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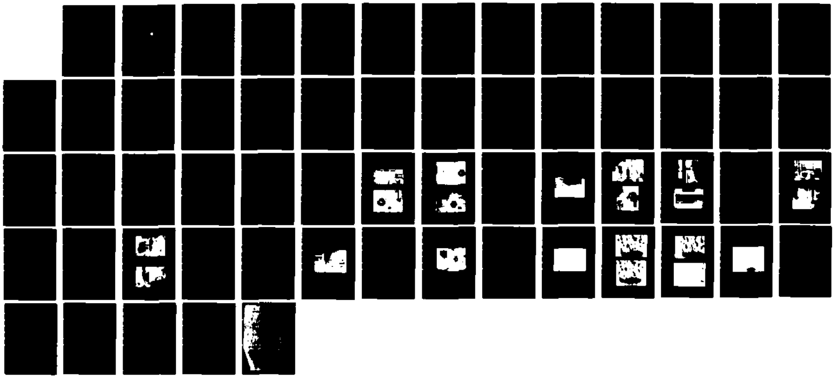

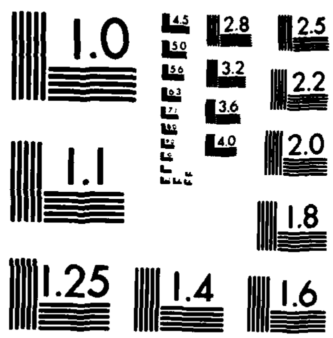

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

MONOCHROMATIC HIGH-SPEED PHOTOGRAPHY
OF SOLID ROCKET PROPELLANT COMBUSTION

by

Ronald James Edington

March 1983

Thesis Advisor: D. W. Netzer

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backlighting films revealed that the flame envelopes surrounding the particles could be eliminated, and that the true particle size could be obtained. However, Schlieren effects obscurred much of the information which was available on the film. The frontlighting technique eliminated the Schlieren effects and allowed good particle behavioral data to be obtained, but the reflected monochromatic light was not sufficient to allow true particle diameters to be taken.

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Monochromatic High-Speed Photography of Solid Rocket Propellant Combustion

by

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Lieutenant Commander, United States Navy
B.S., Northern Illinois University, 1970

Submitted in partial fullfillment of the requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

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Author: ______________________

Approved by: ______________________
Thesis Advisor

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Chairman, Department of Aeronautics

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Dean of Science and Engineering

ABSTRACT

Eight composite solid propellant formulations containing varying diameter and weight percentages of metallic particles were burned in strand form in two different nitrogen purged combustion bombs at a pressure of 500 psi. High-speed cinemotography was used with an argon laser as the primary monochromatic light source. Two illumination approaches were tried, backlighting and frontlighting. Careful examination of the backlighting films revealed that the flame envelopes surrounding the particles could be eliminated and that the true particle size could be obtained. However, Schlieren effects obscurred much of the information which was available on the film. The frontlighting technique eliminated the Schlieren effects and allowed good particle behavioral data to be obtained, but the reflected monochromatic light was not sufficient to allow true particle diameters to be taken.

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For her understanding and patience, I would like to say thank you to my wife. I also would like to thank Professor D. W. Netzer for his direction and assistance. A thank you also must go to the Aeronautical Engineering Department Technicians for their timely assistance in providing some of the many materials that were needed.

I. INTRODUCTION

The propulsion of air-air missiles is generally provided by a solid propellant rocket motor, with all current naval air-air missile systems being based on this propulsion method. References 1-4 present a detailed review of the role an aluminum additive plays in the performance of solid rocket motors. Finely powdered aluminum in the range of 1-100 microns is the most widely used metal additive [Ref. 1]. The advantages and disadvantages of aluminum as an additive are discussed again in Refs. 1-4. Particle size analysis in solid rocket motor combustion has become a major feature in the development and validation of current theoretical models [Refs. 4 and 5]. The influence of particle size on propellant performance is complex, and understanding the degree of influence often is hampered by ambiguous particle size data [Ref. 5].

This thesis was directed at one of the four on-going methods currently being used at the Naval Postgraduate School to study solid rocket motor propellant combustion:

(a) High-speed cinematography of burning propellant in strands and 2-D slab configurations,

(b) Post-fire residue collection and examination using a scanning electron microscope,

(c) Scattered laser power spectra measurements for determining the mean diameter of particles as they pass through the exhaust nozzle,

(d) Holographic image construction of the combustion process of burning propellant strands and of burning propellant slabs in a cross-flow environment.

The use of high-speed cinematography in conjunction with a high pressure combustion bomb in the study of solid rocket propellant combustion provides a time-resolved observation method of a dynamic process with little interference with the process itself [Ref. 6]. This photography covers propellant combustion from the surface burning phase until the agglomerates become obscurred either by the aluminum oxide smoke (combustion products), or by the interacting flame envelopes.

The major advantages associated with high-speed photography used in conjunction with a combustion bomb are:

(a) The time-varying characteristics can be recorded using the slow motion and stop action capabilities of motion pictures,

(b) The combustion bomb facilitates ease in post-fire residue collection,

(c) The combustion environment can be easily controlled,

(d) And, the possible magnification of desired spatial details.

The major disadvantages associated with high-speed photography used in conjunction with a combustion bomb are:

(a) The lack of cross-flow in the simulation of a rocket motor propellant grain,

(b) A cold inert gas is used to pressurize and purge the bomb which can have a quenching effect on the combustion process,

(c) There is no nozzle acceleration due to the lack of a nozzle,

(d) The depth of field is limited by the magnification desired, and

(e) The resolution is limited by the varying and usually numerous types of optics used.

DiLoreto, [Ref. 2], conducted an investigation at NPS to study the effects of operating pressure and propellant composition on the size and velocity of agglomerates leaving the burning surface. His investigation used six types of propellant with a constant percentage, but varying size of aluminum powder. A scanning electron microscope, (SEM), was used in conjunction with post-fire residue collection to provide accurate particle size data for comparison with those observed in the high-speed photography. A minimum particle size of approximately 60 microns was observed on the processed film, although 15 microns could be resolved during the static camera callibrations. This discrepancy was attributed to camera jitter.

Karagounis, [Ref. 3], set out to improve on DiLoreto's results by:

(a) Increasing the magnification,

(b) Using fewer optics, and

(c) Reducing the camera jitter.

The changes improved the obtainable resolution, but significantly better particle size data could not be obtained because of the flame sheaths which obscurred the particles.

In the present investigation, an attempt was made to eliminate the self-luminous interference by filtering out the combustion light. For high-speed photography (in the range of 5,000 frames per second), a monochromatic light source(s) was needed which would provide the necessary illumination at such high framing rates and magnifications. For this purpose a laser light source was used because of its extreme brightness, directionality, and monochromaticity [Ref. 6]. In addition, high intensity arc lamps also were used which provided considerable intensity in the narrow wavelength bands.

The monochromatic property of the laser light source allows the self-luminous interference to be blocked from the exposed film by using an appropriate narrow-pass filter prior to the camera lens. The directionality of the laser allows for ease of focusing all of the light through the small windows of the high pressure combustion bombs. The extreme brightness of the light enables the use of a higher film speed to "stop" the combustion action.

II. METHOD OF INVESTIGATION

Eight composite solid propellant formulations containing varying diameters and weight percentages of metallic particles were burned in strand form in two different nitrogen purged combustion bombs at a pressure of 500 psi. High-speed cinematography was used with an argon laser as the primary monochromatic light source. Two illumination approaches were tried: backlighting, and frontlighting of the burning propellant strands. The data collected was correlated with that found in previous work done at the Naval Postgraduate School.

III. EXPERIMENTAL APPARATUS

A. GENERAL EQUIPMENT DESCRIPTION

The primary light source used was a Control Laser, continuous-wave (CW), argon laser, Model 902A, operating at the 488 nm line. The laser provided between .64 and .74 watts of power. The laser was operated at 32A maximum on a 220 VAC line. Water cooling also was required from an external source. Beamwidth was measured at 2mm, and required a bi-concave lens to diverge the beam to the desired width. Figure 1 shows the laser set-up. The set-up provided a full 360 degree coverage in azimuth, but was limited to .5 inches variation in height.

Two additional light sources were used to augment the laser light source. For this purpose a SLM-1200 projector with a 1200 W filament lamp, and an Oriel 2500 W Universal Arc Lamp Source with a 2500 W Mercury/Xenon arc lamp were used. An infra-red filter was used between the white light source and the combustion bomb window to reduce the influence of the light source on the combustion process. Figures 2 and 3 show the light sources in the experimental set-up.

A Hycam Model K2004E-115 high-speed, 16-mm motion picture camera was used as the recording apparatus. The Hycam is capable of operating between zero and 11,000 frames per second, with 5,000 frames per second being the highest used, and 2,500 the lowest. A Red Lake Millimite TLG-4 oscillator set at 1,000 pulses per second was used to provide timing marks on the film edge on all runs. Figure 4 shows the camera and oscillator.

An Elgeet 77 mm/f1.9 lens was used with an extension tube to provide a focal distance of 2.64 inches (vice the 5 inches used in Ref. 2). Figure 5 gives the focal distance as a function of extension tube length. The camera base supports developed in Ref. 3 were used to reduce camera jitter. They can be seen in Figure 6.

Strand ignition was accomplished by placing a taught, thin wire across the strand top surface, and connecting the wire to electrodes on either side of the strand. The wire was made of nickel-chromium, 0.008 inches in diameter. A 12 VDC battery, in series with a variable resistor to control the current through the wire, provided the necessary ignition current. Figure 7 shows the ignition set-up.

Control of each run was provided from behind a protective control panel. Ignition, pressurization, and camera initiation could all be controlled from behind this panel. Controls provided an option of manual camera initiation, or auto initiation. Auto initiation of the camera could occur after a suitable time delay to allow for strand ignition. Figure 8 shows the control panel. Two different combustion bombs were used in conjunction with the two lighting techniques employed.

B. BACKLIGHTING

The same combustion bomb used in Ref. 2 (as modified in Ref.3) was used during the backlighting experiments. Figure 9 is a schematic of this bomb. The bomb provided the neccessary working pressure capability and opposing windows for the backlighting technique. Figure 10 shows the bomb in the experimental set-up.

C. FRONTLIGHTING

The combustion bomb used for the backlighting technique could not be used for the frontlighting technique because of the insufficient number of windows facing the camera. The combustion bomb used for the frontlighting experiments was the same one used by Kennedy [Ref. 7]. Figures 11 and 12 are schematics of the combustion bomb. Figure 13 shows the combustion bomb in the frontlighting set-up. Because of the larger windows in this combustion bomb, the available pressurization was limited to 500 psi.

A rotating disk was used to present varying illumination (white light and 488 nm light) to the camera during a single burn. The disk was made of aluminum with a radius of 4.125 inches and a thickness of 0.23 inches. A Sargent Cone Drive Stirring Motor was used to rotate the disk at a rate of 1,740 revolutions per minute. Figure 14 shows the motor and disk in the frontlighting set-up. Figure 15 presents a schematic of the disk.

IV. EXPERIMENTAL PROCEDURES

A. BACKLIGHTING

"The most relevant tests are probably those in which observations of combustion are made with a propellant having a few aluminum particles of desired size." [Ref. 1].

With this in mind, initial testing was done using WGS-6A propellant. Table I lists the propellant formulations used in this investigation. These propellants were provided by the Aerojet Solid Rocket Company, Sacramento, California. The propellants were cut to strand size as shown in Figure 16. The width varied slightly so as to fill the camera field of view, but were generally the dimensions as shown. The cut strands were cemented to stainless steel pedestals, then placed in a pedestal holder in the middle of the combustion bomb.

A 2.75 inch extension tube was used with the f/1.9 lens to give an object distance of 2.64 inches. This placed the camera lens to within 0.39 inches of the combustion bomb window. This was the minimum working distance due to the window mounting screws, and the need to provide room for the narrow-pass filter to be placed between the lens and the window. The resolution was 14 μm as determined in Ref. 3. The lens focus was first fixed on the camera, then the fine focusing was done by moving the entire camera. A static focus was made at the start, and the camera position was recorded so that when the camera was moved back into position after loading it would be placed in focus.

The magnification was computed to be 1.90X, [Ref. 11]. The effective f-stop due to the magnification was approximately 5.7, [Ref. 8]. This gave a depth of field of approximately 0.008 inches, [Ref. 9], or 0.2 mm. This was much smaller than the 2 mm thickness of the strand. The focus was made on the front surface of the strand, and then moved inward approximately 0.5 mm.

Backlighting was provided by the laser at 488 nm through the window opposing the camera viewing window. Laser light was blocked until just prior to ignition so as to have as little effect on the combustion process as possible. The 1200 watt projector lamp was used to supplement the laser light source, and was directed through the side window.

The laser light was first used without modification. Two types of filtering were later used: (1) spatial filtering, and (2) diffuse glass. These were placed between the laser and the combustion bomb.

Runs were attempted at rates between 2500 and 5000 frames per second. The f-stop was varied from f/1.9 to f/4.6 in an attempt to obtain varying degrees of exposure. Nitrogen was used as the pressurizing and purging medium. The bomb was first pressurized from the control panel, then a purge valve was adjusted to allow the combustion gasses to escape. Only enough purge was used to provide a clear view of the strand throughout the combustion process. Numerous strand burns were made to determine the correct purge rate.

Strand ignition and camera initiation were accomplished in the manual mode with a conscious delay in camera initiation to allow for strand ignition. One hundred foot rolls of Kodak 7250 film were used for all runs. However, only the last ninety frames provided exposures at the maximum film rates.

Figures 17 and 18 show the backlighting layout. The spatial filter and the diffuse glass were never used together in the same run.

B. FRONTLIGHTING

Because of the larger diameter of the combustion bomb used for the experiments with frontlighting, a 2 inch extension tube had to be used. This, again, put the lens at the minimum working distance possible. The 2 inch extension provided a magnification of 1.8. The effective f-stop in this configuration was 5.3, giving a depth of field of approximately 0.009 inches, or 0.24 mm. As in the case of the backlighting technique, this depth of field was far less than the strand thickness.

The laser light was reflected off a mirror, passed through a bi-concave lens to expand the beam to the strand dimensions, and then put through the window next to the camera. No filtering was done to the laser light. The

1200 W white light source was again used as a supplement to the laser light. It was projected through the same window as the laser light source at an angle which illuminated as much of the propellant surface as possible, and not to interfere with the laser light. The 2500 W white light source was projected through an IR filter, then through the side window. The large diameter of the side window permitted the 2500 W light to be projected in at an angle which would illuminate the front face of the propellant.

The rotating disk was placed between the camera lens and the combustion bomb window. The disk provided three different illuminations of the strand burn to the camera. The first and primary view of the strand burn was with illumination by all three light sources and the appropriate narrow-pass filter in front of the camera lens. A second view was with all three light sources illuminating the strand surface, but with no narrow-pass filter. The third view was with just white light illumination and no laser light and no narrow-pass filter. The disk was spinning at 1,740 revolutions per minute. With approximately 90 frames available at the maximum film rate, the distance travelled by the disk was 11.6 inches during the 90 frames. The circumference of the disk at the mid-point of the filters was 22.0 inches. This provided two complete presentations to the camera. The number of frames per inch of disk travel was 7.75. Figures 19 and 20 show the front-lighting layout.

All other experimental procedures were identical to those used with the backlighting technique.

V. RESULTS AND DISCUSSION

A. BACKLIGHTING

It was anticipated that the flame sheath, which obscurred true particle size analysis by high speed photography in Refs. 2 and 3, could be filtered out using the monochromatic property of the laser light and an appropriate narrow-pass filter. It also was believed that the Schlieren effects associated with a collimated light source would be reduced, if not eliminated, using a diverging light source and appropriate filtering. This would leave the shadow of the particle for the camera to record. Runs were completed as discussed previously. Figure 21 is an example of the results of a typical run. This figure is for WGS-6A at 5,000 frames per second, and f/1.9. Careful examination reveals that the particle size of approximately 60 microns can be obtained from the film. However, the Schlieren effects obscurred much of the information which was available on the film. Similar results can be found in Refs. 10, 11, and 12. A different method of lighting was required which would not be limited by the Schlieren effects.

B. FRONTLIGHTING

The initial set-up for frontlighting was with the laser as the only light source. At the 5,000 frames per second film rate required to stop the action of the burn, the laser did not provide enough light in the 488 nm range needed. The 1200 W light source and the spinning disk were then added. Again, a little more light in the same range was needed. The 2500 W light provided the needed light, not only in the 488 nm range, but also for the white light illumination. The disk provided the multiple types of presentations as seen in the sequence of photos in Figure 22. These photos were taken of WGS-6A at 5,000 frames per second, and f/1.9.

The nonfiltered sequence of photos shows the burning particles leaving the surface as documented in Refs. 1-4. What is different in these photos is the equal number of particles which are leaving the surface unignited, and then igniting anywhere up to 4 mm from the surface. Picture framing prevented analysis at any greater distance from the surface. These unignited particles are seen as a bright ring around a darkened center. This ring continued to get brighter until the flame sheath engulfed the entire darkened area. The filtered sequence of pictures provided another bright ring with a darkened center. The diameter of the dark area in the filtered sequence was about the same diameter as the flame sheath in the unfiltered sequence. Figure 23 is a representation of the different objects seen in the photos and respective diameter references.

Table II is a comparison of the eight propellants burned, including the data taken by DiLoreto, [Ref. 2]. DiLoreto did not test those propellants where N/A appears.

Figure 24 is a comparison of the initial powder diameters versus the burning particle diameters for propellants WGS-5A, 6A, 7, and 7A. Also shown are the data obtained by DiLoreto, [Ref. 2]. What was not seen by DiLoreto or Karagounis [Ref. 3], were the ringed darkened areas seen in the unfiltered and the filtered photo sequence. As can be seen in Figure 24, the computed flame sheath diameters closely correlate with those found by DiLoreto.

Values for Dwc and Dwr in Table II for WGS-7 were not obtained from the films because of the small particle size. The unfiltered dark centers could not be resolved. If an average ratio of the unfiltered dark centers to the initial powder sizes for WGS-5A, 6A, and 7A is used to predict the unfiltered dark center size for WGS-7, then the limit of the resolution capability of the camera was approached.

Propellants WGS-9 and 10 had two and three times the weight percentage of aluminum respectively, as did WGS-5A, 6A, 7, and 7A. This resulted in a significant increase in the number of particles, and a recorded continuous flame all along the strand. The increase in the self-luminous light also obscurred any particle size information contained in the photos.

Particle size data from the propellant containing zirconium could not be obtained from the film because of the irregular shape of the particles. The non-burning particles could be seen to tumble after leaving the strand surface. The tumbling and the reflected light gave the appearance of a rapid, rising bubbling action in water. The tumbling and the irregular shape prevented the taking of any meaningful data.

The motion picture of the propellant containing graphite had the same characteristics as the zirconium propellant. In addition, because the 7 micron dimension of the 50x20x7 micron graphite was well below the resolution capabilities of the camera, the particles appeared to pop in and out of view as they tumbled. The filtered frame had what appeared to be corner reflections from the platelets, but no definitive data could be taken from the photos.

All the motion pictures taken still had what appeared to be the result of camera jitter, although not to the degree experienced in Ref. 2. The jitter was still a factor in the resolution capabilities of the camera.

The propellants used in this study which had five percent aluminum by weight had the expected burning characteristic of the particles immediately leaving the surface without surface agglomeration. These particles probably had little, if any, significant oxide coating on their surfaces. Diameter Dwr (or Dwc) was significantly greater than the powder size, and therefore was apparently the diameter of the metal vapor cloud around the molten center. When the vapor attained sufficient temperature and ignited, the observed flame diameter was a little bigger, and the characteristic Al_2O_3 "tail" was apparent. The cause of the large outer ring in the filtered pictures is not clear at this point.

Although the frontlighting technique eliminated the undesirable Schlieren effects of backlighting, and allowed good particle behavioral data to be obtained, the reflected monochromatic light was not sufficient to allow true particle diameters to be obtained.

VI. CONCLUSIONS AND RECOMMENDATIONS

In the test runs using WGS-5A, 6a, and 7A, the unfiltered bright ring appears to be a veil of metal/metal oxide smoke as discussed in Ref. 1. The dark area in the unfiltered ring may be the result of the strictly frontal lighting. It may be possible to improve significantly the data obtained from the films by using the 2500 W diffuse light to provide rear illumination in conjunction with frontlighting provided by the argon laser. This would provide better contrasting and the shadows from rear illumination, with the possibility of better particle resolution as obtained in the Schlieren obscurred backlighting films.

The fact that some particles left the surface unignited is not unusual under an adverse combustion process, [Ref. 1]. The particles later ignited due to the interaction with the high temperature flame zone.

Meaningful photos might be obtained for propellants WGS-9 and 10 by stopping down the lens one or two stops. This would remove some of the self-luminous light, and as a secondary benefit, would increase the depth of field.

In order to see the entire surface of zirconium or graphite particles, it would be necessary to have a better depth of field because of their irregular shapes. Again, as with propellants WGS-9 and 10, this would mean stopping the lens down one or two stops. Illumination of the filtered photos would be the limiting factor in how far the lens could be stopped down.

Camera jitter could be controlled better if the stablizing bolts were made an integral part of the camera stand, and were torqued down to engage the metal platform.

TABLE I

PROPELLANT COMPOSITION

Propellant Designation	Binder % Weight	Oxidizer* % Weight	Metal % Weight	Mean Metal Diameter, μm
WGS-5A	HTPB 12	AP 83	Al 5	75-88
WGS-6A	HTBP 12	AP 83	Al 5	45-62
WGS-7A	HTPB 12	AP 83	Al 5	23-27
WGS-7	HTPB 12	AP 83	Al 5	7-8
WGS-9	HTPB 12	AP 78	Al 10	23-27
WGS-10	HTPB 12	AP 73	Al 15	23-27
Zirconium	HTPB 14	AP 84	Zr 2	23 **
Graphite	HTPB 14	AP 84	C 2	Approx. *** 50x20x7

* AP is 65% 180 Micron/35% 26 Micron
** Irregularly Shaped
*** Platelets

TABLE II

OBJECT DIAMETER COMPARISON

Propellant Type	Dwc* (μm)	Dwr (μm)	Df (μm)	Dbc (μm)	Dbr (μm)	Ref. 2 Flame Diam. (μm)	Ref. 2** Mean Diam. (μm)	Mean *** Powder Diam. (μm)
WGS-5A	247	423	525	506	752	475	70	82
WGS-6A	124	278	364	340	566	370	58	54
WGS-7A	90	230	280	288	413	285	16	25
WGS-7	****	****	153	163	312	150	7	7
WGS-9	****	****	****	****	****	N/A	N/A	25
WGS-10	****	****	****	****	****	N/A	N/A	25
Zirconium	****	****	****	****	****	N/A	N/A	23
Graphite	206	340	313	306	496	N/A	N/A	Approx. 50x20x7

* See Figure 23 for explanation of symbols.
** Mean Diameter is of SEM collection samples.
*** Initial particle diameter average.
**** Refer to text.

Figure 1. Laser Set-up.

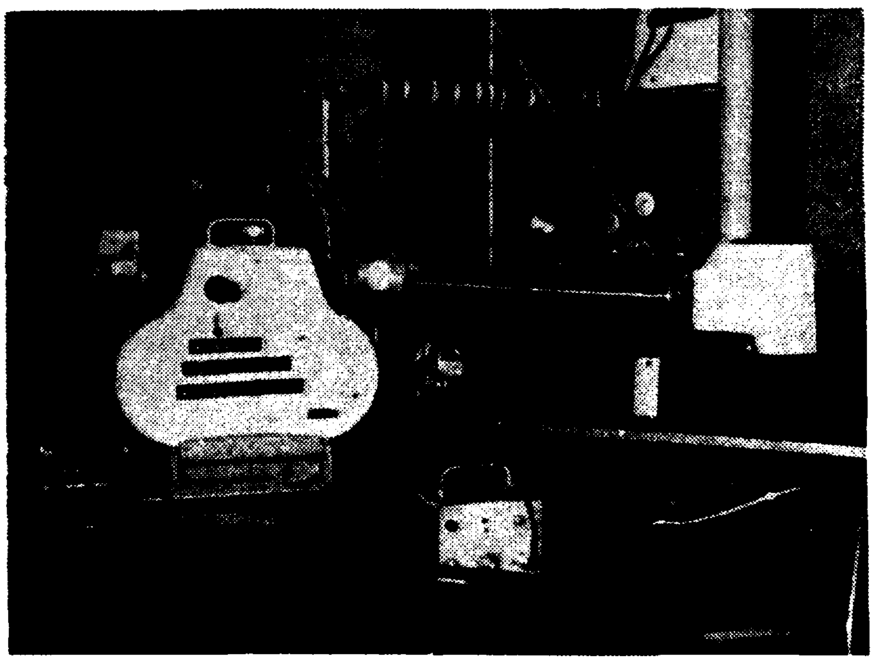


Figure 2. 1200 W Light Source in Frontlighting Set-up.

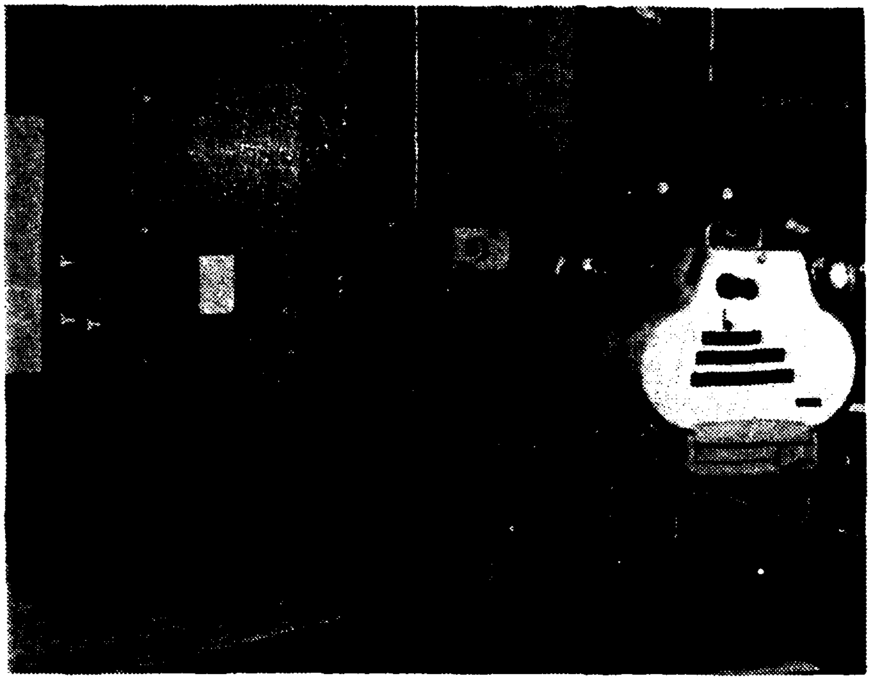


Figure 3. 2500 W Light Source in Frontlighting Set-up.

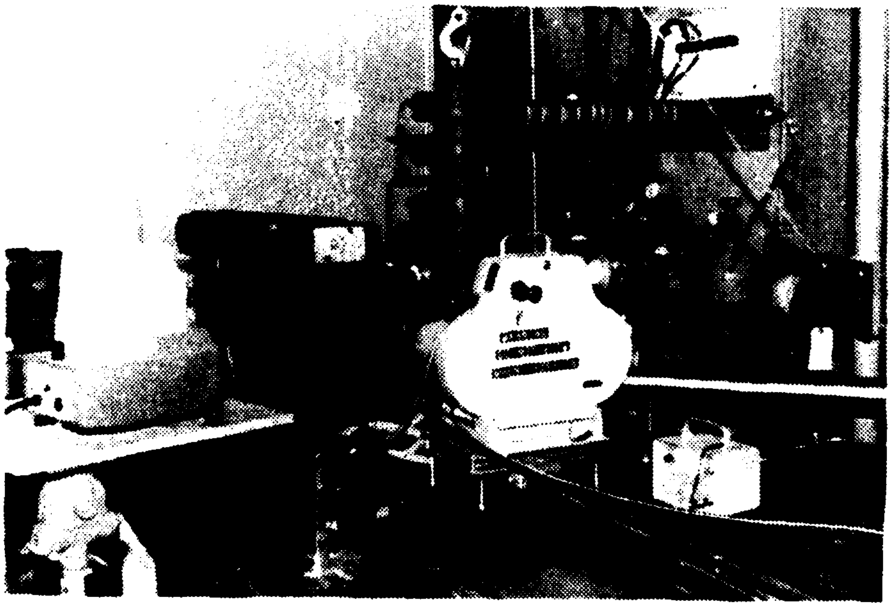


Figure 4. Hycam Camera and Oscillator.

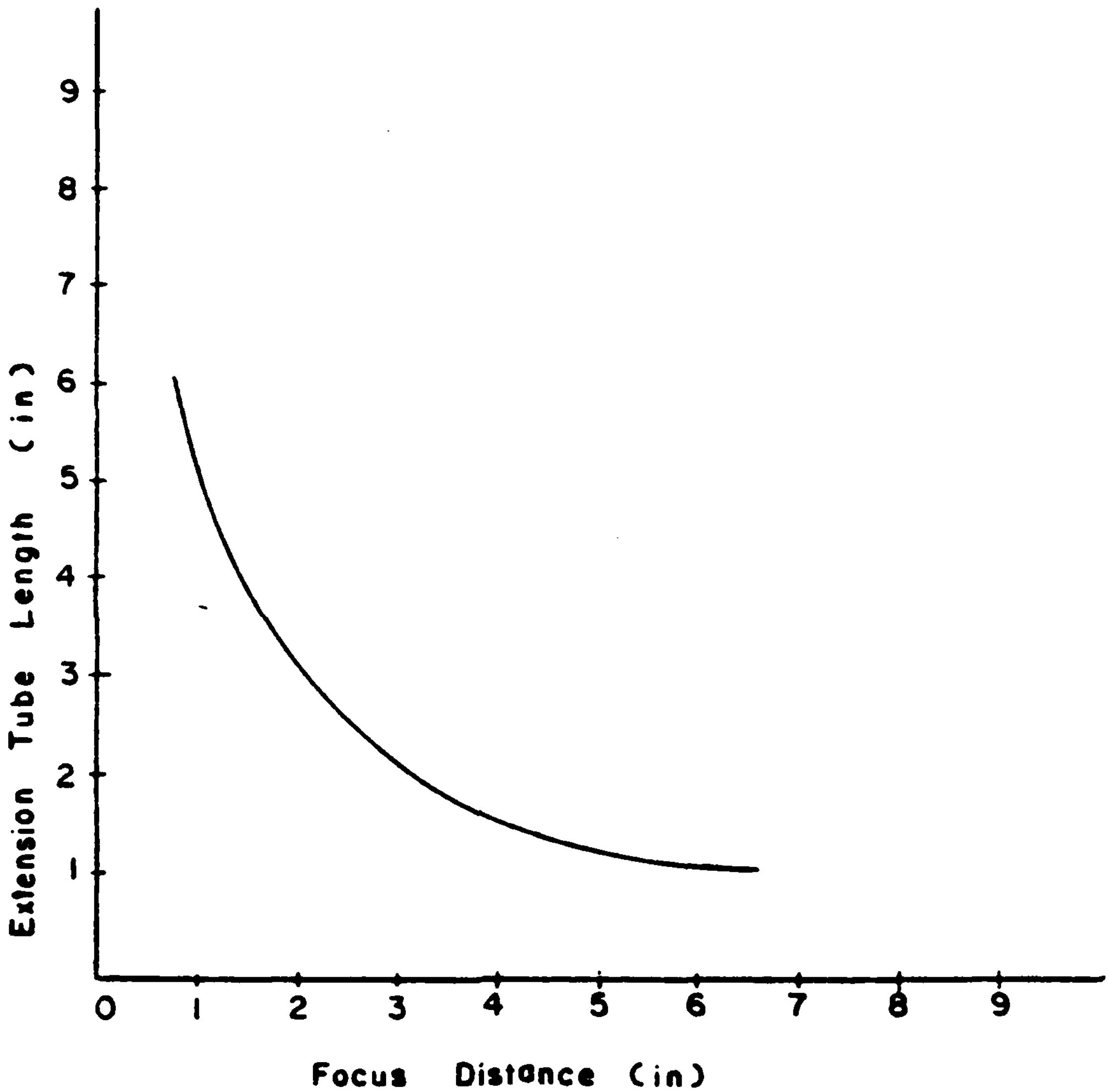


Figure 5. Focus Distance (Lens to Object) Versus Extension Tube Length.

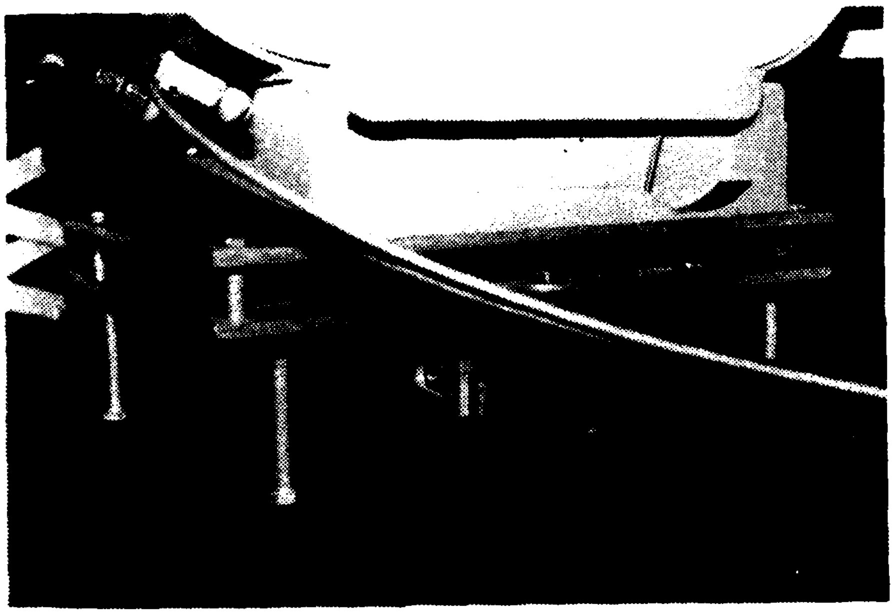
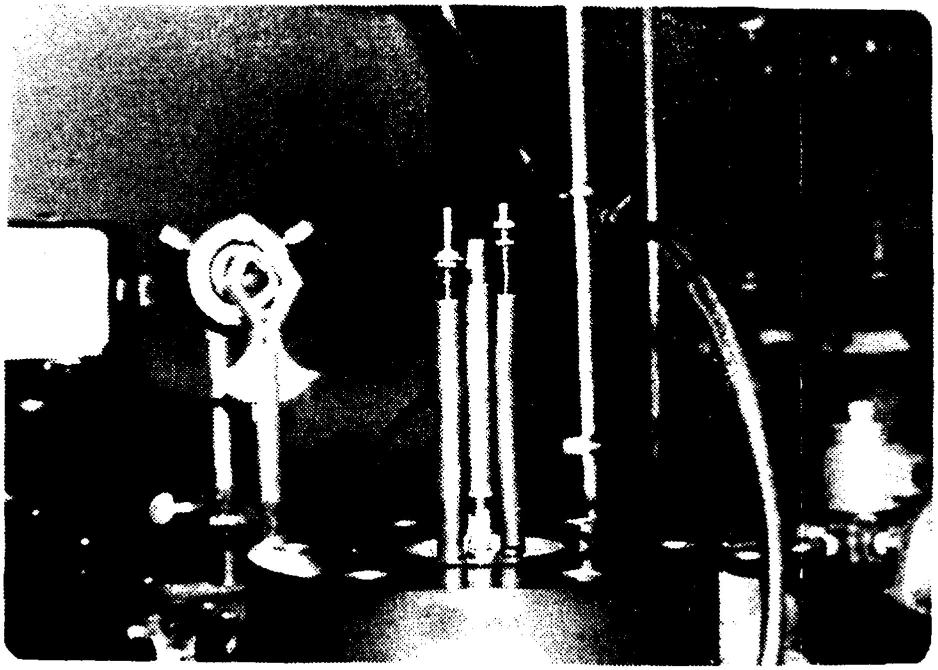
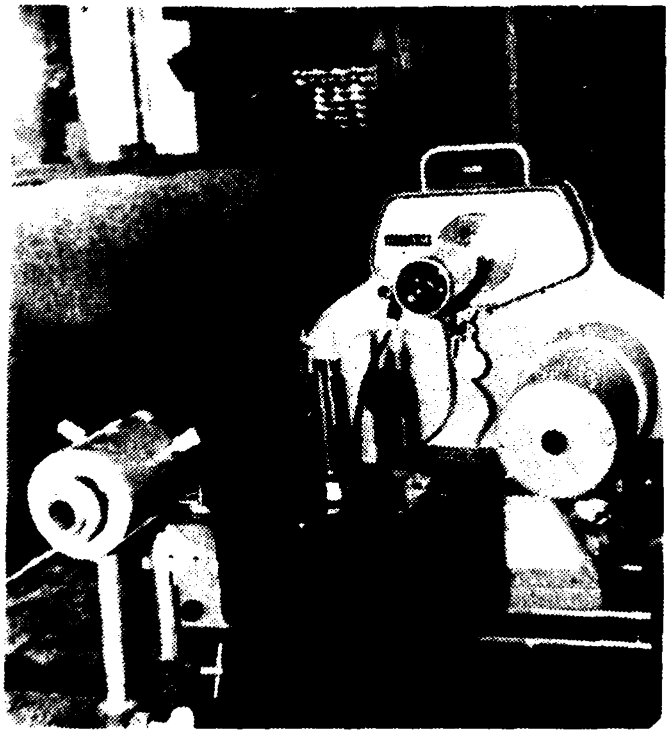


Figure 6. Camera Supports.



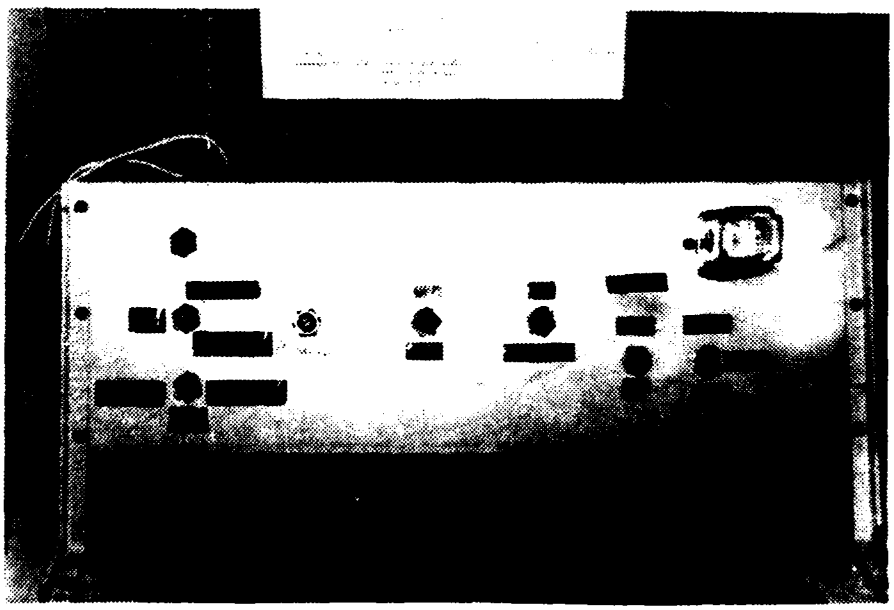
(a) Looking Toward Laser.



(b) Looking Toward Camera.

Figure 7. Strand Positions

(a) Full View.



(b) Panel View.

Figure 8. Control Panel.

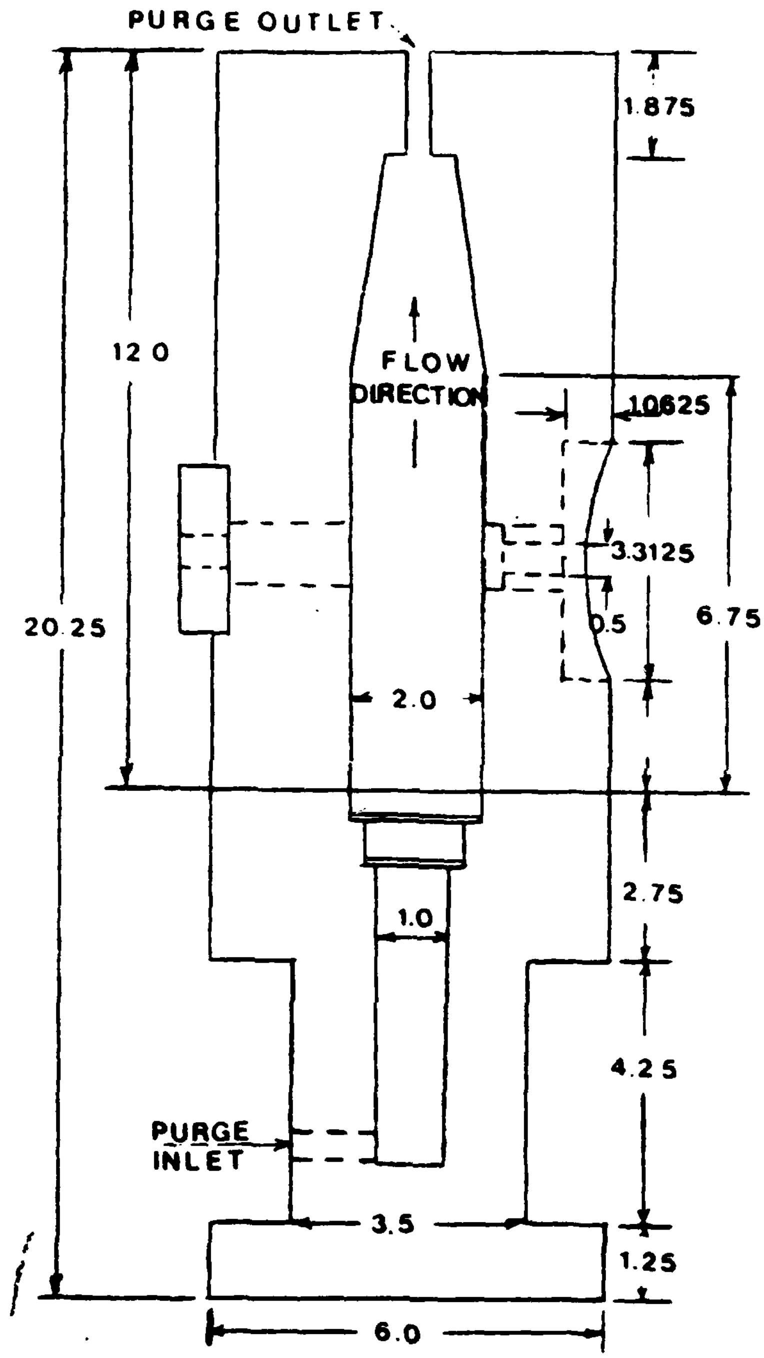
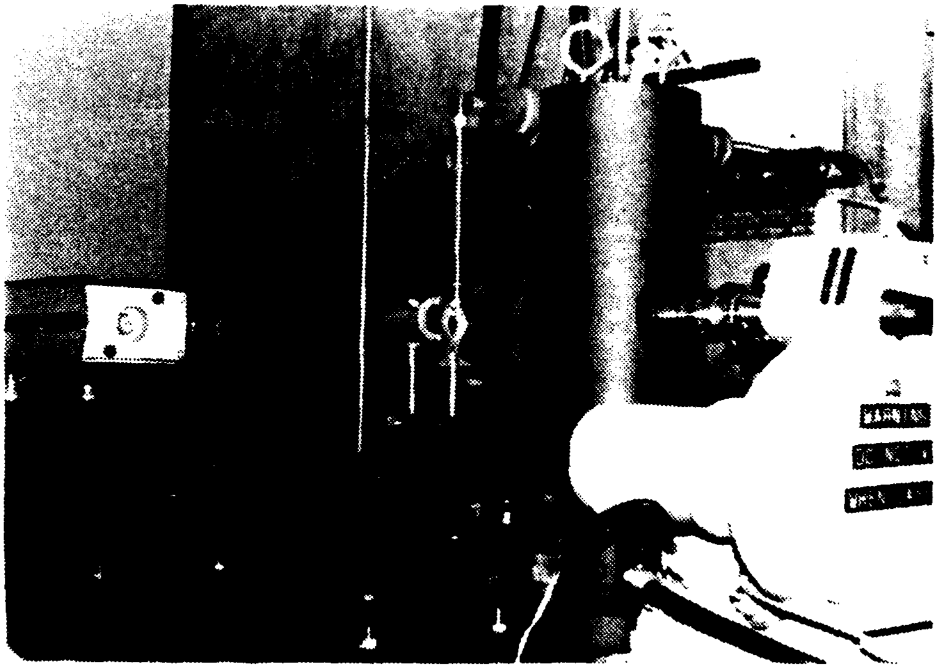


Figure 9. Schematic of Combustion Bomb Showing Principal Dimensions

(a) Facing Camera.



(b) Facing Laser.

Figure 10. Combustion Bomb in Backlighting Set-up

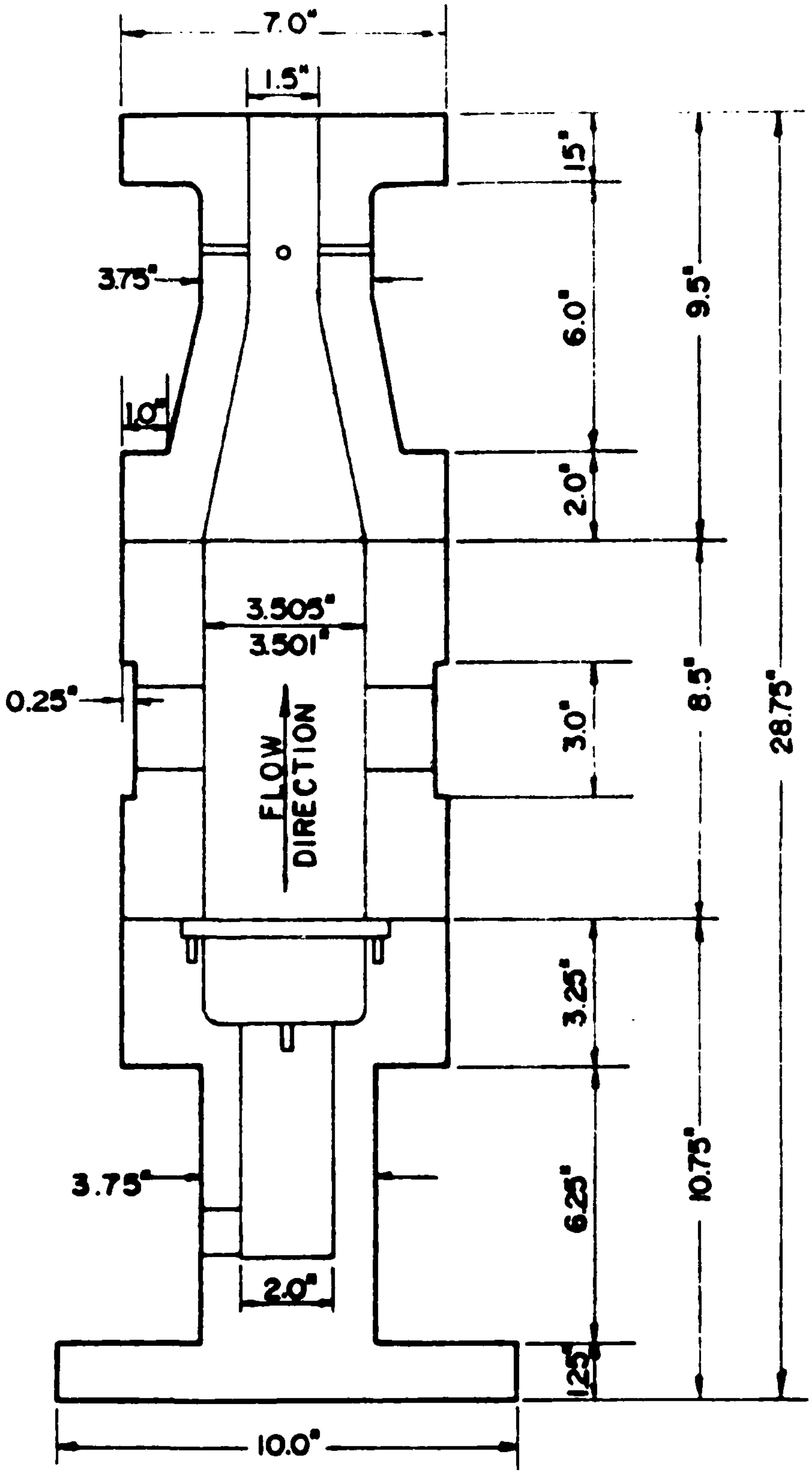


Figure 11. Schematic of Combustion Bomb Showing Principal Dimensions.

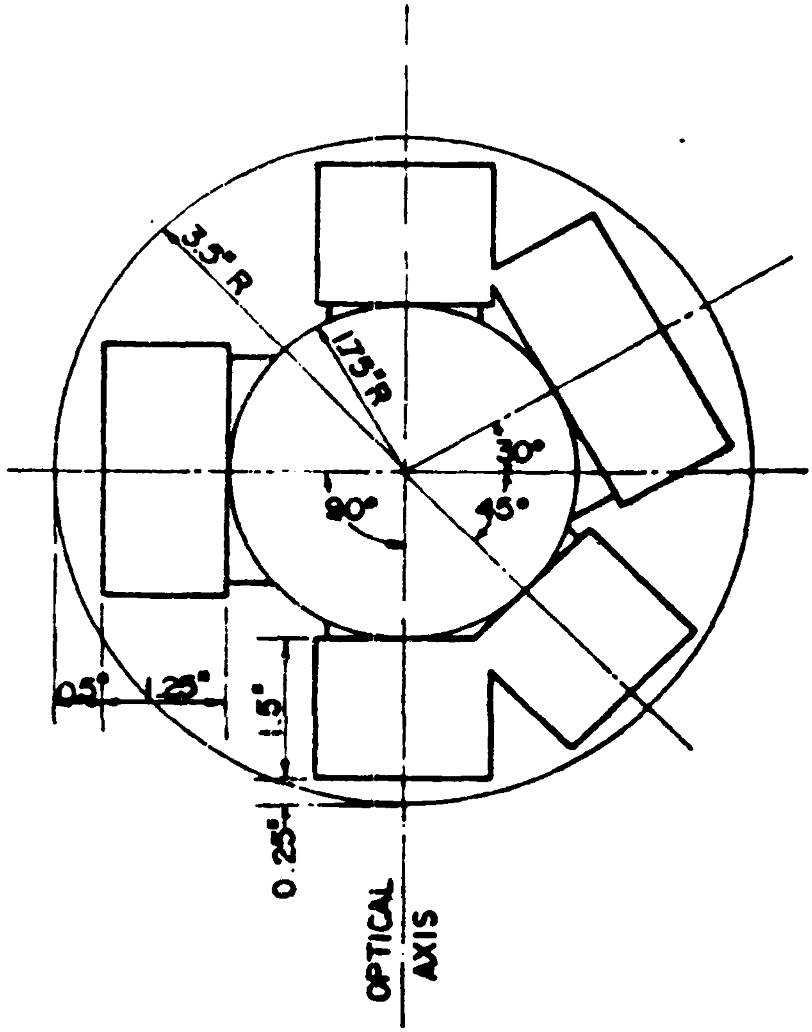


Figure 12. Schematic Showing Angular Relationship of Windows.

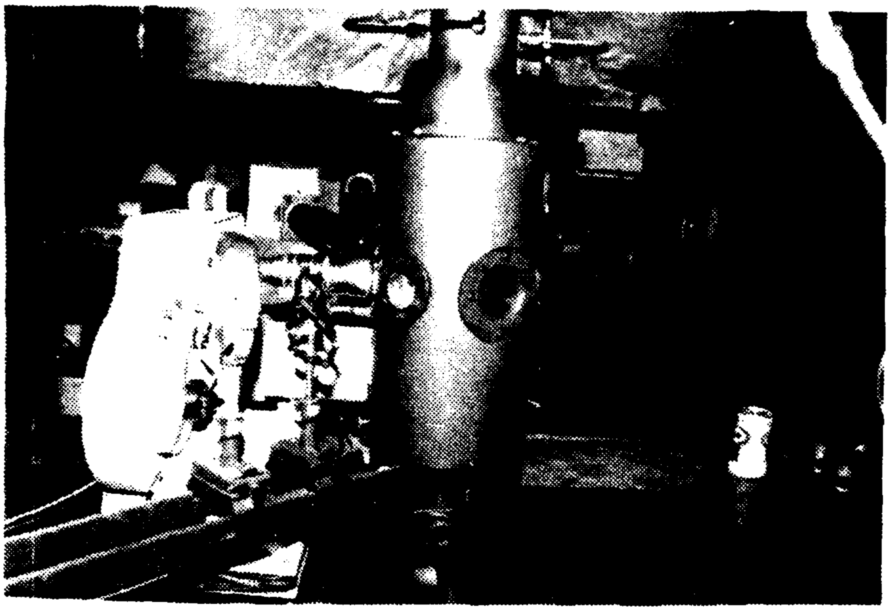


Figure 13. Combustion Bomb in Frontlighting Set-up.

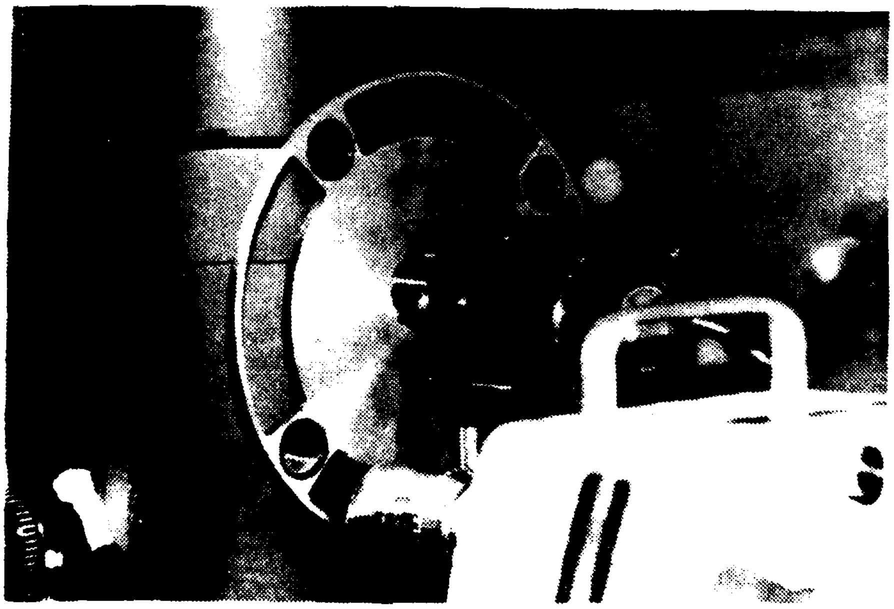


Figure 14. Disk and Motor.

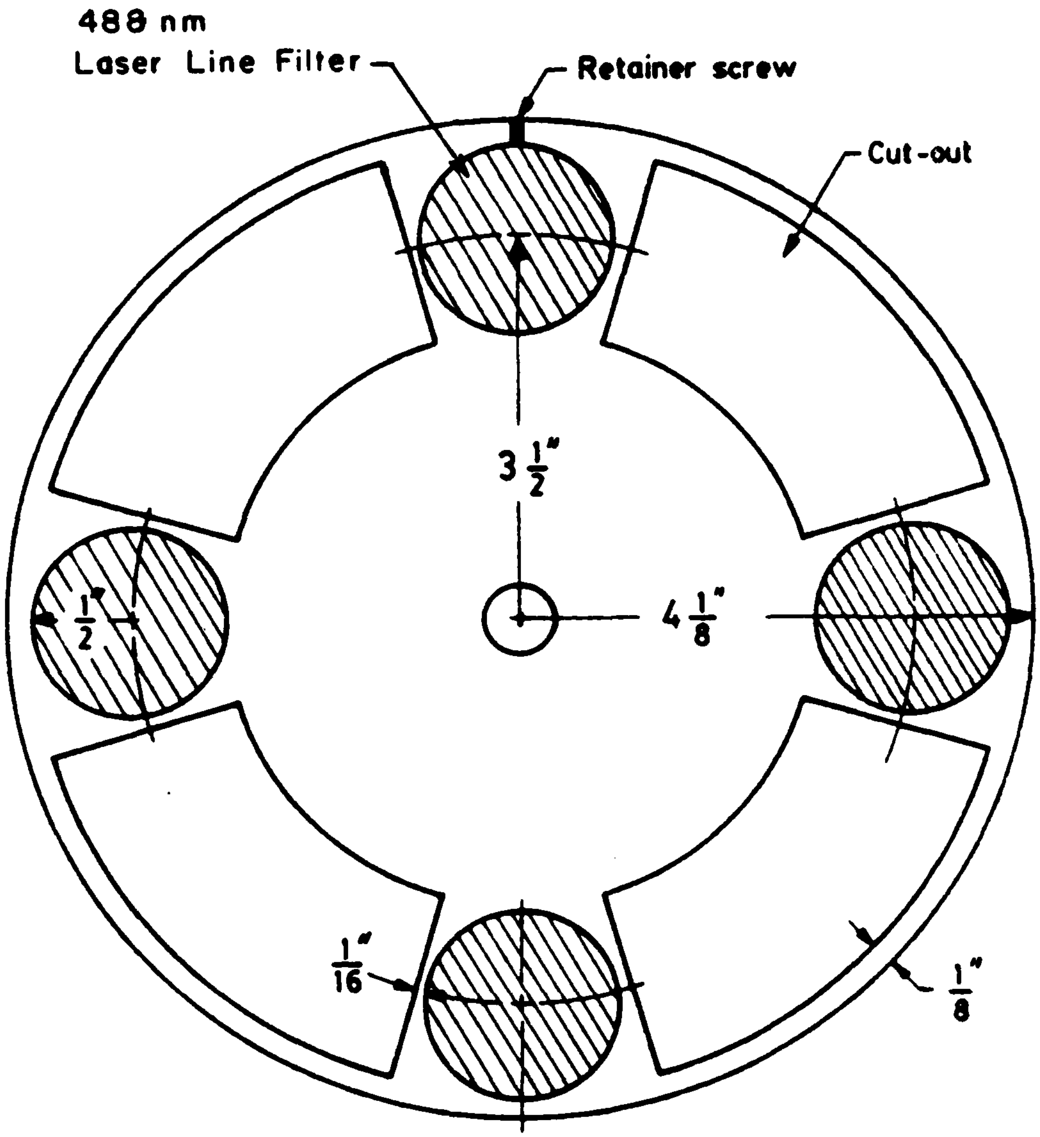
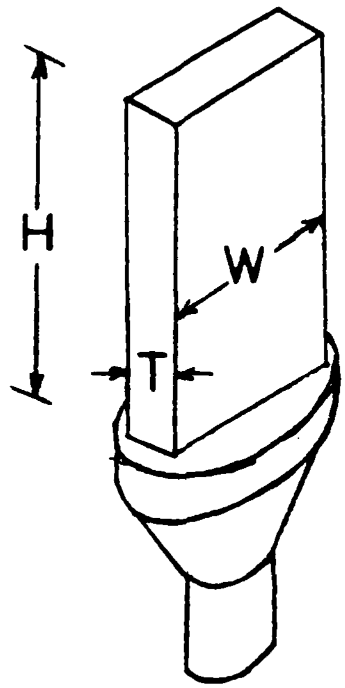


Figure 15. Schematic of Disk Showing Principal Dimensions.



H = 10 mm

W = 7 mm

T = 2 mm

Figure 16. Strand Dimensions.

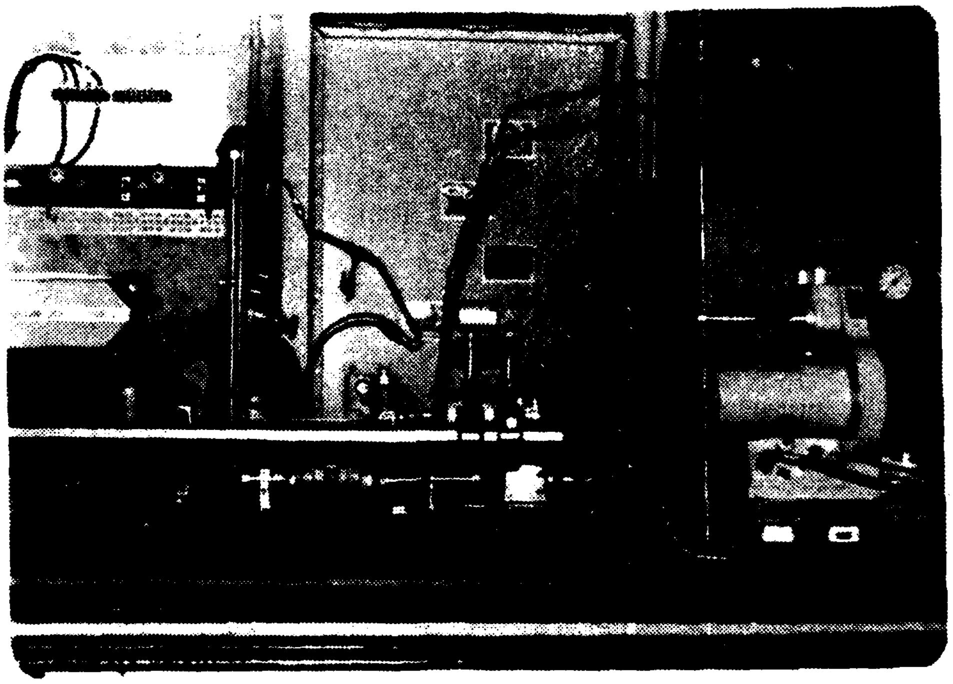


Figure 17. Backlighting Layout.

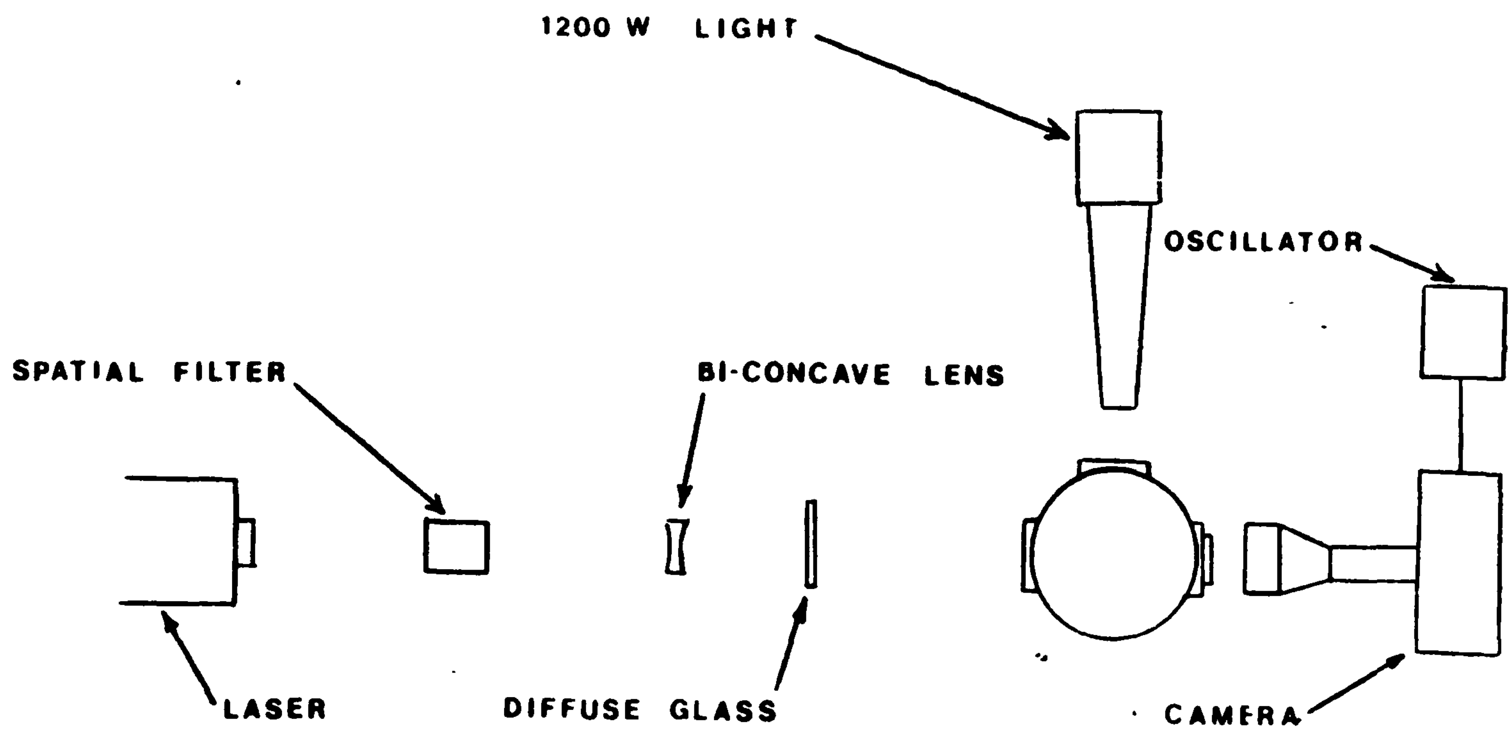


Figure 18. Backlighting Planform

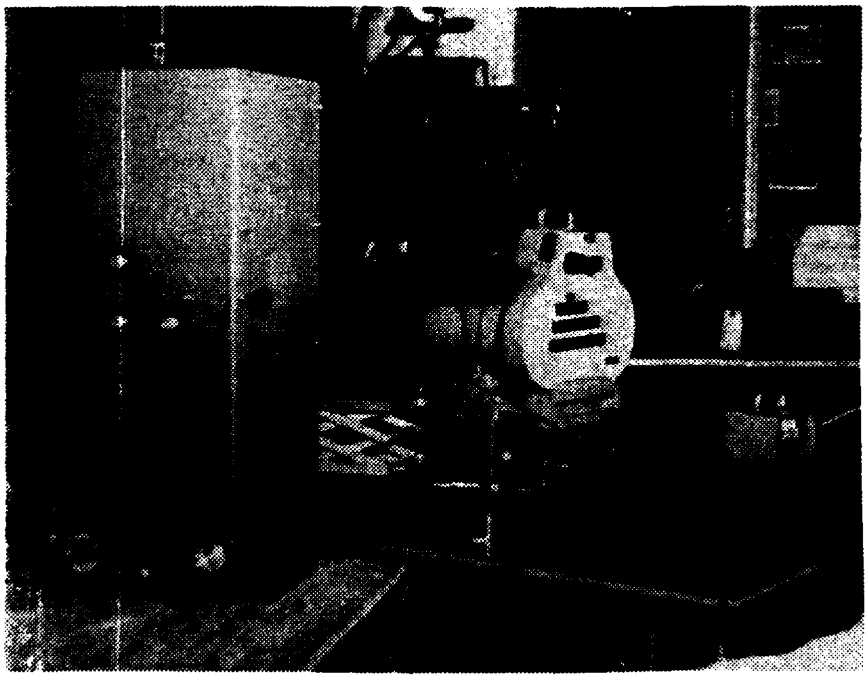


Figure 19. Frontlighting Layout.

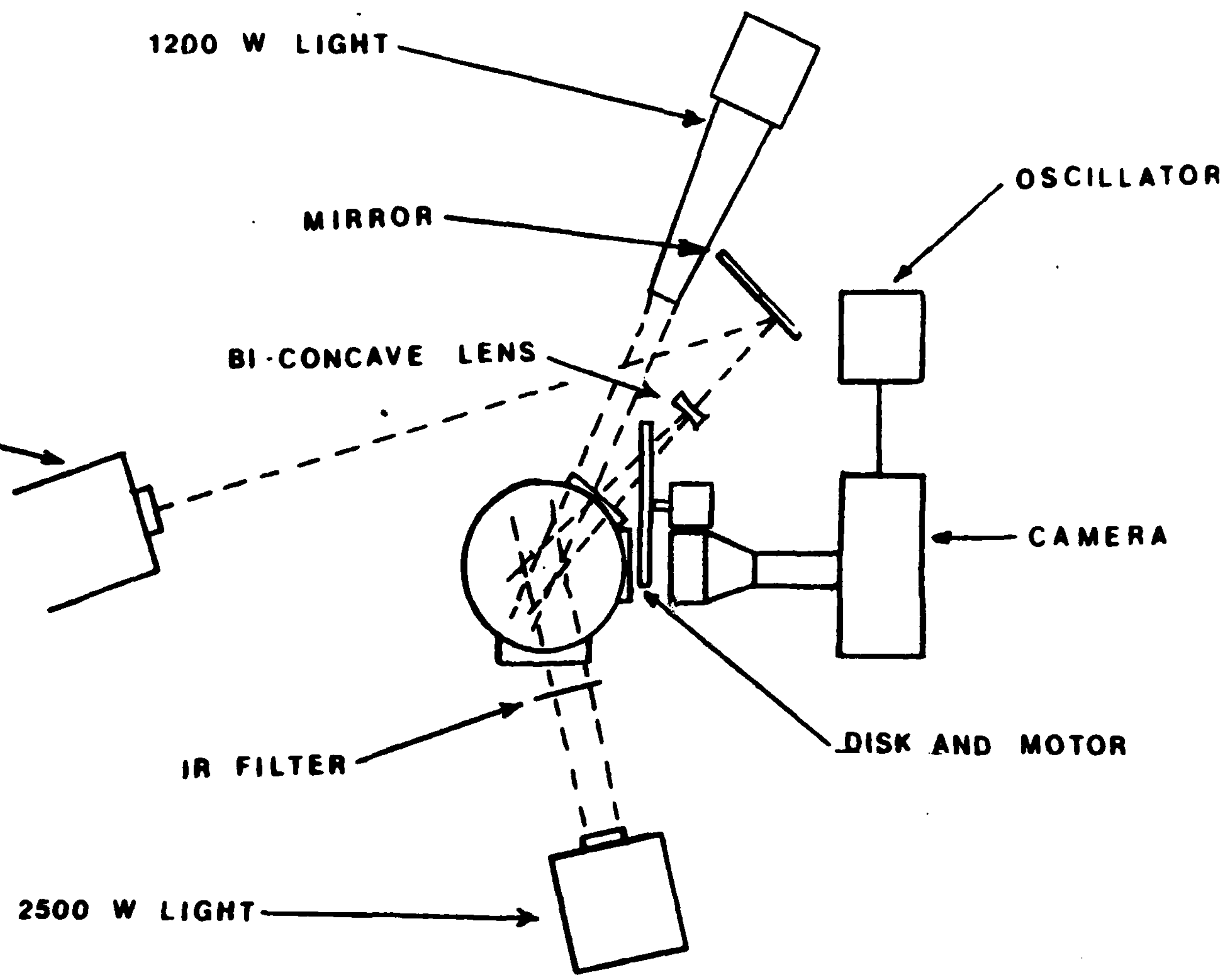
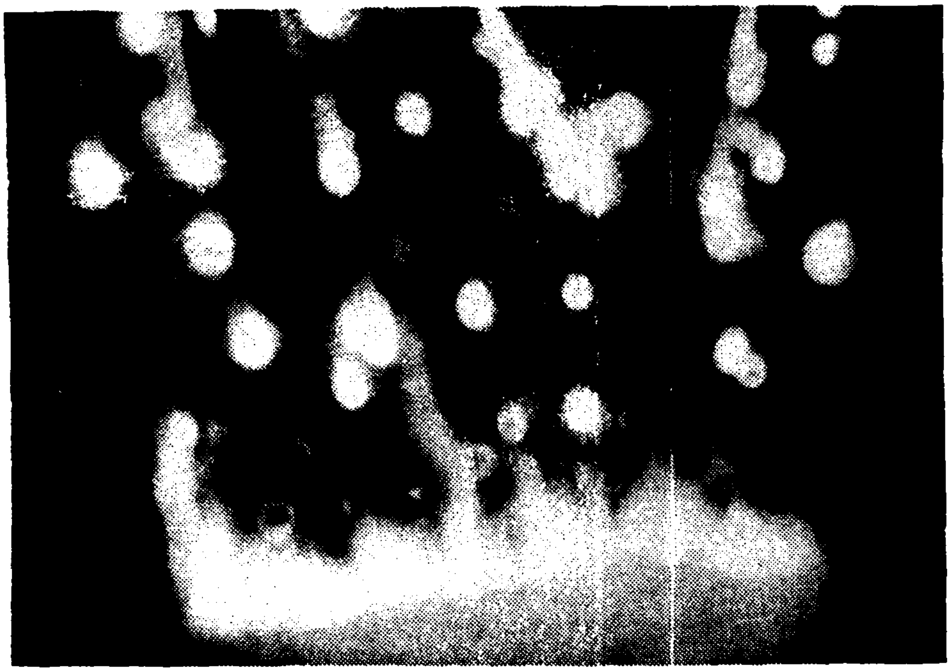
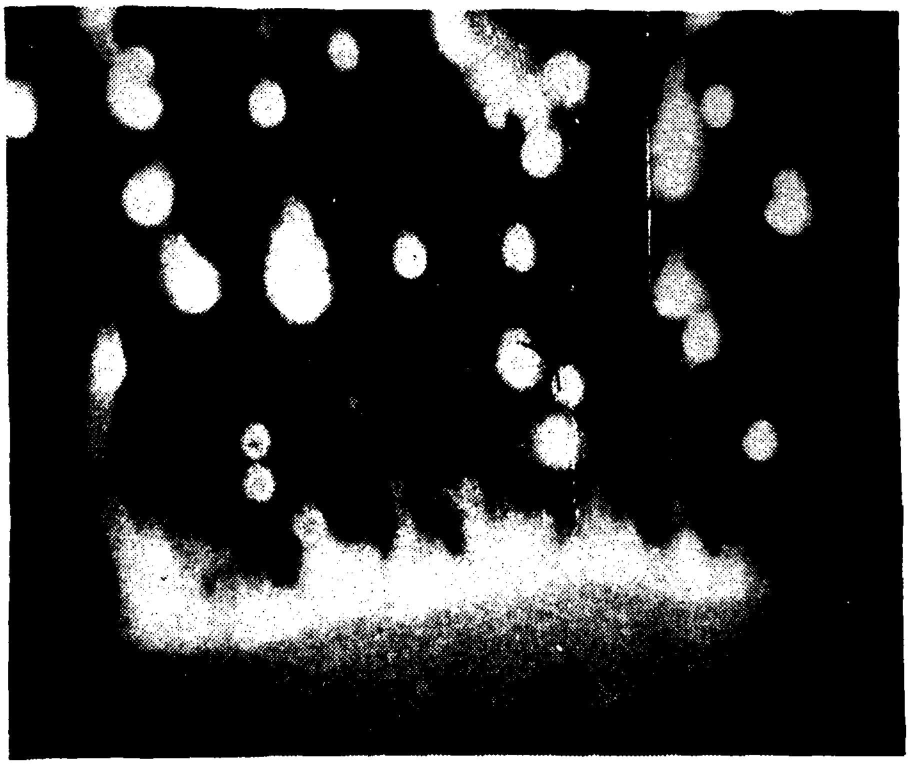


Figure 20. Frontlighting Planform.

Figure 21. Example of Backlighting Result Using WGS-6A.

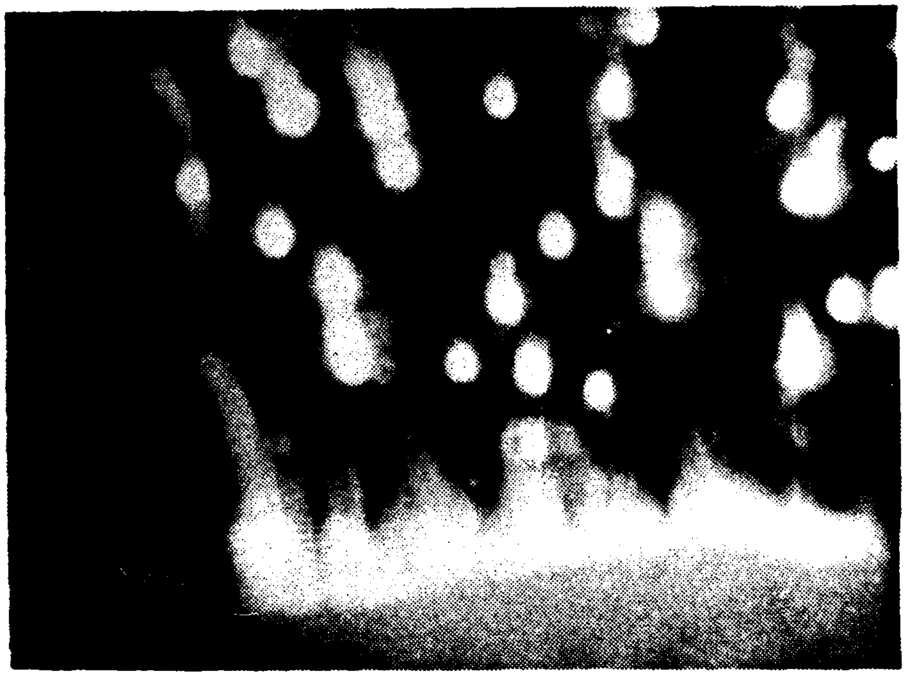


(a)

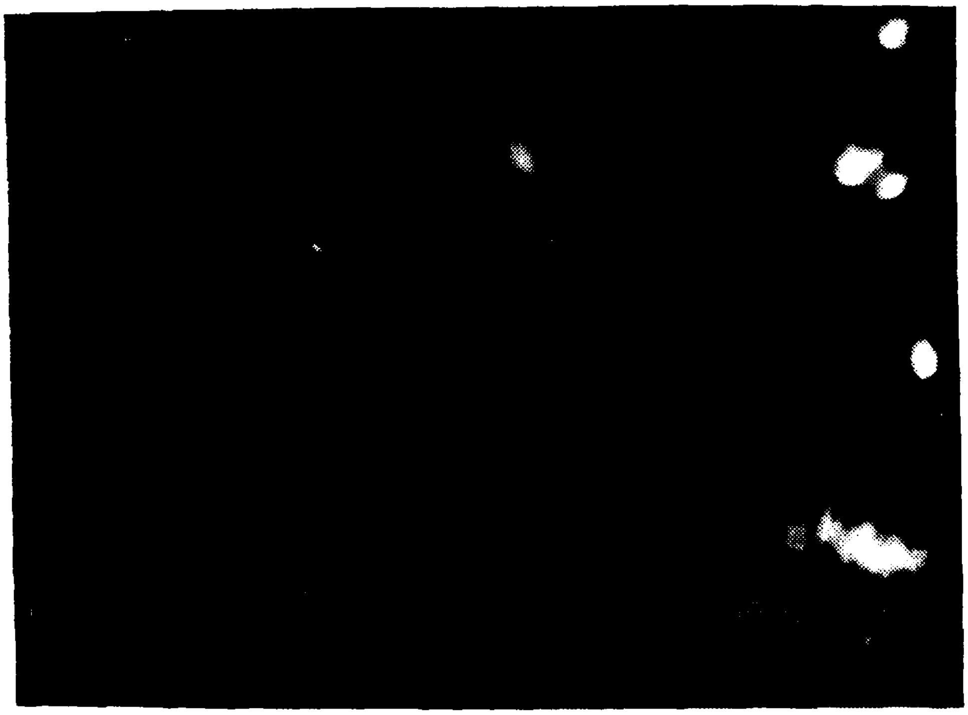


(b)

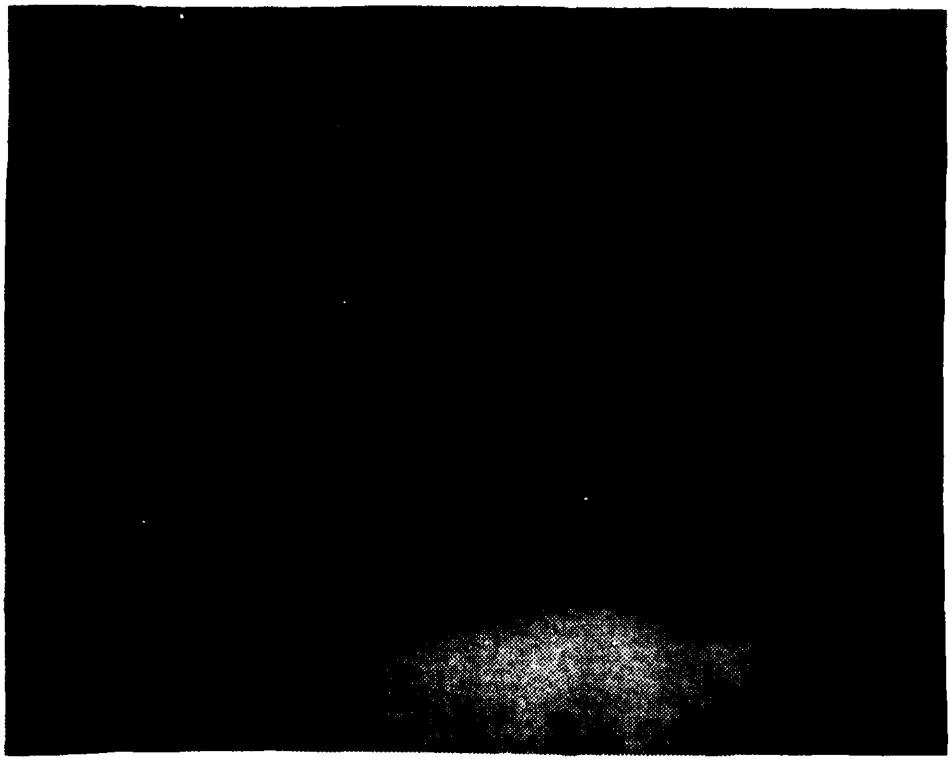
Figure 22. Photo Sequence of Burning WGS-6A Strand



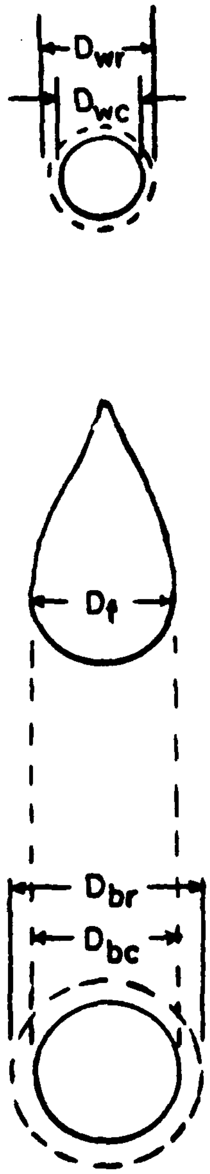
(c)



(d)



(e)



Dwr = White lighting, bright ring diameter

Dwc = White lighting, dark center diameter

Df = Flame sheath diameter

Dbr = Filtered lighting, bright ring diameter

Dbc = Filtered lighting, dark center diameter

Figure 23. Object Diameter References.

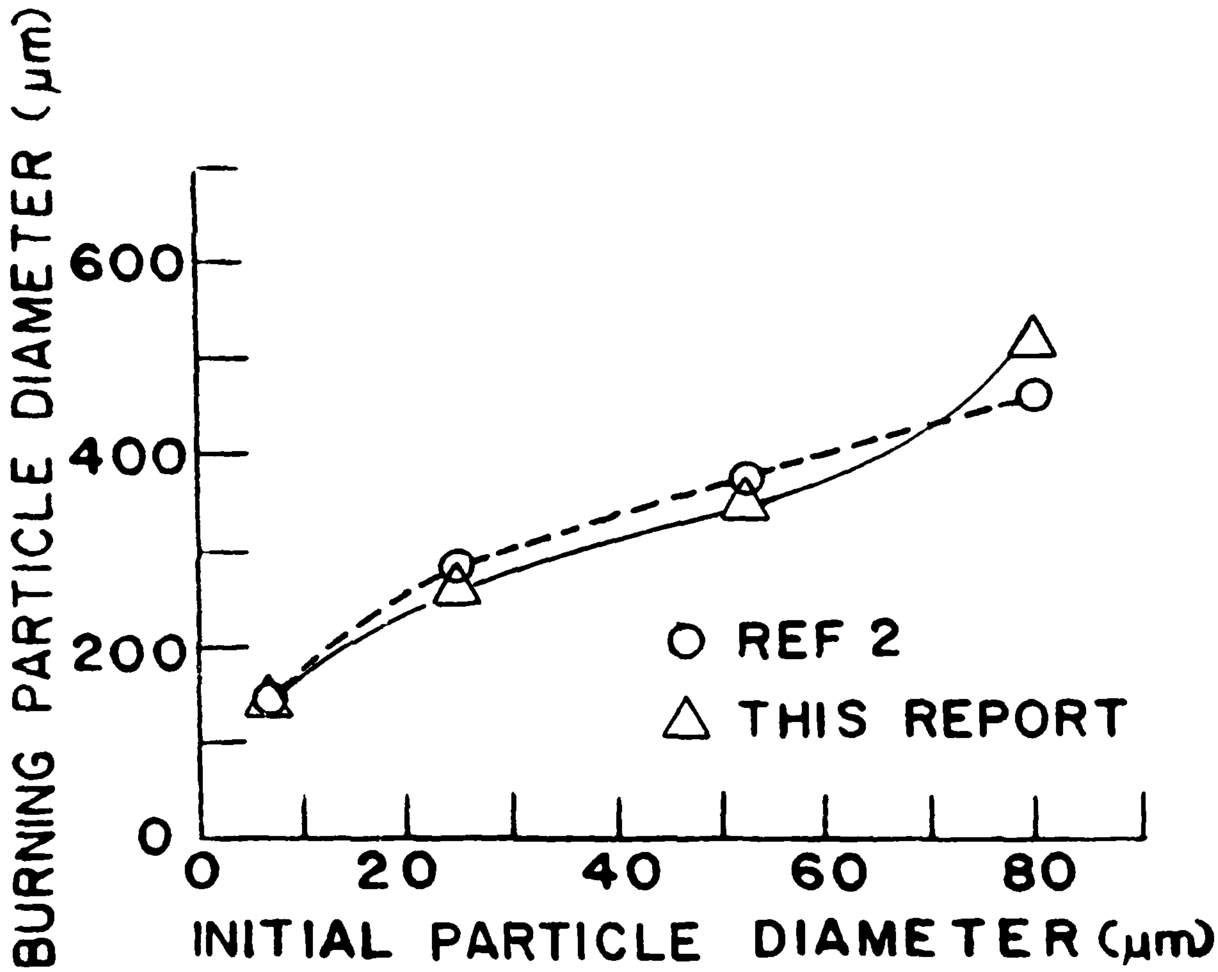


Figure 24. Burning Particle Diameter Versus Initial Particle Diameter.

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