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Laser Ignition in a Medium-Caliber Gun: A Study of Igniter Influence on Action Time

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Abstract

Laboratory experiments and 30-mm-caliber gun tests have been pursued in order to explore the action time of the M230 gun using laser ignition. The laboratory tests explored the response of black powder (BP) to energy levels from 0.2 to 0.5 J. Tests with class 5 and class 7 BP show that response will probably not be fast enough to use BP as the primary initiator for this gun unless more laser energy is available. The limitation is in the time required for initial laser ignition of the BP. In the gun tests, pyrotechnic materials were also used and showed excellent response times well under the 4-ms requirement. Those tested include perchlorates and would not be acceptable for gun use. Several possible cartridge igniter configurations were tested. Low-cost windows were successfully demonstrated.

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1. Introduction

As laser ignition in large-caliber gun systems matures along the path to fielded systems [1], the research community has begun to address other gun systems. An obvious next choice is the application of medium-caliber guns. Limited study has been done with laser ignition of experimental charges in medium-caliber guns [2], but the emphasis in that study was on charge function. The interest in laser ignition for the medium-caliber gun is also attractive because of the electrical ignition used in many of these guns and the resulting susceptibility to electromagnetic radiation. While there are many issues to be addressed (including cost, durability, producibility), the primary issue of performance must be addressed or these other issues are mute.

Among the many differences in laser ignition between the large- and medium-caliber systems, a few are worth noting. The windows in a large-caliber (bag charge) weapon are part of the breech and must survive many firings. Because of this fact, they can be substantial and cost effectiveness is not beyond reach. In the medium-caliber systems, which use a full, metallic cartridge case, the window is a part of the case itself and thus becomes a single-use item. The cost must then drop more than a hundred fold to be considered an economically viable alternative. Concepts using a weak window backed by a stronger, permanent window in the firing-pin assembly have also been proposed.

The second difference of note is the opportunity to impact the design of both the weapon and the round. In the 155-mm systems, the issues of existing charges and multiple weapons systems have limited the possible changes to charges, even when they are under development because of the requirement for compatibility with existing systems. In the medium-caliber cannons, the opportunity has presented itself to impact the round design completely within performance limits. Part of this difference is a result of the large number of rounds fired from the medium-caliber systems.

The third significant difference with medium-caliber systems is the importance of action time. In large-caliber cannons, the delay times may be larger than with primer ignition, but consistency and good interior ballistic performance are the key metrics. Because of the rate of fire and the mechanical time required for placing the next round in the chamber, the total interior ballistic action time (firing pulse to projectile muzzle exit) for a typical 30-mm cannon must be less than 4 ms. This could be problematical with laser ignition, which tends to be slow when used with convention primer materials such as black powder (BP) or a clean-burning igniter. In order to get robust ignition, the laser energy is usually concentrated onto a limited area on the igniter material. After that material ignites, there is a delay while the flame spreads through the igniter bed and pressure rises. While solutions may be had by changing to pyrotechnic materials, as is seen later in this paper, there is a strong incentive to stay with familiar materials for both cost and assembly reasons.

In this paper, we show some of the attempts to understand the small-chamber laser ignition of BP on a scale that emulates a medium-caliber primer. The results are not reported in this paper in chronological order; the laboratory and gun tests were interleaved, and the results of each were used to drive the other.

2. Experimental

2.1 Laboratory Tests. A chamber was constructed for these tests specifically to have the approximate volume and length-to-diameter characteristics of a 30-mm PA520 primer. It was also designed to be easily cycled through experiments so that a large number of data could be readily obtained. A schematic drawing of the chamber is shown in Figure 1. A Mylar diaphragm is used to release the pressure at a predetermined pressure. Values are typically 0.006 in (0.15 mm) thick for a release near 2,000 psi for these measurements. The chamber is mounted vertically so that the propellant rests on the diaphragm; the goal of this is to attempt to make heat loss to the membrane independent of loading density. The major diagnostic is pressure that was measured with a Kistler 2 11 B 1 0-Kpsi transducer.

The laser used for these tests (Kigre MK-480) has a Nd:glass rod with a nominal 100-μs pulse width This laser is highly multimode, which gives it an approximately uniform spatial energy

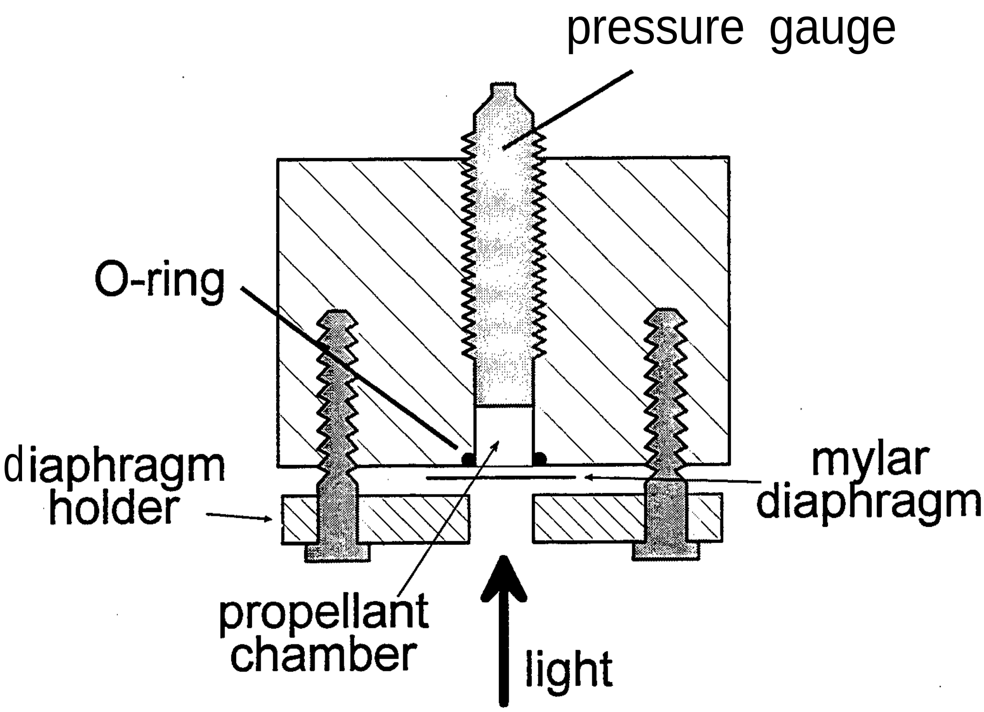

Figure 1. Schematic of Chamber for Laboratory Tests.

distribution. Most tests were done with 0.2 to 0.5 J of laser energy to the -target. The laser output beam was used either unfocused, with a spot size of 0.35 cm, or softly focused to a spot size of 0.15 cm. The corresponding energy densities for 0.5 J are 5 and 28 J/cm^2, respectively. When the light was unfocused, an additional glass window was placed in the optical path to have the same optical losses from surface reflection.

Most of the measurements reported here were made with BP. The materials used were Goex commercial FFFg (approximately class 5) and Goex class 7. Nominal specifications for these are for sieve sizes 1.2 to 0.4 mm and 0.4 to 0.15 mm, respectively. In most cases, we were limited to amounts below 100 mg of powder or a loading density of 1 .O g/cm^3. Other observations were made with finely ground BP, with BKN03 in pellet and powder form, and with a variety of pyrotechnics, as can be inferred from the gun firings. Most of these are not discussed here in detail.

2.2 Gun **Tests.** All range firings were done with an M230 30-mm chain gun in a single-shot mode. The light from the laser was coupled into an optical fiber. The output end of the fiber was mounted into the firing-pin housing of the gun centered with the end near or against the cartridge window. The use of the fiber coupling was chosen for simplicity and safety. It allowed the laser to be in the control room so that it could be disabled while personnel were in the gun vicinity. The laser used was Nd:glass with a pulse of 1 J in 1 ms. Output energy from the fiber was typically about 0.7 J, unless otherwise noted. Various cartridges were designed, assembled, and tested as discussed later.

3. Results

3.1 Laboratory Tests: Black Powder. Although the ignition behavior of the BP was fairly reproducible, there were apparently random variations in how the light coupled into the material and in the response. Two typical pressure-time traces are shown in Figure 2 for 90 and 44 mg. Note that the light pulse is short on this time scale. One pressure starts to rise immediately at a slow rate, while the other delays before rising more sharply. This behavior was independent of loading density. In analyzing the records, an arbitrary value of 250 psi (1.7 MPa) was chosen for ignition; flamespread was measured as the time from 250 psi (1.7 MPa) to 1,000 psi (7 MPa). The choice of the higher value is not critical since the pressurization rate is usually very high once this level is reached.

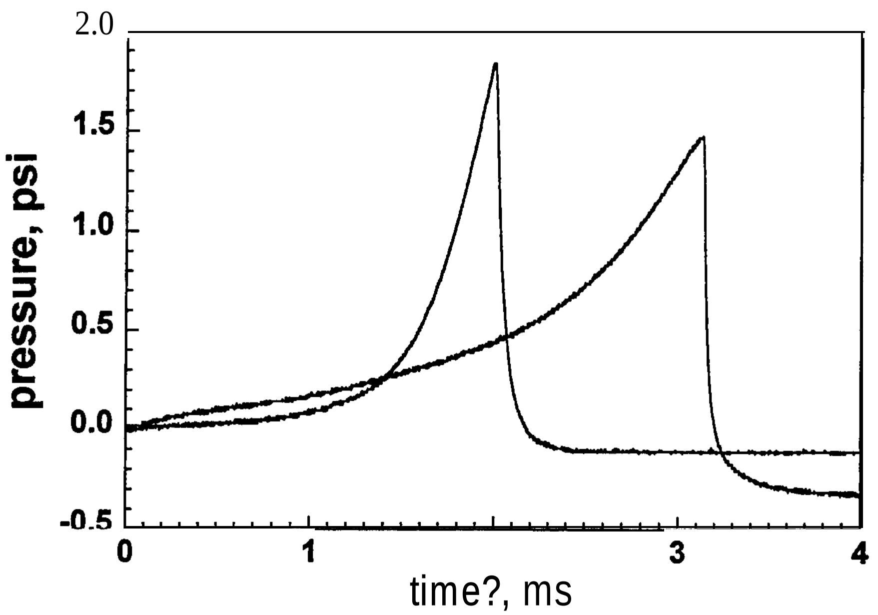

Figure 2. Typical Pressure-Time Records for **44** (Right Peak) and 90 mg of BP.

The amount of energy deposited (or more precisely the energy density) is a controlling factor in the ignition of energetic materials. Figure 3 shows the measured variation in ignition and flamespread (as previously defined). The lines are least-square fits to the measured points. For this series, sample sizes between 65 and 70 mg of **FFFg** BP were used. The laser was unfocused. The behavior is nominal, with energy accelerating the ignition process but having no effect on the flamespread through the bed of powder. While larger values of deposited energy would clearly decrease the ignition time, it was anticipated that the energy available to the igniter in the gun would be close to 0.5 J. This was chosen as a maximum value here.

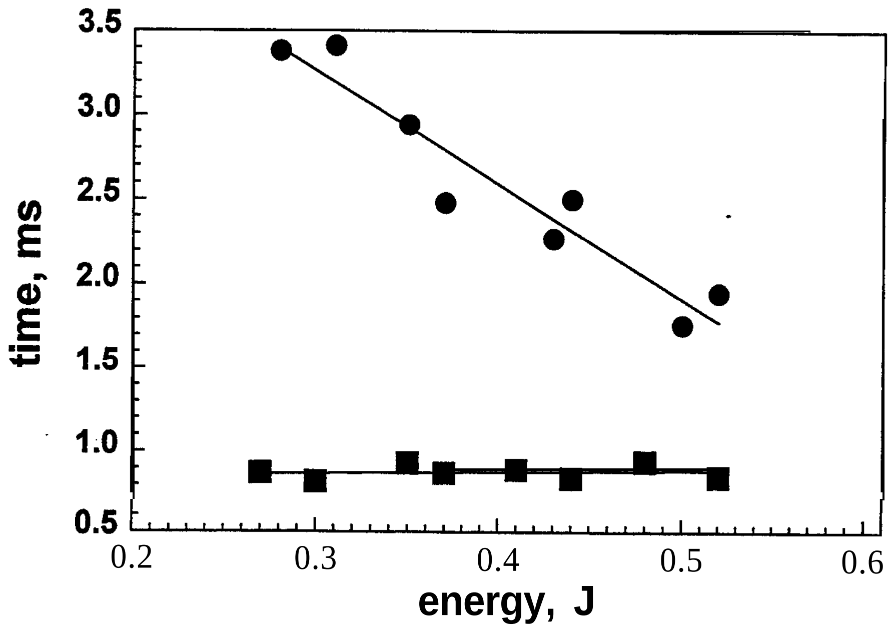

Figure 3. **Ignition Delay (Upper) and Flamespread Time (Lower) vs. Energy for FFFg BP.**

The behavior of ignition as a function of loading density is also of interest. In Figure 4, the behavior for both sizes is shown over the range from 0.2 to 0.9 g/cm^3. The laser energy was fixed near **0.55** J, unfocused. In spite of the variations, two trends are clear. The first is that the **FFFg** ignites more rapidly. The second is that the class 7 powder is slower at the highest densities. This effect may be due to heat loss or some other interaction with the powder against the Mylar that the larger-particle-sized **FFFg** does not suffer.

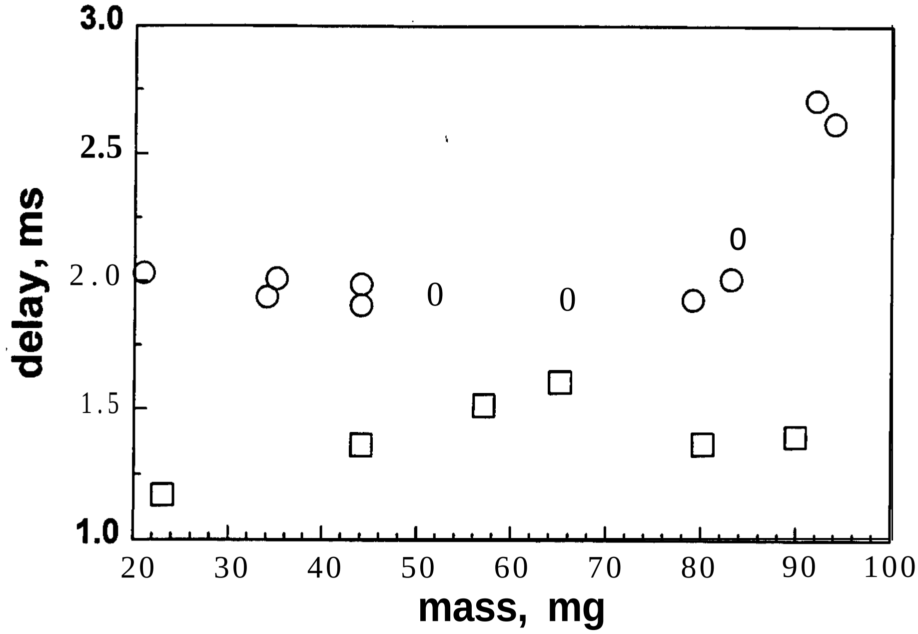

Figure 4. Ignition Delay vs. Loading Density for Class 7 (0) and FFFg (0) BP, Laser Unfocused.

A second series of ignition tests was performed under similar conditions, but with the laser focused to the smaller spot size. The results for three series are shown in Figure 5. Two sets of class 7 data were taken because of the scatter observed the first time. The FFFg is more systematic but is clearly slower than unfocused values of Figure 4. There is also a definite trend toward faster ignition with higher loading densities, unlike the unfocused case. The higher-density FFFg values are close to the unfocussed times for ignition. Some of the high-loading-density class 7 values are near the unfocussed class 7 values. The variation in the data probably has to do with the smaller number of particles that interact with the laser beam at the smaller spot size. It appears that, if a very limited number of particles are ignited under these conditions, low-pressure flamespread to adjacent particles is assisted by loading density. Since the powder is ignited from the bottom of the pile, this is not expected.

The second phase of the ignition process (flamespread) is clearly more dependent on the loading density. Figure 6 shows the variation for both classes of BP. The class 7 data include both focused

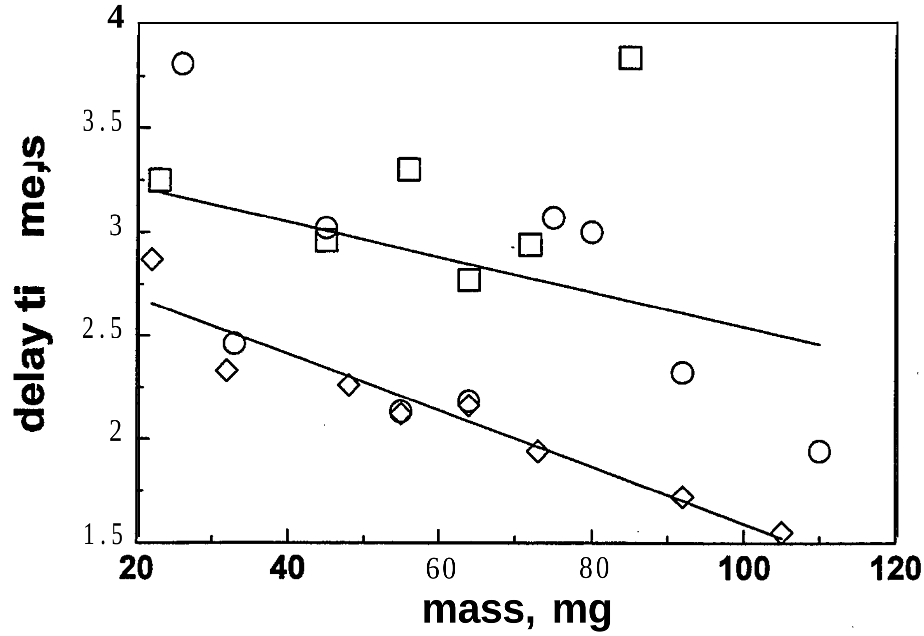

Figure 5. Ignition Delay vs. Loading Density for Class 7 (Cl, 0) and FFFg (0) BP, Laser Focused.

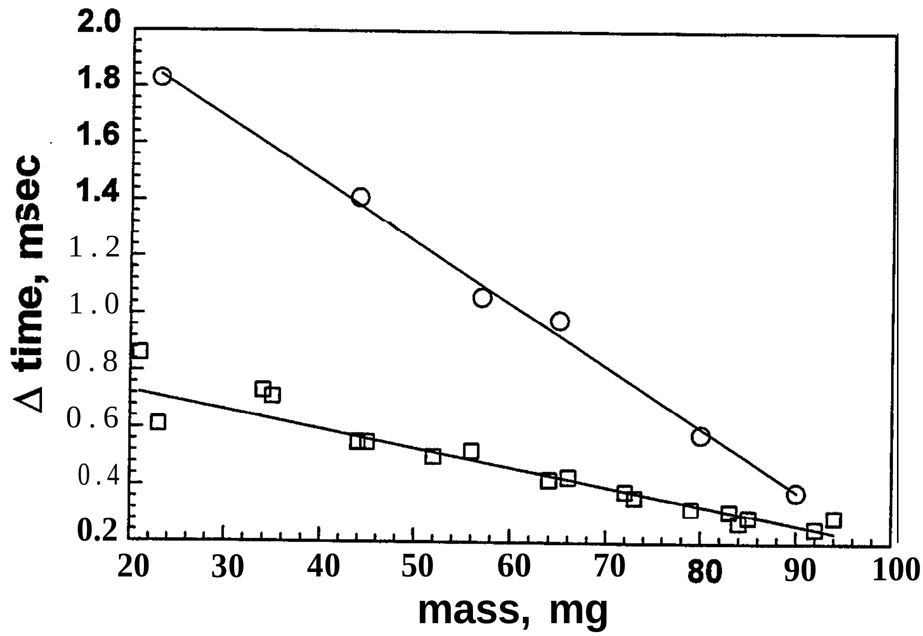

Figure 6. Flamespread Time in Class 7 (□) and FFFg (0) BP.

and unfocused. The trend toward much faster pressurization with the smaller particle sizes is clear, but, as the loading density approaches 1 g/cm^3, the two curves are close enough that particle size is not important if this density can be achieved.

3.2 **Laboratory Tests: Zirconium Potassium Perchlorate.** As seen in the gun tests, action times with zirconium potassium perchlorate (ZPP) were fast. It thus became desirable to compare this material in a more direct fashion with BP. A very limited number of 220-mg ZPP pellets were available from other ongoing tests in the laboratory. One of these was shaved down to fit into the chamber shown in Figure 1. It was also shortened so that it did not press against the Mylar diaphragm. The mass of this smaller pellet was measured to be 160 mg. Ignition was with 0.5 J of energy focused to a 0.15cm spot. The last pulse was 100 µs long.

The result was a very sharp report and displacement of the chamber. The pressure-time record and the photodiode signals are shown in Figure 7. The pressure rise is very sharp and into saturation before 400 ps. Venting of the chamber was complete in about 600 µs. The light signal, while routinely recorded, is used primarily as a trigger signal for the recording device. Thus, the gain settings are not good for observing signals. The first pulse is due primarily to the laser flashlamp. The second should only be present after the diaphragm has broken and venting has started. The duration suggests that a significant portion of the ZPP burned while venting. This difference from BP may have to do with the flamespread behavior of the two materials or to effects from pellet behavior. (BP pellets are typically slower than the powders used here.)

In addition to the short times of the pressure and light signals, there were other indications that this material would be more effective than the BP. The first was that the ZPP was almost totally consumed. Typically with BP, a significant part of the test sample is recovered unreacted. This lack of unreacted residue indicates that flamespread is sufficiently fast to propagate the flame throughout the pellet material before the pressure wave reaches the Mylar and depressurization can take place. The second observation was that the focusing lens, which is subject to the venting process, was severely “sandblasted” by the venting combustion products. With BP, it is coated with a layer of easily removed products. This damage was probably caused by the temperature, quantity, and

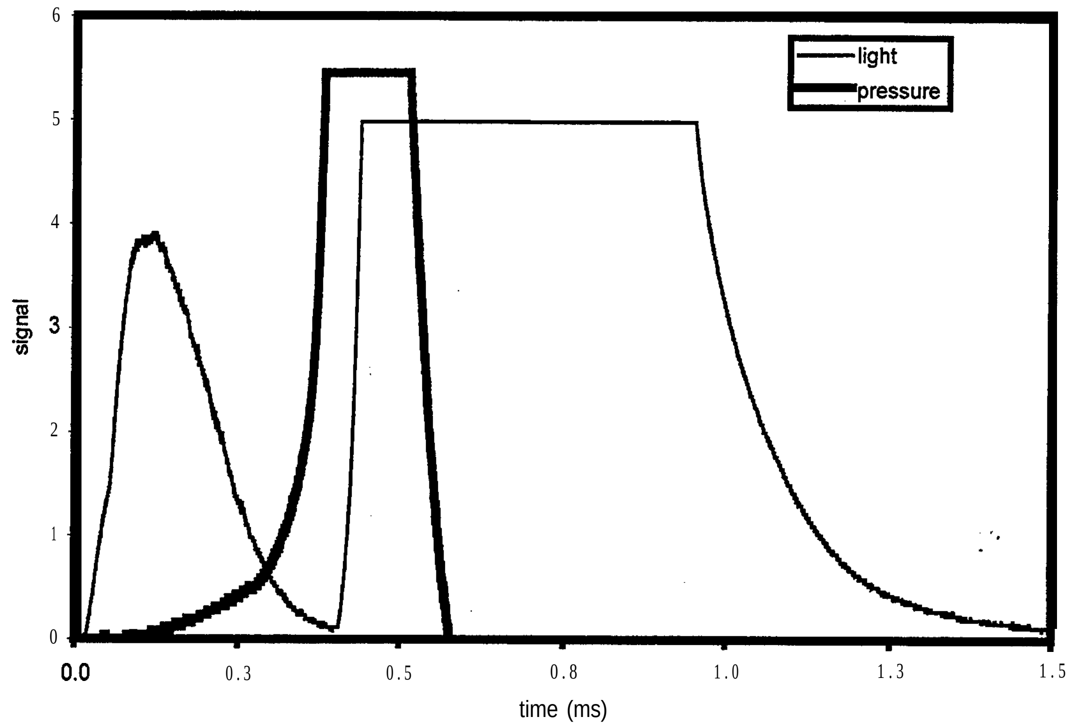

Figure 7. Pressure-Time Record and Photodiode Signals.

velocity of the venting gas/particle mixture. Recall that this chamber was deliberately configured to mimic the size and shape of the cartridge primer. Thus, this output is directly indicative of the output of a primer filled with a ZPP pellet in the gun tests.

Because of the violence of the test with ZPP and limited test time availability, these tests were not repeated with ZPP or the other pyrotechnic materials.

3.3 Gun Tests. The purpose of these tests was to get experience with laser ignition on a medium-caliber gun and to demonstrate that an action time of under 4 ms was a reasonable expectation. Rather than serve as a strict chronology, this report is a summary of observations. The round used for all firings was the M788 30-mm training round. This round uses a primer and flashtube assembly to ignite a main charge. Only components in this igniter train were modified. Standard ball powder was used as the main charge. In some cases, the amount of propellant was reduced slightly to facilitate the assembly process. This is reflected in slightly lower muzzle velocities; it is not thought to affect action time significantly.

A sketch of the standard igniter configuration is shown in Figure 8. An electric primer (primary plus booster) contains about 2.2 grains of lead styphnate, barium nitrate, and calcium silicide with modest confinement. The flashtube is loaded with three IB52 pellets (90% BKNO3/10% ball propellant) with a total weight of about 5 grains.

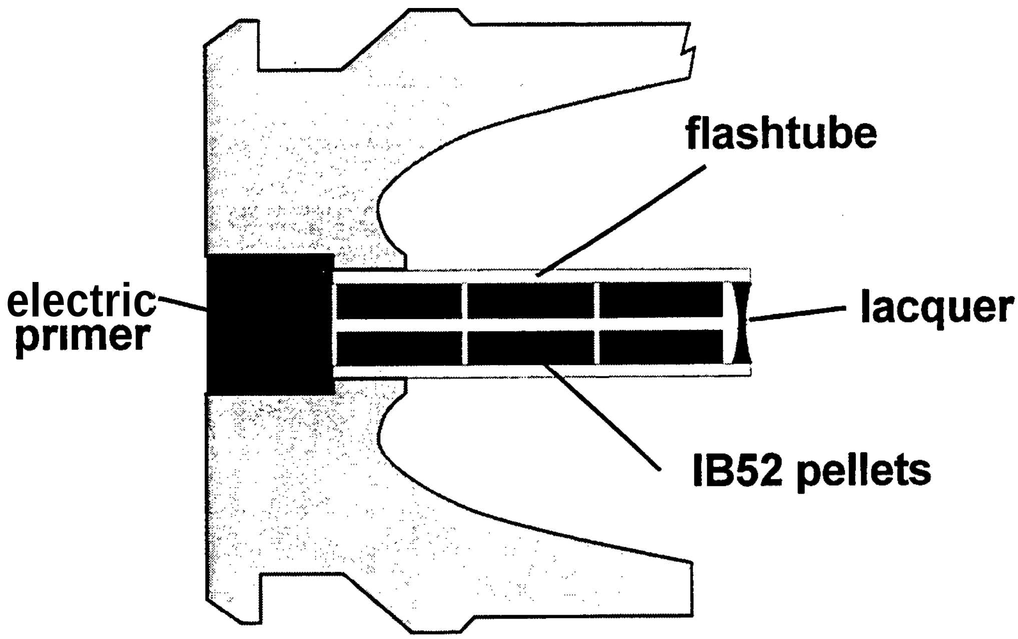

Figure 8. Schematic of Standard M788 Ignition System.

The first laser ignition attempt used a simple replacement for the primer. Shown schematically in Figure 9, it consisted of a sapphire window and a small amount of energetic material mounted into a standard primer shell. In some tests, there was no material immediately inside the window. Although it is reasonable to expect that this would be slower, it greatly facilitated the assembly process for the test rounds. (It would not be expected to affect a production round as much.) Small pellets (-20 mg) of titanium potassium perchlorate (TPP) that could be inserted into the first IB52 pellet or used near the window with class 5 BP filling the remainder of the cavity were available. The results of this first series of tests are shown in Table 1.

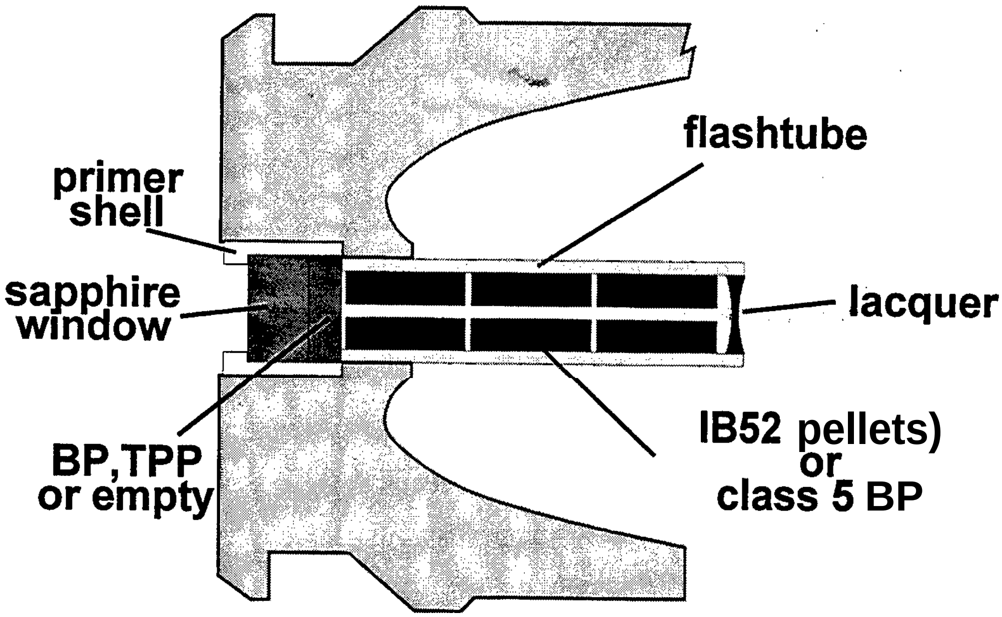

Figure 9. Modified Igniter for First Gun Test Series.

Table 1. Results of First Gun Test Series

Window Cavity	Flashtube	Velocity (m/s)	Action Time (ms)
Empty	IB52 with BP Fill	807.5	9.15
Empty	BP	804.6	8.65
Empty	TPP and IB52	807.9	16.49
Empty	TPP and BP	801.0	7.41
BP	BP	801.7	4.93
BP	IB52 With BP Fill	804.6	5.10
TPP and BP	BP	798.6	3.74
TPP and BP	1B52 With BP Fill	801.1	3.23

In this first series of tests, one of the positive results, in addition to the smoothness of the test and the reasonable action times, was that the rounds with a BP-filled flash tubes had action times comparable to those with the IB52 pellets. This configuration has the potential of being less expensive to produce. Overall, the action times, though obviously not all meeting the 4-ms benchmark, were encouraging. It does appear that very fast primary ignition is important in a multistage igniter such as this one.

In an attempt to determine if the booster process could be made faster by reducing the flashtube time, a design was tested, as shown schematically in Figure 10. In the original design, it is not clear how much the long flashtube is required for ignition of the charge and how much of it is a location transfer to deposit the energy into the main bed of the propellant, away from the end wall of the cartridge. The design of Figure 10 has the potential of allowing a fast robust ignition fairly deep into the propellant bed. A limited number of this design were assembled and tested, along with several more of the flat window, sapphire window design from Figure 9. The window of Figure 10 was a 3-mm glass ball. The test results of this design were plagued with gas leakage and were inconclusive. Overall, this second set of firings was not as successful as the first and demonstrated the importance of careful control of the cartridge assembly process. Among the many contributing factors to large variations in results were thought to be the use of nonstandard seals on the flashtube exit end.

During the second series of firings, the effect of laser energy deposited to the round was measured with BP-loaded primers. The energy is the energy recorded at the end of the optical fiber. A loss of about 15% is expected from surface reflections with the sapphire window. (The corresponding loss for glass is about 8%.) The results are shown in Figure 11. As can be seen, the action time does not appear to be adversely affected as the energy is reduced until near 0.25 J. Below this energy, there were also frequent misfires that were almost certainly due to being below ignition threshold at the BP.

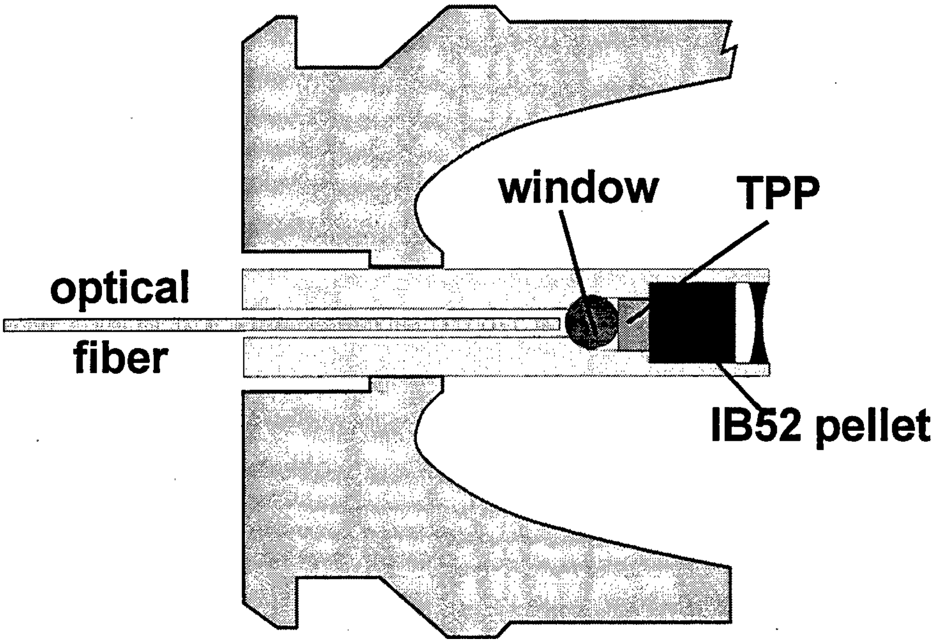

Figure 10. Short Flashtube Configuration.

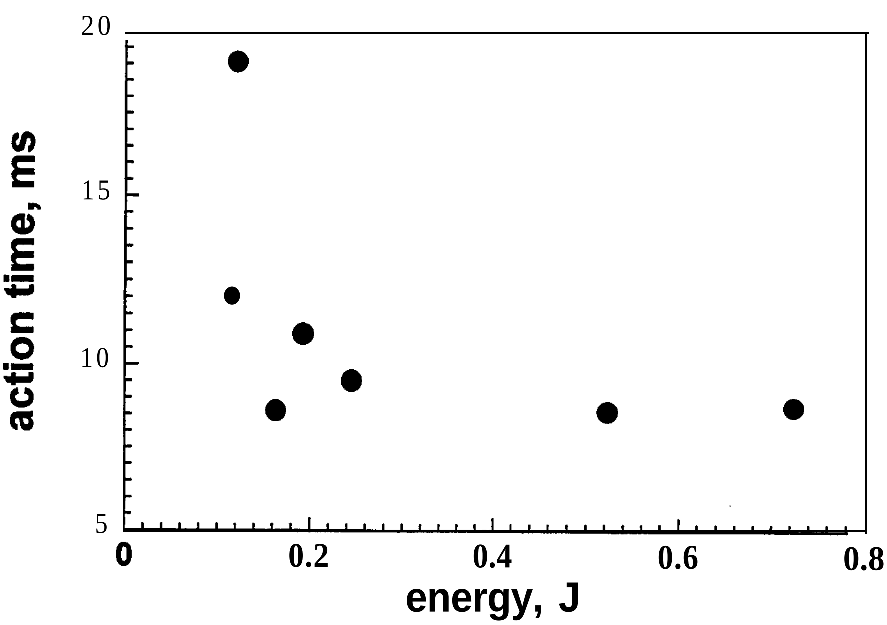

Figure 11. Gun Action Time With Reduced Laser Energy.

A third series of rounds was prepared to test both new igniter materials and a new window design. The window design was based on 8-mm borosilicate glass balls that were mounted into a primer-sized mount. The balls were considered a good candidate both because they can act as a lens to focus the laser energy (recall that energy density is supposed to be the key to ignition) and because they are quite inexpensive. Small-quantity costs of the sapphire window and the ball were about ten dollars and six cents, respectively, at the time of these tests. A diagram of the assembly is shown in Figure 12. Not shown in the figure is a Mylar seal between the primary igniter material and the flashtube. An effort was made to minimize the free volume in the "primer" region, especially with the (class 5) BP. The flash tubes used were production-sealed. Rounds were fired at ambient temperature and conditioned to -54° C.

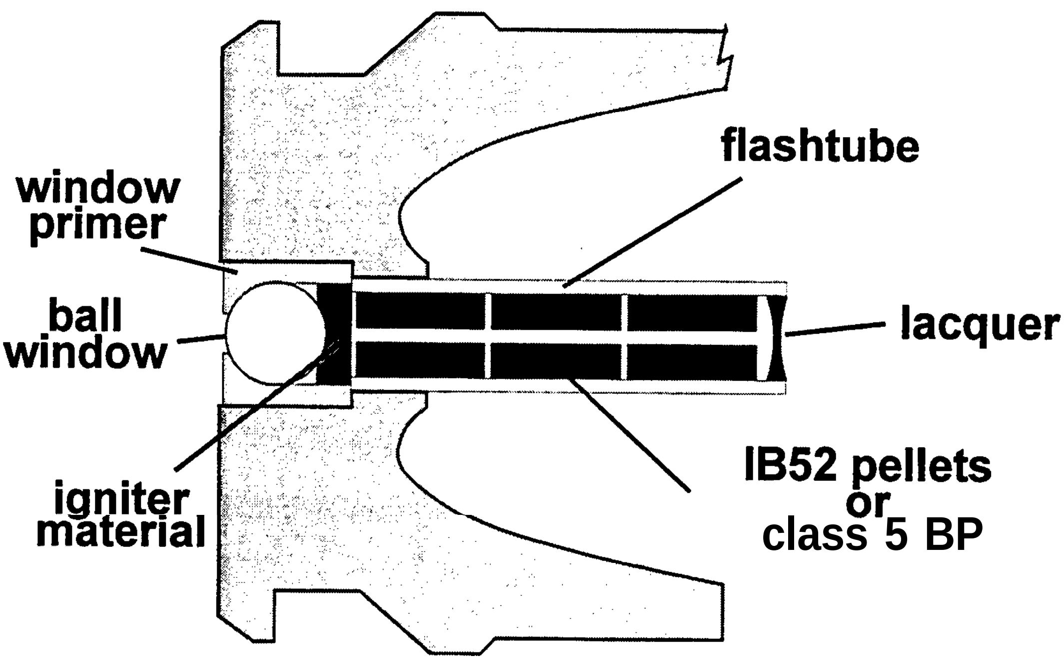

Figure 12. Ball Window **Configuration for Third Gun Test Series.**

The results of the third set of rounds are shown in Table 2. In addition to the overall good success rate of meeting the 4-ms target, several other points are notable on this table. The first is the short action time with the cold ZPP using the ball window. The total time is near the expected total interior ballistic time for functioning of the main propellant charge, which implies not only a prompt

Table 2. Results of Third Gun Test Series

Igniter	Temperature	Window	Number[a]	Velocity (m/s)	Time (ms)
TPP	Ambient	Flat	4	774	3.73
ZPP	Ambient	Flat	5	777	3.71
ZPP	Cold	Flat	5	762	3.58
BP (Class 5)	Ambient	Ball	4	773	9.87
TPP	Ambient	Ball	5	788	3.33
TPP	Cold	Ball	5	737	5.46
ZPP	Ambient	Ball	5	796	2.94
ZPP	Cold	Ball	3	779	1.88

[a] Five rounds were loaded for each configuration. Misfires and outliers have not been listed.

primary ignition but very rapid transfer. Since five equally cold ZPP rounds with a nonfocusing flat window had more "normal" times, there is not an immediate explanation for this result. The ZPP fired at ambient temperature with the ball lens is also faster than the results with ZPP ambient and a flat lens; so, it could be concluded that a particularly prompt ignition is taking place with the high energy density of this configuration. The TPP shows, at most, a slight indication of the same trend. The BP continues to be too slow, in spite of encouraging indications from laboratory studies. The perchlorates are not a satisfactory solution because of concerns for gun barrel life.

4. Discussion

The results with BP in the gun firings indicate that a primary igniter of BP is not likely to yield the action times in the configurations we are testing. The laboratory tests indicate that smaller grain size does enhance the flamespread and pressurization rate, but that the class 5 is sufficiently small if the loading density is reasonably high. Since perchlorates are not expected to be an acceptable solution, even in small quantities, other pyrotechnics will be explored. It would appear that a small amount of a pyrotechnic used as a primary igniter or sensitizer with a BP booster and BP or IB52 pellets in the flashtube will yield good action times.

The results with the perchlorates do show that sufficient action times can be achieved with laser ignition with relatively small amounts of energy deposited in a modest spot size. That is to say, the light, having been conducted to the cartridge via a 0.8-mm fiber optic and only focused by the ball windows, or not at all, is promptly igniting the pyrotechnics. The ignition time of the BP might be enhanced with more energy (and possibly with a smaller focus), but that approach does not appear to be reasonable for this weapon, where the volume, weight, and energy consumption of the laser must be minimized.

5. Future Work

The studies discussed in this paper meet the limited objectives for the first stages of this program. Two other objectives now need to be achieved in order to bring the laser ignition of this class of guns nearer to reality. The first is to identify materials and an igniter tram that will be both prompt (at all temperatures) and cost-effective to produce. The second is to design and demonstrate laser ignition in the M230 in a burst-fire mode. Both of these objectives are being pursued presently and are expected to be met during FY98.

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Laboratory experiments and 30-mm-caliber gun tests have been pursued in order to explore the action time of the M230 gun using laser ignition. The laboratory tests explored the response of black powder (BP) to energy levels from).2 to 0.5 J. Tests with class 5 and class 7 BP show that response will probably not be fast enough to use BP as the primary initiator for this gun unless more laser energy is available. The limitation is in the time required for initial laser gnition of the BP. In the gun tests, pyrotechnic materials were also used and showed excellent response times well mder the 4-ms requirement. Those tested include perchlorates and would not be acceptable for gun use. Several possible cartridge igniter configurations were tested. Low-cost windows were successfully demonstrated.

14. SUBJECT TERMS

laser ignition, black powder, medium-caliber gun, action time

15. NUMBER OF PAGES

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15. PRICE CODE

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