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IGNITION OF HMX USING LOW ENERGY LASER DIODES

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Abstract

The sensitivity of blends of cyclotetramethylenetetranitramine (HMX) with carbon black and graphite to laser diode ignition was investigated. Using a 100-μm optical fiber, a blend of 15,700 cm^2/g HMX with 3% carbon black by weight was the most sensitive material tested, with a threshold of 72 mW. Pure, or undoped, HMX could not be ignited using 10 ms laser diode pulses with power levels up to 880 mW. In general, the HMX/carbon black blends were more sensitive than the HMX/graphite blends. HMX specific surface area also had a significant effect on sensitivity. Doubling the spot size increased the ignition threshold by a factor of approximately 2.7. Increasing the pulse width from 10 to 100 ms did not significantly reduce the laser diode power required for ignition. A photoacoustic spectrometer was used to compare the absorption characteristics of the HMX blends. The absorption spectra obtained correlated well with the sensitivity test data.

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Introduction

When sufficiently confined, the explosive cyclotetramethylenetetranitramine (HMX) can be ignited by a low energy thermal source, such as a hot wire or foil bridge, and will undergo a rapid deflagration [1]. The effects of parameters such as bridge geometry, powder density, and specific surface area on the hot wire ignition characteristics of HMX have been investigated in previous studies [2,3].

Ongoing studies relative to the laser diode ignition of explosives and pyrotechnics warranted a study to determine the feasibility of using laser diodes to ignite HMX. Laser-ignited components offer a number of advantages over conventional hot wire ignited electro-explosive devices (EEDs). Foremost among these advantages is an enhancement in safety achieved by electrical isolation of the explosive or pyrotechnic material from the firing unit.

Accidental ignition resulting from either electrostatic discharge (ESD) or stray currents induced by radio frequency (RF) sources is minimized with laser ignition technology. In addition, resistance-after-fire (RAF) variability and 1 A/1 W no-fire requirements are eliminated. Although bridgewire corrosion is no longer an issue with laser-ignited devices, compatibility studies will need to be performed to ensure there is no degradation of critical optical interfaces.

High brightness laser diodes coupled to small core optical fibers have been used to ignite a number of explosive and pyrotechnic powders, including $B/KClO_4$, $Ti/KClO_4$, $TiH_{1.65}/KClO_4$, 2-(5-cyanotetrazolato) pentaamine cobalt (III) perchlorate (CP), and $B/CaCrO_4/Ti/KClO_4$ (BCTK) [4-6]. It has also been determined that the threshold for laser diode ignition of CP can be lowered significantly by doping the powder with small amounts of either graphite or carbon black to increase the absorptivity of the powder.

The auto-ignition temperature of HMX is relatively low, approximately 250°C [7]. Thus, a large bridgewire is needed to obtain a 1 A/1 W no-fire level. The large bridgewire will, unfortunately, result in a high all-fire current. The low auto-ignition temperature, however, makes HMX attractive for laser ignition using low energy laser diodes. Thus, laser ignition of HMX appears to be feasible given adequate confinement of the powder and sufficient absorptivity at the laser diode wavelength.

<u>Approach</u>

The test device for the HMX laser diode ignition experiments is shown in Figure 1. This device was based on the design of an existing HMX hot wire device. It is well established that the hot wire version of this device provides sufficient confinement for the HMX; therefore, there was no reason to believe that the same would not hold true for the laser-ignited device.

In a conventional hot wire device, an electrical insulator is required to isolate the electrical leads, or pins, from the case. This insulator is typically a glass or ceramic material. There is no need for such electrical isolation with the laser-ignited device, and the glass insulator has

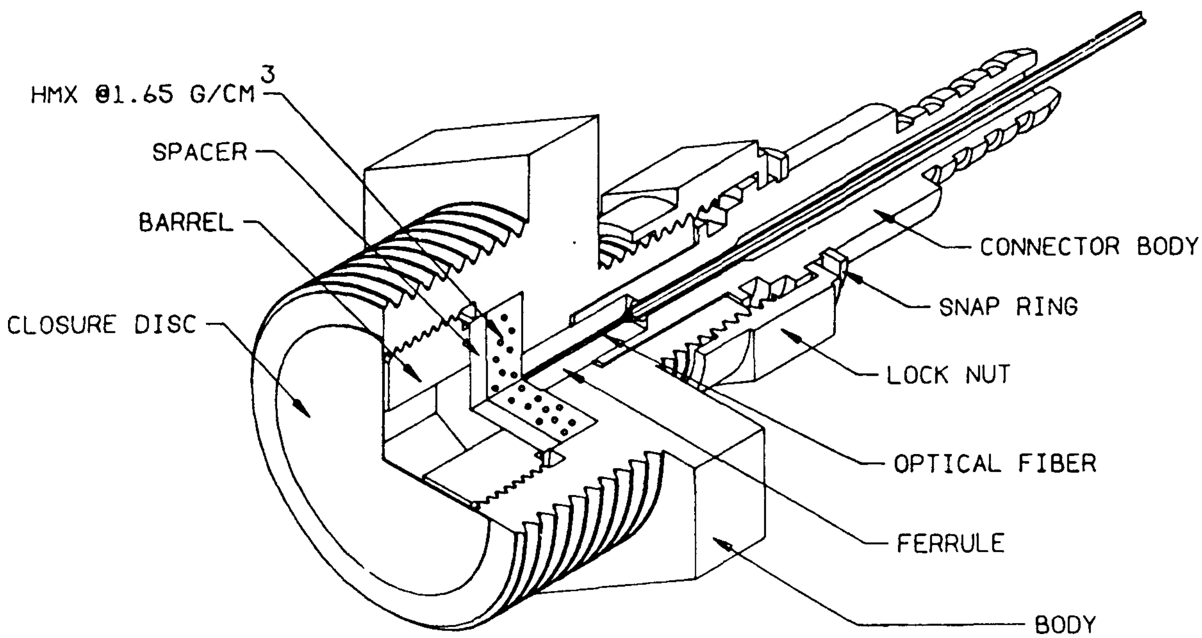

Figure 1 - Test device used in HMX laser ignition studies.

been eliminated, as have the electrical leads. Instead, the laser-ignited HMX device has an adapter for a fiber optic connector. This adaptor accepts a standard SMA906 connector.

The type of optical fiber used in these studies was Spectraguide No. 420, a multimode step index fiber manufactured by Spectran Corp. This fiber has a core diameter of 100 μm and a cladding diameter of 140 μm. The optical fibers were installed into the SMA906 connectors using a standard "pot and polish" process. The connectors included an alumina ceramic ferrule and were procured from Optical Fiber Technologies, Inc. (OFTI).

Because of its white color, one would not expect HMX powder to be an efficient optical absorber. As was noted previously, Kunz and Salas demonstrated that the addition of small percentages of carbon black significantly lowers the laser diode ignition threshold of CP [4]. Graphite, which has a much larger particle size than carbon black, has also been used to increase the absorptivity of energetic materials. The use of such additives to increase the absorptivity of HMX is, therefore, a logical approach.

Several HMX/graphite and HMX/carbon black blends were prepared. Three specific surface areas of HMX were evaluated, ranging from 830 to 15,700 cm^2/g, as measured using a Fisher sub-sieve sizer. The concentration of carbon black or graphite ranged from 1 to 3% by weight. Photoacoustic spectroscopy was used to compare the absorption characteristics of some of these blends.

The test devices were loaded with a metal insert in place of the fiber optic connector. Although a density of 1.65 g/cm^3 is indicated in Figure 1, a slightly lower density of 1.55 g/cm^3 was selected for the sensitivity tests performed on the various HMX/carbon black and HMX/graphite blends. Since it was difficult to press the fine particle HMX blends above 1.55 g/cm^3, this density was chosen as a standard.

After loading 125 mg of powder into the devices, a 0.89-mm (0.35 in.) thick aluminum spacer was placed over the HMX charge. A steel barrel was then threaded in and torqued to 8.5 N-m (75 in-lb). The spacer and barrel provided the confinement necessary to sustain deflagration of the HMX.

The laser diodes used in the testing were SDL-2200-H2 diodes manufactured by Spectra Diode Laboratories, Inc. These diodes are AlGaAs arrays which emit at a wavelength of approximately 820 nm and can deliver up to 1 W from the end of a 100-μm optical fiber pigtail. Pulse widths of 10 ms were generated using a Spectra Diode Laboratories SDL820 laser diode driver. All tests were performed at room ambient conditions.

Before attaching the optical fiber connector to the loaded test device, the SMA906 connector was inserted into an optical power meter and the laser power was measured. Thus, the laser power incident upon the powder surface was well known for each test.

As part of the connector attachment process, a bead of epoxy was applied around the outer diameter of the ferrule. The SMA906 connector was then mated to the loaded test device and a controlled torque was applied to guarantee positive contact of the fiber and powder. The bead of epoxy served as a seal to prevent gas leakage back through the fiber optic connector.

Absorptivity Measurements

Photoacoustic spectroscopy [8,9] was used to compare the absorption spectra of pure HMX to those of the HMX/carbon black and HMX/graphite blends. The measurements were performed using an EG&G Princeton Applied Research model 6001 spectrometer. In this instrument, a xenon arc lamp is electronically modulated through a three-grating monochromator. Monochromatic light is produced at wavelengths between 200 nm and 2.6 μm, with modulation frequencies from 10 to 2000 Hz. This light is focused on the sample, which is contained in a sealed photoacoustic cell. Absorption of the modulated light by the sample produces an oscillating sample temperature, which then creates an oscillating pressure, or acoustic, wave in the photoacoustic cell. The acoustic wave is detected by a microphone, the output of which is sent to a lock-in amplifier and displayed on a recorder as the monochromator is scanned. Thus, the photoacoustic intensity is a measure of the sample temperature rise induced by the absorbed light.

Photoacoustic spectra were obtained for 15,700 cm^2/g HMX and blends of this material with 1 and 3% by weight carbon black, as well as 1 and 3% by weight graphite. The photoacoustic spectra of these powders were referenced to Fisher C-198 carbon black. The spectra are reproduced in Figure 2. The structure around 750 to 800 nm is an instrumental artifact because of the changing of the monochromator gratings in this region. These spectra were taken with a resolution of 8 nm between 220 and 800 nm and 32 nm

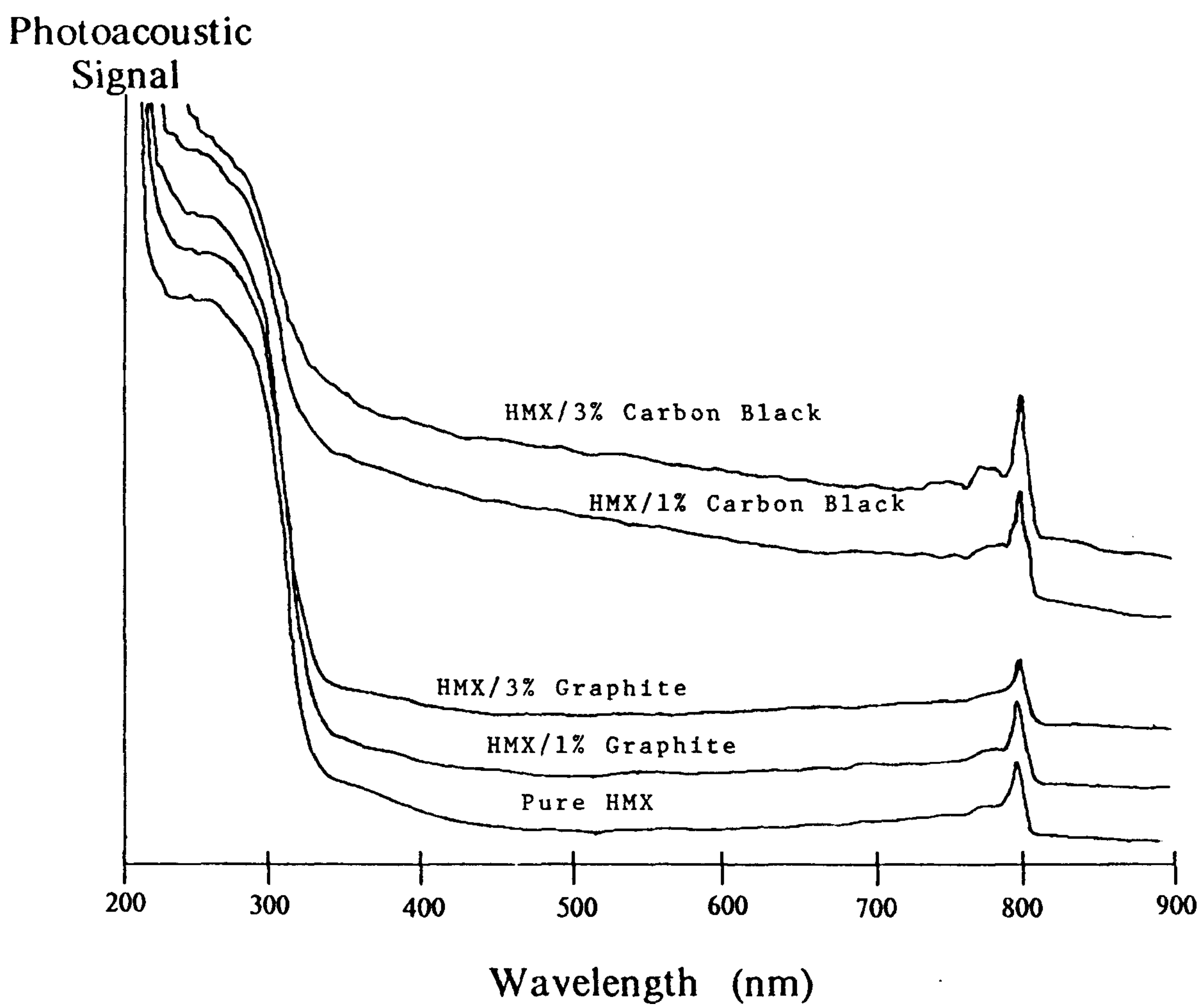

Figure 2 - Photoacoustic spectra of various HMX powders.

between 800 and 900 nm. A modulation frequency of 500 Hz was used to reduce saturation effects that occurred at lower frequencies.

Pure HMX was found to be essentially transparent at wavelengths longer than 400 nm, and it has an absorption edge beginning at about 340 nm in the ultraviolet. The photoacoustic signal was found to increase, in order, with the addition of 1% graphite, 3% graphite, 1% carbon black, and 3% carbon black. If laser diode ignition was predominantly limited by a thermal mechanism, the photoacoustic spectra would predict that the ignition threshold levels would decrease in the same order. For example, the 1% carbon black would be more effective than 3% graphite in lowering the ignition threshold.

Ignition Test Results

Using the test device shown in Figure 1, preliminary tests were performed to determine whether the available laser diodes were capable of igniting pure, or undoped, HMX. These experiments were conducted using 7460 cm^2/ g HMX powder loaded to a density of 1.55 g/cm^3. As noted previously, the maximum rated output of the SDL-2200-H2 laser diodes was 1 W from the end of a 100-μm optical fiber pigtail; however, an in-line ST connector reduced the maximum available power by approximately 12%.

Tests were performed at power levels of 780 and 880 mW using a 10-ms laser diode pulse. In both cases not only did the HMX fail to ignite, but an examination of the powder surface after the tests revealed no visible evidence of reaction. Thus, the undoped HMX powder appeared to be a poor absorber at the laser diode wavelength, as was indicated by the photoacoustic spectroscopy measurements.

Using a 10-ms laser diode pulse, threshold tests were then performed on blends of 15,700 cm^2/g HMX with 1% carbon black, 3% carbon black, 1% graphite, and 3% graphite by weight, the same blends that were used in the photoacoustic spectroscopy studies. Approximately 10 test devices were used to obtain the ignition threshold of each blend. Thus, the test results may be used to suggest trends, but they are not statistically absolute. The mean and standard deviation were calculated using the Neyer technique [10]. Test results are summarized in Table 1.

Table 1

Ignition Threshold Results For Fine Particle HMX Blends

Additive	Mean (mW)	Std. Dev. (mW)
1% Graphite	151	9
3% Graphite	114	7
1% Carbon Black	84	2
3% Carbon Black	72	0

The ignition threshold data for the fine particle HMX blends track in the same order as the photoacoustic spectroscopy results. In addition, the threshold levels obtained with the 1% and 3% carbon black blends indicate at least an order of magnitude increase in sensitivity relative to the undoped HMX powder. The 72-mW threshold level obtained for the 3% carbon black blend is only 15% lower than that for the 1% carbon black blend, indicating that the additional carbon black does not have a significant impact on the sensitivity of the powder.

Ignition threshold tests were also conducted on blends of 830 and 7460 cm^2/g HMX with 1% carbon black by weight. Again, the tests were run using a 10-ms laser diode pulse. The 830 cm^2/g material was found to have the highest threshold level, 158 mW. The 7460 cm^2/g HMX blend had a threshold of 110 mW. The sensitivity of the 7460 cm^2/g HMX, therefore, falls in between the coarser (830 cm^2/g) and finer (15,700 cm^2/g) powders. The ignition threshold as a function of HMX specific surface area for the 1% carbon black blends is summarized in Table 2 and also shown graphically in Figure 3.

The effect of spot size was then investigated by varying the optical fiber diameter. Ignition threshold tests were rerun on the blend of 15,700 cm^2/g HMX with 3% carbon black, using 200 and 400-μm core diameter optical fibers. For the 200-μm diameter fiber, a threshold of 188 mW

Table 2

Ignition Threshold Data for HMX with 1% Carbon Black

HMX Surface Area (cm^2/g)	Mean (mW)	Std. Dev. (mW)
830	158	0
7460	110	14
15700	84	2

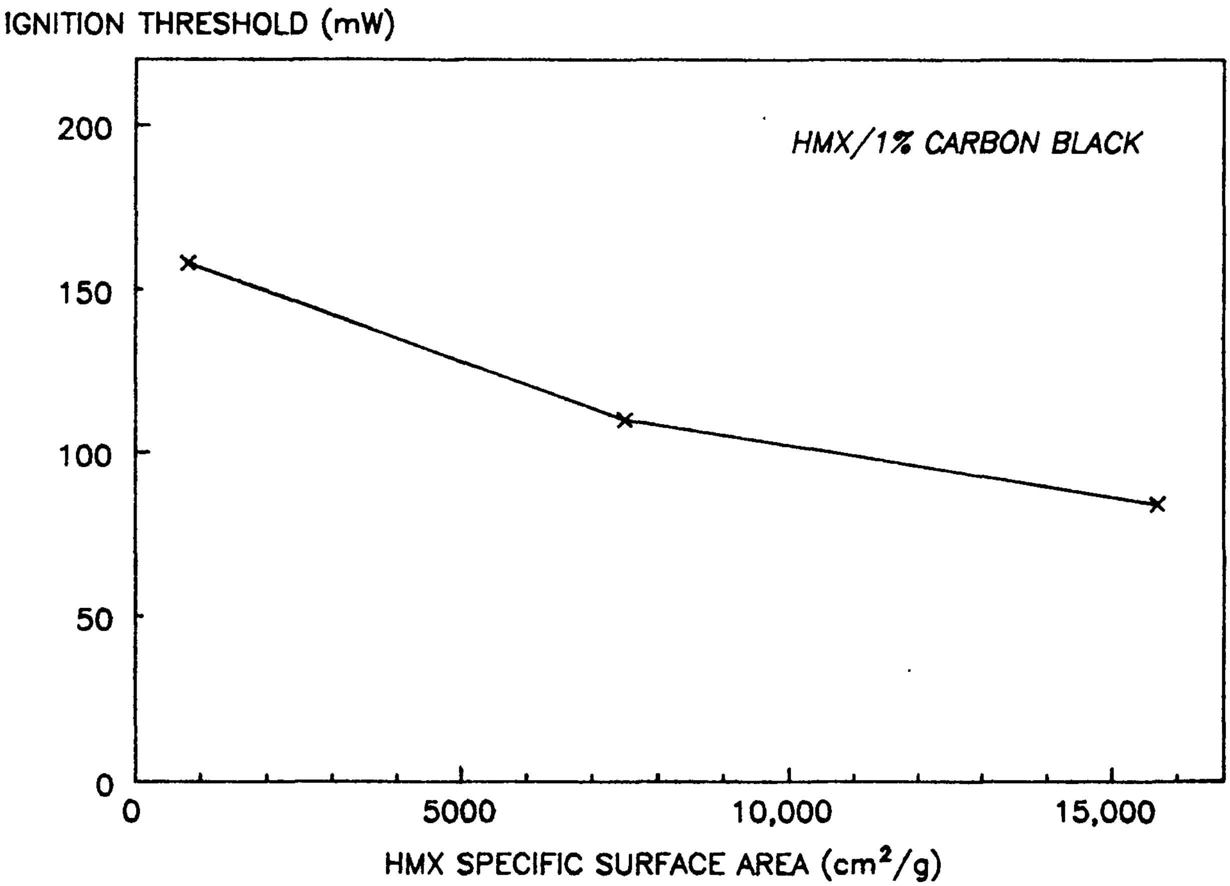

Figure 3 - Effect of specific surface area on the laser ignition threshold of HMX.

was obtained, with a standard deviation of 19 mW. For the 400-μm diameter fiber, the threshold level was 516 mW and the standard deviation was 25 mW. Figure 4 shows the ignition threshold as a function of fiber diameter. The threshold data are plotted in terms of power density in Figure 5.

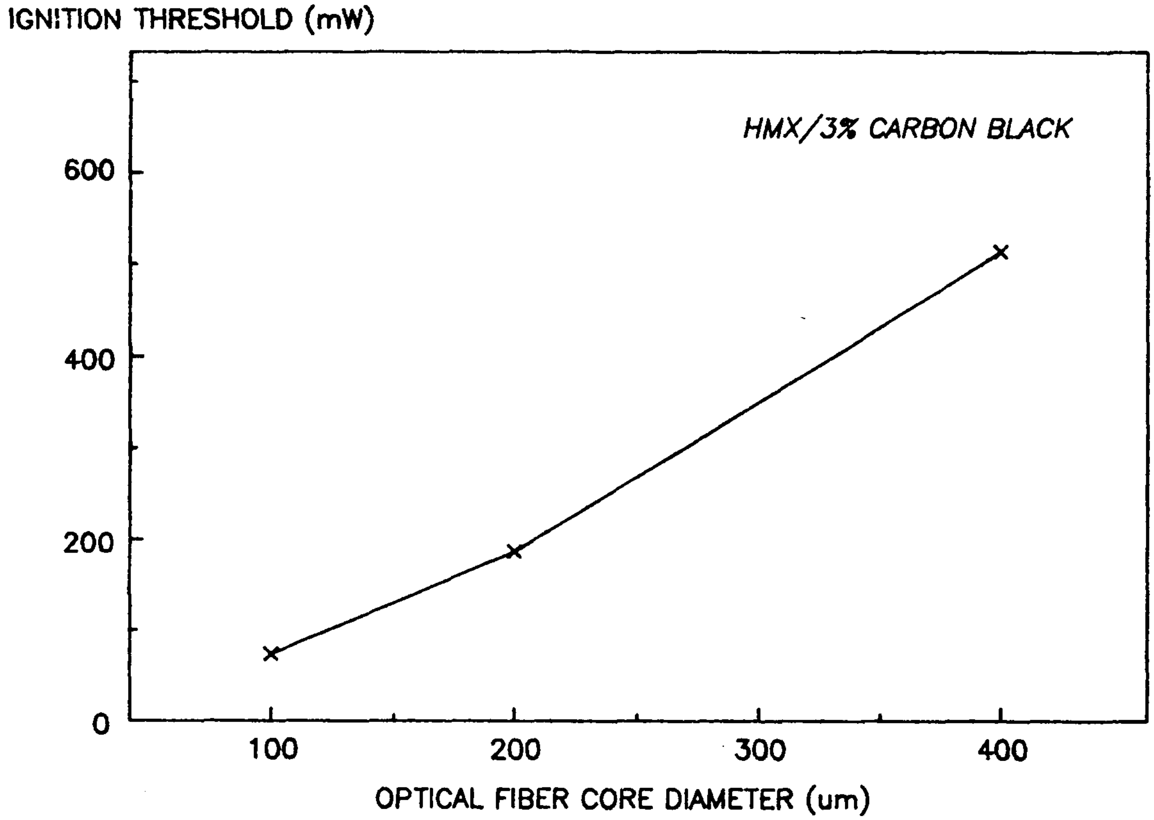

Figure 4 - Effect of fiber diameter on the laser ignition threshold of HMX.

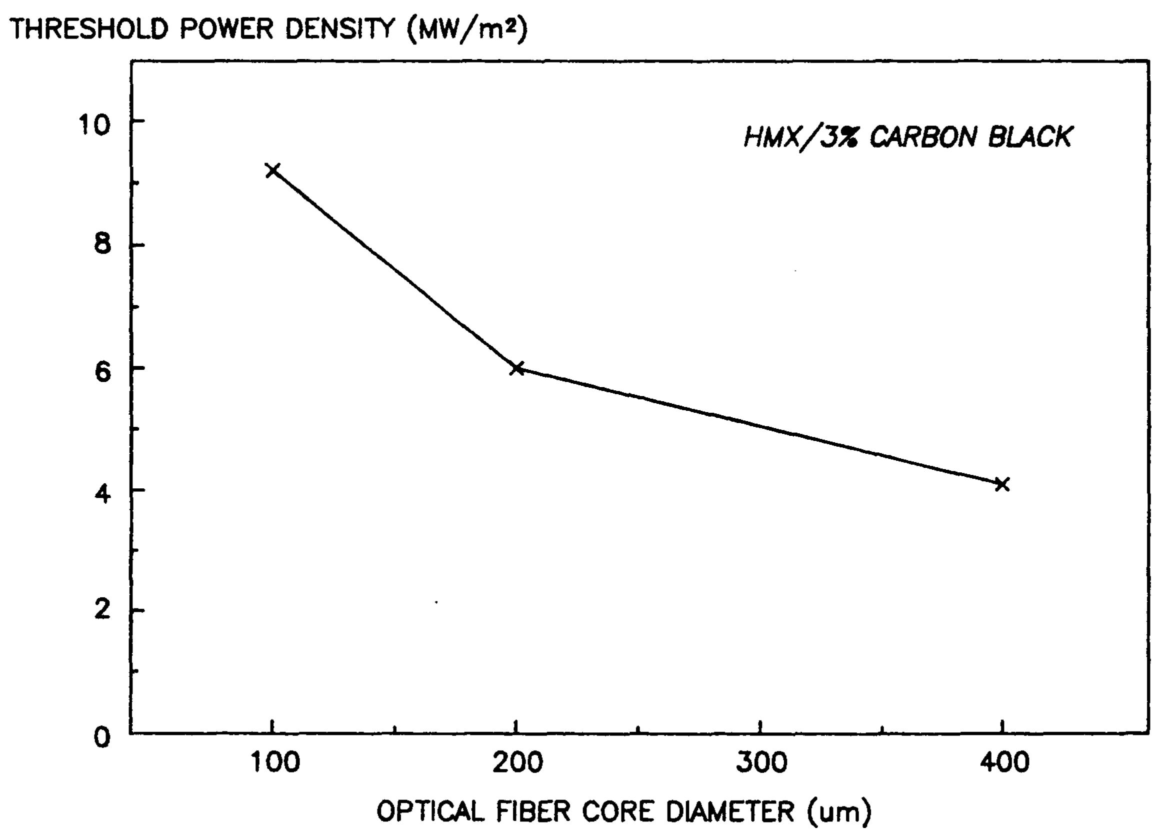

Figure 5 - Ignition threshold of HMX in terms of power density.

The data in Figure 4 indicate that the threshold power scales neither linearly with fiber diameter nor as the square of the fiber diameter, as would be suggested by a power density dependence. Instead, the data fall somewhere in between these two cases. This trend agrees with previous laser diode ignition studies for energetic materials using optical windows of various thicknesses [4], as well as ignition studies performed on pyrotechnics using a Gaussian Ar-ion laser beam [11]. From the HMX studies, it is interesting to note that when the spot size was doubled from 100 to 200 μm, the threshold level increased by a factor of 188/72, or 2.6. Again doubling the spot size from 200 to 400 μm further increased the ignition threshold by a similar factor of 516/188, or 2.7.

A study was then performed to determine the influence of the laser diode pulse width on threshold power and energy levels. Again, using the blend of 15,700 cm^2/g HMX with 3% carbon black, a threshold test was conducted; however, the pulse width was changed from 10 to 100 ms. The threshold for the 100-ms pulse was 61 mW. This represents a decrease of only 15% from the 72-mW threshold obtained using the much shorter 10-ms pulse width. Table 3 summarizes the threshold data for the two laser diode pulse widths. Note that the threshold energy is nearly an order of magnitude greater for the 100-ms pulse (6.1 mJ) than for the 10-ms pulse (0.7 mJ). This suggests that the heat transfer at the fiber/powder interface is very nearly steady-state at 10 ms.

Table 3

Effect of Pulse Width on Ignition Threshold

Pulse Width (ms)	Mean (mW)	Std. Dev. (mW)
10	72	0
100	61	2

Finally, to evaluate the effect of assembly technique on ignition characteristics, 10 units were fabricated in which the fiber optic connectors were first installed in the test devices, then the powder was loaded into the devices, directly against the fibers. The powder used for this study was a blend of 15,700 cm^2/g HMX with 3% graphite by weight. In a previous test using the "conventional" assembly procedures described earlier, a threshold of 114 mW was obtained for this blend. When the powder was loaded directly against the fiber, however, the threshold was only slightly higher, 128 mW.

Discussion

It has been demonstrated that blends of HMX with small quantities (1 to 3% by weight) of either carbon black or graphite can be ignited using low energy laser diodes. The carbon black blends were at least an order of magnitude more sensitive than the undoped HMX powder, which could not be ignited using a 1-W laser diode.

The magnitude of the effect of adding carbon black on the laser ignition sensitivity of HMX is similar to that which has been observed for CP [4,6]. Darker materials such as $Ti/KClO_4$, which have a much higher absorptivity than powders such as CP or HMX, do not benefit significantly from the addition of carbon black or graphite [5].

As has also been observed for CP, the laser ignition characteristics of HMX are strongly influenced by particle size, or specific surface area of the HMX. For blends with 1% carbon black by weight, the threshold levels for 830 and 15,700 cm^2/g HMX differed by a factor of almost two. Specific surface area, therefore, has a much greater effect on laser ignition than it does on hot wire ignition of HMX [2]. This is attributable to the more localized heating involved in laser ignition, where the spot size is typically on the order of 100 μm.

The very localized heating that occurs at the end of the optical fiber also explains why the ignition threshold decreased by only 15% when the laser diode pulse width was increased from 10 to 100 ms. The small volume of powder directly heated by the optical fiber limits the effective thermal mass; thus, the time constant is relatively small and thermal equilibrium is reached quickly.

Fiber diameter, or spot size, is much more critical to laser ignition than bridgewire diameter is to hot wire ignition. In a laser-ignited device, the surface area of the optical fiber that is in direct contact with the powder is proportional to the square of the fiber diameter. In the case of a bridgewire, however, the surface area in direct contact with the powder is linearly proportional to the diameter.

The effect of powder density on laser ignition sensitivity was not investigated as part of this study. In Reference 5, it was determined that powder density did have a measurable effect on the laser diode ignition threshold of $Ti/KClO_4$, but the effect on CP was insignificant. Because HMX, like CP, has a relatively low thermal conductivity compared to $Ti/KClO_4$, density probably does not have a significant effect on the laser ignition sensitivity of HMX/carbon black or HMX/graphite blends. A density study should be performed, however, to confirm or deny this assumption.

Additional studies are also warranted in the area of photoacoustic spectroscopy. It has been shown that there is a definite correlation between the photoacoustic signal level and the ignition threshold obtained with loaded test devices. The photoacoustic signal, however, is a function of many variables, including specific surface area, thermal properties, and optical properties. Although these dependencies can complicate the interpretation of photoacoustic spectra, these spectra should be useful in predicting the effects of dopants or additives on sensitivity to laser ignition and also may indicate the optimum wavelength that produces the maximum temperature increase.

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