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# DIODE LASER IGNITION OF EXPLOSIVE AND PYROTECHNIC COMPONENTS

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The Laser Diode Ignition (LDI) program at Sandia Laboratories has as its objective the development of optically ignited analogs to the presently used low energy, hot wire igniters, DDT detonators, and actuators. In our concept, optical energy would be transmitted from a diode laser to the explosive or pyrotechnic powder via a fiber optic. The laser energy is coupled to the energetic powder through a hermetically sealed optical feedthrough in the charge cavity. Optical ignition has many advantages, most of which are related to the removal of electrical leads to the powder interface. This eliminates concerns such as sensitivity to electrostatic discharge and electromagnetic radiation, conductance after fire, and isolation resistance. The optical interface would also not have the corrosion tendency that has occasionally been a problem with bridgewires. Another convenient property of diode laser sources is that the current and voltage needed to drive them are quite similar to those now applied to bridgewires for hot wire ignition. Therefore LDI devices would have an overall electrical requirement which is nearly identical to that of the hot wire components they are replacing.

Figure 2 shows a schematic diagram of an LDI subsystem. The main parts are the diode laser and its associated power supply, a fiber optic cable, and the explosive or pyrotechnic chargeholder which contains an optical feed through. The two critical interfaces in this subsystem are those between the diode laser and the fiber and the optical interface with the energetic material.

Figure 3 identifies the groups which are supporting the Laser Diode Ignition Project. Explosive interface studies and subsystem design are being carried out in Sandia Division 2512. The development of diode lasers for this application and evaluation of laser interfaces with optical fibers is occurring in Sandia Division 2531. Modeling of the optical ignition process and measurement of optical parameters needed by the models is being done by Sandia Divisions 1512 and 6224. Development of methods for constructing the optical feed throughs which are a critical part of prototype LDI headers is the responsibility of Sandia Division 7471. Finally, EG&G/Mound is also supporting this project in the area of threshold testing and is starting to construct sealed optical feed throughs to be used as headers.

A number of different factors have been examined to determine their influence on ignition so that the performance of diode laser igniters can be optimized. Figure 4 shows some of these having to do with the properties of the energetic material, the form of the laser energy delivery, or the design and materials of the optical header. Some of these will be discussed in more detail shortly. Figure 5 lists the maximum laser power and energy conditions which can be achieved with our laboratory test equipment. One watt of optical power at 820 nm can be obtained from a 100-µm core diameter optical fiber. This is equivalent to a power density

of 13 kilowatts/$cm^2$ and an input energy of 10 mJ (130 J/$cm^2$) with our standard 10 ms laser pulse. The level of laser power obtainable with this system has proved to be more than adequate to ignite materials typically used in our hot wire components. Two energetic materials commonly found in Sandia low energy component applications are CP and Ti/$KClO_4$. CP readily undergoes deflagration-to-detonation transition (DDT) and so can be used to obtain a detonation output from an ignition source.

Figure 6 shows the measured optical absorption spectrum of these materials. Ti/$KClO_4$ is a strong absorber at 820 nm due to the presence of the finely divided Ti particles, but the absorption of CP is not particularly strong in the near-infrared region. It is therefore necessary to add dopants to CP in order to boost the absorption of the wavelengths emitted by the diode lasers (typically 775 - 850 nm depending on the particular diode). The Figure also shows the effect of adding 3.2 weight % graphite to CP. Carbon black has been found to be even more effective than graphite at raising the absorptance near 800 nm.

A standard laboratory test device has been used to measure ignition thresholds for this project. The fixture, shown in Figure 7, is fairly cheap and easy to assemble and still allows some flexibility for testing different configurations of the optical fiber/powder interface. A standard SMA fiber optic connector is used to hold the fiber in tight contact with a 0.0875 inch diameter by 0.1 inch long charge of explosive or pyrotechnic which has been pressed into a stainless steel sleeve. Optical window materials or spacers can also be inserted between the connector ferrule and the powder in order to study their effect on ignition.

Figure 8 shows typical threshold test data which were obtained using this test fixture (at EG&G/Mound). The thresholds are sharp and well within the 10 mJ energy limit of the test laser. Doping the CP with 0.68% carbon black has lowered its threshold below that of Ti/$KClO_4$. CP thresholds show little dependence on powder density over the range studied, however Ti/$KClO_4$ thresholds do start to increase if the density is too high. This is thought to be a result of the increasing thermal conductivity of the charge at higher densities. An extensive investigation of the optimum dopant and dopant level to produce the lowest threshold for CP explosive has also been carried out using the standard test fixture. Results are shown in Figure 9. Even a small amount of dopant lowers the threshold from the 6 to 7 mJ level found for undoped CP. A number of different materials were compared, including carbon black, IR-132 (a laser dye which absorbs selectively near 800 nm in solution) and KTNBC (an energetic material which absorbs strongly at 800 nm). There was not a clear difference in effectiveness among the various dopants over the concentration range shown. IR-132 can also be mixed with CP by coprecipitating the two materials. This forms a mixture where the dopant particles are too small to be distinguished by optical microscopy. These blends are therefore termed "homogeneous", but their ignition thresholds were similar to those of the physical blends. The data point for CP doped with 1.4 weight % carbon black appears to be anomalous, and in fact other data at higher concentrations indicate that thresholds with this dopant also continue a slow decrease. A new blend is being made up to check this, but test results are not available yet. Production CP has been doped with carbon black at concentrations up to 10%, and shows thresholds that are essentially flat from 1% to 10%. This means that the amount of dopant in CP will not have to be controlled to a very tight tolerance in order to use it in LDI components. It was anticipated that KTNBC might continue to reduce CP thresholds at high concentrations since it is energetic, while the inert dopants would eventually dilute the explosive enough that thresholds would start to increase. This has not occurred yet at 1.4%, although the KTNBC sample was the most sensitive at that point by a narrow margin. Additional CP samples containing higher concentrations of KTNBC are being blended to test this idea further.

Figure 10 shows the energy - power relationship for $Ti/KClO_4$ and a doped CP sample. There is a clear minimum laser power required for ignition of both materials. $Ti/KClO_4$, which has the higher thermal conductivity, requires the higher minimum laser power for ignition. At higher laser powers, the function times of these ignition charges decrease, resulting in a slowly decreasing amount of total energy in the ignition pulse.

Another parameter which has been found to be important in determining ignition thresholds is the diameter of the laser spot at the ignition interface. This has been studied by using different diameters of optical fiber in the standard test device. Results from these tests are shown in Figure 11 for both $Ti/KClO_4$ and doped CP. Fiber core diameters up to 300 µm were studied, but the powders were only ignitable from diameters of 200 µm and below. The power density at threshold decreases as fiber diameter increases since the spot area is increasing faster than the power required for ignition. The right hand plot in the Figure shows that the ignition energy in the constant 10 ms width pulse is rising, however. A tradeoff therefore exists between the larger diameter fiber desired for efficient coupling to diode lasers and the smaller diameter which will minimize the laser power required for explosive or pyrotechnic ignition. Reducing the fiber diameter to less than 100 µm did not offer as much of an improvement in threshold performance as occurred when reducing to 100 µm from larger diameters, particularly for CP.

Figure 12 presents several concepts which are being evaluated for constructing prototype LDI headers. These each have advantages and disadvantages, so that a variety of header types will probably eventually be used in LDI components, depending on the particular application. The in-situ sealed pigtail of fiber optic may be needed to produce very small devices since it eliminates a connector on the component itself, but we have done little evaluation of this design to date. A few prototypes have been fabricated and will be loaded and fired soon. The area where the fiber exits the housing is a high stress region which must have some sort of strain relief to avoid fiber breakage. Most of our effort has been with the next two concepts, the sealed fiber connector and the sealed sapphire window. The sealed connector has the advantage of preserving a small laser spot size at the powder interface, but alignment at the connector interface is critical to obtain a high optical throughput. The sealed window removes the alignment requirement, but beam divergence in the window increases the spot size. This could potentially be eliminated by adding some sort of reimaging lens system. Some threshold testing results with sealed connector and window optical feed throughs will now be presented.

Figure 13 shows a test fixture containing a sealed 100-mil diameter sapphire window. Window thicknesses of from 10 mils to 25 mils have been successfully sealed in this configuration. The unit is fairly small and is designed to mate with a standard SMA fiber optic connector. As was mentioned earlier, laser beam expansion occurs in this design and Figure 14 shows the calculated beam diameter at the powder interface as a function of window thickness. A 0.6 mm (25 mil) thick sapphire window expands the beam by about three times. Glass windows, which are being evaluated presently, expand the beam slightly more but may still improve thresholds due to their lower thermal conductivity than sapphire. Sapphire was chosen for initial evaluation because it was felt that its high strength would maximize the chances of surviving the loading operation.

Figure 15 shows the ignition thresholds of a homogeneously doped CP sample in sealed window fixtures with different window thicknesses. The increase in threshold as window thickness increases is evident. $Ti/KClO_4$ was difficult to ignite in this hardware, although some samples were fired through 15-mil thick windows at laser powers near the limit of what is available from our test set up. $Ti/KClO_4$ thresholds are higher than those of doped CP to begin with and are expected to be more influenced by thermal conductivity of materials at the ignition interface. Therefore, glass may be the preferred window material for $Ti/KClO_4$ and experiments are under way to study this.

A sealed fiber segment header is shown in Figure 16. The design incorporates two seals, one between the optical fiber and an alumina ferrule and another between the ferrule and a stainless steel housing. Both seals are formed simultaneously in a belt furnace operation. The side view shows a ceramic split sleeve protruding from the back end which aligns the sealed fiber core with the core of the fiber in a mating SMA connector. Assembly of this fixture is completed by welding a sleeve on the front end to hold the explosive charge and another on the back which is threaded for the SMA connector nut. The fiber is sealed in before attaching these sleeves so that the fiber ends can be more easily polished after the seal is completed. Figure 17 compares ignition thresholds obtained in this fixture with those obtained with the standard test device and sealed window units. The performance of the sealed segment device was as good or better than that of the other two. This is due to its favorable combination of small spot size, low interface thermal conductivity, and good seal of gas pressure during ignition. This design is the preferred one on the basis of these data.

Figure 18 summarizes the results of this advanced development program. The four important points are: (1) High optical absorptance is important and CP must be doped with materials which will enhance this property in order to achieve maximum performance. (2) Other significant parameters are powder density (which can affect thermal conductivity) and confinement, spot size, and thermal conductivity of other interface materials. (3) Prototype sealed optical feed throughs (windows or fiber segments) have been constructed and evaluated. Sealed fiber segments showed superior performance. (4) Ignition of doped CP and undoped $Ti/KClO_4$ was achieved from commercial diode lasers with less than 200 milliwatts of input power.

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# LASER DIODE IGNITION (LDI) PROGRAM

OBJECTIVE: DEVELOP OPTICALLY IGNITED DEVICES TO REPLACE LOW ENERGY, HOT WIRE IGNITERS, DETONATORS AND ACTUATORS

CONCEPT: TRANSMIT OPTICAL ENERGY FROM A LASER DIODE TO AN EXPLOSIVE OR PYROTECHNIC POWDER VIA A FIBER OPTIC. THE FIBER IS COUPLED TO THE POWDER THROUGH A HERMETICALLY SEALED WINDOW, FIBER FEEDTHROUGH OR A REIMAGING LENS / WINDOW SYSTEM

ADVANTAGES: THE ABSENCE OF A BRIDGEWIRE AND ELECTRICAL LEADS ELIMINATES POWDER / BRIDGEWIRE INTERFACE DECOUPLING AND CORROSION CONCERNS; NO-FIRE, CAF, ESD, EMR AND IR CONCERNS ARE REDUCED

INPUT ENERGY REQUIRED IS COMPARABLE TO HOT WIRE DEVICES

LOWER COST (FABRICATION AND TEST)

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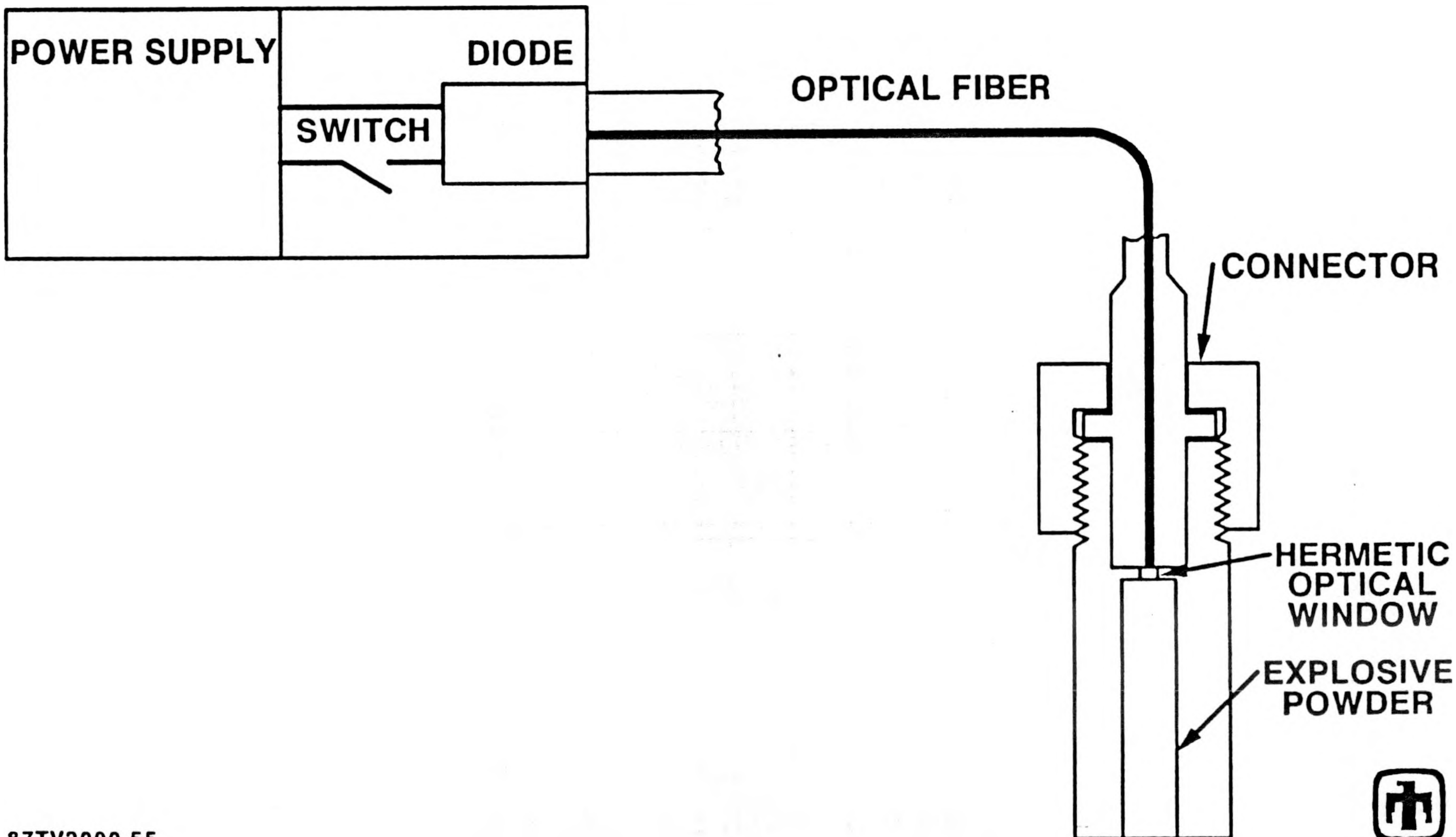
# LDI SUBSYSTEM

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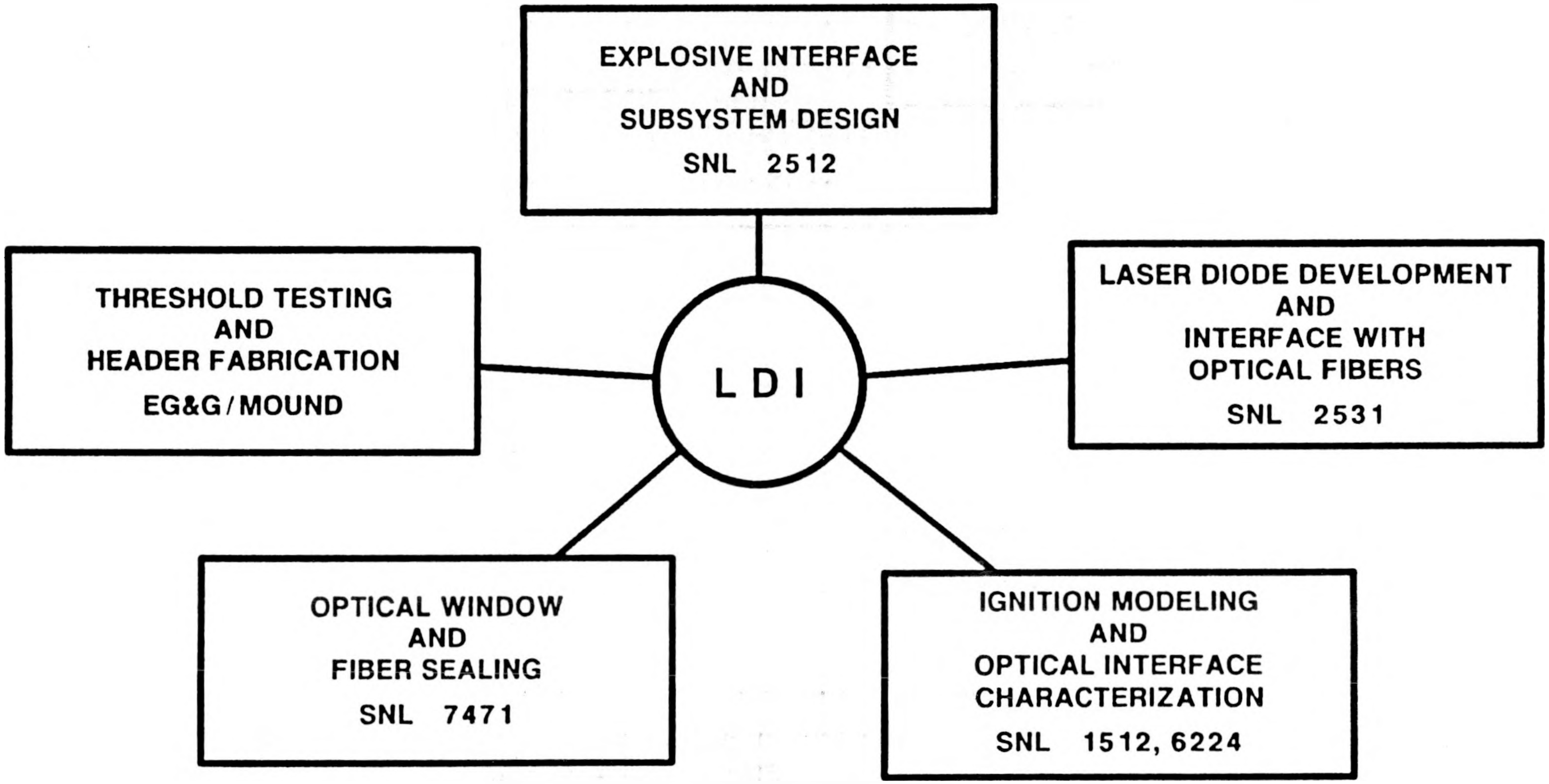
# LASER DIODE IGNITION PROJECT SUPPORTING ORGANIZATIONS

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# DIODE LASER IGNITION FACTORS

Energetic Material Characteristics:

- Optical Absorptance at Laser Wavelength
- Ignition Temperature
- Thermal Conductivity

Laser Energy Delivery:

- Pulse Width and Height
- Spot Size
- Wavelength

Optical Header Properties:

- Thermal Conductivity
- Beam Divergence
- Powder Confinement

# LASER DIODE IGNITION

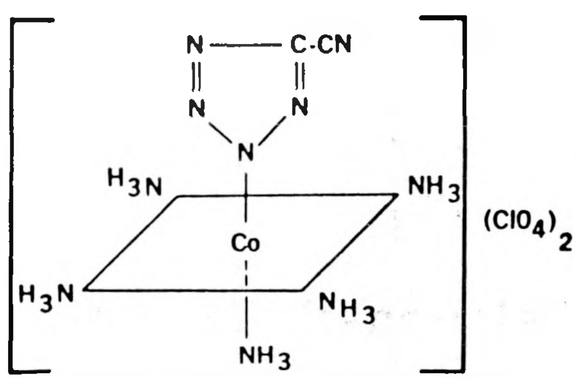
**EXPERIMENTAL CONDITIONS:** Driving a (GaAl)As laser diode (820 nm) yields 1 Watt from the fiber

Diode is butt-coupled to 100 micron core fiber

Power density into HE is 13 kW / cm$^2$

With 10 ms pulse, input energy to HE is 10 mJ or 130 J / cm$^2$

**RESULTS:** Ignition of pure and doped CP and Ti / $KClO_4$




CP
yellow crystals, 2.01 g/cm$^3$

8/21/87
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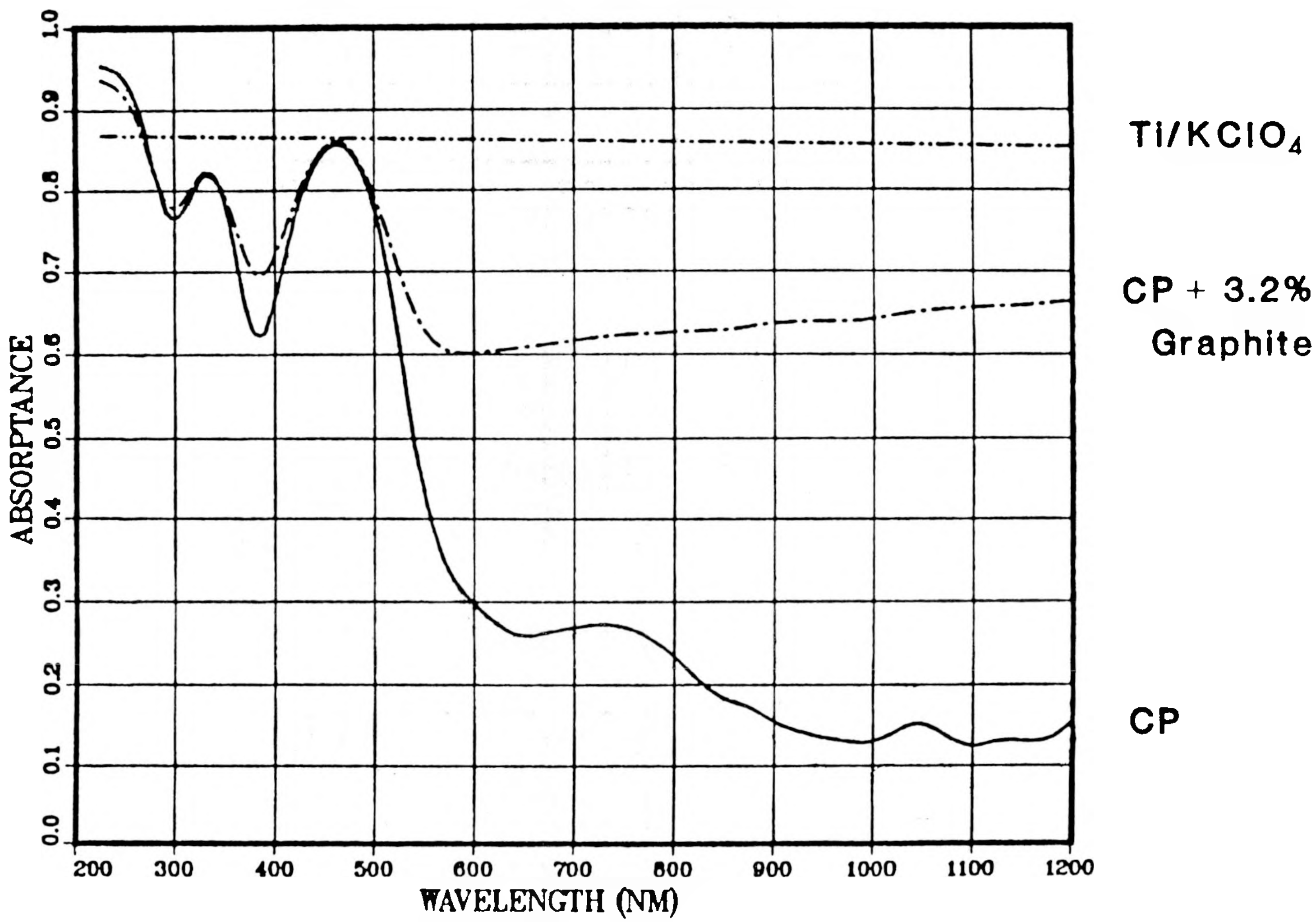
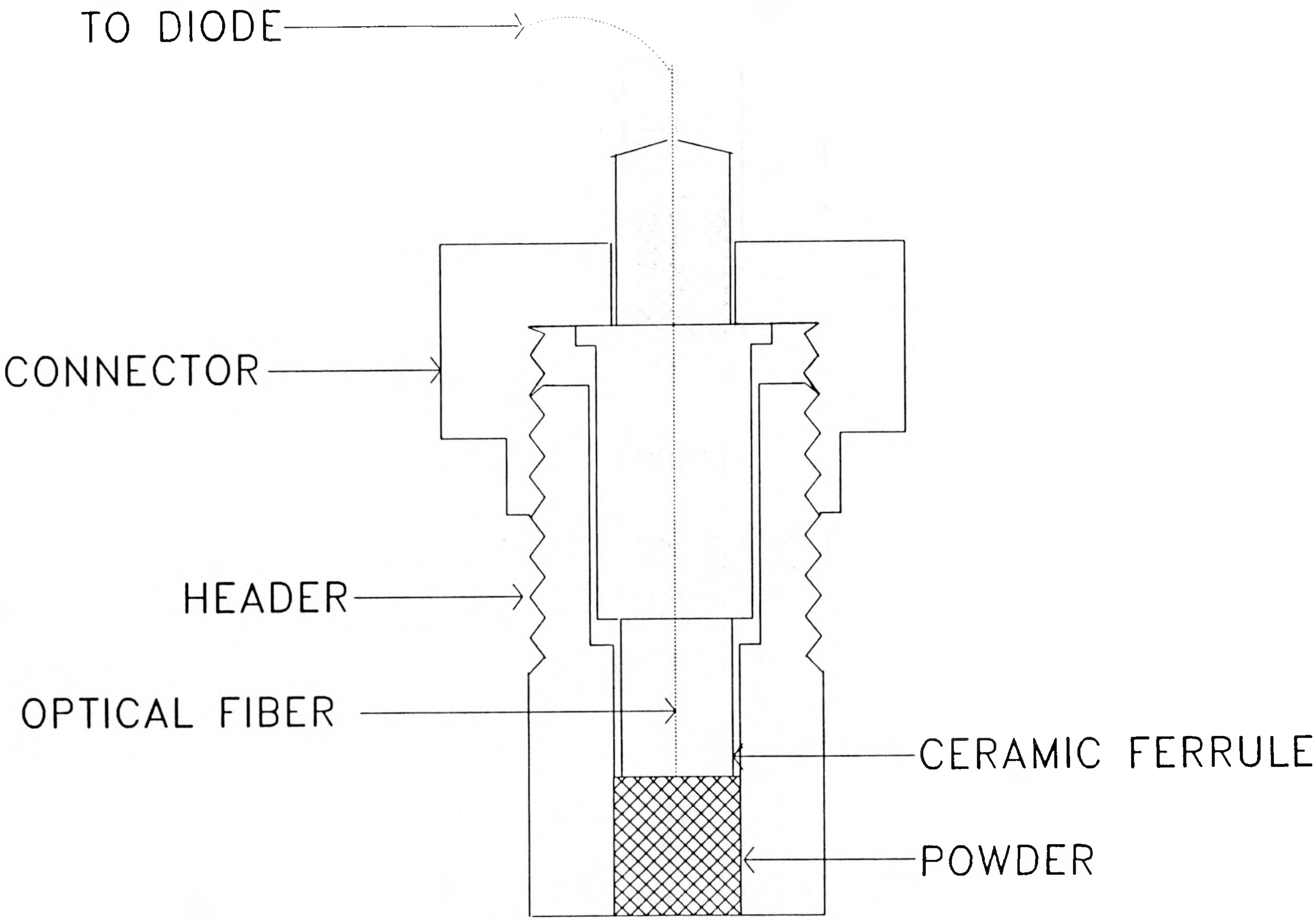
# SPECTRUM OF LDI MATERIALS



# LDI TEST DEVICE



# LASER DIODE IGNITION PROJECT
# THRESHOLD DATA WITH FIBER IN DIRECT POWDER CONTACT

| | DENSITY ($g/cm^3$) | THRESHOLD (mJ) | SIGMA (mJ) | N |
|---|---|---|---|---|
| CP + 0.68% CARBON BLACK (LOT 86028) | 1.3[a] | 1.12 | 0.07 | 10 |
| | 1.5 | 0.98 | 0.12 | 10 |
| | 1.7 | 1.08 | 0.03 | 10 |
| $Ti/KClO_4$ (LOT PB-98) | 1.6[a] | 2.57 | - | 5 |
| | 1.8 | 2.59 | 0.05 | 10 |
| | 2.0 | 2.94 | 0.16 | 10 |
| | 2.2 | 3.52 | 0.16 | 10 |

10ms pulse
100μm core fiber

[a] Assembled with epoxy

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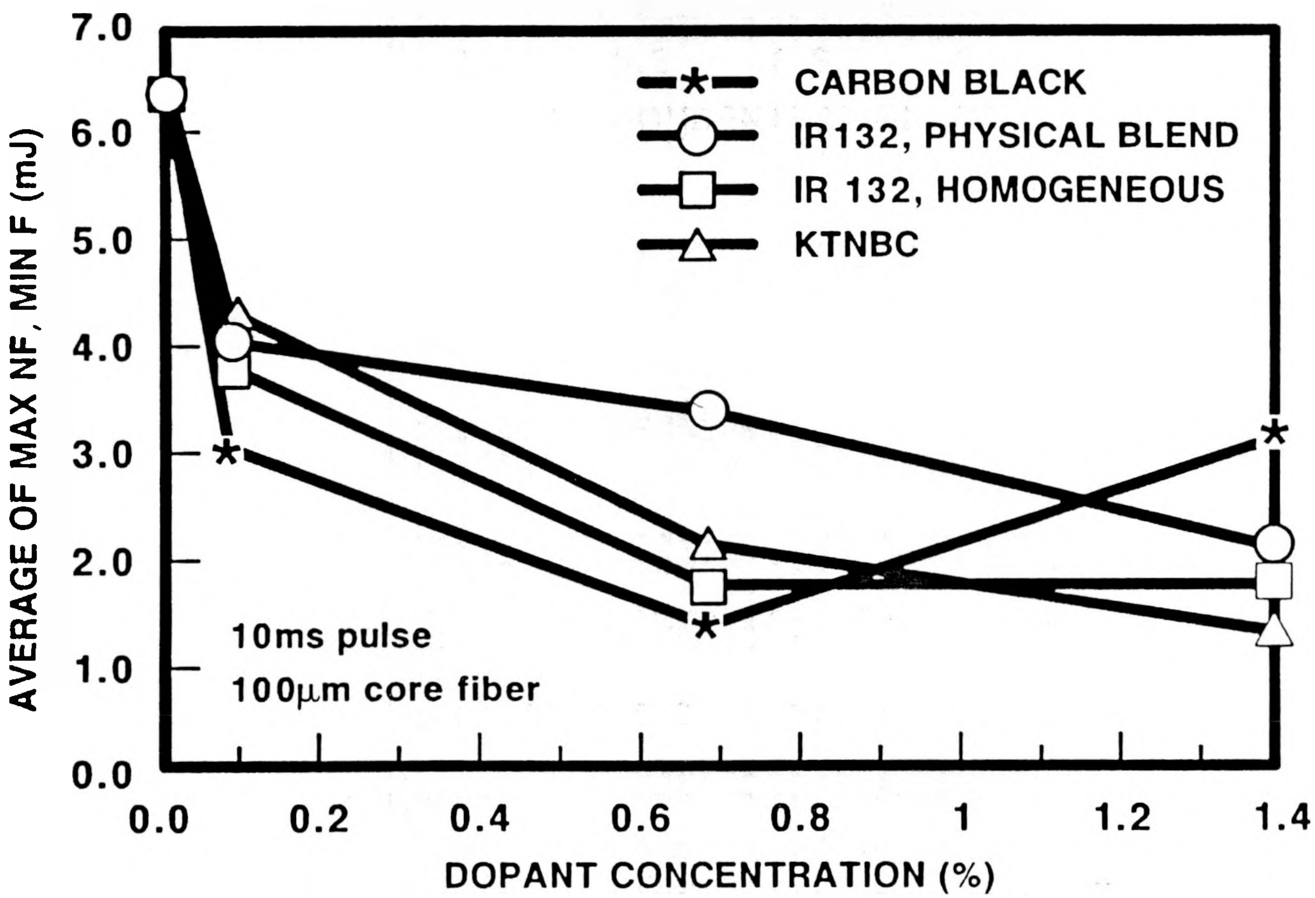
# LASER DIODE IGNITION PROJECT
# DEPENDENCE OF CP THRESHOLD ON DOPANT

PRECIPITATED CP, 1.7 $g/cm^3$

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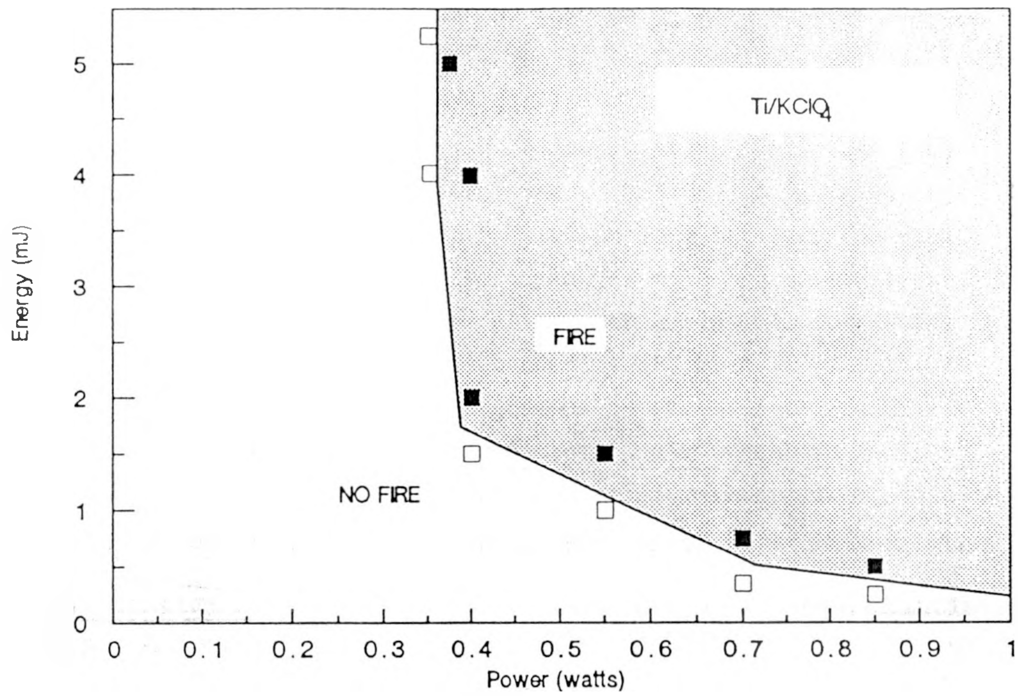
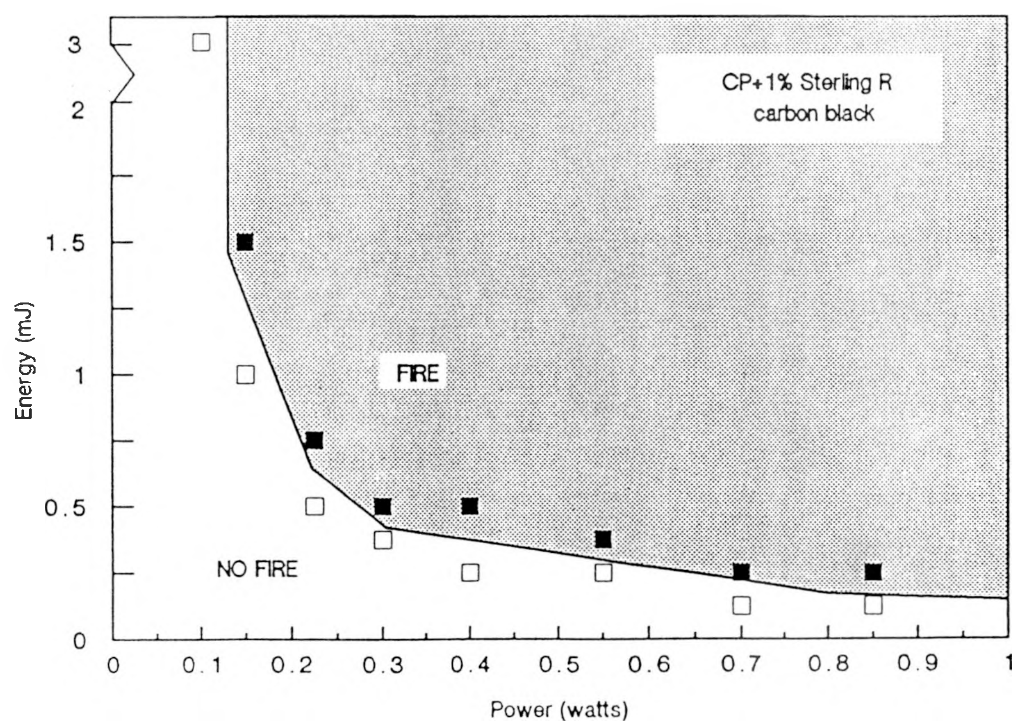
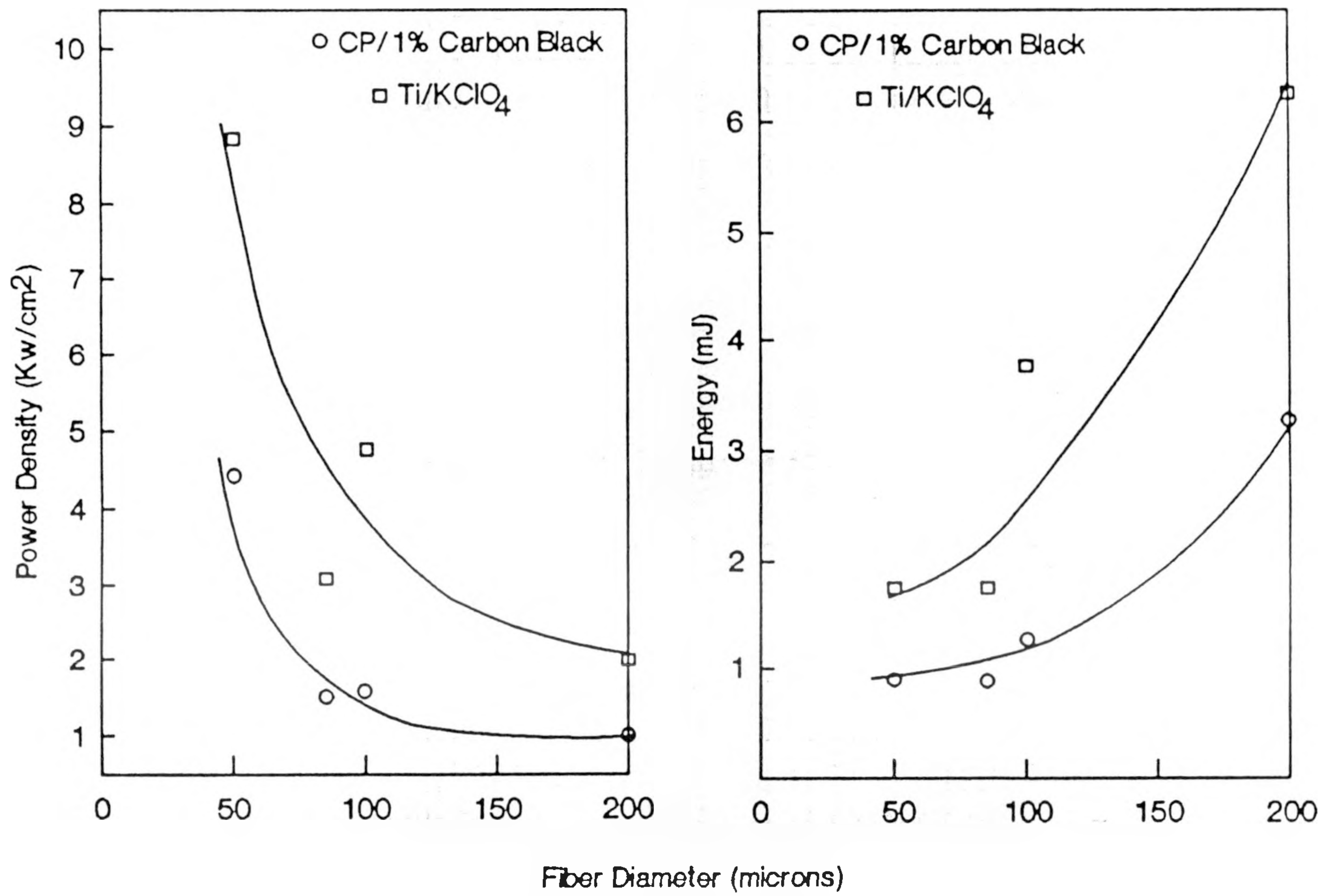
# Energy - Power Relationship for Diode Laser Ignition



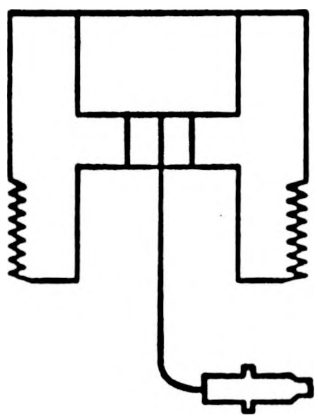




100-μm core diameter, 0.27 NA optical fiber

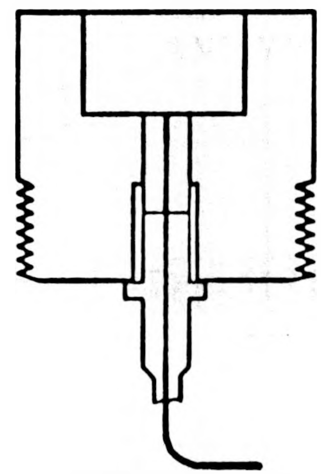
# Fiber Diameter Effect on Ignition Thresholds



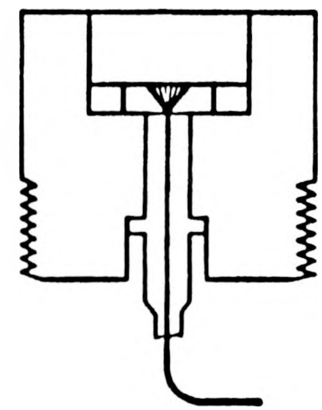
# FIBER / POWDER INTERFACE CONCEPTS



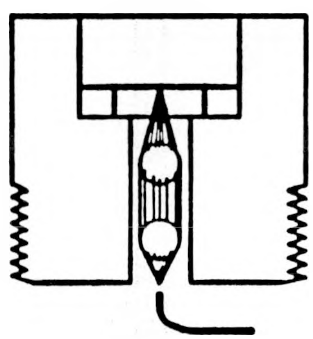
IN-SITU SEALED
FIBER OPTIC PIGTAIL



IN-SITU SEALED
FIBER CONNECTOR

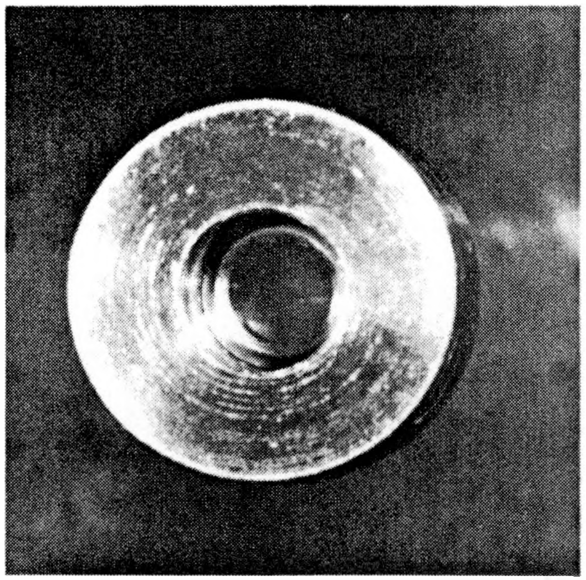


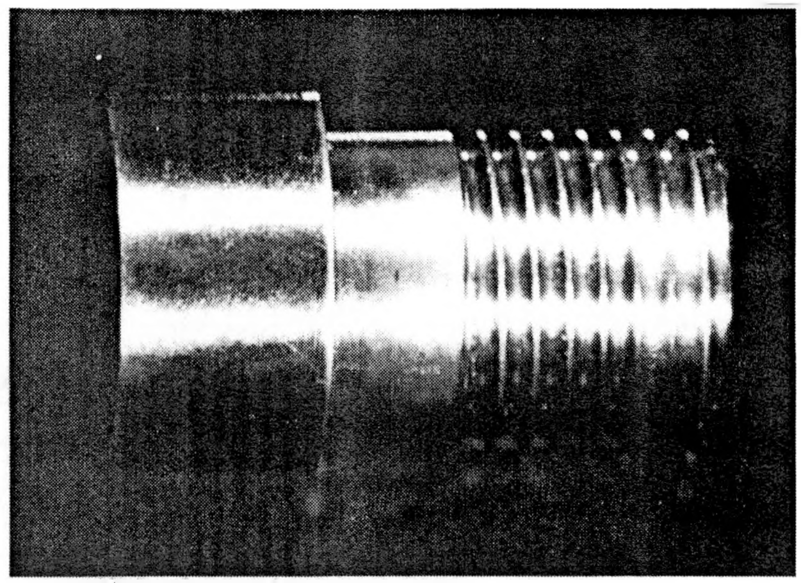
SEALED SAPPHIRE
WINDOW



REIMAGING BALL LENS
AND WINDOW SYSTEM

# Sealed Window Test Fixture

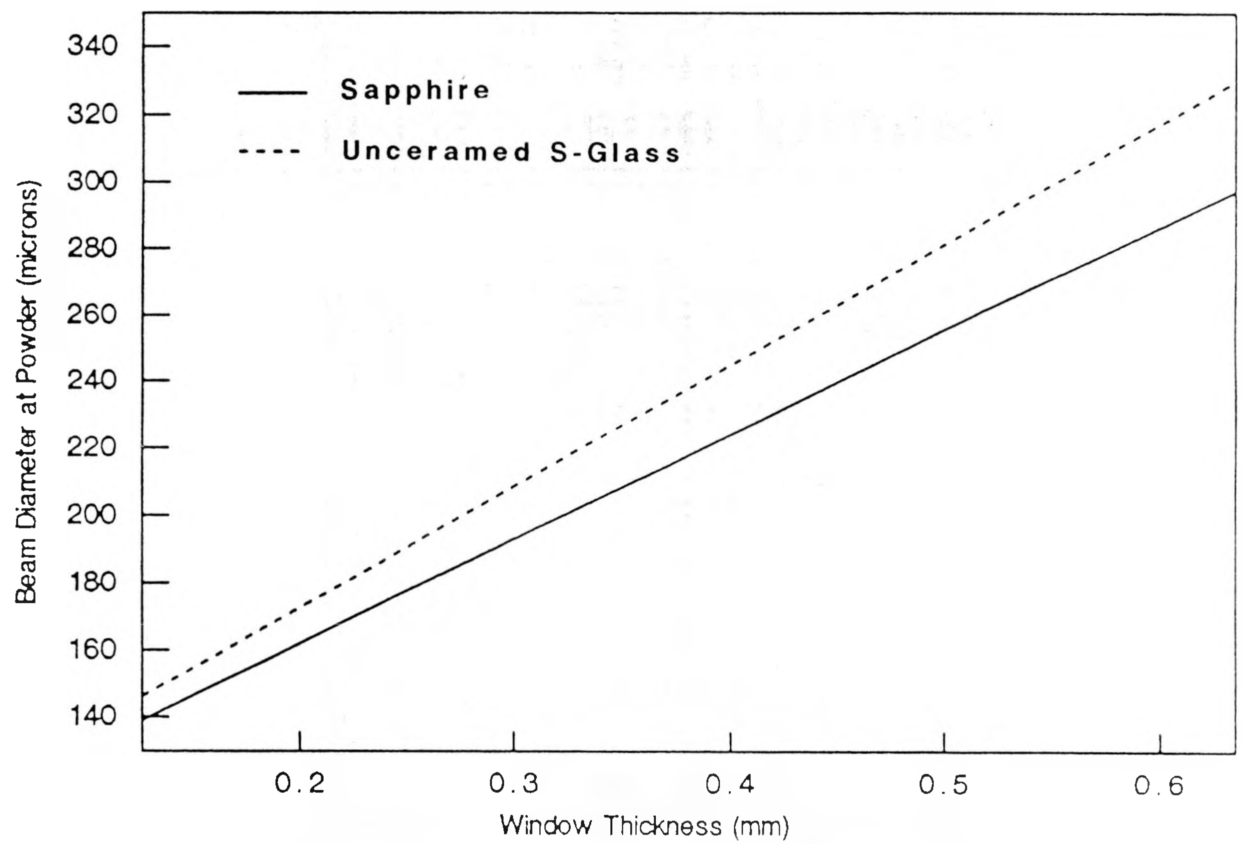




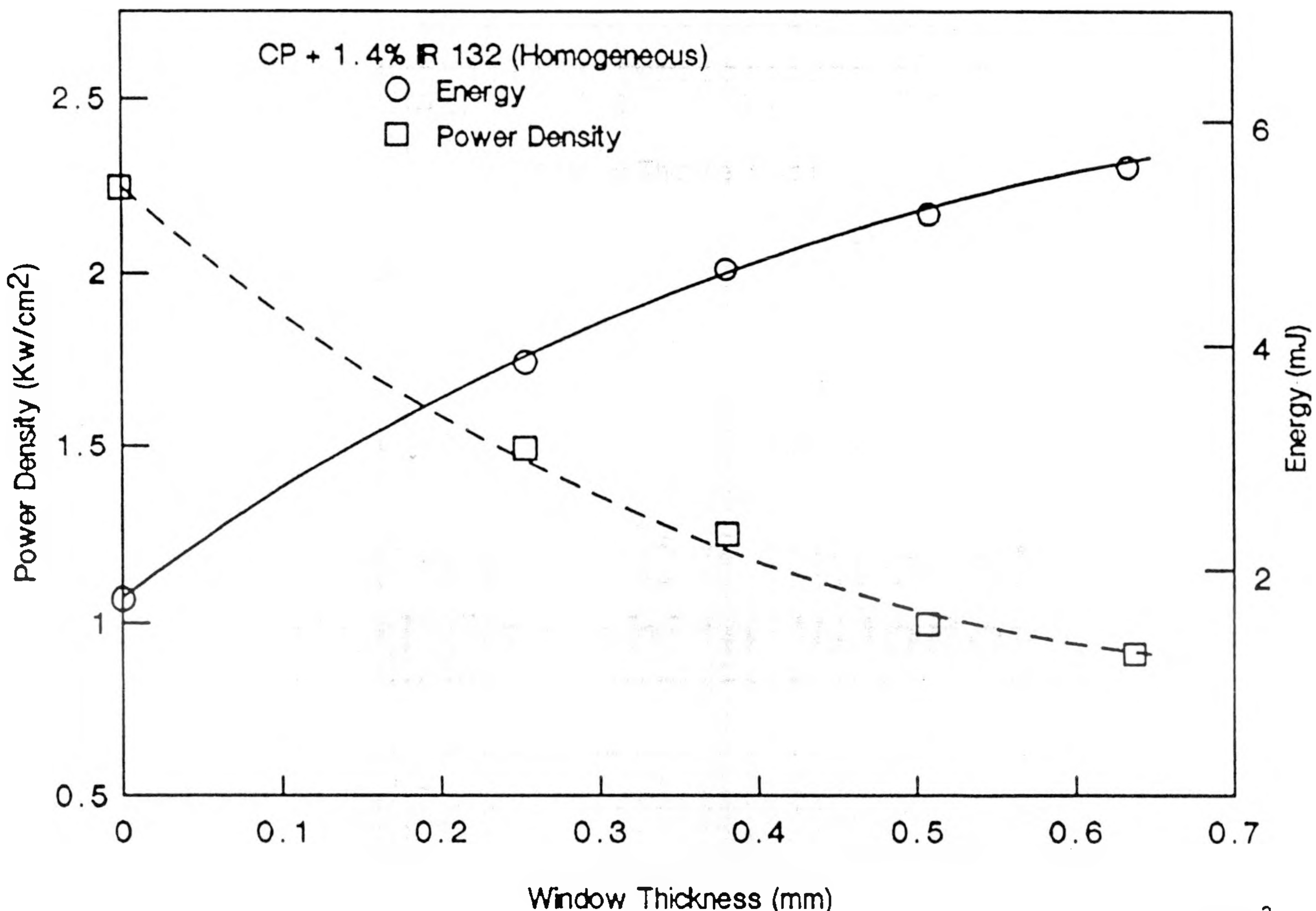
1 cm

# Laser Beam Expansion in Optical Windows

100-μm core diameter, 0.27 NA optical fiber input

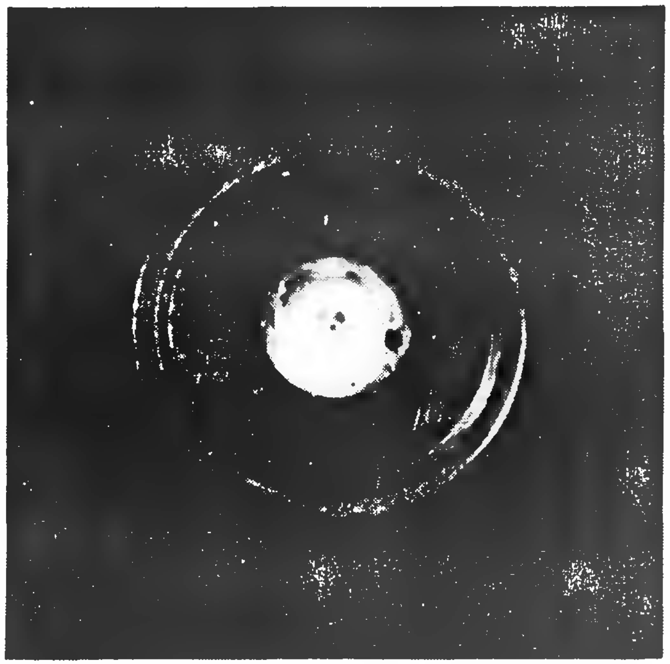


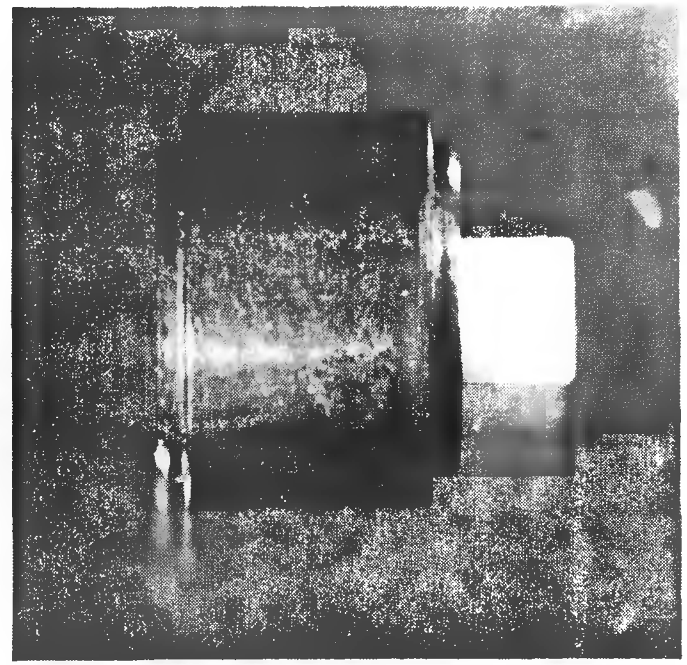
# Ignition of CP Through Sealed Sapphire Windows




1.7 g/cm$^3$ density
10 ms pulse width
100 $\mu$m diameter, 0.27 NA fiber

# Sealed Optical Fiber Test Fixture





1 cm

## COMPARISON OF IGNITION THRESHOLDS WITH DIFFERENT HERMETIC OPTICAL FEED THROUGHS

### Average of Maximum No-fire, Minimum Fire (mJ)[a]

| Material | Standard Test Device | 100 - μm Core Diameter Sealed Optical Fiber | 0.38 - mm Thick Sealed Sapphire Window |
|---|---|---|---|
| CP + 1% Carbon Black | 1.25 | 1.25 | 4.25[b] |
| $Ti/KClO_4$ | 3.75 | 2.75 | 8.25 |

[a]10 ms pulse length
[b]estimated

## SUMMARY

- High optical absorptance at the ~800 nm diode laser wavelength is the most important material factor in obtaining low ignition thresholds. $Ti/KClO_4$ is inherently a good absorber, but the performance of CP can be significantly enhanced by adding dopants.
- Powder density and confinement, laser spot size, and the thermal conductivity of materials at the ignition interface are other parameters which must be considered when optimizing a diode laser igniter.
- Prototype optical headers containing sealed windows or fiber segments have been fabricated, loaded with CP or $Ti/KClO_4$, and test fired.
- Ignition of doped CP and undoped $Ti/KClO_4$ has been achieved from commercially available diode lasers at energies below 2 mJ (200 mwatts for 10 ms).