Ignition Tests With a Fiber-Optic Powered Instrument

Thomas H. Dubaniewicz, Jr.
Electrical Engineer
Electrical and Electronic
Systems,
Pittsburgh Research Center
U.S. Bureau of Mines
Pittsburgh, PA 15236

Kenneth L. Cashdollar
Supervisory Research
Physicist
Gregory M. Green
Physical Science Technician
Fires and Explosions and
Explosives,
Pittsburgh Research Center
U.S. Bureau of Mines
Pittsburgh, PA 15236

Gerald R. Cucci
President
NT International, Inc.
Minneapolis, MN 55421

KEYWORDS

Fiber Optics
Lasers
Hazardous Locations

ABSTRACT

New types of industrial instruments use fiber-coupled laser energy to power remote sensors. Fiber-optic based instruments are useful in classified (hazardous) locations found in many industrial plants because the fiber provides a natural barrier against accidental electrical discharge into potentially explosive atmospheres. However, current safety standards do not cover the use of laser-powered fiber-optic instruments in potentially explosive environments such as found in coal mines. The U.S. Bureau of Mines began an investigation of laser-powered fiber-optic instruments in explosive atmospheres in support of the standards-making process. A commercial fiber-optic interface system, modified to simulate several worst-case operating conditions, ignited explosive hydrogen-air mixtures. Worst-case simulations consisted of disabling a safety shutoff feature, operating the laser at significantly higher powers than intended for normal operations, and cleaving fiber-optic connections to direct laser energy onto selected absorptive materials. At the highest power level available, the fiber-optic interface system did not ignite selected methane-air mixtures. The obtained data should prove useful in establishing appropriate safety standards.

INTRODUCTION

In the past 15 years, fiber optics has become the medium of choice in telephony and data communications. More recently, fiber optics has become the wiring medium of choice in high performance industrial applications (1). Industrial fiber-optic systems are well suited to the underground mining environment where long cable runs and high-voltage distribution systems and machinery present safety and reliability concerns. Optical fiber is virtually immune to electromagnetic interference from sources such as large motors and power lines, and minimizes signal loss and variable ground potential problems associated with long cable runs. Electrical isolation provided by fiber-optic systems can help prevent accidental electrocutions where miners must work in close proximity to power lines often in wet conditions.

New instruments can take electrical isolation one step further by combining both power and communications over fiber-optic cable (2,3). In addition to the benefits already mentioned, these systems can provide a natural barrier against accidental electrical discharge into potentially explosive environments such as found in coal mines. Therefore, an all fiber-optic interface would not be subject to some of the special requirements for wire installations in explosive environments.

However, under certain circumstances, the intense optical energy characteristic of fiber-optic-powered instruments raises concern about current usage in potentially explosive atmospheres (4). Currently, there are no standards or guidelines for the safe use of fiber-optic-powered systems in hazardous (classified) locations in the United States. The International Society for Measurement and Control (ISA) has formed the SP12.21 Fiber Optics subcommittee to establish such standards. In an effort to support the standards-making progress, the U.S. Bureau of Mines (USBM) began an investigation into potential hazards of laser-coupled fiber-optic instruments that may be intended for use in hazardous (classified) environments.

Active members of the SP12.21 subcommittee made several suggestions in regard to the USBM investigation. First, testing should be directed toward materials defined in the hazardous materials classification scheme used in the United States. Subcommittee members also felt that the USBM study should encompass practical aspects of fiber-optic usage in the field. One suggestion was to conduct tests using large-diameter fiber. Large-diameter fibers are popular in industrial applications where potentially explosive atmospheres are most likely to be encountered. For instance, a survey of fiber-optic cable manufacturers identified one type of cable that had been rated by the Mine Safety and Health Administration (MSHA) that was a large diameter fiber (200 µm core diameter). Another suggestion was to include commercially available fiber-optic systems in planned experiments. In this regard, the subcommittee helped to locate a vendor whose product contained a fiber-coupled laser source. The vendor, NT International,[1] entered into a Cooperative Research and Development Agreement (CRADA) with the USBM to test its recently introduced fiber-optic-powered process control transmitter in potentially explosive environments.

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[1] Reference to products of specific manufacturers is for identification purposes only and does not imply endorsement by the USBM.

LITERATURE REVIEW

Most of the research to date involving the safety of fiber-optic systems in potentially explosive atmospheres has been conducted in Europe (including the United Kingdom (UK)) and Australia (5-16). The reported ignition mechanism that requires the least amount of optical energy occurs when absorbing material converts the optical energy to thermal energy. For example, a particle on the end of a broken fiber-optic cable could be heated by laser energy. The most comprehensive study to date was recently completed by a collaboration of researchers from the UK, France, and Germany. This effort began in December 1990, and concluded at the end of May 1994. The final recommendation of this effort, contained in a European Commission (EC) report (5), is as follows:

> "It is concluded broadly, that continuous wave devices radiating in the visible and near visible are not hazardous provided either
>
> a) the radiated power is less than 35 mW, or
> b) the peak radiation flux is less than 5 mW/mm^2.
>
> For pulsed or intermittent light sources, specific atmospheres, sources of area smaller than 0.001 mm^2 and where sensitive materials are present, different values of power and flux may be appropriate."

This recommendation is based on the lowest observed ignition levels for carbon disulfide-air mixtures, plus an additional safety factor of about 2. The recommendation was passed along to the SP12.21 subcommittee for consideration as a U.S. standard. However, the subcommittee is hesitant to support the recommendation as a standard for several reasons. One important reason is the use of carbon disulfide as the model explosive gas. Carbon disulfide is not represented in the hazardous materials classifications established in the United States because it requires safeguards beyond those required for any of the atmospheric group classifications (17). The subcommittee would prefer that safety standards conform with established classification schemes. For this reason, explosive mixtures of hydrogen in air and methane in air were used in the USBM study. In the United States, hydrogen is classified as a Class I group B hazardous material, and methane is classified as a Class I group D hazardous material.

FLAMMABILITY AND IGNITIBILITY OF HYDROGEN (H_2), METHANE (CH_4), AND CARBON DISULFIDE (CS_2) IN AIR

Hydrogen in air is flammable over the range of 4 to 75% H_2 and the stoichiometric value is 29.5% H_2 (18-20). Methane in air is flammable over the range of 5 to 15% CH_4 and the stoichiometric value is 9.4% CH_4 (19-20). Carbon disulfide in air is flammable over the range of 1.3 to 50% CS_2 and the stoichiometric value is 6.5% CS_2. Near-stoichiometric mixtures of H_2-air, CH_4-air, or CS_2-air are very easy to ignite with an electric spark. The minimum spark ignition energies (20) are: 0.017 mJ for H_2-air, 0.30 mJ for CH_4-air, and 0.015 mJ for CS_2. The minimum spark energies are found at concentrations slightly less than stoichiometric (20-21). The autoignition temperature of H_2-air is 500 to 520 °C and the autoignition temperature of CH_4-air is 600 to 630 °C (20, 22-23). The autoignition temperature of CS_2-air is 100 °C, much lower than for H_2 or CH_4. The autoignition temperatures of H_2 and CH_4 are relatively independent of gas concentration from somewhat less than stoichiometric to stoichiometric (22). The autoignition temperatures were measured in closed volume chambers (20, 22-23) with all walls uniformly heated so that there was a large area of contact with the gas and the entire gas volume was heated to the test temperature. The minimum ignition temperatures are much higher if the heated area is much smaller and only part of the gas volume is heated. For example, the ignition temperature of H_2-air was 750 °C and that for CH_4-air was 1,220 °C when they were heated by a 1-mm diameter nichrome wire (20). These latter values may be more appropriate when considering a flammable gas mixture that is ignited by a small particle heated by a laser.

TEST SETUP

NT International modified the fiber-optic powered transmitter in two ways to simulate worst-case operating conditions. First, the laser output was altered from its normal pulse mode operation (which also disabled an automatic shutoff feature) to continuous wave operation. Second, an output power controller was added to the transmitter. The laser diode within the transmitter is normally operated at a fraction of its rated output power to extend the life of the diode. The controller allowed researchers to operate the laser diode above 150 mW, the peak optical power designed for the unmodified instrument. Maximum power output of the modified NT transmitter with 200-μm fiber attached, was about 500 mW. The laser wavelength was approximately 810 nm.

Ignition experiments were conducted in a 20-liter test chamber (Figure 1) designed for explosion testing of dusts, gases, and their mixtures (24). 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. 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, a flame sensor, and a high-speed video camera. The fiber-optic cable was inserted into the chamber through a feed-through in the wall.

Optical energy from the fiber-coupled transmitter was converted to thermal energy by placing various particles on the output end of the fiber. An MSHA-rated fiber-optic cable with a 200-μm core diameter and a 230-μm-cladding-diameter fiber was used for all NT transmitter tests. A fiber optic cleaver (York model FBK 11C) provided a flat, perpendicular, optical surface for each test. The output power from the cleaved end of the fiber was measured using a laser power meter (Scientec Model D200PC) with attached calorimeter (Scientec Model AC2501) prior to each test. The laser was then turned off and a particle attached to the fiber end. First attempts using static electricity to attach the particle were unsuccessful. Better results were obtained by dipping the fiber end into optical coupling gel (Cargille code 608), then wiping off the residue until only a thin film remained. The particle was carefully attached to the cleaved fiber end while viewed under a microscope. Three different types of particles were used in the experiments: coal, aluminum, and limestone rock dust. Coal and rock dust represent material likely to be encountered in a coal mine. Aluminum particles were included because of their incendiary characteristics. Experiments included various particle sizes ranging from 90 to 600 μm diameters.

The chamber was sealed and evacuated after inserting the prepared fiber end. The explosive gas-air mixture was then introduced into the chamber by partial pressures. The flammability of the explosive gas-air mixture was periodically verified using electric matches when experiments resulted in nonignitions. The pressure transducer and photo diode flame sensor detected ignitions in conjunction with the high-speed video camera. A personal computer-based high-speed data acquisition system recorded the pressure and flame sensor data along with an electrical signal triggered when the laser was switched on.

RESULTS

Results of tests using the modified NT transmitter are shown in Figures 2 and 3. The minimum power that produced an ignition was 250 mW. This occurred with a 150- to 212-μm diameter coal particle in a 15% H_2-air mixture. The 15% H_2-air mixture also produced ignitions with inert rock dust particles at approximately 500 mW. Both the coal and the rock dust particles would be heated to a high temperature by the laser energy. An additional amount of energy is produced by the combustion reaction of the coal with oxygen in air. The combustion reaction would contribute to the coal particle igniting the flammable gas mixture at a lower laser power than that for the inert rock dust particle. No ignitions were observed in 10% CH_4-air mixtures with coal or aluminum particles using up to approximately 500 mW.

DISCUSSION

Although this study represents a small fraction of the effort required to adequately study this phenomenon, some general observations can be made. Experiments were based in large part on customer input from a standards-making subcommittee of the ISA. The CRADA effort represents the first known tests of a commercial system employing intense fiber-coupled laser energy intended for use in potentially explosive atmospheres. The NT transmitter, modified to simulate several worst case conditions, ignited an explosive mixture of hydrogen (15% H_2-air) at a minimum power of 250 mW. The NT transmitter produced no ignitions in explosive methane mixtures (10% CH_4-air). Observed ignitions verify the need for safety standards for commercial fiber-optic instruments intended for use in hazardous (classified) locations.

Minimum igniting power levels found in this study are significantly higher than the recommended safe power in reference 4 because of differences in test conditions and procedures. The use of different atmospheres such as carbon disulfide, methane, or hydrogen; absorbers such as rock dust, coal, or aluminum; and many other factors significantly affect ignition levels. A standard based on carbon disulfide testing would not be representative of conditions found in coal mines. The challenge for the various international standard-making bodies is to arrive at a consensus on testing procedures that provide a conservative level of safety without being unreasonably restrictive.

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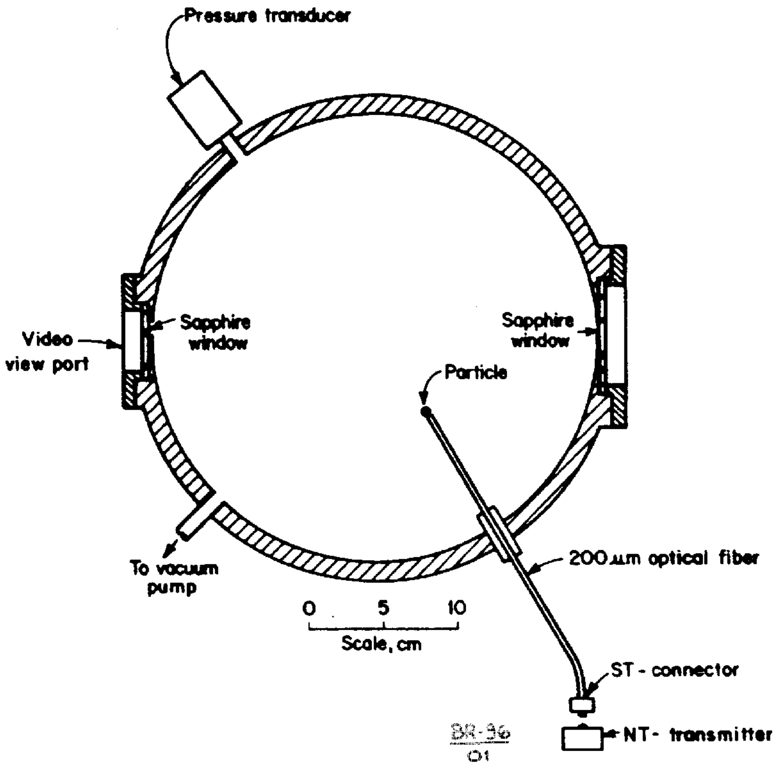

Figure 1. Horizontal cross section of 20-L test chamber.

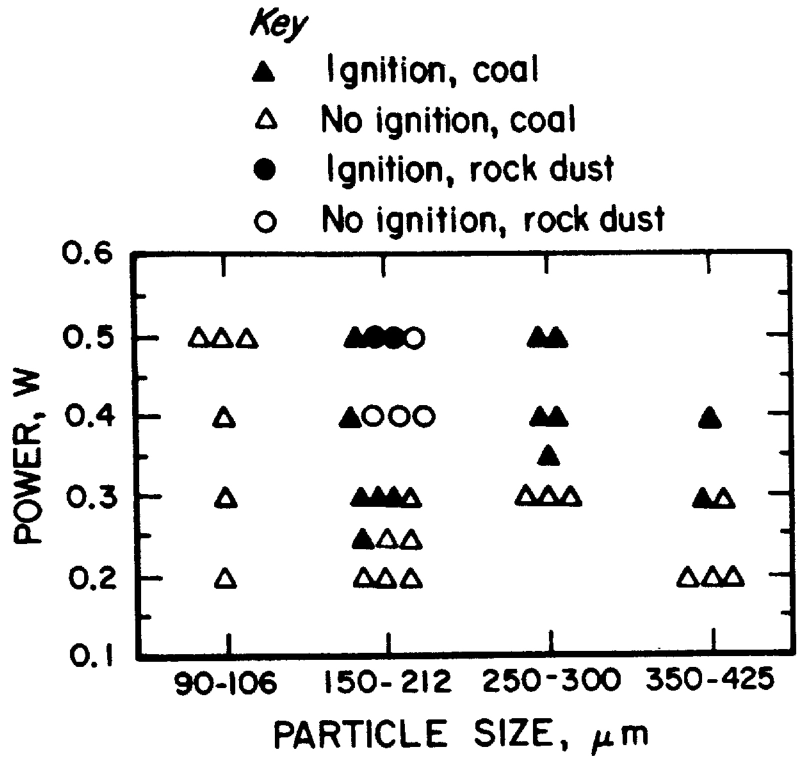

Figure 2. Data for ignition tests in 15% H_2 in air, using the NT laser with 200 μm core fiber, using coal or rock dust particles of various sizes.

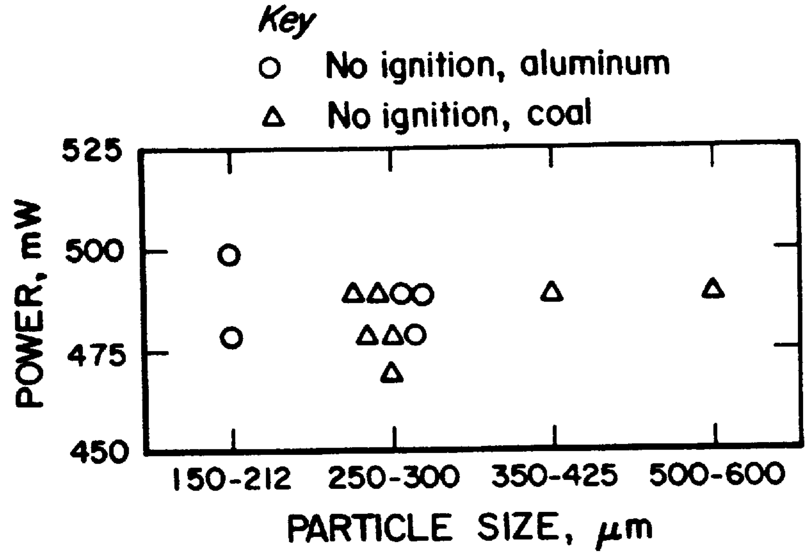

Figure 3. Data for ignition tests in 10% CH_4 in air, using the NT laser with 200 μm core fiber, using coal or aluminum particles of various sizes.