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THESIS

HOLOGRAPHIC INVESTIGATION OF SOLID PROPELLANT COMBUSTION IN A TWO-DIMENSIONAL MOTOR

by

Yoonsang, Lee

September 1984

Thesis Advisor: D.W. Netzer

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This investigation continued the development of a method for obtaining high quality holograms of the combustion products from metallized solid rocket motor propellants burned in a two-dimensional motor to provide a cross-flow environment. The use of borosilicate side plates as a motor casing allowed good quality holograms to be obtained. With the present two-dimensional motor method there were upper limits of combustion pressure and weight percentage of aluminum where holograms could not be obtained because of excessive smoke opacity.

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Holographic Investigation of Solid Propellant Combustion in a Two-Dimensional Motor

by

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B.S., Republic of Korea Air Force Academy, Seoul, 1976

Submitted in partial fulfillment of the
requirements for the degree of

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from the

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September 1984

ABSTRACT

This investigation continued the development of a method for obtaining high quality holograms of the combustion products from metallized solid rocket motor propellants burned in a two-dimensional motor to provide a cross-flow environment. The use of borosilicate side plates as a motor casing allowed good quality holograms to be obtained. With the present two-dimensional motor method there were upper limits of combustion pressure and weight percentage of aluminum where holograms could not be obtained because of excessive smoke opacity.

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I wish to dedicate this thesis to my wife, Kyung Sook. Without her constant love, support, and understanding this work would not have been possible.

I. INTRODUCTION

For many years solid propellants have been used for missile propulsion. Practically all tactical and many strategic missiles use solid propellants. In recent years composite-modified double-base (CMDB) propellants have been developed also.

Many solid propellants also contain metal additives in quantities up to 25% by weight. These metal fuels increase the energy content and also provide an acoustic damping mechanism for combustion pressure oscillations within the propellant port. The most common metal fuel in solid rocket applications to date has been aluminum, which has been used with propellants based on ingredients containing primarily H, O, C, N, and Cl.

Use of powdered aluminum has a number of advantages that enter into its choice as a propellant ingredient [Ref. 6]: 1) aluminum is relatively inexpensive and available, 2) its density increases the propellant density and hence the motor propellant loading, 3) it is generally nonreactive during propellant processing and storage, 4) its reaction products are non-toxic, 5) and it tends to suppress certain classes of unstable combustion. An optimum combination of metallic powder particle size, propellant composition and motor geometry must be chosen such that the metallic particles are completely burned to aluminum oxide prior to exiting the combustion chamber. Large particles may still be burning after exiting the combustion chamber, if residence times are less than approximately 10-15 msec, resulting in lost energy.

The two-phase flow effects within the exhaust nozzle, which result from the thermal and velocity lag of the particles, also cause performance losses. Minimization of these two-phase flow losses is required if theoretically high performing solid propellants are to produce high delivered performance. This minimization of losses must be achieved while meeting the requirements for particle damping. The frequencies dampened are a function of both the particle size and density.

One of the diagnostic techniques available for studying particulate behavior in solid propellant rocket motors is holography. For the exposed scene (the chamber volume illuminated by the laser beam), a hologram provides both amplitude (as in conventional photography) and phase information. The latter characteristics enables a 3-D image to be reconstructed so that particle behavior in the entire depth of field of the combustion chamber may be recorded. The flame envelopes surrounding the burning particles can be eliminated with a narrow pass filter located between the scene and the holographic plate. Single pulsed holography provides a means for effectively stopping the motion. However, it only provides information during a single instant of time.

The objective of this thesis was to continue the development of a simple, reliable method for holographic observation of particle behavior in an environment similar to that found in the port of an actual solid rocket motor. To duplicate motor cross-flow conditions, a 2-D motor which used horizontally opposed slabs was selected. Smoke generation (i.e., small Al_2O_3 and binder products, etc.) during the combustion process is a major obstacle, and consists of two distinct but related problems.

The first is that a laser can only penetrate a finite amount of smoke, and the second involves the required reference beam to scene beam illumination ratio. To obtain a high-quality hologram, the illumination ratio reaching the holographic plate should be between 5-10 : 1. Test-to-test variation of the amount of smoke in the beam path can significantly affect this ratio. To achieve an optimum combination of low levels of combustion chamber smoke and well-developed burning of the propellant slabs (versus the igniter) requires experimental determination of the most suitable slab dimensions and the optimum time for taking the hologram during the burn.

In an earlier investigation, Faber [Ref. 1] was partially successful in meeting these goals. He used free-standing, side inhibited slabs pressed between supporting blocks. Window ports in the support blocks provided the viewing area. Although some holograms were successfully obtained, the window ports and associated window-protection shutters significantly altered the combustion environment during the holographic recording. In addition, side burning of the slabs often occurred when the inhibitor thickness was kept thin to minimize smoke/char production. Mellin [Ref. 5] recently was more successful in obtaining holograms in the 2-D environment. He developed the glass-sided motors used in this investigation. However, pressures were limited to 600 psia and many tests were required to obtain each good hologram.

II. EXPERIMENTAL EQUIPMENT AND PROCEDURES

A. EQUIPMENT

1. Laser

The laser system used was a pulsed ruby laser [Ref. 2]. A one joule pulse with a pulse length of 50 nanoseconds was used throughout this investigation. The laser system is shown in Figures 1 and 2.

2. Holocamera

A holocamera [Ref. 3] was used to expose the AGFA-GEVAERT 8E75 HD holographic plate during the recording process and to support the plate during the reconstruction process. The apparatus is shown in Figure 3.

In order to eliminate the severe "schlieren" effects caused by the burning particles, diffuse scene beam illumination was employed. The required intensity ratio between the scene and reference beams could be met only through experimental evaluation. Essentially, if more smoke was produced for a particular propellant, either a more intense scene beam or a less intense reference beam was required. This required the use of a less opaque diffuser glass and/or a neutral density filter placed in the reference beam.

3. Hologram Reconstruction Apparatus

During image reconstruction, the developed holographic plate was reattached to the plate holder and

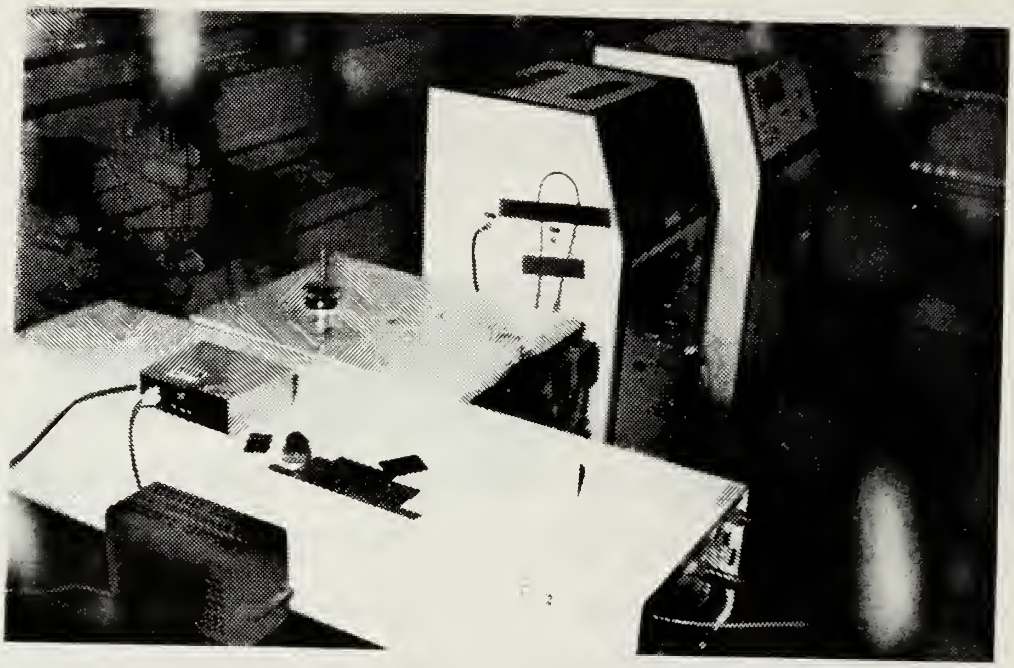


Figure 1. Photograph of RPL Ruby Laser Components

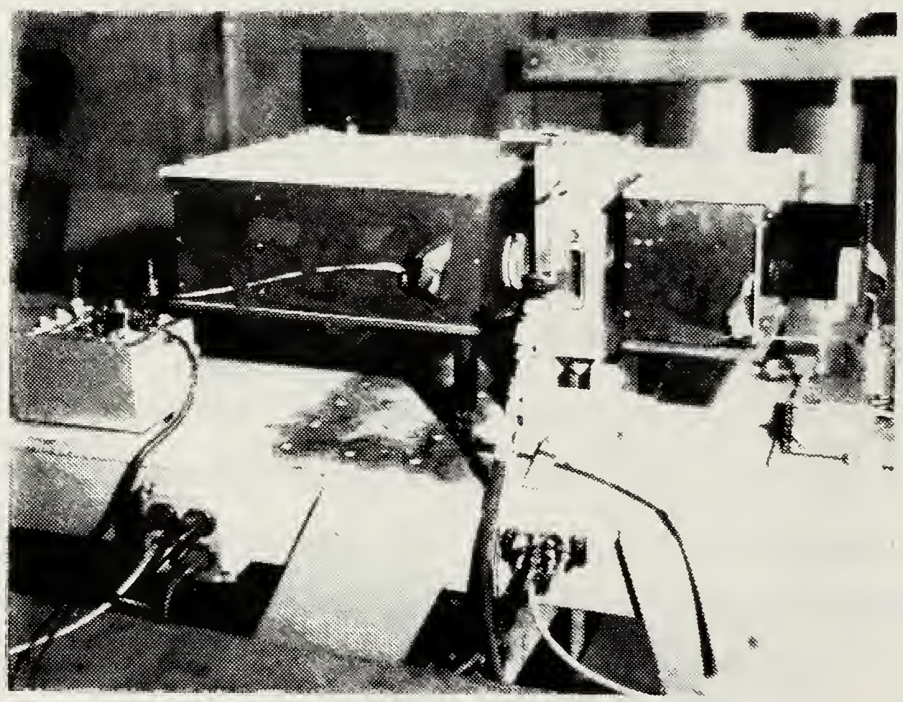


Figure 2. Lens Assisted Holographic System

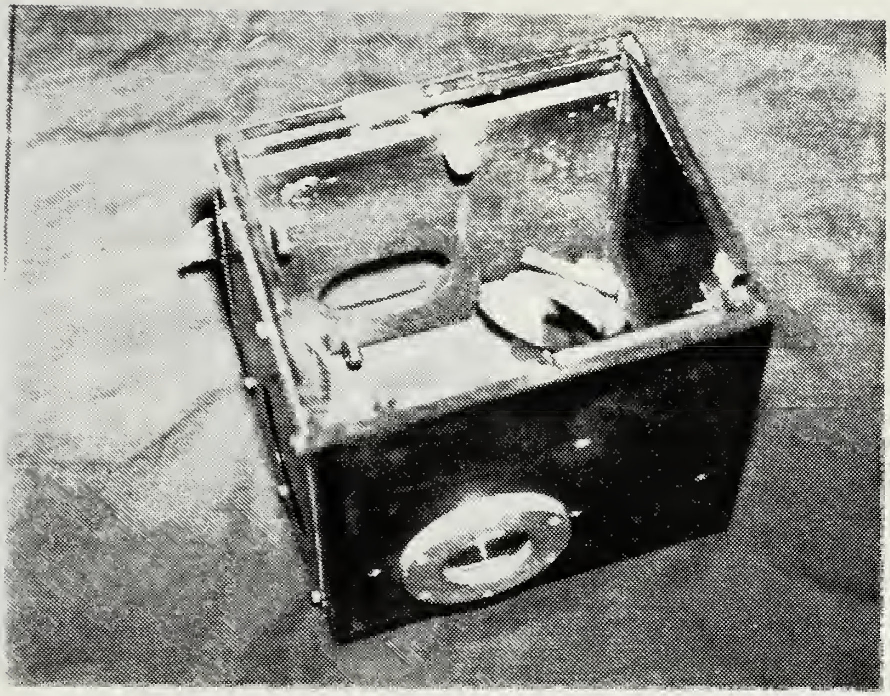


Figure 3. Holocamera Plate Holder

attached to the removable holocamera box. Rear illumination was provided by a Spectra Physics model 165-11 krypton-ion CW gas laser, at an angle of approximately 60° with the plate normal (Figure 4). Output was one watt at a wavelength of 0.6471 microns. A variable power microscope was used to directly view the hologram. In order to minimize speckle, the reconstructed image was positioned on a rotating mylar disc [Ref. 4]. The latter was located at the focal point of the observation microscope. Photographs of the reconstructed scene were made using a 35 mm camera mounted to the microscope eyepiece.

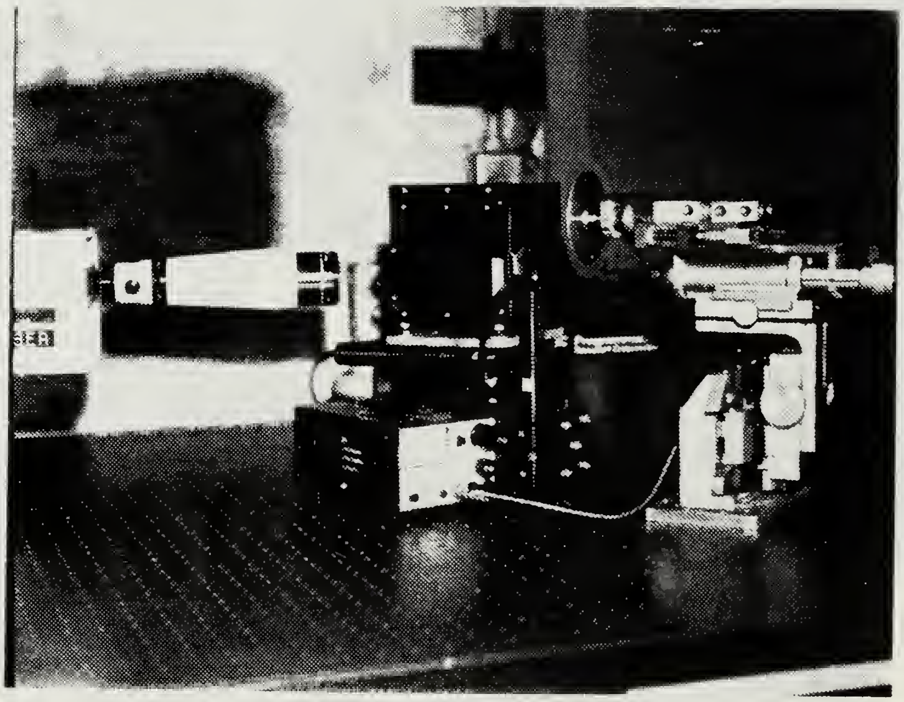
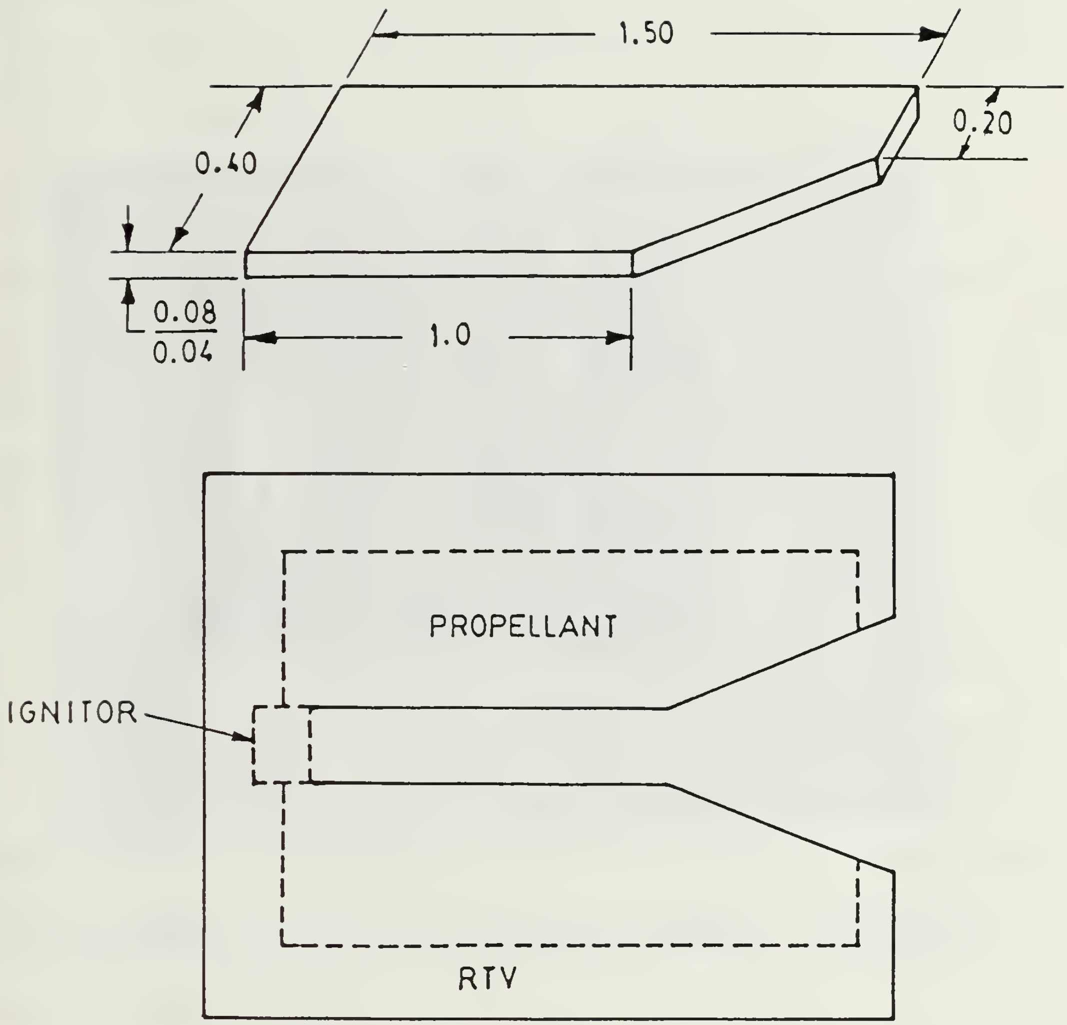


Figure 4. Holographic Reconstruction Apparatus

4. 2-D Motor

The 2-D motors employed two opposed slabs with ends and sides inhibited with a thin coating of General Electric Hi-temp gasket (red RTV). The slabs were placed between two borosilicate glass slides and the inhibitor was then allowed to cure. Propellant slab dimensions are shown in Figure 5 and an assembled motor is shown in Figure 6. Propellant thickness was varied from 0.040 inches (1 mm) to 0.120 inches (3 mm).

The 2-D motor was placed within a 2-D, nitrogen pressurized combustion bomb and was fired vertically



(All Dimensions in Inches.)

Figure 5. Propellant Slab Dimensions

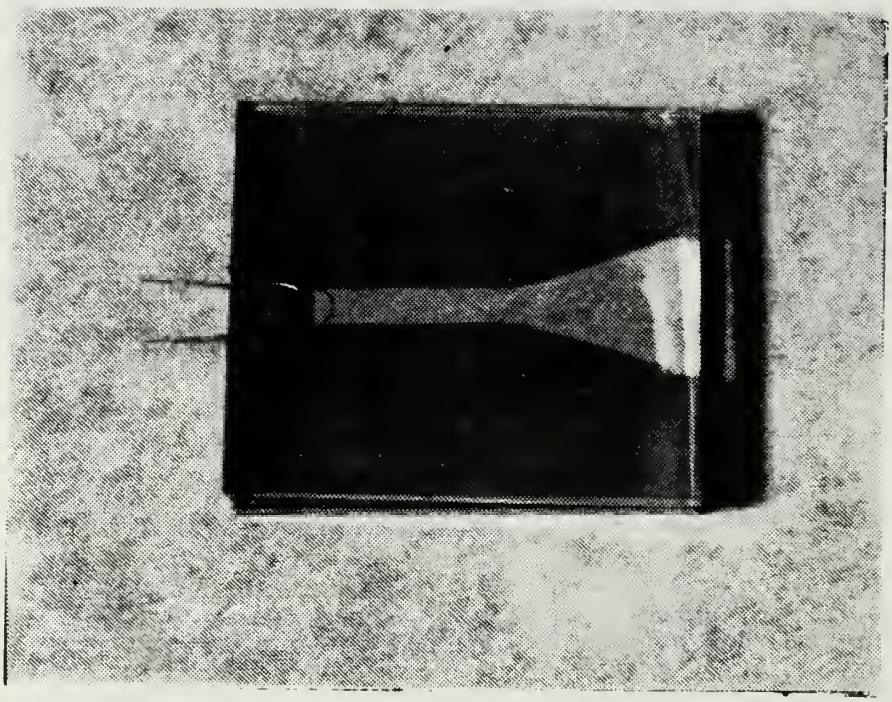


Figure 6. Propellant Mounted Between Glass Plates

(exhaust up) in the test cell (Figure 7). The laser, the holocamera, and all other components were unchanged from those used by Mellin [Ref. 5].

B. PROPELLANTS

Eight propellants were selected for testing. The propellant formulations are listed in Table I.

C. SYSTEM CALIBRATION

The resolution limits of the holographic system were determined by placing a 1951 USAF resolution target in the 2-D motor at the propellant location. A photograph of the reconstructed resolution target is shown in Figure 8. 5/2 (13.9 μm) was readily observed through the microscope. With very careful construction/operation of the rotating mylar disc 5/6 (8.77 μm) has been obtained. Currently, speckle limits the obtainable resolution. Holograms of calibration glass beads were also taken to determine resolution limits. Photographs of reconstructed holograms of 1-37 μm beads and 55-63 μm beads are shown in Figures 9 and 10 respectively.

D. MOTOR CONSTRUCTION

The propellant was rough cut to slightly oversized dimensions, then hand rubbed to the desired size. For WGS-9 (10% AL) and WGS-10 (15% AL) propellants, WGS-7 (5% AL) was used for the igniter to decrease the smoke opacity. All other motors used the same propellant for both slabs and the

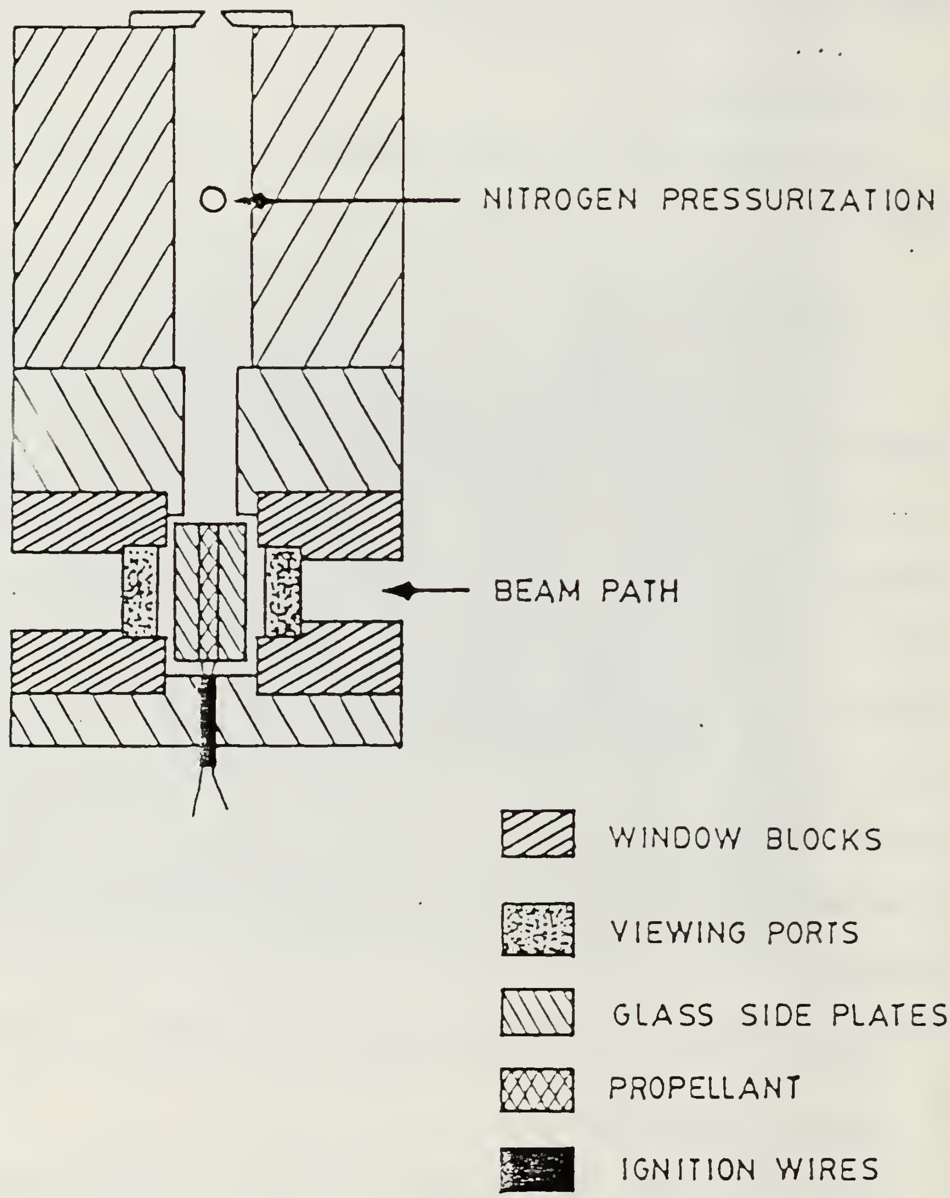


Figure 7. Schematic of Combustion Bomb

TABLE I

Propellant Compositions

Propellant Designation	Binder % Weight	Oxidizer % Weight	Metal % Weight	Mean Metal Diameter, μm
WGS-5A*	HTPB 12	AP 83	AL 5	75-88
WGS-6A*	HTPB 12	AP 83	AL 5	45-62
WGS-7A*	HTPB 12	AP 83	AL 5	23-37
WGS-7*	HTPB 12	AP 83	AL 5	6-7
WGS-9*	HTPB 12	AP 78	AL 10	23-27
WGS-10*	HTPB 12	AP 73	AL 15	23-27
RPL-GAP	GAP/TEGTN 14.7/8.5	AP 70.3	AL 4.7	20
WGS-G	HTPB 14	AP 84	G 2	50x20x7, flakes
WGS-ZrC	HTPB 14	AP 84	ZrC 2	23, irregularly shaped

* 65% 180 μm / 35% 26 μm

All propellants except RPL-GAP were provided by the Aeroject Solid Propulsion Company.

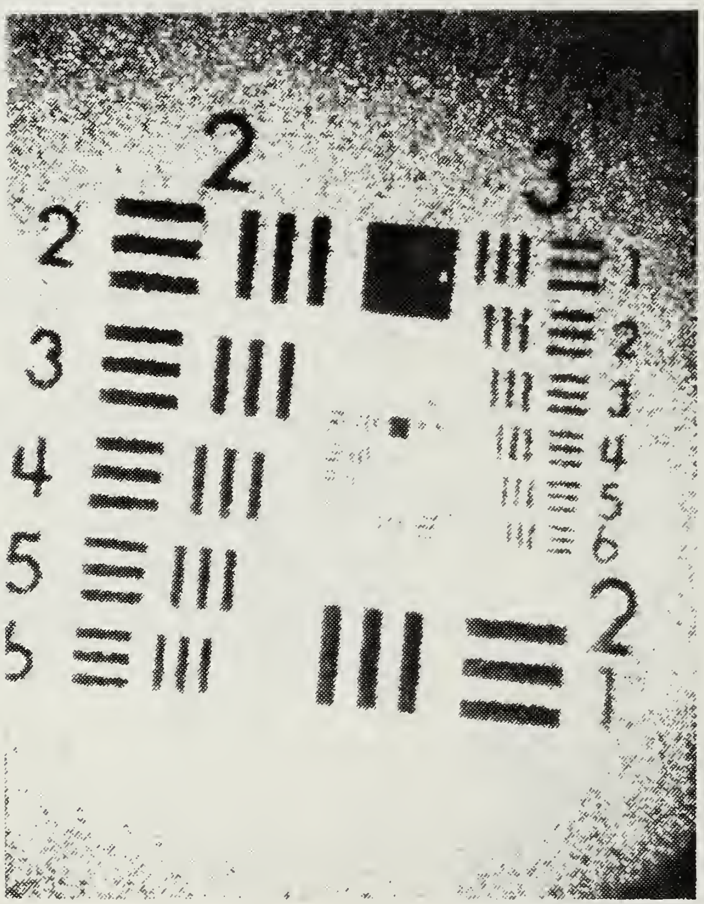


Figure 8. Photograph of Reconstructed Hologram of Resolution Target

Figure 9. Photograph of Reconstructed Hologram of 1-37 μm Glass Beads

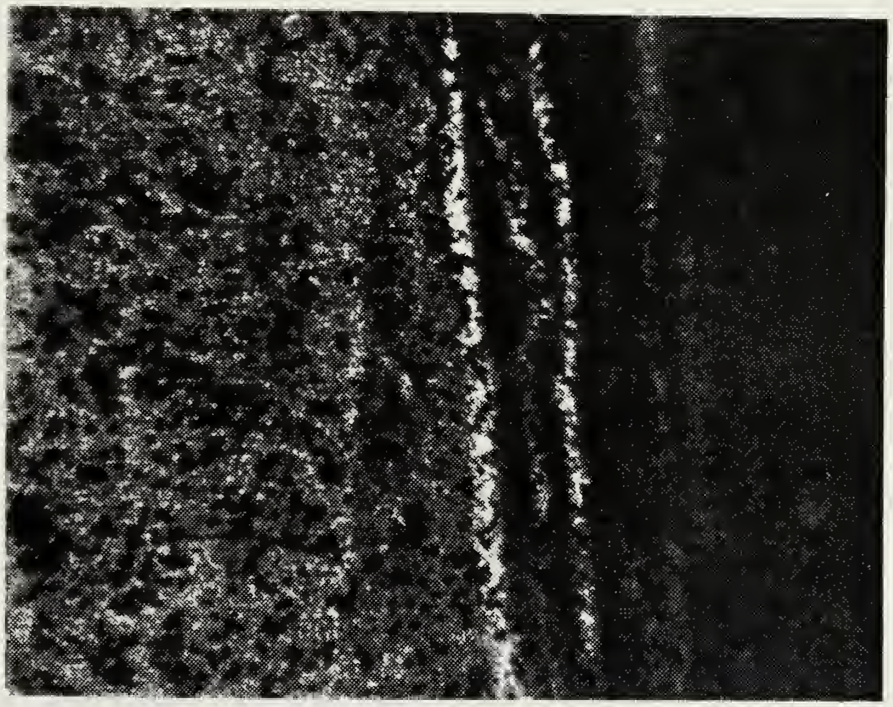


Figure 10. Photograph of Reconstructed Hologram of 55-63 μm Glass Beads

igniter. An assembled motor is shown in Figure 6. RTV was applied to the sides of the slabs to act as an inhibitor and to bond the motor to the side plates.

The glass motors were bonded with quick-drying epoxy to one of the support blocks. After attachment to the support blocks, the motor was inserted into the combustion bomb and a nichrome wire was soldered to the ignition wire which exited the bottom of the combustion bomb.

Since the burning propellant only provided about 10-30% of the desired combustion chamber pressure, a nitrogen pressurization system was used.

Holocamera preparation required ensuring that the box and mirrors were clean. The proper reference beam neutral density filter had to be selected to provide the correct scene/reference beam intensity ratio during combustion. A 0.10 transmittance filter was found suitable for most experiments. Laser and mirror alignment were checked prior to each run to ensure that the scene and reference beams were exactly overlaid on the holographic plate and that the scene beam passed through the correct position in the motor.

E. MOTOR FIRING SEQUENCE

The control room contained a Honeywell Visicorder which provided a time record of the entire sequence of events, including a pulse output which marked the position of the laser firing on the pressure-time trace. The motor firing sequence was the same as used by Mellin [Ref. 5].

F. HOLOGRAM PROCESSING

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

1. Immersed in Kodak D-19 developer for 20 to 40 seconds and inspected periodically under a Kodak safe-light.
2. When a satisfactory opacity was obtained, the plate was immersed in Kodak "Stop Bath" for 30 seconds, then rinsed in fresh water.
3. Kodak "Rapid Fix" was used to set the image. Processing time was 5-7 minutes.
4. Fresh water rinse for 10-15 minutes.
5. Immerse in Kodak "Photo flo" for one minute.
6. Air dry for 2-3 hours.

III. RESULTS AND DISCUSSION

A. COMBUSTION EFFECTS ON OPACITY

The problem which Mellin [Ref. 5] had when using the 2-D slab motors was that many holograms were required to get one good hologram. Even when a minimum amount of inhibitor is used, the slab burners have a high ratio of inhibitor mass to propellant mass. This can result in excessive amounts of inhibitor char in the gases during propellant burning. Too little inhibitor can result in the glass cracking too early during the burn. These effects result in rapid changes in the opacity of the combustion products during the burn. This effect, in turn, causes rapid changes in the scene beam light intensity which reaches the holographic plate. In order to obtain a higher success rate in obtaining good holograms a series of tests were conducted to determine the effects of binder thickness, propellant thickness, binder composition and aluminum content on transmittance versus burn time.

These parameters were systematically varied in a test series while measuring transmittance using a He-Ne laser and a photodiode. Data are presented in Figures 11 and 12. The figures show the effects of the four parameters as a function of burn time (t_b) after steady state burning was

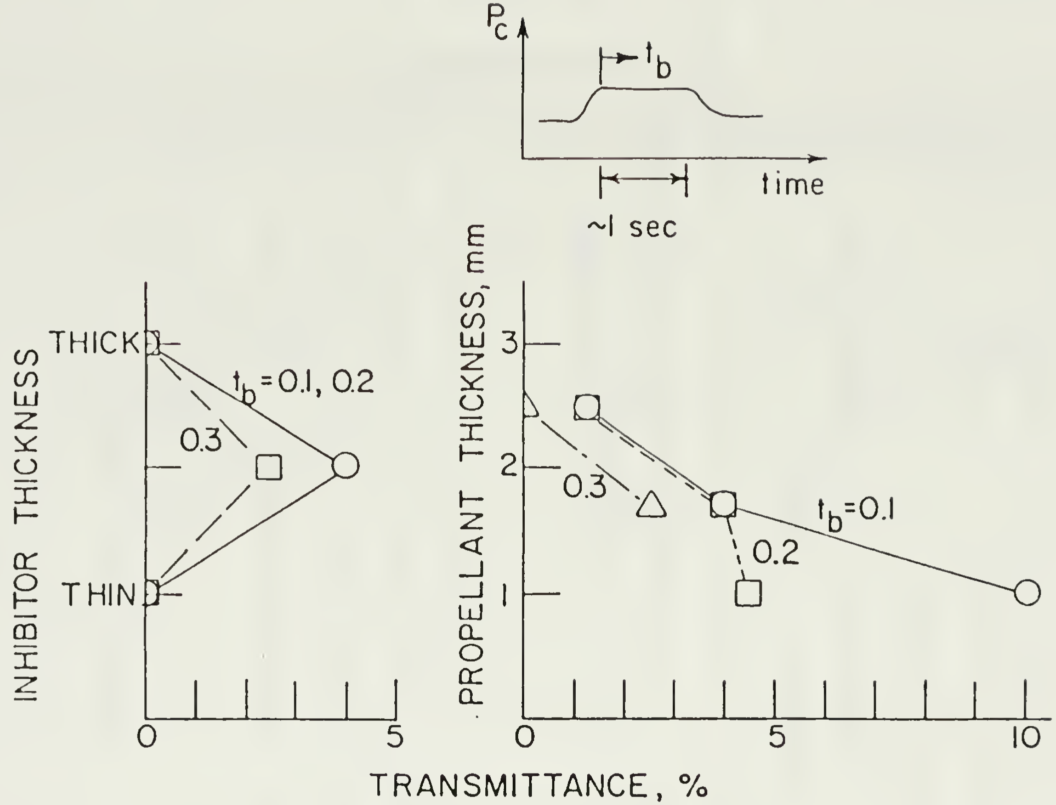


Figure 11. Effect of Inhibitor and Propellant Thickness on Transmittance

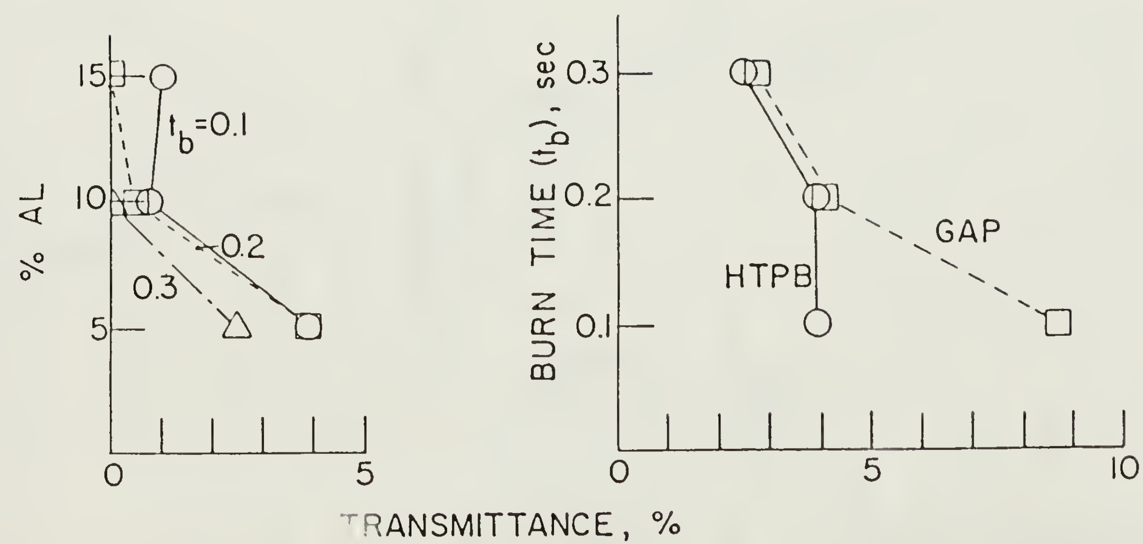


Figure 12. Effect of Aluminum and Burn Time on Transmittance

achieved. Figure 11 shows that there was an optimum inhibitor thickness (approximately 0.07 inches). Thicker inhibitor resulted in too much smoke while the glass would crack with thinner inhibitor. With 5% metallized propellants burned at 500 psia transmittance values were typically 2-5% within 0.2 seconds after steady state combustion was reached (Figure 11). This was true for both HTPB and GAP binders (Figure 12). For these propellants a maximum propellant slab thickness was approximately 2 mm (Figure 11). When the metal content was increased to 10% and 15% transmittance was reduced to between 0 and 1%. This implies that holograms will be very difficult to obtain with these metal levels using the present 2-D geometry and construction techniques.

These results were used in the holographic investigation to provide both the optimum time to take the hologram during the burn and the required reference beam attenuation to obtain the proper scene beam to reference beam intensity ratio on the holographic plate.

B. HOLOGRAPHIC RESULTS FOR CONTROL PROPELLANTS

The objective of this thesis was to further develop the 2-D motor holographic technique so that it could be readily used with higher combustion pressures and % aluminum, and with much smaller aluminum powder size. Table II summarizes the tests which were made. They included both GAP and HTPB

TABLE II

Summary of Test Conditions

Propellant	Pressure (psia)	Time Delay (sec)	Propellant Thickness (in)	Remarks
WGS-5A	405	0.50	0.067	Excellent hologram.
	880	0.42	0.067	Excellent hologram.
WGS-6A	410	0.50	0.067	Excellent hologram.
	880	0.40	0.067	Excellent hologram.
WGS-7A	745	0.50	0.055	Excellent hologram.
WGS-9	480	0.50	0.055	Excellent hologram.
	795	0.50	0.055	Too dark.
WGS-10	465	0.50	0.055	No hologram
	775	0.50	0.055	Too dark.
RPL-GAP	410	0.40	0.067	Excellent hologram.
	775	0.40	0.067	Excellent hologram.
WGS-G	850	0.50	0.055	Good hologram.
WGS-Zrc	830	0.50	0.055	Good hologram.

propellant binders with about 5% aluminum, HTPB binder with up to 15% aluminum and varying size of aluminum powder from 6-82 μm. Also, two HTPB propellants were tested with stability additive (WGS-G, WGS-ZrC).

Representative photographs of the reconstructed holograms which were obtained are shown in Figures 13 through 19. Good quality holograms were obtained with all propellants containing less than 5% metal additive to pressures of approximately 880 psia (the maximum attempted). However, the approximately 7 μm aluminum size in propellant WGS-7 was below the resolution limit of the currently employed diffusely illuminated holograms. A good hologram was also obtained with 10% aluminum at approximately 500 psia. These holograms were obtained with very few repeat tests. This was made possible by using the data presented above for transmittance versus time, propellant thickness and inhibitor thickness to optimize the light intensity and intensity ratio reaching the holographic plate.

No holograms could be attained with 10% aluminum at 800 psia or with 15% aluminum in the propellant. The 2-D motor construction method has proven to be quite good within the limits presented above. Impingement of the particulates on the glass walls and a high inhibitor to propellant mass ratio have provided the upper limits in metal content and propellant thickness in the tests. Holograms may actually

Figure 13. Photograph of Reconstructed Hologram of WGS-5A Burned at 405 psia

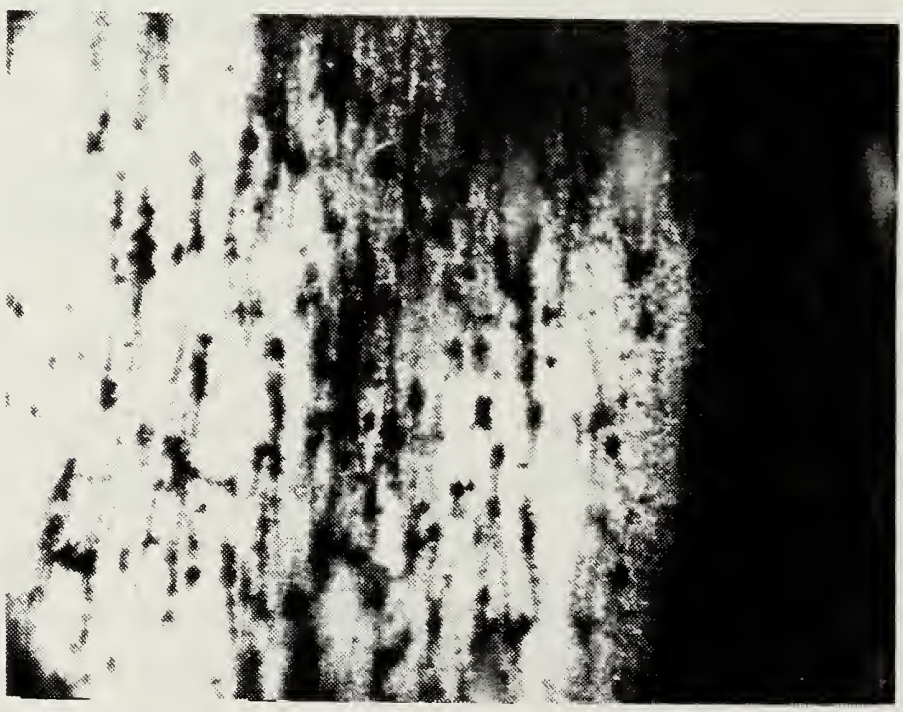


Figure 14. Photograph of Reconstructed Hologram of WGS-6A Burned at 410 psia

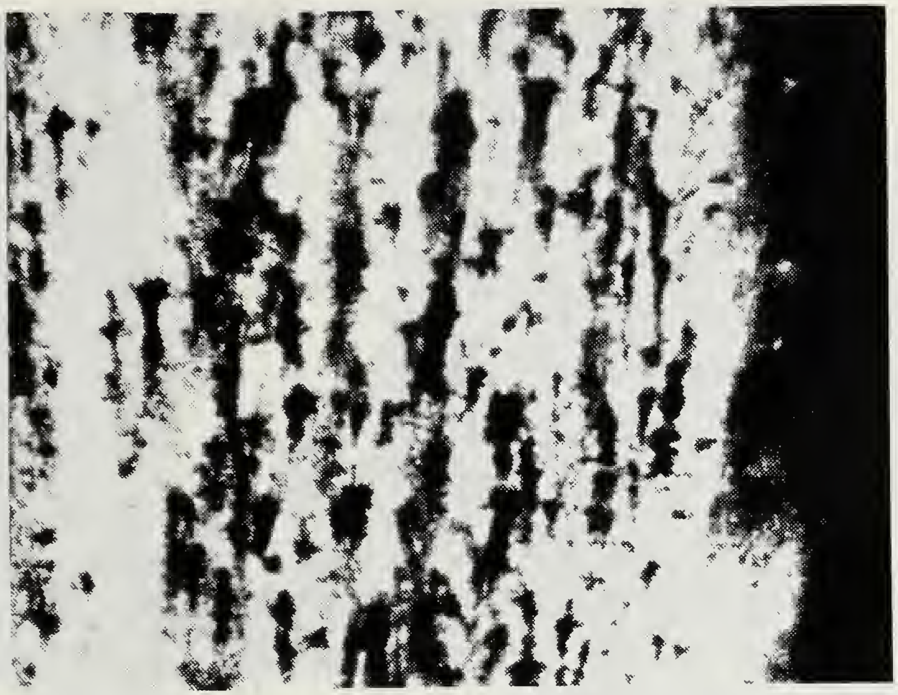


Figure 15. Photograph of Reconstructed Hologram of WGS-6A Burned at 880 psia

Figure 16. Photograph of Reconstructed Hologram of WGS-7A Burned at 745 psia

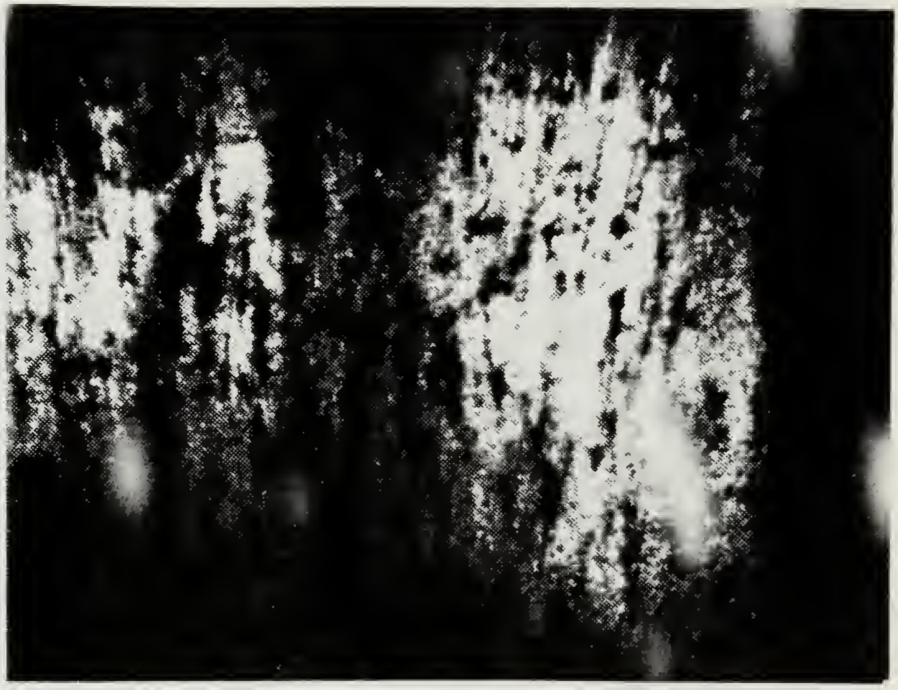


Figure 17. Photograph of Reconstructed Hologram of RPL-GAP Burned at 410 psia

Figure 18. Photograph of Reconstructed Hologram of WGS-G Burned at 850 psia

Figure 19. Photograph of Reconstructed Hologram of WGS-ZrC Burned at 830 psia

be more easily obtained in a 3-D motor. In that case, although the scene depth is greater, both of the above limitations can be significantly reduced.

IV. CONCLUSIONS AND RECOMMENDATIONS

The use of borosilicate side plates on the 2-D motors together with the use of transmittance data as a function of propellant thickness, inhibitor thickness, and burn time have allowed good quality holograms to be obtained of propellants burned in a cross-flow environment. With the present 2-D motor method there is an upper limit in combustion pressure and/or % metal where good holograms can be obtained. To date, pressures have been limited to approximately 900 psia and metal content to 10%.

It is recommended that holograms be attempted using the small 3-D motor which is currently used for the measurement of scattered laser light across an exhaust nozzle.

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