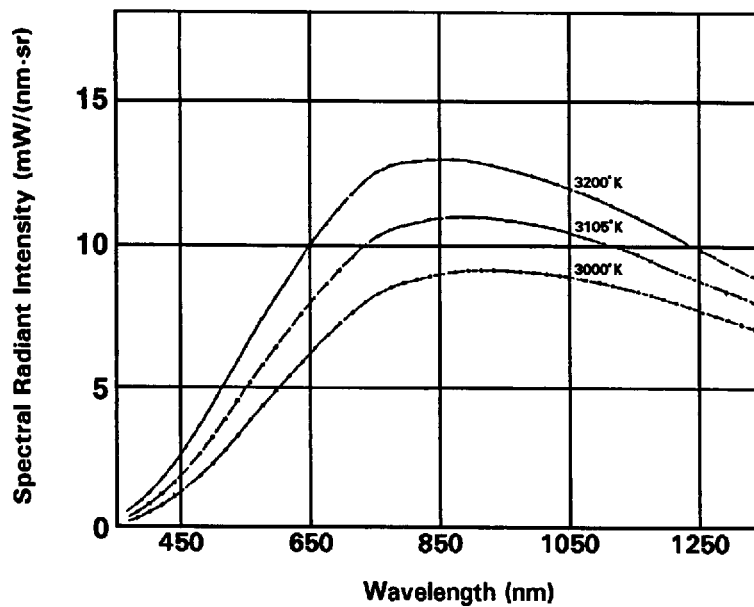
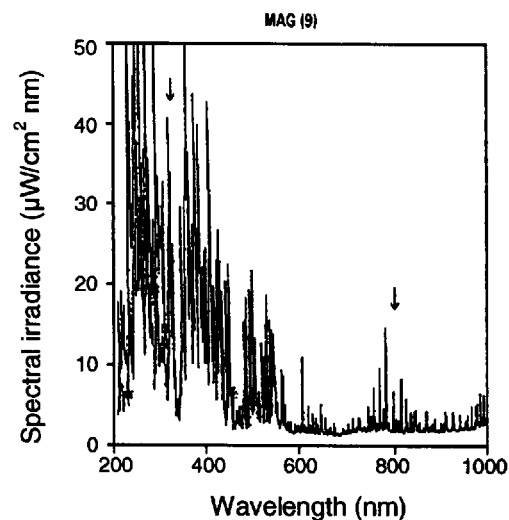
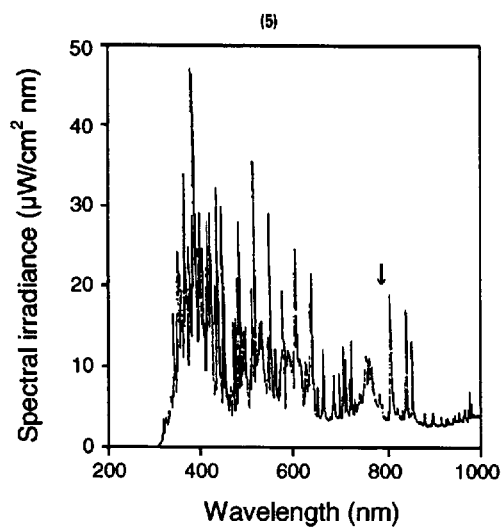
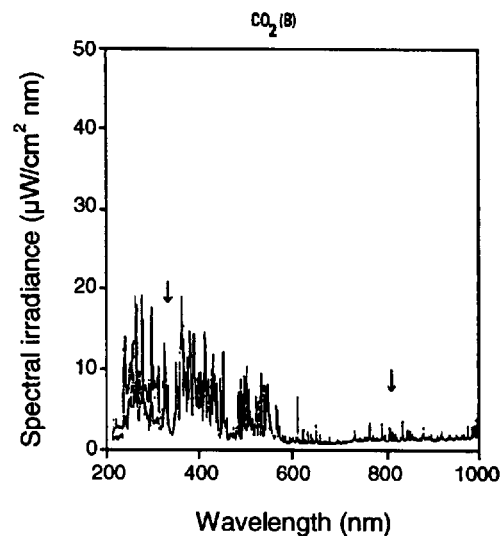
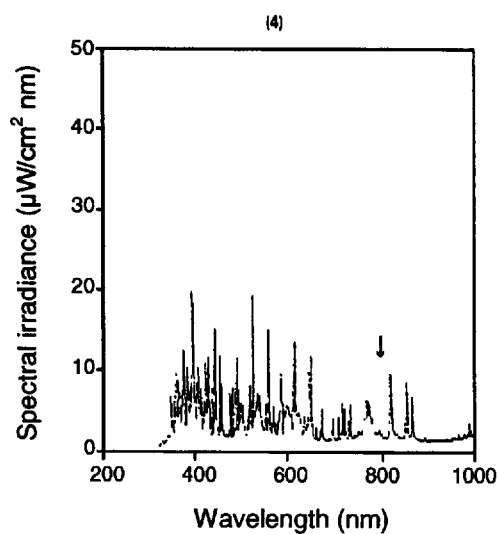


Figure 3.1.1
Spectral radiant
intensity
distribution of
type JPD 100V,
500W tungsten
halogen lamp.



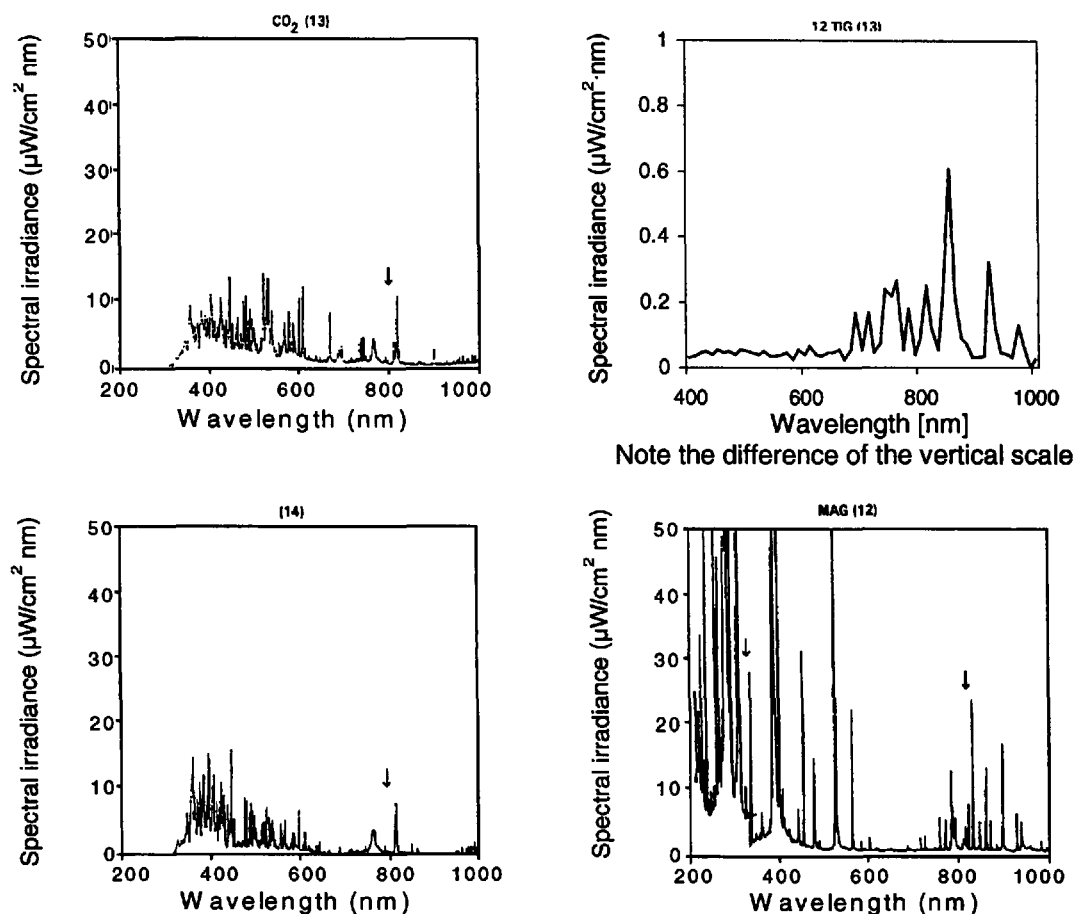


Figure 3.1.2 / 3.1.3 Spectral irradiance distributions of eight types of welding arcs.

4. METHOD TO EVALUATE BLH OF OPTICAL RADIATION

4.1 General

Optical radiation from conventional broad-band (non-laser) light sources consists of a continuum of different wavelengths which pose different relative hazards for photoretinitis, consequently the BLH depends not only on the total radiant power emitted by the light source, but also the relative spectral distribution. The relative hazard of an optical source is defined in equation 7:

$$X_{\text{blue}} = \sum_{400}^{700} X_{\lambda} \cdot B(\lambda) \cdot \Delta\lambda \quad [7]$$

where X_{λ} is the spectral radiance or spectral irradiance of the optical radiation exposure, $B(\lambda)$ is the BLH function which represents the relative spectral effectiveness for the BLH, and $\Delta\lambda$ is a wavelength interval at the center of which $B(\lambda)$ is defined and over which spectral irradiance or spectral radiance is measured. This formula shows that X_{blue} can be obtained by measuring the spectral irradiance or spectral radiance of the source over the wavelength range of 400-700 nm and spectrally weighting this function with the $B(\lambda)$ function. The $B(\lambda)$ function is defined relative to the worst-case normalized wavelengths of 435-440 nm. The blue-light hazard refers to a potential for retinal injury and therefore relates to a radiant exposure threshold at the retina. Therefore the retinal irradiance is the most important radiometric quantity required to assess the risk of the BLH. However, the TLV took into account the relationship of the source radiance to the retinal irradiance and expressed the TLV only in radiometric quantities that could be measured external to the eye. The radiometric quantities that must be measured are either the spectral irradiance from the source, or the spectral radiance at the source or at the corneal surface.

The retinal irradiance produced in the image of a light source (referred to simply as the *retinal irradiance* in subsequent discussions) does not depend on the viewing distance or the size of the light source (Fig. 4.1.1). As the distance decreases the quantity of light (radiant power) entering the eye and reaching the image increases inversely with the square of the viewing distance. But, the area of the image also increases in the same way. As a result the retinal irradiance does not vary with viewing distance or with viewing angle. When one views a large light source, although a great radiant power may enter the eye, the image area is also very large and the retinal irradiance is no greater than if you viewed it at a greater distance, provided that the comparison is not made with a source which has reached the nearly diffraction limited, minimal retinal image size of 15-20 μm . The retinal irradiance is directly proportional to the blue-light radiance for determining the retinal hazard; see Reference 2.

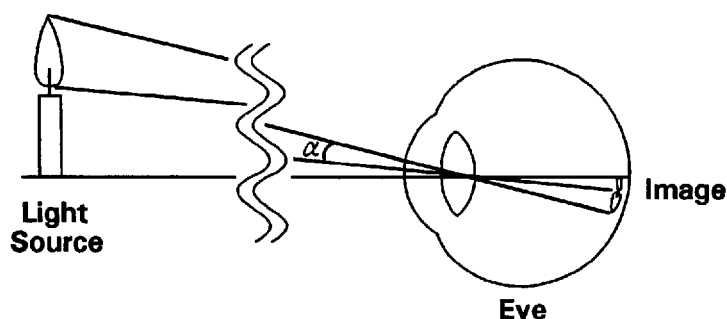


Figure 4.1.1

Light source and retinal image.

When a light source is viewed at a great distance or is very small, the retinal irradiance is no longer proportional to the radiance but to the corneal irradiance, once the source subtends an angle less than approximately 1 mrad. In addition, because of constant eye movements (saccades), the BLH is considered proportional to the source radiance for sources subtending an angle greater than $\alpha_{\min}=11$ mrad, but proportional to corneal irradiance for smaller sources. As one moves away from a source, the apparent size of a light source decreases. The size of the image decreases to the limiting condition and at the minimal image size the image is blurred to result in an image of constant area (as a result of corneal aberrations and diffraction of optical radiation of the pupil). Therefore the ACGIH recommends that when the angular subtense of the light source is less than 11 mrad (about 0,63 degree), the corneal irradiance should be used in the retinal BLH calculation.

Since the radiant power entering the eye is also proportional to the pupillary area, the retinal irradiance is proportional to d_p^2 , where d_p is the diameter of the pupil. The area of the pupil is influenced by various factors such as age, ambient lighting, and emotional condition. However, for the evaluation of the BLH, it is impractical to attempt to measure the pupillary area for individuals under specific conditions. Generally the largest area of the pupil (7 mm) is assumed for short term exposures. The 3 mm pupil was used in deriving BLH limits for continued staring at a source for durations of a second or greater.

4.2 A prototype instrument to measure the BLH of optical radiation

As previously mentioned the BLH of an optical radiation source can be calculated from spectral radiance or spectral irradiance values using Equations 1 and 4. However, measurement of these quantities is technically difficult and may be impractical in everyday situations. It would be convenient to use a measurement instrument designed to have a spectral response identical to the blue-light hazard function. The instrument could measure the degree of blue-light hazard of optical radiation directly. The instrument would automatically perform the function of Equation 1 to spectrally weight the source radiance. At present, instruments to measure the BLH are not commercially available. However a blue-light hazard meter can be readily made by modifying a luminance meter as described below.

To alter the relative spectral sensitivity of a luminance meter (e.g., a Tokyo Optical Company Limited Model BM3): 6 colour glass filters (1 V390, 2 L40, 2 M-10, and 1M-30 filters from Hoya Glass Corporation) were stacked and attached to the meter's aperture. Each filter was fitted into a ring-mount for glass camera filters that was attached to the luminance meter by the mounting screws. The relative spectral sensitivity of this modified luminance meter agrees well with the BLH function (Fig.4.2.1).

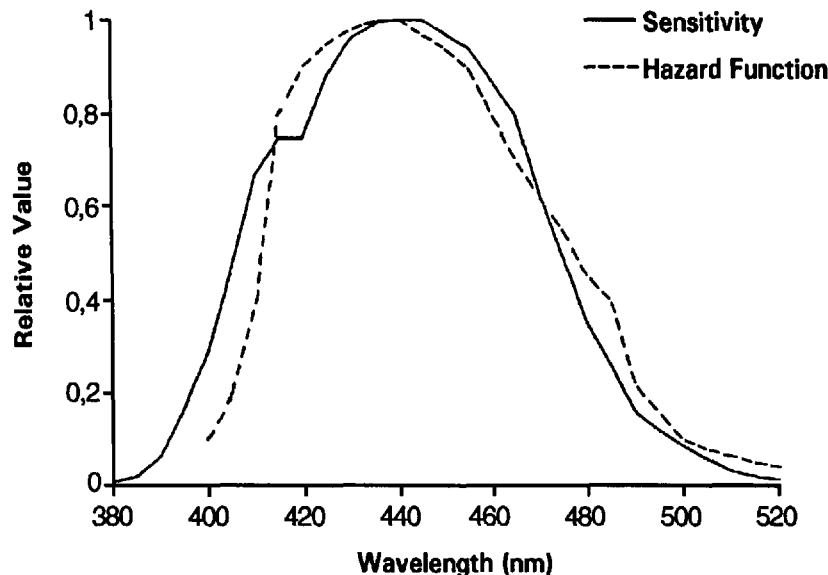


Figure 4.2.1 Action spectrum for the blue-light hazard compared with the spectral response of the blue-light radiance meter designed by K. Kohmoto.

The BLH meter is used in the same fashion as the original luminance meter. The user looks through the finder scope of the BLH meter while aiming the meter at a light source and adjusting the focus. One observes the round reticle in the finder to determine the field-of-view corresponding to the viewing angle of 0,2 degree or 2,0 degrees. The average radiance within this mark will be measured when one presses the switch. A measured value is displayed digitally. One candela per square meter on the display corresponds to $6,92 \cdot 10^{-4} \text{ W} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1}$ ($6,92 \text{ W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}$). The measuring range is $6,92 \cdot 10^{-4}$ to $1,38 \cdot 10^3 \text{ W} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1}$ ($6,92$ to $1,38 \cdot 10^7 \text{ W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}$) for the viewing angle of 0,2 degrees, and $6,9 \cdot 10^{-6}$ to $1,4 \cdot 10^1 \text{ W} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1}$ ($6,9 \cdot 10^{-2}$ to $1,4 \cdot 10^5 \text{ W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}$) for the 2,0 degree of view. It is appropriate to compare the measured value with $10^{-2} \text{ W} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1}$ ($10^2 \text{ W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}$) the threshold limit value recommended by ACGIH for exposure times of more than 10^4 s (Reference 1). The Chairman of TC 6-14 evaluated the BLH meter by measuring a number of sources. The results are provided in Table 4.2.1.

Table 4.2.1 Blue light radiance of optical radiation sources.

Light source	Radiance ($\text{W} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1}$)
Sun	62,4
Welding arc	10,5
Incandescent lamp (100 W)	0,00102
Incandescent lamp (57 W)	0,000865
Fluorescent lamp (36 W)	0,00036
TLV for exposure times of more than 10^4 sec	0,01