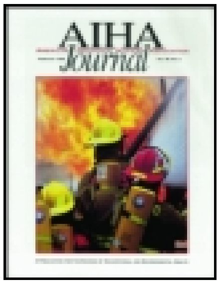

American Industrial Hygiene Association Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/aiha20

Optical Radiation Hazards of Laser Welding Processes Part 1: Neodymium-YAG Laser

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To cite this article: R. JAMES ROCKWELL & C. EUGENE MOSS (1983): Optical Radiation Hazards of Laser Welding Processes Part 1: Neodymium-YAG Laser, American Industrial Hygiene Association Journal, 44:8, 572-579

To link to this article: http://dx.doi.org/10.1080/15298668391405346

Am. Ind. Hyg. Assoc. J. 44(8):572-579 (1983)

Optical Radiation Hazards of Laser Welding Processes
Part 1: Neodymium-YAG Laser

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High power laser devices are being used for numerous metalworking processes such as welding, cutting and heat treating. Such laser devices are totally enclosed either by the manufacturer or the end-user. When this is done, the total laser system is usually certified by the manufacturer following the federal requirements of the Code of Federal Regulations (CFR) 1040.10 and 10.40.11 as a Class I laser system. Similarly, the end-user may also reclassify an enclosed high-power laser into the Class I category following the requirements of the American National Standards Institute (ANSI) Z-136.1 (1980) standard. There are, however, numerous industrial laser applications where Class IV systems are required to be used in an unenclosed manner. In such applications, there is concern for both ocular and skin hazards caused by direct and scattered laser radiation, as well as potential hazards caused by the optical radiation created by the laser beam's interaction with the metal (*i.e.* the plume radiation). Radiant energy measurements are reported for both the scattered laser radiation and the resultant plume radiations which were produced during typical unenclosed Class IV Neodymium-YAG laser welding processes. Evaluation of the plume radiation was done with both radiometric and spectroradiometric measurement equipment. The data obtained were compared to applicable safety standards.

Introduction

The high levels of optical radiation produced by conventional welding techniques has been well documented.(1-8) The actual radiant energy levels generated and, consequently, the biological hazards presented depend on the specific parameters used in a given process. Although several studies have been performed to determine occupational exposure to optical radiation levels in conventional welding practice, comparable data on such levels in laser welding processes have not appeared in the literature.

This study was conducted at several midwestern manufacturing facilities where Neodymium - Yttrium Aluminum Garnet (Nd-YAG) lasers were routinely used in production of various metal parts. The protocol of this study examined different Nd-YAG laser welding parameters to estimate the occupational exposure arising from optical radiation created by the laser beam interaction with the metal. This interaction creates both reflected laser radiation and plume radiation. In this report, plume radiation is used to describe emissions from the plasma and molten metal.

These measurements serve as the initial data base for estimating the occupational exposures to laser and associated optical radiations to workers and passersby. To our knowledge, this study presents the first detailed documentation of potential occupational laser-welding hazards.

Background

Lasers have been used for welding in the industrial environment for over a decade. Recent interest in the use of such devices has resulted from the integration of lasers with microprocessor-controlled mechanical positioning systems. Such integrated systems can reliably and reproducibly perform extremely complex welds more precisely and in shorter time periods than conventional welding techniques.

In some ways laser welding is similar to conventional welding, *i.e.,* in order to weld materials there must be sufficient power density available from a source to cause a molten puddle to form in the material. However, lasers afford certain advantages not otherwise available, such as:

- Small welds can be made on fragile material,
- Welding without the use of an electrode which minimizes surface contamination,

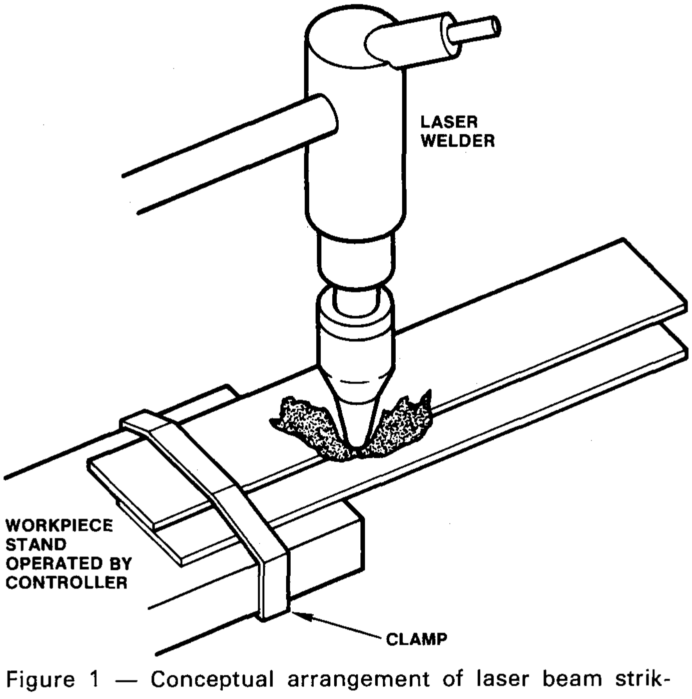

Figure 1 — Conceptual arrangement of laser beam striking workpiece.

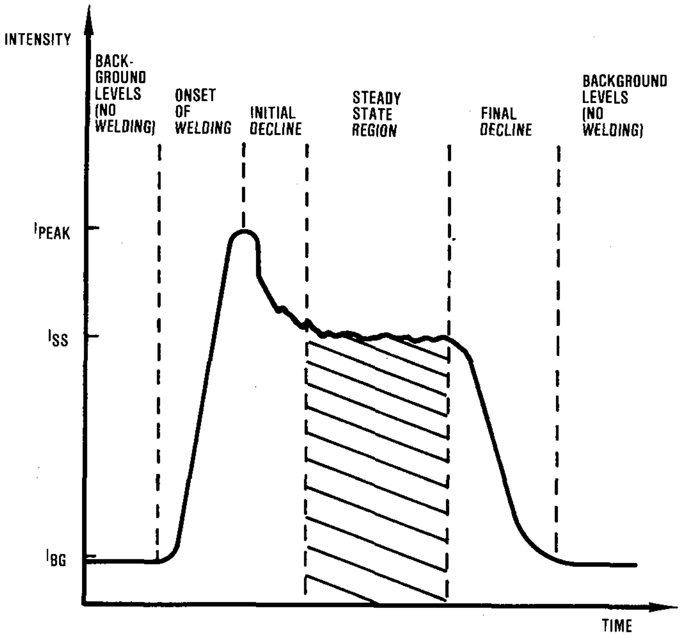

Figure 2 — Time-intensity distribution of optical radiation produced from a typical laser welding event. The shaded area corresponds to the region where measurements were made.

- Localized heating and rapid cooling due to high heat flux and small laser spot,
- Flexibility to update rapid changing material and production line variabilities especially with microprocessor control interfacing.

However, there are also certain disadvantages, such as higher initial production costs, requirements for more welding floor space, careful control of laser beam parameters, and the need to train personnel in laser techniques and safety programs. Several excellent books on laser welding physics and principles exist and are recommended for those readers interested in further information.$^{(9-12)}$

At this time there are two different lasers used for most laser-welding processes. These are the Nd-YAG and the carbon dioxide (CO_2) lasers. These laser types account for nearly 90% of all industrial metal laser-processing uses. The Nd-YAG laser operates at a wavelength of 1.06 μm and ranges in power from several watts (W) to 1 kW (in the continuous mode) and up to 10 kW peak and 400 W average in a repetitively pulsed mode. The CO_2 laser has a longer wavelength of 10.6 μm and can range in power from 10 W to 20 kW in the continuous mode. The Nd-YAG laser is often the laser of choice in welding processes involving small metal parts, due to the ability to focus the shorter wavelength radiation into small spot sizes with a focusing lens. However, the demand to weld larger metal parts using laser techniques generally requires the higher power available from the CO_2 laser. (Part II of this series will examine the related occupational hazards of the CO_2 laser.)

Although the 1.06-μm wavelength emitted by the Nd-YAG laser is in the near-infrared region, it still poses a potential retinal hazard. Consequently, reflections from this laser type could be of potential occupational concern. Unfortunately, minimal information is available on the radiation levels scattered from the laser weld site under actual production conditions. The lack of such data was the stimulus for this investigation.

Instrumentation

All of the laser welding systems measured in this study emitted a multiple-pulse beam operating at a pulse repetition frequency (PRF) of 20 Hz. Although the PRF was a variable of the laser system, measurements at lower values were not performed.

The average power (P_{av}) of a multiple pulsed laser device is expressed as the product of the individual pulse energy (Q_p) and the (PRF), such that

$$P_{av} = (Q_p)\cdot(PRF)$$

where the individual pulse energy is the time integral of the pulse power function

$$Q_p = \int_0^{\tau} \Phi(t)\, dt \quad .$$

In a series of N pulses over a time interval (τ), the total energy (Q_T) of the total of N pulses is:

$$Q_T = NQ_p$$

and the average power is; as before

$$P_{av} = Q_T/\tau = Q_p N/\tau = Q_p\cdot(PRF) \quad .$$

Thus, when measuring a series of pulses, one can electronically integrate the total energy in the pulse train. Division of the resulting total energy value by the time of the total exposure will yield the average power of the pulse train.

When the PRF is sufficiently high, the average radiant power of the laser (and associated plume radiation) may be measured by a fast-response radiometer having an electronic current integrator to yield an estimate of the total energy of the pulse train. Measurements in this study were performed using both the electronically integrated and average power methods in a comparative manner.

Several optical radiation detectors were used to document the radiant energy levels produced in this study. All instrumentation used had been calibrated by the manufacturers within the preceding 6 months.

A United Detector Technology (UDT) model 55A radiometer with a calibrated silicon photodiode detector and appropriate transducer electronics was used to make either continuous power (watts) or integrated (radiant exposure) energy measurements (joules). Since the laser systems emitted at a 20-Hz PRF, then the electronic integration option on the UDT radiometer was used. The radiometer reading was in units of joules per square centimeter.

Spectral irradiance measurements in selected wavelength regions were taken with an EG&G model 555 spectroradiometer. The radiometric units of spectral irradiance expressed as watts per square centimeter were used in the plume measurements. A specific wavelength interval was selected and the welding event was performed for at least a 5-second time interval. The maximum spectral irradiance value from 300 to 800 nm over a 10-nm bandwidth was recorded.

An International Light (IL) Model 730A radiometer with special ultraviolet sensitive detectors was used to evaluate the ultraviolet radiation generated in the process. The detectors were designed to comply with the guideline values promulgated by the American Conference of Governmental Industrial Hygienists (ACGIH).(13) One detector is designed to read the actinic UV region (200 to 315 nm) measuring in biologic effective units, while the second detector measured the near UV (320-400 nm) with no biologic weighting function.

An Eppley thermopile equipped with a quartz window was used to read irradiance (mW/cm^2) in the region from 0.2 to 2.5 μm. The detector was used at only one facility to verify results obtained with the UDT radiometer.

Experimental Protocol

All manufacturing facilities used in the study employed several Nd-YAG laser systems to routinely perform welding with various metals under simulated production conditions. All lasers used in the study were manufacturer-certified as Class IV laser systems and displayed the appropriate performance requirements as mandated by the Laser Product

TABLE I
Summary of Irradiance Measurement Performed on Scattered Nd-YAG Laser Radiation (1.06 μm) During Typical Laser Welding Events^A

Event No.	Laser Power (W)	Pulse Repetition Frequency (Hz)	Base Material	Distance (cm)	Viewing Angle^B (degrees)	Exposure Time (s)	Scattered Radiant Exposure (mJ cm^{-2})	Scattered Laser Irradiance (mW cm^{-2})	Scattered Laser Irradiance Normalized to One Meter (mW cm^{-2})	Remarks
1										
A	300	20	Mild steel	57	55	1.0	2.35	2.35	0.76	Average of three trials
B	300	20	Mild steel	57	55	1.0	-	2.20	0.71	Eppley thermopile
2										
A	320	20	Platinum	59	58	1.0	7.09	7.09	2.47	Average of three trials,
B	320	20	Platinum	100	58	1.0	1.76	1.76	1.76	three trial average,
C	320	20	Platinum	112	58	1.0	0.88	0.88	1.10	two trial average,
3										
A	320	20	Platinum	55	43	0.5	5.30	10.59	3.20	two trial average
B	320	20	Platinum	175	53	0.5	0.42	0.84	2.56	three trial average
4										
A	320	20	Platinum	46	40	1.0	0.20	0.20	0.04	moving away
B	320	20	Platinum	46	40	1.0	0.81	0.81	0.17	moving in
5										
A	150	20	S. steel	130	60	3.0	1.67	0.56	0.95	two trial average,
B	150	20	S. steel	130	60	1.0	0.59	0.59	1.00	one result
C	150	20	S. steel	66.5	60	3.0	7.64	2.55	1.13	two trial average,
6										
A	150	20	Aluminum	50	50	3.0	0.22	0.07	0.02	one result
B	350	20	Aluminum	50	50	3.0	0.96	0.32	0.08	four trial average
7										
A	350	20	Aluminum	74	55	-	-	0.47	0.26	two trial average, moving in
8										
B	350	20	Aluminum	74	55	-	-	0.45	0.25	two trial average, moving out
9										
A	350	20	Aluminum	140	60	5.0	1.08	0.22	0.42	eight trial average, moving in
B	350	20	Aluminum	140	60	5.0	0.73	0.15	0.29	eight trial average, moving away
	150	20	S. steel	180	55	3.0	1.73	0.58	0.98	three trial average

^{A}All measurements made using UDT meter.

^{B}From the normal.

TABLE II
Summary of Highest Spectral Irradiance Levels Obtained on Nd-YAG Laser Welding Events at Selected Wavelengths Over a 30-sec Time Interval[A]

Wavelength (nm)	Detector Current in 10^{-12} Amps				Average Current	Average Spectral Irradiance ($\times 10^{-8}$W cm^{-2}nm^{-1})
	Event #10	Event #11	Event #12	Event #13		
300	0.1	-	-	-	0.1	0.9
350	6.5	7.5	11.0	-	8.3	10.5
370	-	-	10.0	-	10.0	7.6
390	-	-	2.8	-	2.8	2.0
400	-	-	-	9.5	9.5	2.8
410	-	-	5.0	-	5.0	1.1
420	-	-	-	10.0	10.0	1.5
440	-	-	5.0	9.5	7.3	1.1
450	7.5	17.0	-	-	12.3	1.9
460	-	-	-	12.0	12.0	1.7
480	-	-	-	23.0	23.0	2.5
550	48.9	52.0	-	-	50.5	2.7
650	18.0	40.0	-	-	29.0	1.0
750	220.0	20.0	-	-	120.0	3.4

[A] Data taken with 10-nm bandwidth with laser operating at 350 watts. Measurement taken at a distance of 40 cm (at a viewing angle of 65° from normal) from the welding process using Inconel 718 as base material.

Performance Standard, which is regulated by the National Center for Devices and Radiological Health (NCDRH)(14) [formerly called the Bureau of Radiological Health].

During the measurements all detectors were directed at the intersection site of the laser beam and base material (Figure 1). Since different facilities were used during the study, it was not always possible to locate detectors in the same exact spatial position relative to the laser welder. As a result, radiation levels were recorded at different distances and vertical angles. Since the base material could be moved, it was possible to position the interaction site within the field of view of the various detectors.

During the measurements, the laser systems were operated in the automatic-times mode for periods ranging from 0.5 to 30 seconds. The plume radiation produced by the laser weld was electronically integrated by the UDT meter to provide the total energy of the pulse envelope. The EG&G spectroradiometer system would record the highest irradiance value at several wavelengths over that time period. In an effort to confirm the spectroradiometric data, narrow band (30-nm) interference filters were also used with the UDT meter and the results of the two readings compared following appropriate filter corrections.

In order to compare results from the various data sessions at different sites, all data collection for the study was performed only after the welding event was initiated. Consequently, the results are generally applicable only for the constant value of the radiation produced in the event (*i.e.* the shaded region shown in Figure 2). The results collected in this study can not be used to estimate the peak levels produced in a laser welding event. It is obvious from Figure 2 that the peak levels are higher, for a short time period, than the constant values recorded in this study.

Results were obtained as a function of base material, direction of travel, distance, angle of detection, and laser power. All laser systems investigated used appropriate fume

TABLE III
Summary of Maximum Actinic Ultraviolet Radiation Levels Using I.L. 730A Detector

Event No.	Distance (cm)	Base Material	Actinic (eff 10^{-6}W cm^{-2})	Near (10^{-7}W cm^{-2})	Remarks
5C	66.5	S. steel	N.D.[A]	-	2 trial average
5A&B	130	S. steel	-	0.6	3 trial average
6A	50	Aluminum	N.D.	N.D.	
6B	50	Aluminum	N.D.	N.D.	
	50	Aluminum	-	34	
	50	Aluminum	N.D.	26	
	50	Aluminum	-	62	
10-13	40	Inconel 718	N.D.	3.0	8 trial average

[A] Not detected.

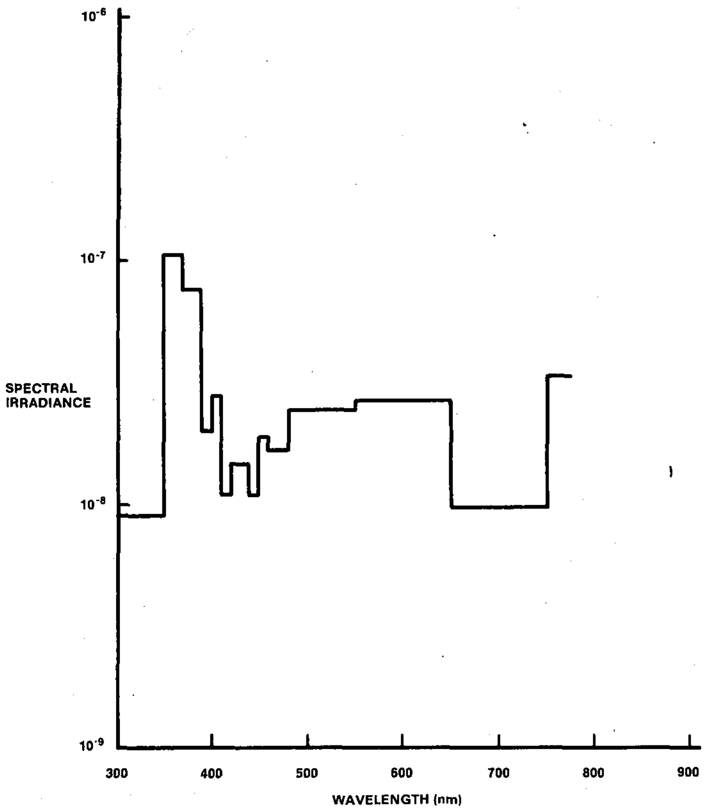

Figure 3 — Composite spectral irradiance curve.

exhaust techniques and each facility provided appropriate laser protective eyewear. All laser operations were performed by personnel employed at the facilities.

Results

The measurement data obtained from all laser welding events are summarized in Tables I, II and III. Table I shows all reflected irradiance data obtained with the UDT meter as a function of laser power, PRF, base material, distance, viewing angle, and exposure time. Table II gives the maximum spectral irradiance levels at various selected wavelengths for four welding events using the spectroradiometer. The data from Table II are combined to produce the composite average spectral irradiance curve shown in Figure 3. This figure should be viewed as a conceptual representation of a typical spectral irradiance plot. Finally, Table III gives the summary of maximum ultraviolet radiation levels produced from the welding events using the IL730A detector.

Discussion

Since this study investigated the occupational significance of radiation levels produced from typical Nd-YAG laser welding events, the discussion will focus on scattered laser radiation, plume radiation and control measures separately.

Scattered Laser Radiation

The data in Table I can be used to demonstrate several important factors about the levels of scattered (reflected) radiation. First, the normalized scattered irradiance levels at 1-m distance vary drastically as a function of base material. Platinum gave the highest value by at least a factor of three followed by stainless steel, mild steel and aluminum. Second, the corrected irradiance levels are strongly dependent on the viewing angle. The data indicate that the greater the viewing angle (defined from the normal) the smaller the irradiance level. This fact suggests that the scattered laser radiation may follow a cosine dependence. Third, the levels are dependent on the direction of the weld. For example, as shown in Figure 4, radiation levels were approximately 25% higher when the metal was moving towards the worker. Finally, the highest irradiance level measured at 1 m in the study was 10.6 mW/cm^2.

The data also show that the scattered laser radiation patterns from a Nd-YAG laser welding process off metal surfaces approximate an inverse square law relationship. This relationship for the irradiance of scatter radiation (E) at distance R is given by

$$E = \frac{\rho \Phi \cos \theta}{\pi R^2}$$

where ρ is the surface reflectivity at 1.06 μm, Φ the total radiant power in watts incident on the metal, $\cos \theta$ the angle of scatter defined from the normal to the metal surface, and R the distance (in centimeters) from the surface of reflection to the point where irradiance is evaluated (see Figure 5). Using typical Nd-YAG laser welding values such as $\rho = 0.8$, and $\cos \theta = 0.5$, $\Phi = 300$ W then the scatter E at a distance of 1 m is approximately 3.2 mW/cm^2 which is of the same magnitude as the experimentally recorded values shown in Table I.

Using the relationship for two distances from the weld site, one can determine the distance at which the Maximum Permissible Exposure (MPE) levels for laser radiation will be reached using the recommendations of the American

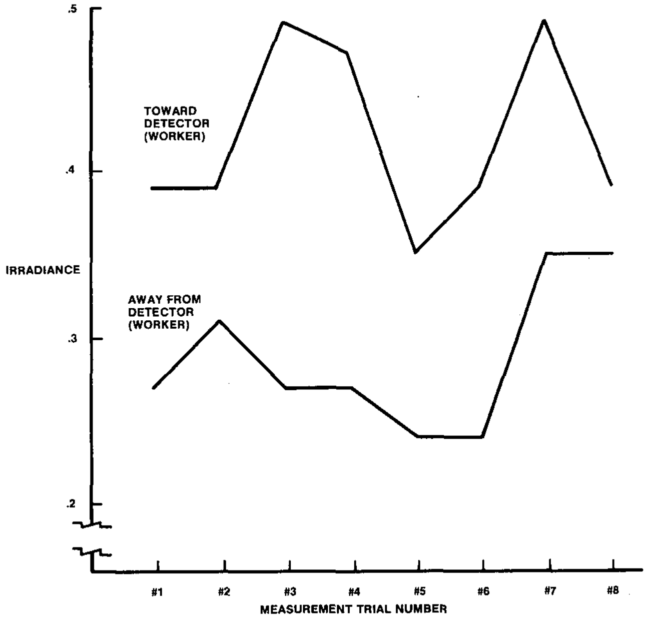

Figure 4 — Irradiance levels from the workpiece as a function of weld direction.

National Standards Institute (ANSI) standard Z136.1-1980.(15) The skin MPE is 10^3 mW/cm^2 at 1.06 μm for long-term (3×10^4 sec) occupational exposures. Using the maximum 1-m irradiance value in Table I of 3.2 mW/cm^2 yields a distance of 5.7 cm. This means that at distances less than 5.7 cm the scattered laser beam will exceed the skin MPE. While this potential situation can occur with unenclosed laser systems, it did not present itself in any of the facilities in this report. The work practice at all facilities did not appear ever to require the operator to be at distance equal or less than 5.7 cm. On the contrary, operators' hands were involved with operating the microcomputer controlling systems or other controls which were typically located 1 m or more from the weld site.

Under the requirements of the ANSI standard, these types of laser systems are considered multiple-pulse (high repetition frequency) lasers. Under this definition, the ocular MPE must be determined using *both* single pulse and multiple pulse (total-on time pulse) criteria. When this evaluation is done under the most restrictive ANSI condition, the results show that the allowable eye exposure corresponds to an average irradiance of 0.22 mW/cm^2.

Using the maximum 1-m irradiance value of 3.2 mW/cm^2 from Table I and assuming an inverse square law relationship, the beam would reach the "worst-case" MPE of 0.22 mW/cm^2 at a distance of 3.8 m. This means that an eye hazard is present at all points within this distance and that no worker should be permitted within this distance from the weld site without wearing appropriate laser protective eyewear. In some facilities a remote potential may exist for reflection of this radiation into a nearby work area. Safety personnel should be on the alert for such radiation escaping the welding area at or above the appropriate MPE level.

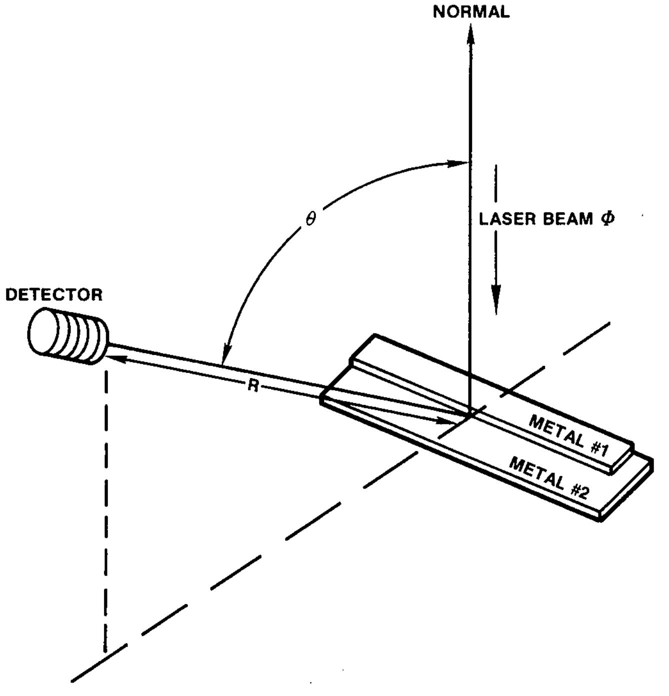

Figure 5 — Reflected laser beam.

TABLE IV
Comparison of Spectral Irradiance Values (E) Obtained from Welding Events 10-13 With the UDT and EG&G Measurement Systems

Wavelength (nm)	E_λ from UDT (10^{-8}W cm^{-2} nm^{-1})	E_λ from EG&G (10^{-8}W cm^{-2} nm^{-1})
400	2.0	2.8
433	3.2	1.1
466	2.0	1.7
500	4.9	2.5
600	1.4	2.7
666	39.3	1.0
700	0.5	1.0

Plume Radiation

The highest spectral irradiance value recorded with the EG&G 550 spectroradiometer was 0.11 μW/cm^2-nm at 350 nm as shown in Table II. The comparative data of spectral irradiance performed at selected wavelengths with the UDT detector using special Corion narrow bandpass optical interference filters is shown in Table IV. The results of these two measurement methods on the same welding event demonstrates that both measurement methods are within at least an order of magnitude. This finding tends to substantiate the magnitudes and validity of the data reported.

When the levels of ultraviolet radiation in Table III are compared to the occupational guideline values reported in Reference 13, it is apparent that there exists minimal concern for UV radiation generated in the plume at these laser power levels. Safety personnel interested in evaluating additional optical radiation concerns should consult Reference 16.

Since significant interest has been recently focused on the concern of optical radiation in the 400- to 500-nm region and its possibility of inducing retinal damage, it is appropriate to address this topic. The total average irradiance of the plume radiation in the blue light region was found to be 3×10^{-6} W/cm^2. This value marginally exceeds the ANSI MPE limit of 1×10^{-6} W/cm^2 over the blue light region for an 8-hour exposure period. Although this MPE value is strictly applicable for point sources only, the plume source formed at the interaction site might be considered equivalent to a point source with dimensions of 2- to 3-mm size. Hence, the ANSI MPE level could be applied for long-term viewing and the point source criteria would be valid for viewing plume dimensions of about 2.5 mm at distances greater than 10 cm. Many of the commercially available laser protective filters used with Nd-YAG lasers will show high transmission in the 400- to 555-nm spectral region. Therefore, laser safety officers and safety personnel should be aware of this potential concern when recommending appropriate laser protective eyewear.

Controls

This study shows that since such Class IV lasers apparently can present laser radiation hazards to both the eye and skin of an unprotected operator under normal work conditions, then specific control measures must be used for safe operations. Table V reviews the mandatory (shall) and advisory (should) control measures for Class IV lasers as specified by the ANSI standard. Use of this table by appropriate safety personnel will aid in establishing proper control measures in laser welding facilities.

This article has shown that for particular laser welding purposes, safety personnel must be aware of the topics listed as enclosed beam path and interaction area, protective eyewear and limiting spectators.

One area of potential worker discomfort might be the orientation of the microcomputer video display terminal (VDT). Quite often, in the industrial setting, the glare from conventional light sources can produce a visual problem in viewing the screen. There is, of course, no harmful radiation concern from such VDT systems. In this study all control systems appear to be placed in a convenient position but given the hazardous level of scattered radiation further facility planning consideration may be warranted. Also, with the high laser radiation levels, and the need to wear eye protection with a high optical density value, there is introduced into this work environment a potential visual problem in actually viewing the VDT faceplate. This problem may be overcome by the use of barriers and screens and proper orientation of the display screen to eliminate direct viewing of the welding process. Some consideration might be given towards designing more appropriate protective eyewear for such processes.(17) The key idea is to design the viewing of both the laser process and VDT screen in such a manner that will minimize worker visual fatigue and eliminate altogether the laser exposure concern.

TABLE V
Required Controls as Specified in the ANSI-Z136.1 Standard for Class IV Lasers

Required by ANSI	ANSI Section (1980 Edition)	Control Measure Topic
X[A]	4.2.2	Protective housing
X	4.2.3	Safety interlocks on laser protective housing
X	4.2.4	Key switch interlock
(Recommended only)[B]	4.2.6	Enclosed beam path and interaction area
X	4.2.7	Viewing windows
(Recommended only)[B]	4.2.8	Beam attenuator
(Recommended only)[B]	4.2.11	Warning system (light or audible alarm)
(Recommended only)[B]	4.2.15	Remote firing
X	4.2.16	Equipment labels
X	4.3.5 & 4.5.2.2	Protective eyewear
X	4.3.2	Safety training for personnel
X	4.3.3	Authorized operators
X	4.3.6	Limiting spectators (access requires supervisory approval)
X	4.3.7	Service personnel requirements training
X	4.2.12.1	Controlled area (Class IV)
	4.2.12.2	1) Knowledgeable supervision 2) Spectator access requires approval 3) Posting area with signs 4) Beam termination 5) Use of diffuse reflectors 6) Entryway interlocks 7) Special access procedures for test procedures 8) Cover windows and access ways 9) Special needs for beams out-of-doors

[A] X - Required sections are mandatory and are instructed in the standard by "shall".

[B] Sections wherein the instructive work "should" is used are considered advisory recommendations and are not mandatory.

Conclusions

Reflection of Class IV laser beams from the various metals used in laser welding procedures can, under certain conditions, produce a hazardous condition. However, the results of the measurements taken using the Nd-YAG laser do not appear to warrant major concern for plume-generated optical radiation at the workpiece during the welding event for lasers operating at power levels less than 300 W. Moreover, if workers use appropriate safety protective eyewear (*i.e.* typically optical density (OD) in excess of 6 at the 1.06-μm laser wavelength and at least OD of one in the blue light region) then ocular concerns for all types of radiation produced directly or indirectly by the laser should be eliminated.

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23 September 1982; Revised 15 April 1983