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Paper Reprinted from
Conference Proceedings No.391

SMOKELESS PROPELLANTS

NORTH ATLANTIC TREATY ORGANIZATION

EXPERIMENTAL TECHNIQUES FOR OBTAINING PARTICLE BEHAVIOR IN SOLID PROPELLANT COMBUSTION

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SUMMARY

A continuing investigation is being conducted to develop techniques to obtain quantitative data that can be used to relate solid rocket propellant composition and operating environment to the behavior of solid particulates within the grain port and exhaust nozzle. The techniques employed are high speed motion pictures of propellant strand burners and slab burners in a cross-flow environment, SEM analysis of post-fire residue (strand, slab, and motor), determination of D_{32} across the exhust nozzle using measurements of scattered laser light, and holograms of burning propellant strands, slabs and motors. In addition, techniques are being studied for automatic retrieval of particle size distributions from holograms taken of the combustion of solid propellants.

Actual particle sizes of burning aluminum particles were obtained in high speed motion pictures by using high intensity rear illumination of the burning propellants to eliminate the flame envelopes surrounding the burning particles.

Measurements of diffractively scattered light have been made for determination of changes in D_{32} across a solid propellant rocket motor exhaust nozzle.

Two-dimensional motors have been employed to obtain holograms of propellant burned in a cross-flow environment. Other efforts have been directed at reduction of speckle in the recorded holograms and optimization of techniques for minimizing excessive smoke in the recorded scenes.

A computer controlled Quantimet 720 is being used in an effort to obtain particle size distributions from reconstructed holograms.

INTRODUCTION AND OVERVIEW

Aluminum is added to solid propellants to increase performance and to suppress high-frequency combustion instabilities. A small amount of a variety of additives in addition to aluminum (aluminum oxide, zirconium, etc.) are also used in reduced-smoke propellants for acoustic stabilization. Although the delivered specific impulse of metallized propellants is higher than that of the base propellants, the specific impulse efficiency is lower. This results from the presence of condensed metal oxides in the nozzle flow and from unburned metal within the motor port. Some particles, upon reaching the burning surface, depart immediately while others agglomerate on the surface before passing into the gas flow. Most of the metal combustion is thought to occur in the gas phase, resulting in small (typically less than two microns) metallic oxide particles. In addition, particle burnout also can result in the break-up of a metallic oxide cap or layer. This can result in larger (greater than five microns) particles. The larger particles are more important in the determination of two-phase flow losses in the exhaust nozzle flow since they can lag the gas flow and, in principle, could be affected through propellant changes. There are several rather complex computer codes [Ref. 1] which attempt to model the important processes of momentum and thermal energy exchange between the solid, liquid, and gaseous phases as well as particle collisions, break-up, and wall collisions. However, these models remain semi-empirical and are generally based upon particle size distributions which were obtained from collected nozzle exhaust flows [Ref.2]. Particle histories from the surface of the propellant to the nozzle exit remain largely unknown, due to the difficulty of making direct measurements within the motor and nozzle. Prediction of performance losses due to the presence of the original metal and the metal oxides are very sensitive to the assumed particle size distribution, and essentially no data are available that give this distribution as a function of position throughout the motor and nozzle.

Collecting exhaust products is feasible only for small rocket motors. Even then, the techniques employed result in considerable variation in the measured sizes [Ref. 2]. Dobbins [Ref.3] and Dobbins and Strand [Ref.4] attempted to use an optical technique for measuring exhaust particle size and to compare the measurements with tank collected exhaust results. The optical technique used was a three-wave-length transmission measurement. This technique requires knowledge of particle index of refraction and the standard deviation of the particle size distribution. The collected exhaust particles indicated that the exhaust particle size was not influenced significantly by either the propellant weight fraction of metal or the chamber pressure. The optical measurements generally yielded sizes which were too small and the results were inconsistent with the collected exhaust data. It was speculated that this discrepancy resulted from a bi-modal exhaust particle distribution.

Light transmission measurements have the advantage of being applicable to dense concentrations where multiple scattering occurs [Ref.5]. However, the method works best for small particles (on the order of the wavelength of the illumination source) and requires a-priori knowledge of the particle characteristics.

Light scattering measurements can also be used to determine particle size [Refs. 6-15]. If the scattering angles used are specifically selected, the technique can be used to look almost entirely at one lobe of a bi-modal size distribution. Ratioing intensities obtained at two forward scattering angles can be used to further reduce the complexity of the method. However, scattering techniques are generally thought to be applicable only to systems where the transmittance is greater than approximately 90% in order to satisfy single scattering requirements.

A combination of light transmission and light scattering measurements [Ref.13] appears to be well-suited for many solid propellant rocket motor exhaust flows. However, experimental efforts are first needed to determine under what conditions (metal loadings, operating pressure, propellant ingredients, etc.) light scattering measurements can be effectively made in this difficult environment.

The goal of the investigation to date has been to develop and compare experimental techniques that can be used for obtaining quantitative data on the effects of propellant properties, operating pressure, and nozzle geometry on the behavior of metallized particulates within the grain port and nozzle of solid propellant rocket motors. These data are needed in order to (1) improve solid propellant performance predictive capabilities, (2) provide needed input to current steady-state combustion models which include oxidizer-metal interactions, (3) provide data on the effects of motor and propellant conditions on exhaust signature and (4) provide in-motor particle size distributions which will allow more accurate predictions of damping in stability analyses. The techniques employed have been high speed motion pictures of strand burners and slab burners in a cross-flow environment, SEM analysis of post-fire residue (strand, slab, and motor), determination of changes in D_{32} across the exhaust nozzle using measurements of scattered laser light, and holograms of burning propellant strands and slabs. In addition, considerable effort has been directed toward development of automatic data retrieval methods for obtaining particle size distributions from holograms taken of the combustion of solid propellants. The holographic effort is a two-part problem. Techniques must be developed for obtaining good quality holograms in a realistic solid propellant combustion environment. However, these holograms are of limited value unless the particle size data can be obtained from them in a reasonable time period. This requires development of computer-aided image analysis techniques.

In previous efforts [Ref.16] the motion picture and holographic techniques were successfully demonstrated using propellant strands with up to 15% aluminum. Fourteen micron resolution was obtained in the high speed motion pictures with a 1.12X magnification (and very small depth of field). In addition, initial determinations of D_{32} were made using measurement of scattered laser light at the exhaust of a small rocket motor. Apparatus modifications were then made to expand and improve the obtainable data. Subsequent results are reported herein.

The high speed motion picture investigation of burning propellant strands was continued using a combination of monochromatic and white-light illumination. The final illumination methods used either intense white-light rear illumination or two side/front illumination sources during one test, a 2500 watt white-light and a 0.8 watt laser at 488 nm. With the latter illumination method a rotating filter disc was placed between the combustion bomb window and the camera lens. This provided alternating frames with high intensity white-light illumination and filtered 488 nm illumination. The camera was mounted on a mill bed to provide both stability and precise focusing. An example of the ability to eliminate the recording on the film of the flame envelopes surrounding burning aluminum particles through the use of intense (2500 watt) rear illumination is shown in figure 1.

A dual-beam apparatus for measuring scattered light was developed to simultaneously measure particle size (D_{32}) at the entrance and exit of an exhaust nozzle of a small solid propellant rocket motor. The diameters were determined using 1024 element linear photodiode arrays to measure diffractively scattered laser light. He-Ne illumination was used at the nozzle exhaust but significant 632.8 nm radiation within the motor combustion zone required the use of 488 nm illumination in that region. Early measurements were successful at both locations. However, the presence of char agglomerates and the use of a short motor with small residence times (less than 5 msec) significantly affected the "measured" D_{32} and produced large amounts of condensate on the converging section of the exhaust nozzle. Several improvements were then made. The motor was lengthened to increase residence time to approximately ten msec, multiple sweeps of the diode arrays were made to improve the statistical validity of the data and the Air Force Rocket Propulsion Laboratory fabricated GAP propellants to replace the HTPB propellants which were originally used in an attempt to provide "cleaner" exhaust products. In addition, the optics and data acquisition methods were modified to improve accuracy. Transmitted light is now blocked with a "stop" so that the non-deflected laser beam can be positioned directly on the first diode of the array if desired. Interactive graphics have also greatly improved the speed and accuracy of the data reduction. A cylindrically perforated, aft-end uninhibited grain is currently being used in an attempt to further eliminate inhibitor char in the exhaust gases while providing a nearly nuetral burning grain.

Efforts have been directed at improvement of the quality of the holograms which are obtained in the 2-D motor in the presence of cross-flow. The propellant slabs are bonded between borosilicate glass side plates and burned within a combustion bomb. Currently, efforts are being directed at obtaining holograms from within a small rocket motor.

Various techniques have been suggested for the automatic retrieval of particulate diameter data from reconstructed holograms; ranging from complete digitization to man-in-the-loop optical methods. A reasonable near-term solution appears to be a combination of both optical and digital methods. Digital methods appear to be needed to reduce non-uniform background illumination and speckle, whereas analog techniques (such as the Quantimet 720) appear to be well suited for rapidly obtaining particle size data from holograms which have improved uniformity in background illumination.

DETERMINATION OF PARTICULATE SIZE USING MEASUREMENTS OF SCATTERED LIGHT

Introduction

The method used in the present effort is the diffractively scattered light technique. The diffraction patterns of light scattered by particles are analyzed to determine the volume-to-surface mean diameter (D_{32}). This method has the disadvantages that size distributions cannot be easily determined and particles larger than some threshold size will not be detected due to the exceedingly small angles at which they scatter light. However, it has the advantage that it is non-intrusive and, in theory, can be used in the internal motor environment. Propellant composition can limit the application of the technique by producing large particulates and/or very dense particle clouds.

The completely general theory of scattering was developed by Mie and is presented by Van de Hulst [Ref.15]. The light scattering characteristics for spherical particles of any size are fully described and the phenomena of reflection, refraction, diffraction and extinction are considered. For particle sizes much smaller than the wavelength of the illuminating light source the Mie equations simplify to what is called Rayleigh scattering.

The size of the particles of interest in solid propellant rocket motor combustion depends upon the application. Most applications are concerned with particles having diameters much greater than the wavelength of visible light. Scattering by these larger particles is described by Fraunhofer diffraction. Measuring the particle size for a monodispersion can be accomplished by measuring the angular position of a dark or bright ring in the diffraction pattern. This method is not used for polydispersions since the discrete rings are not observed. However, Dobbins, et al [Ref.7] found that the volume-to-surface mean diameter of a polydispersion (D_{32}) defined by

$$D_{32} = \int_0^{D_{max}} N_r(D)D^3 dD / \int_0^{D_{max}} N_r(D)D^2 dD \qquad (1)$$

(where $N_r(D)$ is a distribution function describing the proportion of particles with diameter D in the sample), could be accurately measured. The value of D_{32} was shown to be quite insensitive to the form of $N_r(D)$. In addition, since the ratio of forward scattered light at two angles is dominated by Fraunhofer diffraction, it is insensitive to the particle refractive index and the particle concentration [Ref.13]. To evaluate the integrated intensity over all particle sizes requires specification of $N_r(D)$. Dobbins, et al [Ref.7] used the Upper-Limit-Distribution-Function developed by Mugele and Evans [Ref.9] and this approach was followed in the present investigation.

For $\pi D_{32}\theta/\lambda$ (where θ is the scattering angle and λ is the wavelength) less than 3.0, a Gaussian curve [Ref.14] can be used which closely matches the theoretical intensity profile obtained by integrating the Fraunhofer diffraction expression together with the Upper-Limit-Distribution-Function [Ref.7]. This Gaussian expression has been presented by Buchele [Ref.14] and is given by

$$I_\theta / I_{\theta=0} = \exp - (0.57\pi D_{32}\theta/\lambda) \qquad (2)$$

Equation (2) can be used to obtain the intensity ratio between two (within the apparatus limits) forward scattering angles:

$$I_2/I_1 = \exp - D_{32}^2[(\theta_2^2 - \theta_1^2)/(0.57\pi/\lambda)^2] \quad (3)$$

Experimental Apparatus and Procedures

Figure 2 is a photograph of the complete apparatus including the exhaust collection tube. The light scattering equipment was mounted on two optical benches; one for measurements in the nozzle exhaust and one for measurements within the motor cavity. The light sources employed were eight milliwatt helium neon and argon lasers for the exhaust and motor paths respectively.

Each beam passed through the appropriate test volume and was then interecpted by a physical stop located in front of the receiving optics. The further the stop was placed from the test section, the smaller was the angle at which scatatered light could be measured. The upper limit of scattering angle is determined by the diameter and focal length of the focusing lens, the distance between the focusing lens and the particles, the diameter of the motor window, or the height/position of the diode array. In the present apparatus scattered light could be measured within an angle increment of approximately 0.05 radians. The minimum possible scattering angle was approximately 0.008 radians and the maximum approximately 0.07. These angles can be changed by changing one of the above limits. The presently employed angle limits introduce some bias in the collected data as illustrated in figure 3.

The scattered light passed through a laser line filter and a 50cm focal length lens which focussed the light onto the linear diode array. The arrays each contained 1024 silicon photodiodes on a single chip with 25 micron spacing. The accompanying circuits provided a "sampled and held" output which was essentially analog except for switching transients. The actual sampling time of the array was about 34 msec with a a delay between scans of about 6 msec. Currently the system is being improved to permit sampling in approximately 4 msec.

Raw data was plotted on the CRT where any obviously erroneous scans could be excluded from further data reduction. The valid scans were averaged to obtain a mean scattering profile. The mean intensity profile taken before particles were introduced was then subtracted from that taken with particles present. This corrected for the characteristics of individual photodiodes and extraneous light which was independent of the particles.

A symmetric moving-average-type of digital filter was then applied to the profile to achieve smoothing. This type of digital filter was chosen for simplicity and because it does not have the phase lag of analog filters. Smoothing of the data has been found to be necessary if good results are to be obtained using the two-angle methods when only a few scans of the array are possible (as in time-dependent combustion).

Several data reduction techniques have been investigated for obtaining D_{32} from the measured intensity profiles. The initial method required the comparison of the experimentally obtained intensity profile with that produced using equation 2. This required the profile to be normalized using the "unknown"(since the transmitted light dominates at small angles) forward scattered intensity at $\theta=0$. This quantity and D_{32} for the theoretical profile were adjusted using interactive graphics until the theoretical and experimental profiles provided the best match. This technique provided reasonably good results but required considerable user interpretation of the "best fit".

The method currently being used minimizes both data reduction time and "user interpretation". A minimum value of θ is chosen from the filtered profile (where beam stop effects or diode position begin to influence the data). This yields I_1 and θ_1 for use in equation (3) . D_{32} is then varied, each value resulting in a curve for I_2 vs. θ_2. The "best fit" to the experimental profile is then found, without the need to estimate the $\theta=0$ scattering intensity.

The two-angle method is also used. The data is scanned using many values of θ_1 together with several angle ratios to determine θ_2. D_{32} is then found from equation (3) and displayed as D_{32} vs. θ_1 for each value of θ_2/θ_1.

Calibration of the apparatus was accomplished by measuring D_{32} of various particles of known size distribution. Polydispersions of glass or polystyrene spheres and aluminum oxide powder were suspended in water within a Plexiglas or glass container. A scanning electron microscope (SEM) was also used to photograph each particle sample.

Some of the calibration results (using the original method discussed above) are summarized in Table I. Figures 4 and 5 present typical calibration results.

TABLE I CALIBRATION RESULTS FOR LIGHT SCATTERING APPARATUS

PARTICLE MATERIAL	SAMPLE PARTICLE SIZE RANGE (microns)	CALCULATED D_{32} (microns)	MEASURED D_{32} (microns)
Polystyrene	3-6	4.7**	4.5
Polystyrene	6-16	10.2**	10.0
Polystyrene	15-30	21.6**	21
Glass	37-44	38*	40
Glass	53-63	54*	54-58
Glass	1-37	25*	28-30

* From SEM photographs ** From Manufacturers Data

The results of the calibration tests showed that the apparatus is capable of accurately measuring mean particle size for a broad range of mean diameters providing that size range is not too wide (per figure 3).

If the larger sizes in a bi-modal distribution of actual motor products includes a wide range of particle sizes, then care must be taken in the selection of the forward scattering angles so as to not bias the measurements to the larger or smaller particle sizes. Another concern about the measurement technique is the effect of the index of refraction of the exhaust gases in which the particles are present. To examine this, the 6-16 micron polystyrene sphere data was used to find D_{32} with varying assumed values for the index of refraction. The result was that a 10% increase in the index of refraction increases the "measured" D_{32} by approximately 10%. This could present difficulties if the present technique were attempted to be applied to a wide range of propellants/operating conditions where the unknown exhaust index of refraction could vary significantly from test-to-test. In the present effort similar propellant compositions are used with varying solids size and loading and with varying nozzle geometries. Variations in the index of refraction should be small in this case.

A further concern, especially for the "in-motor" measurement, was the maximum attenuation of the transmitted beam which would allow the scattering measurements to be properly made. Measurements have generally been assumed to require less than 10% attenuation in order to insure single scattering . Calibrations using the 6-16 micron polystyrene beads were conducted with transmittances varying from 85% down to 30%. The two-angle method results are shown in Table II.

TABLE II TRANSMITTANCE EFFECTS ON SCATTERING MEASUREMENTS

TRANSMITTANCE, %	D_{32}, MICRONS
85	10
70	10
60	9.5
50	9.5
30	9

These results indicate that a significant attenuation of the transmitted beam did not prohibit use of the single-scattering theory for obtaining D_{32}. However, very low "in-motor" transmittance values are often encountered in highly metallized systems. Fortunately, minimum smoke propellants often have less than 2% metal and, therefore, may often be studied using this diagnostic technique.

Results and Discussion

In this initial investigation, two solid propellant compositions were used. One propellant was non-metallized and used a GAP binder with AP. The other was an HTPB/AP propellant with 2%, 40 micron aluminum and 0.25% Fe_2O_3.

The non-metallized propellant was used to determine the effects of apparatus design, exhaust gas opacity and thermal and velocity gradients on the laser beam transmittance and scattering characteristics. Significant attenuation (greater than 20%) and broadening at small angles occurred in the nozzle exhaust beam. The measurement location was located very close to the exhaust plane of the converging nozzle. This indicated that future tests should be conducted with the measurement location further aft; where jet spreading will both reduce opacity and minimize velocity and thermal gradient effects. The "in-motor" measurement revealed the necessity for very careful alignment of the windows. If the windows are not very nearly perpendictular to the laser beam, changes in the index or refraction of the gas when the motor is fired can cause the transmitted beam to deflect either off of the array or below the beam stop.

When the metallized propellant was fired, the two-angle method yielded a D_{32} in the exhaust products of approximately 8 microns (Fig. 6) for the larger scattering angles (greater than 0.020 radians). SEM photographs of a small portion of the collected exhaust products (Fig. 7) showed particles as large as 20 microns, a few between 5 and 10 microns and many (as expected) in the one micron range. At the nozzle entrance the measured D_{32} using the two-angle method was between 8 and 10 microns (Fig. 8). Residue collected from the combustor wall near the viewing location is shown in figure 9. Particles in the 9 to 10 micron range were evident with many having diameters less than 3 microns.

These limited initial results indicate that the diagnostic method can be used to determine the change in D_{32} across the exhaust nozzle if care is used in window alignment and exhaust measurement location. In addition, the angle limits of the apparatus must not unduly bias the data toward the larger or smaller particles. Little change in D_{32} was observed to occur across the exhaust nozzle in this initial test.

HOLOGRAPHIC INVESTIGATION

One of the diagnostic techniques available for studying particulate behavior in solid propellant rocket motors is holography. For the exposed scene a hologram provides both amplitdue and phase information. The latter characteristic enables a 3-D image to be reconstructed so that particles within in the entire depth of field of the scene may be recorded. Flame envelopes surrounding the burning particles are readily eliminated from the recorded scene through the use of narrow pass laser line filters. Single pulsed holography provides a means for effectively stopping the motion. However, it only provides information during a single instant of the combustion process.

Smoke generation (i.e., small Al_2O_3 and binder products, etc.) during the combustion process presents a major obstacle to obtaining good holograms, 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-resolution hologram, the illumination ratio reaching the holographic plate should be between 5:1 and 10:1. Test-to-test variation in 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 propellant burning requires experimental determination of the most suitable propellant composition and dimensions and the optimum time for taking of the hologram during the burn.

Initial efforts utilized strand burners within a nitrogen-purged combustion bomb. Subsequent to these initial strand burner tests it was desired to obtain holograms in flow environments which more nearly approached that in an actual motor. Small two-dimensional, windowed motors were used next. Currently, efforts are being directed at obtaining holograms within a small rocket motor. Additionaly, holograms have been recorded of resolution charts for calibration purposes. Investigations into changing the recording and reconstruction geometries have also been conducted.

The laser holographic system uses a pulsed ruby laser (Ref. 18) together with a holocamera (Ref. 19). The operating wavelength is 694.3 nm with a beam diameter of approximately 3.2 cm. A one joule pulse with a 50 nsec pulsewidth was used for this investigation.

The 2-D motor employed two opposed propellant slabs with ends and sides inhibited with a very thin coating of GE Hi-temp gasket (red RTV) material. The 1 cm x 4 cm slabs were placed between two borosilicate glass slides and the inhibitor was then allowed to cure. Propellant thickness was varied from 1 to 3 mm.

All holograms were recorded with diffuse illumination from the laser in order to minimize the presence of schlieren interference fringes produced by temperature and density variations of the combustion gas products during the burn. This diffuse illumination introduces speckle into the reconstructed images as discussed later. The primary problem in sizing the particles in the reconstructed image is interference from this speckle which can have a maximum size that is comparable to the particles at the lower end of the expected particle size distribution.

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. Fourteen micron resolution was readily attained through the microscope. With very careful alignment and cleaning of all optical components, together with the use of a rotating mylar disc (discussed below), 9 micron resolution has been achieved.

Holographic recordings have been made successfully using propellant strands burned at pressures of 34 and 68 atm and with various concentrations of aluminum up to 15%. Figure 10 is a photograph taken at one plane within a reconstructed hologram. The propellant and strand dimensions are the same as shown in figure 1 for the high speed motion pictures. It is apparent that the flame envelopes and schlieren effects are readily eliminated from the recorded picture.

A representative photograph of a reconstructed hologram obtained using the 2-D motor is shown in figure 11. Good quality holograms were obtained with all propellants containing less than 5% metal additive to pressures of approximately 59 atm (the maximum attempted). A good quality hologram was also obtained with 10% aluminum at approximately 33 atm. No holograms could be obtained with 10% aluminum at pressures of 53 atm or with 15% aluminum. The 2-D motor construction method has proven to provide good results within the above limits. Impingement of the particulates on the glass walls and a high inhibitor-to-propellent mass ratio have provided the upper limits in metal content and propellant thickness in the tests. Holograms may actually 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.

During reconstruction, the geometry shown in figure 12 is used. The real image of the hologram was focused onto a spinning mylar disk, introduced to reduce speckle effects in the observed image. The spinning disk changes the speckle pattern at a rate faster than the response time of the imaging system, causing a reduction in the contrast of the speckle pattern. A variable power microscope was used to view the reconstructed image either by eye or with the image scanner of the image processing system.

With the successful recording and reconstruction of the holograms, an effort has begun to automatically locate particles against the background, and to size the particles using a computer-controlled image processing system. The Quantimet 720 image processor used in this investigation is a general purpose, television-type image analyzer that is capable of elementary shape recognition and various physical measurements of objects by distinguishing differences in grey levels in the image and performing various logical tests on measured dimensions.

Several problems have been identified in this application of data reduction, and potential solutions are being investigated. The problems can be divided into two parts: those that exist without image speckle being present and those that exist with speckle being present.

The first problem is to compute the number of locations that must be investigated in the hologram. For example, for a nominal depth of interest in the hologram of 2 mm, calculations show that for larger (200 microns) particles only one plane is required by the mimcroscope's depth of focus of 6.18 cm, while for 1 micron particles the depth of focus of 1.54 microns will require 1300 planes to be imaged.

The Quantiment also has limitations which can lead to inaccurate results. One technique of separating particles from background is to accept for measurement only those pixels that are darker than a specified threshold. Once the particle has been isolated, the particle size is measured. The Q720 locates an edge of a particle by noting regions where there is a sharp change in grey level. The edge location is determined by finding the pixels with the greatest and least grey levels and locating the edge midway between these two locations. This technique is consistent only for particles with the same extremes in grey levels. For frames that include particles of differing grey levels, the edge location is variable. Uneven illumination is the primary cause of differences in particle grey level. The illumination problems can occur in the hologram recording (i.e., laser nonuniform beam pattern, smoke), in the development of the hologram leading to a plate with variable transmissivity (bleaching the plate can help this problem), and in the reconstruction proceses (i.e., uneven laser illumination, nonuniform spatial response of the image tube). Additionally, electronic noise in the various modules and quantization noise can corrupt the image signal leading to measurement errors.

Having speckle present, as in our hologram reconstructions (due to the diffuse illumination required to eliminate the schlieren fringes in the reconstruction as previously described), we wish to reduce the maximum size of the expected speckle to the smallest value possible. The speckle can have two effects on the image. It produces black spots in the backgound which cannot be readily distinguished from real particles. The second effect is that the speckle can give the perimeter of the particle a "swiss cheese" appearance where the speckle overlaps the edge. This alters any calculated measurements of the particle, such as area or perimeter. The Quantimet usually ignores any holes within the measured area, but significant error is introduced when the perimeter is altered.

Generally, to reduce the speckle size, large aperture optics are desirable. Once the speckle is smaller than the typical particle size the logic test based on the feature size can be implemented in the Quantimet to extract particle information from the background.

If the speckle size cannot be made negligible compared to the particle size, other techniques must be used to reduce the contrast level of the speckle relative to the particle. These techniques are based on the fact that the speckle pattern will shift if one or more of many variables are changed while the object position remanins fixed. By averaging N images with differing speckle patterns, a reduction in the speckle contrast on the order of $(N)^{-1/2}$ is expected.

Variables that can be changed to cause a shift in the speckle pattern are (a) changing the random phase of the diffuse illuminating wave, (b) changing the image aperture, (c) changing the object position (or, equivalently, changing the image screen position or changing the imaging lens position) and (d) computer superposition of images with different diffuse illumination. Each of these techniques introduces complexity into the processing of the image. The first is the easiest to implement with a spinning diffuser in the image reconstruction. While the image is dramatically improved when the disk is spinning compared to the image on a motionless disk, the image quality is not dramatically improved with increased rotation rate. The techniques other than computer processing appear to present insurmountable problems, leaving computer processing of the images the most likely solution. Work has begun on implementing the computer-controlled configuration in an effort to explore this technique.

An example of an initial effort to use the Quantimet 720 in the manual mode is shown in figure 13. This histogram was taken from a photograph of a reconstructed hologram shown in figure 14. Recently, the Q720 has been operated in the computer controlled mode. A particle calibration reticle (Laser Electro-optics LTD. No. RR-50-30-0.08-102-CF-#154M)was viewed directly by the Q720 television camera through a microscope and the particle diameter distribution was determined. Figure 15 presents a comparison between the measured particle size distribution and that specified by the manufacturer of the reticle.

SUMMARY AND CONCLUSIONS

High intensity white-light and monochromatic light have been used to eliminate the flame envelopes that surround burning aluminum particles from the recorded images in high speed motion pictures.

Light scattering measurements have been used to measure the change in D_{32} across the exhaust nozzle of a small solid propellant rocket motor. The diagnostic technique is sensitive to alignment and must be used with caution in order to ensure that particle size biasing is not severe.

The holographic techniques have been successfully used to record particles from strand burner and 2-D motor combustion of solid propellants. The image particle count and sizing from a hologram has successfully been done in the manual mode but automatic techniques that have been recently initiated are preferred. The diffuse illumination required in the recording process to avoid phase fringes due to thermal effects has led to the presence of speckle in the images. Efforts have been made to analyze the size of the speckle and to reduce the maximum speckle diameter. The remaining speckle is reduced by using a spinning diffuser in the reconstruction process. The computer-processed images appear to have the most liklihood of further reduction of the speckle contrast. This method is currently under investigation.

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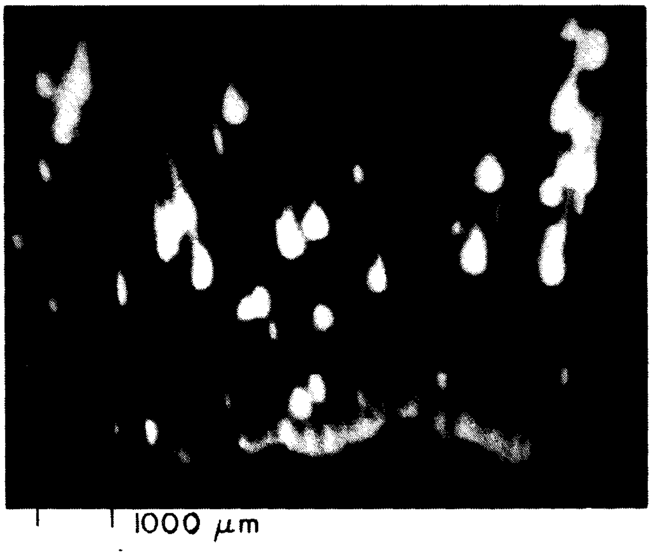
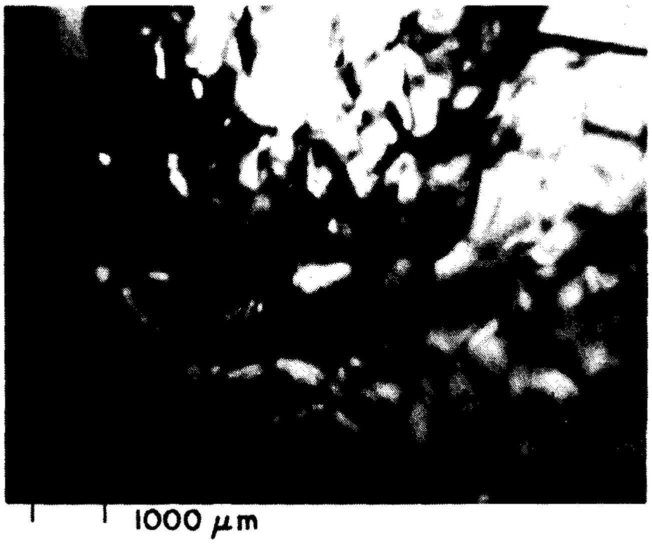
ACKNOWLEDGEMENTS

This paper summarizes work which has been directed by the authors but which has been conducted primarily by graduate students and Naval Postgraduate School engineering technicians. The most recent contributors have been J.M. Glenn, K.J. Graham, R.K. Harris, P.J. Hickey, A. Kertadidjaja, L.A. Klooster, J. Rosa, Y. Lee and P. Shook. This work has been sponsored by the Air Force Rocket Propulsion Laboratory, Edwards AFB, California, USA.



(a) Self-Illumination



(b) 2500 Watt White-Light Rear Illumination

Figure 1. High Speed Motion Pictures of Propellant Strands Burned at 34 atm. Pressure (83% AP, 12% HTPB, 5% Al, 45-62 micron)

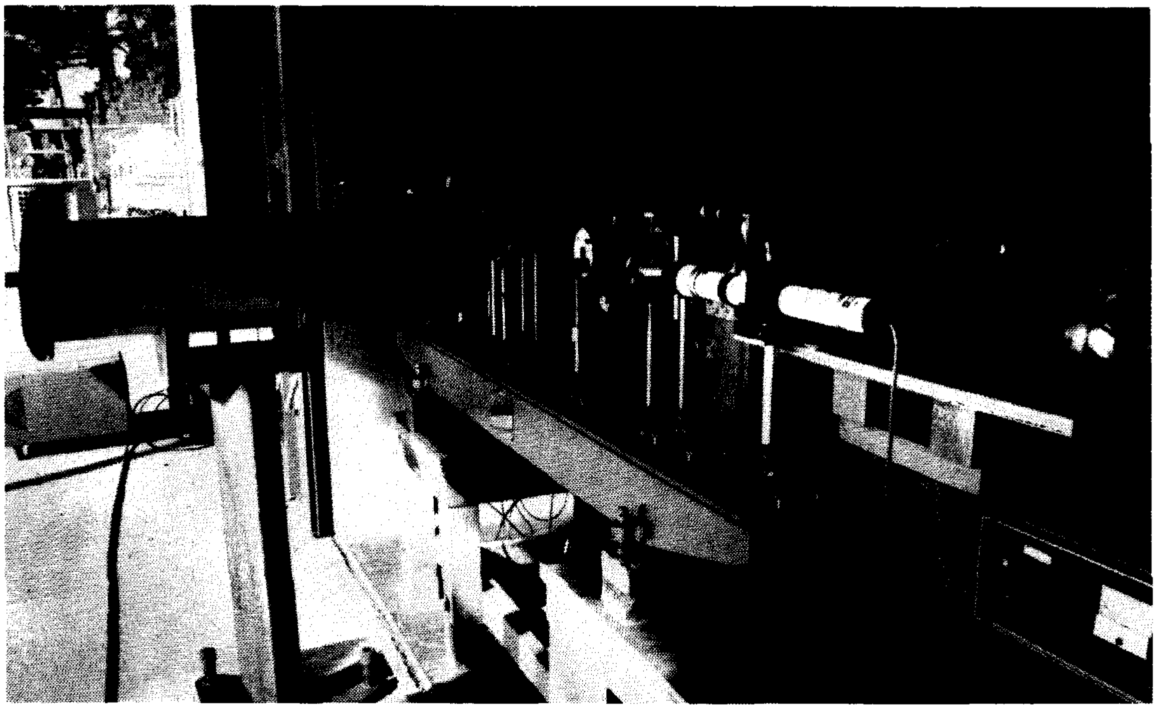


Figure 2. Photograph of Small Rocket Motor With Light Scattering Measurement Apparatus.

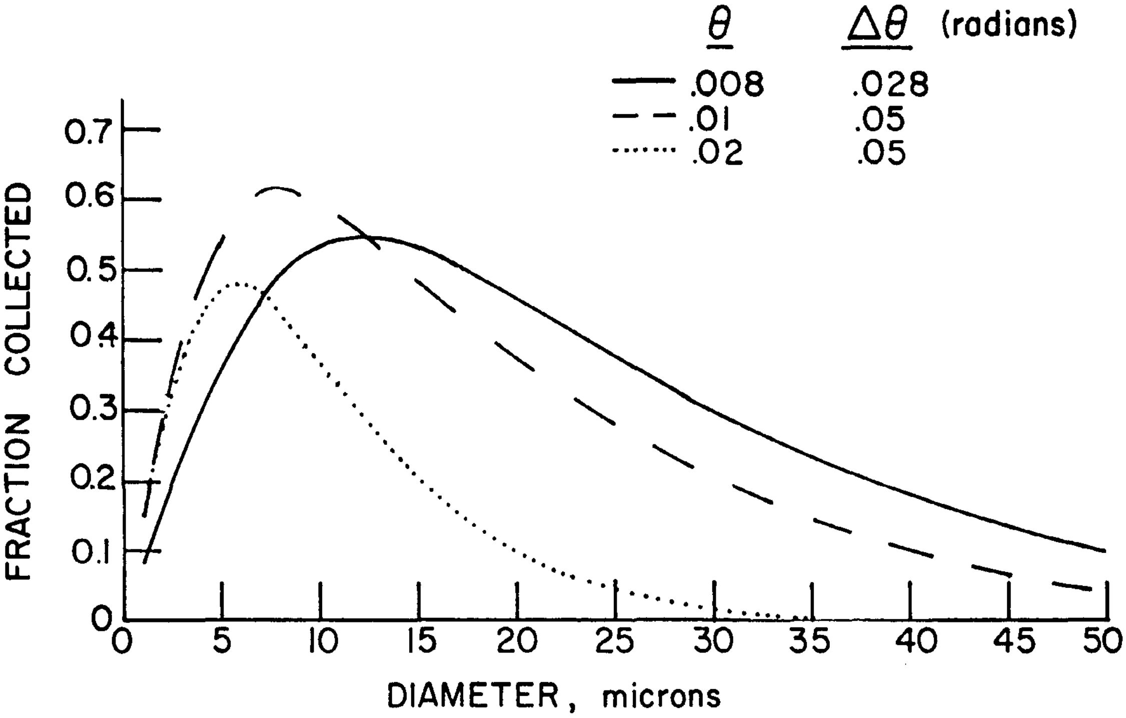


Figure 3. Fraction of Total Normalized Scattered Light Collected as a Function of θ_1 and $\Delta\theta$.

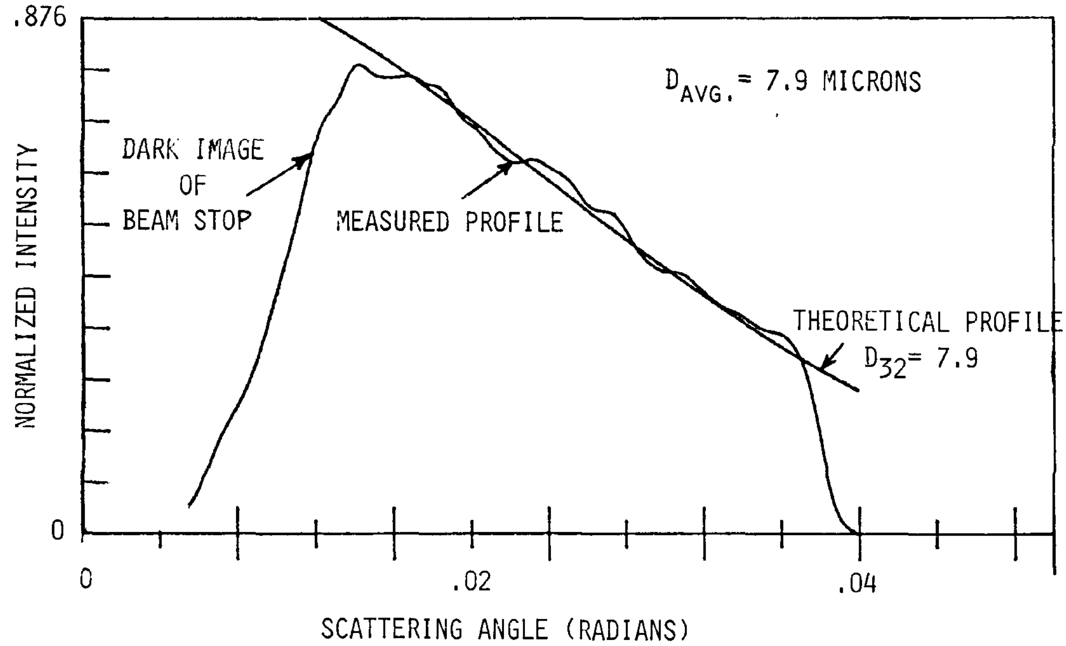


Figure 4. Measured Mean Particle Diameter Using 6-16 Micron Polystyrene Spheres With Curve-Fit Method.

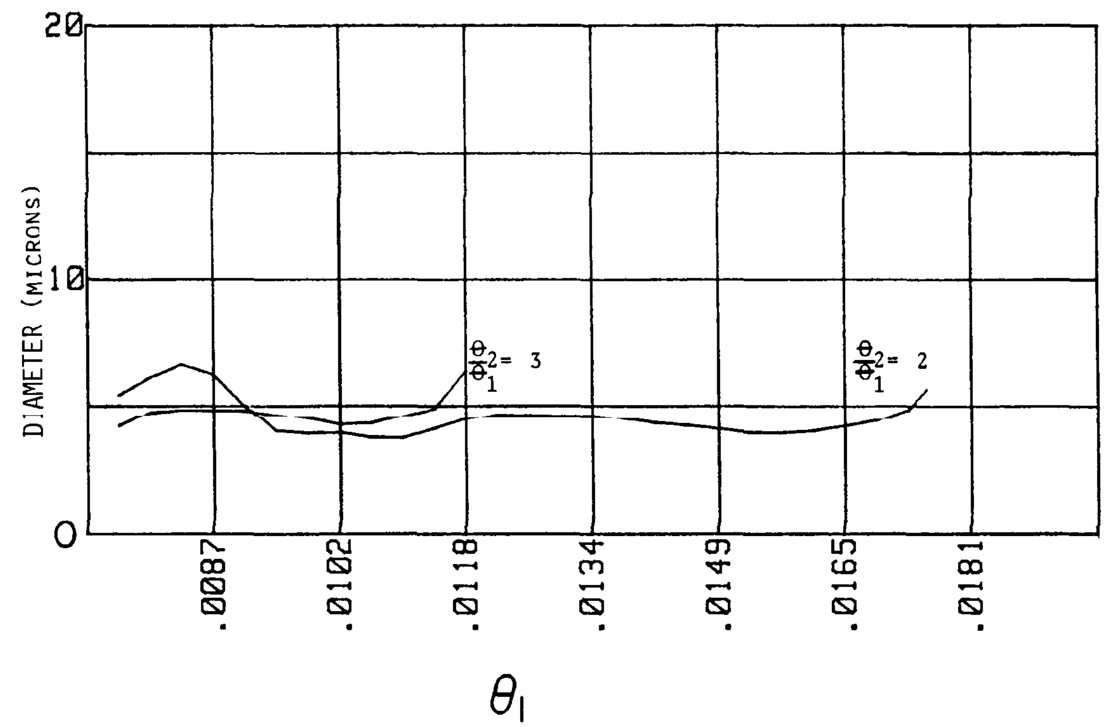


Figure 5. Measured Mean Particle Diameter Using 3-6 Micron Polystyrene Spheres With Two-Angle Method.

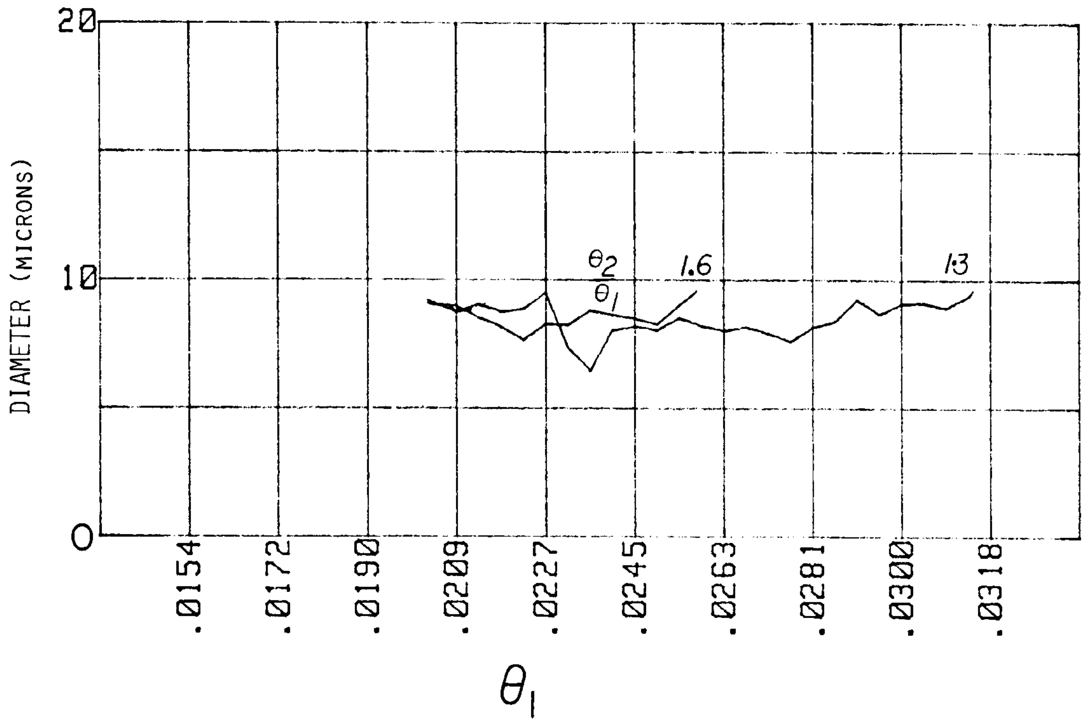


Figure 6. Measured Mean Particle Diameter in Exhaust Flow Using the Two-Angle Method, HTPB/AP Propellant With 2%, 40 Micron Aluminum and 0.25% Fe_2O_3 Burned at a Nominal Pressure of 10 atm.

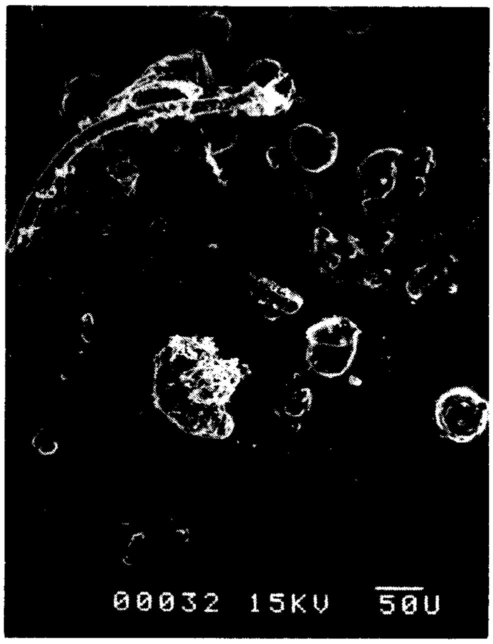


Figure 7. SEM Photograph of Residue From Exhaust Products, HTPB/AP Propellant With 2%, 40 Micron Aluminum and 0.25% Fe_2O_3 Burned at a Nominal Pressure of 10 atm.

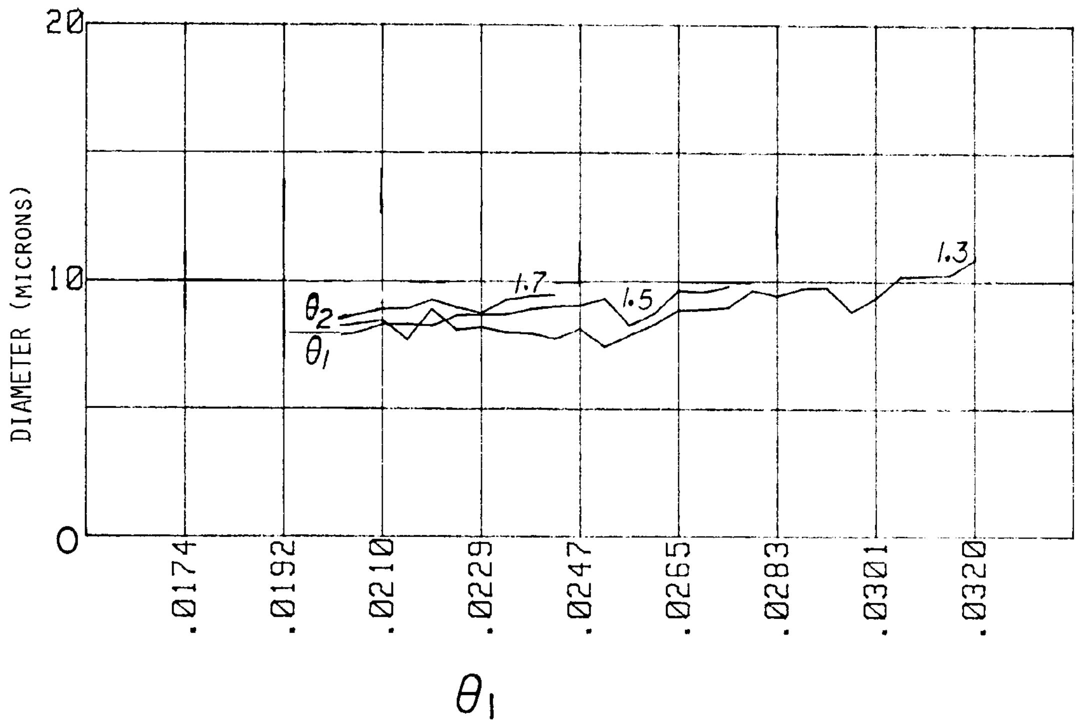


Figure 8. Measured Mean Particle Diameter at Nozzle Entrance Using the Two-Angle Method, HTPB/AP Propellant With 2%, 40 Micron Aluminum and 0.25% Fe_2O_3 Burned at a Nominal Pressure of 10 atm.

Figure 9. SEM Photograph of Residue From Motor Cavity Wall, HTPB/AP Propellant With 2%, 40 Micron Aluminum and 0.25% Fe_2O_3 Burned at a Nominal Pressure of 10 atm.

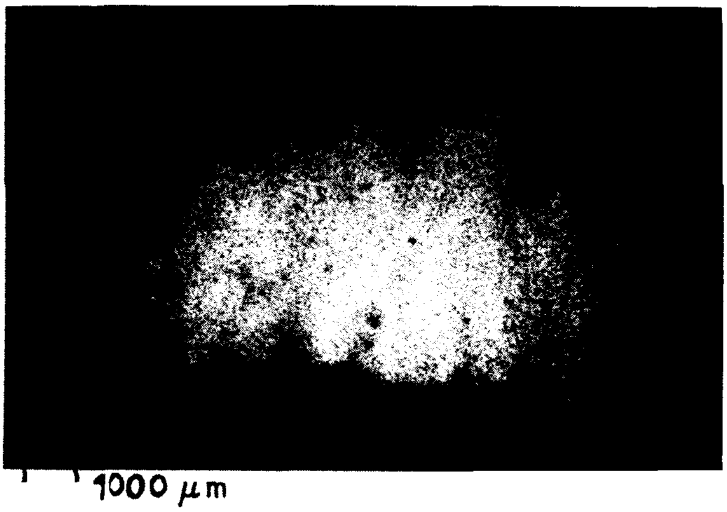


Figure 10. Photograph of Reconstructed Hologram of Strand Burner at 34 atm Pressure (83% AP, 12% HTPB, 5% Al, 45-62 Microns).

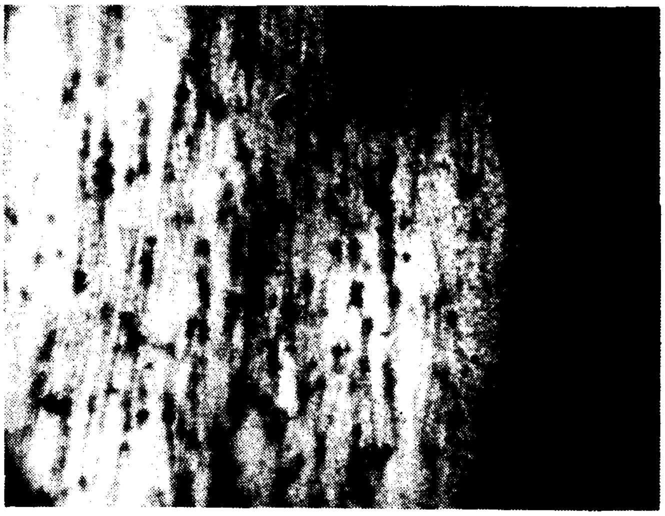


Figure 11. Photograph of Reconstructed Hologram of 2-D Motor Combustion at 28 atm Pressure (83% AP, 12% HTPB, 5% Al, 45-62 Microns).

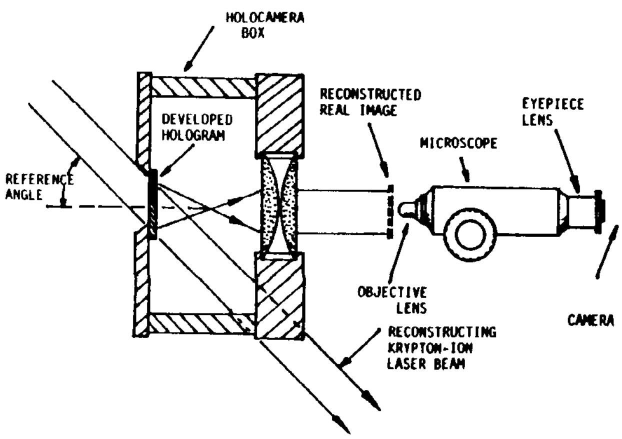


Figure 12. Schematic of Hologram Reconstruction and Viewing Method (Ref. 20)

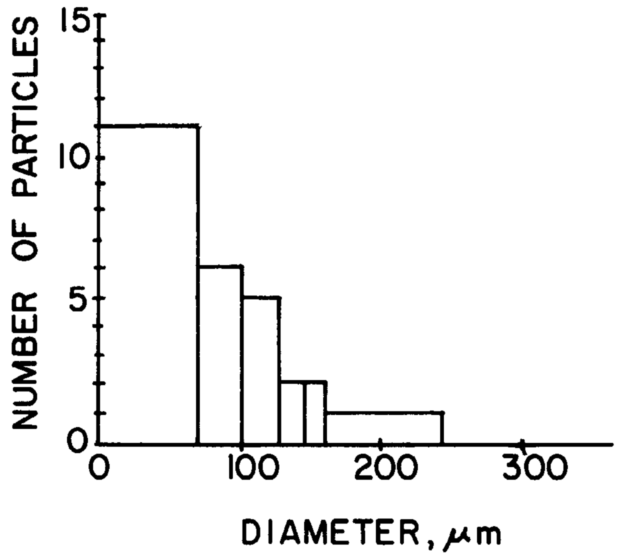


Figure 13. Particle Size Histogram Obtained From Photograph of Figure 14 Using Quantimet 720 in Manual Mode.

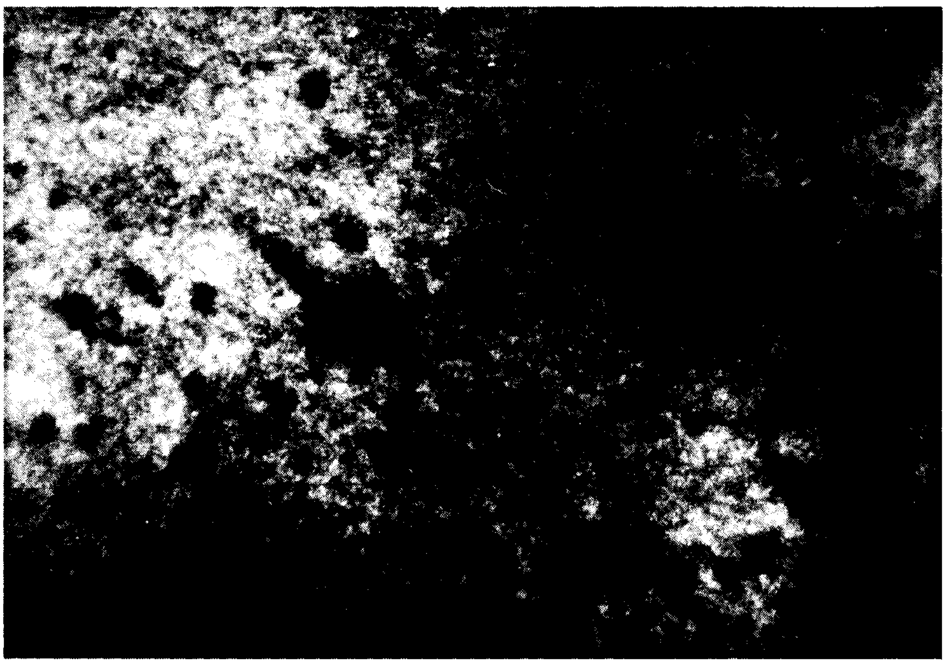


Figure 14. Photograph of Reconstructed Hologram From Propellant Strand Combustion With Stability Additive.

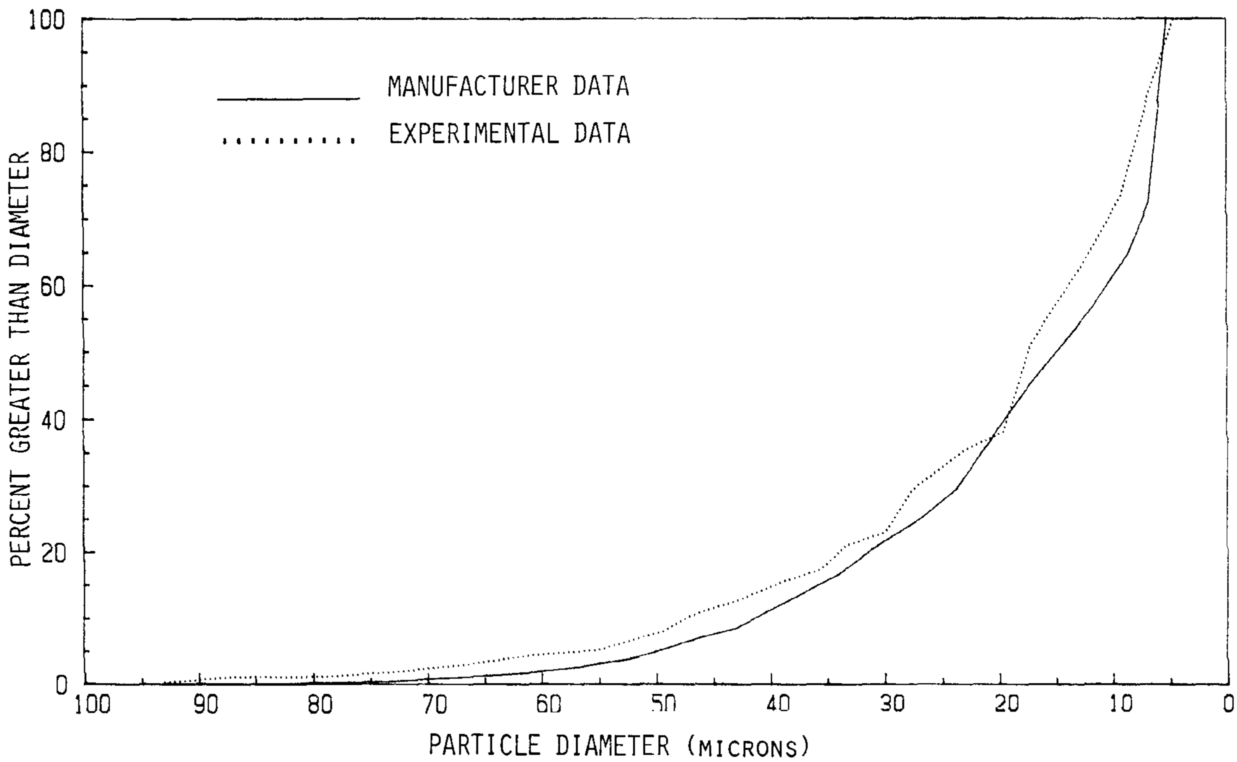


Figure 15. Particle Size Distribution Obtained Using the Quantimet 720 in the Computer-Controlled Mode With a Calibration Reticle.