Continuous wave laser ignition thresholds of coal dust clouds

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Laser-based instruments are used in areas where coal dust ignition presents a safety hazard. The National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory (NIOSH, PRL) is conducting a study to help determine when an optical beam may be considered a potential ignition source in underground coal mines or coal storage facilities. Researchers conducted experiments to determine threshold igniting powers for Pittsburgh seam bituminous coal dust clouds using an 803 nm continuous wave laser. For fine sized coal dust dispersed in air, concentrations ranging from 600 to 2000 g/m^3 were the most easily ignited. A heated layer of coal dust that deposited on the fiber tip during dispersion ignited the dust clouds. Minimum observed igniting powers for laser beams delivered by 200, 400, and 800 μm core fiber optic cables and directed into coal dust clouds were 2.0, 3.0, and 5.0 W, respectively. Threshold igniting power was proportional to beam diameter, and threshold igniting power density decreased with larger fiber diameters. Ignition delay times averaged 0.6 s and did not vary significantly with laser power under initially turbulent test conditions and with flammable targets. Comparisons are made with the results of other researchers.

Key words: laser ignition, coal dust ignition, nonbeam hazard

I. INTRODUCTION

Laser beams can present fire or explosion hazards. Explosion hazards can be divided into ignition of explosive materials (explosives) or flammable atmospheres. Most flammable atmospheres can be further subdivided into flammable gases, vapors, mists, or dusts mixed with air. Flammable concentrations of dust in air can form in places such as grain storage silos, processing plants, and underground coal mines. Laser-based instruments such as level monitors are being introduced into coal dust–air atmospheres.[1] Laser ignition of flammable dust-air mixtures has not been studied extensively. As a result, this important hazard category has not been addressed significantly in safety standards or recommended practices.[2,3] For example, the National Fire Protection Association (NFPA) Recommended Practice on Laser Fire Protection NFPA 115 addresses flammable gases, but does not address flammable dust–air atmospheres.[3]

Minimum requirements of ignition sources for causing dust cloud explosions are usually defined in terms of minimum (electrical) ignition energy (MIE) and minimum autoignition temperature (MAIT).[4–6] MAITs are measured in specially designed furnaces, where the volume inside the furnace is heated to a high temperature before a burst of air disperses the dust into the furnace.[5] Capacitive electrical spark discharges are typically used for determining dust cloud MIE.[6] Neither the MIE nor the MAIT directly relates to dust cloud ignitability by continuous wave (cw) lasers, which are characterized by beam power and power density.

The National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory (NIOSH, PRL) is conducting a study to determine when an optical beam may be considered a potential ignition source where coal is mined or processed. This is relevant not only to lasers already in use in underground mines and processing plants but also to possible future use of higher-power lasers. One phase of the study involved experiments to determine ignition thresholds of a continuous wave laser beam penetrating coal dust clouds. Ignition of coal dust in air[6–9] is a function of several variables, including composition, particle size and shape, and moisture content. Small, dry coal particles with a high volatile matter content generally ignite most easily. Very fine size, dried, Pittsburgh seam high volatile bituminous coal dust was used in this study. Laser beam spatial dimensions and duration also affect threshold igniting powers.[10,11] The spatial dimension of the beam was varied by using fiber optic cables with different core diameters. Beam durations can range from short pulses, to trains of pulses, to cw. Laser-induced spark ignition processes and thermal ignition processes can occur with very high peak power laser pulses.[10,12,13] Laser-induced photochemical ignition processes can occur with ultraviolet or shorter wavelengths as demonstrated in studies reviewed by Tran[12] and Ronney.[13] Ignition mechanisms using cw lasers with wavelengths in the visible or near infrared are primarily thermal processes.[10–13] Strongly absorbing particles facilitate the thermal ignition process.[14] A cw laser with a wavelength centered at 803 nm was used in this study. Since coal dust is highly absorbing over the visible to near-infrared spectral region (as discussed later in the paper in Sec. III), this 803 nm laser would be representative of thermal ignition hazards posed by a wide range of laser wavelengths. The goal of the work reported here was to find igniting power thresholds as function of coal

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dust concentration and laser beam diameters, under the above mentioned experimental conditions.

II. LITERATURE REVIEW

Proust conducted two recent studies of ignition of dust clouds by cw lasers.[15,16] A number of combustible dusts were studied, including lignite coal. The ignition chamber consisted of a vertical glass column, with the dust clouds generated by a fluidized bed of dust at the bottom of the column. The setup could maintain a dust cloud for up to several minutes. A fixture placed in the column held selected targets. A Nd–yttrium–aluminum–garnet laser beam was directed through a window onto the target. Proust's reported igniting laser powers for the dust cloud tests were the calculated powers reaching the target through the dust cloud, and took into account the loss due to attenuation by the dust cloud. The powers directed into the dust clouds at the window were significantly higher than the reported igniting powers at the target. Laser ignition experiments included:

(i) ignition of a layer of combustible dust with no cloud present;
(ii) ignition of a combustible dust cloud by heating a layer of the combustible dust;
(iii) ignition of a combustible dust cloud by heating a layer of inert particles; and
(iv) ignition of a dust cloud with no target present.

A partial list of Proust's findings include:

(i) combustible dust clouds ignite at the lowest powers when a target is present;
(ii) strongly absorbing, inert iron oxide targets generally produced lower dust cloud igniting laser powers than when using targets made of the flammable dust itself;
(iii) lignite coal layers with no dust cloud ignited (appearance of flame) at 4.07 W minimum laser power;
(iv) lignite dust clouds with an iron oxide layer target ignited at 2.5 W minimum laser power;
(v) a range of laser powers (2.5–4 W) was reported as the minimum igniting power for lignite dust clouds ignited with a lignite layer target;
(vi) ignition time delays at minimum igniting powers were on the order of seconds for selected dust clouds and tens of seconds for selected combustible dust layers;
(vii) beam diameters smaller than about 1 mm generally required higher laser powers to ignite selected dusts;
(viii) varying the flow velocity of selected dust clouds from 0 to 0.5 m/s did not affect minimum igniting powers; and
(ix) ignition delay of selected dust clouds increased with flow velocity.

For his experimental conditions, Proust observed that beam diameters smaller than 1 mm required higher laser powers to cause ignition of dust clouds. However, studies of laser ignition of flammable gases show minimum igniting powers typically occur with smaller beam diameters.[10,11,17,18] In studies of ignition of methane–air mixtures by laser-heated targets on optical fiber tips, igniting powers were lower for beam diameters below 1 mm, and were approximately proportional to the beam radius over the range of about 0.1–1 mm.[18,19] In the current study, optical fibers with core diameters ranging from 0.2 to 0.8 mm were used to deliver the beam into the dust cloud to determine if more conservative safe power recommendations are appropriate for beam diameters below 1 mm.

Proust's optical attenuation estimates for the intervening dust cloud were greater than 75% for the high dust concentrations that produced the lowest igniting powers. The PRL method of beam delivery by optical fibers (with the target on the end of the fiber) overcomes uncertainties in estimating the amount of power reaching a remote target through a dense dust cloud and contributing to ignition. The fiber optic method also simulates situations where dust can contact beam delivery optics.

Towle[20] contends a dust cloud is unlikely to be composed of particles of ideal size and absorptivity, which will obligingly remain stationary within the light beam. Dust clouds generally consist mostly of fine particles as larger particles are more difficult to entrain into a cloud and precipitate out of the cloud faster. Fine size coal dust ignites more easily than coarse dust.[6–9] A fine size coal dust was selected for the PRL ignition testing for these reasons. To allow the beam to interact freely with an initially turbulent dust cloud, PRL researchers did not attach targets to the fiber tip, and only the coal dust which deposited on the fiber was used as an absorbing target. This method of ignition testing simulates situations where a dust cloud is dispersed and contacts initially clean beam delivery optics.

III. EQUIPMENT AND MATERIALS

NIOSH PRL experiments were conducted in a 20 L test chamber (Fig. 1) designed for explosion testing of dusts, gases, and hybrid mixtures.[21] It can be used to measure lean and rich limits of flammability, explosion pressures, and rates of pressure rise, minimum ignition energies, minimum oxygen concentrations for flammability, and amounts of inhibitor necessary to prevent explosions. Sapphire windows at the top and sides allow viewing inside the chamber. The chamber can be used at initial pressures that are below, at, or above atmospheric as long as the maximum explosion pressure is less than 21 bar, which is the rated pressure of the chamber. For these tests, chamber instrumentation included a pressure transducer, and high-speed (200 frames/s) video camera. The video camera was positioned at the sapphire window view port. The 20 L chamber dust dispersion uniformity has been extensively studied using optical dust probes.[7,21]

The laser was a SDL model 8110-B Integrated Laser System (ILS). The laser diode wavelength was centered at 803 nm in the near infrared. The ILS output power is variable up to 10 W out of a 400 μm diam aperture. An SMA bulkhead adapter provided fiber optic coupling. The laser system also included a low-power visible (red) aiming laser, which proved useful in setting up the experiments.

Three sizes of fiber optic cable directed the laser beam into the 20 L chamber. The smallest optical fiber had an output core diameter of 200 μm. This was a Fiberguide An-

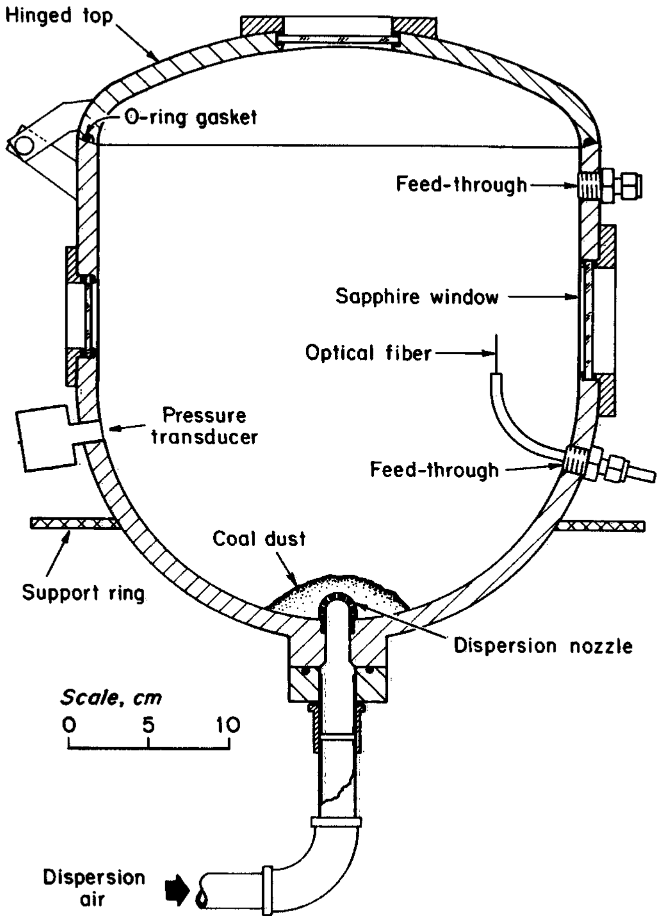

FIG. 1. 20 L chamber laser ignition test setup.

hydroguide plastic clad silica (PCS) 400–200 μm fiber–optic taper. The next size was a Spectran 400 μm core, 430 μm clad Hard Clad Silica cable, 0.4 numerical aperture (NA). The third cable was a Fiberguide Anhydroguide PCS, 800 μm core, 900 μm clad diameter, 0.4 NA cable.

A Scientec power meter (model D200PC) with attached calorimeter (model AC2501) measured the laser powers. The manufacturer documented the meter accuracy annually, traceable to National Institute of Standards and Technology standards. The accuracy was reported to be within ±4% over a 0.265–1.2 μm spectral range during the period covering these experiments.

The coal dust used for this ignitability research was Pittsburgh seam, high volatile bituminous coal mined from the NIOSH PRL Safety Research Coal Mine (SRCM). Pittsburgh coal from the SRCM has been used as a standard at PRL for many years under the former U.S. Bureau of Mines, and the coal's properties are well documented.[7] The volatility is 37% and the ash content is 6%. The Pittsburgh coal is representative of the highest volatile bituminous coals mined in the U.S. Fine size dust is more easily ignited[6–9] than coarse dust, and dust clouds generally consist mostly of finer particles, so a fine size of Pittsburgh coal was chosen for these tests. The Pittsburgh coal known as SRCM fines consists of float dust retrieved from the fines collector of a coal pulverizing process. SRCM fines particles have irregular shapes and different methods used to characterize the particle sizes produce slightly different results. The size of SRCM fines has been studied previously and is 100% less than 75 μm with a volume or mass median diameter of 11 μm, a volume mean diameter of 14 μm, and a surface mean diameter of 9 μm.[7] The moisture content of dust samples measured during the current study averaged 1.4% and ranged from 0.9% to 2.2%.

Labsphere Inc. measured the reflectance of a sample of Pittsburgh coal dust from 250 nm to 5 μm, in 50 nm increments. Absorptance was calculated as unity minus the reflectance. Pittsburgh coal absorptance at the 803 nm laser wavelength was about 87%. The absorptance was between 87% and 88% throughout the visible wavelengths, decreasing to about 75% at 2.5 μm in the infrared. The absorptance was greater than 87% from 2.75 to 3.85 μm, corresponding with a range of resonant vibration frequencies of several chemical bonds found in coal.[22] The highest absorptance was 95.5% at 3.4 μm. Since laser ignition is a thermal ignition process and since coal dust is highly absorbing over the visible to near-infrared spectral region, the 803 nm laser is representative of ignition hazards posed by a wide range of laser wavelengths in the visible to near-infrared spectral region. Ignition tests with the 803 nm laser may not be representative of coal dust clouds ignited by laser wavelengths from about 2.75 to 3.85 μm.

IV. IGNITABILITY TEST METHODS

An adequate length of fiber was pulled through a feed-through in the 20 L chamber (Fig. 1) to allow preparation of the fiber tip. A fiber optic cleaver (York model FBK 11C) provided a flat, perpendicular, optical surface for each ignition test with the 200 and 400 μm core fibers. The 800 μm core fiber required a manual cleaving tool. After each cleave, the red aiming laser was directed onto a flat surface. The cleave was determined to be acceptable when the aiming laser produced a circular spot on the surface. The power emanating from the cleaved end of the fiber was measured before each test. All igniting or nonigniting powers reported for the NIOSH experiments were those measured emanating from the cleaved end of the fiber prior to each test. Excess fiber was then pulled back through the feed-through until the fiber tip was placed about mid height in the chamber, and about 5 cm from the sapphire window for viewing with the high speed camera. The fiber tip was positioned vertically, pointing upwards, for most tests. In two series of tests, the fiber was placed in a similar position but pointed downwards. For the downward-pointing tests, the fiber was positioned through the feed-through above the sapphire window shown in Fig. 1. No attempt was made to place an artificial target on the optical fiber tip. The only target was the coal dust that was deposited on the tip during the dust dispersion process. This coal dust deposit was heated to incandescence by the laser and became the ignition source for the dust cloud.

The dust ignitability test methods were adapted from standard operating procedures developed under extensive previous explosibility research.[7,8,21] Each ignition test was conducted at a fixed laser power and fixed dust concentra-

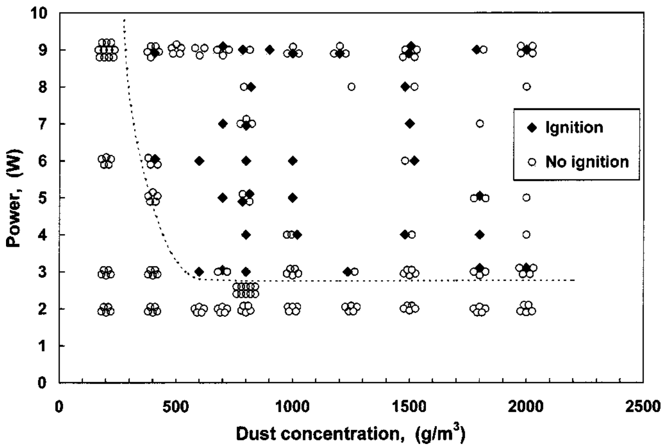

FIG. 2. Coal dust clouds ignited by a laser beam delivered by a 400 μm core diameter optical fiber.

tion. A preweighed sample of dust was placed over a dispersion nozzle in the bottom of the 20 L chamber (Fig. 1). The chamber was sealed and partially evacuated, and a pressurized burst (0.3 s) of dried and hydrocarbon-free air dispersed the dust into the laser beam. After dispersion, the chamber pressure was about 0.9–1.0 bar absolute for the test. The laser beam was turned on at least 30 s prior to dispersing the dust. The pressure transducer detected ignitions in conjunction with the high-speed video camera. The pressure signal was recorded using a personal computer (PC) based high-speed data acquisition system. The criterion for ignition was a pressure rise of at least 0.5 bar. There was a clear distinction between ignitions and nonignitions. Ignitions produced a pressure rise of greater than 4 bar, and nonignitions produced a pressure rise of less than 0.2 bar. In a few tests, some localized flames were observed with the high speed camera without producing a pressure rise of greater than 0.2 bar. These tests were not counted as ignitions.

The ignition delay time was taken as the time between the start of dispersion of the coal dust and a detectable explosion pressure rise at ignition. The delay times were measured from the PC data plots of the pressure and rate of pressure rise (dP/dt) traces versus time.

V. RESULTS

A. Igniting power versus dust–air concentration

Combustion can take place over a wide range of dust–air concentrations.[7,8] Several series of experiments were conducted using the 400 μm core diameter fiber (pointing upwards) over a range of dust concentrations and laser powers to determine how the minimum igniting power varies with concentration. When a test resulted in an ignition, another test was conducted at a lower power. This process was repeated at a particular concentration until the test resulted in a nonignition. At each dust concentration and laser power, the tests were repeated until there was an ignition or until there was no ignition in five tests, as shown in Fig. 2. This process was repeated for different dust–air concentrations ranging from 200 to 2000 g/m^3. It should be noted that the dust concentrations shown in Fig. 2 are the nominal concentrations (mass per chamber volume). For the highest dust concentrations and for long ignition delay times, the actual concentrations may have been less because some of the dust may have settled. In Fig. 2, the plotted powers and concentrations of some of the data points were adjusted slightly to avoid overlap of data points. No ignition was observed for a dust-air concentration of 200 g/m^3 at any power level. No ignition was observed for a laser power of 2 W at any dust concentration. Researchers determined 800 g/m^3 was a representative worst case dust concentration. Additional tests were then conducted using 2.5 W laser power at 800 g/m^3 to confirm the limiting laser igniting power. The boundary between laser powers that ignite a particular dust concentration and laser powers that do not ignite is shown as the dashed line in Fig. 2. There is a fairly large amount of data scatter within the ignitable region of Fig. 2. This shows the variability in the ignition process, which was probably dependent on how the dust was deposited on the optical fiber and heated to become the ignition source. Despite this variability, the regions of ignitability and nonignitability are discernable in Fig. 2. Ignition was never observed to the left of and below the dashed boundary curve. Within the ignitable region (above and to the right of the dashed curve) ignition is possible, but does not always occur.

B. Fiber orientation

The high speed video camera showed that ignition typically occurred at the tip of the upward-pointing fiber. The fiber tip glowed brightly prior to ignitions, presumably due to a layer of coal dust forming on the tip. The fiber was pointed downward in two series of tests to determine if the orientation of the fiber may affect the formation of a layer on the tip, and therefore influence dust cloud ignitability. In ten tests at 9 W laser power and 800 g/m^3 coal dust, no ignition was observed with the fiber pointing downward. Likewise, in ten tests at 5 W and 800 g/m^3, no ignition was observed with the fiber pointing downward. Only brief flashes were observed on the video of the downward pointing fiber tip, indicating that the coal dust did not adhere to the downward pointing fiber tip or had fallen off as it was heated. This was in contrast to sustained incandescence until ignition in the previous tests with the fiber pointed upwards. These tests showed the coal dust did not adhere well to the downward pointing fiber, and that formation of a layer on the fiber tip was key to igniting the dust cloud.

C. Igniting power versus beam diameter

Next, the relationship between laser igniting power and beam diameter was investigated in order to compare with similar data for laser ignition of methane.[18] The fiber was returned to its original upward pointing position. Beam diameter was varied by using three different fiber optic cables with core diameters of 200, 400, and 800 μm. The core diameter was taken as the beam diameter. From Fig. 2, 800 g/m^3 was determined to be a representative worst case dust concentration, and was used for all tests with the 200 and 800 μm core diameter fibers. Nonignitions were repeated ten times before ending each series of tests at a particular beam

TABLE I. Threshold laser igniting powers and calculated power densities for coal dust clouds as a function of laser beam diameter.

Beam diameter (μm)	Maximum nonigniting power, ten attempts (W)	Minimum igniting power (W)	Minimum igniting power density (W/mm^2)
200	1.5	2.0	64
400	2.5	3.0	24
800	4.5	5.0	10

TABLE II. Ignition delay time statistics for all ignitions.

Mean (s)	Sample variance (s^2)	Minimum (s)	Maximum (s)	Count (n)
0.62	0.0177	0.46	0.92	38

diameter. The results listed in Table I are plotted in Fig. 3. The data for the 400 μm fiber in Fig. 3 are taken from Fig. 2. The threshold igniting power density for each beam diameter was calculated by dividing the threshold igniting power by the surface area of the optical fiber core. The linear regression equation and trend line in Fig. 3 show the threshold igniting power was proportional to beam diameter.

D. Ignition delay time

Summary statistics and histogram for all ignition delay times with all three fibers are shown in Table II and Fig. 4. The data show some deviation from the normal distribution. The normal $Q-Q$ plot was also generated and compared to $Q-Q$ plots generated for the Weibull, Gamma, and lognormal distributions. Deviations of similar magnitude were found for these distributions as well. The $Q-Q$ plots were generated by SPSS for Windows statistical software package, version 10, with distribution parameters estimated from the data.[23]

VI. DISCUSSION

A. Ignition delay times

Ignition delay times for the 400 μm fiber at low laser igniting powers (3–4 W) were compared to delay times at a high igniting power (9 W) to see if delay times varied measurably with power. In general, higher laser powers would be expected to have shorter ignition delay times, as observed with flammable gases.[14,18] Ignition delay times from the 9 W tests were taken as a sample from a population with mean μ_1 and variance σ_1^2. Likewise, delay times from the power limiting 3 and 4 W tests were taken as a sample from another population with mean μ_2 and variance σ_2^2. Summary statistics for the two samples are listed in Table III. The two populations are independent and were assumed to be approximately normally distributed based on the parent distribution and reducing the power variability. The null hypothesis was $\mu_1 = \mu_2$, and the alternative hypothesis was $\mu_1 < \mu_2$. The hypothesis that $\mu_1 > \mu_2$ was not considered as ignition delay times should not increase with increasing power. A test of equality of variances suggested equal variances could be assumed.

For the test, the alternative hypothesis would be accepted if

$$T < -t(\alpha, n_1 + n_2 - 2), \tag{1}$$

where T is the t-test statistic with pooled sample variances. The alternative hypothesis was rejected at the $\alpha = 0.1$ significance level. Given the assumptions made, the statistical analysis shows that ignition delay times did not increase measurably with decreasing power, and the deviations from normality in the overall ignition delay time sample were not attributable to variations in laser power.

In previous research on the laser ignition of methane, the delay time was shorter at higher laser powers for a 400 μm fiber.[18] It is reasonable that the time to heat the target to the ignition temperature would be shorter at higher laser powers. Since no such effect was observed for the dust cloud ignition delay times, different processes must have been dominant. For the dust cloud ignitions, the time for dispersion of the dust and for the accumulation of a target layer on the end of the optical fiber probably dominated over the time to heat the target. The times for dust dispersion and target formation

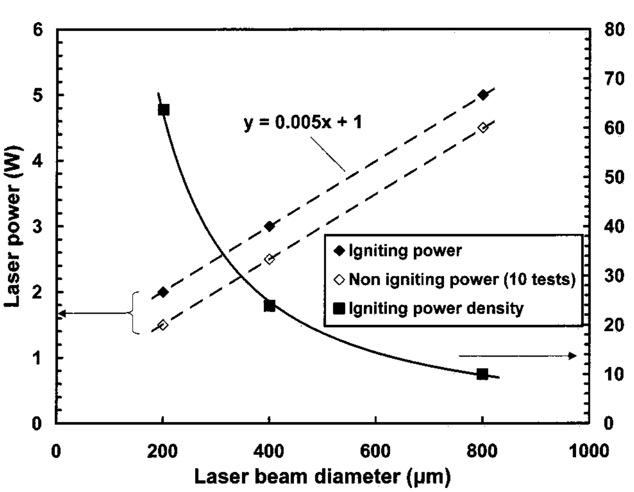

FIG. 3. Laser igniting power and power density as a function of beam diameter, for Pittsburgh coal dust clouds ignited by laser heating of dust on optical fiber tips.

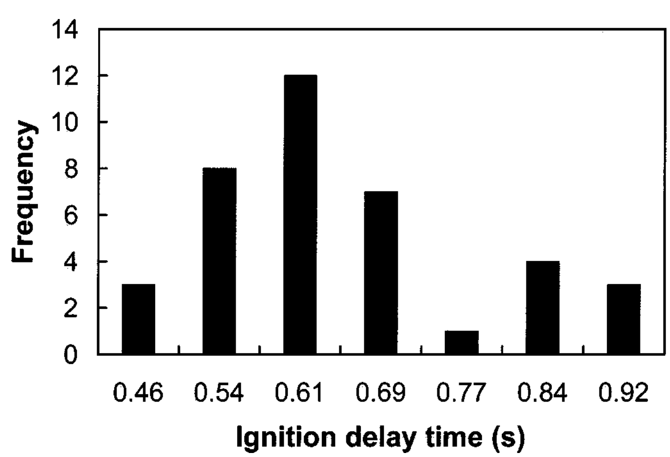

FIG. 4. Histogram of delay times for all ignitions.

TABLE III. Statistics for two independent ignition delay time samples.

	9 W tests	3 and 4 W tests
Mean ignition delay time (s)	0.662	0.668
Sample variance (s^2)	0.0232	0.0169
Standard deviation (s)	0.152	0.130
Count	$n_1 = 10$	$n_2 = 10$

TABLE IV. Coal dust and threshold ignition characteristics.

	Coal rank	Particle diameter (μm)	AIT (°C)	Absorptance (%)	Beam diameter (mm)	Igniting power (W)
Proust[a]	lignite	17	500	60	2–4	2.5–4
This study	bituminous	9	610	87	0.2	2

[a]See Refs. 15 and 16.

would be independent of laser power. The dust was dispersed throughout the chamber by the 0.3 s air burst. However, the dust concentration was probably not uniform on a scale less than 1 mm, based on previous observations using an optical dust probe.[21] Therefore, there would be variability in the depositing of the coal dust onto the end of the fiber to form a target. In addition, the video for some tests showed incandescence at the fiber tip followed by a decrease in incandescence, and then an increase in incandescence until ignition occurred. The initial target apparently burned off of the fiber tip followed by new target formation leading to ignition. The initial turbulence appeared to affect the target forming on the fiber tip in all tests, based on incandescence intensity fluctuations observed at the fiber tip. Target formation processes likely obscured a relationship between laser power and igniting delay times.

B. Threshold igniting powers

ASTM Standard Test Method E 2019-99 recommends procedures for determining the minimum spark ignition energy of a dust–air mixture.[6] Although the standard does not apply directly to laser ignition sources, it does provide some guidance on a reasonable number of tests that should be conducted. The standard calls for producing ten nonignitions at a given energy level and dust concentration, and at least 30 nonignitions total over a range of concentrations, before a given energy level may be considered insufficient to ignite the dust. The minimum laser igniting power was essentially constant for dust concentrations above 600 g/m^3 in tests using the 400 μm fiber (Fig. 2). Fifty nonignitions were recorded at 2–2.5 W over this range. Therefore, 2 W through the 400 μm fiber may be considered as nonigniting under these test conditions, based on the ASTM recommendations for minimum number of nonignition tests.

In comparison, 2 W readily ignited the dust cloud when delivered by the 200 μm fiber. Also, the calculated power density of 2 W through the 400 μm fiber (16 W/mm^2) exceeds the igniting power density (10 W/mm^2) for the larger 800 μm fiber. The values for the intermediate beam diameter exceeded both the minimum igniting power of the smaller beam and the minimum igniting power density of the larger beam without causing ignition.

The linear regression equation for minimum igniting power as a function of beam diameter (Fig. 3) suggests that smaller beam diameters than those tested will produce even lower igniting powers. Further research using smaller beam diameters is warranted to find the absolute limiting igniting power (independent of beam size). A linear relationship between threshold igniting power and beam diameter appears to hold over a range of beam diameters below 1 mm. A similar relationship was observed for methane–air mixtures.[18,19]

An inverse relationship between igniting power and igniting power density as a function of beam diameter as shown in Fig. 3 has several implications for preventing dust cloud ignition. For small diameter cw beams, limiting the beam power to a value below the minimum igniting power can prevent ignitions without considering the beam power density. For large diameter cw beams, limiting the beam power density below the minimum igniting power density can prevent ignitions without considering the beam power. Limiting a cw beam of any diameter below either the lowest minimum igniting power or the lowest minimum igniting power density of all beam diameters can prevent ignitions. cw beams of intermediate dimensions can exceed both the minimum igniting power of smaller diameters and the minimum igniting power density of larger diameters without causing ignition, provided the beam power and power density remain conservatively below their respective ignition curves such as shown in Fig. 3. The observation that power was the limiting coal dust cloud ignition criteria for the smaller diameter cw beams, whereas power density was the limiting coal dust cloud ignition criteria for the larger diameter cw beams, parallels observations made in studies of flammable gas ignition by cw lasers.[24,25]

Proust[16] observed that target diameters below about 1 mm generally required higher powers for ignition. This is in contrast to results of this study where significantly smaller beam diameters were more hazardous. The difference is probably due to the different experimental techniques. Proust observed that smaller beam diameters drilled a hole into his targets, possibly interfering with the ignition process and rendering ignition less likely. Other differences in experimental techniques are discussed below.

The coal and laser properties used in this study and Proust's studies[15,16] are compared in Table IV. The mean particle diameters listed are surface weighted (also known as D_{32} or Sauter mean diameters). The autoignition temperatures (AITs) were obtained using the Godbert–Greenwald apparatus.[16,26,27] All other factors being equal, the lower AIT lignite would be expected to ignite at lower laser powers than the bituminous coal. Proust measured the relative absorptance of lignite with respect to that of Fe_3O_4. The absorptance of the bituminous coal at the 803 nm laser wavelength was calculated from the reflectance data measured by Labsphere, Inc. The most easily ignitable beam diameters listed differ by a factor of ten. The listed igniting powers are for igniting a coal dust cloud with a coal dust target. In

Proust's dust cloud ignition study, the input laser beam was separated from the target by the dust cloud. His reported igniting laser powers were the calculated powers reaching the target through the dust cloud, based on the attenuation by the dust cloud. The powers reported for the NIOSH experiments were measured out of the cleaved fiber tip prior to each test, and the target consisted of coal particles depositing on the fiber tip during the test. Because of the different coals and different experimental techniques used in the two studies, it is difficult to make a direct comparison of the data. The threshold igniting powers in both studies are similar although there is a significant difference between the most easily igniting beam diameters.

Heat of combustion contributions from the target layer appeared to have little impact on dust cloud ignitability. For example, in the NIOSH research, powers that produced ignitions on the 200 μm fiber tip did not produce ignitions on the 400 and 800 μm tips, even though there was presumably more coal present (Fig. 3). The coal was observed to glow brightly and occasional localized flames were observed on the 400 and 800 μm tips for the nonigniting experiments shown in Fig. 3, confirming pyrolysis. Proust observed that strongly absorbing, inert, iron oxide targets generally produced lower igniting powers than reactive targets. These arguments point to the laser beam as the primary source of heat in these studies. One implication is that inert targets (such as iron oxide placed on the optical fiber tip prior to the dust dispersion) that absorb the laser energy well and do not dissipate heat through vaporization, may produce lower igniting powers than those observed in this study. However, the experiments conducted here are more representative of situations where the flammable dust itself is dispersed onto initially clean beam optics.

In the NIOSH laser ignition experiments, no ignition of the Pittsburgh bituminous coal fines was observed at 200 g/m^3 (Fig. 2) for any laser power tested. However, the reported minimum explosible concentration (MEC) of the Pittsburgh coal fines is 85 g/m^3, using a strong ignition source.[7] There are two likely explanations for the higher observed MEC for the laser ignitions. Leaner mixtures generally require stronger ignition sources to ignite.[28] For the laser experiments, the maximum ignition energy was less than 10 J (9 W over 1 s or less). In comparison, the 85 g/m^3 MEC was measured with a 2500 J chemical ignitor, and a 500 J chemical ignitor produced an MEC of 120 g/m^3 for the Pittsburgh coal fines. A more powerful laser may therefore produce ignitions at lower concentrations than reported here. Another possible reason for the higher observed MEC may be related to target formation on the fiber tip. Lower dust concentrations may cover the fiber tip less efficiently, preventing formation of an adequate target for the laser.

Coal dust cloud ignition and methane-air ignition criteria are compared in Table V. The laser igniting powers listed for the coal dust clouds and methane–air mixtures[18] were obtained under similar test conditions, using a 200 μm diam core optical fiber. For the methane, the fiber was coated with a layer of coal dust before the test; and for the coal cloud, the dust was deposited on the fiber during the test. The AIT values listed were measured in various furnaces, including the 0.3 L Godbert–Greenwald furnace,[27] the PRL 1.2 L furnace,[29,30] and a British Gas Corp. 0.8 L stainless steel vessel.[31] The MIE values listed were obtained using electrical sparks.[26,27] The laser igniting powers differ by only a factor of 2.2, while the MIEs of the two materials differ by more than 2 orders of magnitude. The laser igniting powers correlate better with the AITs than with the MIEs. The best correlation may be with a combination of AIT and MIE data, where the AIT relates to the laser thermal ignition process while the MIE relates to the small laser ignition volume.

TABLE V. Coal dust cloud and methane–air ignition characteristics.

	Laser igniting power, 200 μm fiber (W)	AIT (°C)	MIE (mJ)
Coal dust cloud	2.0	560–610[b,c,d]	60[c]
Methane	0.9[a]	600–630[b,e,f]	0.3[b]

[a]See Ref. 18.
[b]See Ref. 26.
[c]See Ref. 27.
[d]See Ref. 30.
[e]See Ref. 29.
[f]See Ref. 31.

In studies of pulsed laser ignition of flammable gases for wavelengths in the visible and near infrared, minimum laser energies needed to cause ignition were generally higher than MIEs produced using electrical sparks.[10,12,13,32–35] In studies[10] where the laser pulse duration was varied from several hundred milliseconds to below 1 ms, the pulse energy needed to cause ignition decreased as the pulse duration decreased. Minimum igniting laser energies occurred with pulse durations of about 70 μs, and were about a factor of 2 higher than MIEs obtained with electrical sparks.[10,32] For short laser pulse durations (<100 μs) and small beam diameters (<100 μm), the energy became the limiting ignition criteria over power or power density.[10,25] That is, limiting the beam pulse energy below a certain energy prevented flammable gas ignition even though the peak beam power and peak beam power density were significantly higher than the minimum igniting power and minimum igniting power density, respectively.

Although a cw laser was used for the experiments described here, ignition energies can be estimated from the igniting power and delay times. The laser MIE was about 1.5 J (3.0 W over a 0.53 s ignition delay time). The MIE may have been lower than 1.5 J since the delay time included the time for the dust to disperse and form a target on the fiber tip. This calculated laser MIE is much higher than the coal dust cloud MIE obtained using electrical sparks listed in Table V. As summarized in the preceding paragraph, gas ignition studies suggest small diameter beams with shorter pulse durations and higher peak powers may produce lower igniting energies in coal dust clouds than observed in this study. Higher powers than 3 W did not produce lower calculated ignition energies, probably another consequence of target formation processes dominating the ignition timing.

VII. CONCLUSIONS

Minimum observed igniting powers for laser beams delivered by 200, 400, and 800 μm core fiber optic cables and directed into Pittsburgh bituminous coal dust–air suspensions were 2.0, 3.0, and 5.0 W, respectively. These results can be considered conservative for bituminous coal dust clouds with larger particle sizes, higher moisture content, and lower volatile matter content under otherwise similar test conditions used in this study.

A laser-heated target ignited the dust clouds at lower powers than a laser beam with no target (fiber pointing downward), in agreement with Proust's observation.

Coal dust–air concentrations ranging from 600 to 2000 g/m^3 were the most easily ignited (2000 g/m^3 was the highest concentration tested). Minimum igniting powers over this range were similar.

Threshold igniting power was proportional to beam diameter for beam diameters from 200 to 800 μm. The linear regression model indicates igniting powers will be lower at smaller beam diameters.

There was an inverse relationship between minimum igniting power and minimum igniting power density as a function of beam diameter. That is, the minimum igniting laser power decreases with smaller beam diameter, while the minimum igniting power density (power per beam area) decreases with larger beam diameter.

Ignition delay times did not vary significantly with laser power for flammable targets forming under initially turbulent test conditions.

Heat-of-combustion contributions from combustible target layers irradiated by small beam diameters appeared to have little effect on igniting dust clouds, in agreement with Proust's observation.

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