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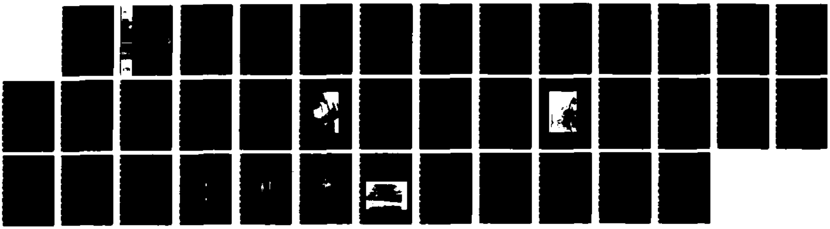

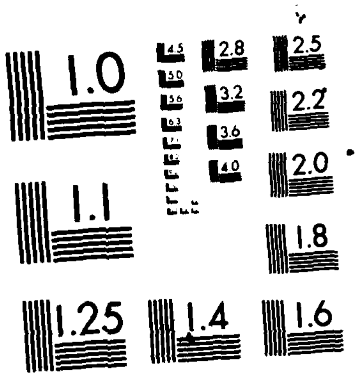

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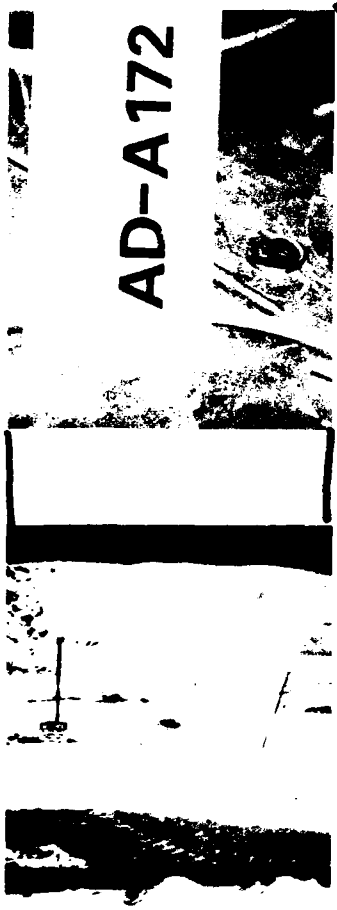

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LIGHT-INITIATED DETONATION SYSTEMS

by

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Final Report

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Explosives can, theoretically, be initiated either by photochemical reactions or by heat and shock effects in sensitive compounds. Explosive photochemical reactions are attractive because they require very low energy inputs and operate at specific wavelengths. However, most of these reactions require energetic (ultraviolet or near ultra-violet) light. The optical fibers that are presently manufactured are intended for data transmission and have low efficiency at short wavelengths. Heat and shock initiation uses longer wavelengths that are transmitted efficiently on existing fibers.

Numerous light sources could be employed in detonation systems, but lasers have the most efficient coupling to optical fibers and can generate energetic light pulses required for detonation. Flash lamp-pumped, solid state lasers are presently the most useful light source for explosives initiation. Laser diodes in current production cannot generate enough energy for practical applications. (Continued)

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The most useful optical fiber for blast line application is a step index fiber with a large core-to-cladding ratio. The large core minimizes energy losses due to misalignment core of fibers in connectors. Couplers that involve mechanically crimped connectors and cleaved fibers, rather than the epoxy-cemented connectors with polished fibers, provide superior energy transmission due to the reduced carbonization at the fiber end.

Detonators for optical initiation systems are similar in basic construction to those employed in electrical initiation systems. Explosive and pyrotechnic charges can also be similar. Either primary or secondary explosives can be initiated in present laser-based systems. Two laser detonation systems are presently accessible; a multiple-shot laser with a single-shot, single fiber system designed for use with detonators containing primary explosives.

Additional research related to development of low-energy, photoreactive detonators, continuity checking techniques and improved connectors and fibers can produce significant improvements in presently fielded systems.

PREFACE

This study was conducted by the US Army Engineer Waterways Experiment Station (WES) for the Assistant Secretary of the Army (R&D) as an In-House Laboratory Independent Research (ILIR) Project under Project No. 4A161101A91D Task Area 02, Work Unit 164. Portions of Parts II and III of this report were prepared by Ensign-Bickford Company under Contract No. DACA39-86-M-0323 dated 7 January 1986.

This report was prepared by Mr. Stafford S. Cooper of the Field Investigation Group (FIG), Earthquake Engineering and Geophysics Division (EEGD) and Dr. Philip G. Malone of the Site Characterization Unit (SCU), Engineering Geology Applications Group (EGAG), Engineering Geology and Rock Mechanics Division (EGRMD), Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES) and Messrs. Stephen W. Bartholomew and William J. Necker, Blasting Products Division, The Ensign-Bickford Company (E-B).

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The management and staff at Ensign-Bickford provided assistance in documenting existing laser-initiating systems and reviewing current developments in laser-detonator technology. Contributions from the following staff members are gratefully acknowledged:

Mr. Stephen E. Cebry	Blasting Products Division
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Mr. Richard L. Williams	Ensign-Bickford Optics Company

Immediate supervisors for the project were Messrs. Joseph R. Curro, Jr, Chief, FIG and James J. May, Chief, SCU. General supervision was provided by Drs. A. G. Franklin, Chief, EEGD and Don C. Banks, Chief, EGRMD and Dr. William F. Marcuson III, Chief, GL.

During preparation of this report, COL Allen F. Grum, USA, was Director of WES, and during publication of this report, COL Dwayne G. Lee, CE, was Commander and Director of WES. Dr. Robert W. Whalin was Technical Director.

CONTENTS

LIGHT-INITIATED DETONATION SYSTEMS

PART I: INTRODUCTION

Background

1. Explosives can be initiated by a wide variety of energy inputs, kinetic energy, electrical discharge, heat and light. Detonation of an explosive occurs when the movement of the reaction front in the explosive compound is faster than the speed of sound in the material. Initiators are devices designed to produce the rapid chemical reaction in the explosive and usually contain shock- and heat-sensitive compounds that can start the rapid reaction front. For example, an electric blasting cap contains a short length of high resistance wire that is heated by the current from the blasting machine to a temperature that will ignite a pyrotechnic mixture that sets off the cap primer charge and base charge. The base charge produces the reaction front in the explosive.

2. The basis of a reliable detonation system is to develop a unique method of inputting energy that cannot be duplicated by external conditions other than those produced by blasting machine. Conventional electric blasting does not satisfy this basic requirement. The commercial, domestic, electric blasting cap requires 1.5 amperes of current to reliably fire but a chance firing may occur with current as low as 0.25 amperes, and a recognized risk of accidental detonation occurs if stray currents of even 0.05 amperes occur in the firing circuit. A lightning strike generates a discharge of 20,000 amperes causing very dangerous levels of extraneous current around a discharge point. Stray electric current from ungrounded or poorly-grounded electrical equipment (especially motors) can produce a serious hazard when blasting circuits are laid across rails, pipelines or duct work. Induced electric currents can also be produced around electric power lines. Radio frequency energy from radio or radar transmitters in the immediate vicinity of an electrical blasting cap can cause accidental detonation (Atlas Powder Co., 1976; E. I. Dupont de Nemours and Co. 1980). Electric blasting caps are vulnerable to a variety of uncontrollable interferences from the surroundings that might occur during a modern military conflict where blasting circuits must be laid down across unknown

areas in any type of weather; radio transmission cannot be controlled and massive electromagnetic pulses can be produced from nuclear weapons.

3. Light-initiated detonators operate in the same manner as electrically-initiated detonators in that the energy pulse traveling in a conduit produces a violent chemical reaction in a sensitive chemical compound that in turn produces a reaction in a primer charge, a base charge and the main charge. The light initiated detonators have inherent advantages because of the easily shielded energy pulse employed (ultraviolet, visible, or infra red light) and the non-conductive transmission line (glass fiber) that is needed. The detonator can be made to respond to only a light pulse of a specific minimum energy density and theoretically can be made to respond only to the light of specific wavelengths.

4. Light-initiated detonators have the characteristics needed to solve the problem of developing a unique energy source for detonation of explosives. The optical fiber energy transmission lines have the advantage of being light-weight, insulators with high survivability (Elliott, 1986). The major advantages when the two-components are put together can be summarized as follows:

a. Light-initiated detonators require an intense light source such as a flash tube or a laser that cannot be easily duplicated by other natural or man-made light sources.

b. Optical fibers are immune to induced-energy from electrical or radio-frequency sources and present no hazards even when in contact with power lines.

c. Optical fibers are not detectable if incorporated into a metal-free cable.

d. Optical fibers are difficult to tap.

e. Fiber cables are lighter than metallic cables.

f. Optical fiber links can survive intense gamma radiation and remain functional.

Purpose

5. The purpose of this interim report is to:

a. outline the bases for current and future light-initiated detonation systems,

b. discuss a current system that uses a laser with glass fiber optic transmission,

c. provide a summary of current status and recommendations for future research activities.

PART II: BASIS OF LIGHT-INITIATED DETONATORS

Photochemical Initiation

6. Light (ultraviolet thru infrared) can initiate or accelerate a wide variety of chemical reactions. In some gas mixtures, light can act as a trigger that begins a reaction that runs to completion without further light input. The reactions of the halogen gases (chlorine, iodine and fluorine) with hydrogen are excellent examples (Lee, Knystautas and Yoshikawa 1978). The most studied chain reaction involves reactions of hydrogen with chlorine. A hydrogen/ chlorine mixture is stable indefinitely in the dark but an explosive reaction can occur if the gas mixture is exposed to light of wavelengths below 546.1 nm (Noyes and Leighton, 1941; Bonhoeffer and Harteck, 1933). The short wavelength light provides the energy necessary to dissociate the chlorine molecule into two highly reactive chlorine atoms. A chlorine atom combines with an H_2 molecule to yield one molecule of HCl and a free hydrogen atom. The reaction proceeds as a rapid chain of reactions until the hydrogen is consumed.

7. Photochemical reactions are unusual in that they require light of specific wavelengths (usually in the ultraviolet) and can be initiated by low energy inputs. Papp (1974) reported the results of some work with dye lasers in the ultraviolet (UV), but this did not develop into a detonation system. Dick (1982) reported unsuccessful results at the direct initiation of liquid nitromethane and solid PETN (2, 2-bis](nitroxy) methyl]-1,3 propanediol dinitrate) using a UV laser. Rooijers et al. (1985) reported successful initiation of primary (sensitive) explosives with a UV excimer laser. Table 1 summarizes the results of work on UV photochemical reactions produced in solid explosives using an excimer laser. In these tests, the spot sizes used were large (600 mm^2) and the power input was small (only one joule). The low energy density is consistent with the theory that photolytic reactions not heating or thermal shock caused detonation in the primary explosives.

8. Gaseous mixtures are generally the most efficient media for rapid photochemical reactions and successful ignition of gas mixtures using lasers was reported by Lee and Knystautas (1969) and successful experiments with flash-tube initiated explosions have been carried out (Lee, Knystautas and

Table 1

Examples of Photochemical Reactions in Experimental Detonation Systems

Energetic* Material	Type of Explosive	Pressing Force** (KN)	Detonator Type	Nominal Wavelength (nm)	Energy Density (KJ/m^2)	Function Time (micro-seconds)	Source	Pulse Duration (micro-seconds)
Lead Azide	Primary	1 KN	Confined	249	0.2	0.5	Excimer Laser	15
Lead Azide	Primary	10 KN	Confined	249	0.2	1.5	Excimer Laser	15
Lead Styphnate	Primary	1 KN	Confined	249	0.6	220	Excimer Laser	15
Lead Styphnate	Primary	10 KN	Confined	249	0.6	750	Excimer Laser	15
Silver Azide	Primary	1 KN	Confined	249	0.4	0.5	Excimer Laser	15
Silver Azide	Primary	10 KN	Confined	249	0.4	1.5	Excimer Laser	15
Mercury Fulminate	Primary	<100 KN	Confined	249	---	3500	Excimer Laser	15
Diazo-dinitrophenol	Primary	1 KN	Confined	249	---	15	Excimer Laser	15
Diazo-dinitrophenol	Primary	10 KN	Confined	249	---	210	Excimer Laser	15

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* From Rooijers et al., 1985.

** Pressing force is the force exerted on a 5 mm-diameter pellet containing 10 mg of energetic material.

Yoshikawa, 1978). No one has attempted to incorporate reactive gases in light-initiated detonators.

9. Although photoreactive detonators are technically possible, no currently fielded explosive detonators are based on photochemical reactions. All present systems are based on the development of heat and shock due to long wavelength (infra-red) laser pulses. The major restrictions on short wavelength (UV) reaction are the high energy loss related to glass fiber transmission and the general problem of developing a stable, but sensitive reactant.

Heat and Shock Initiation

10. Theoretically, any intense light source can be used to heat an unstable chemical mixture to start an exothermic reaction, autoheating and finally detonation (Boddington, 1963; Assouskii and Leipunskii, 1980). Lasers in the visible and infra-red (IR) have proved to be the most efficiently coupled sources of high-energy light pulses and the visible-IR is the most favorable energy range for transmission using presently fabricated optical fibers (Hohimer, 1976). Pyrotechnic mixtures (Department of the Navy, 1977; Ostrowskii, Petrick, Petrow and Smith, 1982) primary explosives (Aleksandrov and Voznyuk, 1978; Barbarisi and Kessler 1969a; Brish and Galeyev et al. 1966, 1969; Harrach, 1975, Menichelli and Yang, 1970, 1975; Yang 1976, 1979, 1981) and secondary explosives (Barbarisi and Kessler, 1969b; Chernai, 1982; Menichelli and Yang, 1972; Volkova, Zinchenko et al. 1977; Yang and Menichelli, 1971, 1974) have all been successfully initiated using solid state lasers.

11. Where photochemical reactions would theoretically require a minor amount of energy to initiate a reaction, a heat and shock initiation requires a relatively large specific-energy density and the heat dissipation characteristics of the surface being impacted by the light become critical. Factors such as surface reflectivity, formation of light absorbing phases (plasma) at the fiber/explosive interface and the density and thermal conductivity of the primary charge become important in the detonator design.

12. Many conventional primary and secondary explosives and pyrotechnics have been detonated using laser-produced heat and shock. Table 2 summarizes the experimental conditions that have been used in detonating a variety of

Table 2

Examples of Heat/Shock Reactions in Experimental Detonation Systems

Energetic Material	Type of Explosive or Pyrotechnic	Density or Pressing Force	Detonator Type	Nominal Wavelength (nm)	Spot Diameter (microns)	Power or Energy (J)	Energy Density (J/M^2)	Function Time (microseconds)	Laser Type	Pulse Duration (microseconds)
Lead Azide[1]	Primary	2.0 g/cc	Confined	1060	600	0.004	-	262	Neodymium/Glass	250
Lead Azide[1]	Primary	2.0 g/cc	Confined	1060	600	0.080	-	170	Neodymium/Glass	250
Lead Styphnate[1]	Primary	10.3 MPa	Confined	1060	600	0.070	-	273	Neodymium/Glass	250
Lead Styphnate[1]	Primary	14 MPa	Confined	820	200	1	30	250	Diode	100,000
Lead Styphnate[1]	Primary	∿1 g/cc	Confined	820	200	1	30	250	Diode	27,500
PETN[2]	Secondary	1.64 g/cc	Unconfined	1060	600	0.26	-		Neodymium/Glass	250
PETN[2]	Secondary	1.64 g/cc	Confined	694	<3000	1		2.9	Q-switched ruby	0.43
PETN[1]	Secondary	1.72 g/cc	Confined	694	<3000	2		2.9	Q-switched ruby	0.36
RDX[2]	Secondary	1.18 g/cc	Confined	694	<3000	1		3.98	Q-switched ruby	0.10
RDX[2]	Secondary	1.18 g/cc	Confined	694	<3000	3.5		4.90	Q-switched ruby	0.35
RDX[2]	Secondary	1.52 g/cc	Confined	694	<3000	3.8		3.62	Q-switched ruby	0.72
Tetryl[2]	Secondary	1.08 g/cc	Confined	694	<3000	4		5.58	Q-switched ruby	1.45
$Zr/KClO_4$ + PETN[1]	Pyrotechnic	4.0 g/cc	Confined	1060	600	0.1		390	Neohymium/Glass	250
$Zr/KClO_4$ + PETN[1]	Pyrotechnic	4.0 g/cc	Confined	1060	600	0.06		1.73	Neodymium/Glass	250
$Zr/KClO_4$[1]	Pyrotechnic	1 g/cc	Confined	820	100	0.1		3390	Diode	

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[1] From Ensign-Bickford Co.

[2] From Yang and Menichelli, 1971.

explosives and pyrotechnic compounds. The most sensitive energetic materials are the zirconium and potassium perchlorate pyrotechnics boosted with PETN.

13. At present, no consistent model exists that describes the heat and shock initiation process although numerous attempts have been made to develop such a model (Boddington, 1963; Assovskii and Leipunskii, 1980). Experimental work on the interaction of light and solids has been hampered by the inability to observe processes in a solid and the speed of the reactions involved.

14. A wide variety of energetic materials can be initiated with a variety of pulsed lasers (Table 2). Successful heat and shock-based detonation systems can be developed from a variety of components and can be designed to meet specific needs related to safety of the energetic materials and the potential power loss over long (2-3 km) blasting lines (Menichelli and Yang, 1972, 1975; Yang, 1976, 1979, 1981).

PART III: LASER INITIATION OF EXPLOSIVES

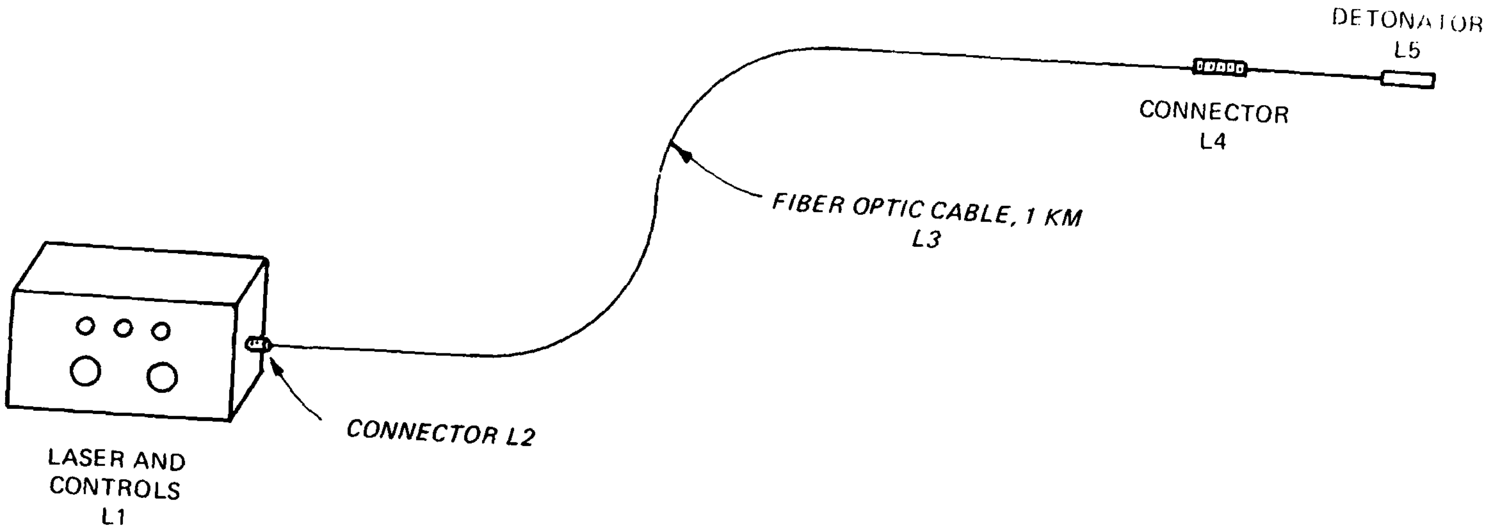
Light Sources

15. A source of light (even incoherent light) can be an ignition source for explosives. From a design aspect, lasers are the most logical light producing component because lasers can be effectively coupled to fibers (up to 90% efficiency) and produce high energy density. Another important characteristic is the ease of redirecting the beam with prisms, mirrors, and crystals allowing the distribution of a single source to many different locations. A single laser can initiate any number of explosive events sequentially with a properly designed optical distribution system. With the proper optics, several explosives can be initiated simultaneously if a powerful laser and sensitive explosives are being used.

16. The most common means for using lasers for initiation purposes is conceptually very simple (Figure 1). The output beam of a laser is launched into an optical fiber which carries the energy to the initiator or detonator causing it to function. This is a direct replacement for an electric detonator (conventional or exploding bridgewire) with the initiation energy source being simply on a different part of the electromagnetic spectrum (light instead of electricity) and the energy transmission medium using a different physical principle (total internal reflection instead of electric conductivity). The end result is the same; a detonator or initiator is remotely functioned at a desired time.

17. Various lasers have been tried on a host of explosives with varying degrees of success. Many of the earlier attempts utilized a free-running ruby laser to initiate sensitive (primary) explosives. Since then, free-running and Q-switched Nd-YAG (Neodymimum-Yittrium Aluminum Garnet) or Nd-glass (Neodymium-glass) have been used quite often, usually to initiate primary explosives like lead azide, lead styphnate and mercury fulminate or pyrotechnics like zirconium-potassium perchlorate or standard delay mixes like silicon-red lead and molybdenum-potassium perchlorate.

18. Attempts to initiate insensitive (secondary) explosives such as RDX (Cyclonite) and PETN have also been successful. It has been found that, in general, the energy density necessary to initiate a secondary explosive is several times higher than that for a primary explosive. Primary explosives



COMPONENT	LOSS dB	REMAINING
LASER OUTPUT	0.2	100%
L1 LOSS DUE TO OPTICS	0.2	95%
L1 FRESNEL REFLECTION AT FIBER END	1.0	91%
L2 CONNECTOR LOSS	1.0	72%
L3 FIBER OPTIC LOSS (3 dB/KM)	3.0	36%
L4 CONNECTOR LOSS	1.0	29%
L5 ENERGY COUPLED INTO REACTIVE MATERIAL	30-90%	0.09-0.26%

Figure 1. Schematic drawing of a laser-fiber optic detonator system, losses are approximately as shown

will detonate with an energy input of approximately one joule per square cm. When secondary explosives are used in place of primaries, the energy input must be two to three times higher. Higher energy outputs can cause unusual and unpredictable effects like plasma formation, self-focusing in the fiber and surface ablation at the fiber interfaces. High energy effects have not been fully studied but probably will be in the future as laser initiation of secondary explosives becomes common. For example, in the case of plasma formation, the electric field of the laser beam (of the order of several million volts per cm at the focal point) ionizes the molecules at the explosive surface, thus producing free electrons. These electrons absorb radiation throughout the electromagnetic spectrum, including that of the laser, and in doing so they halt the subsequent interaction of the laser beam with the explosive. To overcome the problem of plasma formation and light absorption, higher energy levels have typically been employed with increased danger of damage to fibers and other optical components.

19. If primary explosives are acceptable for use in any particular system being developed, the problems with high energy are eliminated. The lower energy levels required to initiate primaries and pyrotechnics allow for a much smaller, simpler system design. The laser can be smaller, alignment is less critical, and connectors are simpler. Also, the system can be cycled repeatedly with less concern for laser-induced damage to optics, connectors or fibers. Thus, when system constraints allow, the use of primary explosives will be preferred. If a system must have only secondary explosives, a laser fiber optic initiation method can be designed with all secondaries.

20. A wide variety of laser types have been employed in experimental application. Dye lasers were used experimentally by Papp (1974); but because of the need to replenish the organic dyes after a few shots; these units were not considered for field use. Excimer lasers that operate in the UV can produce detonation; but the energy loss for UV in glass fiber is so high that they have been employed only in laboratory operations.

21. Initial trials have been run with CO_2 gas laser that radiated in the infrared (IR). The practical application of CO_2-lasers depends on the availability of glass-fibers that transmit efficiently in the IR.

22. Solid state lasers (ruby, YAG and glass) have been widely employed in experimental detonation of explosives. Range finders and target designators commonly use solid state lasers because they are rugged, easily maintained

units. In detonation applications, solid state lasers have been typically operated in the free-running rather than Q-switching mode. Q-switching can raise the power of the laser output, but is generally not employed in current designs for prototype detonators because of the problem of plasma formation and the high risk of damage to optical fibers, connectors and mirrors or prisms.

23. Requirements for solid state lasers are strongly application dependent. The first consideration is the threshold for detonation of the photosensitive cap. System losses caused by fiber attenuation connector losses and coupling efficiency must be added. If a laser light distribution system is to be used, the losses in distribution must also be added. The total losses and the energy requirement for the detonator and a suitable safety factor provide the required output level of the laser. For a detonation system with three connectors and a distributor and a detonator using primary explosives, the required output range is 0.6 to 1.0 joules.

24. The efficiency of a laser in converting electrical power to light is approximately 4%. Assuming the input energy of the laser is provided by flash lamps, the flash lamp circuit should be able to handle 15-25 joules of electrical energy. The power requirement of the unit is determined by the rate of charging that is needed from the pulse forming network (PFN). If the PFN is charged using solid-state switchers, a relatively fast charge can be obtained (several thousand joules per second). The well-designed PFN power supply can have an efficiency up to 85%.

25. Prototype units built for experimental purposes (Figure 2) have been heavier and bulkier than required and had a gel-cell power supply that added additional weight. A commercial Nd:glass laser unit capable of initiating a detonator using secondary explosives (power output of 2 joules) over a 1-km long fiber link could be fabricated with a total weight of approximately one kilogram. A separate battery pack (of equal weight) could provide approximately 100 shots between recharges.

26. Pumping of laser rods using laser diodes rather than flash lamps can raise the total laser efficiency from 4% to 8-10%. Laser diodes are presently too expensive to make this approach commercially practical, but advances in production may result in lower-cost diodes. The power levels on some laser diodes, used by themselves are adequate to initiate pyrotechnics and primary explosives (in detonators) in short fiber circuits (5-10 meters) with only one

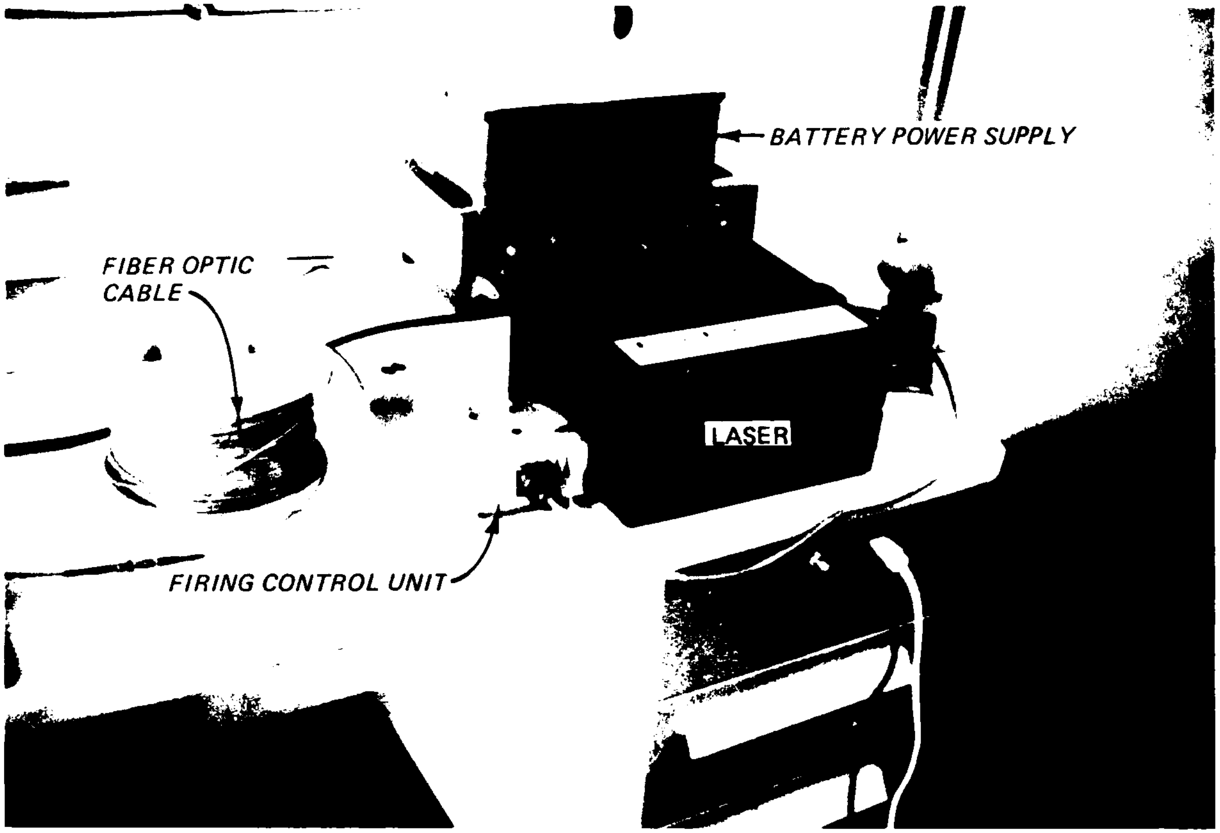


Figure 2. Prototype laser detonator assembly

or two connectors. The technology associated with gallium aluminum arsenide diodes is advancing rapidly. New multiple quantum well devices using stripe geometry produced by metal organic chemical vapor deposition are increasing the power output without damaging light emitting surfaces. It is the technique of employing many stripes in possibly two dimensional arrays that will eventually allow the use of diodes even in secondary initiation applications.

27. Two basic families of lasers can be used for light initiation. Of these, the solid state laser technology can be employed today and prototype systems have already been developed. Laser diode technology may allow the construction of an enhanced light-weight firing unit in the near future.

Fiber Selection

28. The selection of a fiber for use in laser detonation poses a unique problem due to the higher energy levels involved in this application as opposed to the normal signal carrying (data transmission) applications of fibers. Most explosives can be initiated most easily by ultraviolet light because of the many electronic transitions in that region. Unfortunately, this is not a good region to use with fiber optics because most fibers are made of silica compounds which transmit poorly in the ultraviolet spectrum. The best region for fiber optic transmission is in the near-infrared, from 1.0 to 1.3 micrometer. Beyond 1.3 micrometers absorption by water and molecules like carbon dioxide becomes significant and fiber transmission decreases.

29. Most explosives require several joules/sq. cm to assure initiation. The energy transmission properties of candidate fibers become extremely important. Data on the damage threshold of most commercially available fiber is not available. One of the difficulties a laser initiation system will encounter is the launching of sizeable energy levels into small-diameter optical fibers in a reliable, reproducible manner under often adverse field conditions.

30. Generally step index fibers are used for transmitting laser energy for blast lines. Step index fibers consist of a homogeneous silica core and a homogeneous cladding. The decreased index of refraction in the cladding causes total internal reflection and produces the wave guide effect, that is the basis of optical fiber transmission.

31. Glass fibers with high core-to-cladding ratios are the best choice for laser blasting lines. The high core-area ratio maximizes source coupling efficiency, minimizes connector loss due to misalignment and provides for the maximum energy or power densities for a given diameter in high power systems. The core-to-cladding ratio for a good 200-micron blast line fiber is 87% and for 600 micron blast line fiber is 94% (Figure 3). These ratios are achieved by taking the silica rod and drawing it to the desired core dimension and immediately applying a hard polymer cladding which is then cured with ultraviolet (UV) radiation causing a chemical reaction between the polymer and the silica to bond the cladding to the core.

32. Hard polymer cladding serves to add support to the core fiber. Improved handling characteristics translate to much stronger fiber and fiber that can be handled directly without fear of contamination of the glass core. This is especially true in the termination process where connectors are being put onto the core fiber and where breakage occurs the most frequently.

33. Optical fiber connectors, beam splitters and other optical components are also problems when high levels of energy transmission are required. Connectors typically will have a lower damage threshold than the fiber itself. In a typical "pot and polish" connector (Figure 4) subjected to a high energy density pulse the potting material, usually an epoxy, absorbs laser energy and is heated up. The potting compound either carbonizes or transfers heat to the fiber optics possibly causing failure. If carbonization occurs the next laser pulse will ultimately damage the fiber. Repetitive pulsing through the splice will reduce transmission to below ignition levels and system operation will cease. Connectors formed by mechanically crimping metal ferrules around the fiber and cleaving, rather than polishing the fiber end do not have carbonization problems associated with epoxy-potted connector and may solve part of the connector problem. Research on improved connectors is being actively pursued.

34. Ruggedness can be built into a fiber optic cable. The construction of a particular cable depends on the amount of protection the fiber needs in the specific environment where it is employed. All fiber cables are protected and strengthened with polymeric material. A field tactical cable for general blasting operations would consist of a glass fiber with a polymeric jacket and a polymer fiber for longitudinal strength. A loose-tube polymer jacket usually provides more protection for the optical fiber in the event it is

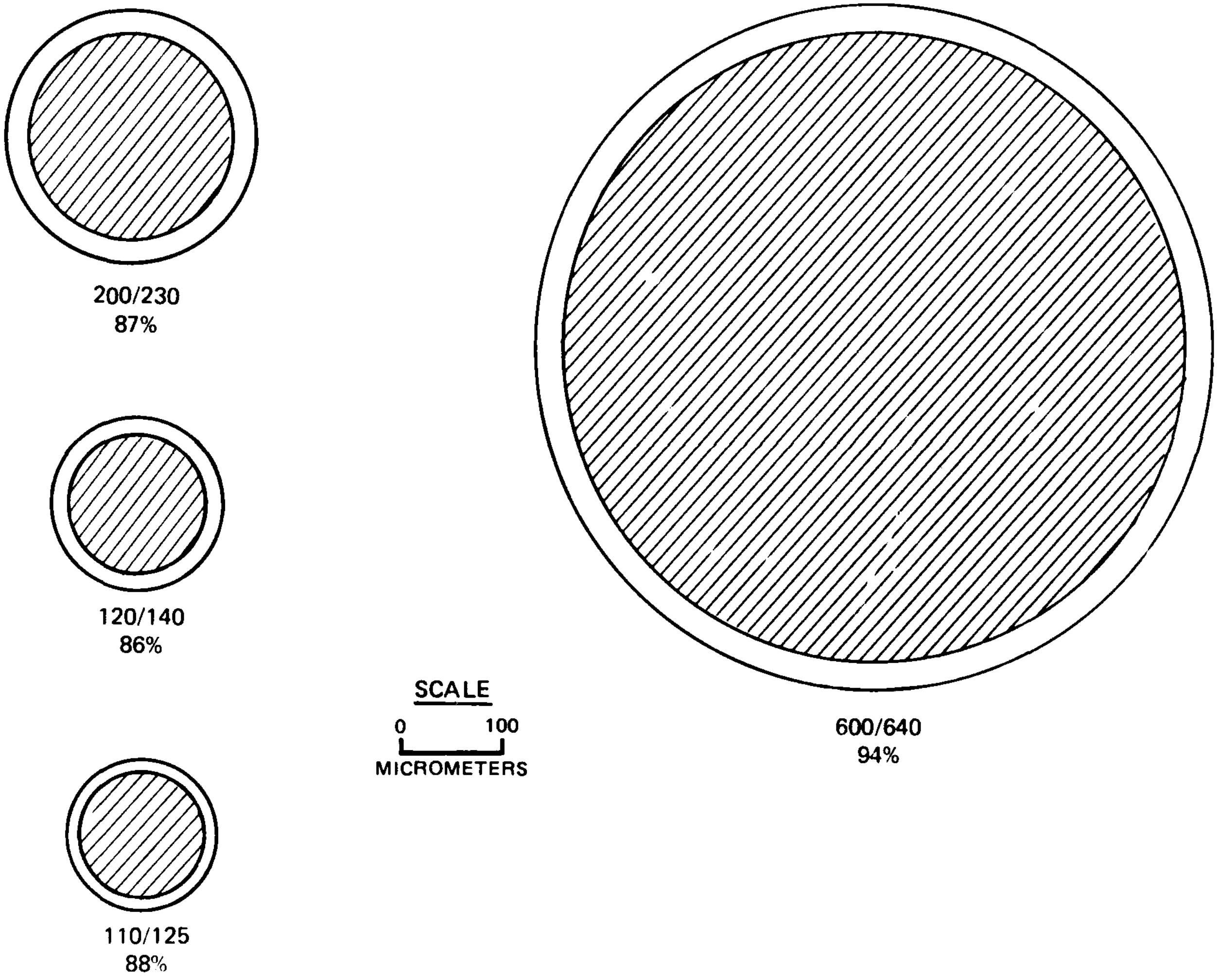


Figure 3. Cross-sections of high core-to-cladding ratio step index fibers. Fibers are typically specified by giving the unreduced ratio of core diameter (in micrometers) to fiber diameter (in micrometers)

Figure 4. Typical optical fiber cable connector prepared using epoxy "pot and polish" techniques

subjected to crushing. Jacketing can be made of almost any polymer material in any required color and can incorporate resistance to hostile environments.

35. The environment that a particular laser/fiber optic initiation system will experience depends entirely upon the application of the system. Some systems may even be required to be reused many times thus must be capable of withstanding widely varying environments. Protection is essentially a parameter directly related to the cost of the cable. The environmental hazards that a field deployable cable is likely to encounter include:

a. Small diameter core on the storage/payout spool (tight bend radius).

b. Multiple twist/flex abuse (due to rewinding of cable on spool many times).

c. Crushing from personnel and vehicles.

d. Temperature range -40 to +150°F.

e. Moisture from rain, muddy soil, puddles, etc.

f. Sunlight.

g. Abrasion from being dragged across rugged terrain.

h. Relatively high pulling tensions due to possible long length of cables.

36. The environment the cable experiences can include battlefield conditions. Fiber optic cables may have unique advantages over copper wire in combat operations because:

a. Fiber optic cables can be lighter in weight than a copper cable of equivalent strength.

b. Fiber optic cables have no magnetic signature. (This can be particularly important to some users).

c. Fiber optic cables are immune to radio frequency energy, from radio transmission or radar.

d. Fiber optics should be less susceptible to sabotage.

37. Experience with the installation and repair of optical fiber cable has heretofore been limited to communications systems. This can be extrapolated to certain initiation systems. Large scale systems that would be permanently located and predeployed would be almost identical in installation techniques to their communications relatives.

38. The installation and repair of optical fiber cable has presented several unique problems including:

a. Cable crew training
b. Handling technique/equipment
c. Tie off techniques/aerial cable
d. Cable strength
e. Splicing techniques/hardware

39. If the advantages of optical cable are to be realized, methods and equipment to install and maintain such systems must be efficient. The installation of the cable must not be encumbered by highly specialized sophisticated tools and procedures.

40. Fiber optic cables are routinely manufactured with the tensile strengths in excess of 500 lbs which is several times stronger than its conventional, metallic counterpart. However, some essential differences must be recognized. Glass is intrinsically very strong, but it is also a relatively brittle material. Glass will not elongate like its counterpart (metallic cable) and if loaded beyond the recommended pulling load, will break. It is therefore recommended that regardless of the application that the pulling load be monitored.

41. Another consideration when installing optical cable in the minimum bend radius, which is supplied by the manufacturer. If during installation the optical cable is pulled around a bend radius less than recommended, permanent damage may result. Before any installation begins it will be necessary to properly instruct the cable crew of the limits that the manufacturer recommends, and the following information should be well-understood before the operation begins:

a. Type of outside cable jacket
b. Maximum pulling tension
c. Minimum bend radius static, and under load
d. Central strength member (composite/steel)
e. Recommended installation temperature
f. Type of cable lubricant to be used if any

The required information is readily available from the manufacturer. Under no circumstances should the cable be installed at more than 80% of the recommended pulling tension or damage may result if transient effects occur in the tensioning. If the installation requires more than 50% of the pulling tension a dynomometer must be used in conjunction with the pulling device to insure uniform pull stress at an acceptable load.

Detonators

42. The detonator interfaces an intense light pulse from a fiber optic cable with an energetic material. The energy transmitted to the interface is a function of the light source power and pulse length as follows:

Energy transmitted (joules)=Source Power (watts) × Pulse Length (sec.)

This relationship is exact for a square pulse shape. A more typical pulse shape is shown in Figure 5. Integration of the power over the pulse duration yields the total energy. A general description of the pulse is made by defining the maximum power and pulse width (Figure 5). Note that the pulse width is defined as the time during which the power is greater than 1/2 Pmax. The most important interface parameter is the energy density, defined by the following relationship:

$$\text{Energy Density} = \frac{\text{Energy Transmitted}}{\text{Cross Section Area of Fiber Optic}}$$

This parameter is generally critical when determining an explosive compound's sensitivity to initiation. Determination of a minimum energy density and spot size (i.e. fiber size) for initiation of a detonator will allow sizing of the light source and transmission lines.

43. Typical end preparation techniques range from cleaving to producing a highly polished finish. The cleaved end technique results in a smooth, mostly planar finish with random flaws. The polished finish is very flat with a smoothness dictated by the polishing media. In practice, these methods give varying degrees of transmission at the interface based on the laws of reflection and refraction. Some reflective loss suppression techniques have been suggested but have yet to be experimentally verified. Practical experience has shown the cleaved end preparation technique to result in lower initiation threshold levels and more reliable detonation.

44. The powder packing conditions involved in light initiation are similar to those encountered when designing an electric explosive device (EED). Variables such as density, particle size, crystal morphology, charge diameter and charge length must be considered. One unique and important aspect for

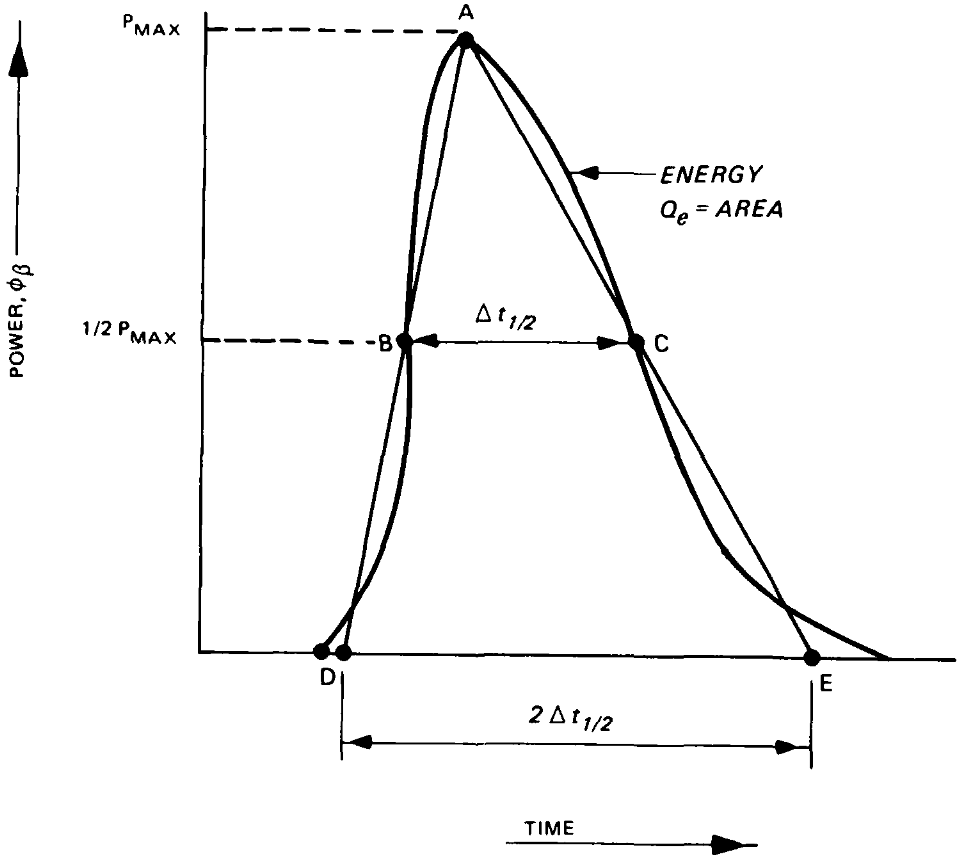


Figure 5. Typical laser pulse shape

light initiation is the light absorbency of the powder. The powder's absorbence is a complicated matter. Among other factors, the effective refractive index at the fiber-to-powder interface plays a role in determining the amount of light affecting the powder. Efforts are being made to determine the resonant frequencies (i.e. greatest absorption) for powdered explosives so that the most efficiently absorbed part of the spectrum can be provided in order to initiation reactions at lower energy levels. One technique employed to determine the resonant frequencies of a powder is photoacoustic spectroscopy (Selzer, 1981). Subjecting the powder to a narrow band of light causes excitation (e.g. vibration) of the powder which is sensed and recorded by the instrument. A typical spectrum of PETN using this method is shown in Figure 6. Note the uneven absorbence at typical laser frequencies (1,000 to 1,300 nm). Unfortunately, without a clear understanding of the initiation mechanism (e.g. thermal, electrical) and better techniques to study the initiation process, this area of research has progressed slowly.

45. In a practical sense, the light source selection is based on availability and dependability. These sources are often not of the proper frequency for resonant absorption by the powder. Because of the mismatch, a small portion of the incident light will be absorbed (less than if a resonant frequency) and the remaining portion is scattered (reflected or refracted) by the powder. The major effect of the absorbed light is to create heat via intermolecular collisions which in turn promotes initiation. Methods to improve light absorption involves changing the appearance of the powder at the interface. "Doping" of the powder with a suitable light absorbing agent can improve light sensitivity to initiation.

46. Another method involves changing the density of the powder. This changes the particle orientation of the bulk powder at the interface and therefore alters the reflection/refraction energy ratio at the interface. Similarly the irregularity of the powder surface at the interface is also changed thereby effecting the diffusion (scattering) of light into powder. Density variations also change the powder thermal transfer properties. Conduction of heat away from the focus is not beneficial to obtaining the desired effect. In theory, the density relation to thermal conductivity is well-established and this problem can be addressed with existing heat transfer models.

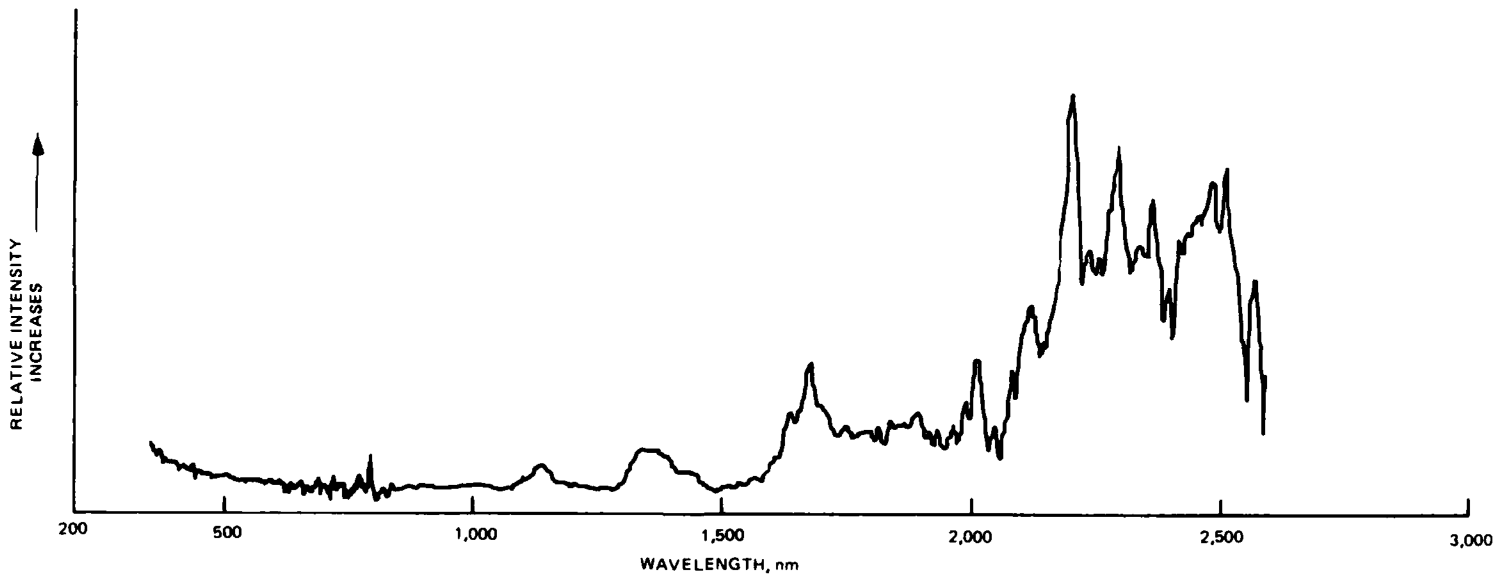


Figure 6. Photoacoustic spectrum of PETN

47. Practical experience with $Zr/KClO_4$ (see Table 2) pyrotechnic mix has shown a loose charge (∿ 1 g/cc) to be more sensitive than a higher density charge. Similarly work conducted by Yang and Menichelli (1971) showed lead azide and lead styphanate to be more sensitive at lower density levels (see Table 2).

48. The materials of construction for the detonator housing are typically metal. An all plastic housing for a standard explosive train design is available. Non-metallic units may be of interest to applications where a magnetic signature is detrimental. The fiber optic detonator's resistance to the various environmental conditions (moisture, sunlight, temperature extremes) is similar to that of a standard electric detonator. One unique difference, however, is the fiber optic detonators inherent resistance to radio frequency initiation. In addition, the effects of electromagnetic pulses on the detonators are minimized.

49. The detonator housing design is primarily based on practical experience involving EED's. A standard EED explosive train can be initiated with comparable function times by light. The function times are generally inversely proportional to the incident energy density. This will hold true over a considerable range of input energy and then level out to a peak beyond which the function time is independent of the input energy. As previously noted, very high input energies may actually hinder initiation by the formation of a plasma.

50. In addition to the standard explosive train (Figure 7), other common detonators such as a deflagration-to-detonation transition (DDT) detonator (Figure 8) and a flying plate detonator (see Figure 9) can be initiated via light. The application typically will determine the choice of detonator type. A PETN DDT detonator with and without a $Zr/KClO_4$ igniter has been successfully fired with a laser. The advantage of the pyrotechnic igniter is a lower initiation energy threshold.

51. Assembly of the detonator requires special attention to the fiber. The fiber is glued (typically with epoxy adhesive) into a supporting alignment sleeve. From experience, the buffer coating must be removed from the fiber where adhesion is required. The fiber/sleeve assembly is then inserted into the detonator to form the fiber/powder interface. The fiber end is typically flush with the sleeve face. In some cases, however, (when dealing with low density and loose charges) the protrusion of the fiber end beyond the sleeve

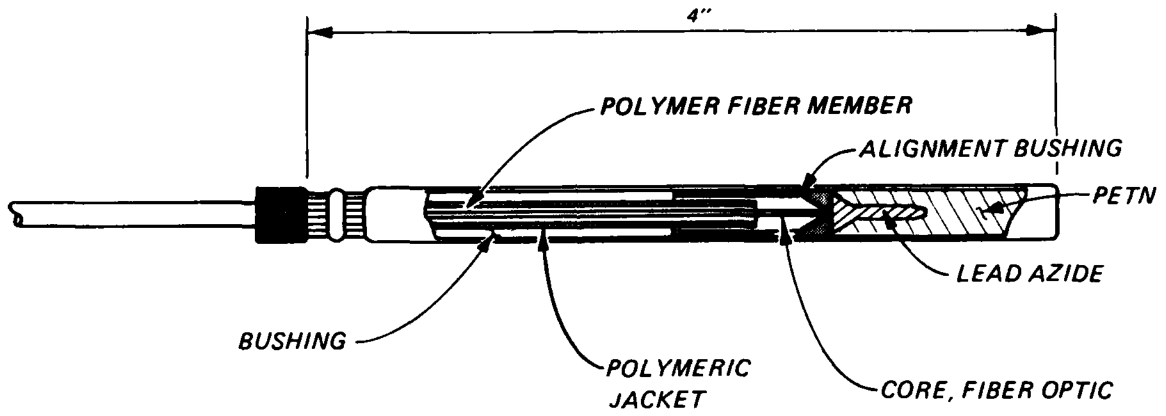


Figure 7. Schematic drawing of laser detonator with standard explosive train

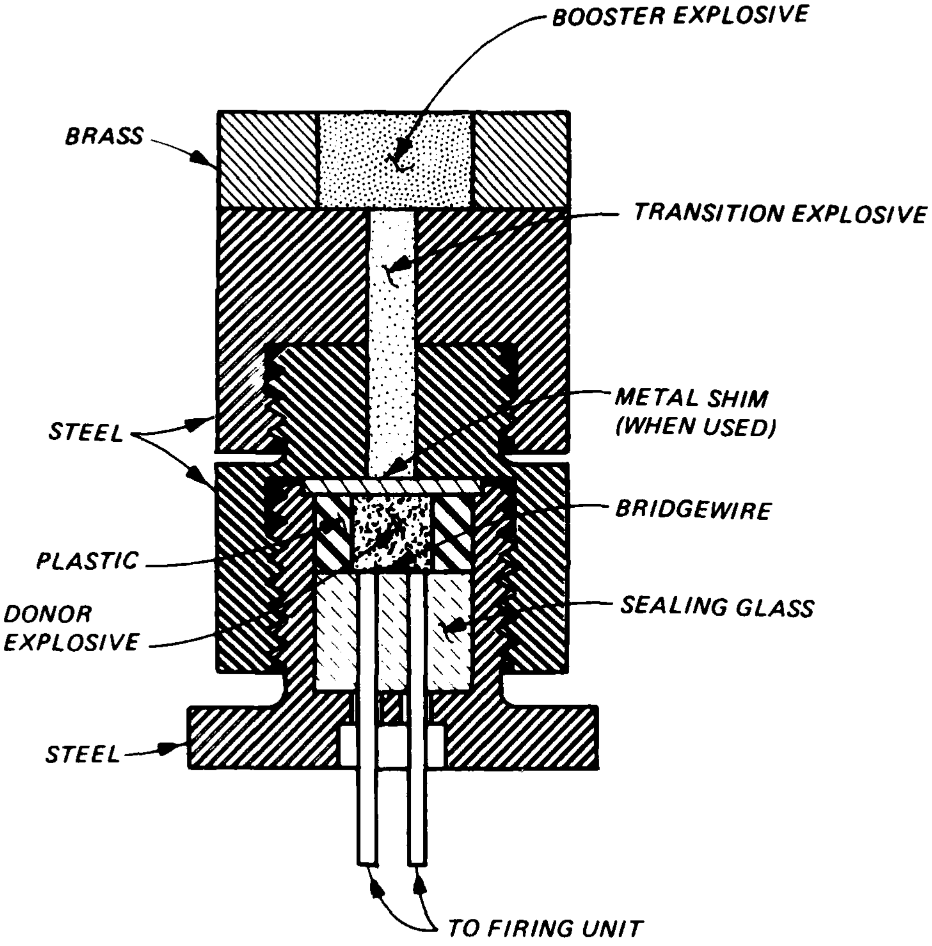


Figure 8. Schematic drawing of an electric deflagration-to-detonation transition (DDT) detonator

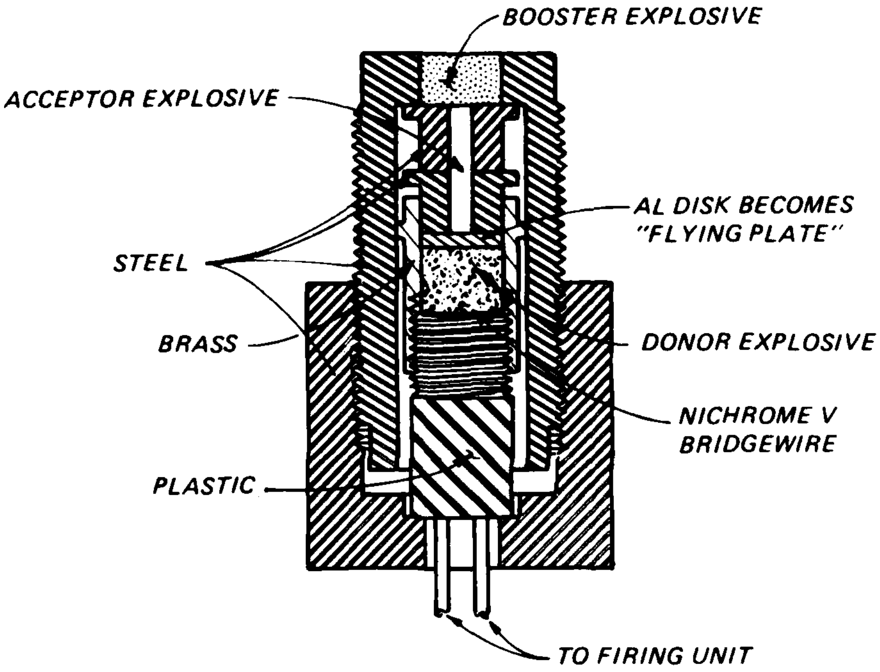


Figure 9. Schematic drawing of an electric "flying plate" detonator

face has been shown to benefit initiation. The protrusion of the fiber into the powder may decrease heat losses to the sleeve face and therefore promote initiation.

Initiation Systems

52. Laser initiation systems are available for specific applications such as the firing of ordnance and precision detonation of explosives for seismic investigations. The ordnance initiation systems generally incorporate the capability to produce and distribute multiple, precision-timed pulses that are needed in compact weapon systems. The seismic initiation system has been tested successfully in single shot applications (Figure 10). A multiple shot system is undergoing extensive testing. Research is being concentrated on minimizing fiber size and simplifying field assembly techniques.

Figure 10. Test with single shot laser initiation system detonating a test charge through 30 meters of optical fiber cable

PART IV: SUMMARY AND RECOMMENDATIONS

Summary

53. Theoretically, explosives can be initiated using light sources that can produce photochemical reactions or can cause heat and shock effects in sensitive compounds. The photochemical pathways are attractive in that they should require low energy levels and should operate at specific wavelengths. Difficulties arise in the transmission of energetic (short-wavelength) light in existing optical fibers. The heat and shock detonation systems use longer wavelengths that are well-suited to transmission on existing optical fibers.

54. Numerous light sources could be employed in detonation systems, but lasers produce efficient coupling to optical fibers and generate light pulses that are sufficiently energetic to initiate primary and secondary explosives. Solid state lasers operating in the 1,000 to 1,300 nm region are proving most useful because optical fibers are most efficient in this area of the spectrum. Currently designed laser diodes are too low in power to be useful, but rapid changes in diode technology indicate that power output will be significantly increased in future designs.

55. Most optical fibers are designed for data transmission, but fiber designs for transmitting power pulses are appearing. The most useful fibers are step indexed glass fibers that have large core-to-cladding ratios. The large core minimizes energy losses due to misaligned connectors. Connectors account for large energy losses and newer coupling designs are moving to crimped connectors with cleaved fiber ends rather than epoxy-imbedded connectors with grit-polished fiber ends.

56. Detonators for optical initiation systems are very similar in construction to those employed in electrical ignition systems. The explosive and pyrotechnic charges used can also be similar. Either primary or secondary explosives can be initiated with current laser-fiber optic systems.

57. Two laser-fiber optic initiation systems are presently accessible. A ordnance-initiation system that uses precision timed beam distribution is being employed in weapon systems such as rocket launchers. A single-shot explosive initiation system for seismic work has been tested and is available as a prototype.

Recommendations

58. Light-initiated detonators offer the promise of safer, more reliable blasting equipment that could be of great benefit in military operations. Additional research is needed in the following areas:

a. Low-energy photoreactive detonators that can operate with existing laser-diodes or small conventional solid state lasers.

b. Continuity checking systems that can be used to verify that a complete light transmission link is available.

c. Improved optical fiber cables that can better withstand bending or have some residual transmission after fracture.

d. Improved connectors that have low loss and can be rapidly fabricated.

A continuing effort should be made to follow fiber optic blasting developments for civilian use and to promote and participate in Army research involved in this new fiber optic application.

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