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Paper

EXPOSURE ASSESSMENT OF ALUMINUM ARC WELDING RADIATION

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Abstract—**The purpose of this study is to evaluate the non-ionizing radiation (NIR) exposure, especially optical radiation levels, and potential health hazard from aluminum arc welding processes based on the American Conference of Governmental Industrial Hygienists (ACGIH) method. The irradiance from the optical radiation emissions can be calculated with various biological effective parameters [i.e., $S(\lambda)$, $B(\lambda)$, $R(\lambda)$] for NIR hazard assessments. The aluminum arc welding processing scatters bright light with NIR emission including ultraviolet radiation (UVR), visible, and infrared spectra. The UVR effective irradiance (E_{eff}) has a mean value of 1,100 μW cm^{-2} at 100 cm distance from the arc spot. The maximum allowance time (t_{max}) is 2.79 s according to the ACGIH guideline. Blue-light hazard effective irradiance (E_{Blue}) has a mean value of 1840 μW cm^{-2} (300–700 nm) at 100 cm with a t_{max} of 5.45 s exposure allowance. Retinal thermal hazard effective calculation shows mean values of 320 mW cm^{-2} sr^{-1} and 25.4 mW cm^{-2} (380–875 nm) for L_{Retina} (spectral radiance) and E_{Retina} (spectral irradiance), respectively. From this study, the NIR measurement from welding optical radiation emissions has been established to evaluate separate types of hazards to the eye and skin simultaneously. The NIR exposure assessment can be applied to other optical emissions from industrial sources. The data from welding assessment strongly suggest employees involved in aluminum welding processing must be fitted with appropriate personal protection devices such as masks and gloves to prevent serious injuries of the skin and eyes upon intense optical exposure.**
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INTRODUCTION

It is well known that exposure to non-ionizing radiation (NIR), especially ultraviolet radiation (UVR), can result in both recoverable and permanent injury to the eyes and skin. Exposure to NIR is generally associated with many production processes involving either the use of NIR or the emission of unwanted NIR as a by-product. Welding arc machines are widespread sources of intense UVR, as well as visible and infrared (IR) radiation. Non-ionizing radiation, which is produced in large amounts by welding arcs, may induce photophthalmia, keratoconjunctivitis, and cataracts. Retinal injuries resulting from exposure to welding arcs have been reported (Magnavita 2002; Kozleowski 2001; Mariutti and Matzeu 1988; Schulmeister et al. 1997; Chou and Cullen 1996; Elsner and Hassam 1996). To evaluate the hazard associated with optical exposure to NIR during welding processes, the spectral irradiance should be measured and weighted in terms of biological effectiveness.

A comprehensive approach to monitoring the UVR magnitude from arc welding was established in a previous study (Peng et al. 2007). NIR effects with separate types of hazards from aluminum arc welding processes based on the American Conference of Governmental Industrial Hygienists (ACGIH) method were further investigated in this study. The integration of three biological effective parameters [$S(\lambda)$ for UVR, $B(\lambda)$ for blue-light, and $R(\lambda)$ for retinal thermal hazard] for optical radiation emissions is utilized for aluminum arc welding exposure assessment. Standardization of routine field measurement procedures is difficult because the emission depends on time-dependent parameters and unstable NIR intensity. This paper develops a procedure suitable for the spectral irradiance measurement of welding arcs. The irradiance measurements were performed using broad-band instruments with a linear cosine corrective detector (CCD) array and an optical bench that accepts light energy transmitted through single-strand optical fiber and disperses it via a fixed grating across the linear CCD array. Measurements were taken with a scanning spectroradiometer at operating working distances of 100 cm. The effective irradiance that the ACGIH defined to evaluate NIR hazards was transformed and derived for NIR assessment (ACGIH 2006).

MATERIALS AND METHODS

Spectroradiometer system

A spectroradiometer (USB2000, Ocean Optics Inc., Dunedin, FL) was used to measure NIR emitted from aluminum arc welding. The USB2000 spectroradiometer system has stray light as follows: <0.05% at 600 nm, <0.10% at 435 nm, and <0.10% at 250 nm. According to the spectroradiometry system, the highest photon counting values can be measured around 4,000 to 4,500. A UV attenuator could be used for photon count emission over 4,000 due to the saturation limitation of the detector. A relative constant calibration source (DH-2000-CAL) used to calibrate the Ocean Optics spectroradiometer was used in this study. The DH-2000-CAL (Deuterium Tungsten Halogen Calibration Standard Instrument, Ocean Optics Inc., Dunedin, FL) is a UV-NIR light source used to calibrate the absolute spectral response of a spectrometric system. The DH-2000-CAL is a National Institute of Standards and Technology (NIST) standard UV-NIR (220–1,050 nm) calibration source. It is specifically calibrated for use with optical fibers or a cosine corrector; the calibration data include absolute intensities for wavelengths between 210–1,050 nm at the fiber entrance port of a CC-3 detector. Calibration ranges are 210–400 nm (a standard deuterium bulb) and 360–1,700 nm (a tungsten halogen bulb). The optical fiber transmission efficiency is less than 60% at the optical wavelength below 220 nm. The blind detector test where the detector is covered with an opaque material showed non-response of any spectral radiance. Furthermore, tests from electromagnetic emissions such as from microwaves, hot plates, and hair dryers ensure non-response of the spectroradiometer system to electromagnetic frequency.

ACGIH spectral weighting function and biological effective parameters

In previous studies, the $S(\lambda)$ values of each single 1-nm wavelength unit had been applied to the integration of the UV irradiance data based on biological effectiveness considerations (Chang et al. 2007; ACGIH 2006; ICNIRP 1996, 2004; IRPA/INIRC 1985, 1989). In addition, the ACGIH guidelines provide the exposure limit (EL) values or relative effective spectral factors for blue-light and retinal thermal hazard assessments (Sliney et al. 2005; ICNIRP 1997, 2000). Relative spectral effectiveness values of $B(\lambda)$ and $R(\lambda)$ from the ACGIH guidelines are applied for actinic spectral transfer in this study. By using Microsoft Excel spreadsheets to transform measuring irradiances, the biological weighted irradiance values can be integrated and transformed within the wavelength range from 220 to 880 nm conveniently and efficiently to obtain the effective irradiance.

UVR hazards

The UVR hazards studies focus on the effects of acute injury on human eyes and skin. The action spectrum for UVR damage to the crystalline lens (cataract) for acute exposure peaks near 305 nm and for damage to the cornea (photokeratitis) at 270 nm (Sliney et al. 2005). The ACGIH spectral weighting function provides UVR exposure assessment of optical radiation measurement. The intensity of the UVR was measured using the spectroradiometry system for a UVR range from 220 to 400 nm. The spectral emission and intensity data were combined to calculate the spectral power distribution. The t_{max} for each measurement point was calculated from the spectral power distribution by using spectral effectiveness factor $S(\lambda)$ (ACGIH 2006):

$$E_{eff} = \sum E\lambda \times S(\lambda) \times \Delta\lambda, \qquad (1)$$

where:

E_{eff} = effective irradiance (μW cm^{-2});
$E(\lambda)$ = spectral irradiance from measurements μW (cm^{-2} nm^{-1});
$S(\lambda)$ = relative spectral effectiveness factor (unitless); and
$\Delta\lambda$ = bandwidth of the measurement (nm).

An integration of the spectral emission and the biologically weighted effectiveness factors [$S(\lambda)$] results in biologically weighted effective irradiance. The equation for permissible exposure time (t_{max}) for actinic UVR incident upon unprotected skin or eyes is as follows:

$$t_{max}\,(s) = 3{,}000\ (\mu J cm^{-2})/E_{eff}\ (\mu W cm^{-2}). \qquad (2)$$

Blue-light hazard

Blue-light retinal injury (photoretinitis) can result from viewing either extremely bright light for a short time (acute) or a less bright light for longer time (chronic). Occupational safety limits for exposure to UVR and bright light are based upon data from experimental animals and human eyes in accidents. UVR hazard does not take account of photoretinitis action spectra though there is the possibility of UVR around 340–365 nm being transmitted to the retinal area. The photoretinitis risk is evaluated by applying the blue-light hazard assessment. The blue-light photoretinitis hazard criteria were based on the ACGIH (2006) threshold limit values (TLVs) and biologically effective irradiances (BEIs). The limit for time t is expressed as a $B(\lambda)$ spectrally weighted irradiance:

$$E_{\mathrm{Blue}} = \sum_{305}^{700} E(\lambda) \times t \times B(\lambda) \times \Delta\lambda, \qquad (3)$$

where:

$E(\lambda)$ = spectral irradiance from measurements μW (cm^{-2} nm^{-1});
t = time (s);
$B(\lambda)$ = relative spectral effectiveness factor (unitless); and
$\Delta\lambda$ = bandwidth of the measurement (nm).

Wavelengths between 305 to 700 nm of $B(\lambda)$ parameters can be transformed for the blue-light effective irradiance dosage (E_{Blue}). The maximum tolerance exposure time can be calculated as:

$$t_{\max}\ (\mathrm{s}) \leq 10{,}000\ (\mu\mathrm{J\ cm^{-2}})/E_{\mathrm{Blue}}\ (\mu\mathrm{W\ cm^{-2}}) \quad (\text{for } t \leq 10^4\ \mathrm{s}). \qquad (4)$$

Retina thermal hazard

The retinal thermal criteria are based on the studies of Sliney et al. (2005), Satrom et al. (1987), and ACGIH (2006) TLVs and BEIs. For optical sources, the retinal thermal hazard must be evaluated for a single exposure and the entire spectral range from 385 to 1,400 nm must be considered. The action spectrum $R(\lambda)$ has been applied for retinal thermal effectiveness to pulsed-light sources and to intense sources for which the longest viewing duration of potential concern is 10 s. The retinal thermal hazard EL is not specified for longer durations because the pupil will certainly be tightly constricted within less than 0.5 s. The eyelids will be closed within 0.2 s owing to an aversion response. The closure of the eyelids might prevent optical radiation from going into the ocular system. The aversion response can protect the eye against injury from viewing bright light sources. Eye movements and other factors would all limit the exposure to preclude thermal injury even if individuals forced themselves to overcome their natural aversion response. The retinal thermal limit is as follows:

$$L_{\mathrm{Retina}} = \sum_{385}^{1400} L(\lambda) \times R(\lambda) \times \Delta\lambda \leq \frac{5}{\alpha \times t^{1/4}}, \qquad (5)$$

where:

$L(\lambda)$ = spectral radiance from measurements μW (cm^{-2} sr^{-1} nm^{-1});
$R(\lambda)$ = relative spectral effectiveness factor (unitless);
$\Delta\lambda$ = bandwidth of the measurement (nm);
t = time (s); and
α = angular subtense of the source (radians).

The ACGIH TLV derived to protect the human retina from thermal injury requires the use of the spectral weighting function, $R(\lambda)$. The EL for the hazardous radiance is denoted as L_{HAZ}, which is a function of the angular subtense α of the source (which is the light-source dimension divided by the viewing distance to give the angle in radians) and the exposure duration t (in s):

$$L_{\mathrm{HAZ}} = 5/\alpha \times t^{1/4} \quad (\text{in W cm}^{-2}\ \mathrm{sr}^{-1}). \qquad (6)$$

The spectral radiance $L(\lambda)$ of the source is weighted against the retinal hazard function $R(\lambda)$ and the resulting effective radiance must not exceed L_{HAZ}:

$$\sum L(\lambda) \times R(\lambda) \times \Delta\lambda \leq L_{\mathrm{HAZ}} \quad (\text{for } t < 10\ \mathrm{s}). \qquad (7)$$

Aluminum arc welding process

Welding machines are widely used in industry. The arc is initiated no sooner than the electrode touches the base metal. After igniting the electrode, the heat of the arc melts the surface of the base metal to form a molten pool at the end of the electrode, and the electrode supplies the filler-metal in the welding process. In the welding process, the aluminum electrode acts as a consumed material. The welding current command is set between 250 and 280 A with the working current recorded at 268 A. The electrode is kept vertical to the welding path and is moved tangentially to the welding path. An IA 5356 type of alloy electrode (Lembo Enterprise Co. Ltd., No.1160–2, WunSin S. Rd., TaLi City, Taichung County 412, Taiwan) is used with a core wire diameter of 1.6 mm. Local exhaust ventilation is applied to remove welding fumes, dusts, and gases at the source and keep them from dispersing into the workplace environment. It draws less air make less impact to the fume cloud on optical irradiance measurement. Optical measurements were made at locations that have a clear view of the welding arc puddle. The NIR level was measured while the welding arc was struck and maintained on a flat plate of aluminum steel at a distance of 100 cm from the welding torch. A set of welding instruments (Lembo Enterprise Co. Ltd.) was utilized to strike and extinguish the torch (the arc). The welding current was set in the arc

Table 1. Welding measurement conditions.

Welding items	Welding properties
Wire	Solid wire (Indalco Alloys Co., Ltd, Alloy IA 5356) 1.6 mm in diameter
Machine	AC ARC Welder, Trans Puls Synergic TPS450 Fronius (Lembo Enterprise Co. Ltd.)
Welding current	Set internally by the machine as 250 ~ 280 A
Working current	Steady around 268 A
Arc voltage	220 V
Shielding gas	Argon 50 L min^{-1}
Measurement distance	100 cm from welding torch
Measurement time	70 s continuous
Spectroradiometer record	Data log with 0.5 s per data point
Wavelength scan range	200 ~ 880 nm
Scan mode	Spectral irradiance ($\mu W\ cm^{-2}\ nm^{-1}$) vs. wavelength (nm)

machine internally with the AC Arc Generator (Trans Plus Synergic TPS 450 Fronius, Lembo Enterprise Co. Ltd.) while the arc voltage was set at 220 V. Table 1 summarizes the welding conditions.

NIR irradiance measurement from aluminum arc welding

The optical radiation measurement system was described in detail in a previous study (Chang et al. 2007). A brief description is as follows. This meter measures NIR in the wavelength range 200–880 nm. The radiometer was calibrated with the DH-2000-CAL calibration procedure before the NIR measurement. The NIR measurement was recorded continuously for a 70-s exposure time with the CCD head attached to the spectroradiometry system that allowed the adjustment of position and angle. The aperture of the detector head was fixed at a given angle at 100 cm distance from the center of the trajectory of the arc and was turned to face it. A schematic diagram of the experimental setup for optical radiation measurement from arc welding processing is shown in Fig. 1. The original irradiance [$E(\lambda)$] was retrieved and exported to Microsoft Excel software for actinic spectral irradiance calculation. The actinic spectral data analysis was integrated with $S(\lambda)$, $B(\lambda)$, and $R(\lambda)$ values for the calculation of NIR biological effective irradiances (E_{eff}, E_{Blue}, E_{Retina}). The biological weighting equations are calculated from the sum of the total integration of $E(\lambda)$ times effective parameters and $\Delta\lambda$. The NIR spectra were deployed and transformed by using Microsoft Excel spreadsheets analysis. The permissible exposure time per day was calculated as described above in accordance with the ACGIH and ICNIRP standards (ACGIH 2006; ICNIRP 1996, 2004; IRPA/INIRC 1985, 1989).

RESULTS

The spectra (200–880 nm) of NIR irradiance and three transformed biological effective irradiances from the aluminum arc welding process are shown in Fig. 2. The benchmark wavelength of effective irradiances for E_{eff} irradiance is weighted to 270 nm, and for E_{Blue} and E_{Retina} irradiances occurred at 430–440 nm. The worst case was selected from the highest irradiance intensity among the 70-s continuous NIR measurement. The spectral weighting factor $S(\lambda)$ for E_{eff} of radiance exchange is based on the 270 nm biological effective curve. The spectrum of E_{eff} irradiance showed the relative maximum peak at 270 nm used as a UVR weighting function which is diminished on both sides. The blue-light hazard peaks at approximately 440 nm and drops to insignificant levels above 600 nm. The retinal thermal hazard function also peaks at 440 nm but extends well into the IR range above 800 nm. Both the spectra of blue-light hazard and retinal thermal hazard show a peak at 420–500 nm.

The spectra of 70-s continuous measurement from the arc together with the biological weighting irradiances E_{eff},

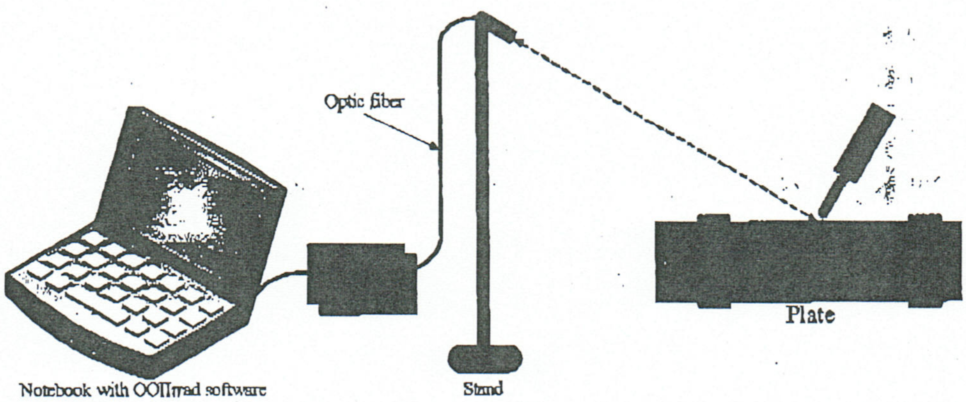

Fig. 1. Schematic diagram of the experimental setup.

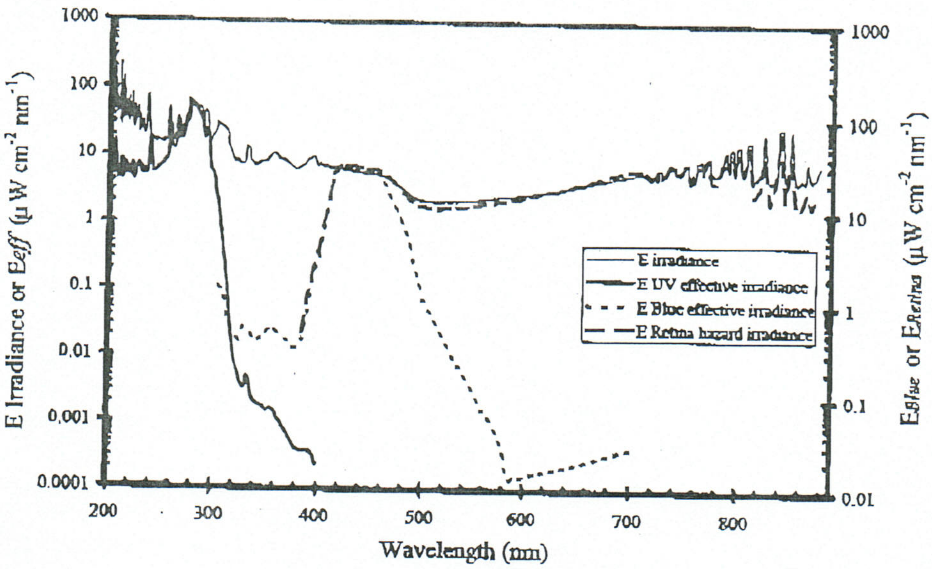

Fig. 2. The spectral irradiances of the worst case from aluminum arc welding processing.

E_{Blue}, and E_{Retina} are shown in Fig. 3. The first 10 s showed lower effective irradiances due to the arc not being ignited. After 10 s, all the three biological effective irradiances then showed steady and constant NIR emission.

The effective irradiance is the sum of the total integration of $E(\lambda)$ times the spectral weighting factor $[S(\lambda), B(\lambda)$, or $R(\lambda)]$ and $\Delta\lambda$. E_{Retina} irradiance possessed the highest level among the three effective irradiances because spectral weighting factors $R(\lambda)$ have higher values. The spectral weighting factors of both $S(\lambda)$ and $B(\lambda)$ have the relative unit value of 1 at 270 nm and 435–440 nm, respectively. However, the spectral weighting factor of $R(\lambda)$ has the relative unit value of 1 from the range 435–700 nm. The extended spectral weighting factor of $R(\lambda)$ integration causes E_{Retina} irradiance values to have a higher level than those of $S(\lambda)$ and $B(\lambda)$ integration for the E_{eff} and the E_{Blue} irradiances after 10 s arc emission during the 70-s continuous welding processing measurements.

Fig. 4 demonstrates the permissible exposure time ($t_{\max}$) of the E_{eff} and the E_{Blue} irradiances derived from the ACGIH TLVs and BEIs. The ACGIH refers to its ELs as TLVs. The permissible exposure time ($t_{\max}$) of each data point could be appropriate for NIR assessment in arc welding processing in consideration of a total 70 s continuous NIR emission. The first 10 s showed higher

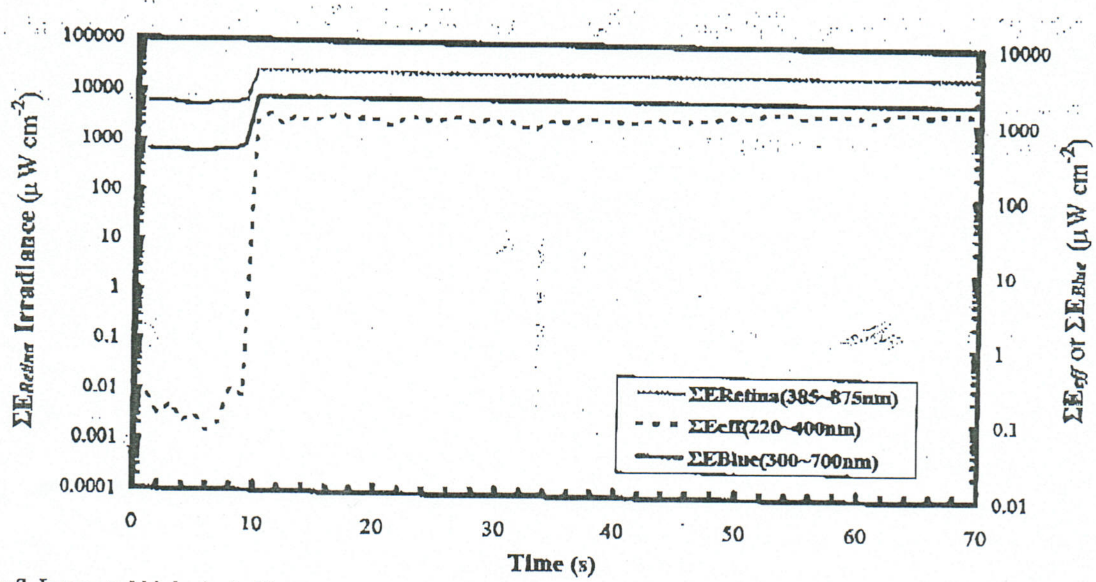

Fig. 3. Integrated biological effectiveness irradiances from aluminum arc welding processing with continuous scanning. (The first 10 seconds arc was not ignited.)

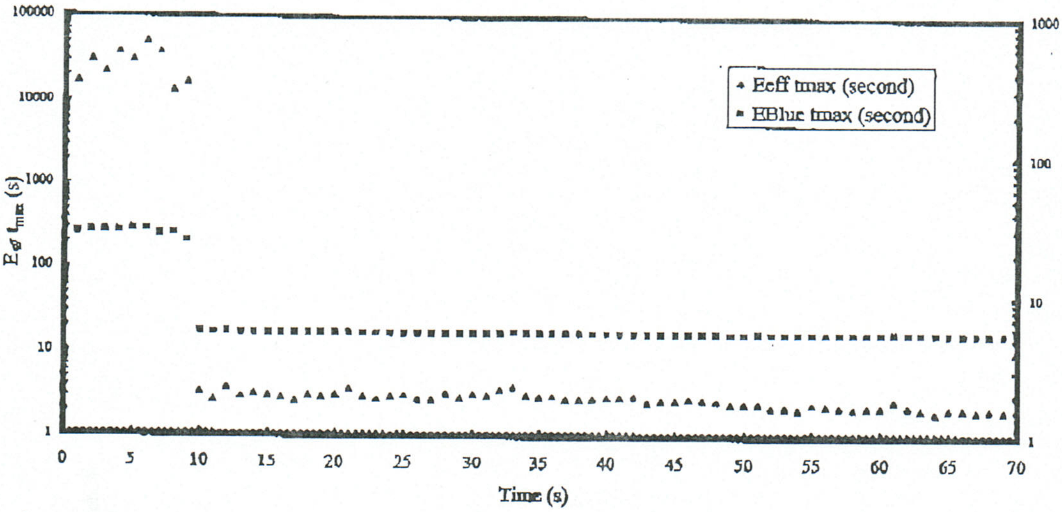

Fig. 4. The maximum allowance time (t_{max}) of E_{eff} and E_{Blue} from aluminum arc welding continuous measurement.

t_{max} due to the arc not being ignited during 70 s continuous welding processing. After 10 s, both t_{max} decreased to single digit values.

Table 2 lists the data of three effective irradiances, t_{max} values of the E_{eff} and the E_{Blue} irradiances, and the L_{Retina} radiance value. The E_{eff} irradiance at 100 cm from the arc is in the range 759–1,490 μW cm^{-2} integrated between 220 to 400 nm wavelengths from measurement in the last 60 s of the 70 s of continuous welding. The average effective irradiance is 1,100 μW cm^{-2} with the average permissible exposure time per day being 2.79 s. The E_{Blue} irradiance at 100 cm from the arc is in the range 1,820–1,850 μW cm^{-2} integrated between 300 to 700 nm wavelength with little variation. The average effective irradiance is 1,840 μW cm^{-2} with the average permissible exposure time per day being 5.45 s.

The measured E_{Retina} irradiance is in the range 25.1–25.8 mW cm^{-2}, only integrated between 385 to 875 nm wavelengths due to the detection limit of the radiospectrometry system. The irradiance, E_{Retina}, from a uniform source is related to the radiance of the source by the following unit intensity conversion: 1 W sr^{-1} (watts per steradian) = 12.566 watts (isotropic) = 4π W. A steradian is defined as the solid angle which, having its vertex at the center of the sphere, cuts off a spherical surface area equal to the square of the radius of the sphere. Radiant intensity is a measure of radiometric power per unit solid angle, expressed in watts per steradian. Mean spherical measurements are made in an integrating sphere, and represent the total output in radiance divided by 4π sr in a sphere (Ryer 1998). Thus, an isotrophic light source of 4π watts irradiance produces one watt per steradian radiance. The L_{Retina} radiance at 100 cm from the arc is in the range 315 ≈ 324 mW cm^{-2} sr^{-1} derived from the E_{Retina} irradiance values.

Table 3 gives the results of the thermal hazard calculation and exposure guideline limits. The ACGIH hazard formula is only valid for a range from 1 ms to 10 s. From this study, none of the retina thermal hazard values have a weighted integrated spectral radiance (320 mW cm^{-2} sr^{-1}), or irradiance (25.4 mW cm^{-2}) great enough to give a hazard time of 10 s for guideline limits (28,117 mW cm^{-2} sr^{-1} or 3,374 mW cm^{-2}).

DISCUSSION

A comprehensive approach to monitoring NIR magnitude from aluminum arc welding was established in this study. In the past, several studies on arc welding using field or laboratory measurements of NIR have been conducted. However, most measurements were not provided a clearly defined effective irradiance suitable for

Table 2. The biological effective irradiances and t_{max} from aluminum arc welding processing.

	ΣE_{eff} (220 ≈ 400 nm) μW cm^{-2}	E_{eff} t_{max} (s)	ΣE_{blue} (300 ≈ 700 nm) μW cm^{-2}	ΣE_{blue} t_{max} (s)	ΣE_{Retina} (385 ≈ 875 nm) mW cm^{-2}	ΣL_{Retina} (385 ≈ 875 nm) mW cm^{-2} sr^{-1}
Average	1,100	2.79	1,840	5.45	25.4	320
Minimum	759	3.95	1,820	5.50	25.1	315
Maximum	1,490	2.02	1,850	5.41	25.8	324
Std. dev.	178	0.45	12	0.03	0.49	6.16

Table 3. Exposure limits for aluminum arc welding on retinal thermal hazard.

Hazard measurement	Exposure guideline limit[a]	ΣL_{Retina} & ΣE_{Retina} from arc welding	Comments
Retinal radiance	$L \leq (5/\alpha) \times t^{-0.25}$ (W cm^{-2} sr^{-1}) λ = 380–1,400 nm $L_{Haz} \leq$ 28,117 (mW cm^{-2} sr^{-1})	ΣL_{Retina} (m W cm^{-2} sr^{-1})[b] = 4π. ΣE_{Retina} (385 ~ 875 nm) 320 (mW cm^{-2} sr^{-1})	Assumes that pupil diameter constricts from 7 to 3 mm between 0.25 and 10 s. α = 0.1 and t = 10 s
Retinal irradiance	$E_{Retina} \leq (0.6/\alpha) \times t^{-0.25}$ (W cm^{-2}) λ = 380–1,400 nm $E_{Retina} \leq$ 3,374 (mW cm^{-2})	ΣE_{Retina} (mW cm^{-2}) = $\Sigma E(\lambda)$. $R(\lambda)$. $\Delta(\lambda)$ (385 ~ 875 nm) 25.4 (mW cm^{-2})	Pulse-light sources or brief exposure. The angular subtense α expressed in radians α = 0.1 and t = 10 s
Retinal irradiance	$E_{Retina} \leq (10/d_r) \times t^{-0.25}$ (W cm^{-2}) λ = 380–1400 nm $E_{Retina} \leq$ 3,308 (mW cm^{-2})		The retinal image diameter d_r is in mm. d_r = 1.7 mm and t = 10 s

[a] Silney et al. (2005).
[b] Ryer (1998).

NIR hazard evaluation. Most of the studies showed the spectra of welding optical emission without biological hazard transformation such as the ACGIH weighted function (Alfaro et al. 2006; Li and Zhang 2000; Kim et al. 1987). Few studies were investigated to evaluate NIR effects with biological hazard assessments from arc welding processes based on the ACGIH method. Three types of NIR hazardous effects from aluminum arc welding processes based on the ACGIH method were investigated simultaneously in this paper. The effective irradiance from welding NIR was calculated with the biological effective parameters [$S(\lambda)$, $B(\lambda)$, $R(\lambda)$] for human exposure assessment. The spectral weighting function for NIR measurement and evaluation is followed by the ACGIH guidelines. Aluminum arc welding processing scatters bright light with unstable NIR radiation emission covering the full UV spectrum (UVA, UVB, and UVC), visible and IR radiation. A continuous welding recording procedure was particularly useful for measuring unstable and flickering sources in such arc welding operations.

Many intense optical sources produce significant amounts of NIR, which may be hazardous to the eye and skin. There are several separate types of hazards to the eye and skin from optical sources (ICNIRP 1997):

1. Ultraviolet photochemical injury to the skin (erythema and carcinogenic effects), and to the cornea (photokeratitis) and lens (cataract) of the eye (180 nm to 400 nm);
2. Blue-light photochemical injury to the retina of the eye (principally 400 nm to 550 nm);
3. Thermal injury to the retina of the eye (400 nm to 1,400 nm);
4. Near-infrared thermal hazards to the lens (approximately 800 nm to 3,000 nm); and
5. Thermal injury (burns) to the skin (approximately 400 nm to 1 mm) and the cornea of the eye (approximately 1,400 nm to 1 mm).

The first 3 types of hazards seem to cause serious injuries upon intense optical exposure because of higher energy with shorter wavelength. The biological weighting E_{eff} irradiance, the E_{Blue} irradiance, and the E_{Retina} irradiance, therefore, were assessed in this study. Due to the detection limits of the spectroradiometry system (USB2000) and the light calibration device (DH-2000-CAL), the measured irradiance can only be evaluated and assessed from 220 to 880 nm wavelengths. Part of the retinal thermal injury (wavelengths above 880 nm) cannot be assessed although the effect of long wavelengths seems to be insignificant. Both the NIR thermal hazards to the lens (approximately 800 nm to 3,000 nm) and the thermal injury (burns) to the skin (approximately 400 nm to 1 mm) and the cornea of the eye cannot be discussed in this monitoring system. Since no industrially useable radiation sensors have spectral sensitivities from 380 to 1,400 nm, both hazard assessments beyond 800 nm might need a specific IR spectroradiometry system in future investigations.

Blue-light is the most hazardous component of the visible spectrum and has considerable potential for phototoxicity (Wu et al. 2006; Okuno et al. 2002). The action spectrum for photochemical retinal injury peaks at approximately 440 nm. The action spectrum peaks in the short wavelength region, contributing to the basis of the blue-light hazard. In general, the blue-light hazard can be frequently used as a quick check to determine the need for further hazard assessment. Another primary hazard in relation to an intense visible light source is the retinal thermal hazard. The effects of thermal injury are most profound from short wavelength (from 400 to 500 nm) light with the peak at 440 nm. In the spectral range between 380 and 500 nm, however, the effect of the retinal thermal hazard function is larger than the blue-light hazard function by a factor of 10 (Satrom et al. 1987). The spectrum of E_{Retina} irradiance showed a higher level than that of E_{Blue} irradiance in Fig. 3 and Table 2. In both visible spectrum assessments, it seems quite adequate to measure in the range between 300 to 880 nm, since light sources exhibit insignificant differences in the integrated totals from 880 to 1,200 nm and to 1,400 nm.

The results listed in Table 3 represent the weighted integrated spectral radiance and irradiances of retinal thermal hazard required to produce a 10-s EL. The determination of the retinal thermal hazard ELs was more complex, since thermal retinal injury thresholds are required and dependent on factors such as the angular subtense α expressed in radians or the retinal image diameter d_r. To protect against retinal thermal hazards that would only occur for pulsed illumination of large retinal areas, the limit of $5\ \alpha^{-1}\ t^{-1/4}$ was adjusted to apply only to the worst-case, large source size, corresponding to 0.1 rad, i.e., d_r = 1.7 mm. In this way, one radiance unit would be protective for all larger source sizes, although overly conservative for smaller source sizes. Hence a single, conservative limit would be $5\ \alpha^{-1}\ t^{-1/4}$ (in W cm^{-2} sr^{-1}) = $50\ t^{-3/4}$ (J cm^{-2} sr^{-1}). If the transmittance of the ocular media is taken as 0.9, the corresponding retinal irradiance is $E_{Retina} = 6\ t^{-1/4}$ (in μW cm^{-2}) for exposure durations of less than 10 s. By setting α_{min} = 0.1 due to $\alpha > 0.1$ and d_r =1.7, retinal thermal hazard ELs could be utilized for exposure assessment. The calculated thermal hazards of aluminum arc welding produced a total weighted output that was below the value allowed for a 10-s exposure.

The results seem to demonstrate that the effective radiance for retinal thermal injury was not exceeded, the hazard was not critical, and operation time could be safe. Actually, the determination of the potential for retinal thermal injury requires one to consider and examine other factors, such as the time-averaged retinal irradiance, eye movements, the equivalent of a repetitive-pulse exposure, pupillary activity, the retinal area illuminated, the image size, and visual task behavior (ICNIRP 2000). These factors can affect the retinal thermal injury threshold due to radial heat flow during and after the exposure and make the retinal thermal hazard assessment more complicated. In addition, light usually induces retinal injury that occurs only after prolonged exposure is generally agreed to result from a photochemical (blue-light) injury mechanism, rather than from retinal thermal injury. The photochemical (blue-light) hazard is due to a separate and unique mechanism causing retinal damage and plays an important role synergistic with thermal injury mechanisms to cause serious retinal damage. Although the specific action mechanism is not certain, it is known that retinal damage occurs at power levels below that required for thermal injury, and the effects are most profound from short wavelength (from 400 to 500 nm) light, with the peak action at 440 nm for both blue-light and retinal thermal hazards.

Based on the data, the ACGIH has proposed ELs, and these limits were used as the basis for the calculations in this study. A broad-band light source is spectrally weighted by the appropriate action spectrum. Action spectra are specified and used to spectrally weight source emissions to derive a "biologically effective irradiance." This provides the most accurate hazard assessment and ELs can then be specified in terms of exposure duration for risk criteria evaluation. The obtained E_{eff} effective irradiance of 759–1,490 μW cm^{-2} at 100 cm from the arc, with the range of permissible exposure time per day of 2.02–3.95 s, suggests that UVR from aluminum arc welding is actually hazardous to the eye and skin.

In a previous study, the obtained effective irradiance was 33.1–311.0 μW cm^{-2} at 50 cm with the permissible exposure time per day of 9.65–90.63 s from shield metal arch welding (Peng et al. 2007). The UVR levels from aluminum arc welding were stronger than those from the general arc welding. The obtained E_{Blue} effective irradiance of 1,820–1,850 μW cm^{-2} at 100 cm from the arc, with the range of permissible exposure time per day of 5.41–5.50 s, demonstrates that blue-light from aluminum arc welding is hazardous to the eye. Besides, the arc contact positions of welders must be even closer than those in measurements because the welders are usually less than 100 cm away from the strike of arcs and the effective irradiance is inversely proportional to the square of the distance.

Welders, therefore, should be aware of potentially hazardous risks for both UVR and blue-light exposure injuries. Photokeratoconjunctivitis cases from work-related welding process were observed in occupational ophthalmological emergencies in Taiwan (Yen et al. 2004). Welders must always wear an appropriate face protector (welding helmet or shield mask) and appropriate clothing and gloves to protect eyes and skin against NIR when conducting welding processes.

CONCLUSION

The E_{eff} effective irradiance of 759–1,490 μW cm^{-2}, with the range of permissible exposure time per day of 2.02–3.95 s, was evaluated at 100 cm from the aluminum arc welding location under the conditions of the study. UVR from the aluminum arc welding is actually hazardous to the eye and skin. The E_{Blue} effective irradiance of 1,820–1,850 μW cm^{-2} at 100 cm from the arc, with the range of permissible exposure time per day of 5.41–5.50 s, was assessed from the measured irradiance. Blue-light injury assessment from such aluminum arc welding demonstrated that it was hazardous to the eye, especially for photoretinitis.

REFERENCES

Alfaro SCA, de S Mendonca D, Matos MS. Emission spectrometry evaluation in arc welding monitoring system. J Materials Processing Technol 179:219–224; 2006.

American Conference of Governmental Industrial Hygienists. 2006 TLVs and BEIs. Cincinnati: ACGIH; 2006.

Chang CP, Liu HH, Peng CY, Shieh JY, Lan CH. UVR measurement of a UV germicidal lamp. Health Phys 92:242–250; 2007.

Chou BR, Cullen AP. Ocular hazards of industrial spot welding. Optometry Vision Sci 73:424–427; 1996.

Elsner P, Hassam S. Occupational UVC-induced exacerbation of atopic dermatitis in a welder. Contact Dermatitis 35:180–181; 1996.

International Commission on Non-Ionizing Radiation Protection. Guidelines on UV radiation exposure limits. Health Phys 71:978; 1996.

International Commission on Non-Ionizing Radiation Protection. Guidelines on limits of exposure to broad-band incoherent optical radiation (0.38 to 3 μm). Health Phys 73:539–554; 1997.

International Commission on Non-Ionizing Radiation Protection. Revision of guidelines on limits of exposure to laser radiation of wavelengths between 400 nm and 1.4 μm. Health Phys 79:431–440; 2000.

International Commission on Non-Ionizing Radiation Protection. Guidelines on UV radiation exposure limits. Health Phys 97:171–186; 2004.

International Radiation Protection Association/International Non-Ionizing Radiation Committee. Guidelines on limits of exposure to UVR of wavelengths between 180 nm and 400 nm. Health Phys 49:331–340; 1985.

International Radiation Protection Association/International Non-Ionizing Radiation Committee. Proposed change to the IRPA 1985 guidelines on limits of exposure to UVR. Health Phys 56:971–972; 1989.

Kim EW, Allemand C, Eagar TW. Visible light emissions during GTAW and its application to weld image improvement. Welding J 66:369s–377s; 1987.

Kozleowski C. UV radiation emitted by selected sources at work stands. International J Occupational Med Environmental Health 14:287–292; 2001.

Li PJ, Zhang YM. Analysis of arc light mechanism and its application in sensing of GTAW process. Welding J 79:252s–260s; 2000.

Magnavita N. Photoretinitis: an underestimated occupational injury? Occupational Med 52:223–225; 2002.

Mariutti G, Matzeu M. Measurement of ultraviolet radiation emitted from welding arcs. Health Phys 54:529–532; 1988.

Okuno T, Saito H, Ojima J. Evaluation of blue-light hazards from various light sources. Dev Ophthalmol 35:104–112; 2002.

Peng CY, Liu HH, Chang CP, Shieh JY, Lan CH. Evaluation and monitoring of UVR in shield metal arc welding processing. Health Phys 93:101–108; 2007.

Ryer A. Light measurement handbook. Newburyport: International Light, Inc.; 1998.

Satrom KD, Morris MA, Crigger LP. Potential retinal hazards of visible-light photopolymerization units. J Dent Res 66:731–736; 1987.

Schulmeister K, Schmitzer C, Dufschmid K, Liedl G, Schroeder K, Brust H, Winker N. Hazardous ultraviolet and blue-light emissions of CO2 laser beam welding. Laser Institute America 3:229–232; 1997.

Sliney D, Aron-Rosa D, DeLori F, Fankhauser F, Landry R, Mainster M, Marshall J, Rassow B, Stuck B, Trokel S, West TM, Wolffe M. Adjustment of guidelines for exposure of the eye to optical radiation from ocular instruments. Statement from a task group of the International Commission on Non-Ionizing Radiation Protection (ICNIRP). Applied Optics 44:2162–2176; 2005.

Wu J, Seregard S, Algvere PV. Photochemical damage of the retina. Survey of Ophthalmol 51:461–481; 2006.

Yen YL, Lin HL, Lin HJ, Chen PC, Chen CR, Chang GH, Guo HR. Photokeratoconjunctivitis caused by different light sources. Am J Emerg Med 22:511–515; 2004.