American Industrial Hygiene Association Journal

ISSN: 0002-8894 (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/aiha20

Optical Radiation Hazards of Laser Welding Processes Part II: CO_2 Laser

R. JAMES ROCKWELL & C. EUGENE MOSS

To cite this article: R. JAMES ROCKWELL & C. EUGENE MOSS (1989) Optical Radiation Hazards of Laser Welding Processes Part II: CO_2 Laser, American Industrial Hygiene Association Journal, 50:8, 419-427, DOI: 10.1080/15298668991374912

To link to this article: https://doi.org/10.1080/15298668991374912

Published online: 04 Jun 2010.

Am. Ind. Hyg. Assoc. J. 50(8):419-427 (1989)

Optical Radiation Hazards of Laser Welding Processes Part II: CO_2 Laser*

R. JAMES ROCKWELL, Jr.[A] and C. EUGENE MOSS[B]
[A]Rockwell Associates, Inc., P.O. Box 43010, Cincinnati, OH 45243; [B]Division of Surveillance, Hazard Evaluations, and Field Studies, National Institute for Occupational Safety and Health, 4676 Columbia Parkway, Cincinnati, OH 45226

There has been an extensive growth within the last five years in the use of high-powered lasers in various metalworking processes. The two types of lasers used most frequently for laser welding/cutting processes are the Neodymium-yttrium-aluminum-garnet (Nd:YAG) and the carbon dioxide (CO_2) systems. When such lasers are operated in an open beam configuration, they are designated as a Class IV laser system. Class IV lasers are high-powered lasers that may present an eye and skin hazard under most common exposure conditions, either directly or when the beam has been diffusely scattered. Significant control measures are required for unenclosed (open beam), Class IV laser systems since workers may be exposed to scattered or reflected beams during the operation, maintenance, and service of these lasers. In addition to ocular and/or skin exposure hazards, such lasers also may present a multitude of nonlaser beam occupational concerns. Radiant energy measurements are reported for both the scattered laser radiation and the plasma-related plume radiations released during typical high-powered CO_2 laser-target interactions. In addition, the application of the nominal hazard zone (NHZ) and other control measures also are discussed with special emphasis on Class IV industrial CO_2 laser systems.

Introduction

Previous estimations have projected more than one million United States workers of all types will be involved directly with laser applications before 1990, with about 90% of these workers being craftsmen, operators, and service personnel.[1] This suggests that the potential for accidental exposure to laser radiation now will include not only research engineers and scientists, where a high number of exposure incidents already have occurred,[2] but also the general occupational work force, where the laser safety background may be even more limited.

In a previous article,[3] radiant energy measurements were reported on both the scattered laser radiation and the resultant plume radiations which were produced when a 350-W neodymium-yttrium-aluminum-garnet (Nd:YAG) laser beam interacted with various metals. This report presents the optical radiation hazards associate with 1-5-kW CO_2 laser welding processes. The intent of both studies was to initiate an occupational radiation exposure data base for workers using CO_2 and Nd:YAG lasers for materials processing applications. The data base will be expanded on a periodic basis as new laser types enter the workplace.

Laser-Target Interaction

The availability of high-powered CO_2 lasers and the limitations of current welding technology have created interest in deep penetration welding. The ability of the CO_2 laser to produce focused irradiance levels on a continuous basis in excess of 10^8 W/cm^2 and the precise manipulation of materials relative to the beam make it unmatched as an accurate and reproducible industrial tool. The CO_2 laser operates at an infrared wavelength of 10.6 μm with a continuous wave (cw) radiant power ranging from 100 W-10 kW in commonly available commercial systems. CO_2 laser systems having power levels greater than 10 kW can produce significant diffuse reflection hazards within normal working distances from the target (< 2 m) and, consequently, impose major hazards for workers when the beam is not enclosed.

Since many metals used in industry are specular mirror reflectors at far infrared wavelengths, absorption of radiant energy into the metal often is very low. As the temperature increases and the metals approach liquid phase, however, the absorption of the beam power increases significantly. This particular absorption change occurs at a critical intensity, I_c, which is on the order of 10^5-10^7 W/cm^2 for a wide range of metals.[4] This increase in absorption, or enhanced coupling of the laser energy into the material, is a result of surface plasma formation.[5]

From a safety viewpoint, once I_c has been reached, there is increased absorption in the material and less reflection of the beam. For intensities greater than 10^7 W/cm^2, it is possible for the surface plasma to become detached and migrate into the laser beam. When this occurs considerable loss of transmitted laser energy occurs, leading to process interruption. The use of shielding gases, such as argon, helium, and acetylene, helps to minimize plasma movement and eliminate oxidation embrittlement and porosity. Argon is a frequent choice for shielding gas at lower laser power levels, but as the power is increased, the gas will ionize, producing a plasma that absorbs energy. Hence, helium or a helium-argon gas mixture is used as a shielding medium. In addition, many CO_2 laser cutting systems utilize a jet of compressed air to help produce a clean cut by blowing away the molten metal. The use of shielding gases also may alter the distribution of scattered laser radiation levels incident upon a worker.

*Part I was published in the *Am. Ind. Hyg. Assoc. J. 44(8)*:572-579 (1983).

TABLE I
Percent Reflection of Typical Metals at 10.6 μm (Percent)

Metal	Reflection (%)
Aluminum	97
Tantulum	94
Nickel	95
Copper	96

An important consequence of the reflectance factor, therefore, is that it represents a measure of the laser radiation that can be back scattered to produce a potentially hazardous effect. As shown in Table I, the reflectance of metals at the CO_2 laser wavelength of 10.6 μm normally will be very high when the beam irradiance is less than I_c levels.

It should be stressed that "rough" surfaces do not always act as diffuse reflectors at all wavelengths. For example, in applications such as laser welding or cutting, melting and surface disruption can occur if sufficient laser energy is absorbed by the metal. This can lead to greatly reduced reflectance levels, as illustrated in Figure 1, where the reflectance level is shown to vary with time for a pulsed CO_2 laser beam pulse striking a metal surface.(6)

During such an event, the back-reflected laser beam has been shown to follow an inverse-square law and cosine scattering relationship.(7) In addition, a constant power distribution of the diffusely reflected radiation is not exactly radially symmetric but will skew toward the specularly reflected component.

CO_2 laser systems often utilize high speed cutting formats with robotic beam delivery. Consequently, the laser beam may be delivered to the metal surface at many unique angles. This can result in potential scattering geometries where the hazard analysis can be complex.

While the 10.6-μm wavelength emitted by the CO_2 laser does not represent a retinal hazard; the plume radiation (rich in blue light), produced by the beam interactions with the metal, can present retinal concerns.(7) Consequently, the emissions associated with the target-beam interaction sites should be considered an occupational concern.

This study was undertaken to gather and evaluate data on the radiation levels resulting from CO_2 laser welding and cutting conditions. This phase of the study was conducted at several midwestern manufacturing, research, and fabrication facilities which routinely utilized CO_2 lasers.

Instrumentation

Several optical radiation detectors were used to document the radiant energy levels produced by the welding/cutting events analyzed in this study. All instrumentation used had been calibrated by the manufacturers within the preceeding three months of use.

A radiometer with a calibrated silicon photodiode detector (United Detector Technology [UDT], Model 55A, Hawthorne, Calif.) was used for continuous power measurements in irradiance units of milliwatts per square centimeter (mW/cm^2) over the wavelength range from 0.4–1.1-μm region. Since the UDT detector cannot record optical radiation at 10.6 μm, it is used in this study as an indication of the scattered radiation produced by the laser interaction with the metal. In addition, a thermopile equipped with a quartz window (Eppley, Newport, R.I.) was used to read irradiance (mW/cm^2) in the region from 0.2 to 10.6 μm.

An International Light, Inc., model 730A radiometer with special ultraviolet sensitive detectors (Newburyport, Mass.) was used to evaluate the presence of ultraviolet radiation. The detectors were designed to comply with the guideline values promulgated by the American Conference of Governmental Industrial Hygienists (ACGIH).(8) One detector is designed to read the actinic UV region (200–315 nm) and measures in biologic effective units, while the second detector measures the near UV (320–400 nm) with no biologic weighting function.

Spectral irradiance measurements in selected wavelength regions were taken with a double grating spectroradiometer (EG&G Model 555, San Diego, Calif.). The radiometric units of spectral irradiance (W/cm^2) were used in the plume measurements. A specific wavelength interval was selected, and the welding event was performed for at least a 10-sec time interval. The maximum value of spectral irradiance was recorded from 0.4–0.6 μm over a 10-nm band width.

Luminance or brightness levels in the visible region (400–760 nm) were measured with a hand-held Spectra Mini-Spot photometer (Photo Research, Chatsworth, Calif.) having a 1° field of view. The values recorded were expressed in units of candelas per square centimeters (cd/cm^2).

Results

The measurement data obtained from all CO_2 laser welding events are summarized in Table II, which quantitates the

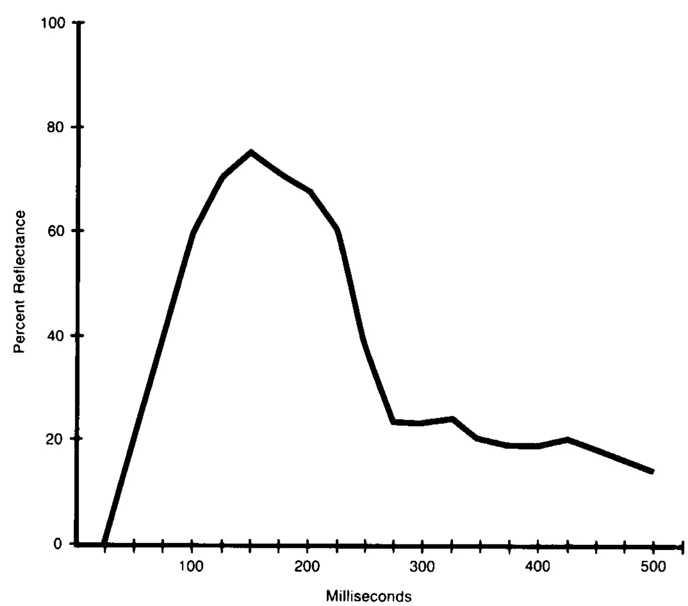


Figure 1—Variation of reflectance from a metal surface over time for a pulsed carbon dioxide laser.

TABLE II
Maximum Optical Radiation Measured at 1.0-m Distance from Plume Radiation Generated by CO_2 Laser on Different Metals

Laser Power (W)	Base Material	Shield Gas ($3\ m^3/hr$)	UDT (mW/cm^2)	Eppley (mW/cm^2)	Spotmeter (cd/cm^2)	I.L. (Near)[A] (uW/cm^2)	I.L. (Far) (eff uW/cm^2)
3650	m. steel	He	0.08	2.0	1.1	—[B]	—
3650	m. steel	He	0.10	—	—	45.7	—
3650	m. steel	He	0.02	—	—	—	—
1950	titanium	He	—	—	1.9	—	15
3650	aluminum	He	—	1.5	—	—	—
440	s. steel	Ar	0.01	0.01	—	—	0.4
1060	s. steel	Ar	0.02	0.5	1.4	—	50
1950	s. steel	Ar	0.10	1.3	—	—	50
1950	s. steel	He	0.02	0.5	—	—	80
3650	s. steel	He	0.05	0.8	6.2	—	200
3650	s. steel	He	—	—	3.0	88	—
3650	s. steel	He	—	—	—	—	—
3650	s. steel	He	—	—	—	78	—
3650	s. steel	He	—	2.4	—	—	50
3650	s. steel	He	0.07	3.0	5.3	—	—
3650	s. steel	He	0.07	2.0	—	—	—

[A]IL = international light meter
[B]— = data not taken

maximum reflected irradiance data obtained at a distance of 1.0 m, using several types of instruments as a function of laser power level, base material, and shield gas. All measurements were made on laser systems that had the beam traveling straight down onto the metal surface. The incident laser power levels were obtained from measurements performed by the laser facility using calibrated power measurement instruments.

Figure 2 shows a comparison of the maximum spectral irradiance on three different welding events using mild steel, titanium, and stainless steel as the base material. The spectral irradiance levels obtained using titanium as the base material were smaller because of much reduced power levels. Spectral irradiance levels recorded for the other two base materials at the same power level were similar in magnitude. It is clear from both Table 1 and Figure 2 that optical radiations are produced in the welding plasma at wavelengths other than 10.6 μm.

Measurements of the brightness, or luminance, of the welding source gave values ranging from 1.1 to 6.2 cd/cm^2. Variations in the brightness of the laser-metal intersection area probably were caused by the angle at which the meter was held while measurements were made.

Levels of ultraviolet radiation in the near UV region ranged from 46–88 $\mu W/cm^2$ while far UV levels were as high as 200 effective $\mu W/cm^2$.

The total integrated irradiance from 400–500 nm produced by the 2–5-kW CO_2 lasers used in this study was about 60 $\mu W/cm^2$ (using the results from Figure 2).

At one facility diffuse scattered irradiance measurements were made with a 1-kW laser during a mild steel welding event using the Eppley thermopile. A maximum value of 7.2 mW/cm^2 was recorded at a distance of 1 m.

Discussion

Scattered Laser Radiation

The relationship for the irradiance of diffusely scattered radiation at a distance R is given by the inverse-square law equation:

$$E = \frac{f\,P\cos\theta}{\pi R^2}$$

where f is the coefficient of surface reflectivity at 10.6 μm, P is the total radiant power (W) incident on the metal, $\cos\theta$ is the cosine of the scatter angle defined from the normal to the metal surface, R is the distance (cm) from the surface of reflection to the point where irradiance is measured, and E is the irradiance produced (W/cm^2).

Using typical CO_2 laser welding values ($p = 0.5$, $\cos\theta = 0.5$, and $P = 1000$), the scattered irradiance E at a distance of 1 m is approximately 8 mW/cm^2. This compares well with the 7.2 mW/cm^2 measurements made using a 1-kW laser.

Metal cutting is another major application for CO_2 lasers. In fact it is the largest single application for high-powered CO_2 lasers.[9] It has been reported in previous work[10] that since a laser cutting process removes metal—unlike welding processes, which bond metal—the optical radiation levels in the produced plasma plume will be lower because there is no weld puddle formed.

Often a mirror-like reflected beam from laser sites can cause potential problems that cannot be predetermined. For example, in one test done during part of this study, a mirror-like reflected beam from a metallic surface produced a melt down in some of the laser system wires near the laser nozzle area and eventually led to a system failure. Similar events actually have produced massive internal fires and destruction of the entire laser. Because of the space requirements in cutting material, many industrial laser systems occupy large floor space and, in an open configuration, are designed as Class IV laser installations, which require special precautions. For example, workers may move about the area where there is a large automated positioning table on which material is moved during the laser cutting process. Throughout the various material adjustment phases, workers may find themselves in locations which yield a high level of scattered laser radiation.

During safety audits performed by both authors, workers have expressed "feeling the beam's warmth." Research is underway to develop a barrier-type enclosure designed with laser resistant materials that can surround the immediate laser work station area, confine most of the laser scattered radiation, and, therefore, provide user protection.[11]

Nominal Hazard Zone

The expansion of industrial laser applications, particularly in the materials processing and robotic areas, has produced a need for detailed analytical methods to evaluate laser hazards more precisely. Under the requirements of the American National Standards Institute (ANSI) Z-136.1 standard,[12] it is useful to define the area where there is a high probability for receiving a potential hazardous exposure. This region is called the nominal hazard zone (NHZ)

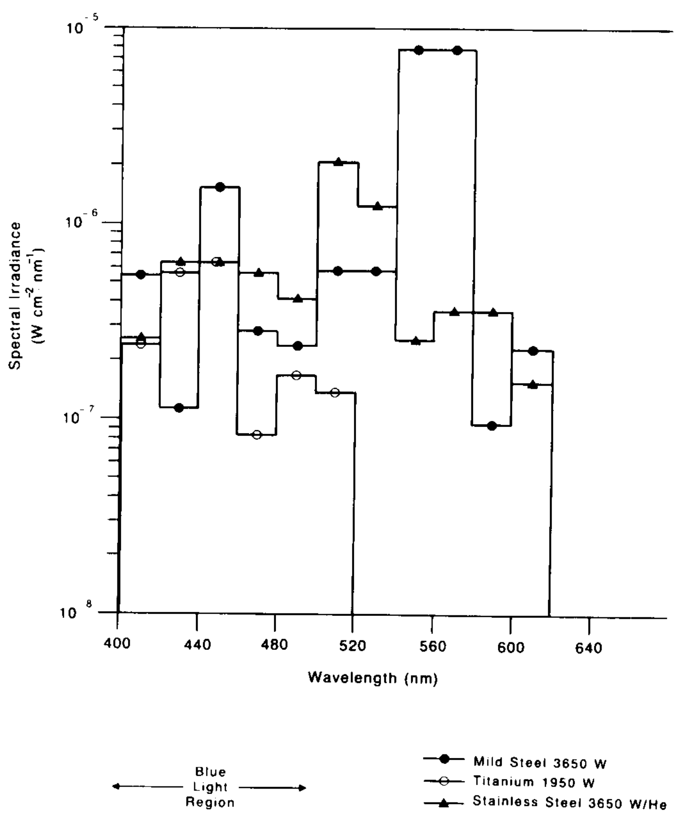


Figure 2—Maximum spectral irradiance at 1.0 m for selected wavelengths on three different welding events.

and is defined as that space within which the level of direct, reflected, or scattered radiation exceeds the applicable maximum permissible exposure (MPE). From another perspective, the NHZ perimeter is the envelope of MPE exposure level produced by a specific laser in a given application or geometry. The space within the NHZ usually requires control measures. The ANSI standard specifies that the laser safety officer (LSO) effect a laser hazard analysis and establish the NHZ for a given laser system.

The 8-hr MPE for CO_2 lasers is 100 mW/cm^2. For diffusely scattered beams where the area of the potential exposure on the worker could be in the range of 100–1000 cm^2, the MPE is determined by the relation: MPE = 10 000/area. For large area exposures, where the possible exposure area can be greater than 1000 cm^2, the minimum MPE is 10 mW/cm^2.

Four different occupational exposure situations that can occur in the industrial setting are illustrated in Figure 3. The intrabeam viewing situation is considered the most hazardous. For lasers such as the Nd:Yag, operating in the spectral range of 400–1400 nm, the beam can be focused by the lens of the eye directly onto the retina to the smallest possible image size (typically about 20 μm). This is the so-called "point source" viewing condition. Because the CO_2 beam would be absorbed totally in the cornea, this condition would not be applicable for this laser.

The diffuse reflection situation occurs with more frequency in industry and is assumed, often incorrectly, to be of only minor occupational concern. This is not the case, however, with Class IV lasers which, by definition, are capable of producing a hazardous diffuse reflection. Another common industrial situation is illustrated with the lens-on-the-laser case. Most industrial processing lasers incorporate a lens as the final component in the beam path. The final situation depicts an optical fiber connected to the laser.

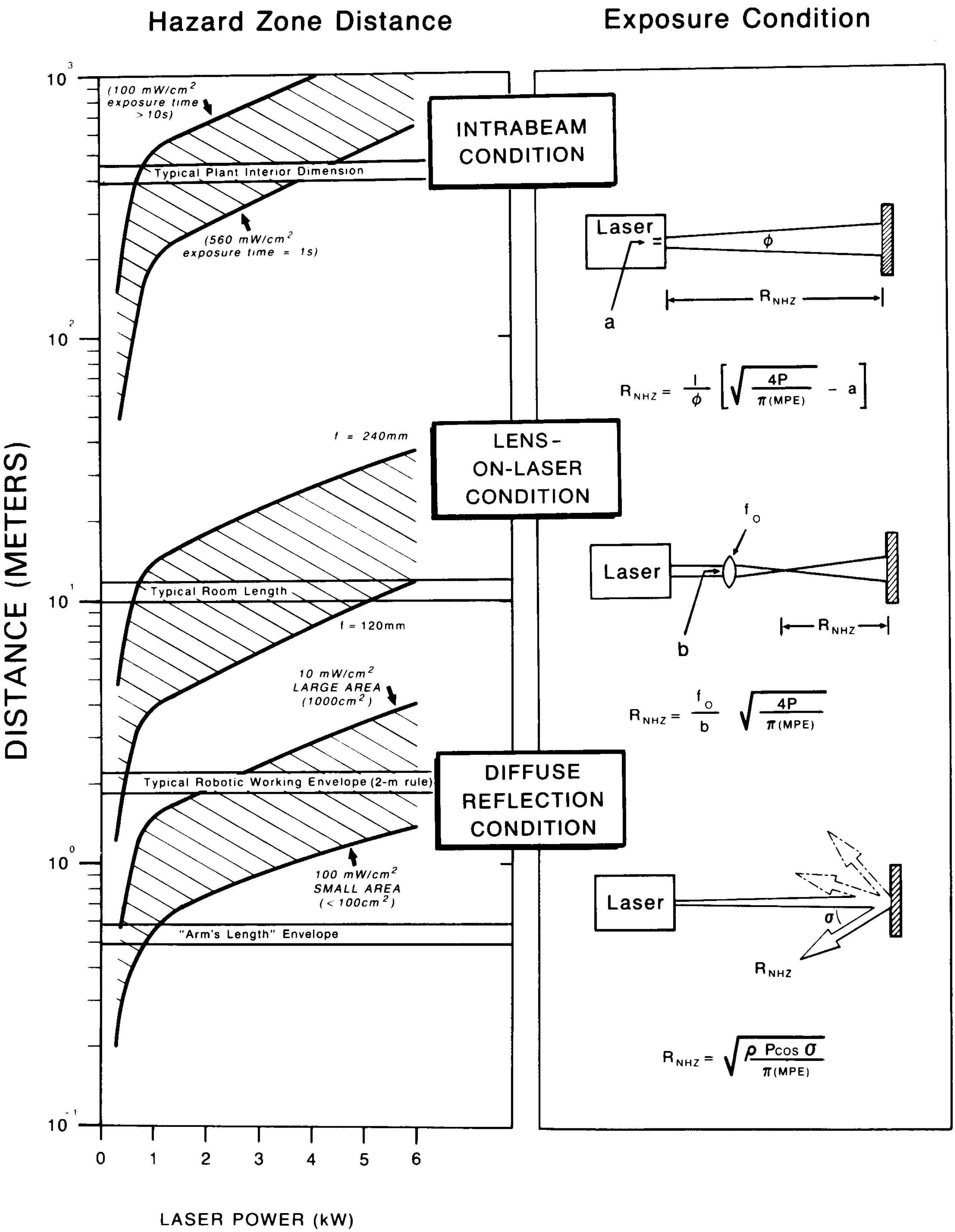
Some discussion and explanation can be helpful to understanding the results of NHZ calculations. Figure 3 also shows comparisons between the NHZ associated with intrabeam, diffuse, and lens-on-laser situations as a function of total beam power for a typical industrial CO_2 laser system. The laser parameters used to calculate the curves are given on the figure.

The following general conclusions from the NHZ evaluation for CO_2 can be stated.

(1) The intrabeam NHZ exceeds most plant dimensions (400 m) when the laser power exceeds 500 W for long-term (> 10 sec) ANSI MPE exposure criteria. The intrabeam NHZ for a momentary, 1-sec, exposure to a 500-W CO_2 laser is reduced only to 160 m.

(2) The lens-on-laser NHZ exceeds most room dimensions (10 m) when the laser power exceeds 1800 W. The specific conditions obviously depend on the focal length of the lens being used.

(3) A NHZ separation distance of 2 m from a diffuse reflection will provide adequate safety for laser powers up to 12.5 kW. This has some importance in defining the safe working envelope distance associated with a laser on a robot.



$$R_{NHZ} = \frac{1}{\phi}\left[\sqrt{\frac{4P}{\pi(MPE)}} - a\right]$$

$$R_{NHZ} = \frac{f_o}{b}\sqrt{\frac{4P}{\pi(MPE)}}$$

$$R_{NHZ} = \sqrt{\frac{\rho\, P\cos\sigma}{\pi(MPE)}}$$

Figure 3—Nominal hazard zone as a function of distance for carbon dioxide lasers in an industrial setting.

(4) "Arm's length" NHZ separations from a diffuse reflection of 50 cm are adequate for laser powers up to 80 W. Users should be aware of the potential for partial body heat stress conditions when working at these distances.

(5) At distances less than 50 cm from the interaction site, users must be reminded that various gases, fumes, and vapors may exist at dangerous concentration levels. Consideration must be given to utilizing properly designed exhaust systems.

Plume Radiation

During cutting processes, material constantly is being removed and blown away, hence there is limited material left for luminescence and, hence, minimal blackbody (plume) radiation is produced. With low luminance levels, there is a tendency for users not to wear any or wear inappropriate laser protective eyewear. For example, the maximum plume luminance level was about 1–2 cd/cm^2 for a 3650-W CO_2 laser during cutting processes. These luminance levels are low when compared to traditional nonlaser welding luminance values.[10,13]

The data in the results section illustrate that under some exposure situations, it is possible to have a plume radiation component that occurs in the far ultraviolet (less than 320 nm) region. In fact the actinic radiation level measured from a 3600-W CO_2 event exceeded the ACGIH threshold limit value (TLV®) within 10–30 sec. This result suggests that without appropriate protection, the far UV levels are of sufficient magnitude to present an ocular or skin hazard when compared to the ACGIH TLVs.[8] Since the luminance level of the visible optical radiation is not excessive, it is possible that workers might view a reflected laser situation without appropriate UV protective eyewear and receive photokeratitis.

Interest has been expressed on the level of radiation produced within the blue light spectral region where photochemical retinal damage is possible in some long-term (> 10 sec) exposure conditions. The average irradiance of the plume radiation in the blue light region was about 60 μW/cm^2. This value exceeds the ANSI MPE limit of 1 μW/cm^2 by a factor of 60 for an 8-hr exposure period. While this MPE is applicable strictly for point sources only, the plume source formed at the interaction site might be considered equivalent to a small point source having dimensions of 2–3 mm. 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. An optical density of at least 2 would be required for plume radiation protection in the blue light region for such levels. One appropriate method to address both the issues of the 10.6-μm and 400-500-nm wavelength concerns that could be present in a CO_2 exposure situation would be to use a labeled CO_2 laser eyewear protection that has a yellow or orange tint.

In conventional, nonlaser industrial welding/cutting processes, the confinement of the optical hazard within a designated area often is accomplished by surrounding the work station with a transparent welding curtain designed to protect nonwelding personnel in the vicinity.[13] In the past the ability to protect workers in a similar manner when using unenclosed (Class IV) laser welders has been considered extremely limited because of the potential for exposure to significant levels of laser radiation. For example, the direct beam from a typical 1-kW CO_2 laser can easily exceed 300 W/cm^2 and may be significantly higher if only partially focused. Few materials, unless specially designed to be laser resistant, can withstand such irradiance levels for more than a few seconds. Consequently, conventional welding curtains are not appropriate in laser welding applications. Moreover, if plastic materials are used to block plume radiation, the user should be aware that plastic products may support combustion, thereby representing a fire hazard. For example, a CO_2 laser exposure of 300 W/cm^2 for 8 sec is sufficient to ignite Lexan® plastic.

Nonbeam Issues

Most facilities visited had the same type of basic safety problems arising over and over again. Several of the recognized nonbeam hazards and concerns that exist within a typical industrial facility using lasers include the following[14]:

- Noise
- Fire hazard
- Plume radiation
- X-ray production
- Electrical shock/death
- Combustion concerns
- Waste disposal issues
- Human factors/ergonomics
- Chemical and vapor toxicity
- Potential explosions
- Ventilation requirements
- Visibility issues.

One of the more important hazards associated with laser cutting of plastics is that of fume production. It has been shown in two independent studies that the analysis of the by-products produced by CO_2 laser cutting of polymethyl methacrylate and polyvinyl chloride samples contain potentially hazardous fumes which can include polycyclic aromatic hydrocarbons and other chemicals.[15,16] Another recent study has shown that when certain high-temperature fabric, such as Kevlar®, is cut with a CO_2 laser, several toxic and carcinogenic compounds may be produced.[17] One of the highest concentration compounds reported in that study was benzene. It was shown that the time to reach the threshold level in the environment immediately around the laser was about 40 min.

In all of these studies, attention was drawn to the need to protect workers adequately by the use of appropriate exhaust or containment systems. Of interest was the fact that, in the latter study,[17] it was shown that the use of argon as the shielding gas enhanced the formation of benzene. Therefore, it appears that the choice of a shielding gas is important for basic industrial hygiene reasons as well as for the engineering requirements in the process.

Users of Class IV laser systems often ignore that such high-powered lasers, by definition, represent not only radiation concerns but a fire hazard as well. Fires have been reported as a result of equipment malfunction. These concerns for fire can impose need for flame resistant barriers in controlled areas.

There have been a significant number of deaths and "near misses" from electrical shock among workers performing adjustments on laser systems. This is not surprising since certain pulsed laser systems can carry instantaneous electrical currents near 2000 amperes (A). A typical, high-powered, CW industrial CO_2 laser will support electrical currents on the order of 20-30 A during emission. Current levels of 50-100 mA at 60 Hz into the body are considered fatal.[7]

The combination of a CO_2 laser with a robot is now very much a reality within many manufacturing industries. The anticipated growth of robotic use in the United States presently is projected at 35% per year.[18] The increase in use of such systems raises new safety questions, such as the following.

(1) Is the NHZ within the protected working envelope of the robot?

(2) Is there a hazard from the beam in the event of robot malfunction?

(3) Are there potential hazards during servicing of the unit when beam access is often required?

(4) Can the "pinch effect" occur? (This occurs when a worker is pinned between a robot and some confining object—such as a rigid cinderblock wall or ceiling support post.[19]

TABLE III
Suggested Laser Safety Training Format

History and Theory of Lasers: wavelength; atomic and molecular energy levels; photon concept; stimulated emission; laser operational theory; need for laser safety; definitions

Basic Laser Physics: properties and characteristics of lasers; types of lasers; modes; pulsed and continuous wave; nature of source domain, target domain, and people domain; penetration, reflection, and refraction issues.

Laser Bioeffects: effects on skin and eye; absorption issue; thermal versus photochemical effects; origins of maximum permissible exposure values; structure of eye and skin; wavelength dependence of effects; type of accidents reported; population at risk; accidents' relationship to power levels; laser classes.

Laser Standards: discussion of various standards (ANSI, FDA, OSHA, military, state, and international); discussion of when to use each standard.

Sample Laser Calculations: retinal irradiance; optical gain concept; laser range equation; nominal hazard zones; inverse-square law; optical density for various laser types; and classifications.

Nonbeam Issues: discussion of how laser safety officers can solve some of the nonbeam issues that arise when working with lasers.

Control Measures: protective housing; beam shutters and safety interlocks; area posting; temporary protected areas; baffles and beam stops; out-of-door controls; requirements by laser class.

Eye Protectors: selection of the eye protector appropriate for the job task being performed.

A working envelope of 3-6 m (10-20 ft) around the robot is typical for many industrial robot uses. When a laser is added to the robot, however, the "robot working envelope" now also should include the NHZ evaluation associated with the laser. As discussed earlier, this includes a dependence upon the optics and scattering from the target. Since lens-on-laser conditions usually will be required to maintain the NHZ within the robot's working envelope, there must be a means to ensure that the focusing lens remains in position during operation.

Control Measures

The applicable Class IV laser system control measures recommended by the ANSI Z-136.1 standard include the following:

- Protective housing
- Interlocks
- Service access panel
- Key switch master
- Totally open beam path
- Limited open beam path
- Remote interlock connector
- Beam stop or attenuator
- Activation warning system
- Controlled area
- Labels and signs
- Administrative and procedural controls
- Standard operating procedures
- Education and training
- Authorized personnel
- Alignment Procedures
- Eye protection
- Spectator control
- Service personnel†

These control measures are divided into two major groups: engineering and administrative/procedural.

Detailed training is recommended for those personnel working with all Class IV CO_2 laser systems. A sample topical content for a course to meet this type of training is shown in Table III. Such training sessions should be a requirement for all new personnel, and frequent update programs for previously trained personnel are recommended. The need for recurrent training has been supported by laser accident victims.[20]

In performing CO_2 laser audits at various facilities, one of the authors repeatedly has noted the presence of laser systems, many which had been imported into the United States,

†Information modified from Table 10, page 38, of ANSI Z-136.1, safe use of laser standard, 1986. Readers should consult standard for more details on these control measures for their applications.

TABLE IV
Guidelines for Preparing Standard Operating Procedures for Laser Operations[A]

1. **Introduction**
   a. location of laser (site, building, room)
   b. description of laser
   c. purpose of laser
2. **Hazards**
   a. identification of the hazards in the room
   b. analysis of hazards and potential for accident
3. **Controls**
   a. access control
   b. beam control
   c. electrical controls
   d. eye protection
   e. other
4. **Operating procedures**
   a. initial preparation of laboratory environment
   b. personnel protection
   c. target preparation
   d. countdown procedures
   e. shutdown procedures
5. **Emergency procedures**
   a. list potential emergencies and corresponding procedures
   b. describe specific rescue or evacuation procedures
6. **Training**
   a. indoctrination of workers in room
   b. training of on-site LSO
7. **Responsibilities**
   a. supervisory
   b. emergency contact
   c. support personnel

[A]These guidelines are intended to aid users in the preparation of SOPs that detail specific requirements and procedures for operation of the lasers with which they work.

that did not comply with the Food and Drug Administration (FDA) Laser Product Performance Standard.[21] LSO's, therefore, must ensure, prior to purchase, that the system manufacturer is fully aware of the various compliance requirements imposed on laser products. One method to assure that a manufacturer of a given laser has applied to the FDA for adherence to the standard is to request the accession number prior to purchase. The LSO also should be aware of potential provisions of applicable local and state regulations, if any, pertaining to safe use of lasers. Many lasers manufactured in other countries use warning signs/labels that contain foreign words, slogans, and/or symbols which may confuse industrial users in the United States.

One of the most important, but often least used, control measures is requiring the development of a written standard operating procedure (SOP). Under the ANSI standard, an SOP is required for a Class IV laser. The key to an effective SOP is the involvement, during its preparation, of all individuals (including the LSO) who will operate, maintain, and/or service the equipment. Table IV contains basic information that will help supervisors and safety personnel in preparing SOPs for Class III and IV lasers.

Laser Eye Protection

Laser eyewear protection devices are goggles or spectacles that incorporate special high optical density filters or reflective coatings to reduce the potential ocular exposure below the MPE, while at the same time permit viewing of the specific task. Laser protective eyewear normally is specified in terms of optical density (OD) at a given laser wavelength. This is related by the equation:

$$OD = \log 10\,(Hp/MPE)$$

where Hp is the "worst case" exposure. In general, while laser eyewear protection is necessary, other controls should be emphasized rather than sole reliance on the use of protective eyewear.

Typical CO_2 laser eyewear products often are made from polycarbonate plastics. These materials are lightweight, relatively inexpensive, and have a high optical density at the 10.6-μm CO_2 wavelength. Most plastic protective eyewear have a penetration threshold level (PTL) of about 5 W/cm^2.[22] Using this value and formulas similar to the NHZ relationships, one can calculate the allowed total laser power necessary to penetrate plastic eyewear at an arm's length distance for the different viewing conditions illustrated in Table V.

Plastic eyewear is acceptable for almost any conceivable diffuse reflection condition and for most lens-on-laser conditions when the power is less than about 200 W. Plastic eyewear is not applicable for direct beam hazards unless the power is less than 17 W.

An increase in the PTL to 100 W/cm^2 only increases the allowed total beam power to 340 W for the direct beam case. It does allow, however, powers over 4000 W for lens-on-laser conditions.

Conclusions

The success of numerous industrial CO_2 laser applications has been well documented over the past decade. Such systems are proliferating now in virtually every industrial area. The hazards of welding/cutting uses have been demonstrated to include numerous nonbeam concerns (electrical shock, toxic fumes, optical plume radiations, *etc.*) along with the beam hazards.

Because the long wavelength CO_2 beam is absorbed so well in all tissues, it is basically a "surface effect" agent. This initially may seem to reduce the beam-related concerns.

TABLE V
CO_2 Laser Beam Power Required to Penetrate Plastic CO_2 Eye Protectors

Viewing Condition	Maximum Power Limit[A] (W)
Intrabeam	17
Lens-on-laser	220
Diffuse	39 300

[A]Required to reach PTL of 5 W/cm^2 at "arm's length" (50 cm).

Nonetheless, because of the high CO_2 beam powers and the production of UV and visible light radiations on the plume radiations, the CO_2 laser, if not properly controlled, can present major beam hazards, especially for industrial welding uses where the beam is not enclosed.

Protection can include eyewear, barriers, and gloves which are selected for use based upon their ability to withstand the CO_2 laser beam's thermal insult ability.

References

1. **National Institute for Occupational Safety and Health:** *Lasers: Applications and Occupational Safety Concerns of Today and the Future.* by R.J. Rockwell. Cincinnati, Ohio: National Institute for Occupational Safety and Health, September 1982.
2. **Radiation Incidents Registry:** Report on Radiation Accidents. Rockville, Md.: Center for Devices and Radiological Health, Food and Drug Administration, 1987.
3. **Rockwell, R.J. and C.E. Moss:** Optical Radiation Hazards of Laser Welding Processes, Part 1: Nd:Yag Laser. *Am. Ind. Hyg. Assoc. J. 44(8)*:572-579 (1983).
4. **Herziger, G.:** The Influence of Laser-Induced Plasma on Laser Materials Processing. In *Industrial Laser Annual Handbook.* edited by M. Levitt and D. Belforte. Tulsa, Okla.: Penn Well Books, 1986. pp. 108-115.
5. **Rockstron, T.J. and J. Mazumber:** Spectroscopic Studies of Plasma during CW Laser Materials Interaction. *J. Appl. Phys. 61(3)*:917-923 (1987).
6. **Ready, J.F.:** *Industrial Applications of Lasers.* New York: Academic Press, 1978. p. 131.
7. **Rockwell, R.J., ed.:** *Laser Safety Training Manual.* 6th ed. Cincinnati, Ohio: Rockwell Associates, Inc., 1987.
8. **American Conference of Governmental Industrial Hygienists:** *Threshold Limit Values for Chemical Substances and Physical Agents in the Workplace Environment.* Cincinnati, Ohio: American Conference of Governmental Industrial Hygienists, 1987.
9. **Darchuk, J.M. and R.E. Migliore:** The Basics of Laser Welding. *Lasers Appl. 4(3)*:59-68 (1985).
10. **Marshall, W.J., D.H. Sliney, M. Hoikkala and C.E. Moss:** Optical Radiation Levels Produced by Air Carbon Arc Cutting Processes. *Weld. J. 59(3)*:43-47 (1980).
11. **Wilson, D.F.:** Safety Control Measures for Laser Welding Processes. *Ind. Saf. Hyg. News 20(11)*:15 (1987).
12. **American National Standards Institute:** *American National Standard for the Safe Use of Lasers.* (ANSI Z-136.1). Toledo, Ohio: Laser Institute of America, 1986.
13. **Sliney, D.H., C.E. Moss, C.G. Miller, and J.B. Stephens:** Semi-Transparent Curtains for Control of Optical Radiation Hazards. *Appl. Opt. 20*:2352-2366 (1981).
14. **Spaeth, D.:** Non-Beam Hazards in the Laser Workplace. *Laser Topics. 8(4)*:12 (1986).
15. **Doyle, D.J. and J.M. KoKosa:** Hazardous By-Products of Plastics Processing with Carbon Dioxide Lasers. In *Laser Welding, Machining and Materials Processing* edited by C. Albright. (Proceedings of ICALEO). Bedford, United Kingdom: IFS LTD., 1985. pp. 201-203.
16. **National Institute for Occupational Safety and Health:** Final Report by R.J. Rockwell (NIOSH Grant No. 08590H00371) 1976.
17. **Doyle, D.J. and J.M. KoKosa:** Laser Processing of Kevlar: Hazardous Chemical By-Products. *Polym. Prepr., Am. Chem. Soc., Div. Polym. Chem. 26(2)*:255-256 (1985).
18. **Rockwell, R.J.:** Ensuring Safety in Laser Robotics. *Lasers and Appl. 3(11)*:65-69 (1984).
19. **National Institute for Occupational Safety and Health:** *Request for Assistance in Preventing the Injury of Workers by Robots.* (DHHS[NIOSH] Publication No. 85-103). Cincinnati, Ohio: National Institute for Occupational Safety and Health, 1984.
20. It Could Happen to You. *Laser Focus. 18(4)*:10 (1982).
21. "Laser Products," *Code of Federal Regulations,* Title 21, Pt. 1040.10. 1985. pp. 33682-33702.
22. **Department of Health, Education and Welfare:** *Evaluation of Commercially Available Laser Protective Eyewear* by K.R. Envall and R. Murray (DHEW Publication [FDA] 79-8086). Rockville, Md.: Food and Drug Administration, Department of Health, Education and Welfare, May 1979.

1 August 1988; Revised 2 February 1989