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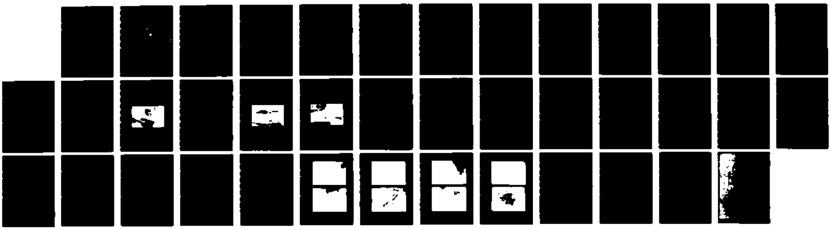

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THESIS

HOLOGRAPHIC INVESTIGATION OF
SOLID PROPELLANT COMBUSTION PARTICULATES

by

Douglas E. Faber

March 1983

Thesis Advisor: D.W. Netzer

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(20. ABSTRACT Continued)

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Holographic Investigation of Solid Propellant Combustion Particulates

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

This investigation refined the technique for obtaining holographic images of solid propellant combustion products in a two-dimensional motor with high pressure and a cross-flow environment. High quality recordings were made of composite propellants with smokeless metal and aluminum additives which had particulate sizes greater than 45 microns and metal mass content of 5 percent or less by weight. The reconstructed holograms provided data on the behavior of aluminum, zirconium carbide and graphite particulates in a steady state combustion environment as a function of the initial additive size cast into the propellant.

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I. INTRODUCTION

The vast majority of tactical guided missiles and most strategic missiles are powered by solid propellant motors. The need is to provide the maximum thrust for a minimum weight while ensuring long shelf life and safety of handling. To increase thrust/specific impulse for a minimum weight penalty, metal additives of varied compositions, sizes and weight percentages have been incorporated into these propellants. Metal additives provide the advantages of high combustion temperatures if they are effectively consumed within the combustion chamber. For a given weight percentage of metal in the propellant, the smaller the particles that are released into the motor port, the greater the exposed surface area and the faster the energy is released. There are other considerations to be examined, however. Pressure oscillations created in the combustion chamber can have catastrophic consequences if left unchecked. The metal agglomerates are capable of dampening these oscillations. The oscillatory frequencies affected are a function of the agglomerate size and mass.

Exhaust smoke (small aluminum oxide particles) is a by-product of aluminum combustion, which is by far the most commonly used metal additive. The material size and mass as well as the other propellant ingredients affect the amount of smoke produced. Smoke is obviously a disadvantage in a tactical missile as it provides a visual warning of its presence and a clear view of the maneuvering missile. Another disadvantage is the two-phase flow losses resulting from the velocity and thermal lags between the gas and particles as they pass through the nozzle. These unburned solid particles slow the exhaust velocity, reducing thrust and specific impulse. Specific impulse is also reduced if the total energy available from the heat of combustion of the aluminum is not released.

It is highly desirable to minimize the losses through complete combustion of the metal additives prior to their exiting the combustion chamber. To do this data are needed on the optimum required size and percentage of metal additives and on the effect of operating conditions on the behavior of particulates in the combustion chamber and the exhaust nozzle. At the present time there are very little data available in this area.

An experimental investigation is being conducted at the Naval Postgraduate School to develop better techniques for obtaining the needed data on particulate behavior. Four experimental techniques are under study:

a. High speed cinematography of burning strands within a combustion bomb and a 2-D slab motor under various operating pressures.

b. Post-fire, burning strand residue collection and examination under a scanning electron microscope (SEM).

c. Scattered laser power spectra measurements to determine the mean particle diameter and concentration of particles throughout the exhaust nozzle.

d. Holographic imaging of propellant combustion in both strand and two-dimensional environments.

Karagounis [Ref. 1] developed a procedure for holographically studying burning strands in a combustion bomb.

Gillespie [Ref. 2] refined the holographic study procedure using a single slab in a cross-flow environment in a 2-D motor at relatively low pressure (400 psi). He was able to obtain only one hologram of reasonable quality despite repeated efforts.

Data from burning propellant strands do not properly simulate an actual combustion chamber operating environment and provide useful data only with respect to observed behavior of metal particulates near the surface of the burning strand. The single slab in a cross-flow environment more closely approximates the actual environment but has limitations. The study of two burning opposed slabs in a cross-flow environment more closely approximates actual motor conditions and can be expected to yield excellent data if the motor is operated at actual operating pressures.

A holographic study is unique for a variety of reasons. It provides both amplitude information, as in conventional photography, and phase information for the exposed scene. This provides the capability for reconstructing the original three-dimensional image. It also results in a significantly improved depth of field over conventional photography. Resolution using diffuse illumination is on the order of 9 to 11 microns. The flame envelopes surrounding the burning particles can be eliminated with narrow pass filters in the beam path. However, two disadvantages to a holographic study are readily apparent. First, it provides only a single instant, or "slice," of the process under study. Second, retrieval of particle size data from the hologram is presently a lengthy process.

This investigation used pulsed holography to further examine solid propellant combustion in the realistic cross-flow environment created by two opposed, end-inhibited propellant slabs in a 2-D motor (using a modified version of the combustion bomb used by Gillespie [Ref. 3]).

II. EXPERIMENTAL APPARATUS AND PROCEDURE

A. BACKGROUND

The pulsed ruby laser used in this investigation made possible the recording of high velocity particles without blurring the image. The depth of field characteristics facilitated the imaging of the entire depth of the 2-D combustion chamber. High resolution was attained on the photographic plate by using a fine grained recording medium, high quality optics, and by maximizing the light incident on the plate.

B. EXPERIMENTAL APPARATUS

The laser system used was a pulsed ruby laser built by TRW, Inc., under contract to the Air Force Rocket Propulsion Laboratory. It is described in detail in Ref. 4. The system consists of a Q-switched oscillator, ruby amplifier, beam expanding telescope, alignment autocollimator, low power helium-neon pointing laser, coolant system and pump, associated power supplies and capacitor bank. The laser operates at a wavelength of 0.6443 microns. A one joule pulse with a pulse length of 50 nanoseconds was used throughout the investigation. The output beam diameter was approximately 1.25 inches in diameter. A photograph of the apparatus is shown in Figure 1.

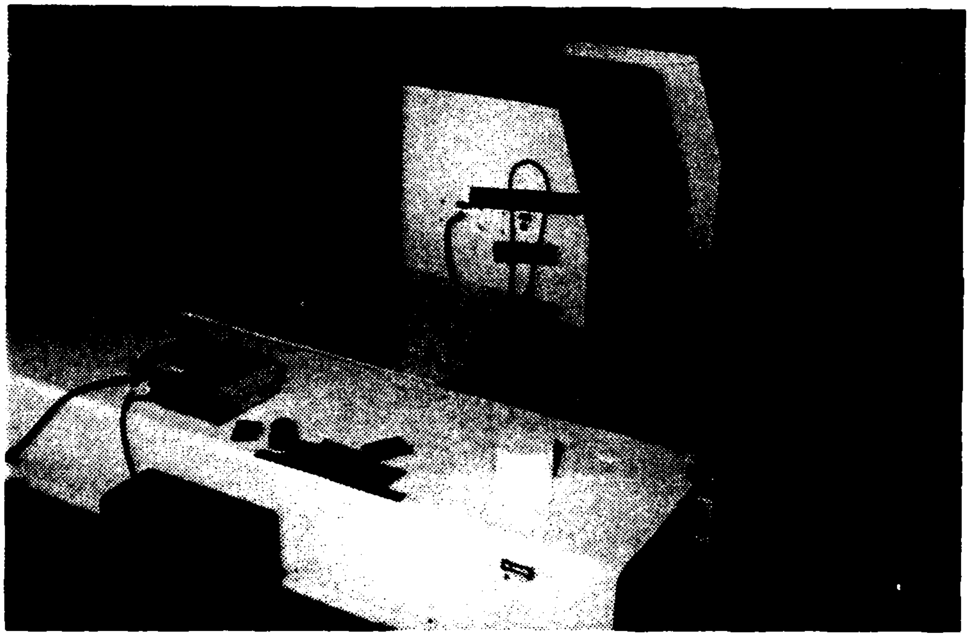


Figure 1. Q-Switched Pulsed Ruby Recording Laser

The holocamera was also originally developed by TRW, Inc. A complete description of the system is contained in Ref. 5. The holocamera was used to expose the photographic plate in the recording process and also for the reconstruction process. The camera box used an AGFA-GEVAERT 8E75 HD photographic plate secured in a kinematic plate holder. The photographic plate was positioned near the focal plane of a pair of plano convex lenses through which passed the image to be recorded. A photograph of the apparatus is shown in Figure 2.

During image reconstruction the developed photographic plate was reattached to the kinematic plate and returned to the holocamera. Rear illumination was provided by a Spectra Physics Model 165-11 krypton ion CW gas laser. This laser has an output of one watt at a wavelength of 0.6471 microns. A variable power microscope was used to view the hologram. The image was photographed using a Canon F-1, 35mm camera mounted on the microscope and using Kodak Plus-X pan film. This apparatus is shown in Figure 3.

The two-dimensional motor was designed for two opposed, end-inhibited propellant slabs. A 0.35 inch diameter high quality glass window port was positioned where the laser beam entered the motor. The glass window port through which the laser beam exited the motor was enlarged to 0.73 inches in diameter. This increased the laser power density incident on the photographic plate, facilitating exposures through a

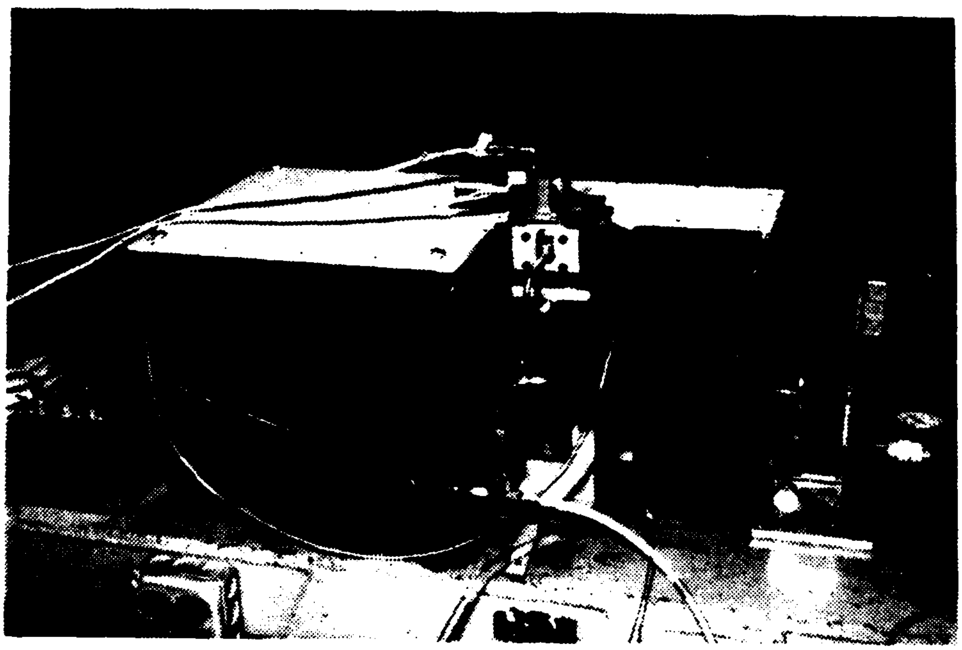


Figure 2. Lens Assisted Holographic System

Figure 3. Holographic Reconstruction Apparatus

more opaque chamber medium. These glass windows were moved as close as possible (given the current motor configuration) to the propellant to minimize the combustion chamber free volume, and to minimize the flow-disturbing effects produced as the shutters (described later) were retracted.

The windows were centered at the lengthwise midpoint and inboard edge of the largest propellant slab. The smallest propellant slab was out of view of the smaller window port to facilitate maximum viewing of the combustion chamber volume and also to create a reasonable cross-flow environment.

The free volume of the combustion chamber was 0.011 cubic inches. However, when including the free volume of the viewing window ports, the chamber free volume increased to 2.32 cubic inches. This was significantly less than that of Gillespie's 2-D motor.

A plexiglas spacer was mounted on each window shutter block as shown in Figure 4. The spacers were shimmed during motor assembly to insure that both sides of the propellant slabs were in physical contact with the plexiglas. This reduced the possibility of uncontrolled side burning, kept chamber free volume to a minimum, and facilitated a cross-flow environment. The shim mounting procedure was improved, which provided closer tolerances between the propellant slab and the plexiglas spacer. As a result, firings were more consistent from run to run.

Retractable shutters protected the glass windows prior to laser activation and were retracted just prior to laser

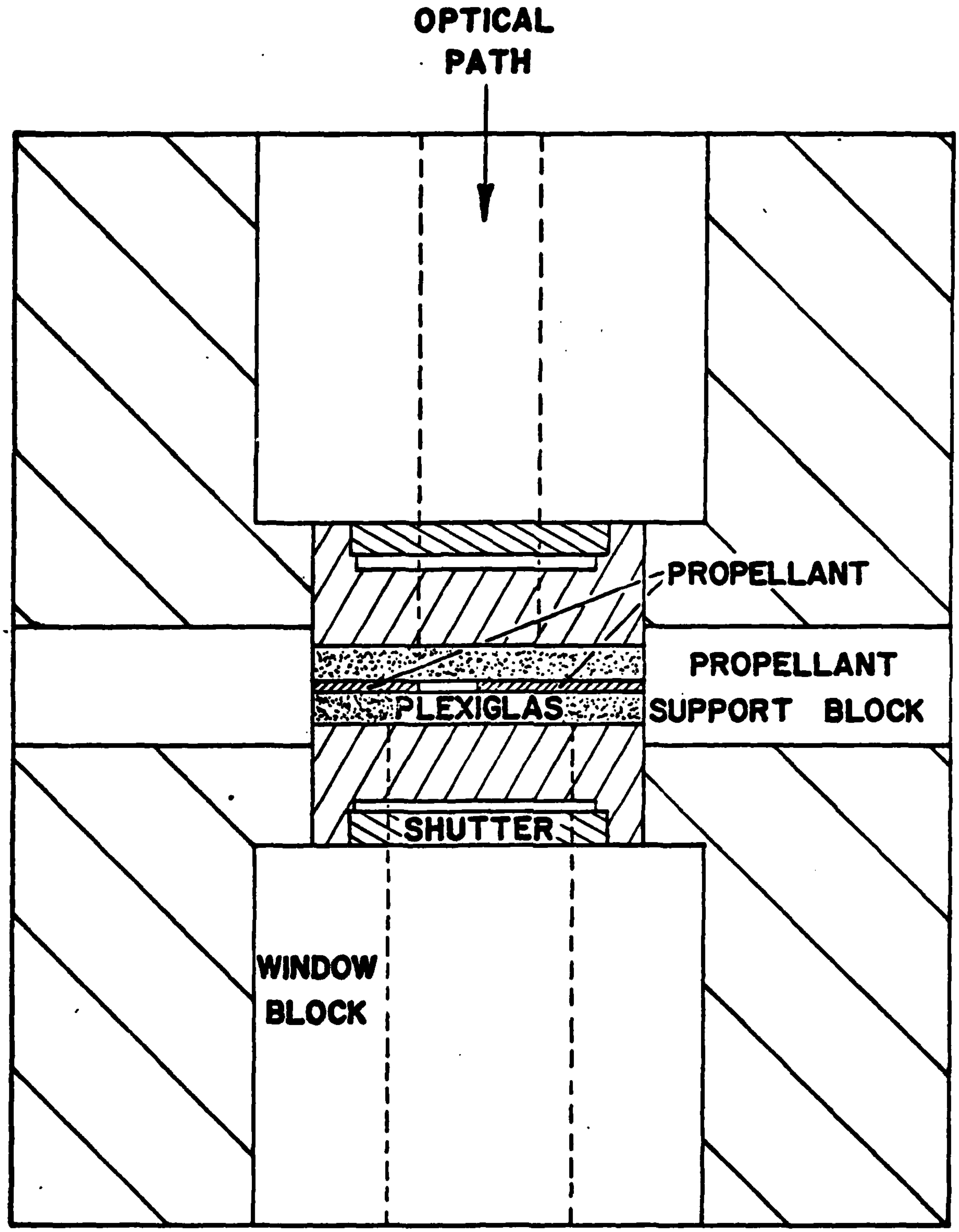


Figure 4. Plexiglas Spacer Arrangement, Top View

firing. The nitrogen purge system was modified as in Figure 5 to direct nitrogen across each window throughout the firing/hologram recording sequence. This kept the optical surfaces cleaner and disturbed the flow less during the combustion sequence.

The ignition and ignition assembly procedures were also modified to eliminate the need for black powder as an igniter. This reduced the amount of contaminating particulates. Stainless steel spacers (1 mm thick) were epoxy bonded to the plexiglas spacers at the base of each propellant slab. This reduced the possibility of uncontrolled end burning as they were also epoxy bonded to the propellant end. The steel spacers also restricted the flow of hot gases and kept them directed toward the exit nozzle. Between the stainless steel spacers, a 0.125 inch square of igniter propellant (1 mm thick) was epoxy bonded to the plexiglas. The igniter propellant was of the same composition as the propellant slabs. A nichrome wire was looped across the igniter propellant to provide ignition. This is shown in Figure 6. These ignition improvements further enhanced the run-to-run consistency. The need for a combustion chamber pressure sensor-triggered solenoid was eliminated, resulting in improved time delay sequencing in firing the laser. The time delay was activated at ignition initiation. At the expiration of the time delay the spring-loaded shutters were released. The rising shutters in turn tripped a microswitch, which triggered the holocamera

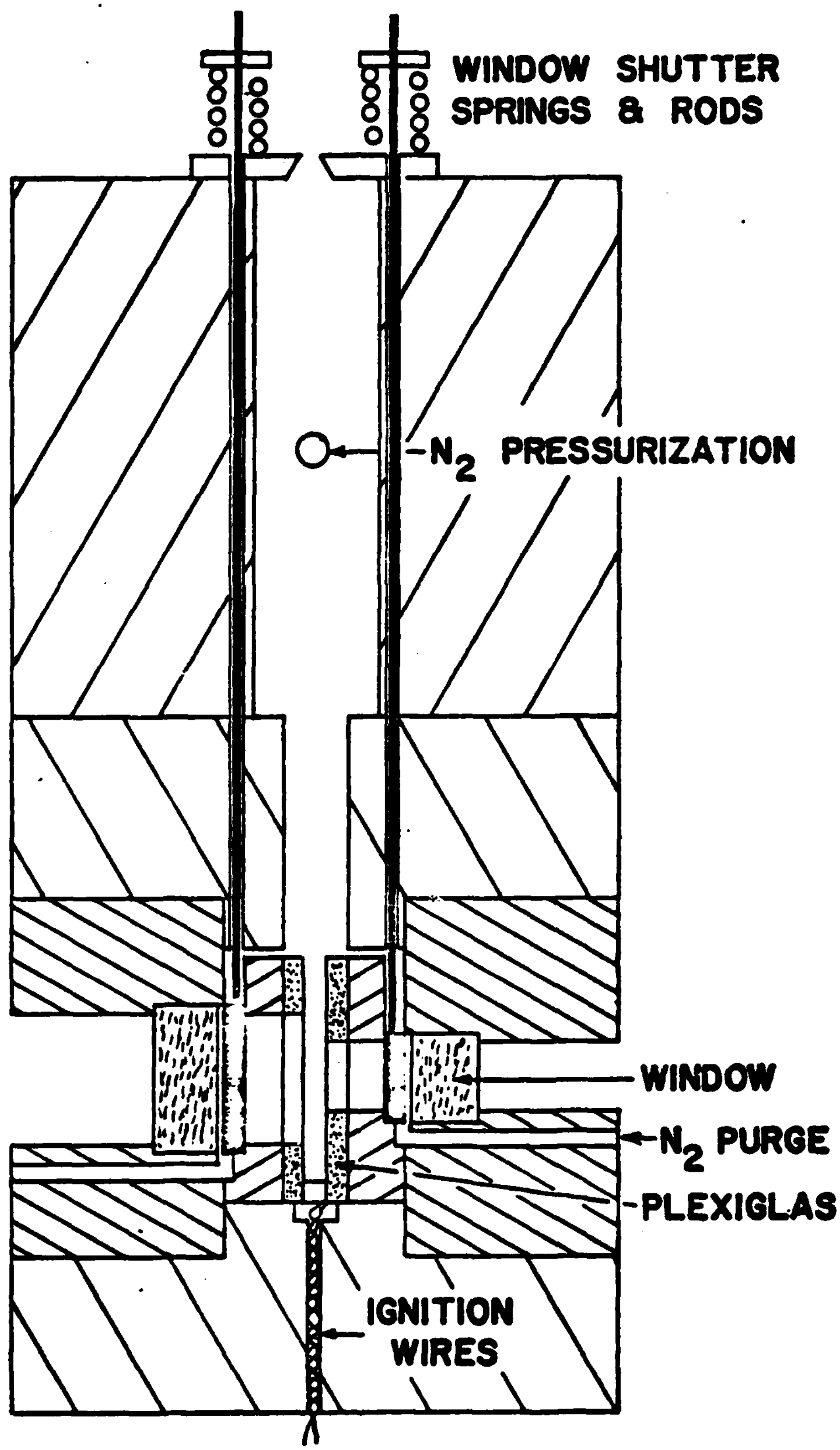


Figure 5. Motor Line Drawing, Side View

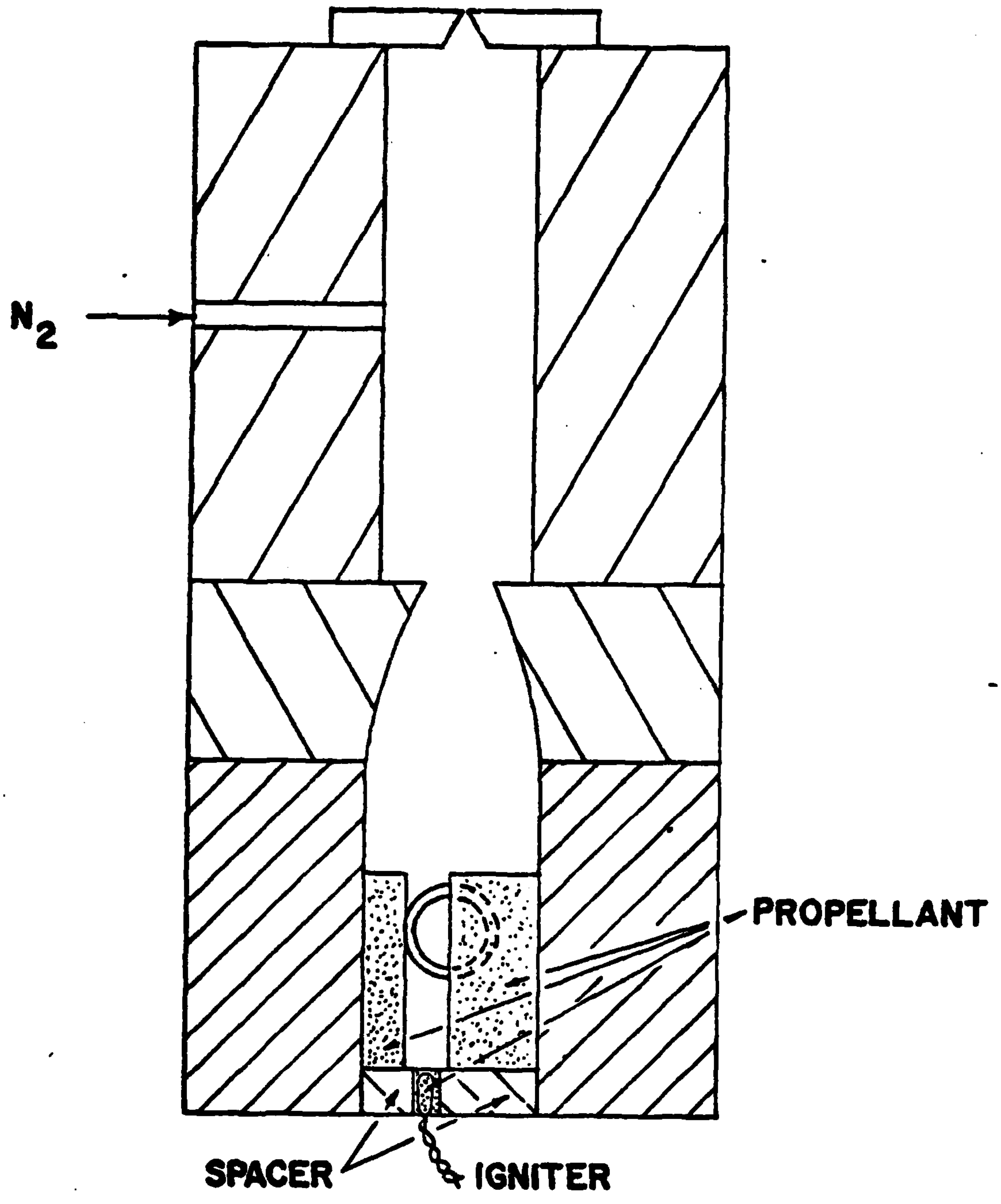


Figure 6. Motor Line Drawing, Window Side View

shutter and fired the laser simultaneously. Pressure-time plots were provided by a Honeywell Visicorder which also marked the various events as they occurred. A photodiode sensor was added to the laser system to mark the precise time of laser activation on the pressure-time plot.

The propellant slabs produced insufficient pressure to pressurize the combustion chamber to the desired 500 psig. The chamber mounted above the combustion chamber (Figure 6) was pressurized with nitrogen and the burning propellant slabs provided the remaining pressure. In the opposed slab configuration, the propellant provided approximately fourteen percent of the desired steady state pressure. The majority of the chamber pressurization was provided by the nitrogen introduced downstream of the propellant. Use of the upper chamber reduced the tendency of the pressurizing nitrogen to recirculate into the combustion region.

A combustion chamber pressure sensing port at the base of the motor was used to provide real-time pressure data for the Visicorder and was also connected to a pressure gauge used to initially set chamber pressure.

A 0-80 screw (80 threads per inch/317.5 microns peak-to-peak) was mounted outside the large exit window in the scene beam path and used to provide a scale for particulate sizing in the reconstructed hologram.

C. EXPERIMENTAL PROCEDURE

The propellant slabs were rough-cut, then hand rubbed to the final dimensions indicated in Figure 7 to remove loose

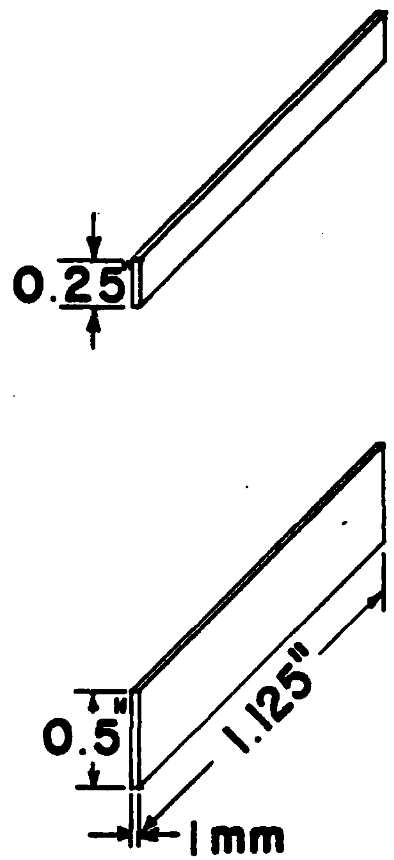


Figure 7. Propellant Slabs

material which could cause the inhibitor to debond during firing, resulting in uncontrolled side burning. The slab was epoxy bonded to the propellant support base and inhibited with a thin coating of General Electric Hi-Temp Gasket (Red RTV), then allowed to cure for twenty-four hours. The RTV was carefully finger-rubbed into the surface of the propellant to reduce the possibility of debonding. One 0.5 inch and one 0.25 inch web slab were used in each run. The propellants used are as described in Table I.

TABLE I

Propellant Composition and Metal Additive Particle Size

Propellant Designation	Binder % Weight	Oxidizer % Weight	Metal % Weight	Mean Metal Diameter, microns
WGS-5A	HTPB 12	AP 83	AL 05	75-88
WGS-6A	HTPB 12	AP 83	AL 05	45-62
WGS-7A	HTPB 12	AP 83	AL 05	23-27
WGS-7	HTPB 12	AP 83	AL 05	6-7
WGS-9	HTPB 12	AP 78	AL 10	23-27
WGS-10	HTPB 12	AP 73	AL 15	23-27
WGS-ZrC	HTPB 14	AP 84	ZrC 02	23
WGS-G	HTPB 14	AP 84	G 02	23

The assembly sequence began with the soldering of a 0.625 inch long nichrome ignition wire to the ends of the ignition leads. Next, the propellant slabs were installed in the motor. The window blocks were inserted and the propellant/plexiglas slab clearance was checked. Each plexiglas slab was shimmed until the plexiglas fit snugly against the propellant. The stainless steel spacers and igniter propellant were epoxy bonded to the small window plexiglas slab, the igniter wire was looped across the igniter propellant and the large window block was installed in the motor. After completing motor assembly, the shutter rods were cocked, electrical and pressure connections were made, chamber pressure was checked, the holocamera was set in place and the laser was prepared for firing.

A typical firing sequence follows:

1. Check electrical connections.
2. Open reference beam shutter.
3. Charge the laser capacitor bank to its firing voltage.
4. Start the Visicorder.
5. Pressurize the motor with nitrogen to 450 psig for a desired test pressure of 500 to 550 psig.
6. Initiate the fire switch.
7. Propellant ignites and time delay is initiated.
8. Time delay expires, energizing window shutter solenoid.
9. Shutter solenoid retracts, releasing window shutters.
10. Window shutters open, tripping laser fire microswitch which opens holocamera shutter and fires laser simultaneously.

The exposed photographic plate was removed from the holocamera in a dark room and processed as follows:

1. The plate was immersed in Kodak D-19 Developer for four to five minutes and inspected periodically under a Kodak safelight.

2. When a satisfactory image was apparent, the plate was immersed in Kodak "Stop Bath" for thirty seconds, then rinsed in fresh water.

3. Kodak "Hypo-Fix" was used to set the image. Processing time was 5 to 7 minutes.

4. After fixing the image, the plate was washed in fresh water for 15 minutes.

5. A one minute bath in Kodak "Photo-Flo" was followed by a 2 to 3 hour drying period.

D. DISCUSSION

To most closely simulate realistic steady-state combustion conditions it was essential that the hologram be taken while the propellant was burning in a steady state environment. However, to minimize the combustion smoke in the beam path it was essential that the hologram be taken early in the run. The accomplishment of both of these criteria using Gillespie's pressure sensing solenoid was beyond system capabilities. However, bomb/procedural improvements which resulted in consistent and predictable runs made the fulfillment of both criteria a reality. The time delay switch was used exclusively and was activated at initiation of the fire sequence.

The use of an optical diffuser in the scene beam prior to its passing through the motor to reduce "thermal cells" around each particle of combustion products was discussed by Gillespie [Ref. 6]. The reduction of the resulting speckle during image reconstruction using a spinning mylar disk was also discussed by Gillespie [Ref. 7].

As a result of the small power density of the laser scene beam that exits the motor, the reference beam intensity must be reduced. A neutral density filter of 10 percent transmittance was determined to be ideal for a high resolution hologram in the current motor configuration. This neutral density filter was inserted into the holocamera in the reference beam path.

The presence of large quantities of smoke in the combustion chamber precluded the recording of holograms for four of the eight propellants studied in the opposed slab geometry. The smoke from black powder used as the igniter by Gillespie was eliminated. However, the burning propellant and burning RTV inhibitor produced sufficient quantities of smoke to prevent laser scene beam penetration of the combustion environment when the particulate size was small (less than 45 microns) or when the aluminum loading was high (greater than 5 percent).

The pressure-time traces of all propellant runs exhibited a sharp pressure rise each time the shutters were retracted. This was most probably due to disruption of the cross-flow environment caused by suddenly increasing the chamber free volume and increasing it unevenly as the shutters were of different sizes.

III. RESULTS AND RECOMMENDATIONS

This investigation resulted in the development of a technique for obtaining high quality holograms of burning solid propellant in a two-dimensional motor with smokeless metal additives and with aluminum additives with particulate size greater than 45 microns and metal mass content of 5 percent or less by weight. However, the improvements to the motor and procedures were insufficient to provide holograms of all samples propellants. Table II lists the propellants and the maximum pressures at which holograms were obtained.

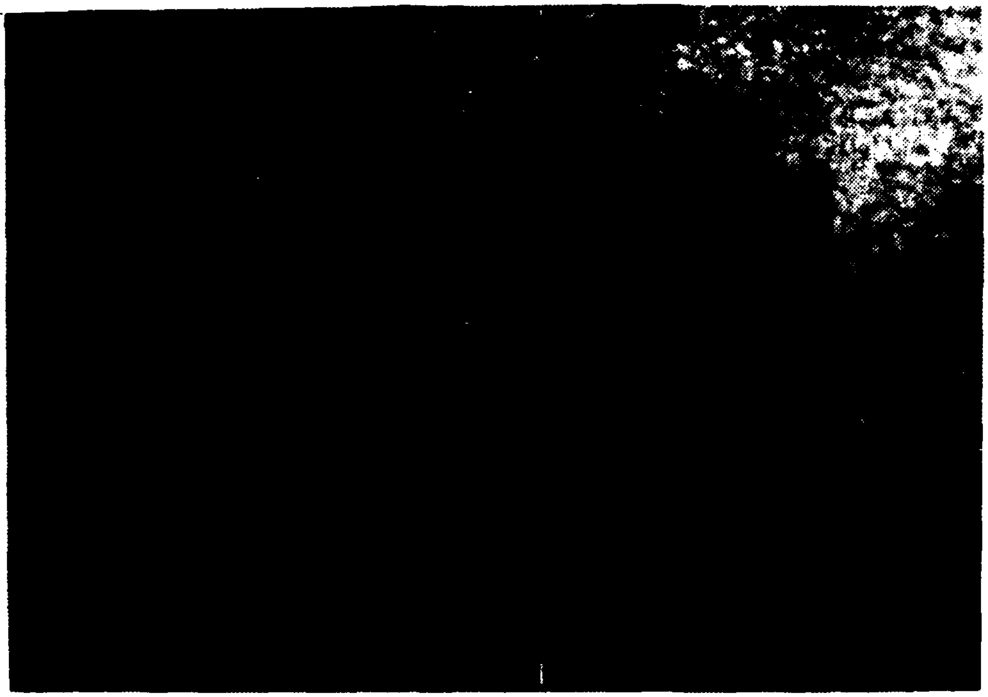
TABLE II

Combustion Particulate Data

Propellant	Pressure (psi)	Remarks
WGS-5A	470	Hologram
WGS-6A	500	Hologram
WGS-7	NA	Dense smoke precluded hologram
WGS-7A	NA	Dense smoke precluded hologram
WGS-9	NA	Dense smoke precluded hologram
WGS-10	220	Premature hologram, taken during ignition phase
WGS-ZrC	535	Hologram
WGS-G	530	Hologram

Figures 8(a), 9(a), 10(a), and 11(a) are reconstructed holograms of the 0-80 screw from four different propellant runs as noted. Figures 8(b), 9(b), 10(b), and 11(b) are reconstructed holograms of the burning propellant. The vertical propellant surface is on the right side and the flow direction is from bottom to top. Higher pressures were not attempted, but should be attempted in further studies.

The technique developed herein provided a greater range of data and more consistent runs than was possible with the original apparatus. However, shutter retraction noticeably disturbed the flow as evidenced by (1) the location of many of the particulates in the reconstructed image nearer the large exit window and not abeam the burning propellant slabs as would be expected under steady state, cross-flow conditions, and (2) the sharp pressure rise following shutter retraction. It is recommended that to reduce combustion chamber free volume, both windows be moved closer to the burning propellant slabs and that the shutters be reduced in thickness to reduce disturbances in the flow during shutter retraction. A less effective alternative approach is to increase the dimensions of the inlet window to those of the exit window to better balance the conditions during shutter retraction and reduce circulation irregularities. A third possible method involves the elimination of the hole in the plexiglas spacers. This would serve two purposes: 1) restrict the chamber free volume to .011 inches, and 2) create a true cross-flow environment.



(a) 0-80 Screw

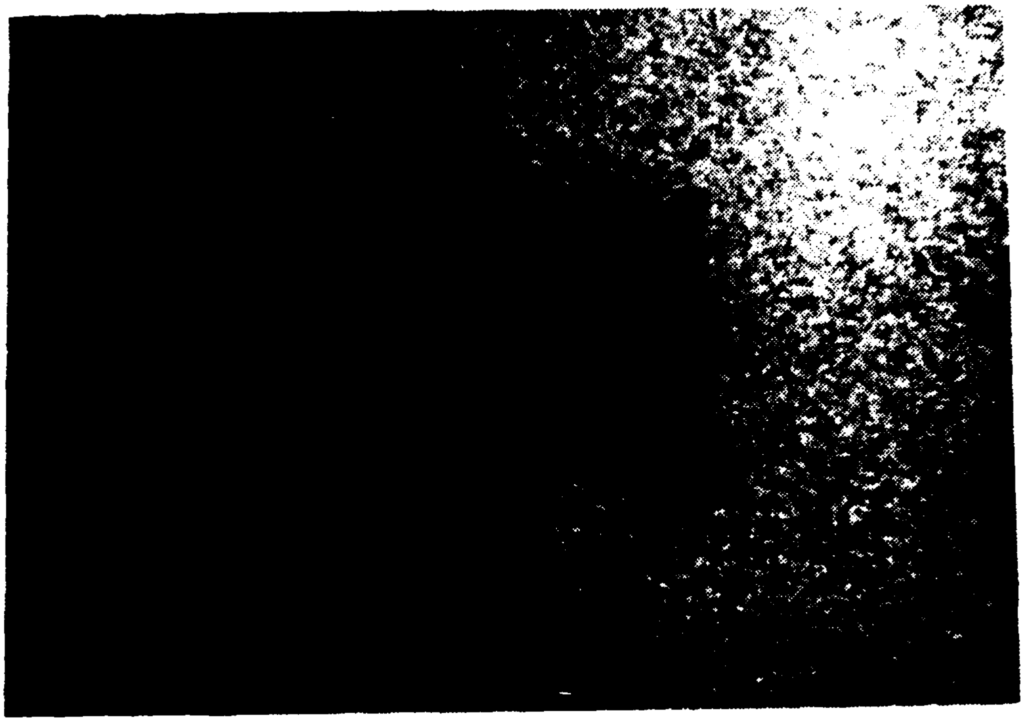
(b) WGS-5A Propellant

Figure 8. Photographs of Reconstructed Hologram of WGS-5A

(a) 0-80 Screw

(b) WGS-6A Propellant

Figure 9. Photographs of Reconstructed Hologram of WGS-6A



(a) 0-80 Screw

(b) WGS-ZrC

Figure 10. Photographs of Reconstructed Hologram of WGS-ZrC

(a) 0-80 Screw

(b) WGS-G

Figure 11. Photographs of Reconstructed Hologram of WGS-G

Two possible problems with this procedure are foreseen, however. First, the high chamber temperature might distort the plexiglas causing a problem with the scene beam (in both the recording and the reconstruction processes), and second, the smoke might be more intense in the smaller volume.

Greater laser power to penetrate the combustion smoke might be directed to the scene beam by changing the beam splitter ratio in the holocamera.

The reduction of smoke generation during the ignition phase is also of primary importance. The use of smokeless propellant as the igniter would perhaps accomplish this and should be tested. Contamination of the resulting hologram with igniter particulates is a resultant risk. The current ignition cycle time sequence puts the time delay switch at its minimum limit. Any further shortening of this sequence would result in earlier steady state conditions and in the need for a time delay shorter than present system limits.

Motor preparation and assembly, and firing preparations have been significantly shortened to 4 to 5 hours. However, the problems addressed herein require solution if timely data are to be obtained.

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