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Navy Explosive Ordnance Disposal Project: Optical Ordnance System Development Final Report

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Prepared by
Sandia National Laboratories
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Abstract

An optical ordnance firing system consisting of a portable hand held solid state rod laser and an optically ignited detonator has been developed for use in explosive ordnance disposal (EOD) activities. Solid state rod laser systems designed to have an output of 150 mJ in a 500 microsecond pulse have been produced and evaluated. A laser ignited detonator containing no primary explosives has been designed and fabricated. The detonator has the same functional output as an electrically fired blasting cap. The optical ordnance firing system has demonstrated the ability to reliably detonate Comp C-4 through 1000 meters of optical fiber.

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Navy Explosive Ordnance Disposal Project: Optical Ordnance System Development

Final Report

1.0 Scope

RF signals can cause electrically activated ordnance to detonate. Explosive Ordnance Disposal (EOD) technicians working with ordnance are restricted from using RF generating equipment to prevent this from occurring. A requirement exists for an alternative means to detonate Comp C-4 other than electric blasting caps. This may be achievable by using a laser firing system, optical fibers and an optically ignited detonator. A project has been undertaken to develop optical ordnance to replace electric blasting caps for the initiation of Comp C-4 in EOD applications. Electrically activated ordnance using sensitive explosive materials and long electrical leads are susceptible to electrostatic discharge paths and stray electrical signals or electromagnetic radiation. The use of optical components, non primary explosives, and optical fibers eliminate these concerns.

1.1 Identification

This project is funded by the Navy Explosive Ordnance Disposal Technology Center, NAVVEODTECHCEN in Indian Head, Maryland.

Document number NO464A91WR10380 Laser/Fiber Optic Initiator for C-4.

1.2 System Overview

Sandia National Laboratories has served as a contractor to the Naval Explosive Ordnance Disposal Tech Center to develop optical ordnance that can replace electric blasting caps for the initiation of C-4 or detonation cord in explosive ordnance disposal applications. The system is intended to be an additional tool for EOD applications that provides HERO (Hazards of Electromagnetic Radiation to Ordnance) safe detonation output from an optical detonator. The system consists of a portable battery operated rod laser, an optically ignitable detonator and optical fiber that couples the laser output to the detonator. A schematic of the optical ordnance system is shown in Figure 1.

Figure 1. Optical Ordnance System Schematic.

Sandia National Laboratories has been developing optical ignition technology as part of its continuing nuclear weapons charter. The resulting technology base for this system, including the explosive component design and analysis, the laser system, and environmental testing, is substantial. This technology base represents a unique combination of all the necessary resources for a design project of this nature. References' 1-6 are publications dealing with various aspects of optical ordnance that are available in open literature. Our primary motivation for this development effort is one of safety, specifically reducing the potential of accidental ignition that can occur with a low energy electrically ignited device. Laser ignition of energetic materials provides the opportunity to remove the bridgewire and electrically conductive pins from the charge cavity. This isolates the explosive from stray electrical ignition sources such as electrostatic discharge (ESD) or Electromagnetic Radiation (EMR). The insensitivity of the explosive devices to stray ignition sources allows the use of these ordnance systems in environments where electro explosive device (EED) use is a safety risk.

Sandia has designed an optical detonator with the same output characteristics as electric blasting caps. The prototype detonators were built and tested by Pacific Scientific - Energy Dynamics Division, formerly Unidynamics in Phoenix. Sandia has contracted with suppliers to develop and build the laser firing systems. Laser prototypes were procured from Whittaker Ordnance (now Quantic) and Universal Propulsion Company and tested by Sandia National Laboratories. Sandia has characterized optical fibers that are acceptable for delivering the optical energy to the detonator. Optical fiber and connectors used to couple the laser to the detonator are commercially available.

1.3 Theory of Operation

The intent of the optical firing system is to provide the same functional output performance as an electrically fired blasting cap without the use of primary explosives. Electrical detonation systems use electrical current to heat a bridgewire that in turn heats an explosive powder to its auto-ignition temperature through conduction from the bridgewire. An optical system uses light emitted from a laser source that is absorbed by the powder, thus raising the temperature to its auto-ignition temperature. Regardless of the stimuli, when the auto-ignition temperature of the explosive is attained, the explosive will burn or deflagrate. Proper confinement of the explosive will produce a transition to a detonation through a process known as the deflagration to detonation transition or DDT. This phenomena is different from the mechanism for primary explosives that detonate immediately upon reaching their auto-ignition temperature. A comparison between an electrical and optical detonation system is shown in Figure 2.

Figure 2. Comparison of Electrical and Optical Systems.

1.4 Tasks

The project was divided into three phases.

Phase 1 included the determination of system requirements, locating available commercial products, and the design of an optical ordnance system. The system requirements were defined through meetings with Naval officials from both the EOD Group One in San Diego and the Naval Explosive Ordnance Disposal Technology Center, Indian Head, Maryland. Phase 1 of the project included the development of the concept into a specification for operational hardware that can be used to produce a working prototype unit by:

1. Determining the needs of an EOD team, investigating current state of the art, evaluating conceptual designs and defining feasible parameters for the system.
2. Preparing preliminary hardware specifications and concept drawings based on the results of step 1.

3. Presenting the results, including possible approaches, expected results, and the technical risks associated with the various approaches.

Phase 2 of the project delivered two complete prototype systems that were built to the specifications developed and approved in Phase 1. The prototype systems are completely functional and were designed to be operational in the specified environments.

Phase 3 of the project included the field evaluation of the prototype systems that included evaluation by EOD technicians and engineers.

1.5 Laser Description

Prototype, solid state, rod laser firing units for the Navy EOD laser ordnance system were built by Whittaker Ordnance (now Quantic) and Universal Propulsion Company (UPCO). Contracts were awarded to these suppliers to develop the laser system with the following specifications:

1. The system must be man portable.
2. The system must be weather-proof (capable of withstanding normal climate variations, including rain, snow, blowing sand, etc.).
3. The laser must be battery operated, using either standard military or commercial batteries.
4. The laser must have a covered operation switch that must be lifted for arming and firing.
5. The laser must have a dust or weather cover on the output connector that will be large enough to handle with gloves.
6. The laser must deliver between 100 and 200 mJ of optical energy during a 500 microsecond pulse into a 200 micron fiber optic cable.
7. The system shall meet storage requirements of -65°F to +165°F.
8. The system shall meet operational requirements of -30°F to +130°F.
9. The laser shall have a ready light to inform the operator the unit is fully charged and ready to fire.
10. The system shall have to be reset after firing so it cannot be recharged until it is armed.

Whittaker produced the first prototype, and they were followed by Universal Propulsion Company with theirs. Both systems have been shown to be effective at igniting the optical detonator through 1000 meters of optical fiber. Both designs are shown in Figure 3.

Whittaker Ordnance Laser System

Universal Propulsion Laser System

Figure 3. Solid State Rod Laser Systems.

Whittaker's unit contains a 9-volt battery that supplies power to a DC/DC converter that steps up the voltage to approximately 500 volts. This voltage charges a 300 μ f capacitor that supplies current to the flash lamps. Functioning the flash lamps excites the laser rod material (Nd doped YAG) and causes the laser to function. The laser is designed to deliver between 100 and 200 mJ of optical energy during a 500 microsecond pulse. This exceeds the energy required to ignite the detonator by at least two orders of magnitude. The laser is contained in a cylindrical container that is approximately 3.5 inches in diameter and 6 inches tall. The package weighs about 2 pounds. The laser output is coupled into a 200 μ m optical fiber with a standard SMA 906 optical connector.

The second prototype laser was designed and built by Universal Propulsion Company. They improved the packaging, specifically with respect to environmental protection, and maintained a comparable laser output to the Whittaker laser. This laser employs either six 1.5 Volt AA batteries or three 3 Volt AA batteries to power the laser with a 9 Volt supply. The 9 V supply is stepped up to 360 V to charge a 200 μ f capacitor. The body of this laser is more rugged and sealed better environmentally than the Whittaker design. The housing is similar to a flashlight and is 10.1 inches long, 2.75 inches in diameter, and weighs 2.1 pounds. The design utilizes a rotary arm/fire switch located in the rear of the laser housing. The laser delivers 200 - 300 mJ of optical energy in a 200 microsecond pulse. The optical energy is coupled into a 200 μ m fiber using a press fit SMA 906 connector that attaches to the front of the laser housing.

Neither laser system is eye safe, and care must be taken to properly protect the operator and any casualties from exposure to the beam. Laser safety glasses with an optical density of 4.6 or greater, are required for personnel located within 10 feet (3 meters) of the laser (or the output end of a fiber when it is coupled to the laser). During operation, one person maintains positive control of the laser and the optical detonators, and that persons' responsibility is to assure that all personnel within the exposure radius of 3 meters are wearing proper eye protection.

1.6 Detonator Description

The design intent of the optical detonator is to provide a HERO safe detonation output sufficient to directly initiate Comp C-4 or det cord without the use of primary explosives such as Lead Azide. The detonator size closely approximates the standard electrical blasting cap currently used in EOD applications. The output characteristics of the optical detonator are the same as electrical blasting caps. A sketch of the detonator design is shown in Figure 4. Appendix 2 contains the drawing package of the detonator.

The detonator relies upon the deflagration to detonation transition or DDT process to produce a detonation that is sufficient to initiate C-4. The detonator contains approximately 90 mg of 2-(5-cyanotetrazolato)pentaaminocobalt(III)perchlorate or CP (see Figure 5) for the DDT column and 1 g of cyclotetramethylenetetranitramine or HMX for the output charge. The detonator wall around the HMX output charge is thin in order to minimize the attenuation of the shock produced by the detonation of the HMX.

The optical ignition of explosives depends on the optical power delivered and the energy absorbed by the explosive. [1,2] This dependence is important at low power as shown in Figure 6. At low power, it is necessary to dope some explosives with other materials such as carbon black or graphite in order to increase their absorbency of the optical energy and thus lower their ignition threshold. We have chosen to use CP doped with 1% carbon black so that these detonators can be fired from lower power laser sources such as laser diodes. At high powers, such as that provided by the Navy EOD system, a minimum energy must be delivered to the explosive in order to achieve ignition. As seen in Figure 6, this minimum energy for doped CP is on the order of 0.25 mJ.

The Navy EOD system uses a solid state rod laser capable of delivering 100 to 200 mJ of optical energy in a fraction of a millisecond. The detonator incorporates threads that will accept a standard SMA 906 optical connector. The optical connector positions the fiber in direct contact with a sapphire window as shown in Figure 4. This optical interface, and the use of optical fibers instead of electrical wires, completely de-couples stray electrical sources from the detonator by removing any electrical path to the explosive.

Successful ignition and function of the optical detonator have been achieved with both portable solid state rod laser systems and laser diode systems. The operational goals for the detonation system require the use of long optical fiber lengths, (up to 2000 meters) which may have optical attenuation or loss near 90 percent with fibers that have 4 - 5 dB/km loss. Fibers with higher loss per kilometer will intensify the optical attenuation problem. The portable laser diode system is capable of delivering 2 Watts of optical power, well within the ignition requirements, but insufficient to overcome the cable losses in 2000 meters of optical cable. For this reason, the EOD system uses a solid state rod laser for the optical energy supply.

Figure 4. SMA Compatible Optical Detonator.

Figure 5. Chemical Structure of
2-(5-cyanotetrazolato)pentaamminecobalt(III)perchlorate.

Figure 6. Optical Ignition Threshold for Doped CP.

1.7 Optical Fiber and Connections

The energy from the laser is transmitted to the detonator through an optical fiber. A typical fiber is shown in Figure 7. The fiber contains a glass core and either a glass or plastic cladding depending on the specifications. The mismatches of the index of refraction of the core and cladding are such that all of the optical energy in the core glass is internally reflected by the cladding in a process known as total internal reflectance. Each optical fiber is described by a size and numerical aperture (NA). The size of the fiber is determined by the core glass diameter. The Navy EOD system uses 200 micron fiber that could easily be adapted to larger diameters such as 400 micron fiber. The NA of the fiber describes the acceptance angle of the light that can be coupled into the fiber such that the light in the fiber does not exceed the critical angle and is totally internally reflected. The core and cladding are coated with an organic buffer to add strength. As shown in Figure 7, additional layers of plastic and other strength members, including Kevlar, are used in the optical fiber cable to give it additional strength. The overall cable diameter can vary depending upon the jacketing and strength member materials but it is typically about 0.125 inches in diameter.

Optical cable assemblies are relatively durable; however, like any cable, they can be broken. Care should be taken to avoid sharp bends (less than 0.5 inch radius) or kinks. Continuity checks of cable assemblies can be accomplished by using a light source that is eye safe. The operator can check for breaks by coupling the light source to the fiber and verifying the output at the end of the cable. Only a low power light source should be used for checking fiber continuity. Never use the laser firing unit to check continuity. It is not eye safe and the laser light is invisible to the human eye. If

the cable is not transmitting light, the cable must be repaired or replaced. Light leakage, due to broken fibers, may be detectable through light colored outer jackets available on optical cables. Utilizing those types of jackets may be helpful in determining what section of the optical cable will need to be repaired.

Connections with optical fibers can be made with standard connectors. The fiber optic jumpers will be destroyed in the explosive tests, so it is recommended that replacement jumpers be prepared ahead of time to minimize the number of cables that would be made in the field. Terminating optical fibers with connectors can be done in the field if required, but that job is easier and quicker if the jumper cables are made ahead of time.

The surface finish of the input end of the optical fiber is important. Cracks in this area of the fiber will reduce the coupling efficiency and lower the power delivered to the detonator. The polish or surface finish on the detonator end is not as critical, and a simple cleave of the optical fiber is sufficient.

Figure 7. Optical Fiber and Cable Structure.

1.8 Test Results

1.8.1 ESD Testing

Optical ordnance offers improved insensitivity over EED systems with respect to stray electrical signals such as ESD. The explosive component itself is immune to ESD pulses due to its continuous metal construction that provides a Faraday cage around the explosive materials. This Faraday cage eliminates the development of electrical potentials that can lead to arc formation and possible ignition of the powder.

The EOD detonator has been subjected to the Sandia Severe Human Body tester that has been designed to simulate an ESD pulse from a human body. The detonator was tested by discharging the ESD pulse through two electrodes from the ESD tester. One electrode is in contact with the window of the detonator, while the other is in contact with the outer shell that houses the HMX output charge. Five optical detonators were each subjected to 10 ESD pulses. The detonators survived the pulses with no eventful results.

While the detonator housing can give protection from stray electrical signals, there is a question concerning the sensitivity to stray optical signals from intense light sources

found in the environment that may couple into the optical fiber. Test results on laser ordnance devices have supported claims that these detonators are insensitive to an intense light source such as those generated by a lightning strike. Tests were performed using the Lightning Simulation Facility at Sandia to determine the effect of a near-by lightning flash and the coupling efficiency of the optical power into an optical fiber. An arc from the simulated lightning pulse was positioned approximately 1 inch from the optical fibers. Several tests were run with 100 and 400 micron fibers. The 400 micron fibers and some of the 100 micron fibers were connected to photo diode detectors in order to measure the optical power and energy coupled into the fibers from the simulated lightning pulse flash. The remaining 100 micron fibers were connected to CP detonators as shown in Figure 8. These detonators were chosen because they have the lowest ignition thresholds of the optical devices that we use. None of the detonators functioned during the simulated lightning pulse. Postmortem analysis of the explosive powder interface indicated no change to the powder surface exposed to the flash energy. Figure 8 shows a typical optical pulse as measured through the optical fibers and produced by the lightning simulator. The pulse shows an instantaneous rise to its peak power. The pulse quickly decays in a manner termed a "double decaying exponential" with a pulse duration of approximately 300 nsec.

The maximum observed peak powers measured through the 400 micron and 100 micron fibers were 22.4 Watts and 1.5 Watts, respectively. This optical pulse contains very little energy and is insufficient to ignite CP.

Figure 8. Lightning Simulation Setup.

1.8.2 Detonator Thresholds

A contract was awarded to Pacific Scientific, Energy Dynamics Division to build and test the optical detonator. A series of environmental tests was performed on four

groups of detonators. A control group of 10 detonators was tested at ambient temperature; 20 devices were tested after conditioning at -65°F; 20 devices were thermally cycled, and 13 devices underwent temperature and humidity cycling. A Neyer analysis [7] was used during the testing to determine the statistical all-fire level of the detonators after each of the environments.

Function times were measured from the start of the laser pulse to the output of the detonator. The function times of the 10 detonators in the baseline group ranged from 17.55 μ sec at an energy of 1.56 mJ to 38.10 μ sec at 0.69 mJ. The threshold test data yielded a mean threshold level (Mu) of 0.72 mJ with a standard deviation (sigma) of 0.04 mJ.

The next test series consisted of 20 detonators conditioned overnight at -65°F, and tested at -65°F. The Mu decreased to 0.61 mJ with a sigma of 0.08 mJ. The decreased mean is difficult to explain, because one would expect that the extra energy required to raise the temperature of the powder to its ignition point would result in higher mean energies.

A third group of 20 detonators was thermally cycled from 165°F to -65°F. Each cycle had a soak time of one hour with a 30 minute transition period. They were tested at -65°F after cycling. The Mu increased slightly to 0.63 mJ and the sigma jumped to 0.13 mJ.

The final group of 13 detonators underwent 32 temperature/humidity cycles, covering the same temperature range as in the last test group. The humidity at temperatures above ambient exceeded 90%. These devices all suffered cracked windows during the loading process. Some of the cracks went through the center and ran parallel to the window axis, while others ran at oblique angles to the axis. The effect of this added variable is apparent in the increased sigma of 0.2 mJ. The Mu also went up to 0.69 mJ.

1.8.3 Thermal testing of the UPCO Laser

An evaluation of the UPCO laser was done to determine its performance as a function of temperature. Various batteries were incorporated into the laser system, including: alkaline (Duracell), NiCad (Radio Shack), lithium (Energizer), and 3.6 volt lithium batteries that were supplied with the laser. The UPCO laser design incorporates a Nd:YAG rod flash lamp and electronic charge circuitry. For its power source, the laser uses either six 1.5 volt or three 3 volt AA batteries that are in series to produce ~9 volts. The 9 volt supply provides the energy for a DC to DC converter to step up the voltage to 500 volts which charges a 200 μ f capacitor. The capacitor is then discharged across the flash lamp to excite the Nd:YAG rod producing a beam of light with the wavelength of 1064 nanometers. Figure 9 summarizes the test results.

Temperature	Battery Type	Condition Time	First Shot Energy	Energy Range	Comments
-40°C	Alkaline	~18 Hours	> 2 mJ	.24 mJ to 53 mJ	Note 1, 2
	NiCad	~ 4 Hours	> 2 mJ	.77 mJ to 58 mJ	Note 1, 2
	Lithium 3.6 V	~ 17 Hours	No output	No output	Note 1, 2, 7
	Lithium Energizer	~ 17 Hours	> 10 mJ	31 mJ to 125 mJ	Note 1
-30°C	Alkaline	~ 5 Hours	> 10 mJ	91 mJ to 145 mJ	Note 1, 2
	NiCad	~ 5 Hours	116 mJ	116 mJ to 146 mJ	Note 1, 2
	Lithium Energizer	~ 17 Hours	112 mJ	112 mJ to 200 mJ	Note 1
-20°C	Alkaline	~ 5 Hours	117 mJ	177 mJ to 227 mJ	Note 3
	NiCad	~ 17 Hours	265 mJ	265 mJ to 263 mJ	
	Lithium Energizer	~ 17 Hours	257 mJ	257 mJ to 232 mJ	
-10°C	Alkaline	~ 5 Hours	285 mJ	285 mJ to 310 mJ	Note 1
	NiCad	~ 5 Hours	239 mJ	239 mJ to 280 mJ	Note 1, 6
	Lithium Energizer	~ 17 Hours	323 mJ	323 mJ to 283 mJ	
38°C	Alkaline	~ 17 Hours	314 mJ	314 mJ to 299 mJ	Note 5
	NiCad	~ 5 Hours	286 mJ	286 mJ to 293 mJ	Note 4
	Lithium Energizer	~ 17 Hours	290 mJ	290 mJ to 314 mJ	
65°C	Alkaline	didn't test	didn't test	didn't test	didn't test
	NiCad	~ 5 Hours	267 mJ	276 mJ to 269 mJ	Note 6
	Lithium Energizer	~ 17 Hours	297 mJ	297 mJ to 254 mJ	Note 3

Figure 9. Temperature Performance Table.

Notes:

1. The plastic alignment ferrule in the laser came out with the SMA connector when the connector is removed from the laser.
2. The LED charging indicator didn't work. UPCO stated that the LED would only emit when the charging voltage is 6 volts or greater.
3. The charging switch didn't rotate back to the safe position from the charging position. The laser charging switch was then rotated to the firing position to see if it would fire and it did.
4. The batteries were not recharged from the last test.
5. The batteries for this test had been used before.
6. The batteries seem to be outgassing or leaking.
7. The laser would not charge.

Some issues surfaced during the above tests and should be addressed in future designs. The charging/firing switch seemed to have tolerance or spring problems that caused the switch to stick in the charging position and intermittently fail in the firing position. Markings are needed to indicate the charging and firing positions. A potential problem exists with the DC to DC converter charging a 200 μ f capacitor rated at 360 volts to 500 volts.

Conclusions of the temperature tests indicate that the charging capacitor has the greatest effect on the laser performance. To reach optimum performance at -40°

Celsius, a capacitor with a lower temperature rating is needed. The lithium batteries seem to have the best cold temperature performance. In warmer environments the existing capacitor and alkaline batteries perform quite adequately.

1.8.4 VISAR Testing of the EOD Detonator.

Sandia's Explosive Projects and Diagnostic Department employs state of the art diagnostic capabilities to assess explosive component performance. Although the Department has historically characterized hot wire and exploding bridgewires, its diagnostic capabilities can also be used to characterize optical ordnance such as the EOD detonator. The Velocity Interferometer System, commonly called VISAR, is a non intrusive measurement tool that is capable of determining flyer velocities from 0.5 to 6 mm/ μ s. It is used to study shock wave phenomena and thereby evaluate explosive component performance.

Velocity measurements are taken by directing and focusing laser light on the surface of an explosive component, in this case the EOD detonator, and then firing the unit and capturing the reflected beam from the front surface of the detonator. The flyer plate velocity is measured by analyzing the Doppler shifted signals from the reflected beam.

When the unit is fired, the reflected beam from the surface of the detonator is routed to an optical table and is telescopically reduced and filtered. The beam is then split into two independent velocity interferometers that employ their own unique optical delay paths. The light signals are converted to electrical signals. Through high speed digitizing, a computer system then analyzes the Doppler shifted data and computes the velocity. Figure 10 shows the data taken from one of the experiments on the EOD detonator. Terminal velocity of the flyer thrown by the detonator was about 2.9 mm/ μ s, and was very repeatable from unit to unit. The output from the detonator will have more than sufficient margin to ignite Comp C-4 or Det cord directly.

Figure 10. VISAR Data from an EOD Detonator.

1.9 Field Demonstration

A field demonstration of the optical ordnance system for EOD applications was held on March 17, 1993, at Camp Pendleton, CA. Military and civilian personnel were in attendance for the briefing and the field demonstration. After conducting the briefing, the group traveled to the test range where a series of seven shots, utilizing the Whittaker Ordnance laser system, was fired. The tests are described below, and the Safe Operating Procedure that was utilized during the field operations is attached as Appendix 1.

A 1000 meter spool of optical fiber was utilized to demonstrate the down range capabilities of the laser firing system. A 20 meter jumper was connected to the end of the fiber spool and placed downrange for the shots. The optical fiber was checked with a low power Helium-Neon laser source (red light, 1mW optical power) to assure that there was optical continuity throughout the entire length of the spool and jumper. Once the optical continuity was verified, an optical blasting cap was placed at the end of the cable and jumper assembly. Positive control of the high power ignition laser was maintained by the person handling the explosives during all the explosive testing activities. Once the range was clear, the laser firing unit was connected to the input end of the optical fiber spool. The laser was then charged and fired. The optical detonator was successfully ignited through the 1000 meters of optical cable.

The second shot was identical to the first in setup, except that the detonator was placed in a ball of 100 grams of Comp C-4. The intent of shot #2 was to demonstrate that the optical blasting cap was capable of initiating C-4. When the range was clear, the laser was connected to the fiber spool, charged and fired. The detonator and C-4 detonated as expected.

The third shot involved testing the detonator in water. Both the detonator and a 100 gram ball of C-4 were placed in a container of water where they were successfully detonated.

The fourth shot involved igniting standard det cord with the optical detonator. The detonator was attached to the det cord with black electrical tape, as would usually be done with electrical blasting caps. The test was conducted through the same 1000 meter spool with a new jumper cable. This shot was successful and demonstrated that the detonator has sufficient energy to initiate det cord.

The fifth shot used a second laser that had been temperature pre-conditioned for about 1.5 hours in an ice bath. This laser used lithium batteries, made by Panasonic for use in cameras, instead of the regular alkaline batteries. The laser was charged, fired and successfully detonated a ball of C-4.

The sixth shot demonstrated the performance of the system in dirty or sandy conditions. The detonator had been coated with dust and dirt and was only cleaned off by blowing on it to dislodge the bigger particles. The detonator was then placed in a ball of C-4 where it and the C-4 were successfully detonated.

For the last shot, a demonstration was performed to repair the jumper used in a previous shot. The damaged optical connector was cut off, and a field connection was

made to replace it with a new optical connector. The field connection took about 10 minutes and was then used to attempt to fire a detonator that had been pre-conditioned in an ice bath. The first attempt did not work due to water leaking into the laser that had been conditioned in water. The leak resulted from an O-ring seal that had failed and allowed the laser to fill with water. A dry laser previously used in the first four shots was connected to the fiber spool, and the shot was fired successfully with that laser source. The O-ring failure was a problem area that ultimately lead UPCO to redesign their laser package.

1.10 Manufacturing Considerations

1.10.1 Hermetic Seals

Consideration must be given to decide if the optical detonator has a real requirement to be a hermetic device. Manufacturing costs to produce hermetic devices compared to non hermetic devices are substantial. Hermetic optical detonators have been successfully manufactured and tested. Hermetic devices have been manufactured using a sapphire window and a glass pre-form to seal the window in the metal housing by elevating the temperature to approximately 600°C, flowing the glass pre-form around the sapphire window and providing a glass seal for the sapphire window and the metal housing. This process has demonstrated hermeticity to 1×10^{-9} cc/sec at STP Helium leak rate.

Alternative device designs incorporating non hermetic seal configurations should be addressed. Development efforts for such a device should not be very costly and would make the optical detonators much more cost effective.

1.10.2 Laser Sources

Man portable laser systems capable of supplying enough optical energy and meeting the requirements as stated in Section 1.6 (System Requirements) can be manufactured by several suppliers. (Figure 3 shows two such device designs.) While prototype builds of the laser systems may seem expensive, much of the cost was due to the initial engineering costs associated with manufacturing the prototypes. As engineering and design goals mature and demand for these types of devices grow, we anticipate the price per device will be reduced considerably.

1.10.3 Powder Alternatives

The prototype optical detonators discussed in this report eliminates any primary explosives normally found in the ignition portion of electrically ignited blasting caps. While the explosive CP was chosen for the ignition mix and the DDT portion of the detonator, other non primary explosives may be used. A CP replacement, BNCP, has the same optical ignition characteristics and the same DDT characteristics as those needed to ignite the next assembly of HMX explosive. HMX was chosen as the

output portion of the detonator because it has the output characteristics necessary to easily ignite Comp C-4 or det cord.

1.10.4 Laser Diode Systems

The laser firing system was designed to incorporate a high power rod laser to ignite the detonator. Another alternative for firing these devices is available and could be considered as an alternative tool for the EOD. Laser diode devices currently being manufactured by many suppliers have enough power to ignite this type of optical detonator. Optical detonators have been fired using a diode laser through 1000 meters of optical fiber. Due to the lower power output of the diode lasers compared to the output of the rod laser, the margin for firing the detonators is smaller than it would be using the rod laser through this length of optical fiber. Laser diodes can be manufactured to have an optical fiber pigtailed into the package and be readily adaptable to the detonator jumper cable assembly. The laser diode system may be more cost effective than a rod laser system and could be considered for short standoff distance firings.

1.11 Summary

The optical ordnance firing system utilizes laser light that is emitted from a portable, hand-held rod laser and an optical fiber to ignite an explosive powder contained in a hermetically sealed optical detonator. The system has demonstrated the ability to reliably detonate Comp C-4 through 1000 meters of optical fiber.

The laser firing system is man portable and is powered by batteries. The optical energy from the laser is coupled into a standard optical fiber assembly that is readily connected to the optical detonator. Optical fiber jumpers are used to minimize the number of optical fiber termination's that must be made in the field with multiple shots.

The optical detonator has the same output characteristics as an electric blasting cap, is HERO safe and produces a detonation output sufficient to detonate Comp C-4 or det cord. The optical detonator does not contain any primary explosives.

1.12 References

1. S. C. Kunz and F. J. Salas, "Diode Laser Ignition of High Explosives and Pyrotechnics", Proceedings of the Thirteenth International Pyrotechnics Seminar, Grand Junction, CO, 11-15 July 1988, p. 505
2. R. G. Jungst, F. J. Salas, R. D. Watkins and L. Kovacic, "Development of Diode Laser-Ignited Pyrotechnic and Explosive Components", Proceedings of the Fifteenth International Pyrotechnics Seminar, Boulder CO, 9-13 July 1990, p 549.
3. J. A. Merson, F. J. Salas and J. G. Harlan, "The Development of Laser Ignited Deflagration-to-Detonation Transition (DDT) Detonators and Pyrotechnic Actuators", Proceedings of the Nineteenth International Pyrotechnics Seminar, Christchurch, New Zealand, 20-25 February, 1994, p. 191
4. D. W. Ewick, T. M. Beckman and D. P. Kramer, "Feasibility of a Laser-Ignited HMX Deflagration to Detonation Device for the U. S. Navy Lites Program", Rep. No. MLM-3691, EG&G Mound Applied Technologies, Miamisburg, OH, June 1991, 21 pp.
5. D. W. Ewick, T. M. Beckman, L. R. Dosser, and D. P. Kramer, "Development of Laser Diode Ignited CP Detonators", Rep. No. MLM-3713, EG&G Mound Applied Technologies, Miamisburg, OH, November 1991, 18 pp.
6. C. M. Woods, E. M. Spangler, T. M. Beckman and D. P. Kramer, "Development of a Laser-Ignited All-Secondary Explosive DDT Detonator", Proceedings of the Eighteenth International Pyrotechnics Seminar, Breckenridge, CO, 9-13 July 1990, p. 277.
7. B. T. Neyer, "More Efficient Sensitivity Testing", MLM-3609, EG&G Mound Applied Technologies, Miamisburg OH, October 1989, 31 pp.

Appendix 1

Standard Operating Procedure Used During the Demonstration at Camp Pendleton.

This SOP does not supersede any site specific SOP's, and should not be used for all optical ordnance testing.

Safety Note: The laser is not eye safe when operated with the protective cover removed or without a closed optical fiber delivery system. Do not operate the laser without a fiber optic cable or with the protective shutter cap removed.

Never view the output of the laser or any optical fiber connected to the laser. Serious eye damage or blindness may result from direct or indirect viewing of the laser beam. The laser operator shall use eye protection with at least an optical density of 4.6. Casuals within 3 meters shall also have equivalent eye protection.

1. These instructions do not supersede any other instructions. Procedures should be consistent with safe demolition and range safety.
2. Check the fiber optic cable for continuity. This can be done by removing the plastic connector covers, hold one end of the fiber towards a light and look for light throughput at the other end of the optical fiber.
3. The fiber optic cable is made with SMA 906 connectors on both ends. The cable can now be connected to the main spool of optical fiber by using an optical feed through connector. **Insure that the laser is not attached to the other end of the main spool of optical fiber at this time.** The explosive handler shall remain in positive control of the laser at all times.
4. Lay out the optical fiber. Avoid making sharp bends in the cable. Kinks in the cable can result in fiber damage that must be repaired. Place a barricade or otherwise stabilize the fiber optic cable approximately 1 meter from the explosive working end of the fiber before installing the optical detonator. This is done to try to protect as much of the fiber as possible.
5. The optical detonator can now be attached to the end of the fiber optic cable. The detonator is designed to accept an SMA optical connector. Thread the optical connector onto the detonator. (Finger tight is sufficient, do not over tighten.)
6. Observe all safety precautions while handling any explosives.
7. Once a safe stand off distance with frontal and overhead protection has been established, and the range closed, the firing sequence can be started.
8. Insure that the range has not been violated, and take a head count of all personnel.
9. With the laser in the off or safe position, attach the fiber optic connector to the laser. Do not look into the end of the laser under any circumstances.

10. The laser can now be activated, and can be fired when the conditions are ready.
11. In the event that the operator wishes to abort for any reason, the laser system is to be turned off and the optical cable removed from the laser. The protective cap will be attached to the laser system immediately.
12. To initiate the detonator, wait for the laser to become charged and depress the laser firing button.
13. Turn the laser off, remove the optical cable and replace the cover on the laser. Insure that the laser is not energized.
14. In the event of a misfire, allow the laser to recharge and attempt to fire again. If no initiation takes place, follow the standard misfire procedures. Wait at least 30 minutes before going down range.
15. Before the next shot, replace or repair the optical fiber jumper segment.

Appendix 2
Drawing Package of the Detonator.

SI METRIC

NOTES:

1. LASER BEAM WELD AND INSPECT PER 9912700.
2. WARNING: THIS DATA BASE HAS BEEN CONVERTED FROM ENGLISH TO METRIC UNITS. METRIC DIMENSIONS AND TOLERANCES MAY NOT EXACTLY REPRESENT THE ELECTRONIC GEOMETRIC DEFINITION.

DESIGN AND CY PART NUMBER		REVISIONS					
ISS	SHEET	PREPARED BY	DESCRIPTION	DATE	CHK	APVD	
R42130-000	A	D. SOUTH, 2783/ J. MASON, 2652 J. SALAS, 2652				JM	

1	R42130-000	SHELL ASSEMBLY				4
1	R42130-000	HOUSING ASSEMBLY				3
NA	9912700	WELDING, LASER BEAM, GENERAL PROCESS				2
NA	9900000	GENERAL REQUIREMENTS				1
NO. 1000	PART/CONTROL NO.	DESCRIPTION/MATERIAL	NOTE	SHEET	ITEM	
ALT-ALTERNATE	ALT-AS REQ'D	ALT-AS REQ'D FOR ASSY	EX-EXPOSED MATERIAL	NA-DOCUMENT	NA-PROCESS MATERIAL	
AGENCY APPROVALS		SHEET	1	2	3	4
ORG	DATE	APPROVALS	100%	A		
PART CLASSIFICATION		TITLE				
UNCLASSIFIED		EOD DETONATOR ASSEMBLY (U)				
DRAWING CLASSIFICATION		SIZE	DRAWING NUMBER			
UNCLASSIFIED		C	R42130			
STATUS		SA-FEL-7-25-04	DATE 14213 SCALE 10/1 SHEET 1 OF 1			
			GUIDE SA-ANG-VZ.1			

SI METRIC

THIRD ANGLE PROJECTION

SI METRIC

NOTES:

1. GENERAL REQUIREMENTS PER 9900000.
2. MATERIAL: STAINLESS STEEL, 430 PER MIL-S-18732.
3. WARNING: THIS DATA BASE HAS BEEN CONVERTED FROM ENGLISH TO METRIC UNITS. METRIC DIMENSIONS AND TOLERANCES MAY NOT EXACTLY REPRESENT THE ELECTRONIC GEOMETRIC DEFINITION.
4. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS EXCEPT THREADS AND RAW STOCK CALLOUTS ARE IN MILLIMETERS FOLLOWED BY THE INCH EQUIVALENT ENCLOSED IN [].

DESIGN AGENCY PART NUMBER		REVISIONS					
150	SHEET SIZE	PREPARED BY		DESCRIPTION	DATE	CHKD	APVD
R42131-000	A	D. SOUTH, 2783/ J. MERTON, 2632 J. SALAS, 2652					JM

SI METRIC

THIRD ANGLE
PROJECTION

SHEET	1	2	3	4	5	6	TITLE
150	A						SHELL, EOD DETONATOR (U)
PART CLASSIFICATION UNCLASSIFIED							
DRAWING CLASSIFICATION UNCLASSIFIED							
SIZE C							DRAWING NUMBER R42131
STATUS SA-REL-7-26-94							ORIGIN SA-ANS-V2.1

GEOMETRIC PRECISION = XX.XXX XX

4. WARNING: THIS DATA BASE HAS BEEN CONVERTED FROM ENGLISH TO METRIC UNITS. METRIC DIMENSIONS AND TOLERANCES MAY NOT EXACTLY REPRESENT THE ELECTRONIC GEOMETRIC DEFINITION.
5. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS EXCEPT THREADS AND RAW STOCK CALLOUTS ARE IN MILLIMETERS FOLLOWED BY THE INCH EQUIVALENT ENCLOSED IN [].

NOTES:

1. GENERAL REQUIREMENTS PER 99000000.
2. MATERIAL: ROUND, STAINLESS STEEL, 304L PER ASTM A276 OR E BRITE 26-1.
3. DEBUR ALL SHARP EDGES UNLESS OTHERWISE SPECIFIED.

DESIGN AGENCY PART NUMBER	REVISIONS						
	ISS	SHEET DATE	PREPARED BY	DESCRIPTION	DATE	CHKD	APVD
R42132-000	A		D. SOUTH, 2783/ J MERSON, 2652 J SALAS, 2652				JM

SHEET 1 2 3 4 5 6 TITLE HOUSING, EOD DETONATOR EXPLOSIVE (U)	
PART CLASSIFICATION UNCLASSIFIED DRAWING CLASSIFICATION UNCLASSIFIED	
SI METRIC THIRD ANGLE PROJECTION	SIZE C DRAWING NUMBER R42132 SCALE 10/1 SHEET 1 OF 1

SI METRIC

NOTES:

1. IN HOUSING (ITEM 1), USE ITEM 6 IN FIRST PRESSING AND ITEM 7 IN LAST THREE PRESSINGS. FINAL PRESSING OF ITEM 7 TO BE FLUSH $\pm .002$ FROM EDGE.
2. WARNING: THIS DATA BASE HAS BEEN CONVERTED FROM ENGLISH TO METRIC UNITS. METRIC DIMENSIONS AND TOLERANCES MAY NOT EXACTLY REPRESENT THE ELECTRONIC GEOMETRIC DEFINITION.

DESIGN AGENCY PART NUMBER		REVISIONS				
100	2187	228	PREPARED BY	DESCRIPTION	DATE	CHKD
R45589-000	A		O. SOUTH, 2783/ J. MERTON, 2652 J. SALAS, 2652			JM

ARS	1.5 g/cc OP DOT EXPLOSIVE CHARGE (.120 EA)	1				7
ARS	1.7 g/cc OP EXPLOSIVE CHARGE (.120)	1				6
						5
						4
						3
						2
1	R45589-000	WINDOW SEAL SUBASSEMBLY				1
NA	9912700	WELDING, LASER BEAM, GENERAL PROCESS				
NA	9900000	GENERAL REQUIREMENTS				
NO	PART/CONTROL NO.	DESCRIPTION/MATERIAL	NOTE	245T	228	110M
ALT-ALTERNATE	AR-AS REQ'D	AR-AS REQ'D PER ASSY	IN-EXPENSE MATERIAL	NA-COOLMENT	IN-PROCESS MATERIAL	
AGENCY APPROVALS		SHEET	1	2	3	4
DRG	DATE	APPROVALS	ISSUE	A		
PART CLASSIFICATION		TITLE				
UNCLASSIFIED		HOUSING ASSEMBLY (U)				
DRAWING CLASSIFICATION		SIZE	DRAWING NUMBER			
UNCLASSIFIED		C	R45589			
STATUS		SA-REL-7-25-94	ORIGIN	SA-ANS-V2.1	SCALE	10/1
					SHEET	1 of 1

SI METRIC
THIRD ANGLE
PROJECTION

NOTE:

1. WARNING: THIS DATA BASE HAS BEEN CONVERTED FROM ENGLISH TO METRIC UNITS. METRIC DIMENSIONS AND TOLERANCES MAY NOT EXACTLY REPRESENT THE ELECTRONIC GEOMETRIC DEFINITION.

SI METRIC

DESIGN AGENCY PART NUMBER		REVISIONS				
ISS	SHEET SIZE	PREPARED BY	DESCRIPTION	DATE	CHKD	APVD
R45590-000	A	D. SOUTH, 2783/ J. NELSON, 2652 J. SALAS, 2652				JM

ALT	1,7 g/cc HMX EXPLOSIVE CHARGE (.1850 TL)		4
ISS			3
I	R42131-000	SHELL, EOD DETONATOR	2
NA	9012700	WELDING, LASER BEAM, GENERAL PROCESS	1
NA	9000000	GENERAL REQUIREMENTS	
NO. / REQ	PART/CONTROL NO.	DESCRIPTION/MATERIAL	NOTE SHEET SIZE ITEM
ALT-ALTERNATE	AR-AS REQ'D	ANS-AS REQ'D PER ASSY	EN-EXPLOSIVE MATERIAL NA-DOCUMENT IN-PROCESS MATERIAL
AGENCY APPROVALS		SHEET 1 2 3 4 5 6	TITLE
ORG	DATE	APPROVALS	ISSUE A
PART CLASSIFICATION		SHELL ASSEMBLY (U)	
UNCLASSIFIED			
DRAWING CLASSIFICATION		SIZE	DRAWING NUMBER
UNCLASSIFIED		C	R45590
STATUS		SA-FEL-7-25-94	ORIGIN SA-ANS-V2.1

SI METRIC
THIRD ANGLE
PROJECTION

ELECTRIC PRECISION = XX.XXX XX

SI METRIC

NOTES:

1. HERMETIC SEAL REQUIRED PRIOR TO LOADING AT NEXT ASSEMBLY LEVEL.

2. WARNING: THIS DATA BASE HAS BEEN CONVERTED FROM ENGLISH TO METRIC UNITS. METRIC DIMENSIONS AND TOLERANCES MAY NOT EXACTLY REPRESENT THE ELECTRONIC GEOMETRIC DEFINITION.

DESIGN AGENCY PART NUMBER		REVISIONS					
ISS	SHEET TYPE	REVISED BY	DESCRIPTION	DATE	Q MR	APVD	
R45588-000	A	D. SOUTH, 2783/ J. MERSON, 2652 J. SALAS, 2652				JM

SI METRIC
THIRD ANGLE
PROJECTION

1	R45457-000	RING, PROFORM				4
1	R42123-000	WINDOW, EOD DETONATOR				3
1	R42132-000	HOUSING, EOD DETONATOR EXPLOSIVE				2
NA	9912700	WELDING, LASER BEAM, GENERAL PROCESS				1
NA	9900000	GENERAL REQUIREMENTS				
NO.	REV	PART/CONTROL NO.	DESCRIPTION/MATERIAL	NOTE	SHEET REV	ITEM
ALT-ALTERNATE	NA-AS REV'D	NA-AS REV'D PER ASSY	EX-EXPLODE MATERIAL	NA-OCCLMENT	NA-PROCESS MATERIAL	
AGENCY APPROVALS		SHEET	1	2	3	4
ORG	DATE	APPROVALS	ISSUE	A		
PART CLASSIFICATION		TITLE				
UNCLASSIFIED		WINDOW SEAL SUBASSEMBLY (U)				
DRAWING CLASSIFICATION		SIZE				
UNCLASSIFIED		C R45588				
STATUS		SA-REL-7-25-94				
		ORIGIN SA-ANS-V2.1				

NOTES:

1. GENERAL REQUIREMENTS PER 99000000.
2. MATERIAL: EN-1 GLASS SOLID PREFORM OR EQUIVALENT.
3. WARNING: THIS DATA BASE HAS BEEN CONVERTED FROM ENGLISH TO METRIC UNITS. METRIC DIMENSIONS AND TOLERANCES MAY NOT EXACTLY REPRESENT THE ELECTRONIC GEOMETRIC DEFINITION.
4. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS EXCEPT THREADS AND RAW STOCK CALLOUTS ARE IN MILLIMETERS FOLLOWED BY THE INCH EQUIVALENT ENCLOSED IN [].

SI METRIC

DESIGN AGENCY
PART NUMBER

R45457-000

REVISIONS

ISS	SHEET ZONE	PREPARED BY	DESCRIPTION	DATE	CHK	APVD
A		D. SOUTH, 2783/ J. MERSON, 2652 J. SALAS, 2652				JM

SI METRIC

THIRD ANGLE
PROJECTION

SHEET	1	2	3	4	5	6	TITLE	
ISSUE	A						RING, PREFORM (U) (EOD)	
PART CLASSIFICATION UNCLASSIFIED							SIZE: DRAWING NUMBER B R45457	
DRAWING CLASSIFICATION UNCLASSIFIED								
STATUS SA-REL-7-25-94								
CAGEC 14213							SCALE 20/1	SHEET 1 OF 1
ORIGIN SA-ANS-V2.1								

GEOMETRIC PRECISION = XX.XXX XX

SI METRIC

NOTES:

1. GENERAL REQUIREMENTS PER 99000000.
2. MATERIAL: SAPPHIRE .381 (.015).
3. MAY BE OBTAINED FROM:
MELLER OPTICS, INC
P.O. BOX 6001
PROVIDENCE, RI 02904
PHONE: 401/331-3717
OR SNL APPROVED EQUIVALENT.
4. WARNING: THIS DATA BASE HAS BEEN CONVERTED FROM ENGLISH TO METRIC UNITS. METRIC DIMENSIONS AND TOLERANCES MAY NOT EXACTLY REPRESENT THE ELECTRONIC GEOMETRIC DEFINITION.
5. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS EXCEPT THREADS AND RAW STOCK CALLOUTS ARE IN MILLIMETERS FOLLOWED BY THE INCH EQUIVALENT ENCLOSED IN [].

GEOMETRIC PRECISION = XX.XXX XX

DESIGN AGENCY PART NUMBER	REVISIONS					
	ISS	SHEET ZONE	PREPARED BY	DESCRIPTION	DATE	CHKD APVD
R42129-000	A		D. SOUTH, 2783/ J MERSON, 2652 J SALAS, 2652			JM

SHEET	1	2	3	4	5	6	TITLE	
ISSUE	A						WINDOW, EOD DETONATOR (U)	
PART CLASSIFICATION							UNCLASSIFIED	
DRAWING CLASSIFICATION							UNCLASSIFIED	
SIZE							B R42129	
STATUS							SA-REL-7-25-94	
ORIGIN							SA-ANS-V2.1	

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