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LASER IGNITION OF SOLID PROPELLANT FORMULATIONS

FINAL REPORT

JUNE, 1979

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GEO-CENTERS, INC.
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NEWTON UPPER FALLS, MA 02164

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20. ABSTRACT

Combustion waves associated with the individual laser pulses were observed to originate at the surface of the grain and propagate outwards from the surface, forming a cloud of material in front of the grain. It was found that when the laser pulse was adjusted to deliver a power density of 2×10^5 w/cm^2 to the grain, self-sustained combustion could be achieved. At higher values of the power density, dynamic extinction of black powder occurred, i.e., combustion was not self-sustaining. Flame diagnostic measurements indicate that thermal mechanisms may be responsible for the observed phenomena. Additional experiments with douibe and triple based propellants show that other ignition mechanisms may prevail with these classes of propellants.

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Abstract

The ignition of single grains of black powder using a pulsed ruby laser (6943A) was investigated. The experiments were performed in air at atmospheric pressure with a laser which delivered up to 22.6 j of total energy. The ignition process was monitored by streak interferometry, open shutter photography and by recording light emissions from the grain with a photodiode.

The experiments showed that focussing of the laser beam was required in order to initiate combustion. Also, the ignition process for black powder was found to occur in a detonative mode. Combustion waves associated with the individual laser pulses were observed to originate at the surface of the grain and propagate outwards from the surface, forming a cloud of material in front of the grain. It was found that when the laser pulse was adjusted to deliver a power density of 2×10^{5} w/cm^{2} to the grain, self-sustained combustion could be achieved. At higher values of the power density, dynamic extinction of black powder occurred, i.e., combustion was not self-sustaining. Flame diagnostic measurements indicate that thermal mechanisms may be responsible for the observed phenomena.

Additional experiments with double and triple based propellants show that other ignition mechanisms may prevail with these classes of propellants.

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Acknowledgment

Portions of this work were performed in the Mechanical Engineering Laboratories of the University of Connecticut. The assistance of Dr. E.K. Dabora and Mr. Robert Lester is greatly appreciated.

1.0 Introduction

1.1 Background

One of the major goals of U.S. Army solid propellant combustion research is to obtain a better understanding of the physical and chemical processes which take place in both the ignition and combustion phases. It is well known that the ignition process can have a significant effect on solid propellant combustion rates. Thus, elucidation of the mechanisms involved in the ignition of propellants provides a potential for improved control over the pressure rise which occurs during combustion. Also, such information can be used to develop improved models for interior ballistics calculations.

The laser appears to be well suited as a radiant energy source for ignition purposes. The pulse shaping capability and accurate repeatability of the laser have obvious advantages over pyrotechnic and electrical igniters. This is especially true in propellant combustion research experiments, where timing is an important factor.

Radiant ignition of solid propellants using laser energy has received only limited attention. The usefulness of high power lasers for radiant ignition of gun propellants has been demonstrated in a Navy prototype gun by Weiland.[1] This study utilized a neodymium laser which delivered approximately 5 j in 5 msec through a 1.25 cm. diameter window (power density = 8×10^3 w/cm^2) to a lead styphnate primer which was used to ignite black powder. Lead styphnate was utilized because of it's known high sensitivity to radiation at 1.06 μm wavelength.

While successfull repetitive operation of the prototype gun was demonstrated, no fundamental ignition or combustion studies were performed.

Radiant ignition of solid propellants with a CO_2 laser has been studied by DeLuca et. al.[2-4] In these studies, the laser was investigated as a possible alternative ignition source to the arc image furnace which produces heating rates which vary both temporally and spatially. These studies utilized relatively low heating rates (20 - 420 w/cm^2) compared to the capabilities of modern pulsed high-power lasers. At these low heating rates, the ignition process was found to be thermal in nature, involving melting and vaporization of the propellant. The actual ignition occurred in the gas phase at low pressure and on the surface of the propellant at high pressure.

Radiant ignition was observed by DeLuca to be a complicated process involving the interrelated effects of propellant optical properties, slow gas phase kinetics near the propellant surface, combustion dynamics during irradiation, and non-uniform distribution of radiant energy. These processes are still not well understood. In particular, it is not known how the optical properties of the propellant affect the interaction of the incident radiation with the propellant in the gas, liquid or solid phase.

In laser ignition experiments with non-catalyzed double based propellants in a nitrogen atmosphere, DeLuca observed the phenomenon of dynamic extinction, wherein after a steady flame was developed during irradiation, burning ceased soon after termination of the laser pulse. This phenomenon was not observed with ammonium perchlorate and catalyzed double base propellants in nitrogen, or with any propellant in air. Experiments in an arc image apparatus also failed to produce dynamic extinction.

DeLuca was able to show on a theoretical basis that dynamic extinction should occur for all propellants in the proper range of externally controlled variables, e.g., wavelength, pressure, temperature, O_2 concentration, etc. The major conclusions reached are that thermal inertia of the solid phase of the propellant is the basic cause of dynamic extinction, large heat release at the surface of the propellant is destabilizing, and that large heat release in the gas phase has a stabilizing effect.

The laser ignition of black powder has been investigated by Williams.[5] This study was performed with a pulsed neodymium-glass laser operating at 1.06 μm. The energy deposition rate was about 1 joule in 0.2 msec, but no information is given about the size of the laser beam. For typical sized laser rods (9/16 inch), the power density would be at least 10^3 w/cm^2 and considerably greater if the beam was focussed down to the size of the grains used, which was 0.5 to 3 mm. High speed photography showed that intense burning of the black powder occurred while the grain was subjected to the laser radiation, but that extinguishment of the flame immediately followed termination of the laser pulse. This phenomenon appears to be identical to the dynamic extinction observed by DeLuca with non-catalyzed double based propellants. The films also revealed a long flame which projects forward from the surface of the grain, as well as bright streaks caused by hot particles moving outward with a velocity on the order of 50 m/sec. The composition of these particles is not known, but they are suspected to be one mechanism by which the flame is spread from grain to grain. Scanning electron micrographs of the black powder grains show that some melting had occurred on the surface of the grain during irradiation.

1.2 Scope of Present Effort

The ignition experiments reported here were performed almost exclusively with black powder. A few preliminary tests were also conducted with a double base (M26) and a triple base propellant (M30).

Williams' laser ignition experiments with black powder showed that dynamic extinction can occur in air at atmospheric pressure. Previously, this phenomenon had been observed only in an inert atmosphere. While DeLuca has shown that at low heating rates, thermal effects (coupling of the flame to the propellant surface) control burning stability, our understanding and theoretically modeling of these effects is far from complete.

The present experiments were aimed at a more thorough examination of the ignition of single grains of black powder with a high power pulsed ruby laser. The major objective of the experiments was to monitor the flame optically and determine the effects of the laser input energy parameters such as total energy of the pulse, pulse duration and shape, and focussing of the beam on the structure and evolution of the flame.

2.0 Laser Ignition Experiments

2.1 Experimental Arrangement

Single grains of black powder were ignited with a pulsed ruby laser. Each grain was cemented to a hollow glass rod about 2 mm in diameter which was then clamped in a holder in front of the laser. The experiments were performed in open air (no test cell) at room temperature and pressure.

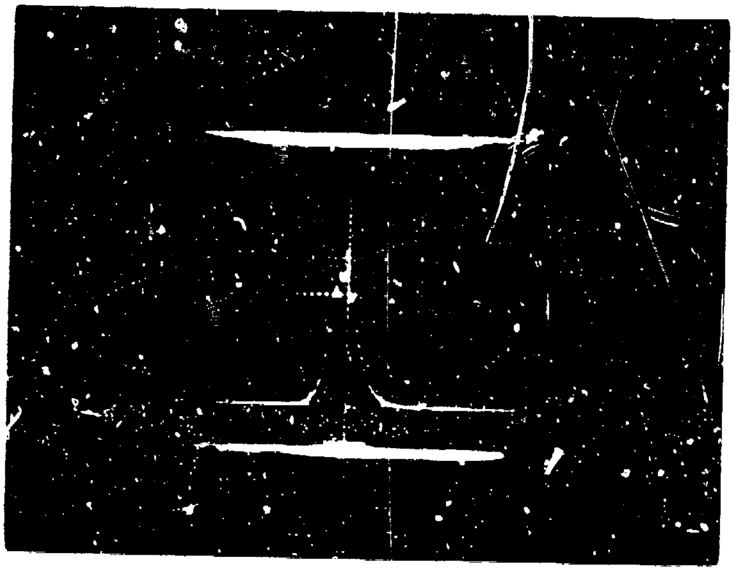
Two experimental arrangements were utilized. Preliminary studies were performed with a Korad KIQDH ruby laser and open shutter photographs of the flame were taken with a Polaroid camera. The majority of the experiments were conducted with a TRW Model 691 ruby laser. Diagnostic instrumentation consisted of a Carl Zeiss Model 1981 Mach-Zehnder interferometer combined with a Beckman and Whitley Model 200 streak camera to produce streak interferograms of the ignition process. A Spectra Physics Model 166 Argon laser was used as the light source for the interferometer. The output of the ruby laser was monitored with a Holobeam HPD-1 photodiode, while an EG&G Model 561 LITE MIKE was used to record emissions from the black powder grain.

The Korad laser was operated in both the Q-switched and conventional single pulse modes (double pulses are possible with this model). Calibration of the pulse energy vs. electrical storage capacity was performed with a Quantronix 504 Energy/Power Meter. The data are summarized in Table 1, and Figure 1 shows typical oscilloscope traces recorded with the

Table 1

Average Energy Output of KORAD KIQDH Ruby Laser

Storage Capacitor Voltage (KV)	Total Energy (joules) Q-switched	Conventional
4.0	-	2.30
4.5	3.62	8.35
4.75	4.05	11.35
5.0	4.50	19.1



(a) Q-switched mode
E = 4.5 joules
Time scale: 20 nsec/div

(b) Conventional mode
E = 19.1 joules
Time scale: 200 μsec/div

Figure 1. Typical KORAD K1QDH ruby laser pulses.

photodiode. It was found that in the Q-switched mode, the Korad laser could deliver up to 4.5 joules in about 20 nanoseconds (full width at mean height). In the conventional mode, the output ranged from about 2.3 joules in 1 msec to 19.1 joules in about 1.8 msec.

The TRW laser has the capability of producing a train of from 2 to 100 pulses at intervals of 2 to 100 μsec apart. Each type of pulse train used in the experiments is designated by the total number of pulses and the time interval between them. Thus, 100 P-10 corresponds to 100 pulses 10 μsec apart. A HADRON ballistic thermopile was used to determine the total energy in each pulse train. Average values obtained are given in Table 2.

Figure 2 shows oscilloscope traces of the TRW laser output with the pulse trains used in the ignition experiments. The emissions from a single grain of black powder are recorded simultaneously. It was found that truly discrete laser pulses could not be generated below a spacing of 20 μsec. Evidently, the Pockels cell cannot switch fast enough, and in the 100 P-10 and 100 P-2 modes a more or less continuous output (temporally) was obtained. These pulses were characterized by energy peaks occurring regularly at the proper frequency, but with the total pulse lasting up to 1600-1800 μsec. The peak light emissions from the grain show excellent correlations with those in the output of the laser.

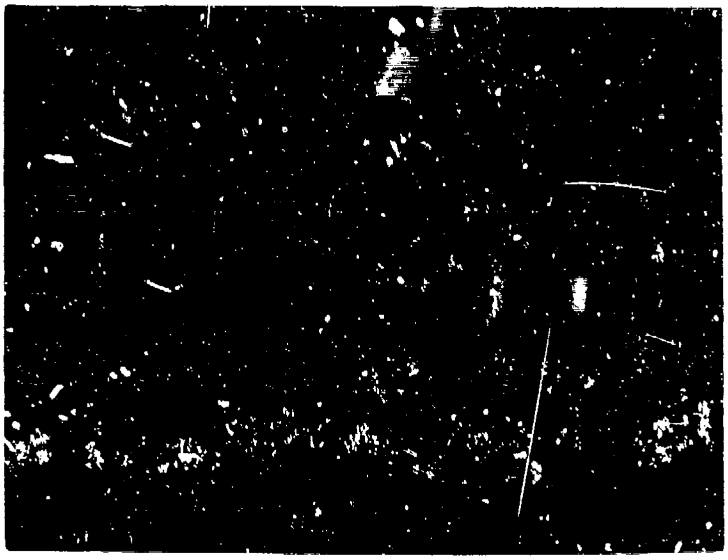
2.2 Propellant Sample Information

In the early experiments in which open shutter photographs of the flame were taken, random samples of black powder were used.

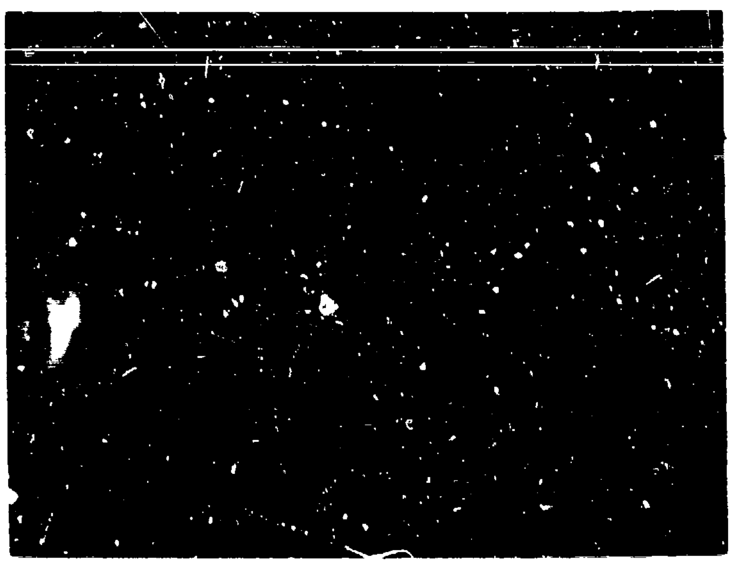
Table 2

Energy Output of TRW Ruby Laser

pulse train	total energy (joules)	approximate time duration (μsec)	Power (watts)
2P-100	5.65	100	5.65×10^4
4P-50	5.65	200	2.825×10^4
35P-20	18.9	700	2.70×10^4
50P-20	19.6-22.0	1000	$1.96 \times 10^4 - 2.2 \times 10^4$
100P-10	22.6	1800	$1\text{-}256 \times 10^4$
100P-2	19.6	1600	1.225×10^4

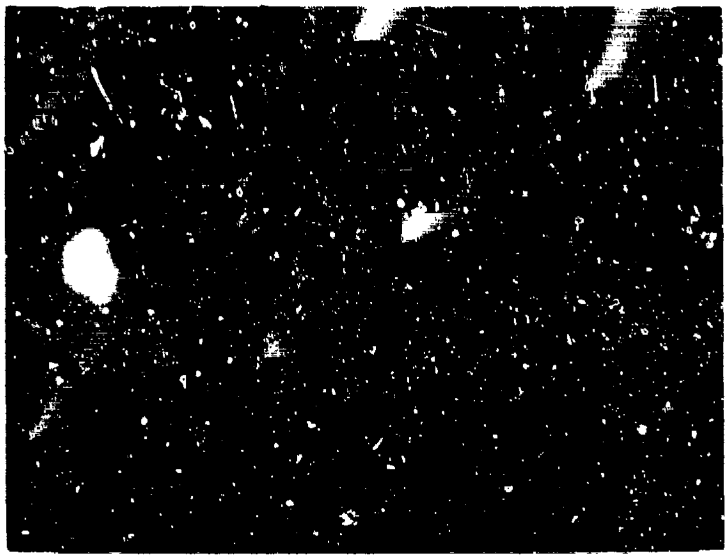


(a) 100 P-2 train.
Time scale: 200 μsec/div



(b) 100 P-10 train
Time scale: 200 usec/div.

Figure 2. Pulse trains produced by TRW Model 691 ruby laser.
Lower trace - laser pulse
Upper trace - propellant response



(c) 35 P-20 train
Time scale: 100 μsec/div.

(d) 2 P-100 train
Time scale: 50 μsec/div

Figure 2. (continued)

There is no information available concerning the physical properties of these samples. For the majority of the tests, the black powder grains used were all taken from the same lot (Gearhart-Owen GOE 75-24). No chemical analysis of this particular lot has been performed, but it is expected that since the powder was manufactured under MIL Spec P-223, there is no significant deviation from the standard composition (75% Potassium Nitrate, 15% charcoal, 10% sulfur).

The double base (M26) and triple based (M30) propellants used were obtained from Radford Army Ammunition Plant Lots RAD-65116 and RAD - 63574, respectively. Sample information is given in Table 3 below.

Table 3 - Properties of Double and Triple Based Propellants

Propellant	M 26	M 30
Lot	RAD - 65116	RAD - 63574
Composition (%)		
Nitrocellulose	67.43	28.55
Nitroglycerin	24.72	22.62
Nitroguanidine	-	46.84
Ethyl Centralite	5.94	1.64
Cryolite	-	0.22
Potassium Nitrate	0.77	-
Barium Nitrate	0.69	-
Graphite	0.25	-
Moisture	0.20	-
Total Volatiles	0.92	0.24
Graphite Glaze	0.04	0.02
Dust	-	0.012
Ash	-	0.06
Grain Dimensions (inches)		
length	.5169	.7936
diameter	.2211	.3231
diameter of perforations	.0234	.0382
Web Dimensions (inches)		
inner	.0385	.0539
outer	.0369	.0503
average	.0377	.0521

2.3 Experimental Results

a) General Ignition Characteristics of Black Powder.

Initial experiments showed that sustained burning of a single black powder grain could not be accomplished with the Korad laser in the Q-switched mode. Visual examination of the grains after exposure to an unfocussed beam showed little effect other than removal of the carbon glaze. Focussing of the beam to about 2 mm in diameter produced slight cratering at the highest energy level possible (4.5 joules), power density = 7.16×10^9 w/cm^2) and some melting of the surface was observed. With conventional laser operation and a focussed beam, sustained burning (consumption) of the grain could be achieved, but on a sporadic basis. It was found that at the higher energy levels (8-19 joules), complete consumption of the grain would occasionally occur on the first shot but happened more often on the second or third shot with the same grain. Figure 3 shows 12X magnified photographs of two grains which survived exposure to single laser pulses of 2.25 and 8.35 joules in the conventional mode. Both grains exhibit removal of the shiny carbon glaze and show evidence of melting and flow. At the higher energy, some cratering is also evident. Thus, it appears that a single laser pulse is capable of conditioning the surface of the grain in some manner, even at low energies. This process is probably responsible for the occurrance of self sustained combustion after repeated pulses.

The flame produced during ignition with an 8.35 joule pulse is shown in Figure 4. Figure 4 (a) is an open shutter photograph taken during the second pulse delivered to this

(a) E = 2.25 joules

(b) E = 8.35 joules

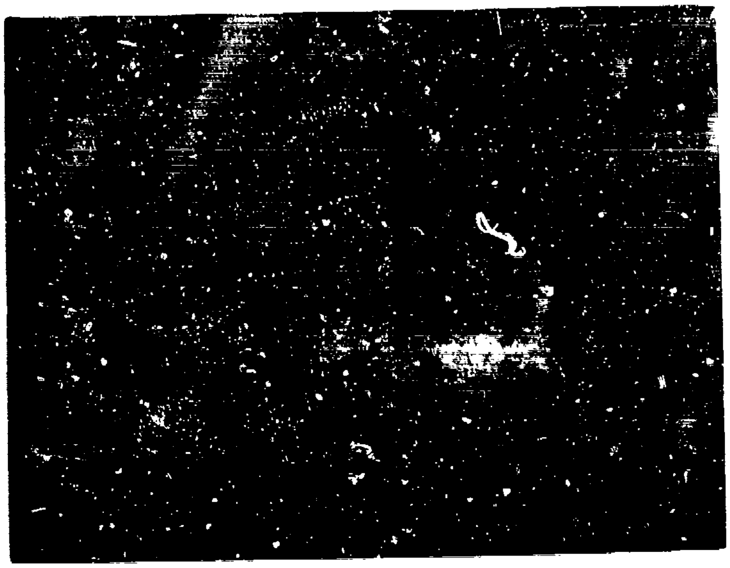
Figure 3. Photographs showing the effects of the KORAD laser pulse on single grains of black powder. (12 x magnification)

particular grain. The photograph shows that the laser beam produces a cloud of material which extends about 65 mm in front of the grain. Figure 4 (b) shows the same grain on the next pulse but with the camera stopped down to reduce overexposure of the film. This photograph reveals that the brightest portion of the flame occurs at the surface of the grain and extends outward about 30 mm. The grain was consumed on this shot.

Some additional information about the flame was obtained by placing a 6943Å, 50 Å bandpass interference filter in front of the camera. Figure 5 shows an open shutter photograph taken with the filter in place at a laser energy of 2.25 joules. At the same conditions but without the filter, the film is completely overexposed. Thus, most of the light emissions from the grain are due to combustion and not to reflected or scattered laser light. Some scattering from the laser beam is visible to about 28 mm in front of the grain, indicating the presence of solid particles. Close inspection of the photograph also reveals at least three (3) luminous particles about 18 mm in front of the grain.

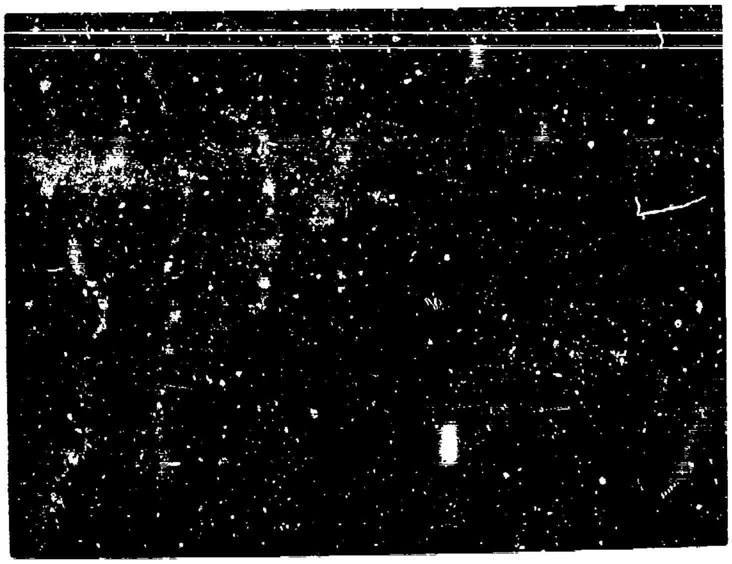
Further characterization of the laser ignition process with black powder was made possible through the use of streak interferometry. With this technique one space dimension is lost, but time measurements are gained, so that flame speeds can be determined. For these experiments, the slit of the streak camera was placed coincident with the glass rod supporting the grain, which was aligned with the laser beam. Thus, recorded wave motion is essentially along the path of the laser beam.

←20mm→



(a) f/2 camera aperture (second pulse)

←20mm→



(b) F/16 camera aperture (third pulse, grain consumed)

Figure 4. Open shutter photographs showing flame produced by exposure of a single grain of black powder to an 8.35 joule ruby laser pulse.

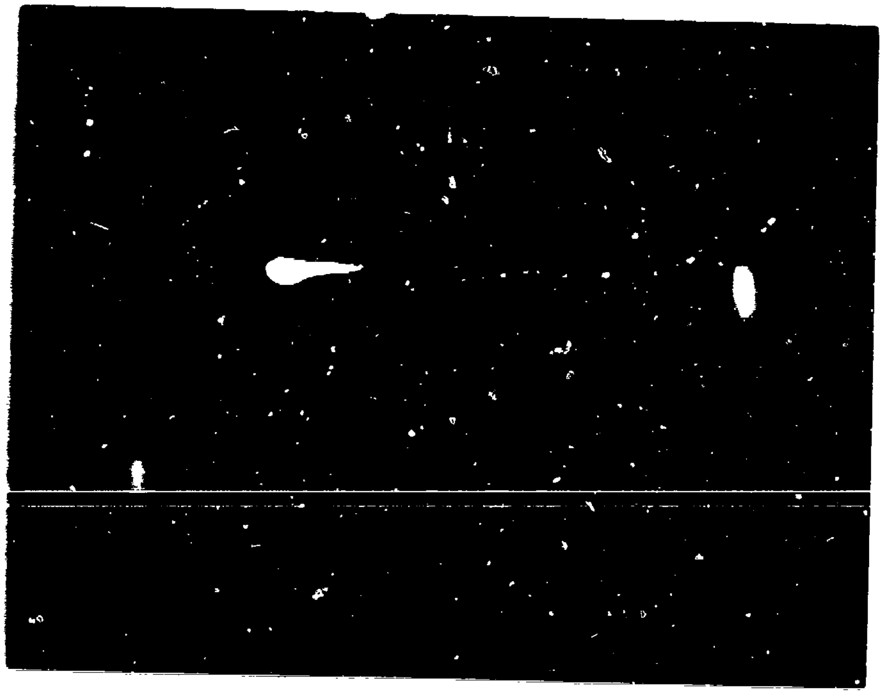
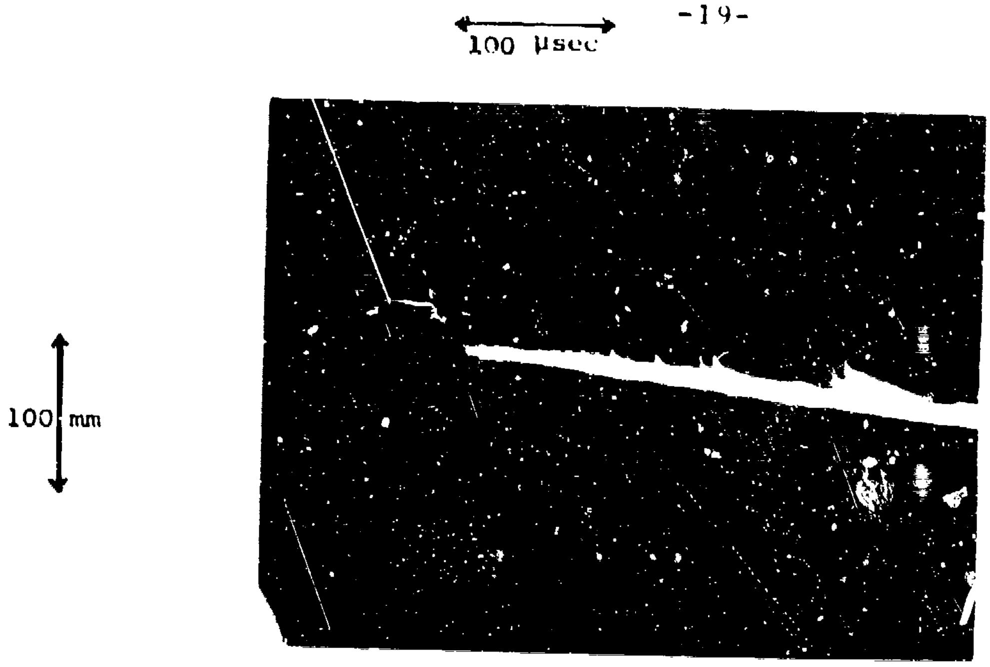


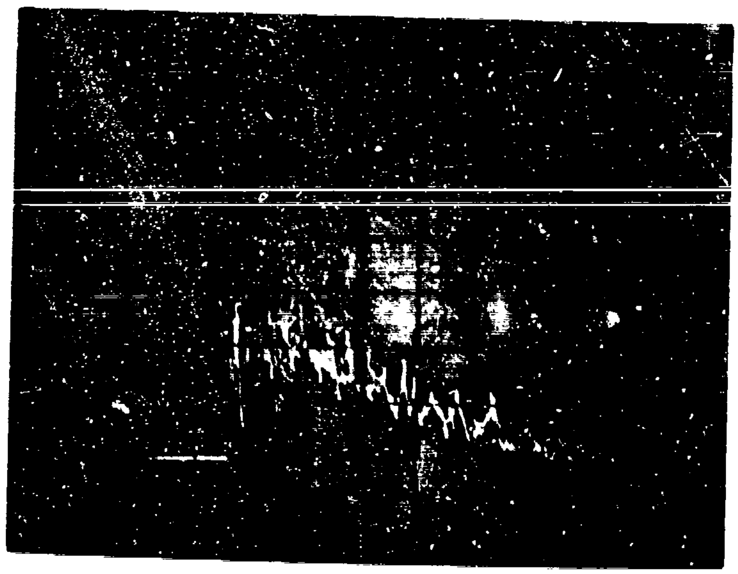
Figure 5. Open shutter photograph taken with 6943 Å interference filter in front of camera. E = 2.25 joules.

Figure 6 shows the streak interferogram and light emissions from the grain with a 100 P-10 pulse train from the TRW ruby laser. The pulse shape is shown in Figure 2 (b). For this shot, the total energy of the pulse was 24.1 joules and the beam was focussed to 1.25 mm diameter, giving a power density of 1.024 X 10^6 w/cm^2. For these tests, the rotational speed of the mirror in the camera was 1 revolution in 15 msec. Thus, only about 400 μsec of the event could be captured. The 100P-10 pulse lasts about 1800 μsec, so that it was not possible to record the entire event. As was pointed out earlier, the 100P-10 pulse is continuous, but actually consists of a train of pulses having 10 μsec intervals between peaks in intensity. Corresponding peaks are evident in Figure 6(b). Also, the amplitude of the peaks shows a steady decline after about 100 μsec.

Figure 6 (a) shows that ignition of the grain occurred at the surface, and commenced on the second pulse, i.e., after 10 μsec. Successive pulses were observed to produce combustion waves which also originate at the surface of the grain and move outward at high speed. As can be seen in the photograph, the wave trajectories are curved, and thus the waves are decelerating. Thus, the waves originate as detonation waves and degenerate to blast waves. This behavior makes the speed of the waves difficult to measure. However, they are estimated to be as high as 2600 m/sec in this particular shot. Repeat shots give speeds which range from 2000 to 2600 m/sec. The high wave speed and also the close coupling with the combustion are indicative of detonation. In this experiment, it was not possible to determine how much of the energy driving the detonation waves was contributed by the laser, and how much was contributed by the black powder itself.



(a) Streak Interferogram



(b) Light Emissions

Lower Trace - Laser Pulse
Upper Trace - Propellant Response
Time Scale: 200 μsec/div

Figure 6. Streak interferogram and light emissions for a black powder grain subjected to the 100 P-10 pulse train.

Another interesting feature of the ignition process is the formation of a plume of material in front of the grain. This plume appears to expand at a reasonably constant rate, and the slope measured in Figure 6 (a) gives an expansion rate of 122 m/sec. Additional tests at the same conditions resulted in expansion rates which ranged from 80 to 150 m/sec. These values compare favorably with the speed of hot particles observed by Williams.(5)

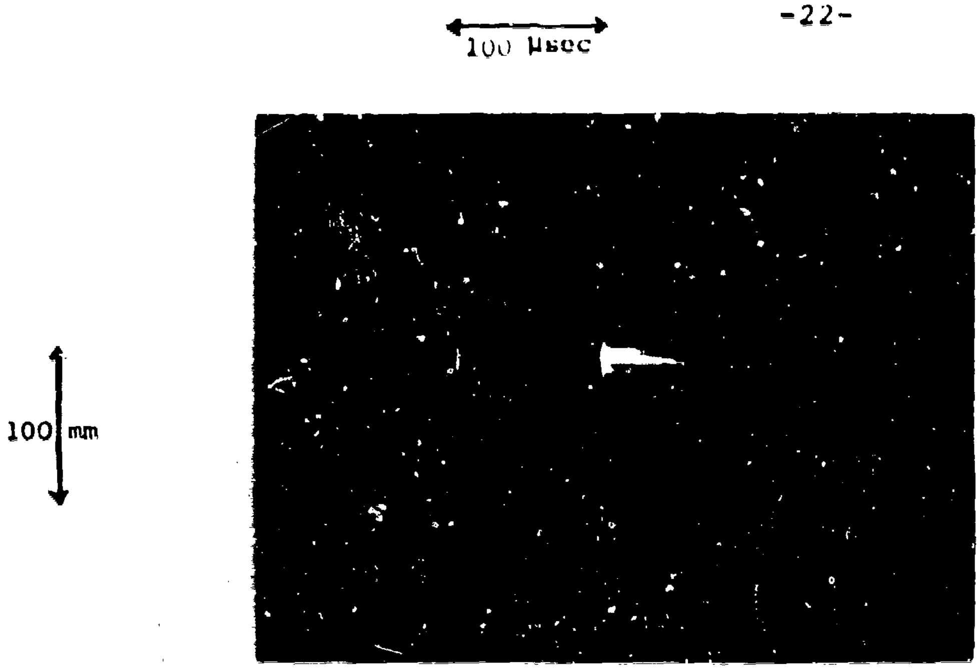
The individual blast waves decelerate as they traverse the plume and exit as weak pressure disturbances at sonic speed. These waves serve as an ignition source for an intense flame which originates at the surface of the grain, where the waves are still strong. Also, since the later laser pulses are weaker than the initial ones, the resulting blast waves are not as efficient in igniting and maintaining the flame. Thus, the flame remains associated with only the initial material which leaves the region near the surface of the grain due to the convective flow behind the blast waves, which is away from the surface. The flame therefore leaves the surface of the grain and remains at the outer edge of the plume. In these experiments, sustained combustion of the grain was rarely achieved, and combustion ceased upon termination of the laser pulse. Figure 6 (b) shows that light emissions from the grain follow the laser pulse intensity, and terminate at the end of the pulse.

This behavior is identical to the dynamic extinction observed with double based propellants by DeLuca and also with black powder by Williams. DeLuca's analysis shows that heat feedback to the propellant surface from the flame is one of the mechanisms which controls extinction of the flame. The present experiments suggest that reduced heat transfer to the surface, caused by the movement of the flame away from the surface of the grain, may therefore be responsible for dynamic extinction with high power pulsed lasers. The remaining experiments were performed in order to investigate this possibility more fully by systematically varying the laser energy deposition rates and observing the effect on the flame produced.

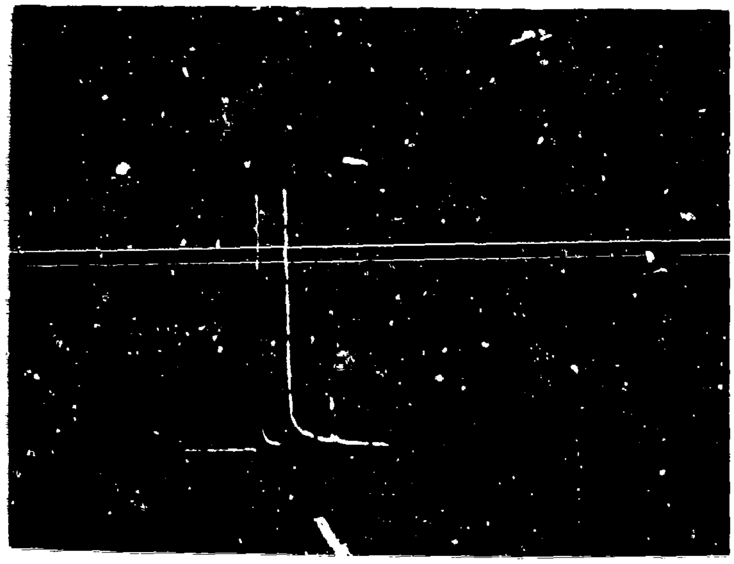
b) Effects of Laser Pulse Shape

Figure 7 shows the effects of a 2P-100 laser pulse. For this case, the total energy is about 5.7 joules. Here it is seen that little or no ignition occurs on the first pulse which produces a small plume which extends to about 20 mm in front of the grain. The second pulse seems to have little effect on the size of the plume, which is considerably smaller than that produced by the 100 P-10 pulse. While some burning takes place near the surface of the grain, rapid extinguishment occurs. Also, several shock waves are evident, but no blast or detonation waves are observed. It appears, then, that too little material was removed from the surface of the grain to support appreciable combustion.

In order to be able to record a longer portion of the ignition and combustion process, the mirror speed of the streak camera was slowed down to 1 revolution in 30 m/sec. This doubled the recording time to about 800 μsec. The laser pulse was then changed to the 35P-20 mode with the hope of obtaining the entire event on one photograph. As it turned out, exact synchronization of the laser pulse with the streak camera could not always be achieved. Figure 8 shows the beginning and almost the entire 35 P-20 pulse while Figure 9 shows the end and almost the entire



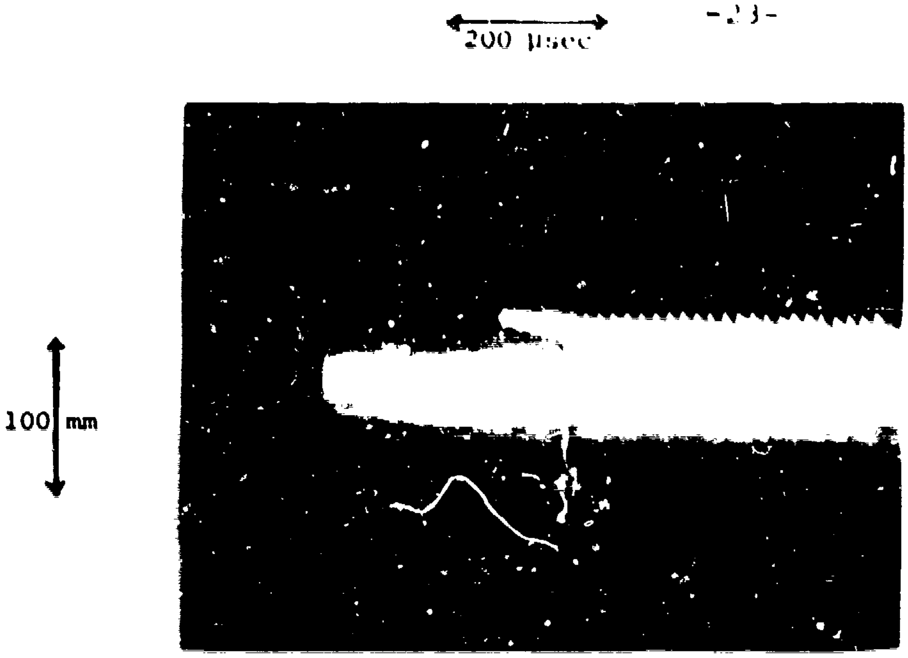
(a) Streak Interferogram



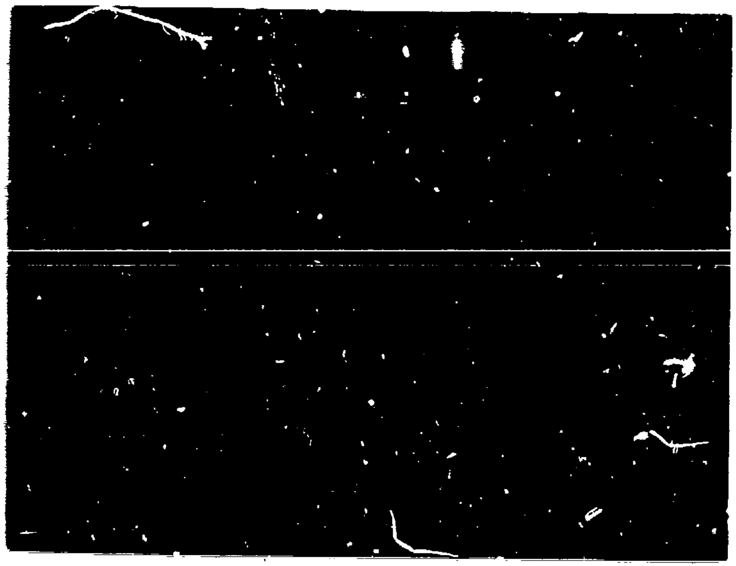
(b) Light Emissions

Lower Trace - Laser Pulse
Upper Trace - Propellant Response
Time Scale: 200 μsec/div

Figure 7. Streak interferogram and light emissions for a black powder grain subjected to the 2 P-100 pulse train.



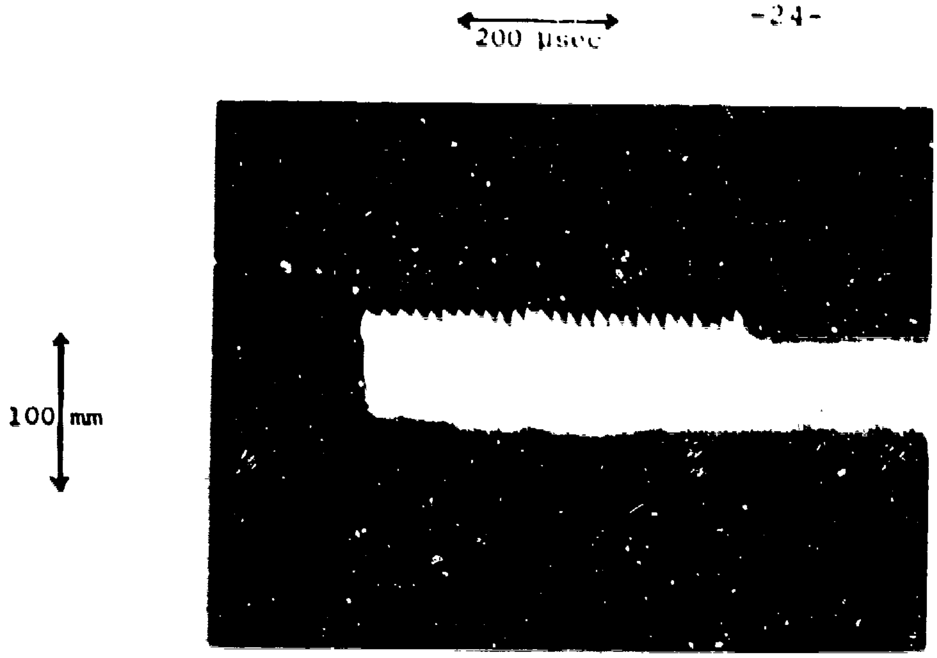
(a) Streak Interferogram



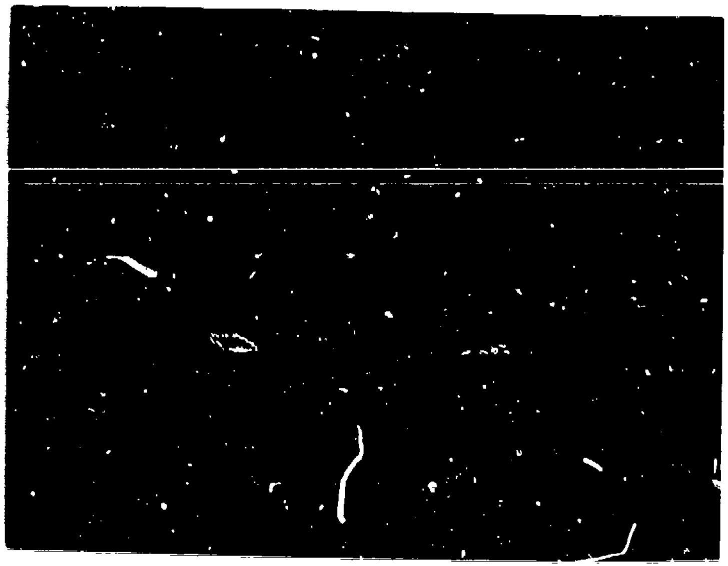
(b) Light Emissions

Lower Trace - Laser Pulse
Upper Trace - Propellant Response
Time Scale: 100 μsec/div

Figure 8. Streak interferogram and light emissions for a black powder grain subjected to the 35 P-20 pulse train. Beginning of event.



(a) Streak Interferogram



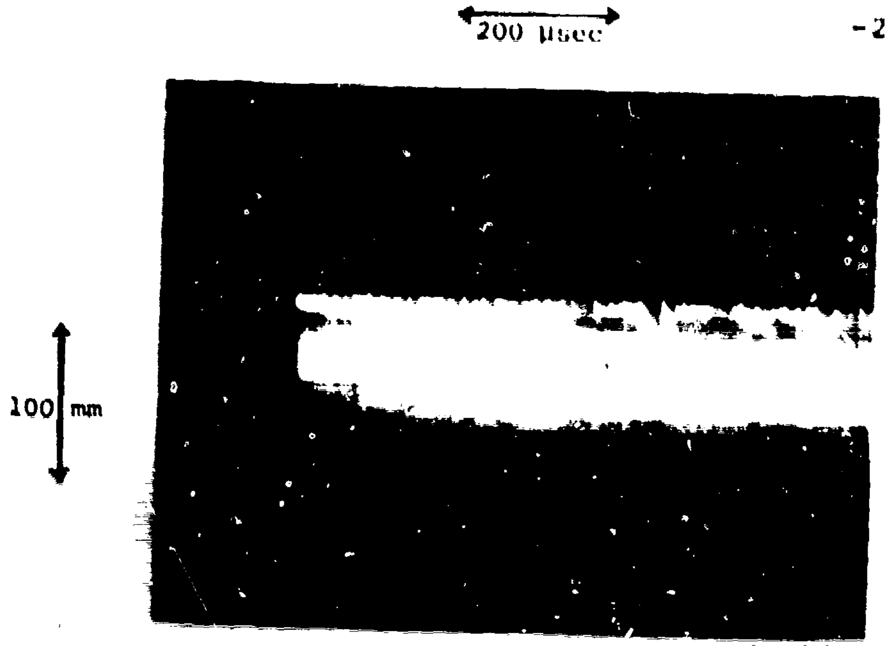
(b) Light Emissions

Lower Trace - Laser Pulse
Upper Trace - Propellant Response
Time Scale: 100 μsec/div

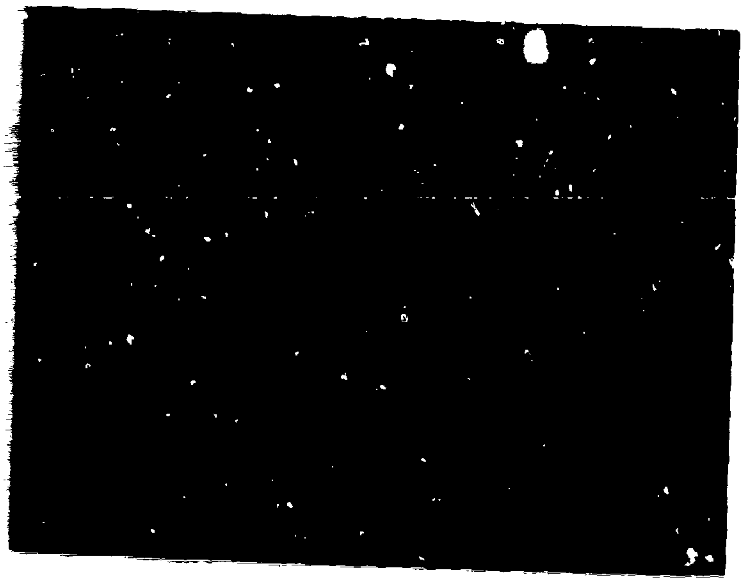
Figure 9. Streak interferogram and light emissions for a black powder grain subjected to the 35 P-20 pulse train. End of event.

event for another similar pulse and different grain. The interferograms show that strong blast waves are produced by the discrete laser pulses which occur at 20 μsec. intervals. The slower camera speed steepens the slopes of the wave trajectories, making wave speed measurements more difficult. It is evident, however, that the initial speeds of the waves are considerably faster than the sonic speed of the Mach waves leaving the envelope of the flame. As was the case with the other pulse trains, ignition is seen to occur on the second pulse, and a bright flame is produced which again is observed to move away from the surface of the grain. Figure 9 shows that flame extinguishment is coincident with termination of the laser pulse, but that cloud expansion continues, although at a somewhat reduced rate. Also, the general level of the light emissions from the grain are much more uniform with the 35P-20 pulse than with the 100 P-10 pulse, for which the laser intensity has a characteristic peak and monotonic decrease over much of the pulse duration. For the 35P-20 runs, the laser beam diameter was about 2.2 mm and with a lower total energy of 18.9 joules compared to 22.6 joules for the 100P-10, a lower power density of 7.1 X 10^5 w/cm^2 was obtained. Plume expansion rates were also somewhat lower, being 44.1 m/sec. for one run, and ranging from 75.1 - 81.2 m/sec for others. These results suggest that significant reductions in power density could result in reduced plume expansion rates which could in turn lead to sustained combustion by maintaining the flame close to the propellant surface.

This possibility was examined by utilizing a 100 P-2 pulse with the beam diameter maintained at 2.2 mm. This delivers 19.6 joules in about 1600 μsec, producing an overall power density of 3.22 X 10^5 w/cm^2. Figure 10 shows a typical streak interferogram



(a) Streak Interferogram



(b) Light Emissions

Lower Trace - Laser Pulse
Upper T ace - Propellant Response
Time Scale: 200 µsec/div

Figure 10. Streak interferogram and light emissions for a black powder grain subjected to the 10^3 P-2 pulse train.

and light emissions recorded in one run. Comparison with Figures 8 and 9 indicates that spreading the pulse out in time reduces the strength of the combustion waves, which are initially supersonic (compare slopes to the sonic waves emanating from the plume), and thus still in the detonative mode. The slower blast waves dissipate more quickly than those for the 35 P-20 pulse, and do not extend as far from the surface of the grain. The main flame, however, which originates with the initial pulses in the train, extends to the outer edge of the plume as before. For the 100 P-2 pulse, plume expansion rates are somewhat reduced, being 51.1 to 64.5 m/sec. Also, light emissions with the 100 P-2 pulse appear to be similar to those with the 100 P-10 pulse having peak emissions occurring around a time of 200 μsec, which is at peak output of the laser. Sustained combustion of the grain was not attained in any runs with the 100 P-2 pulse at the above power density level.

c) Effects of Laser Pulse Intensity

The preceding experiments showed that reductions in laser power density by roughly a factor of 2.0 reduced plume expansion rates by 15-27%. This was done by spreading the laser pulse out in time to the maximum possible with the TRW laser. In order to obtain further reductions, the laser pulse intensity was reduced by the use of neutral density filters. Table 4 summarizes the results obtained.

It was found that sustained burning could be consistently established with the power density of the laser pulse reduced to 1.39 X 10^5 w/cm or less. Also, it was noted that significant reductions in plume expansion rate (about 100%) also occurred at

Table 4

Effects of Neutral Density Filters On Ignition of Single Grains of Black Powder (Beam Diameter Equals 2.2 mm)

Run	Neutral Density Filter	E (Joules)	Power Density (w/cm^2)	Plume Expansion Rate (msec)	Sustained Combustion
71	0.7	3.37	5.54×10^4	15.2	yes
73	0.7	3.37	5.54×10^4	33.6	yes
74	0.7	3.37	5.54×10^4	25.0	yes
75	0.7	3.37	5.54×10^4	32.5	no
76	none	19.6	3.22×10^5	53.4	no
77	0.4	6.17	1.02×10^5	52.5	yes
78	0.2	11.8	1.94×10^5	43.6	no
79	0.3	8.43	1.39×10^5	41.7	yes
80	0.2	11.8	1.94×10^5	-	no
81	0.3	8.43	1.39×10^5	-	yes

the lower power density. Figure 11 shows the streak interferogram and light emissions observed for one run with the 0.7 neutral density filter. These data show that the intensity of the flame is considerably less with the reduced power density but is much closer to the surface of the grain due to the reduced plume expansion rate. This combination evidently results in sustained burning. Curiously, although the grain was completely consumed in the shot shown in Figure 11, light emissions appear to cease at termination of the laser pulse, exactly as when the grain is not consumed. These results would suggest that either

(a) when sustained combustion occurs, the time scale is short compared to the laser pulse, or

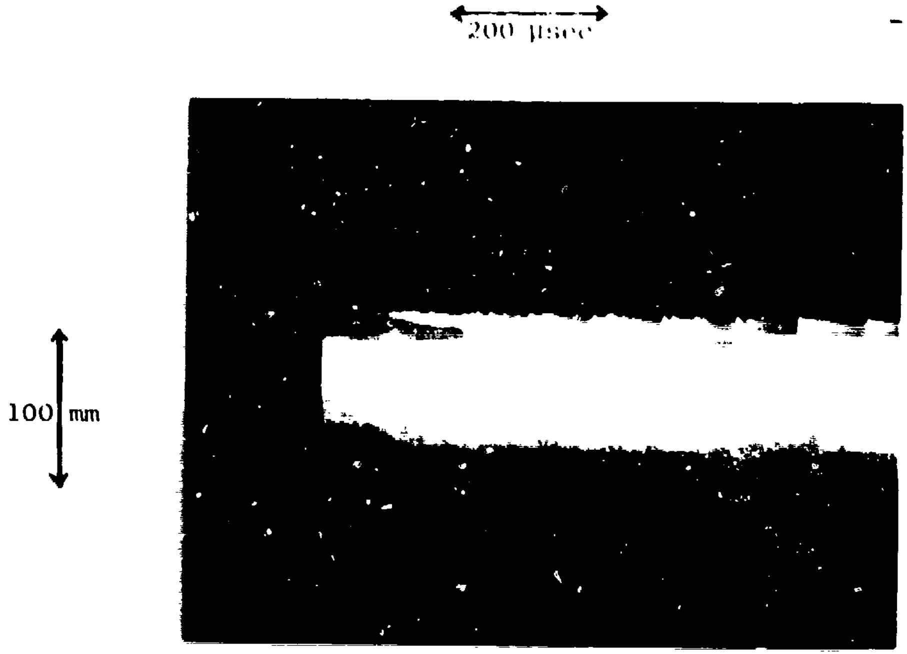
(b) the normal flame is considerably less intense than that produced by the action of the laser beam.

Additional experiments were performed where light emissions were monitored at the same photodiode sensitivity for up to 10 msec. No further emissions were noted in this time period.

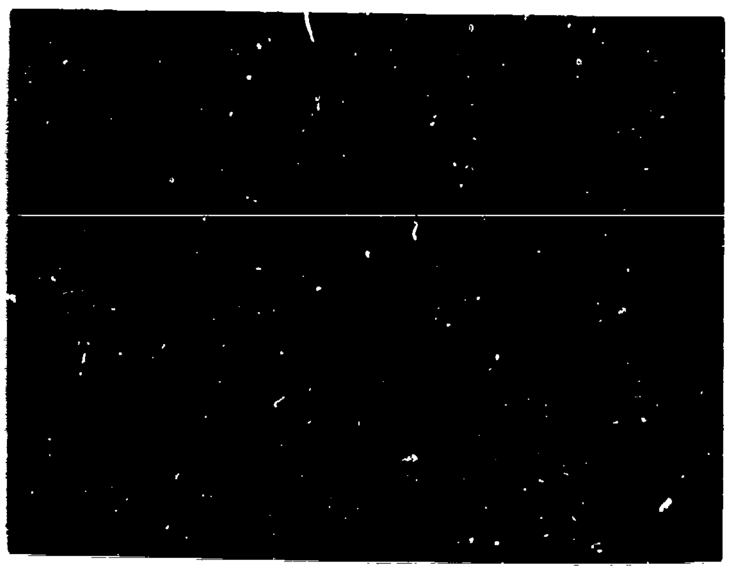
d) Effects of Laser Beam Diameter

A few additional experiments were performed to see if power density alone is the controlling factor in the ignition of black powder. For these experiments, the power density of the laser beam was varied by changing the diameter of the beam as opposed to the intensity. The 100 P-2 pulse was used so that the results could be compared directly to the earlier tests. The data obtained is presented in Table 5.

These results are difficult to interpret when viewed by themselves. In general, it was found that increasing beam diameter does in fact reduce the plume expansion rate. The effect on sustained ignition is inconclusive, however. On the other hand, when the data appearing in Tables 4 and 5 are



(a) Streak Interferogram



(b) Light Emissions

Lower Trace - Laser Pulse
Upper Trace - Propellant Response
Time Scale: 200 μsec/div

Figure 11. Streak interferogram and light emissions for a black powder grain subjected to the 100 P-2 pulse train. 0.[illegible] neutral density filter in front of beam.

Table 5

Effect of Laser Beam Diameter on the Ignition Characteristics of Black Powder (100 P-2 Pulse)

Run	Beam Diameter (mm)	Power Density (w/cm^2)	Plume Expansion Rate (m/sec)	Sustained Combustion
82	1.65	5.73×10^5	91.2	no
83	2.2	3.22×10^5	73.6	no
84	2.7	2.14×10^5	56.2	yes
85	2.7	2.14×10^5	-	yes
86	2.7	2.14×10^5	61.5	no
87	2.7	2.14×10^5	103.4	yes
88	2.7	2.14×10^5	-	no

combined as shown in Figure 12, a definite trend is observed. Here it is seen that reducing power density (either by reducing the laser intensity or by increasing the beam diameter) causes a reduction in plume expansion rate. Furthermore, below a power density of about 2×10^5 w/cm^2, sustained combustion occurs with reasonable consistency. These all occur, with one exception, below a plume expansion rate of about 60 m/sec. A typical streak interferogram and light emissions recorded for the larger laser beam is shown in Figure 13. Comparison with the data in Figures 10 and 11 shows that considerably more flame is produced with a higher intensity beam spread out over a larger area. Also, the flame is more uniformly distributed within the plume. These results suggest that thermal effects may determine whether sustained combustion occurs.

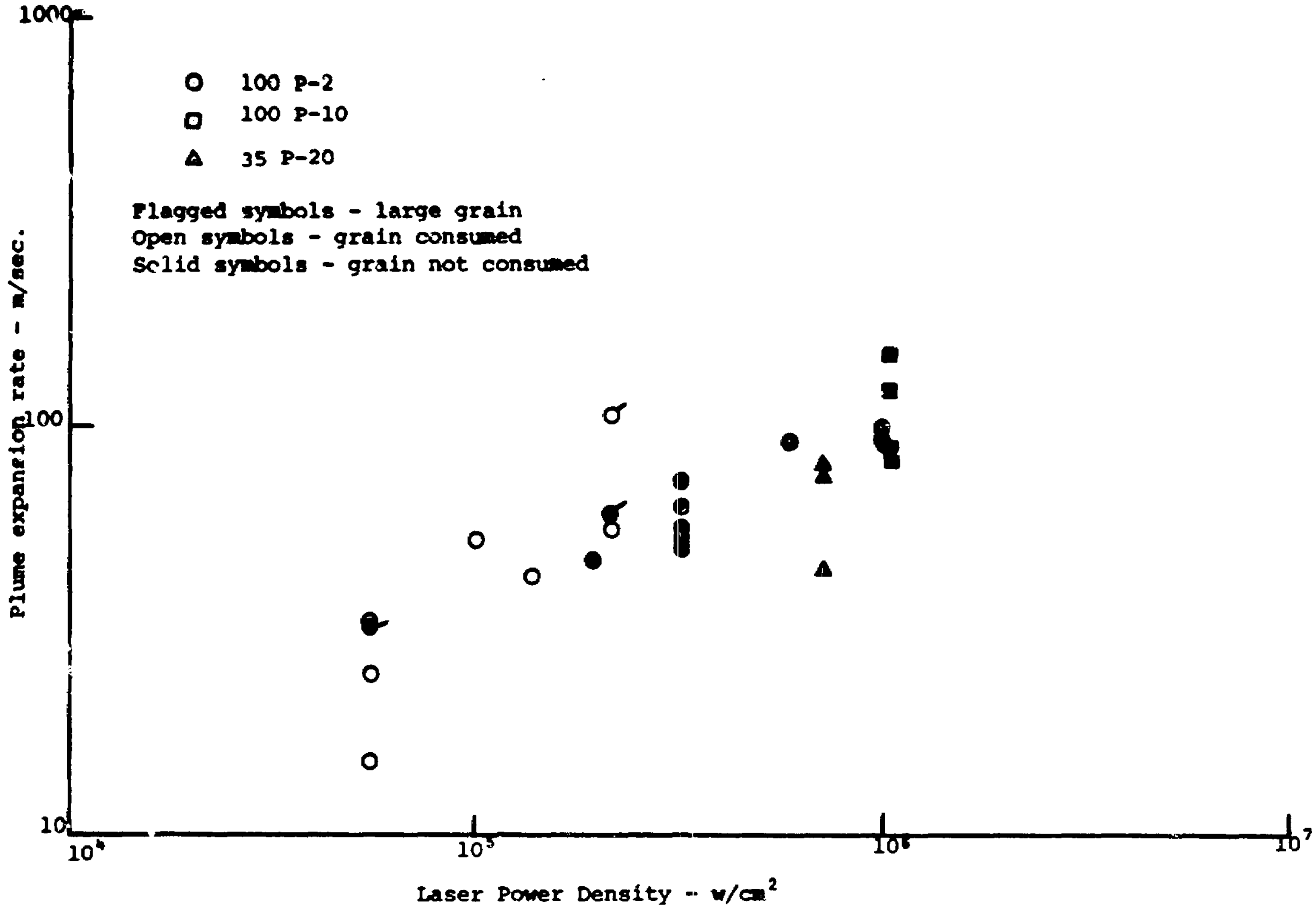
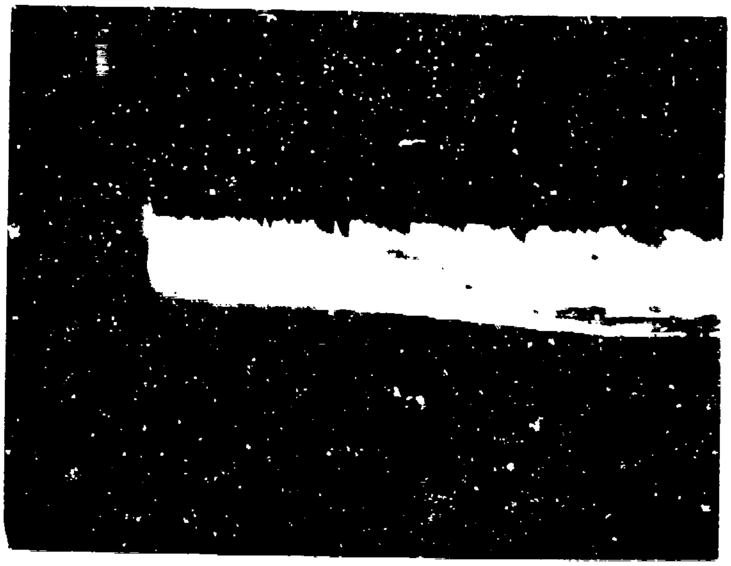


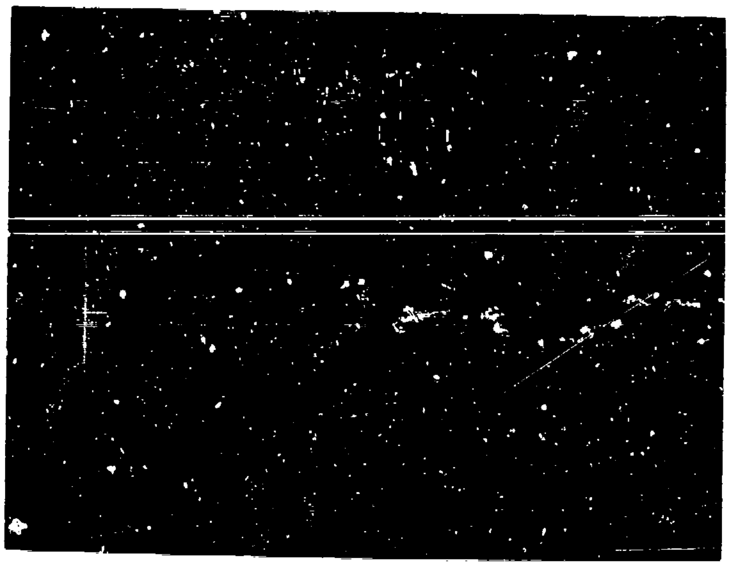
Figure 12 - Effect of laser power density on plume expansion rate for black powder.

200 μsec

100 mm



(a) Streak Interferogram



(b) Light Emissions

Lower Trace - Laser Pulse
Upper Trace - Propellant Response
Time Scale: 200 μsec/div

Figure 13. Streak interferogram and light emission for a black powder grain subjected to the 100 P-2 pulse train. Laser beam diameter = 2.7mm.

e) Grain Size Effects

In order to maintain as much consistency as possible in these experiments, all propellant grains were weighed prior to exposure to the laser beam. Individual grain weights varied from 37.1 to 52.5 mgs. for the majority of the tests. Three additional runs were made with single grains weighing 109.4, 112.4, and 107.3 mg. utilizing the 100 P-2 pulse and a beam diameter of 2.7 mm (power density - 2.14×10^5 w/cm^2). The two smallest grains were consumed, while the largest was not. One additional test at a power density of 5.54×10^4 w/cm^2 with a grain weighing 150.5 mg. also was not consumed. Three lighter grains were consumed at this same test condition, however. These tests were unable to establish any clear trend with respect to grain weight. The post test photograph of the 150.5 mg. in Figure 14 shows considerable melting and pitting of the surface.

f) Tests with M26 and M30 Propellants.

Some preliminary tests were performed with M26 and M30 propellants for the purpose of comparison to results with black powder. [illegible] propellants had graphite coatings, while the M26 also h[illegible] .25% graphite mixed into the composition and was completely black. The samples used were perforated cylinders which were sliced with a razor blade to obtain semi-circular samples weighing about 50 mg. each. Both the graphite coated and uncoated surfaces of each sample were subjected to the 100P-2 laser pulse at a power density of 3.22×10^5 w/cm^2 (beam diameter - 2.2 mm). Figure 15 and 16 show the respective streak interferograms and light emissions for each propellant. These show very little visible flame produced by the action of

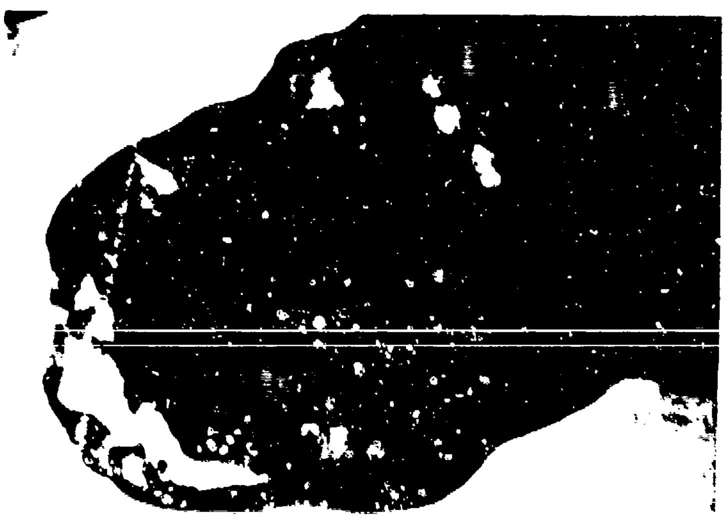
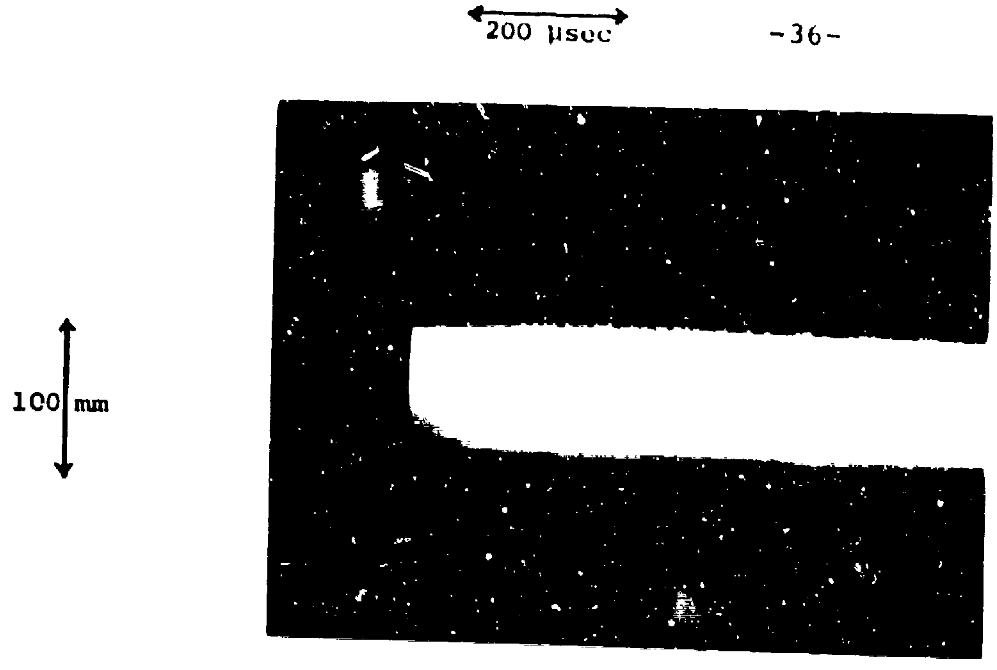
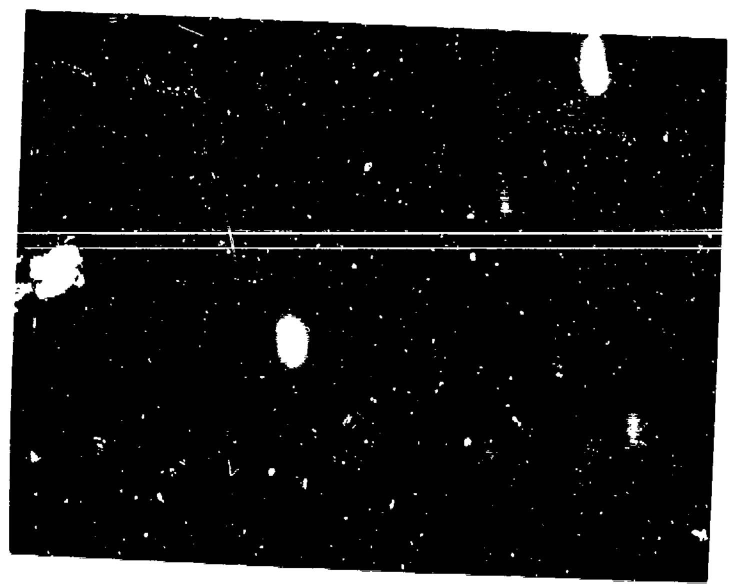


Figure 14. Photograph showing 150.5 mg black powder grain subjected to 100 P-2 laser pulse train. (12x magnification)



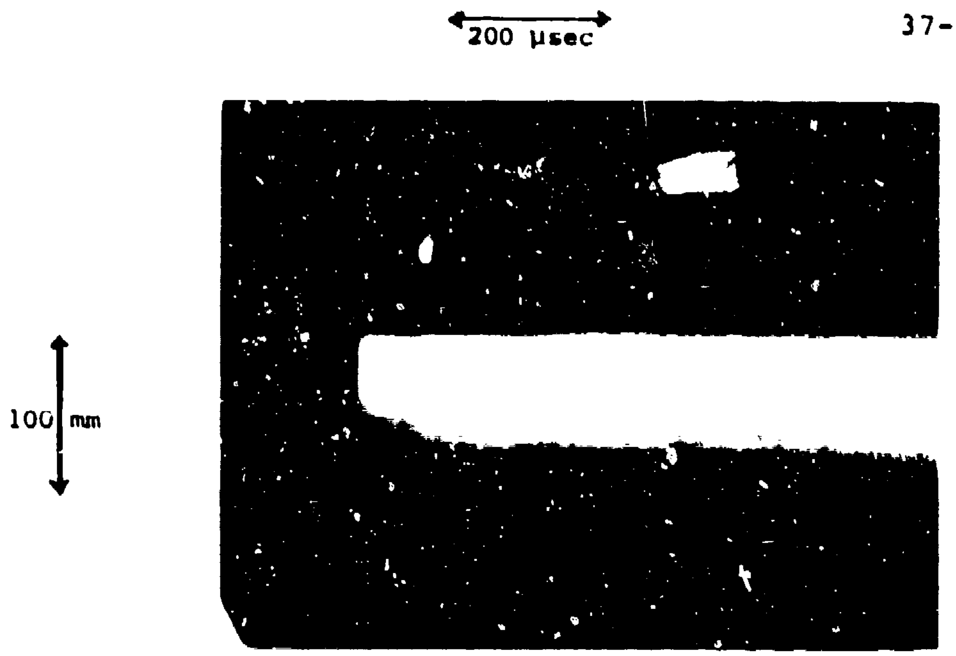
(a) Streak Interferogram



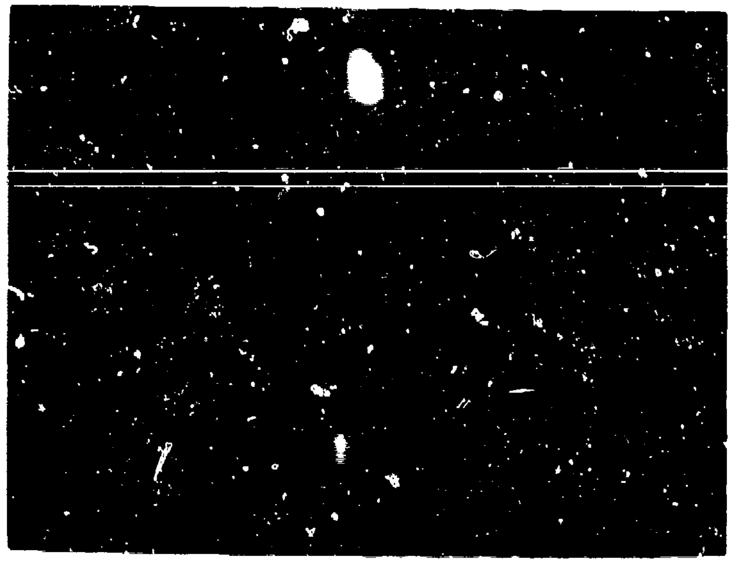
(b) Light Emissions

Lower Trace - Laser Pulse
Upper Trace - Propellant Response
Time Scale: 200 c/div

Figure 15. Streak interferogram and light emissions for an M30 propellant sample subjected to the 100 P-2 pulse train.



(a) Streak Interferogram



(b) Light Emissions

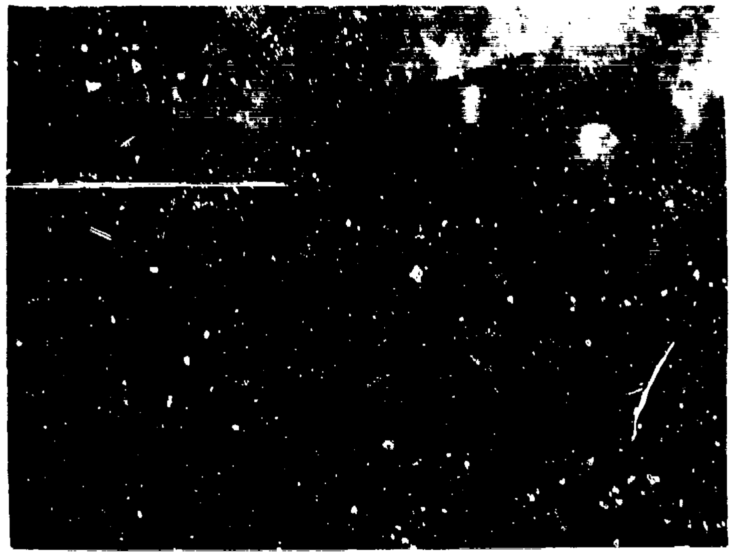
Lower Trace - Laser Pulse
Upper Trace - Propellant Response
Time Scale: 200 µsec/div

Figure 16. Streak interferogram and light emissions for an M26 propellant sample subjected to the 100 P-2 pulse train.

the laser beam with either the M26 or M30 as compared to black powder. Also, a much smaller plume is produced with the M30, and the post test photographs in Figure 17 show that very little of the propellant was consumed. A small hole in the sample is visible near the center of the beam, and the graphite coating has been removed. The M25, however, was observed to burn on a time scale of perhaps 10 sec. or so. In fact, there was enough time at the end of each shot to close the shutter on the streak camera switch on the room lights, and watch the end of combustion process with the naked eye. In both shots, the sample was observed to fall from the glass straw, presumably because of melting of either the glue or the propellant itself, and fall to the floor of the laboratory where burning continued until complete consumption had occurred.

The photographs in Figure 15 show no evidence of blast waves with the M30, although light emissions do correlate with the individual laser pulses. A second shot at this same condition (data not shown) produced one weak (sonic) shock wave. Also, the stringy appearance of the plume indicates a relatively constant density in the plume and therefore a lack of combustion.

The data in Figure 16 show a somewhat different situation for the M26 propellant. Here it is seen that several shock waves are produced initially, but as was the case with the M30, no strong blast waver can be seen. The mottled appearance of the plume is indicative of combustion, but no bright flame is visible. Also, the expansion rate of the plume is initially very high (269 m/sec. for the case shown), and then levels off after about 200 μsec or so. In view of the fact that sustained combustion did occur for the M26, and not for the M30, it appears that the ignition mechanism is different than that for black powder.



(a) Unglazed surface facing laser beam.

(b) Carbon glazed surface facing laser beam.

Figure 17. Post-test photographs of M30 propellant samples subjected to the 100 P-2 pulse train. (12 x magnification)

3.0 Discussion of Results and Conclusions

The basic ignition process of black powder with ruby laser energy was found to be a detonative mechanism. The interaction of the laser beam with the surface of the grain was observed to produce a series of blast waves which serve as an ignition source for an intense flame which initially remains on or near the surface of the grain. The correlation of the temporal spacing of the waves with the individual pulses of the laser indicates that the blast waves are produced by the laser beam. As this process proceeds, a plume of material is formed in front of the grain. The plume appears to consist of both vaporized black powder and products of combustion (smoke), as well as some hot particles of unknown composition. The plume is observed to expand at a nearly constant rate which can be as high as 150 m/sec while the laser is active. The expansion continues, although at a somewhat reduced rate, after termination of the laser pulse. This same type of behavior was noted by Williams, although reported speeds are lower - 50 m/sec.[s]

The blast waves must at least contribute to the expansion of the plume, since the compression of the gas behind them requires a convective velocity which is in the same direction as the propagation of the wave. Additional expansion is probably provided by the main combustion processes as well. Also, in the later stages of the laser pulse, the flame, which initially occupies the entire plume, leaves the surface of the grain. The convective flow behind the blast waves appears to be at least partially responsible for this occurrence. Some evidence to this effect was obtained by systematically varying the strength of the laser pulse. It was found that by spreading the pulse out in time or reducing the intensity of the laser beam, the strength of the blast waves could be reduced, and this in turn lead to reduced plume expansion rates. It was also found that when the laser power density was reduced in this manner to a value below a level of about 2×10^5 w/cm^2, sustained combustion of individual grains could be achieved on a regular basis. With power densities above this critical value, sustained combustion did not occur, and burning of the grain ceased at the end of the laser pulse.

The same value of the critica power density was obtained by increasing the diameter of the laser beam. When the beam area was increased, only slight reductions in plume expansion were observed, and the blast waves did not seem to be that much different, as well. On the other hand, the resulting flame seemed to be more uniform. It should be noted that the variations in beam diameter required to reach the critical power density were quite small, being 25% or less. Also, in the experiments, the diameter of the laser beam was obtained by measuring burn spots on light sensitive paper glued to the glass support rod. Since relatively small changes in beam diameter were made, it is felt that this method is not extremely accurate. Also, the grains varied in thickness and a converging lens was used to focus the beam, thus the outer surface of the grain did not always see precisely the same beam diameter. Thus, it is not clear that the same mechanism is responsible for sustained ignition when laser power is reduced as when beam area is increased.

The above results suggest that thermal effects may be the determining factor with regard to establishing sustained combustion of individual grains of black powder. Reducing plume expansion rates would keep the flame closer to the surface of the grain and thereby improve heat feedback to the surface. A more uniform distribution of the flame within the plume, as opposed to one concentrated near the outer edge of the plume, would have the same result. Thus, both effects can be explained by a thermal mechanism. DeLuca has shown that heat feedback controls dynamic extinction with double based propellants at low heating rates.(4) Also, a recent paper by Lenchitz shows that the ignition of black powder in an arc image furnace is controlled by thermal effects.(6) In addition, Harris et.al. present evidence that indicates that grain to grain flame propagation with black powder can possibly be caused by a thermal conduction/convection mechanism.(7) The laser ignition experiments of Capellos with nitromine explosives have shown that in many cases, confinement of the flame by means of glass is required in order to obtain sustained combustion.(8) All these studies emphasize the role of thermal effects in maintaining self-sustained ignition and combustion of black powder and other energetic materials. The present results provide additional support to these conclusions. In fact, it has been shown here that proper adjustment of the laser energy deposition rates produces a certain degree of self-confinement of the black powder flame which then allows sustained combustion to occur. This is no different in principle than the confinement afforded by a piece of glass.

Finally, the experiments with M26 and M30 propellants show that propellant chemistry also influences the ignition process. With both propellants, no strong blast waves were observed although sustained combustion appeared to be easily attained with the M26 and very difficult to attain with the M30. In these experiments, light emissions from the propellant sample were monitored during the time period of the laser pulse. These appeared to be very intense with black powder and much weaker with both the M30 and M26. Although the M26 continued to burn after termination of the laser pulse, no light emissions were recorded up to one 10msec later. However, light emissions were observed visually after seve al seconds. This behavior could be the result of a continuous low intensity flame which could not be detected by the photo-diode, or possibly by a "fizz-flame" mechanism. Thus, the experimental results with M26 and M30 indicate that the ignition mechanism of these propellants may be different than the detonative mode observed with black powder. It was not possible to resolve this question in these experiments.

4.0 Recommendations

While the experiments described in this report have elucidated some of the physical processes involved in the laser ignition of solid propellants, perhaps as many questions have been raised as have been answered. The proper technique for ignition and sustained combustion of black powder using a ruby laser has been established, but as yet it is not known whether there is accelerated combustion during the laser pulse, or whether the majority of the combustion takes place later on in time. Initial experiments with an M26 double based propellant show that grain consumption definitely occurs after the laser pulse has terminated. The absence of strong blast waves also suggests that the ignition mechanism may be different than that for black powder. In addition, the ignition of a triple based M30 propellant could not be achieved under the same experimental conditions which produced self-sustained combustion of both black powder and M26.

Also, the effects of several parameters, such as laser wavelength, ambient pressure, and multiple grain flame propagation have not been investigated. Additional experiments in the future should be concentrated on these questions. The following specific recommendations are made:

1. Continue experiments with black powder to establish when self-sustained combustion actually occurs. The use of high speed cinematography and Schlieren photography can be used to monitor grain consumption and blast wave motion.

2. The same experimental techniques in Item 1 can be used to uncover possible differences in the ignition mechanism of double and triple based propellants.

3. Nitramine based propellants are expected to have increased US Army application in the future. The laser ignition characteristics of this class of propellants should therefore be investigated.

4. Perform high pressure experiments (up to 1000 psi) in a test cell, and compare results to those obtained at atmospheric pressure.

5. Interface laser ignition studies with on-going CARS/RIKES experiments to obtain spectroscopic information during the ignition phase. Supplement these efforts with conventional UV, visible, and IR spectroscopy as required.

5.0 References

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