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Laser Ignition in Guns, Howitzers and Tanks: The LIGHT Program

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Recent advances in large-caliber gun propulsion systems have exacerbated the problems associated with reproducible and reliable ignition. The use of liquid propellant in the Advanced Field Artillery System (AFAS) 155-mm howitzer, multicomponent Unicharge in 155-mm howitzers and two-piece ammunition in the Advanced Tank Cannon System (ATACS) 140-mm tank gun introduce new constraints on the ability of conventional primers and igniter materials to achieve reliable ignition. In response to these challenges a new program entitled Laser Ignition in Guns, Howitzers and Tanks (LIGHT) has been developed. The goals of the program are two-fold and address the concepts of indirect and direct ignition of propelling charges. The short-term goal (indirect laser-based ignition) involves replacement of mechanically autoloaded primers with laser-assisted ignition of igniter material within the propelling charge. The long-term goal (direct laser-based ignition) involves the elimination of all conventional primer and igniter materials from the ignition train and the use of laser radiation distributed through embedded optical fibers to simultaneously (isochronically) ignite the propelling charge. Anticipated benefits include decreased system vulnerability, a reduction in pressure waves for improved system safety and reliability and a potential improvement in performance through programmed and/or temperature compensating ignition.

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TABLE OF CONTENTS

Page

LIST OF FIGURES v

ACKNOWLEDGMENTS vii

1. INTRODUCTION 1

2. EXPERIMENTAL 4

3. DISCUSSION 6

3.1 Blackpowder Ignition (Unicharge) 6
3.2 Blackpowder Ignition (ATACS) 13
3.3 Direct Propellant Ignition 18
3.4 LP Ignition 20
3.5 Double-Laser Pulse Ignition 24

4. CONCLUSIONS 25

5. REFERENCES 27

DISTRIBUTION LIST 29

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LIST OF FIGURES

Figure | Page

1. Laser Interaction With Propellant Surface 5
2. Pump-Probe Laser Experimental Setup 5
3. Unicharge Interior Ballistics Calculations 7
4. Solution to Unicharge Stand-Off Problem 7
5. Schematic of Unicharge Laser Ignition Concept 8
6. Transmission of Nd:Glass Laser Radiation Through a Mylar Window 9
7. Laser Ignition Test Setup 9
8. Trends Observed in Blackpowder Ignition 11
9. Effect of Laser Pulse Duration on Blackpowder Ignition Delay at Constant Laser Energy 11
10. Temporal Profiles of Laser Pulses (Top Drawing) and Effect of Increased Laser Energy on Ignition Delay at Constant Laser Pulse Width (Lower Drawing) 12
11. Light Emission From the Simultaneous Laser Ignition of Confined Blackpowder Igniters 14
12. Pressure-Time Curve for Laser Ignition of Confined Blackpowder Samples 14
13. BRL ATACS Laser Ignition Concepts 16
14. Characteristics of Tapered Optical Fibers 16
15. Tank Round With Embedded Optical Fiber Distribution System 17
16. Simultaneous Delivery of Two Laser Pulses for ATACS Ignition 17
17. Simultaneous Laser Ignition of Two ATACS Blackpowder Igniters Using Various Laser Pulse Widths (Through Optical Fibers) 19
18. Simultaneous Laser Ignition of Two 1-oz ATACS Blackpowder Igniters 19
19. Light Emission From the Laser Ignition of JA2 and M30 Propellants 20
20. Pressure-Time Curves for the Direct Laser Ignition of Confined M30 and XM43 Propellants 21

Figure | Page

21. BRL Conceptual Depiction of LP Gun With a Laser-Based Igniter 22

22. Schematic of BRL Laser-Based LP Igniter 23

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1. INTRODUCTION

The Laser Ignition in Guns, Howitzers, and Tanks (LIGHT) Program was established at the Ballistic Research Laboratory (BRL), in part, as a result of an ignition concept which was discovered at BRL called *resonance laser microplasma ignition* (Forch and Miziolek 1986, 1987, 1991; Forch, Morris, and Miziolek 1990). It was found that reactive gaseous mixtures such as H_2/O_2, D_2O_2, and H_2/N_20 could be ignited into combustion very efficiently with laser energies less than 1 mJ at very specific laser wavelengths. A new laser ignition mechanism was formulated based upon the efficient and well-controlled resonant formation of laser-produced microplasmas. Briefly, if the laser is tuned to well-known absorption transitions of molecular or atomic species that are constituents of the gas mixture or are photolytically produced by the laser, then ionization and electron formation and amplification processes produce a microplasma which serves as an ignition source. When the laser is tuned off of the resonance absorption transitions of these species, it was found that as much as 60 times more laser energy was required for ignition. The attractive feature of this ignition source clearly lies in the efficiency of the process which may allow for the development of small, low-energy lasers to be used as igniters for energetic solid materials such as gun propellants. A laser source which is tuned to absorption transitions in solid materials or in pyrolysis gas produced at the solid-gas interface, could lead to efficient, low-energy ignition thresholds. Furthermore, the ability to directly ignite propellant beds could lead to the elimination of primers and igniters from the ignition train which would dramatically minimize vulnerability, simplify the ignition train, and facilitate the ignition of insensitive munitions which are inherently difficult to ignite.

There are several well-known laser ignition methods which include spark formation, photochemical ignition, resonant formation of microplasmas, and thermal heating. All of these ignition mechanisms are currently under evaluation for applications to the initiation of propellant beds in large-caliber guns. The overall goal within the LIGHT Program is to eliminate all primers and igniter material from the ignition train. Within the LIGHT Program, ignition has been categorized into two regimes called *direct* and *indirect laser-based ignition.* The direct laser ignition concept (the long-term program goal) focuses on initiation of propellant beds via the interaction of laser light with the charge; no igniter material whatsoever is used to facilitate the ignition. Indirect laser ignition (the short-term program goal) involves the removal of current primers and igniter material from the ignition train in their present configurations within the munition. Here, the laser light is first transmitted to a sensitizer which is a small quantity of energetic material which then transfers the ignition stimulus to the propellant bed. Both laser ignition concepts involve the transfer of laser radiation into the gun through the use of optical fibers connected through a breech window. An obvious important consideration is the transfer of the laser light through the gun breech. Concepts where a small optical window is incorporated into the breech have been developed and shown to be highly successful. The breech window must be composed of a material which will readily transmit the laser radiation with no optical damage and, in addition, withstand the high pressures and temperatures encountered with large-caliber guns. A suitable breech window material made from aluminum oxide (sapphire) easily satisfies these requirements. Synthetic sapphire is routinely used in high-pressure, hostile environments. In addition to the requirements of the window for robustness and high transmission at the laser wavelengths used, problems associated with contamination must also be addressed. The breech window may well survive a single initiation; however, combustion products and particulates (debris) may contaminate the window and reduce the transmission of the laser beam in subsequent firings. Repeated firings may produce a degree of contamination such that the transmitted laser energy is no longer sufficient for reliable ignition. Simple concepts have been developed where the breech window can be partially shielded from the combustion event and/or cleaned using a breech brush. It has been demonstrated that if the breech window is incorporated into a debris trap in an artillery gun, then contamination can be minimized. Although the window does indeed become somewhat obscured by particulates, a steady-state condition is achieved which inhibits further loss in transmission. BRL has proposed a unique double-window concept which may have important applications in the laser-based ignition of tank rounds which utilize a stub case.

Lasers may be mounted on external hardware at the gun mount or may be directly attached to the gun breech. In either scenario, the laser must be sufficiently sturdy to survive the high-energy gun recoil forces. The optical components of the laser such as lenses, flashlamps, and rod can survive recoil forces if the laser is attached to the gun mount and isolated from moving parts of the gun. The laser radiation can be coupled to the breech through optical fibers which can dissipate recoil forces. Investigations to ascertain the survivability of a breech-mounted laser system are anticipated. The laser must also use fail-arm-safe electronics to both alleviate unwanted firings and serve as an integrity verification of the optical ignition train. In this configuration, optical shutters (beam blocks) prohibit unwanted firing unless the munition is loaded into the gun. Inert, low-energy laser diodes which are incapable of initiation themselves can readily be incorporated within the optical train and electronics of the primary ignition laser system to check for optical continuity.

There are many important characteristics of the laser which must be addressed. These laser parameters include energy, power density, pulse length, wavelength, and repetition rate. Lasers which have been examined as ignition sources include rare-gas discharge lasers (excimers), CO_2 lasers, solid-state lasers such as Nd:YAG or Nd:glass, and small diode lasers. Excimer lasers are convenient sources of ultraviolet (UV) light which can be delivered at high repetition rates. Most energetic materials used in gun propulsion absorb well in the UV, however, the pulse length of these lasers (nanoseconds) is too short for reliable initiation. The high peak-powers that are generated tend to cause ablation (blow-off) rather than ignition of the energetic material. In addition, the UV wavelengths produced by these lasers is not readily transmitted through optical fiber material and/or can damage the input coupler ends of the fibers. CO_2 lasers can readily generate high-energy pulses which can easily ignite energetic materials, however, the laser wavelength it produces (10.6 µ) cannot be readily transmitted through conventional glass optical fibers. Germanium fibers have been developed which will readily transmit this wavelength, but they are very brittle, expensive, and cannot be manufactured in lengths suitable for gun applications. There are many other types of lasers which may serve as candidate igniters. A particularly attractive source is the solid-state laser based upon the Nd^{+3} ion. Generic lasers of this type are the Nd:YAG and Nd:glass which operate near 1.06 µ and 1.05 µ, respectively. These laser systems can be made very small (pyrotype), rugged, reliable, long-lived, and inexpensive. Laser radiation near 1 µ can readily be transmitted through very durable and inexpensive fused silica optical fibers over great distances with negligible loss. These lasers can operate in continuous mode or produce picosecond to millisecond pulses. This laser wavelength is also readily transmitted through sapphire breech window material. The Nd:glass laser has been extensively used as an ignition source within the LIGHT Program as a result of these attributes.

The aforementioned discussion summarizes key issues which have been considered in the ongoing development of a laser-based ignition system for large-caliber guns. The bulk of this report describes the preliminary experimental research and testing in the development of a laser-based ignition system for the Advanced Field Artillery System (AFAS) 155-mm howitzer with candidate propulsion concepts—Unicharge and Liquid Propellant (LP)—and the Advanced Tank Armament Cannon System (ATACS) 140-mm tank gun round. The goal of the Unicharge laser ignition program at present is to eliminate the current M82 primer from the gun breech and to ignite the blackpowder igniter pad with a laser with no modification to Unicharge. The long-term future goal is to eliminate all igniter material from the ignition train and directly ignite the propelling charge with a laser at multiple points to achieve isochronic ignition. The immediate goal of the ATACS laser ignition program is to replace the primer with an optical feed to couple laser energy into two blackpowder pads within the two-piece ammunition. The long-term future goal is to similarly eliminate all primer and igniter material from the round. The current Unicharge and ATACS propellant candidates are M30 and JA2, respectively; however, because of future insensitive munition requirements for all large-caliber gun systems, LOVA-type propellants, which are inherently difficult to ignite, will be utilized.

2. EXPERIMENTAL

There are numerous experimental setups and configurations of apparatus that are currently being employed in this work. LIGHT is a broad-based, basic, developmental research program aimed at understanding the chemical and physical interactions of lasers with energetic materials such as propellants. Figure 1 depicts the interaction of laser light with the surface of a propellant sample. Important parameters include laser absorption at the surface of the grain, depth penetration, pyrolysis gas generation, thermal diffusivity, heat conduction, surface reflectivity, ignition, pressure generation, transient and sustained combustion, flamespread to adjacent grains, and extinction. These parameters are fully characterized in a diagnostic laboratory in order to optimize the conditions for successful ignition. The ignition technology developed in the laboratory may then be tested and evaluated in small-scale simulators in an indoor range. Important parameters such as ignition delay times, pressure-time curves, light emission measurements, and high-speed photography are measured. The laser-ignition train is then repeatedly tested in a full-scale ballistics simulator and these parameters are measured again. Successful testing in the simulator is a prerequisite for firing in the actual large-caliber gun.

Figure 2 depicts a schematic of a typical laboratory setup. There are numerous diagnostic lasers which are available to probe ignition and combustion events in the laboratory such as a Nd:YAG-Dye laser system which produces tunable laser light. Two high-energy Laser Photonics Nd:glass lasers serve as ignition sources. These lasers are variable energy (up to 30 J laser energy/pulse) and can generate pulse widths (using a pulse-forming network) from 100 µs to 10 ms. Diagnostics equipment includes optical multichannel analyzers, spectrometers, pressure sensors, digital scopes, and other high-speed image processing equipment. The beam diameter is 6.35 mm and divergence is 3–4 mrad. The calculated diameter of the laser beam at the focus of this laser varied from 300 to 500 µ, depending on the focal length of the lens used in either a pyrolysis or laser ignition experiment. This laser beam was focused into a single 300-cm-length, 1-mm-diameter, cladded, solid-core, fused silica optical fiber or into an optical fiber bundle with a nine-way split which gave ~ 1–2 J laser energy at the end of each SMA connector. The pulse energy was measured with a Scientech volume-absorbing disc calorimeter Model No. 38-0103 and analog meter.

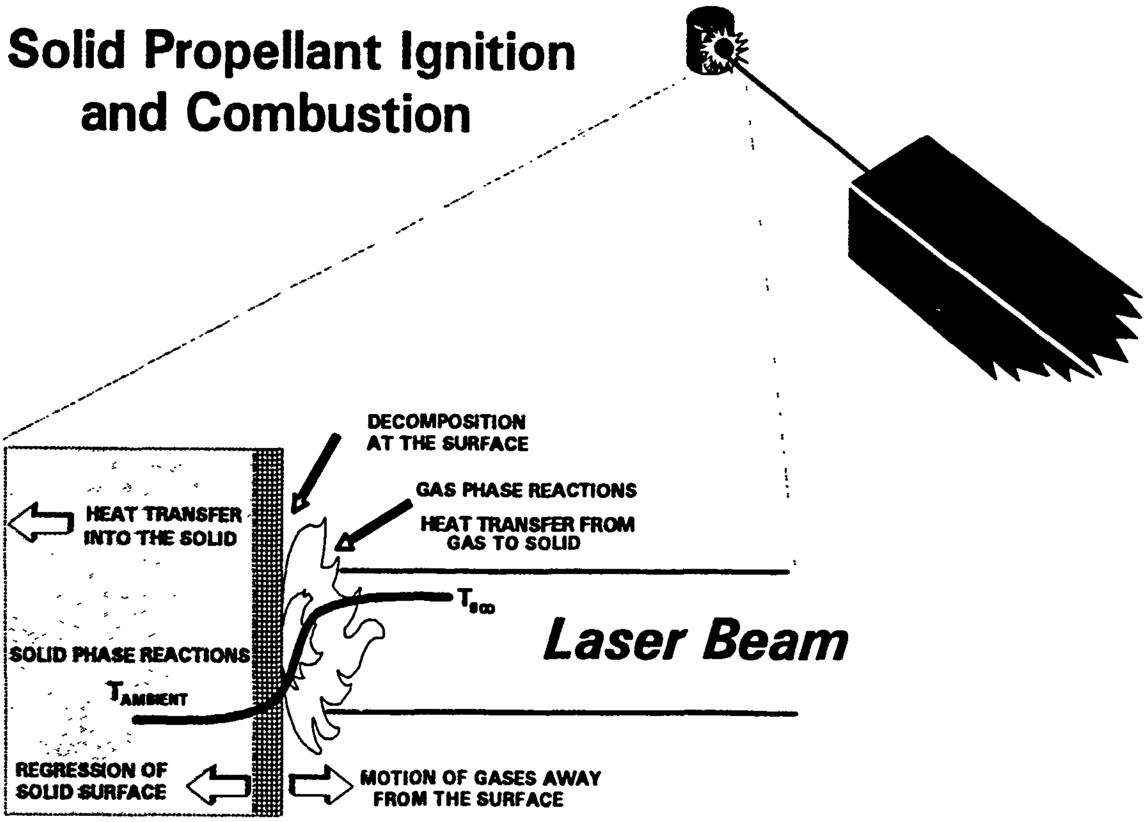

Figure 1. Laser Interaction With Propellant Surface.

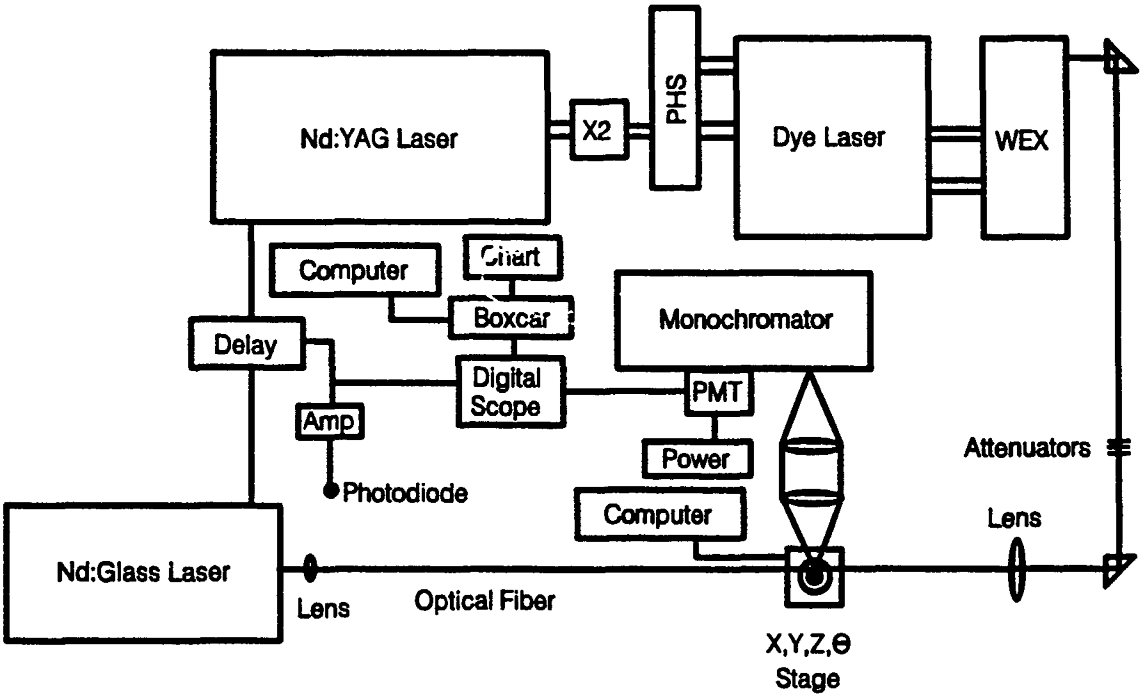

Figure 2. Pump-Probe Laser Experimental Setup.

The propellant grains were mounted on a high-precision motion stage (a stack of three Daedal series 100000 linear micropositioners and one Daedal series 20000—five in rotary table) with 4 degrees of control (X,Y,Z, H). The translational stages each provide 4 inches of travel with a translational accuracy (straight and positional) of +/-5.0 x 10^{-5} in/in of travel and bidirectional repeatability of 5.0 x 10^{-5} in. The rotational stage provides angular repeatability of 0.2 arc/min with an accuracy of 3.0 arc/min. Each stage is driven by a stepper motor with microstepping controlled by an Epson Model Plus microcomputer. Time sequencing of the two lasers was accomplished using a high-precision (+/-10 picoseconds) digital delay generator (Stanford Research Systems, Model No. DG 535) which was triggered with the amplified signal from a high-speed pin-photodiode. A remote control outlet at the long-pulse laser generates a TTL trigger pulse when the laser fires which can trigger another source or it accepts a similar TTL pulse for firing by an external trigger.

3. DISCUSSION

3.1 Blackpowder Ignition (Unicharge). Interior ballistic (IB) calculations suggest that isochronic ignition of multicomponent ammunition can lead to substantial benefits such as system safety and reliability. Representative results of IB calculations which model the simultaneous ignition of six Unicharge components in a 155-mm gun using a laser system are given in Figure 3. Localized ignition (nonisochronic), which leads to nonuniform flamespread within the propellant bed, may produce pressure differentials (axial pressure waves) which can lead to gun failure. Gun pressures calculated at the breech and forward chamber areas (curves b and c, respectively) as the result of the simultaneous ignition of all components show essentially no pressure differential (curve a). A laser-based ignition system for Unicharge also has the potential to solve stand-off problems in low zones. The conventional M82 primer cannot reliably ignite the component if it were to slide up the gun barrel at large stand-off distances. A laser-based igniter can easily achieve ignition regardless of the stand-off (Figure 4). A laser-based ignition system can also simplify the ignition train through the complete elimination of the primer which is inherently difficult to insert and/or extract using an autoloader system. Thus, a laser-based ignition system can potentially solve many gun-related problems either as a primary ignition system or as an alternate ignition system. It is desirable for either conventional or alternate ignition sources for large-caliber guns to be readily used or interchanged as required. A conceptual drawing of a Unicharge laser-based igniter train is shown in Figure 5. In this concept, no alteration whatsoever is required to existing Unicharges.

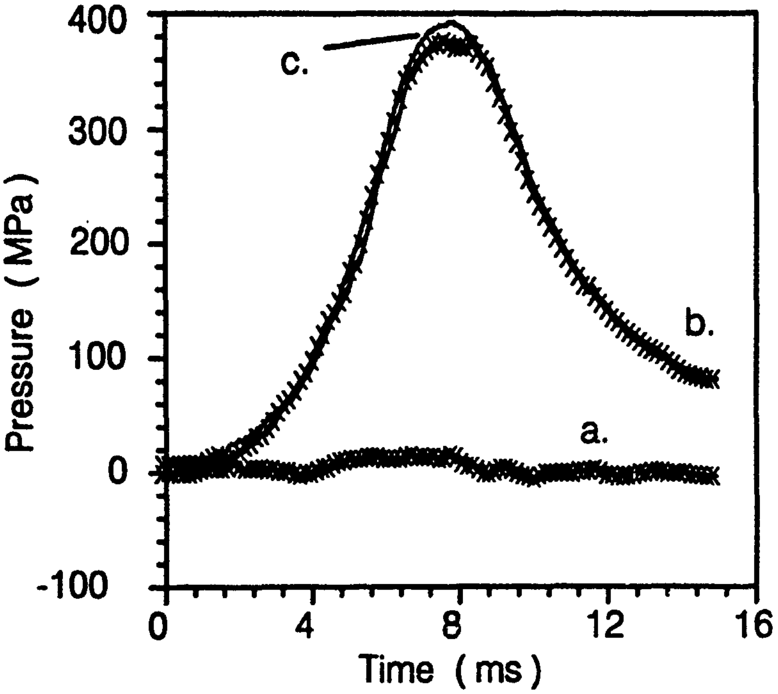

Figure 3. Unicharge Interior Ballistics Calculations. Simultaneous Laser Ignition of Six Unicharges Reduces Pressure Differentials in a 155-mm Gun Chamber.

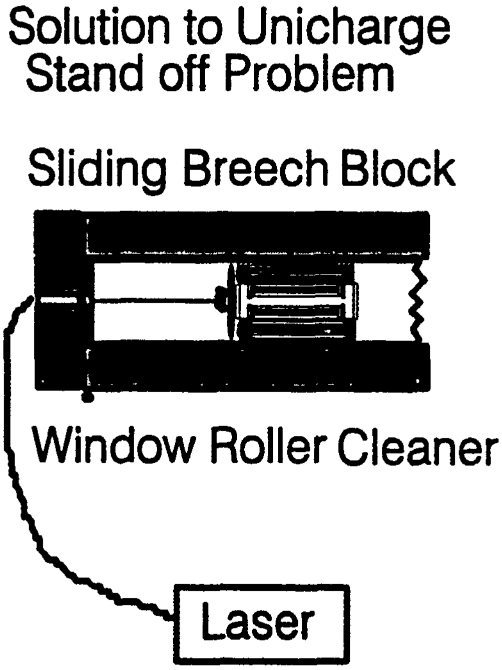

Figure 4. Solution to Unicharge Stand-Off Problem.

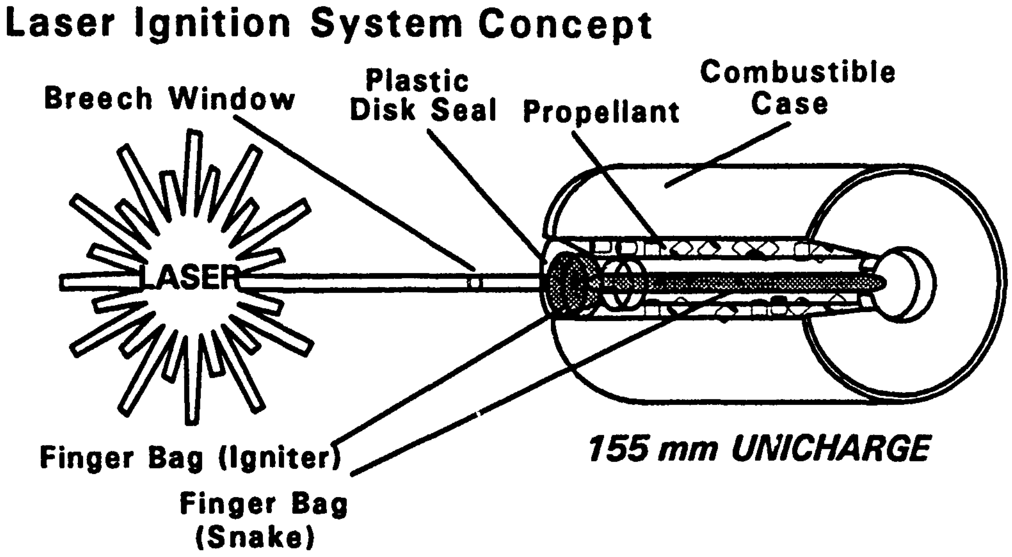

Figure 5. Schematic of Unicharge Laser Ignition Concept.

The laser beam must pass through several interfaces within the chain to be effective. These include: a sapphire window in the breech, a thin window covering on Unicharge (which is composed of mylar), and a mesh bag which contains blackpowder. The transmission of the laser beam through these media has been evaluated. The Nd:glass laser at 1.05 μ transmits nearly 100% of the incident beam through the sapphire window. Small reflection losses of a few percent are encountered at the window surface. These losses can be minimized by using hard dielectric coatings on the sapphire substrate. The laser beam must also pass through the mylar window with low loss. Detailed experimentation has shown that, regardless of the laser pulse duration (2–10 ms), 70% of the laser was transmitted through with no damage to the mylar in 20 repeated shots (Figure 6); 30% of the laser beam was absorbed and/or scattered. It is interesting to note that the window was not burned or charred as a result of laser transmission. An investigation of the interaction of the laser beam with the blackpowder bag material gave no evidence whatsoever of ignition. The weaving (mesh) of the bag material was sufficiently loose to readily allow for laser transmission though the bag.

A detailed investigation of the laser parameters required to ignite small blackpowder igniters (blackpowder in bags) through sapphire and mylar windows was performed. A schematic of the test configuration is shown in Figure 7. An electronic pretrigger signal from the laser triggered the sweep of a high-speed digital oscilloscope. Two high-speed photodiodes observed the ignition event. The first photodiode was optically shielded and insulated to observe light emission other than that which resulted from the laser. The second photodiode captured light emission from the blackpowder ignition. The laser pulse was characterized by having a Gaussian-type spatial intensity distribution across beam. Mode

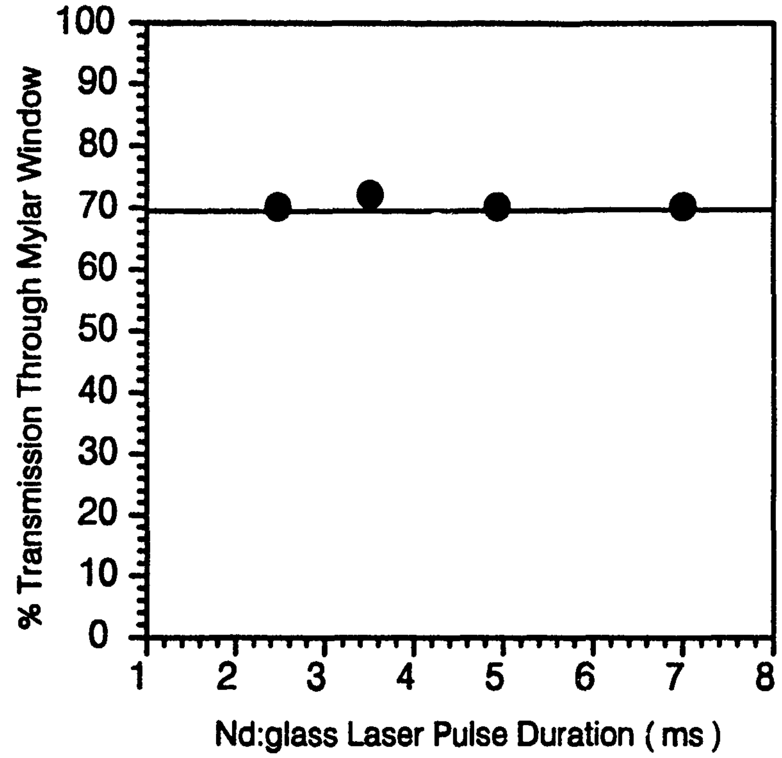

Figure 6. Transmission of Nd:Glass Laser Radiation Through a Mylar Window.

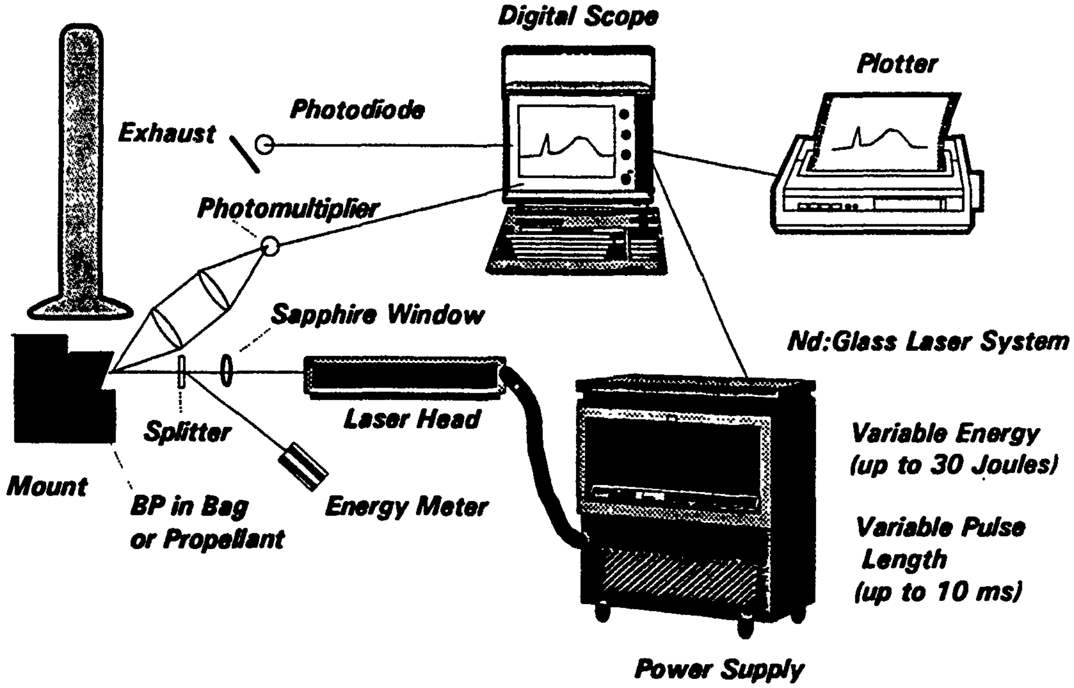

Figure 7. Laser Ignition Test Setup.

structure can indeed vary spatially from pulse-to-pulse as a result of thermally induced distortions (photon modes) within the rod as it is heated. A parametric investigation of the laser pulse duration, laser energy, and ignition delay on the ignition of blackpowder revealed several reproducible trends. Tests were all performed at atmospheric pressure on unconfined samples. The criterion for ignition was a single laser pulse which resulted in sustained ignition and complete combustion which consumed the entire sample (Ostrowski 1979). If the sample did not ignite, then it was discarded and replaced with an identical sample. A second laser shot into a previously irradiated sample showed that the first laser pyrolyzed the material which produced new chemical products with reactivities that differed from the original sample; this resulted in a lower ignition threshold. A similar behavior was also observed in solid propellant direct ignition and in the ignition of LPs. Figure 8 is a schematic which illustrates the trends that were observed in blackpowder ignition. At constant energy of 2 J/pulse, the ignition delay increased with increasing laser pulse widths, but the ignition energy threshold decreased with increasing laser pulse length (i.e., longer laser pulses required less energy for ignition than shorter laser pulses). Regardless of the laser pulse duration, for a given laser pulse, increasing the energy reduced the ignition delay. Although longer laser pulses had a lower energy threshold than shorter pulses, the increased ignition delay time is due to conductive losses early on in time. Figure 9 (a–d) shows plots of ignition delay versus laser pulse duration at constant energy of 2 J for 1-, 3.5-, 5- and 7-ms pulses. The first signal in each curve is laser scatter and the second curve is light emission from the burning blackpowder. In all ignition tests, the blackpowder burned (unconfined) within a 30–40 ms time period measured full width at half maximum (FWHM). These investigations were made using an unfocused laser beam.

It was found that if the laser beam were focused very tightly to a narrow beam waist, then energy input to the material cannot compete with thermal diffusion of the energy into the material such that ignition delay times became much longer or sustained combustion was not achieved. These conditions, however, required extreme focusing. A key feature of this work which is readily apparent is that, although at constant energy, longer pulses have a longer ignition delay, simply increasing the energy results in minimal ignition delays (Figure 10). The top plot in Figure 10 shows an example of two different laser pulses. The lower plots in Figure 10 show the effect of doubling the laser energy using two identical blackpowder igniters. Using 4-J input laser energy, the blackpowder begins to burn during the laser pulse; therefore, a plausible method of minimizing ignition delay times for blackpowder is to use as much unfocused laser energy as possible. Note that special care must be taken when examining the effect of laser pulse duration on delay time. The laser pulse shape from a 1-ms pulse is somewhat Gaussian in shape; however, the pulse-forming network in the laser produces square wave pulses that vary in intensity

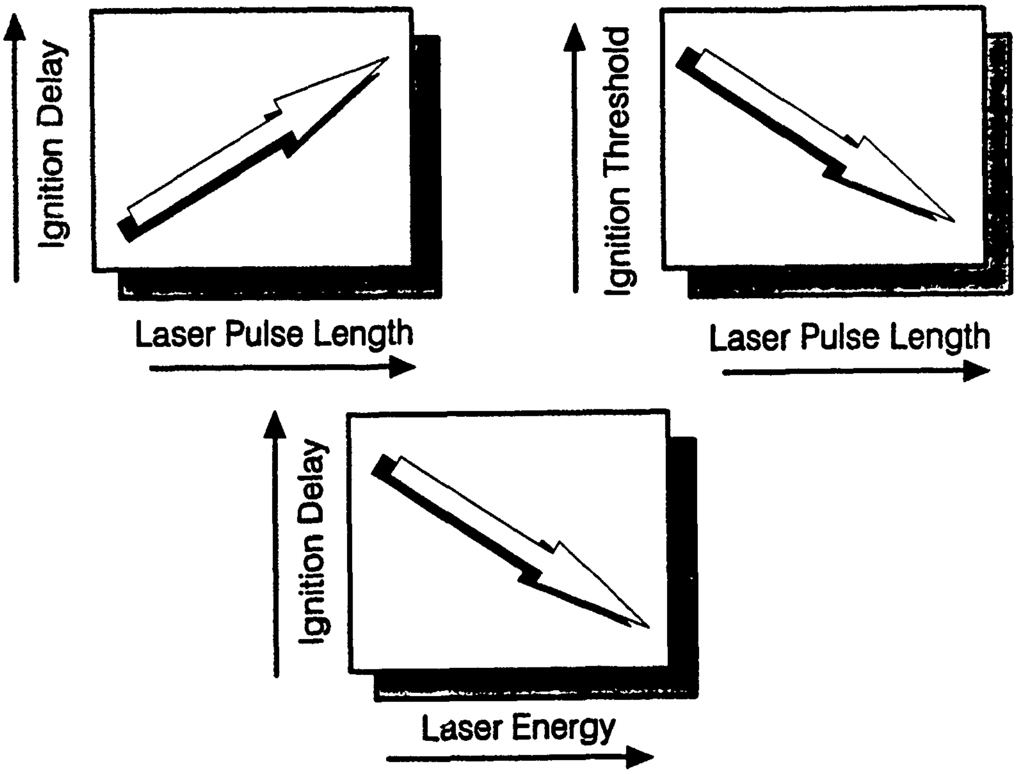

Figure 8. Trends Observed in Blackpowder Ignition.

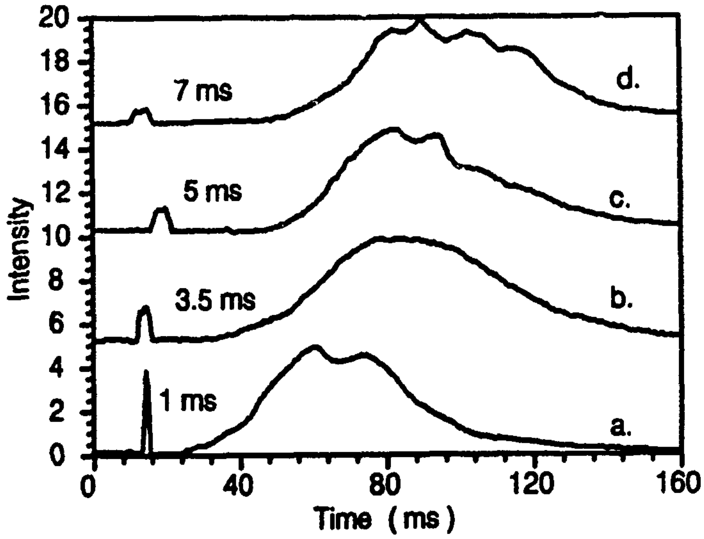

Figure 9. Effect of Laser Pulse Duration on Blackpowder Ignition Delay at Constant Laser Energy (2 J).

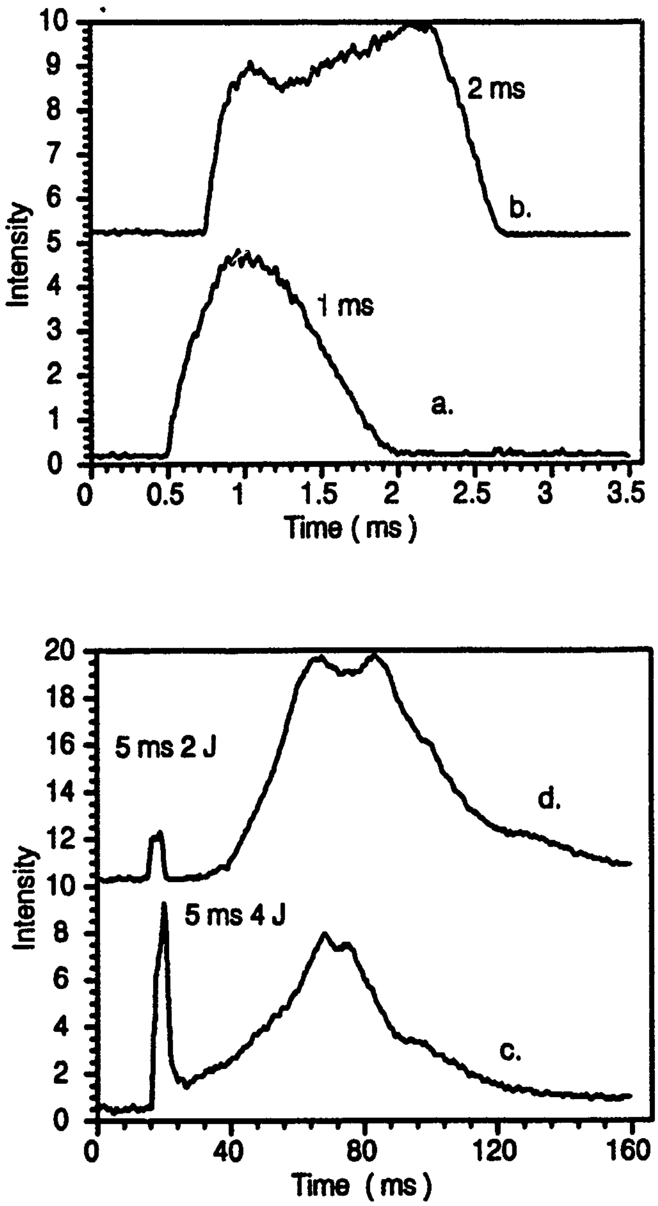

Figure 10. Temporal Profiles of Laser Pulses (Top Drawing) and Effect of Increased Laser Energy on Ignition Delay at Constant Laser Pulse Width (Lower Drawing).

by ~10%. Nonetheless, the trends we have observed in blackpowder ignition are reproducible. The research-type lasers, which were used in these experiments, were purchased in order to determine the optimal laser energy and pulse duration to employ in a fieldable system. These results suggest that laser pulse lengths 1 ms or greater which deliver several joules of energy will reliably ignite blackpowder charges with a safety factor about five.

Extensive laser ignition tests were also performed in an indoor range using large samples of blackpowder (28 g, 1 oz) similar to the blackpowder charge contained in a Unicharge increment. It was found that these charges could be readily ignited using the same parameters as the smaller samples. Tremendous volumes of gas and hot particles were generated in the ignition event and all of the igniter material was completely consumed. Next, a series of experiments using an optical fiber network for multipoint ignition of blackpowder were performed. The Laser Photonics system has provided for connection to a nine-way optical splitter which is interfaced to the laser through standard SMA-type connectors. The laser beam was focused into the bundle and about 2 J of laser energy were measured at the end of each 5-m optical cable. Figure 11 shows the laser ignition data for the initiation of six blackpowder igniters. Curve a in Figure 11 shows a timing trace of the 10-ms laser pulse used in this experiment. Curve b in Figure 11 shows a time-intensity trace which results from the ignition of six 1-oz blackpowder igniters which was detected by a single photodiode and demonstrates the near simultaneous ignition of all igniters. It is important to reiterate that the initial Unicharge ignition system which is being developed requires no alteration to the existing Unicharge. The ignition stimulus (laser light) strikes the first blackpowder pad in the first Unicharge loaded into the gun. Ignition of this first blackpowder igniter spreads to the remaining charges loaded in the gun. A conventional M82 primer generates a gas jet of hot gases and particles which assists propagation of the ignition stimulus into the full charge. Investigations in a full-scale ballistics simulator are in progress to compare the ignition stimulus provided by the M82 primer with that of the laser igniter.

Laboratory experiments are now underway to examine pressure-time traces from the ignition of blackpowder samples which are confined. Blackpowder charges are contained in a small windowed pressure vessel equipped with a sapphire window and a mylar blow-out disk for safety in the laboratory. An example of preliminary data recorded under these experimental configurations is shown in Figure 12. Within a few milliseconds after the laser has fired, there is a rapid increase in pressure from the gassification process occurring during the blackpowder combustion. The sudden drop in pressure signals the rupture of the mylar diaphragm. These experiments indicate that hot gases required for the ignition of the propellant bed are produced very quickly and can facilitate the spread of the ignition stimulus into the charge.

3.2 Blackpowder Ignition (ATACS). A laser-based ignition system is also being developed for the ATACS 140-mm tank gun. Similar to artillery guns, the incorporation of multicomponent ammunition in the propelling charge introduces interfaces which can interfere with reliable flamespreading

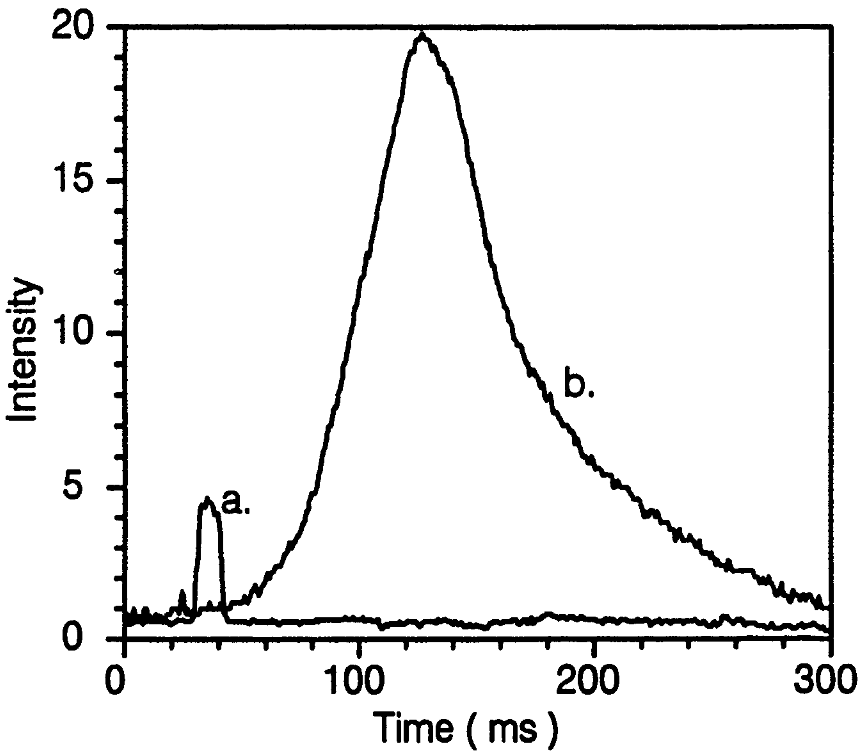

Figure 11. Light Emission from the Simultaneous Laser Ignition of Six Blackpowder Igniters.

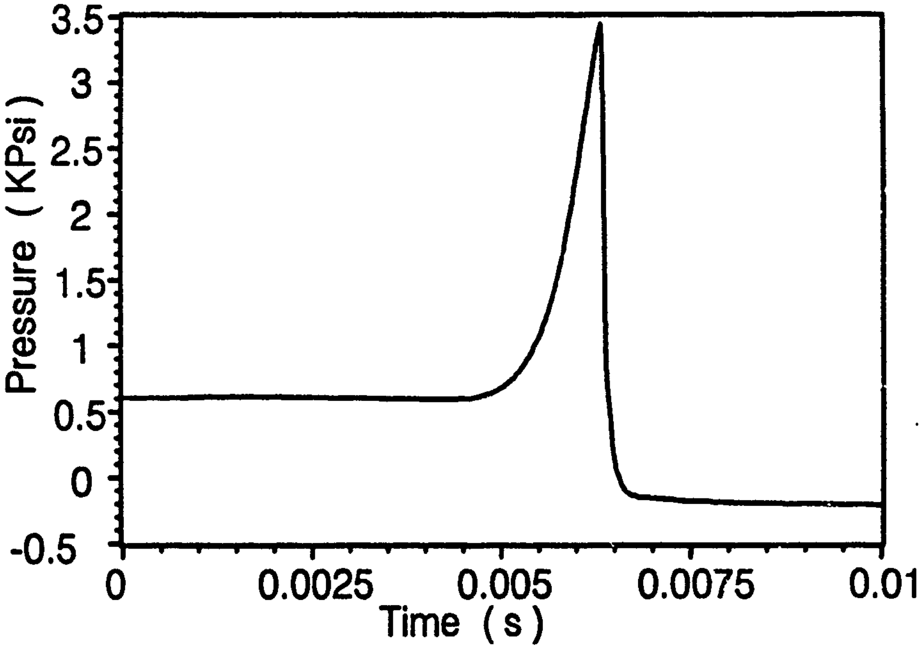

Figure 12. Pressure-Time Curve for Laser Ignition of Confined Blackpowder Samples.

characteristics in the combustion event. Interfaces which inhibit rapid flamespread within the propellant bed can lead to localized ignition which, in turn, may produce pressure differentials between the charge and projectile base. Pressure differentials can lead to oscillations which may result in catastrophic failure of the gun. IB calculations performed at BRL have shown that simultaneous ignition of multicomponent ammunition, such as the two-piece tank round, can minimize localized combustion, enhance flamespreading characteristics, and minimize the probability of gun failure. The rear component of the two-piece tank ammunition contains mainly propellant and igniter material. The forward component contains propellant and the projectile. Both components are assembled and loaded mechanically. The ignition requirements for tank munitions are much more stringent than those of artillery guns. Ignition of both components must be achieved on a millisecond timescale. The ATACS round, unlike an artillery charge, utilizes a stub case which makes an effective seal of the round to the breech. BRL has developed an ignition concept for ATACS which is presented in Figure 13. The gun breech contains a sapphire window through which the laser beam is transmitted; however, in addition, the stub case also contains a window. Combustion products may contaminate the stub case window, but the breech window remains protected from this environment. The next ATACS round which is loaded contains a fresh window. The laser can be mounted on the breech or coupled to the breech using optical fibers. An optical fiber which is contained within the first component of the two-piece ammunition delivers a portion of the laser energy to a blackpowder igniter in the rear of the forward ammunition component. The optical fiber in the rear component can easily be contained in an igniter tube or combustible case which will facilitate loading of the propellant. BRL also proposes the use of tapered optical fibers to facilitate the transfer of the laser beam from the breech into the optical fiber contained in the rear component (Figure 14). The tapered fibers easily align with the input laser beam from the breech and can be designed to partially transmit a portion of the laser beam to both igniters in the front and rear components The laser beam which exits at the front end of the rear component can easily pass through the mylar interface and strike the rear igniter in the forward component to achieve simultaneous ignition. Optical fiber networks can also be distributed within the charge to achieve multipoint ignition or to accommodate complex projectile geometries which may extend into the rear portion of the ammunition (Figure 15).

Preliminary testing of a two-piece blackpowder igniter system is underway. Figure 16 gives time traces of a single laser pulse delivered to two ignition sites. Both pulses overlap exactly in time and, because the same laser pulse is delivered through a single fiber with a two-way split-off, the spatial mode structure of both pulses are essentially identical. Thus, variations in ignition delay can be minimized. Extensive experiments were performed utilizing this ignition concept for the simultaneous ignition of two

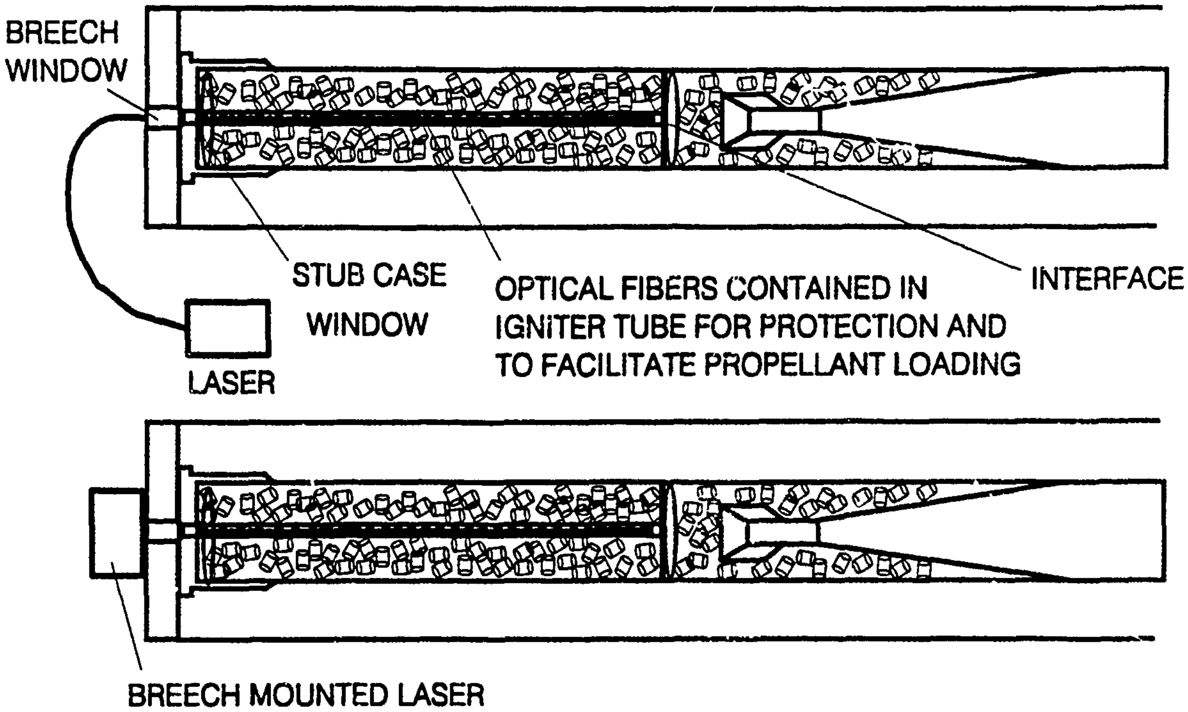

Figure 13. BRL ATACS Laser Ignition Concepts.

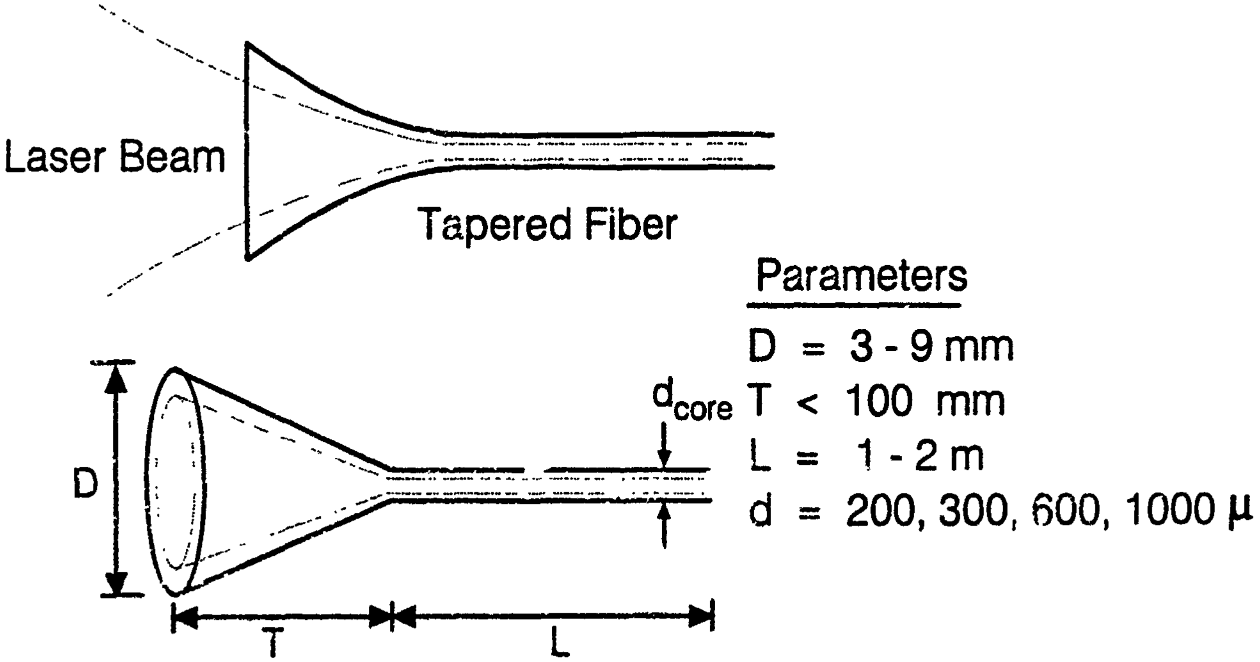

Figure 14. Characteristics of Tapered Optical Fibers.

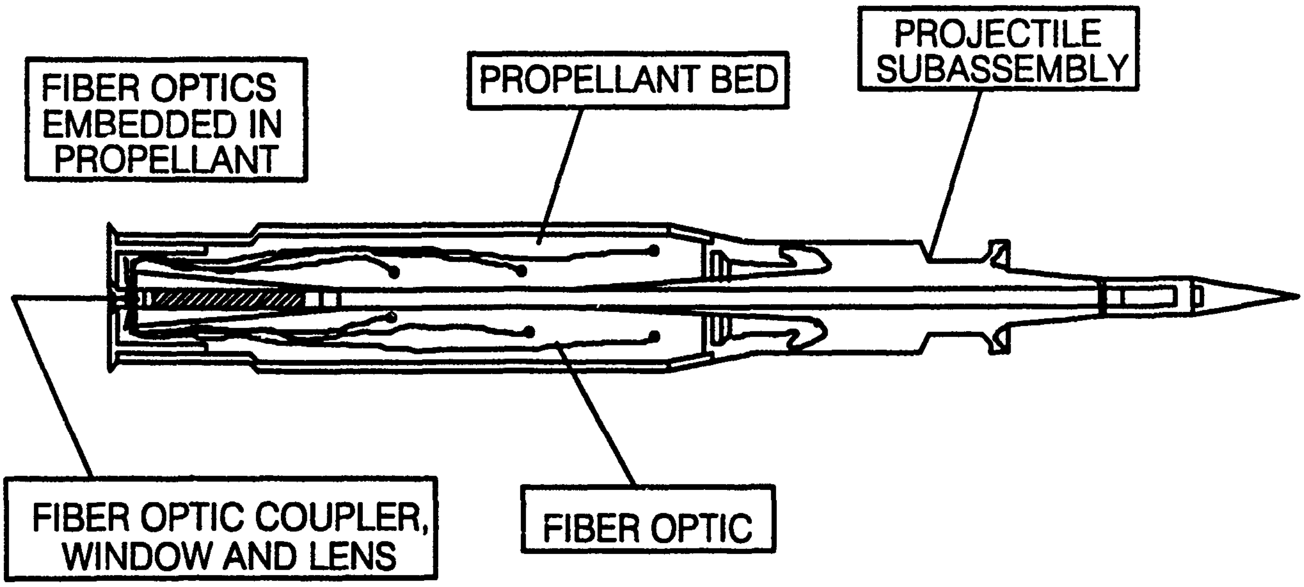

Figure 15. Tank Round With Embedded Optical Fiber Distribution System.

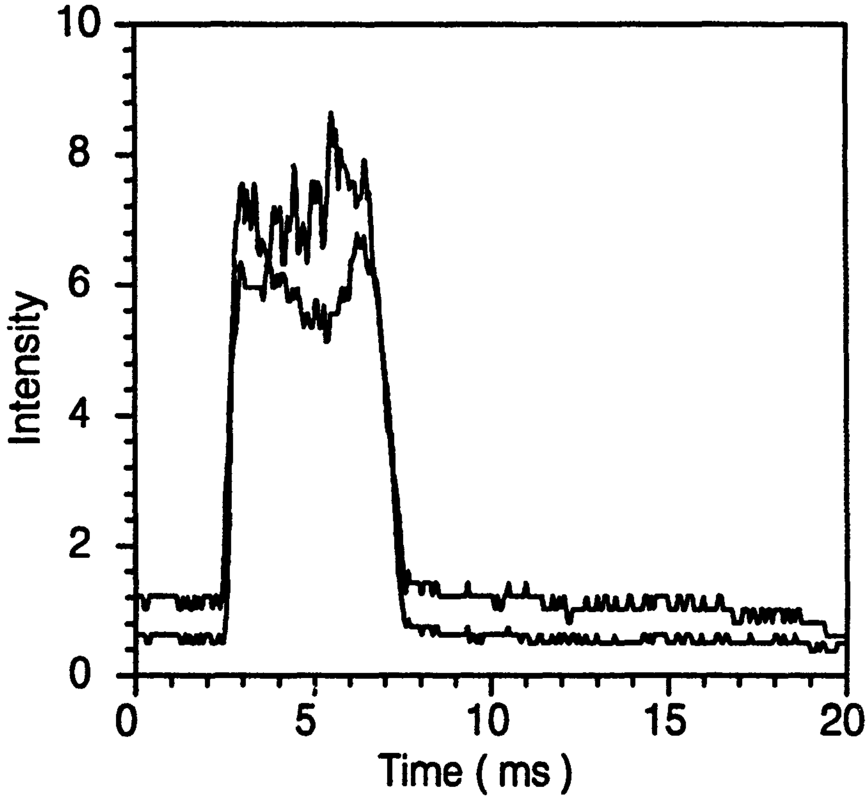

Figure 16. Simultaneous Delivery of Two Laser Pulses for ATACS Ignition.

blackpowder igniters for ATACS (Figure 17). Laser pulse energy was ~ 0.7–2.3 J/pulse depending on the laser pulse duration. Essentially simultaneous ignition of both igniters was achieved using this system. Next, the ignition of two large samples of blackpowder for ATACS was investigated using this ignition concept (Figure 18). A single photodiode captured the light emission from the initiation of both igniters. Successful ignition of both igniters resulted in complete consumption of the blackpowder.

3.3 Direct Propellant Ignition. The overall goal of the LIGHT Program, as previously mentioned, is to eliminate all primer and igniter material from the ignition train in large-caliber gun systems. Propellants can indeed be ignited using single laser pulses (Robitaille 1964; Ostrowski 1980); however, the heat transfer and subsequent flamespreading throughout the charge can be slow without the use of a distributed ignition system. For example, blackpowder and primer material are, relatively speaking, very energetic. They have fast burn rates, fast gas generation rates, and produce hot particles which serve to spread the ignition stimulus throughout the propellant bed. Direct laser-based ignition of a series of propellants using the Nd:glass laser was investigated. These include JA2, M30, LKL, LOVA (HELP1 (XM43), HELP2), and HMX1. An important consideration is the coupling of the laser energy into the propellant at the surface. Coatings on the propellant, such as graphite, greatly enhance the absorption of laser energy at 1.05 μ. Ignition is also enhanced when graphite is dispersed within the propellant formulation. An additional important consideration is the laser pulse duration. It was found that short laser pulses (nanosecond time scale) produce an intense light flash of ignited pyrolysis gases; however, sustained combustion of the bulk solid was not achieved after the laser pulse subsided. Apparently, the rate of energy input to the solid greatly exceeds the rate of thermal diffusion into the bulk sample such that "hot spots" are formed which results in surface ablation and ejection of material which inhibits sustained combustion. Longer laser pulses on the order of 3–10 ms, 5–10 J successfully ignited propellant samples in ambient air. Figure 19 gives two representative plots of the laser ignition of JA2 (ATACS) and M30—Unicharge propellants.

The laser pulse successfully ignited both samples and sustained combustion was achieved after the laser pulse subsided. JA2 propellant burns with a highly luminous flame and M30 propellant fizz burns at atmospheric pressure. During the initial stages of ignition in a gun system, the propellant is initially at ambient temperature and pressure, however, confinement allows for the subsequent pressure buildup which may serve to accelerate burn rate and flamespread throughout the bed. These types of experiments are therefore representative of the early stages of direct laser ignition of the propellant. Unconfined LOVA propellants were very difficult to ignite under ambient conditions. Confined LOVA samples (XM43)

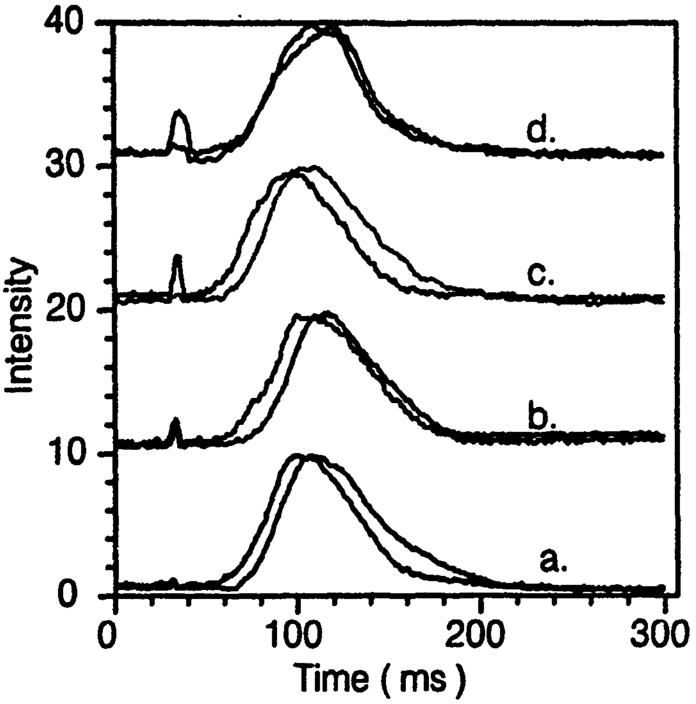

Figure 17. Simultaneous Laser Ignition of Two ATACS Blackpowder Igniters Using Various Laser Pulse Widths (Through Optical Fibers).

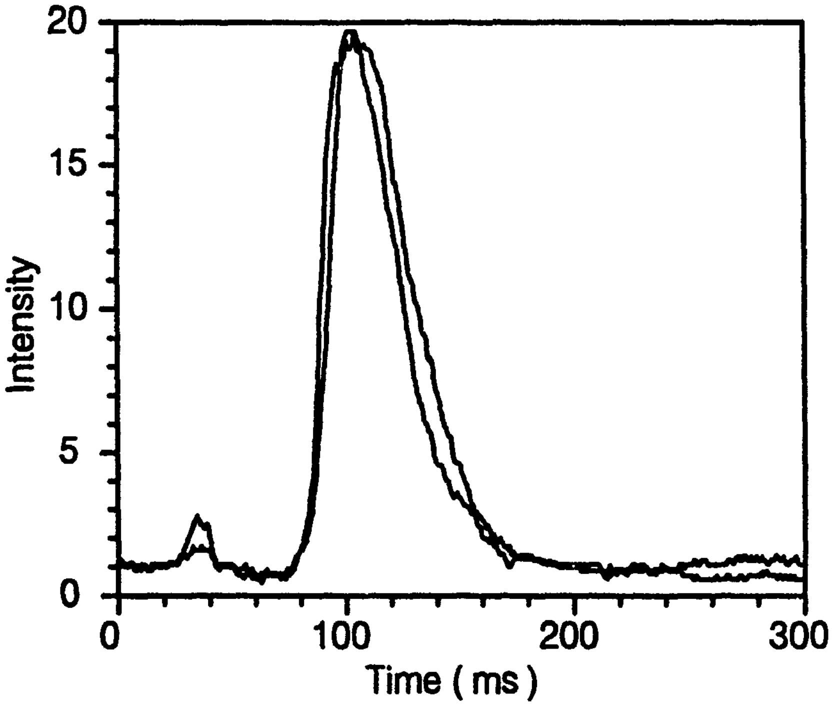

Figure 18. Simultaneous Laser Ignition of Two 1-oz ATACS Blackpowder Igniters.

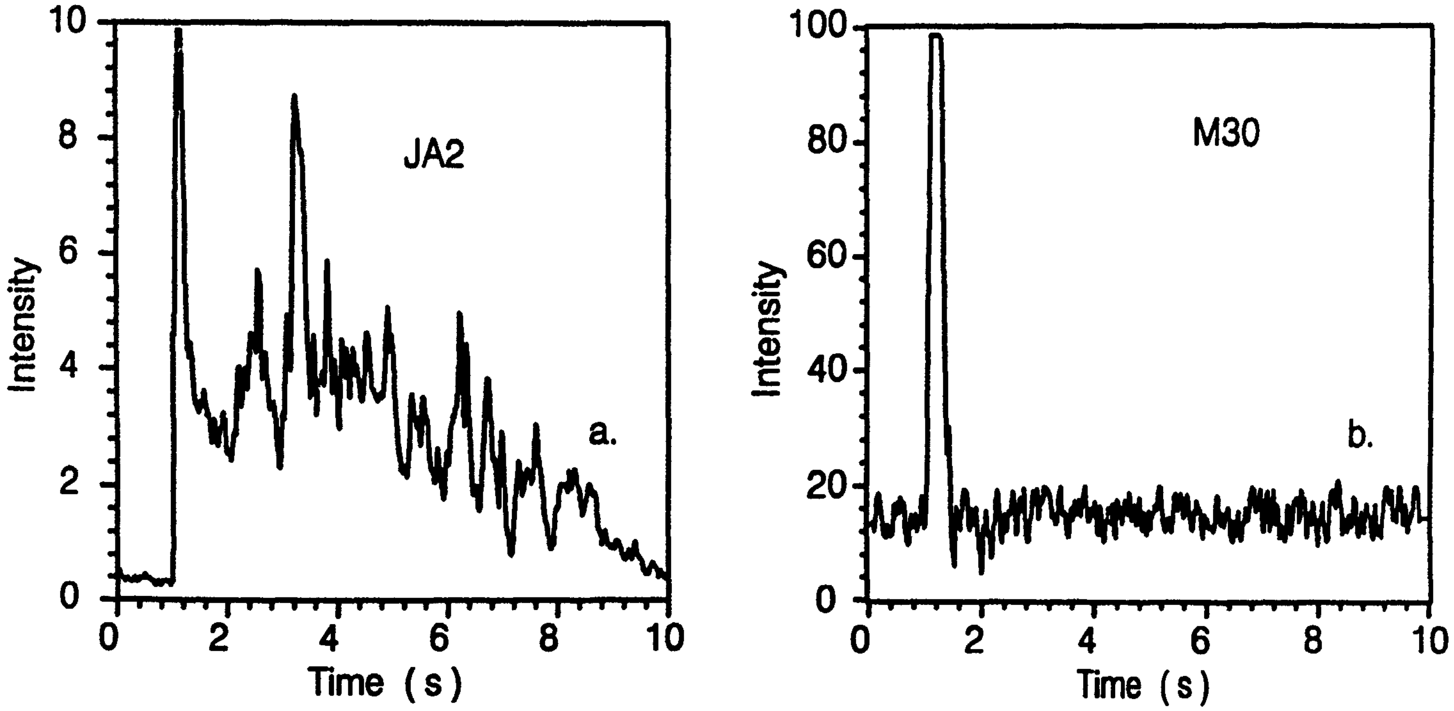

Figure 19. Light Emission From the Laser Ignition of JA2 and M30 Propellants.

were successfully ignited with a single laser pulse (10 ms, 8 J) (Figure 20). Rapid gas generation produced during the ignition and confinement (as illustrated in the pressure-time trace) led to sustained combustion until the mylar diaphragm burst. These experiments clearly demonstrate feasibility of direct propellant ignition in large-caliber guns. Experiments were also performed on early generation LOVA propellants. In particular, the formulations which used a HTPB binder could be ignited with as little laser energy as 0.5 J using a 2-ms laser pulse. Laser radiation at 1.05 µ is readily absorbed deep within the propellant surface which facilitated the ignition. In general, all propellants which were graphite coated required less laser energy for ignition.

3.4 LP Ignition. LPs are also a candidate propulsion system for the AFAS 155-mm large-caliber gun. The current ignition system for the LP gun is a staged electrical igniter. A 30-mm electrical igniter is attached to the gun and contains three small volumes of LP. Discharge of 45 J of electrical energy across an electrode spark-gap ignites a small, 2-cm^3, confined volume of LP. The flame propagates into a 20-cm^3 volume, then finally into a third 200 stage. The hot-burning LP is injected into a chamber fill volume of bulk LP (500 cm^3) wherein up to 17 L of LP is then injected (full charge for high zones). Apparently, there are problems associated with flamespreading within the staged ignition and survivability problems with the electrodes for repeated firings. BRL is presently investigating the development of a laser-based

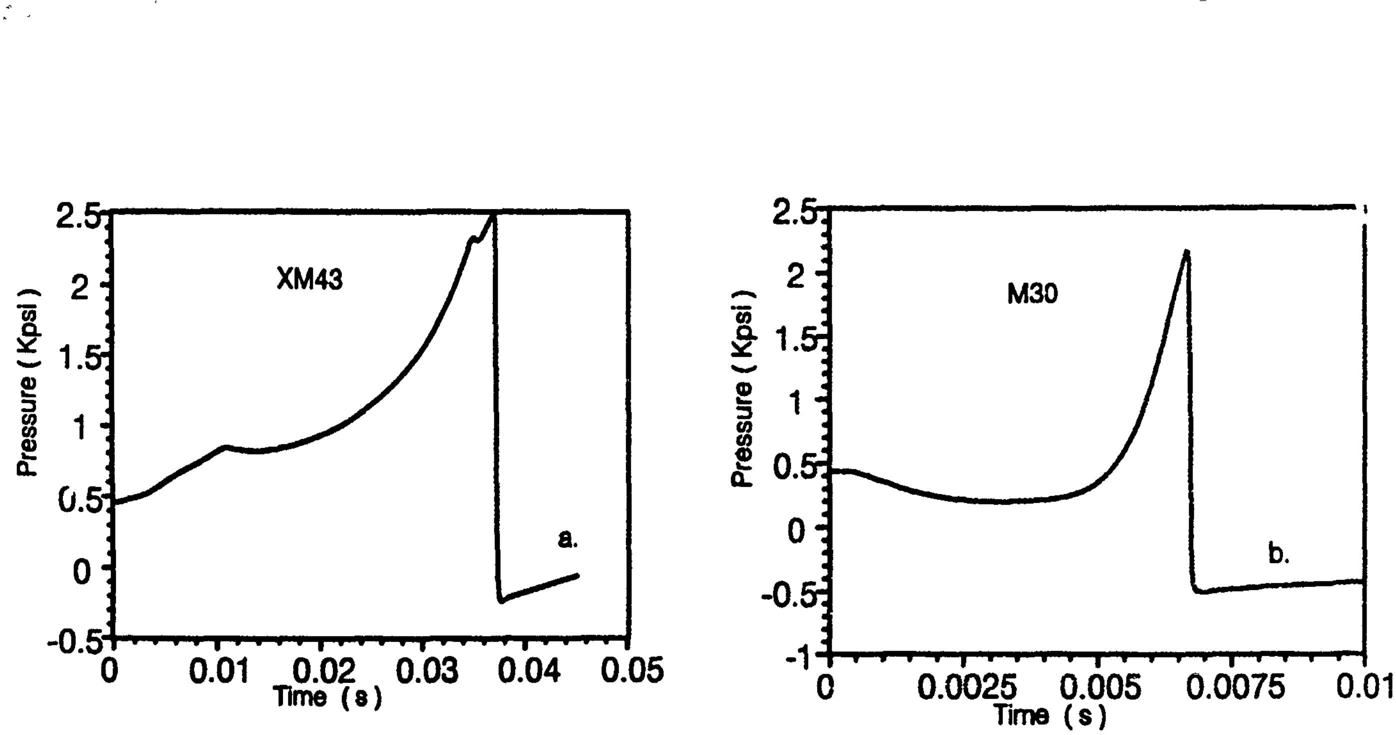

Figure 20. Pressure-Time Curves for the Direct Laser Ignition of Confined M30 and XM43 Propellants.

ignition system for the LP gun. A conceptual schematic is depicted in Figure 21. A laser-based ignition system may allow for one or more stages in the current igniter to be eliminated. In addition, a laser-based ignition system could replace existing electrodes in the current igniter which are not long-lived. Conversely, a laser-based igniter could be used in conjunction with an electric igniter to facilitate flamespread throughout the staged ignition system. A conceptual illustration of this concept is shown in Figure 22. Laser energy could be coupled into multiple points within the igniter using an optical fiber network. Sapphire windows and ignition points can be located at various points as required. The sapphire windows can be formed as a lens as required to increase the energy density at the ignition points. Contamination of the windows may not present the same problem as encountered in solid propellant gun environments.

A series of experiments on LP ignition using pulsed laser systems have been performed. We found, using a focused-pulsed Nd:glass laser, that suspended droplets of LP can be ignited into transient combustion; however, sustained combustion is difficult to achieve without confinement. The absorption cross section of LP increases in the UV and decreases in the near infrared where the Nd:glass laser

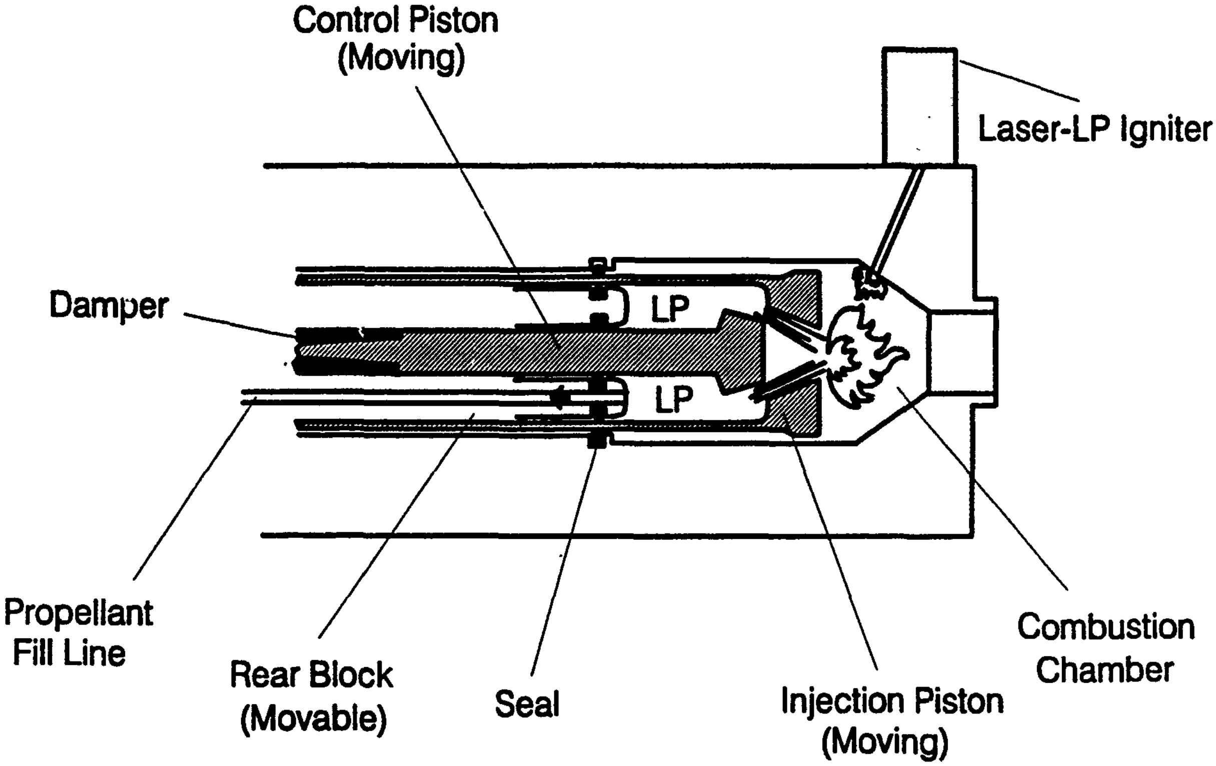

Figure 21. BRL Conceptual Depiction of LP Gun With a Laser-Based Igniter.

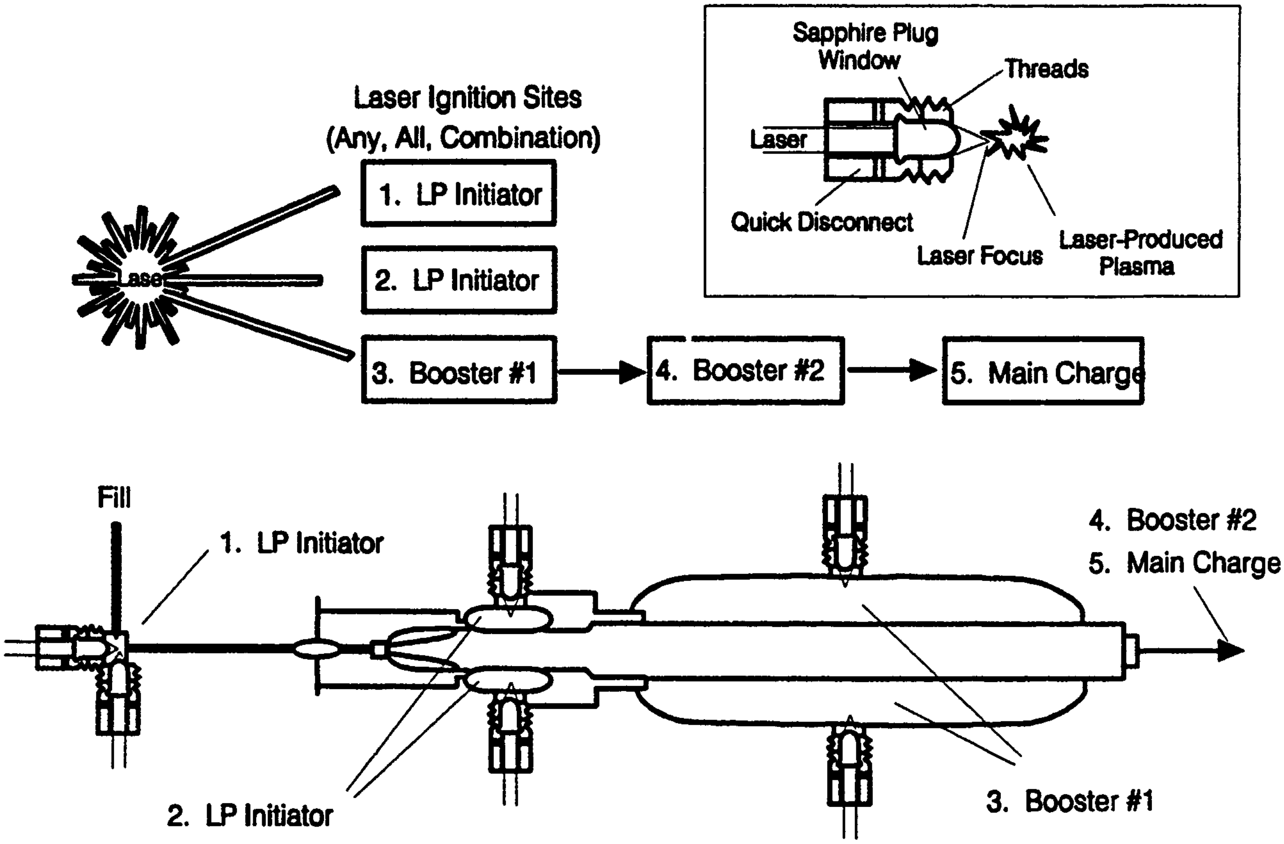

Figure 22. Schematic of BRL Laser-Based LP Igniter.

operates. Focused nanosecond UV pulses at 193 nm ignite the droplets, but combustion was not sustained under ambient conditions. Suspended droplets of LP were easily ignited at 1.05 μ, although sustained combustion was not possible without confinement and pressure buildup. Additives, such as graphite suspensions and IR dyes were doped into LP samples; however, confinement was required for sustained ignition. It is interesting to note that LP samples that did not ignite with a first laser pulse could be ignited or reignited with much less laser energy. This phenomenon has been attributed to laser decomposition of the LP (pyrolysis) to produce chemically different and more reactive products. These products have not yet been identified. A first laser pulse initiates the LP into transient combustion which subsides. A second laser pulse reignites the droplet with less laser energy and, in addition, combustion is sustained for a longer time duration. Laser ignition experiments on confined LP samples are currently in progress.

3.5 Double-Laser Pulse Ignition. Experiments aimed at utilizing multiple pulses with a single laser system and double pulses utilizing double-laser systems are being investigated for ignition of solid propellants and LPs. This concept involves the pyrolysis (Beyer 1978) of the sample to produce intermediates, which can then be ignited by a second laser pulse from a different wavelength laser. Initial experiments on the pyrolysis of JA2, for example, have identified both the presence of atomic oxygen and hydrogen. A probe laser system, which is tuned to resonant multiphoton excitation transitions of these atoms, shows the formation of laser-produced microplasmas, similar to those observed in reactive gases. The techniques required to generate the probe laser wavelengths is described elsewhere. When the probe beam is tuned to the multiphoton absorption transitions of these radicals, free electrons are produced from multiphoton ionization. Interaction of the intense laser field with the electron field results in a nonlinear amplification process which generates microplasmas. These microplasmas have sufficient intensity to ignite the pyrolysis gases, but have insufficient thermal feedback to the bulk material to achieve ignition of the solid. Pyrolysis gas diffusion away from the propellant surface may be sufficient to inhibit the ignition. Furthermore, the second probe laser energy is only ~ 1 mJ. This energy range has been shown to be sufficient to ignite reactive gases, but is not sufficient to cause ignition of the bulk solid. Similar types of experiments utilizing an excimer laser which can deliver more that a factor of 100 times more laser energy will be investigated.

4. CONCLUSION

The development of laser-based ignition systems for large-caliber guns has the potential to solve problems associated with reliable and reproducible flamespreading characteristics within propellant beds. The recent advances in gun propulsion systems which utilize multicomponent ammunition, autoloading devices for projectiles, and charges and primers, place new constraints on the ignition train. In addition, insensitive munition requirements for future gun systems may require alternate or nonconventional ignition sources to be implemented. As a result, laser-based ignition systems may prove to be the only viable initiation source for these munitions. Laser energy distributed through optical fibers embedded in a propellant bed cannot only insure simultaneous ignition of the charge, but also reduce overall system vulnerability from the elimination of all primer and igniter material from the munition. Recent advances in electronics and engineering technology have produced small, high-energy laser systems which are suitable as igniters. Extremely small, high-power laser diodes are being developed which can easily initiate high explosives and similar energetic materials. These types of devices may prove to be the lasers of choice in future gun systems as new technology developments increase energy output suitable for large-caliber gun initiation. Laser ignition systems may also have an impact on gun performance through temperature compensating and/or programmed delivery of laser energy through optical fibers. New developments in optical fiber material may produce energetic and consumable fibers which leave no residue in gun systems and, in addition, enhance ignition. BRL anticipates the development of a laser ignition model of a predictive to further understand the chemistry and physics of laser ignition and design igniters with specified characteristics.

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