CONF-900792--6

DEVELOPMENT OF DIODE LASER-IGNITED PYROTECHNIC AND EXPLOSIVE COMPONENTS*

Received by OSTI

MAY 2 9 1990

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SAND--90-0031C

DE90 011238

ABSTRACT

Studies are described which have led to the development of prototype diode laser-ignited pyrotechnic and explosive devices. These are of interest because they eliminate some concerns associated with ignition from hot wires such as conductance after firing, sensitivity to electromagnetic radiation and electrostatic discharge, and bridgewire corrosion. The availability of high power diode lasers is a key feature for the success of this concept.

A pyrotechnic, $Ti/KClO_4$, and the deflagration-to-detonation transition (DDT) explosive CP have been evaluated and found suitable for use in LDI components. Doping with materials such as carbon black to increase light absorption near 800 nm is a major factor in reducing the laser power required to ignite CP, but does not strongly affect the ignition of $Ti/KClO_4$. Other material and laser input parameters were also studied to determine their influence on ignition thresholds. Even though they contain different energetic materials, the energy - power relationship of these optical igniters was generally similar in shape to those of other thermal ignition devices such as stab and electric igniters.

Prototype, hermetically sealed, optical headers have been fabricated, loaded, and test fired with CP and $Ti/KClO_4$. Glass to metal sealing technology has been developed to insert sapphire windows or optical fiber segments in these fixtures. Devices containing fiber segments demonstrated superior performance in threshold tests.

*This work supported by the U. S. Department of Energy (DOE) under contract number DE-AC04-76DP00789.

INTRODUCTION

Semiconductor diode lasers are finding increasing use in communications, optical pumping of solid-state lasers, medical applications, and consumer products.[1,2] High power (GaAl)As laser diodes have been available commercially for several years and units capable of emitting several watts from a facet area smaller than 100 μm^2 have been manufactured.[3] Diode lasers are attractive as ignition sources for energetic materials due to their small size, low electrical energy requirements (less than the 3.5 V, 3.5 A typical hot wire inputs), and inherent radiation hardness. While diode lasers currently available cannot directly initiate explosives, a detonation output is obtainable from a diode laser source by means of the deflagration-to-detonation transition (DDT) process.

Optical igniters, actuators, and DDT detonators will eliminate many safety and reliability concerns normally associated with placing electrical leads at the explosive or pyrotechnic interface in a hot wire component. The optically ignited devices are not sensitive to electromagnetic radiation or electrostatic discharge. They have no bridgewires to corrode and are not limited by such system concerns as conductance after firing or isolation resistance.

We have been developing prototype diode laser ignition subsystems for several years and previously reported on the feasibility of thermal ignition using diode lasers.[4] This work has now been extended to a more complete investigation of material and interface parameters which are critical for optical ignition. The resulting information has been used to design and successfully demonstrate the performance of prototype optical headers. One of the constraints used in this effort was that the explosive charge cavity must be hermetically sealed to exclude moisture and other materials posing compatibility concerns in the local environment.

EXPERIMENTAL

Laser Sources

The (GaAl)As semiconductor laser sources employed in the majority of this work were model 2200-H2, 10 stripe phased arrays manufactured by Spectra Diode Laboratories. These laser diodes were interfaced to step index optical fibers supplied by SpecTran Corporation (type SR420, glass-on-glass, 100 µm core diameter). A maximum output power of 1 watt was obtained from the end of the fiber with this configuration. The laser wavelengths varied from 782 to 843 nm depending on the particular diode. Currents up to 10 A with pulse widths of 10 µs to 300 ms were supplied by the Spectra Diode Laboratories model 820 laser diode driver power supply. Energy emitted from the optical fiber was measured with a Photodyne model 66XLA optical power/energy meter with a type 350 miniature integrating sphere silicon sensor head.

High power ignition tests were performed with a CVI model 212QT cw Nd-YAG laser gated with a rotating wheel mechanical light chopper. This apparatus was capable of generating multimode light pulses of 150 µs or longer at powers up to 55 watts. The cw laser power was monitored with a Coherent Labmaster system attached to a model LM45 detector head.

Sensitivity Testing

A fixture used for much of the threshold testing is shown in Figure 1. The optical fiber was mounted in the ceramic ferrule of a standard SMA fiber optic connector and then polished. After the 304 stainless steel housing was loaded with 15-20 mg of explosive or pyrotechnic at the desired density, a 0.13-mm thick closure disk (not shown in Figure 1) was glued or laser welded onto the output end, and the SMA connector attached. Thin pieces of window materials or controlled stand-offs can be placed between the ferrule and the powder in order to test their effect on thresholds.

Ignition thresholds were approximated in these fixtures by firing a nominal 4-6 shot series at various laser power levels. Therefore thresholds are quoted as the maximum no-fire, minimum fire levels or

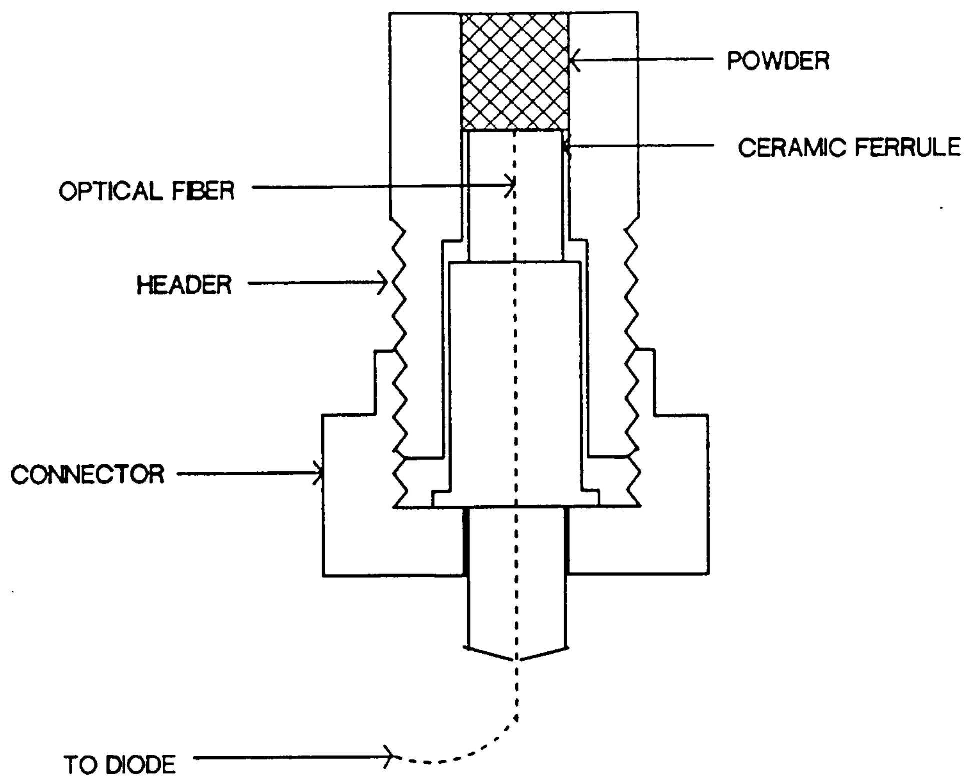


Figure 1. Standard test fixture for diode laser ignition.

the average of these two points. Thresholds were sharp and no crossover reversals were generally observed with the 25 or 50 milliwatt step size used in the sensitivity testing.

Hermetically Sealed Optical Feed-Throughs

Two approaches have been successfully demonstrated; one design incorporates a thin single crystal sapphire window, and the other design employs a short optical fiber segment. Both headers were designed to be compatible with standard, commercially available SMA 905 ceramic fiber optic connectors (OFTI).

Sapphire Window Seals: Polished sapphire windows (Adolph Meller Co.) were sealed into steel housings at the base of the powder charge cavity using CABAL-12 glass (Sandia Laboratories), as shown in Figure 2. A range of window thicknesses were selected from 0.25 to 0.64 mm to permit evaluation of seal quality as a function of geometry and to determine the effects of laser beam divergence on ignition thresholds.

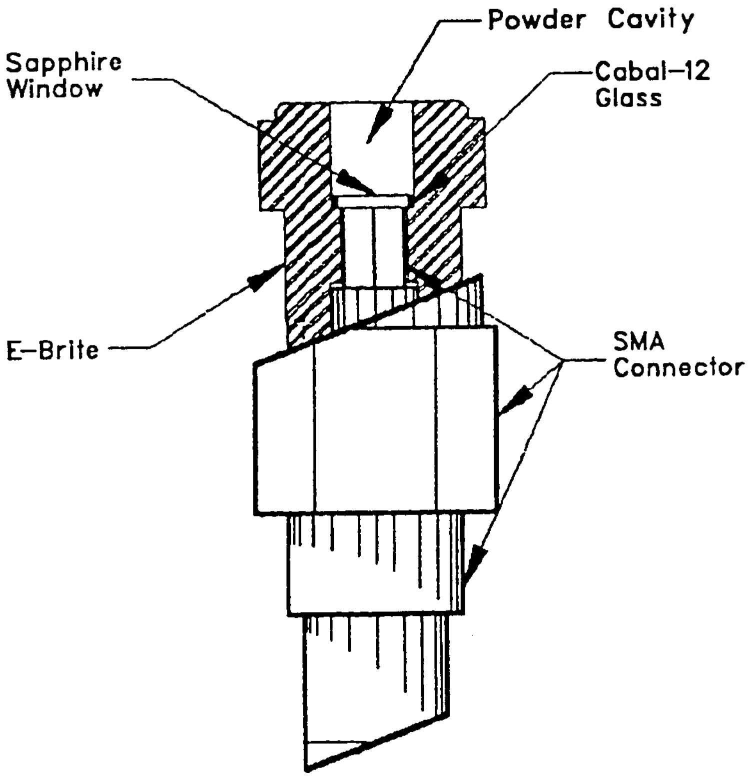


Figure 2. Connector-ready sapphire window seal.

E-brite (alloy 26-1) and 304 stainless steel were both initially selected as potential header shell material, but successful prototype seals were produced only with the E-brite. Empirical studies suggested that the coefficient of thermal expansion (CTE) of the 304 (~172 x 10^{-7}/°C) was too high relative to the sealing glass and the sapphire (each ~70 x 10^{-7}/°C). The thinner window seals were often observed to crack, apparently due to large residual thermal stresses. E-brite, a weldable ferritic stainless alloy, has a CTE of about 114 x 10^{-7}/°C, and finite element stress calculations concur with experimental seal trials showing that residual stresses generated in the glass and sapphire are well within acceptable levels.

The minimum allowable diameter of the charge cavity was determined to be 3.3 mm due to constraints imposed by the diameter of the ceramic ferrule (2.18 mm) in the SMA connector. A 2.5-mm diameter sapphire window is supported on a ledge above the connector region at

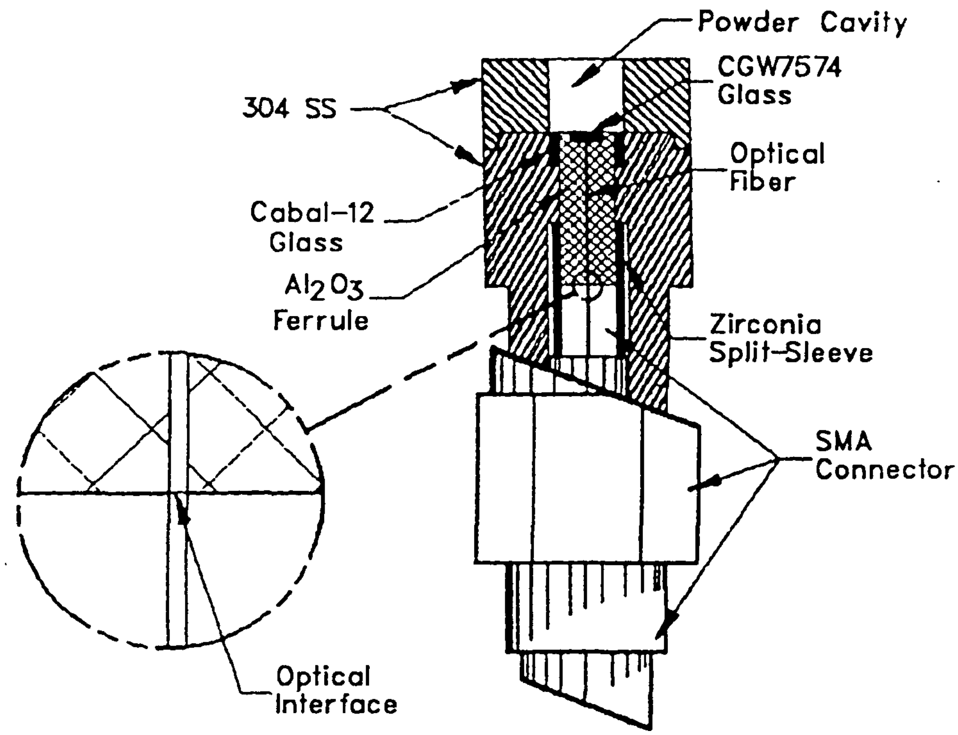


Figure 3. Connector-ready optical fiber seal.

the base of the charge cavity, and is sealed to the E-brite housing with a ring of glass 0.38 mm wide. The entire header is axisymmetric about the center of the window. Successful seals were fabricated with 3.3 and 5.7-mm diameter charge cavities, although the larger diameter seals were not, in general, able to withstand subsequent powder loading forces without cracking and losing hermeticity.

Optical Fiber Seals: A technique to seal a short segment of optical fiber into a 304SS housing was developed using a "graded seal" approach. A graded seal is often used when the expansion coefficient of one member is substantially different from another. A series of one or more additional materials is selected with CTEs intermediate to the two original materials. The result is a reduction to below critical levels in the magnitude of the residual stresses generated during sealing. In the present case, the CTE of the optical fiber is

~6 x 10^{-7}/°C and is quite low relative to 304SS (CTE ~172 x 10^{-7}/°C). The seal is graded by bonding the fiber into a precision bore alumina ferrule (Kyocera, CTE ~70 x 10^{-7}/°C) with 7574 glass (Corning Glass, CTE ~30 x 10^{-7}/°C). The alumina ferrule is sealed into the stainless housing using CABAL-12 glass (again, CTE ~ 70 x 10^{-7}/°C). A cross section of the graded seal header design is shown schematically in Figure 3.

One advantage of this specific material system is that the two glasses (7574 and CABAL-12) can be sealed under identical thermal conditions. This allows the entire assembly to be fabricated using a one-step heat treatment, nominally 800°C for 20 minutes in a slightly oxidizing atmosphere (ZnO and PbO are major species in the 7574 glass and are unstable under reducing conditions). Following sealing, the tip of the fiber on the charge cavity surface is ground flush and finely polished. The fiber tip on the connector side of the header is fixtured flush with the base of the alumina ferrule, and it is at this surface that the commercial optical fiber connector mates with the fiber segment in the seal. Alignment of the connector ferrule with the seal ferrule is aided by the use of a zirconia ceramic split sleeve (Kyocera) as shown in Figure 3.

Materials

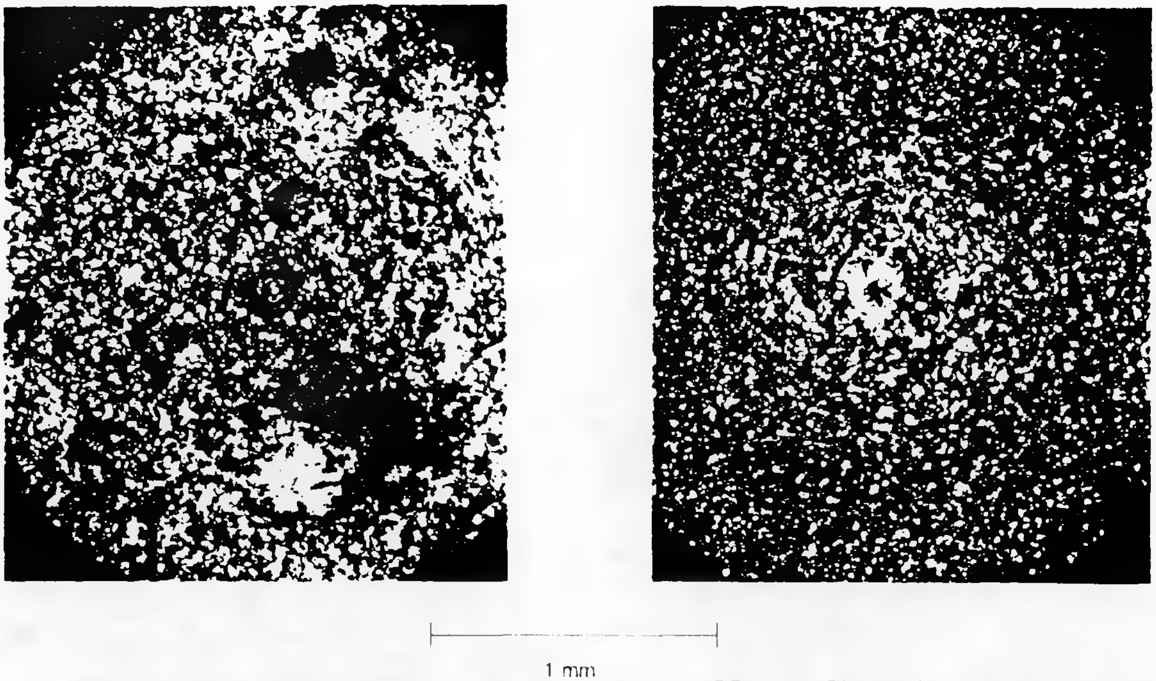
Ti/$KClO_4$ was a 33/67 mixture of 2 μm Ti particles and 8 μm $KClO_4$ blended by EG&G/Mound. CP explosive was manufactured and blended with dopants by Unidynamics Phoenix, Inc. Carbon black was procured from Cabot Corporation (ELFTEX 8, Sterling R) or Degussa Corporation (Lampblack 101). IR-132 laser dye was obtained from the Eastman Kodak Company. KTNBC was manufactured by Unidynamics Phoenix, Inc.

RESULTS AND DISCUSSION

Material Parameter Dependence

We have examined the diode laser ignition behavior of two materials commonly used by Sandia in hot wire components - Ti/$KClO_4$ and 5-cyanotetrazolatopentaamminecobalt(III) perchlorate (CP). CP undergoes DDT readily if density and confinement are controlled and, therefore, can be used to obtain a detonation output from an ignition source. As reported previously,[4] both of these materials can be ignited by diode lasers through 100-μm core diameter optical fibers. Also, the threshold of CP was lowered from 6-7 mJ in a 10-ms pulse to less than 3 mJ by adding dopants to form a blend with enhanced light absorption at the nominal 800 nm diode laser wavelength. Only the initial powder increment needs to be doped since the diode laser energy is absorbed close to the surface. The DDT function of the intermediate portion of the powder column is therefore not affected. There is little evidence that adding dopants improves the threshold performance of $Ti/KClO_4$[5], which is already highly absorbing at 800 nm due to the titanium particles. Earlier results that indicated 0.5% graphite added to $Ti/KClO_4$ actually degraded the threshold slightly[4], could have also been due to variability in the surface texture of the pressed charge.

CP containing different types of dopants and a wider range of dopant concentrations has now been tested. Materials evaluated as dopants included carbon black, graphite, IR-132 (a laser dye which absorbs near 800 nm in solution), and KTNBC (an energetic compound which absorbs strongly at 800 nm). Most tests were with physical blends, but the more soluble IR-132 was also coprecipitated with CP. The latter samples were termed "homogeneous" since no individual dopant particles were observed using optical microscopy. Because coprecipitation also produced a smaller CP particle size (4-6 μm mean) than is present in standard production material (15 μm mean), some of the physical blends were repeated with the finer particle material to determine whether particle size had any effect on the apparent ignition thresholds. It was also found that very fine particle carbon black dopants did not blend easily with the coarser CP samples, but tended to remain as undispersed agglomerates. This was considered to be an undesirable situation since pressed charges contained "islands" of carbon black on the surface which were larger than the 100-μm laser spot size employed for ignition. Changing from a dry to a wet blend and adding Teflon spheres as a mild mixing aid improved homogeneity. Figure 4 shows the appearance of the charge surface.



CP + .8% Elftex 8 carbon black dry blend

CP + 1% Sterling R carbon black wet blend with Teflon spheres

Figure 4. Surface appearance of doped CP charges pressed at 1.7 g/cm^3.

Figure 5 shows typical threshold results for precipitated CP samples containing different dopants at varying concentrations. These data were all obtained using a 100-µm core diameter optical fiber in the standard test fixture, a 10-ms laser pulse, and a 1.7 g/cm^3 explosive charge density. Optical ignition thresholds of CP are relatively unaffected by changes in density.[6] Most of the threshold reduction from doping occurs at concentrations below 1%. Carbon black, whose blends with CP show higher optical absorption at a given concentration than those of larger particle size dopants such as graphite,[4] was the most effective at a low doping level. There was not a great deal of difference in performance among the various types of dopants at higher concentrations or between homogeneous and physical blends in the case of IR-132. The threshold for the 1.4% carbon black sample is not representative based on other test data.[6] The general trend in thresholds is slowly downward at a 1.4% dopant concentration,

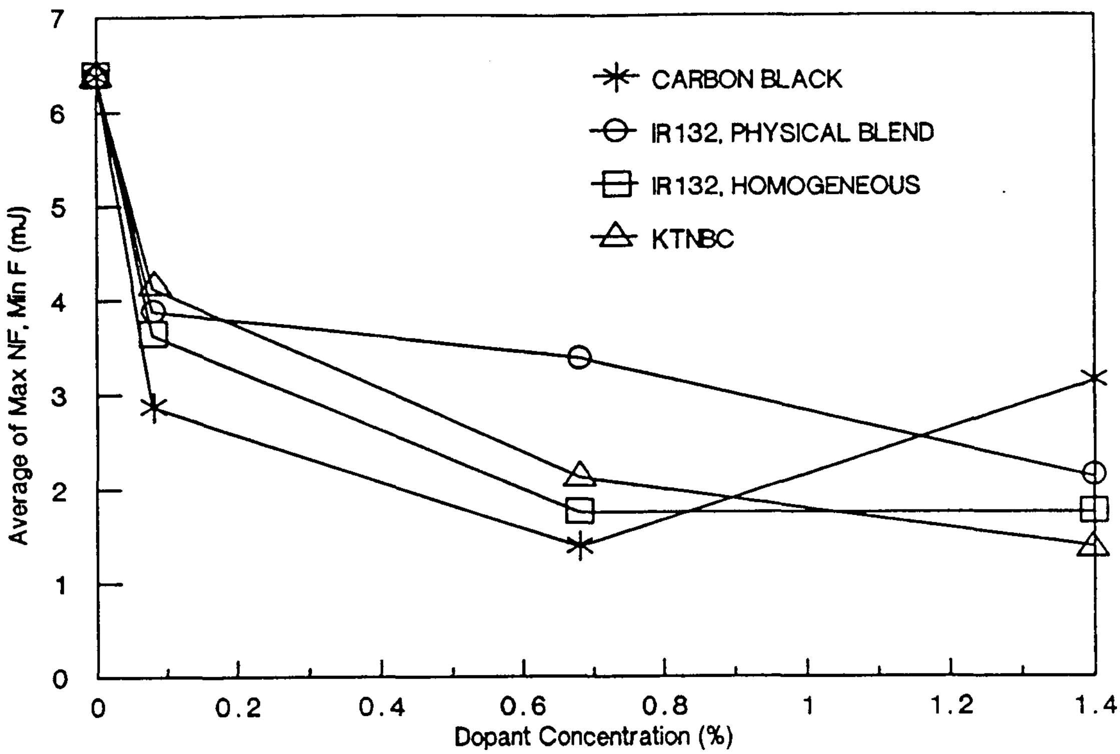


Figure 5. Enhancement of CP thresholds by doping. The samples were all blended from precipitated CP and pressed to 1.7 g/cm^3. A 10 ms diode laser pulse through a 100 µm core diameter optical fiber was used to ignite the powder.

so higher dopant levels can still make modest improvements in threshold. Eventually, inert dopants would be expected to dilute the energetic nature of CP, causing thresholds to rise again. The energetic dopant KTNBC may not show this tendency and in fact the KTNBC blend was the most sensitive by a slight amount at the 1.4% concentration.

A few samples of production CP have been doped with higher amounts of carbon black to determine the maximum useful levels. Somewhat surprisingly, a rather broad minimum that extends to near 10% dopant was found in the threshold response. These results are shown in Figure 6. The major effect from this high concentration of carbon black in the sample was that material tended to delaminate from the surface of the charge after pressing. KTNBC has not been tested at

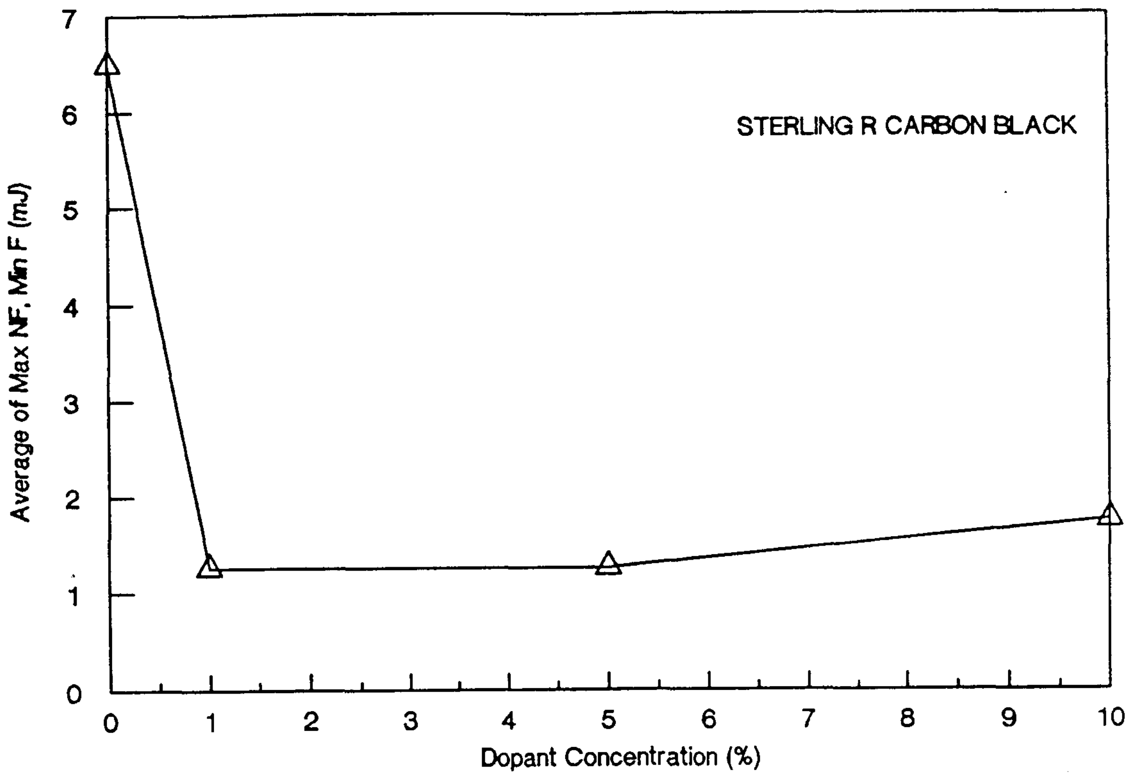


Figure 6. Concentration dependence of carbon black-doped production CP thresholds. The samples were pressed to 1.7 g/cm^3 and ignited with a 10 ms laser pulse through a 100 μm core diameter optical fiber.

these doping levels yet, although further work is in progress in this area.

The foregoing data provide a few comparison points to show if CP particle size has any effect on ignition thresholds. These samples all contain carbon black dopant and the comparisons of production versus precipitated CP are shown in Figure 7. There is no significant shift which could be attributed to the particle size range covered.

Laser Input Dependence

The ignition response of these materials has been examined with reference to parameters such as laser spot size, pulse width, and power level. Since the optical power currently available from diode lasers is not sufficient to directly initiate explosives, the mechanism for ignition is presumed to be entirely thermal. The form

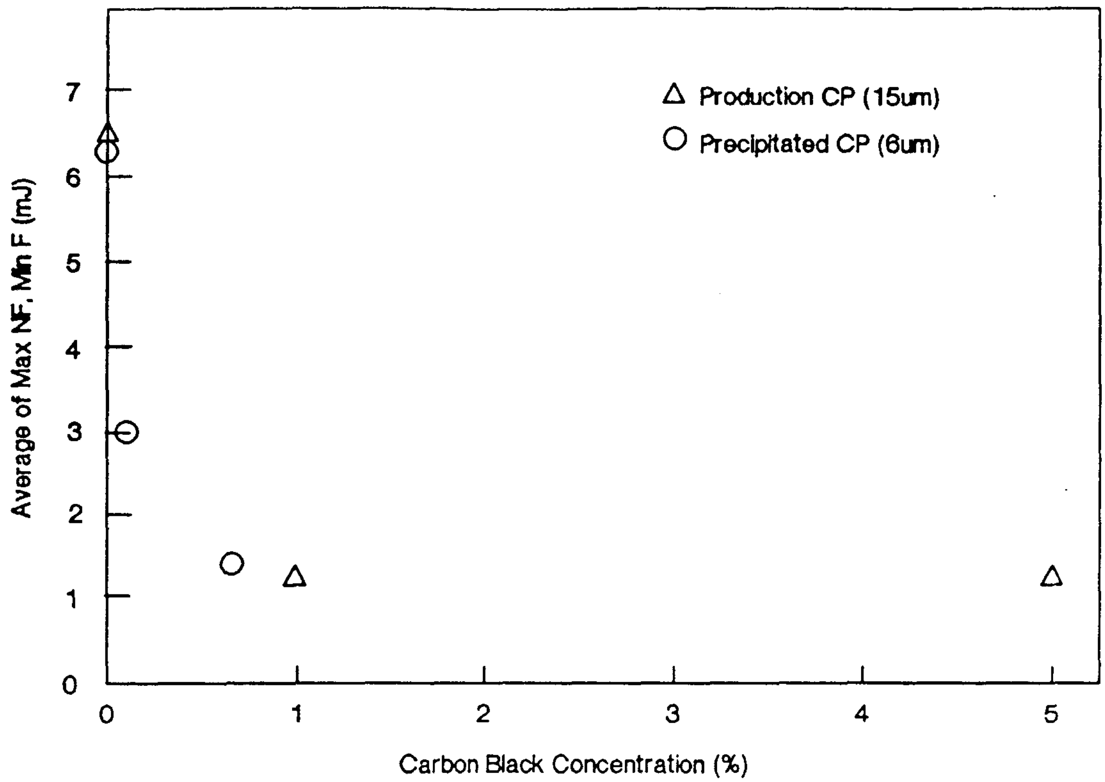


Figure 7. Particle size dependence of CP ignition thresholds. These carbon black-doped samples were all loaded at 1.7 g/cm^3 density and ignited through a 100 μm core diameter, 0.27 numerical aperture optical fiber.

of the energy - power relationship for diode laser ignition of several different types of powder supports this belief. Figure 8 shows these curves for both Ti/$KClO_4$ and a doped production CP. Similar curves were found for CP doped with different amounts of carbon black or homogeneously doped with IR-132 laser dye. There exists a minimum laser power below which the materials cannot be ignited, no matter how long the pulse is applied. This level is highest for the highest thermal conductivity material tested, Ti/$KClO_4$. At high power, where the thermal losses in the system are insignificant compared to the rate at which energy is delivered, the energy required for ignition tends toward a minimum. This functional form mirrors the case for hot wire and stab ignition devices.[7]

As laser power increases, the function time of ignition charges decreases. Typical numbers for the materials considered here are several milliseconds at threshold and 200-500 µs near 1 watt of input diode laser power. Because of this decreasing function time, the energy required for ignition decreases to only 0.25-0.5 mJ near the diode laser power limit. This trend appeared to continue past that point, however, so some testing was done with a Nd-YAG laser in order to raise the power available from the 100-µm core optical fiber to 10 watts. Function times were 100-200 µs longer with the Nd-YAG input compared to that from laser diodes at one watt. This is mostly due to the slow rise on the mechanically-chopped Nd-YAG beam. The pulse is flat-topped with a rise time which depends on pulse width, decreasing from just under 100 µs for a 500 µs width at half-height to about 30 µs for a 150 µs pulse (the shortest possible with this equipment). Figure 9 shows the gradual decrease in CP function times to about 40 µs at 10 watts. Here the function time is again nearly the same as

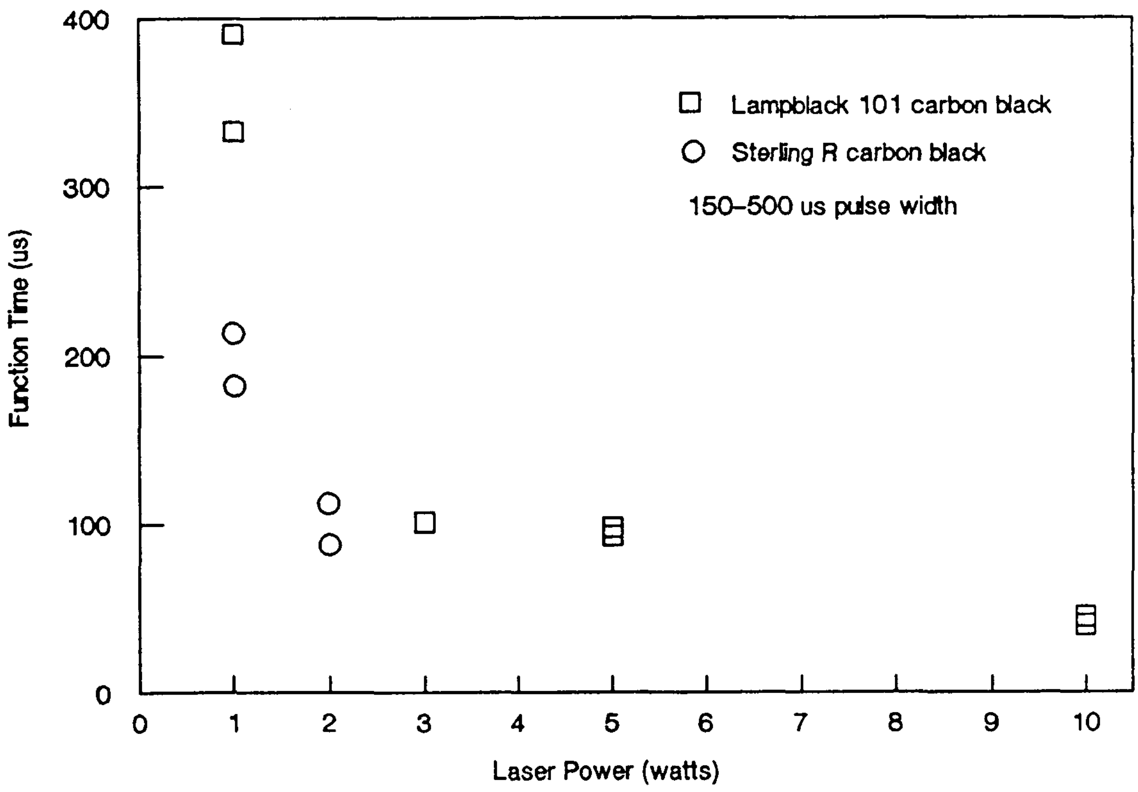


Figure 9. Function times of CP ignition charges from a Nd-YAG laser input pulse. The laser energy was transmitted to the powder interface through a 100 µm core diameter, 0.27 numerical aperture optical fiber.

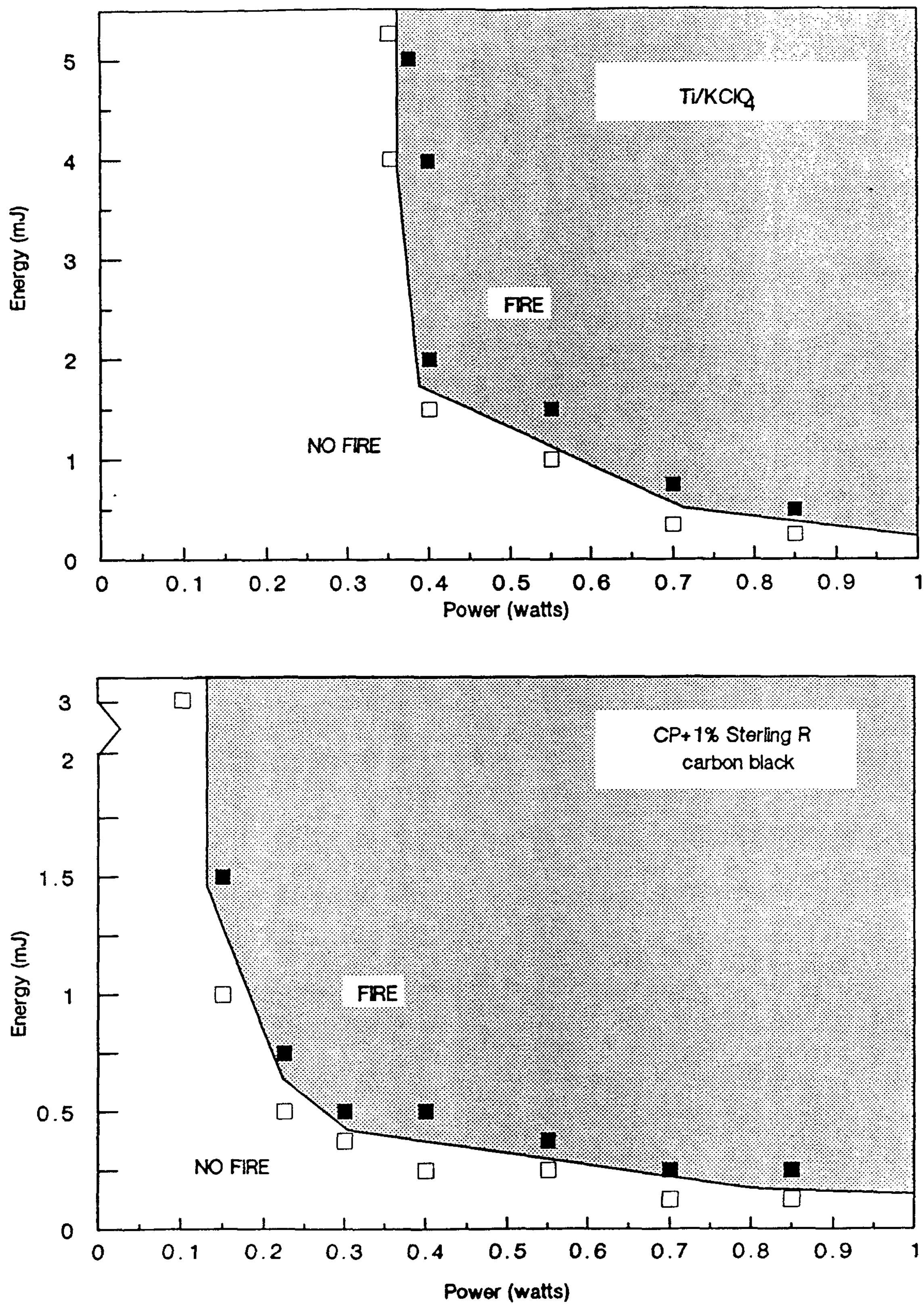


Figure 8. Energy - power relationship for diode laser ignition through a 100 µm core diameter, 0.27 numerical aperture optical fiber.

the pulse rise time and so is system limited. Still faster function times should be attainable with further increases in power, ideally from a faster rising source. This is the optical analog of CP function from a hot wire where times drop from 500 μs at 3-5 A to about 10 μs at 100 A.

Finally, experiments have been run to assess the effect of laser spot size on thresholds. This was done in earlier studies by allowing the beam to diverge through windows of varying thicknesses.[4] In this work, different diameter optical fibers have been interfaced directly to the powder using the standard test fixture. Figure 10 shows the results of these fiber diameter studies. Both CP and $Ti/KClO_4$ increase in threshold as the fiber diameter (spot size) increases. Similar trends were observed in the window thickness studies. Neither type of powder follows a strict power density dependence, the materials being somewhat more sensitive at larger spot sizes than expected based on an equivalent power density.

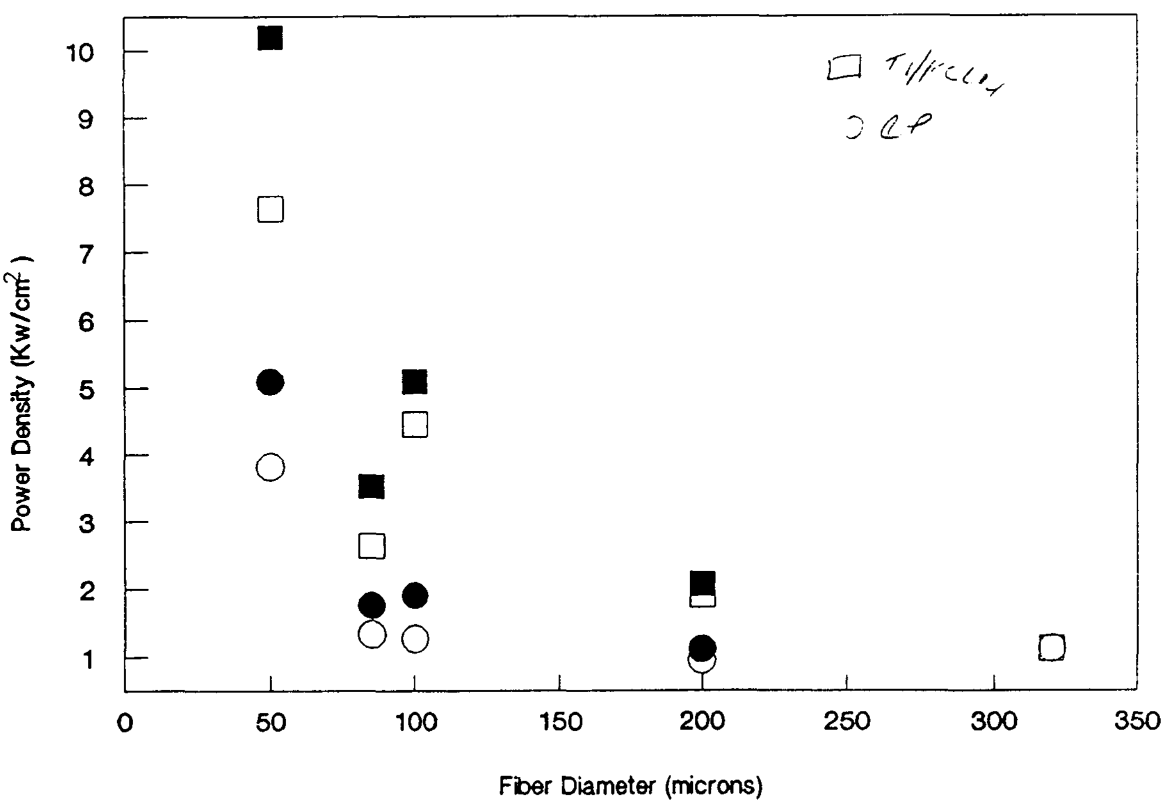


Figure 10. Fiber diameter effect on diode laser ignition thresholds.

Prototype Hermetic Optical Header Evaluation

Charge holders containing sealed sapphire windows were evaluated initially. Sapphire was chosen for its high optical transmission at diode laser wavelengths and its high strength which would improve resistance to damage during loading operations. Unloaded housings incorporating 0.25 to 0.64-mm thick windows were found to have a 90% transmission at diode laser wavelengths. This could be increased further by applying anti-reflection coatings. Parts were successfully loaded with CP at 1.7 g/cm^3 and $Ti/KClO_4$ at 2.0 g/cm^3. CP loading is the more severe test for part survival, requiring an applied pressure of about 40 kpsi. Firing data for those parts loaded with CP are shown in Figure 11. The increase in threshold compared to direct contact of the fiber with the same powder is partly due to beam expansion while traversing the window and partly due to the higher

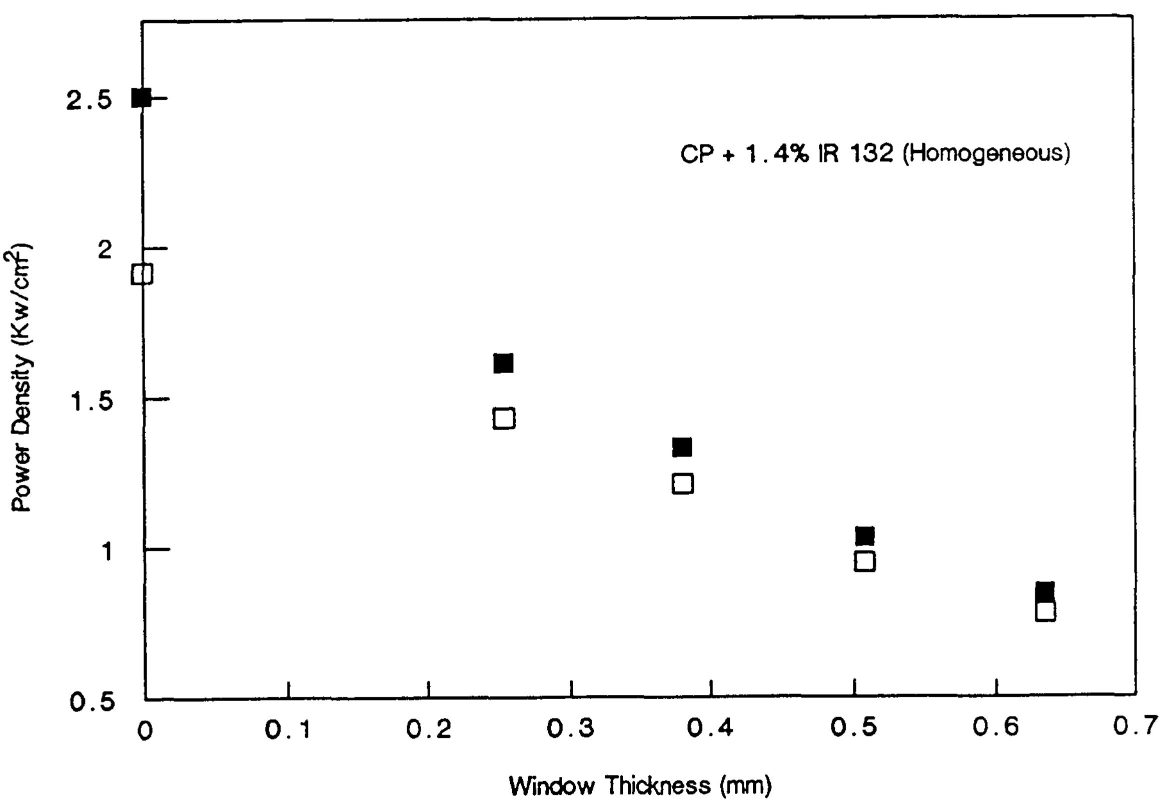


Figure 11. Ignition of CP through sealed sapphire windows. The powder was pressed to 1.7 g/cm^3 density and ignited using the standard 10 ms diode laser pulse through a 100 µm core diameter, 0.27 numerical aperture optical fiber.

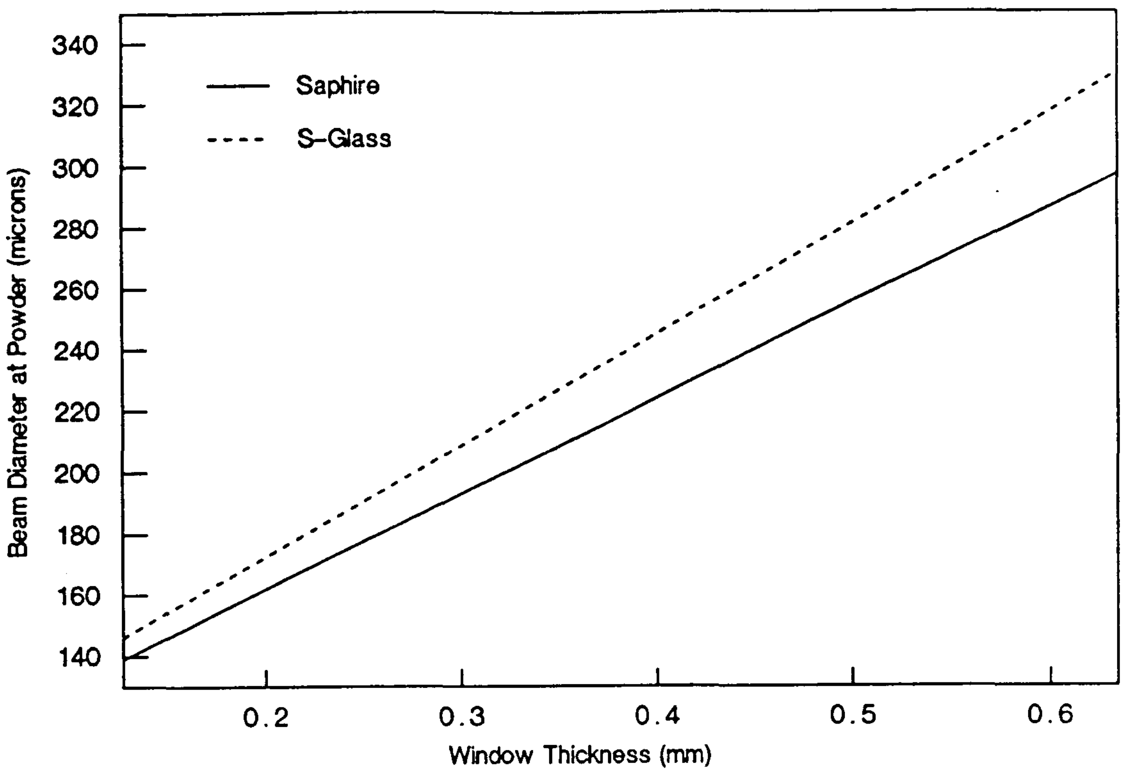


Figure 12. Diode laser beam expansion in optical windows starting from a 100 μm core diameter, 0.27 numerical aperture optical fiber.

thermal conductivity of sapphire (0.1 $cal \cdot cm \cdot s^{-1} \cdot cm^{-2} \cdot C^{-1}$) compared to silica (0.0032 $cal \cdot cm \cdot s^{-1} \cdot cm^{-2} \cdot C^{-1}$). Figure 12 shows the calculated beam expansion through various thicknesses of sapphire from a 100-μm core diameter, 0.27 numerical apperture (NA) optical fiber. The beam has expanded to three times its original size at the back of a 0.64-mm thick window. Ignition of $Ti/KClO_4$ was erratic in these devices, although a few did function when exposed to an optical power in excess of 800 milliwatts

Improved performance from a window header would be obtained by lowering the window thermal conductivity while maintaining a refractive index near to that of sapphire in order to limit beam expansion. Unfortunately, it is not possible to optimize both of these properties simultaneously. Preliminary information indicates that the most benefit is gained from lowering the thermal conductivity. This indicates glass to be the best overall choice for a window material if it is strong enough to survive loading. Reducing the NA of the fiber reduces beam expansion, but also lowers coupling efficiency at the interface to the diode laser. Lensing to refocus the laser output at the powder interface has also been proposed.[4]

Prototype headers containing sealed segments of optical fiber have also been fabricated. The particular fiber sealed was a 100/140 glass on glass step index fiber, but larger diameters could also be readily inserted. Test fire results (see Table 1) are identical to or better than those with the standard test fixture. This was expected since the only difference in the interface from an ignition standpoint is that the gas pressure may be slightly better confined in the sealed units. $Ti/KClO_4$ thresholds, in particular, have been sensitive to gas pressure and confinement in past studies.[8] The fiber segment ends are polished in these assemblies before attaching the explosive load sleeve and the threaded ring for the SMA connector lock nut. A visual inspection of the polish on the fiber ends can be effectively used to identify parts with poor optical throughput. Units with no visible defects showed diode laser output transmissions of 80-90%. Typical data are shown in Table 2.

Table 1. Ignition Thresholds with Hermetic Optical Feed Throughs

	Average of maximum no-fire, minimum fire (mJ)		
Material	Standard Test Device	100 um Dia. Sealed Fiber	0.38 mm Sealed Sapphire Window
CP + 1% carbon blk	1.25	1.25	4.25*
$Ti/KClO_4$	3.75	2.75	8.25

*estimated

CONCLUSIONS

Several parameters important for efficient ignition of energetic materials by laser diodes have been identified. The material characteristics which are most beneficial include high optical absorption near 800 nm and relatively low thermal conductivity.

Table 3. Optical Throughput of Sealed Fiber Segments

Transmission (%) of Diode Laser Output	Visual Defects	Transmission (%) of Diode Laser Output	Visual Defects
30	Rough	72	Chipped
82	-	83	-
83	Cladding chipped	47	Rough
35	Rough, chipped	81	-
87	-	35	Rough
86	-	87	-
50	Rough, chipped	86	-
90	-	52	Rough
82	-	86	-
45	Chipped	83	-
80	Small Chip	81	Small chip

Material performance can be enhanced, if necessary, by use of high optical absorbance dopants such as carbon black. Dopant concentrations of a few percent are optimum for the DDT explosive CP. The response of CP and $Ti/KClO_4$ pyrotechnic to diode laser energy is similar to that from the thermal processes involved in electric and stab igniters. Function times are reduced by increasing the applied optical power, although only a rather limited range is available from laser diodes before reaching the practical limit of 1 watt from the end of a 100-μm optical fiber. Tests with larger diameter fibers showed higher thresholds. With smaller diameters, there was no change from the 100 μm results. Protoype hermetic optical headers have been constructed and found to perform as expected based on these fundamental studies. CP can be ignited through sapphire windows, but thresholds are elevated due to beam expansion and higher thermal conductivity at the powder interface. Headers containing sealed 100-μm diameter fiber segments show lower thresholds for $Ti/KClO_4$ than found in the standard laboratory test fixture. This is likely due to an improved gas seal at the ignition surface.

ACKNOWLEDGEMENTS

We are pleased to recognize the contributions of C. D. Tuthill who fabricated header seals and C. E. Haynes who pressed most of the explosive charges. We also wish to thank D. W. Ewick and J. W. Fronabarger for furnishing energetic materials and for helpful discussions.

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