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Laser Ignition of Flammable Gas

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Abstract

Emerging laser technologies are quickly gaining acceptance in the industrial workplace. Besides the risk of human exposure, one safety concern with the more intense lasers is the potential for ignition of flammable gases, vapors, dusts, fibers, or flyings often found in hazardous (classified) industrial settings. In underground coal mines, lasers are being considered for remote measurement of explosive methane gas. Current federal safety regulations for underground mines contain no specific guidance for evaluating the safety of optoelectronic components such as diode lasers. The National Institute for Occupational Safety and Health is conducting research to help provide a scientific basis for developing appropriate safety guidelines for optical equipment in the presence of flammable methane gas and/or coal dust. One phase of the study is an experimental evaluation of methane-air ignition by laser heated small particles. Minimum observed igniting powers for laser energy delivered by 200-, 400-, and 800-µm core diameter fiber optic cables and directed onto selected targets in methane-air atmospheres were 0.6, 1.1, and 2.2 W, respectively. Comparisons are made with other ignition phenomena, including heated wires.

Introduction

Today, laser diodes capable of producing several hundred milliwatts or more are found in industrial measurement and control applications[1,2,3]. Equipment that may contain intense laser sources include closed or open path optical analytical devices, fiber-optic links for communication or power transmission, and others. One application of laser technology in underground coal mines currently under evaluation is the remote measurement of explosive methane gas (figure 1). Methane gas is often released during the mining process. Federal regulations require periodic methane measurements at the mining face, and abatement measures should methane exceed a specified concentration. The process of making methane measurements in the roof-fall prone face area can require extensive safety precautions to prevent injury. The possibility of such injuries occurring has been cited as a safety concern by the United Mine Workers of America. A simple-to-use remote methane monitor would therefore enhance miner safety in the roof-fall prone face area.

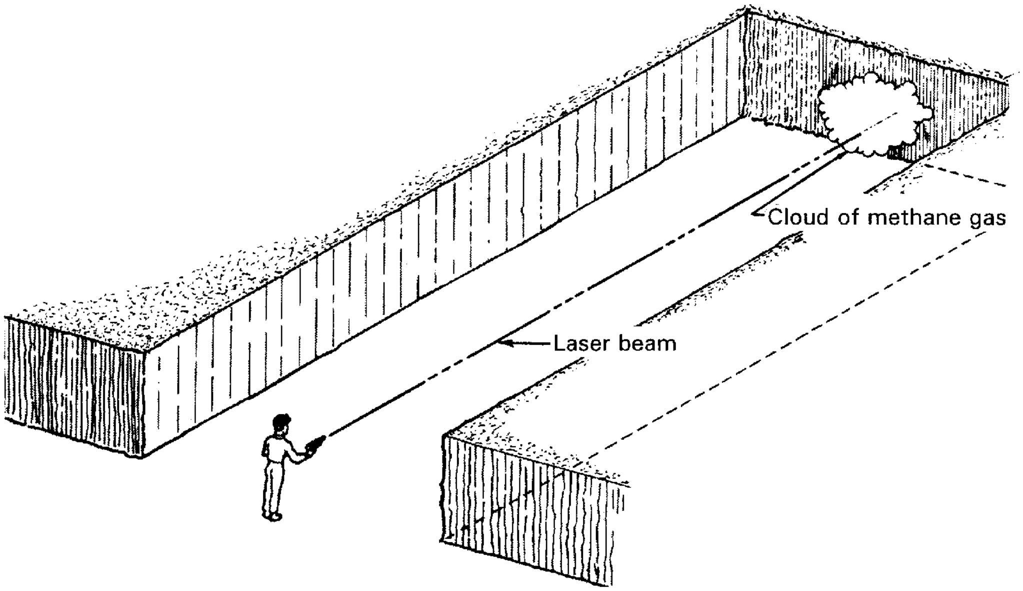

Figure 1. Concept drawing of remote methane monitor.

In this scenario, the open laser beam passes through an area where both methane gas and coal dust are normally present. How does one ensure the risk of ignition is not significant? Most methods for reducing explosion hazards due to the presence of energized equipment are based on the ignition triangle shown in figure 2. Eliminating any leg of the triangle will prevent ignition from occurring. (Notable exceptions to this general rule are techniques that allow combustion to occur under known or controlled conditions, such as explosion-proof enclosures.) One protection method prevents the formation of combustible mixtures near the ignition source. An example is the pressurization technique, where a small overpressure is applied to an enclosure to prevent the entry of flammable gas. Another protection method isolates the ignition source from the flammable atmosphere. An example is encapsulation, where a physical barrier is placed between the ignition source and combustible mixture. Another popular approach limits the amount of energy introduced into the combustible mixture, effectively removing the ignition source. An example is the intrinsic safety technique, where electrical circuits are designed so that under both normal and fault conditions they cannot release sufficient thermal or electrical energy to cause ignition. Very careful consideration of a particular situation is required to ensure proper application of any of these protection techniques[4].

Referring again to the open-beam remote methane monitor (figure 1), the protection method that appears most relevant is the energy limitation approach applied to beam strength. Federal regulations for underground coal mines contain very strict guidelines for equipment intended for use in gassy underground mines where permissible equipment is required. However, little or no consideration has been given to optical ignition mechanisms because typical lasers used thus far in mines have very low power. For example, the Mine Safety and Health Administration (MSHA) document "Criteria For The Evaluation and Test of Intrinsically Safe Apparatus and Associated Apparatus" contains no specific guidance for apparatus containing optoelectronic components such as diode lasers[5]. Inadequate safety evaluation criteria are problematic in two ways. Obviously, allowing ignition capable optical beams in a potentially explosive environment is an invitation to disaster. Conversely, overly conservative evaluation criteria resulting from a lack of understanding of the phenomena could unnecessarily prohibit useful, potentially safety enhancing technology.

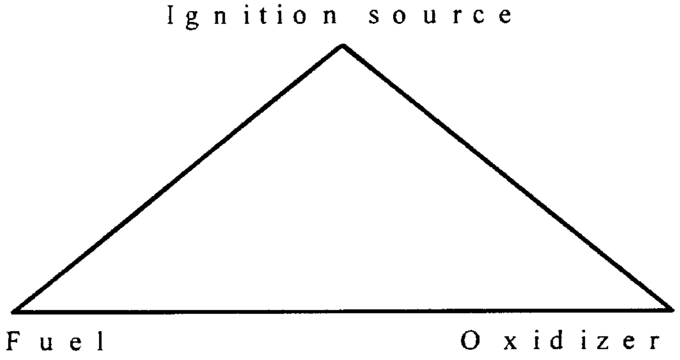

Figure 2. Ignition triangle.

The National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory (NIOSH, PRL) is conducting a study to develop safety recommendations for lasers used in underground coal mines. The project is limited in scope to visible and near infrared continuous wave (CW) sources. (Very short duration, high peak power optical pulses represent a fundamentally different hazard that is not directly applicable to anticipated undergound applications.) Beam powers and spatial distributions required to ignite methane-air and/or coal dust are considered. It is believed that the results of this research are also applicable to other industries that use or produce flammable gases or combustible dusts.

Technical Approach

Several optical ignition processes have been identified in the literature. Magison[4] has grouped these into four categories:

- Thermal ignition of a gas volume, where the laser wavelength matches an absorption band of the gas.
- Photochemical ignition due to photodissociation of oxygen molecules by radiation in the ultraviolet region.
- Direct laser induced breakdown of the gas at the focus of a strong beam, producing a plasma.
- Thermal ignition of a gas by an intermediate target heated by optical radiation. The intermediate target may be inert or flammable.

The first three processes require either relatively high peak powers or ultraviolet radiation, and therefore fall outside the scope of the present study.

The fourth listed ignition process requires the conversion of optical energy to thermal energy by absorption in an appropriate target (figure 3). The target needs to attain a minimum ignition temperature for a given ignition volume in order to ignite the surrounding gas. Some relevant target properties include absorbance, surface area, volatility, and reactivity with air. There is agreement in the literature that strongly absorbing targets facilitate ignition[6]. The role of target surface area, volatility, and reactivity can be somewhat convoluted. For example, small, volatile or combustible targets may vaporize, dissipating the laser energy before igniting the surrounding gas. Larger combustible targets have sufficient mass to contribute significant heat of combustion to ignite methane-air more easily than a similar sized inert target. Also, larger heated surfaces can ignite methane-air at lower temperatures than smaller surfaces, but require higher powers to attain similar temperatures as small targets. Small targets that vaporize near appropriate ignition temperatures may ignite gases more readily than other small targets by achieving a minimum volume (Carleton[6]). All of these issues are relevant to coal targets that may intercept the laser beam.

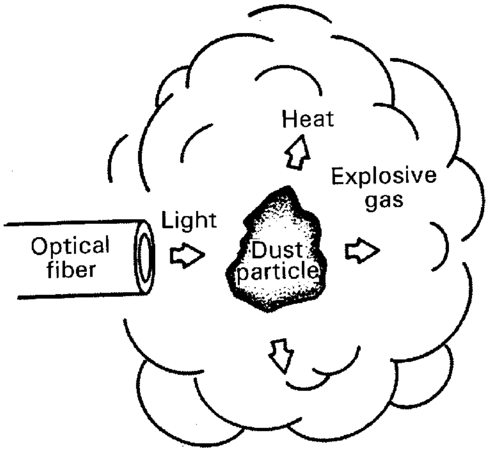

Figure 3. Flammable gas ignition by laser heated small particle.

Experimental Results

Recent PRL research[7] included several series of experiments to investigate one aspect of this ignition process - the role of laser-heated small particles in methane-air ignition. Targets were carefully attached to the ends of optical fibers and placed in a 20-L ignitability/explosibility chamber[8] (figure 4.). The chamber was sealed and flammable mixtures of methane-air were introduced. Laser power levels were varied in an attempt to determine minimum igniting powers under various test conditions. The laser wavelength was centered at 803 nm. Test variables included fiber diameter, methane-air concentration, target material, and target surface area. Targets consisted of Pittsburgh seam bituminous coal particles (PC) and inert but strongly absorbing black iron oxide. Methane-air concentrations were varied from 5 to 10% methane, in 1% increments.

Three sizes of fiber optic cable were used. The smallest had an output core diameter of 200 µm. This was a Fiberguide[a] Anhydrous plastic clad silica (PCS) 400 to 200 µm fiber-optic taper. The next size was a Spectran 400 µm core, 430 µm clad diameter Hard Clad Silica cable. The third cable was a Fiberguide Anhydrous PCS, 800 µm core, 900 µm clad diameter cable. Targets were selected to match the surface area of the fiber tips, thus providing a convenient way to vary target surface area while ensuring most of the laser energy was absorbed. Krytox, a nonflammable material, was used to adhere targets to the fiber tips.

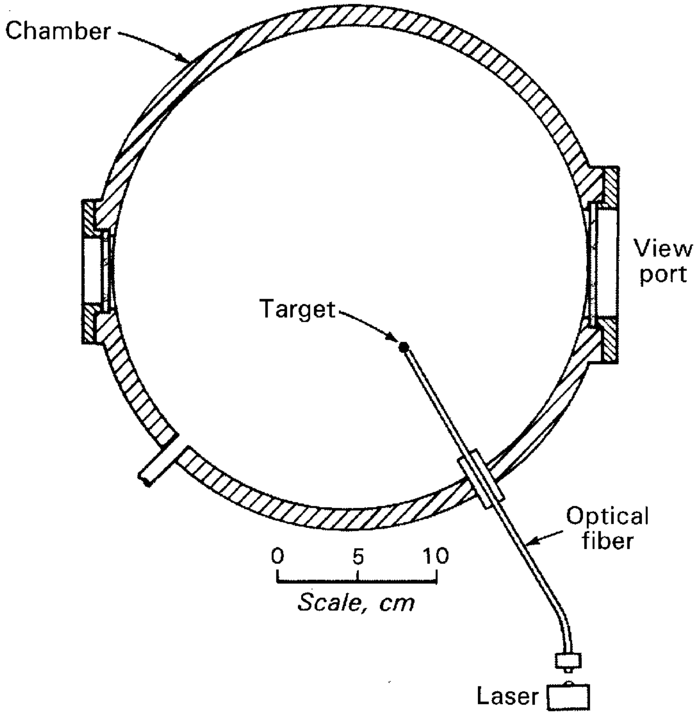

Figure 4. Cross section of 20 liter chamber methane-air ignition test setup

Figure 5 shows a summary of minimum observed igniting powers as a function of fiber optic core diameter under various test conditions. Out of over 150 ignitability experiments, 45 produced ignitions. Minimum igniting powers with iron oxide-based targets were 0.6, 1.1, and 2.2 W with 200, 400, and 800 µm core diameter fibers, respectively. Similar tests with PC consistently required slightly higher incident powers to cause ignition. Results reported by Hills et al[9,10] are included for comparison. Hills found minimum methane-air igniting powers of about 300 mW when 38-45 µm diameter coal particles placed in a glass dish were irradiated by single

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[a] Mention of any company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health

mode and 50 µm core diameter optical fibers. Ignition of an 8% methane-air mixture was also reported when a 40 µm particle attached to a 100 µm core diameter optical fiber was heated by 360 mW.

In the most recent work, an Agema 550 thermal imaging camera recorded temperatures of particles on optical fiber tips heated by laser powers that produced methane-air ignition. The Agema camera system measures the infrared (IR) radiation at wavelengths of 3.6 to 5 µm and shows the calculated temperatures as a false-color display on a monitor. The maximum temperature in the area of interest is displayed as a numerical value. The IR camera was calibrated up to 1500°C by the manufacturer. A 30/80-mm close-up lens allowed very high spatial resolution. Prior to observations of the optical fibers, the temperature calibration and spatial resolution of the IR camera were confirmed by using small apertures placed in front of a blackbody source. Temperature measurements were within manufacturer's specifications down to the smallest aperture on hand - a 340-µm hole drilled through a thin metal sheet.

To measure the temperatures of targets on the ends of optical fibers, both the IR camera and optical fiber were positioned on an optical bench (outside the 20-L chamber). The camera was positioned about 5 cm from the end of an 800-µm core diameter fiber coated with an iron oxide target. The fiber was tilted approximately 40° from vertical (50° from the camera axis) to maximize the viewing area of the fiber tip while avoiding direct exposure of the camera to the laser beam. In preliminary measurements, laser powers of 2.2 W produced target temperatures in the range of 1400-1500°C in three separate tests. Additional tests under these and other conditions are in progress.

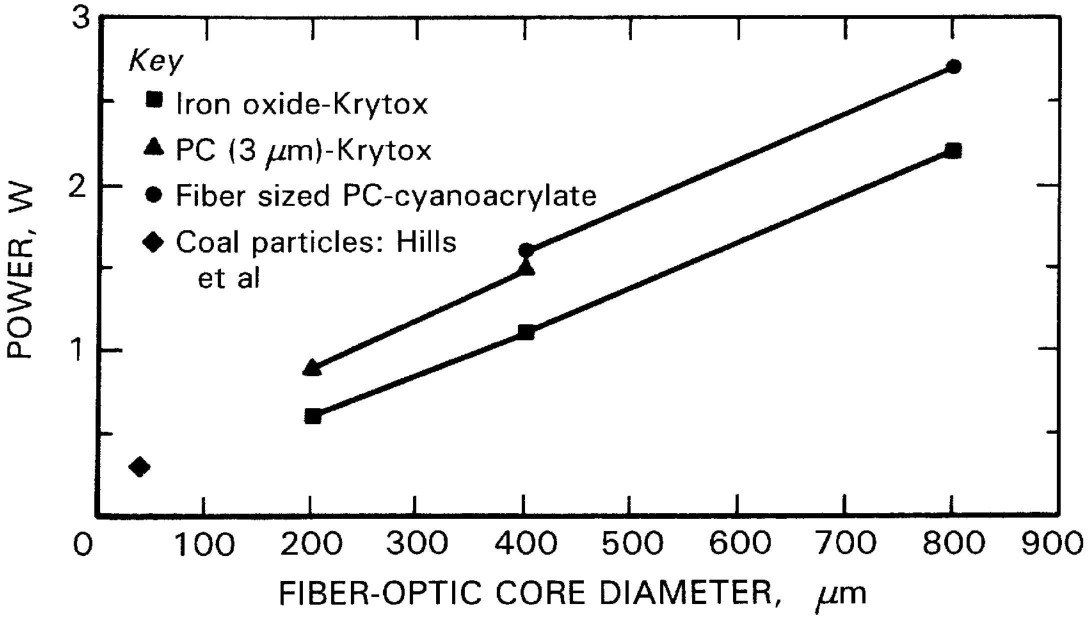

Figure 5. Minimum igniting power vs. Fiber-optic diameter, various targets.

Discussion

The high temperatures measured for targets on the fiber tips are on the order of temperatures required to ignite methane-air with electrically heated wires. For example, in previous research, the temperature of a 1-mm diameter nichrome wire had to be 1,220°C in order to ignite methane-air[11]. This is considerably higher than the 600 to 630°C autoignition temperature (AIT) for methane-air in a furnace[11,12]. Figure 5 shows that small, inert, strongly absorbing targets ignited methane-air more easily than similar sized coal particles under certain test conditions. These results are in agreement with trends observed by others[6, 13,14] . Progressively larger coal particles required higher incident powers to ignite methane-air, indicating heat of combustion contributions from the coal were negligible. Smaller targets require less power to reach high temperatures. Nonflammable, small targets may remain intact longer than comparably sized flammable targets, allowing them enough time to reach temperatures high enough to cause ignition. One important implication of these observations is the need to consider nonflammable targets as well as flammable targets in assessing potential ignition hazards.

Minimum igniting power densities for iron oxide-based targets calculated by dividing the igniting power by the surface area of the fiber core produces values of 1920, 870, and 440 W/cm^2 for 200, 400, and 800-μm fibers, respectively. Comparing these calculations with igniting powers of figure 5 shows that smaller core fibers required lower incident powers for ignition than larger core fibers, but larger power densities. Power limits appear appropriate for small beam diameters, while power density limits appear appropriate for larger diameter beams.

Igniting powers and power densities observed for methane-air are much higher than those observed for some other flammable atmospheres. For example, Welzel[6] reported ignition of a carbon disulfide-air atmosphere when a layer of black iron oxide on the tip of a 50 μm core optical fiber was heated by 50 mW from a Nd:YAG laser. Carleton[6] reported ignition of a carbon disulfide-air atmosphere when a 15 mm diameter, 0.934 W/cm^2, Argon ion laser beam was directed onto a layer of coal dust. Similar disparities are seen when comparing minimum spark ignition energies (MIE) and AITs of these two gases. MIEs are 0.015 and 0.3 mJ, and AITs are about 90° and 600 to 630°C for carbon disulfide and methane, respectively[11]. Carbon disulfide test data were used as a partial basis for optical power and power density safety recommendations by McGeehin[6]. Using carbon disulfide test data as a basis for safety recommendations would be overly conservative for methane-air atmospheres.

Several standards organizations are pursuing these and other issues pertaining to lasers used in hazardous (classified) locations. ISA - The International Society for Measurement and Control has established the SP12.21 Fiber Optics committee, concerned primarily with fiber optic systems routed through hazardous locations. The International Electrotechnical Commission, Technical Committee 31, has chartered a working group to develop safety recommendations for optical equipment used in hazardous locations (IEC TC 31\ WG 8). These findings may also be of interest for the ANSI Z136.1 standard. Flammability hazards for gases exist below power levels of 0.5 W (i.e. in class 3) and power densities of 10 W/cm^2, indicating existing guidelines in the standard related to fire hazards are not directly applicable.

Several other aspects of laser ignition hazards applicable to coal mines and other industries that use or process combustible dusts are being considered in the present NIOSH study. Coal dust suspensions in air are another explosion hazard besides methane-air. Larger accumulations of coal dust on surfaces represent a smoldering fire hazard. The next phases of the current study will examine laser ignition of coal dust suspensions using the 20-L ignitability/explosibility chamber, as well as smoldering ignition of coal dust layers.

Conclusions

Temperatures required to ignite methane by laser heated small particles were on the order of temperatures required by electrically heated wires, and much higher than the AIT. Igniting powers with iron oxide targets were proportional to fiber optic diameter over the range of 200 to 800 μm. Igniting powers and power densities observed for methane-air are significantly higher than those observed for some other flammable atmospheres.

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[b] The Pittsburgh Research Center was part of the U.S. Bureau of Mines until 1996, when it became the Pittsburgh Research Laboratory of the National Institute for Occupational Safety and Health.

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