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PARTICLE SIZING IN A SOLID-PROPELLANT
ROCKET MOTOR USING SCATTERED LIGHT
MEASUREMENTS

by

John S. Rosa

December 1985

Thesis Advisor:

David W. Netzer

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Particle size measurements were consistent with the sizes
found in the collected exhaust products.

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Particle Sizing in a Solid-Propellant
Rocket Motor Using Scattered Light
Measurements

by

John S. Rosa
Lieutenant, United States Navy
B.S., United States Naval Academy, 1978

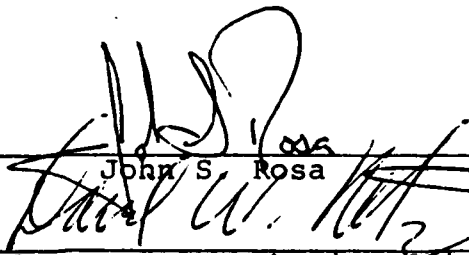
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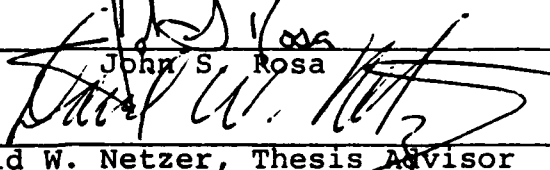
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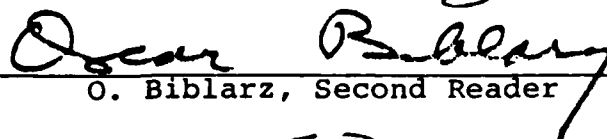
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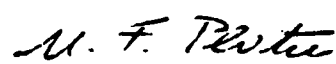
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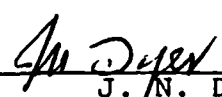

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ABSTRACT

An experimental investigation was performed to determine, in situ, the change in mean particle size across the exhaust nozzle of a small metallized solid-propellant rocket motor. Light scattering profiles were recorded at both the exhaust and the entrance of the nozzle. The experimental method used provided excellent results within the exhaust. However, combustion light at the wavelength of the transmitted light hampered light scattering measurements within the motor. Particle size measurements were consistent with the sizes found in the collected exhaust products.

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I. INTRODUCTION

The importance of aluminum oxide (Al_2O_3) particle size produced in solid-propellant rocket motors has been recognized since aluminum was first introduced as a fuel additive. Aluminum added to a propellant will increase the thrust produced and aid in suppressing high-frequency combustion instability. Although the performance improves with aluminum addition, two phase flow losses adversely affect specific impulse efficiency. Specific impulse efficiency is the product of several component efficiencies, i.e., chemical-kinetic, combustion, two-phase flow, two-dimensional flow, submergence and throat erosion. In aluminized propellants, the two-phase flow loss is one of the more significant losses. Two-phase flow losses result from particle-gas thermal and velocity lags. The latter strongly depends on particle size. Parametric studies involving small motors, with throat diameters less than one inch, at AFRPL [Ref. 1] and CSD [Ref. 2] have revealed that a 1 micron change in particle diameter results in a change of 1% in Isp. The effective use of particle damping for suppression of combustion pressure oscillations is also strongly dependent upon the particle size distribution.

One of several analytical computer programs used to predict performance of a solid-propellant rocket motor is the SPP (Solid Performance Program) [Refs. 3,4]. As the above

discussion indicates, it is of critical importance to accurately predict particle size. This is especially true for particle damping with minimum smoke propellants which typically contain less than 2% metal by weight. The 1975 version of the SPP [Ref. 3] contains a particle sizing empirical model developed by Cohen. This model was based on correlating collected exhaust samples. After a critical review, this model was considered inadequate. A new model was therefore required for a new SPP version, titled Improved SPP [Ref. 4]. In order to meet SPP accuracy goals, this model had to predict particle size within $\pm 10\%$. Unfortunately, there are no adequate theoretical models relating particle size to propellant and motor parameters. This necessitates the use of empirical methods for correlating particle size.

There are two methods that can be employed to develop an empirical relation. One is to correlate particle size data to propellant and motor variables, as was done by Cohen. The other method is to calculate particle size based on a critical Weber number for a maximum stable drop size [Ref. 5]. After considering the relative merits of each method, Hermesen [Ref. 5] devised an empirical model based on collected particle size data for the improved SPP. This model was correlated to a much broader data base than was previously available to Cohen.

The particle diameter correlated was D_{43} , the mass-weighted diameter, given by:

$$D_{43} = \sum N_i D_i^4 / \sum N_i D_i^3$$

Smith [Ref. 6] has shown that D_{43} was the most appropriate average to use in predicting two-phase flow losses.

Hermesen's empirical relation [Ref. 5] is presented below:

$$D_{43} = 3.6404 D_t^{.2932} (1 - e^{-.0008163 \xi P \tau}) ,$$

where:

D_{43} = mass-weighted average diameter, μ_m

D_t = nozzle throat diameter, in.

ξ = Al_2O_3 concentration in chamber, g-mol/100 g

P = chamber pressure, psia

τ = average residence time, msec

The predicted D_{43} is now applied to the expression below in order to calculate the two phase flow loss [Ref. 7].

$$ETATP = C_3 (\xi C_4 D_p^{C_5} / P^{.15} \epsilon^{.08} D_t^{C_6})$$

where:

ETATP = impulse loss effect, %

ξ = mole fraction of condensed species, moles of condensed species per 100 grams of mixture

D_p = D_{43} in microns

- P = average motor chamber pressure, psia
- ϵ = nozzle expansion ratio at ignition conditions
- D_t = nozzle throat diameter at ignition, inches
- e = Napierian base 2.71828
- $C()$ = coefficients that are a function of D_t and D_p

The two-phase flow loss is applied with the other aforementioned efficiencies to a theoretical Isp. The Isp loss from boundary layer effects is then subtracted from the corrected theoretical Isp to obtain delivered Isp.

Collecting exhaust products is feasible only for small motors and the techniques used often result in variation in the measured size. Validation of the SPP model must be based on data collected within the motor environment. Light scattering measurements are well-suited for this application. These measurements are more easily made if the particles are large compared with the wave length of the transmitted light and the transmittance is greater than 90%. The former allows the accurate application of Fraunhofer diffraction, whereas the latter specification is necessary in order to satisfy single scattering requirements.

The Naval Postgraduate School has conducted a series of investigations to determine the applicability of light scattering measurements to the solid rocket motor exhaust products

[Refs. 8,9,10,11]. This investigation was directed at modifying the apparatus and techniques developed in the previous efforts in order to more accurately determine particle size. Validation of the apparatus was also a goal. The SPP particle prediction model can then be verified by a comparison of the predicted size to the experimental data.

II. THEORETICAL BACKGROUND

The most general theory of light scattering was developed by Mie and is presented by Van de Hulst [Ref. 12]. Mie's theory, although not restrictive in its assumptions in regard to particle size and refractive index, is however very complex to utilize for data reduction. Dobbins, et al. [Ref. 13] and Powell, et al. [Ref. 14] derived similar expressions for intensity ratios at two forward scattering angles based upon an Upper Limit Distribution Function (ULDF). and Fraunhofer diffraction. The ULDF was initially proposed by Mugele and Evans in Reference 15. Although the expressions developed by Dobbins and Powell are extremely useful in relating intensity ratios to D_{32} , the volume-surface mean diameter, these models are still somewhat cumbersome to use for data reduction purposes.

Particle sizes found in solid-propellant rocket motors are often bi-modal. Particles in the larger mode are the most important for two-phase flow loss calculations and are generally much greater in diameter than the wavelength of incident light. Scattering by these large particles is described by Fraunhofer diffraction. Hodkinson [Ref. 16] and others [Refs. 13,14] have demonstrated that diffraction theory (within the forward lobe) can be used to approximate the Mie theory. Buchele in Reference 17 summarized the experimental

techniques for determining the particle size by measurements of diffractively scattered light. Buchele presents a function which closely approximates the curves given in References 13 and 14.

$$I(\theta) = \text{EXP}[-(.57 \alpha \theta)^2]$$

where:

$I(\theta)$ = ratio of intensity of scattered light at some angle (θ) to the intensity of scattered light at theta equal to zero degrees

α = $\pi D/\lambda$ is the particle size parameter for diameter D_{32} and wavelength of light λ .

The above expression was used in the current study for data reduction to obtain D_{32} . Unfortunately, D_{43} is the mean diameter used in the SPP. Therefore, D_{32} must be related to D_{43} either by analyzing exhaust samples or by approximate analytical means.

A final important point is that the above expression is valid for $\alpha \leq 3$ (the center lobe). For the expected ranges of theta and D_{32} , this proves to be a very mild restriction.

III. EXPERIMENTAL APPARATUS

A. ROCKET MOTOR

The rocket motor used in this investigation was the same as the long motor described in Reference 11. The motor components are presented in a photograph in Figure 3.1 and the installed motor is shown in Figure 3.2. A schematic is also presented in Figure 3.3. The propellant grain dimensions remained the same as in the previous effort [Ref. 11]. The grain was two inches in diameter, one inch in length and had a web thickness of .725 inches. The grain was cylindrically perforated and allowed to burn also on the aft end. The igniter was composed of BKNO_3 . Ignition of the igniter was achieved by heating a resistance wire with a 12 VDC source.

Some of the exhaust products were collected in an eight inch diameter stainless steel exhaust tube. The products were collected from both the side walls of the tube and the end cap. Another particle sample was collected from the walls of the combustor, near the nozzle entrance. Both samples were then cleaned and mounted for observation using a scanning electron microscope.

B. LIGHT SCATTERING APPARATUS

The apparatus shown in Figures 3.4 and 3.5 was basically the same as used in Reference 11 with some exceptions. The

light source used for the nozzle exhaust was a 8-milliwatt, helium-neon laser. The nozzle entrance also used a 8-milliwatt helium-neon laser. The lasers were mounted on two parallel optics benches, such that one beam could pass through the exhaust and the other beam could pass through the motor cavity adjacent to the nozzle entrance. A beam expander/collimator was used with the helium-neon laser in the exhaust. Each beam was intercepted by a stop placed directly in front of the narrow pass filter. The narrow pass filter was used to eliminate extraneous light. The stop and narrow pass filter were placed 30.5 centimeters from the motor centerline for the exhaust beam and 11.5 centimeters from the motor centerline for the motor cavity beam. The exhaust beam narrow pass filter had a diameter of 5.08 centimeters and the motor cavity narrow pass filter had a diameter of 2.3 centimeters. Both beams passed through the centers of these filters. In the present arrangement of the apparatus this resulted in a maximum angle for collecting scattered light of 4.8 degrees in the exhaust and 6.0 degrees in the motor cavity. The placement of the optics closer to the motor centerline allowed for a greater maximum angle to be recorded than in the original design. Directly following the narrow pass filters were condensing lenses. Both paths used a lens with a diameter of 5.08 centimeters. These lenses had a focal length of 50 centimeters and were utilized to focus scattered light onto a linear array of photodiodes. The array consisted of 1024 silicon photodiodes

with .025 millimeter spacing. The apparatus in Reference 11 positioned the lenses such that only angles from 0 to .04 radians could be observed. In actuality, however (as a consequence of diffraction around the beam stop and beam spreading), the range of useful angles where only scattered light occurred was from .02 radians to .04 radians. In the current arrangement the diode array was placed 1.0 centimeters below the main beam and the collecting tube diameter was enlarged. This allowed a range of angles from .02 to .07 radians to be observed.

C. DATA ACQUISITION AND DATA REDUCTION

The data acquisition system is presented in detail in Reference 10. The system controller was an HP 9836S computer and the HP 6942A multiprogrammer provided A/D conversion and storage. The data acquisition system was programmed to take data at a specified point in the motor firing by inputting a trigger pressure and a time delay after the trigger pressure was reached. The number of diode scans for the exhaust and motor cavity were eight and four respectively (limited by the current data acquisition system memory size).

Two methods were used in References 10 and 11 for data reduction, one of which was altered for this study. The modified method pertained to the iterative graphics technique. In References 10 and 11 the experimental data were normalized and compared to a theoretical profile that was also normalized to some assumed scattered light intensity at zero degrees

for a specified D_{32} . A "best-fit" of the experimental profile to the theoretical one yielded D_{32} . The current investigation determined that this method resulted in ambiguity in determining D_{32} as a consequence of assuming a centerline intensity for the scattering profile. The method used in the present study was one in which the experimental data were not altered. A theoretical curve was generated for any specified value of D_{32} based upon a selected initial angle (θ_1) and the corresponding intensity at that angle (I_1) from the unaltered experimental data. The approximate intensity profile for a polydispersion given by Reference 17 is:

$$I_2 = I_1 \text{EXP} - \{(\theta_2^2 - \theta_1^2) (.57 D\pi/\lambda)^2\}$$

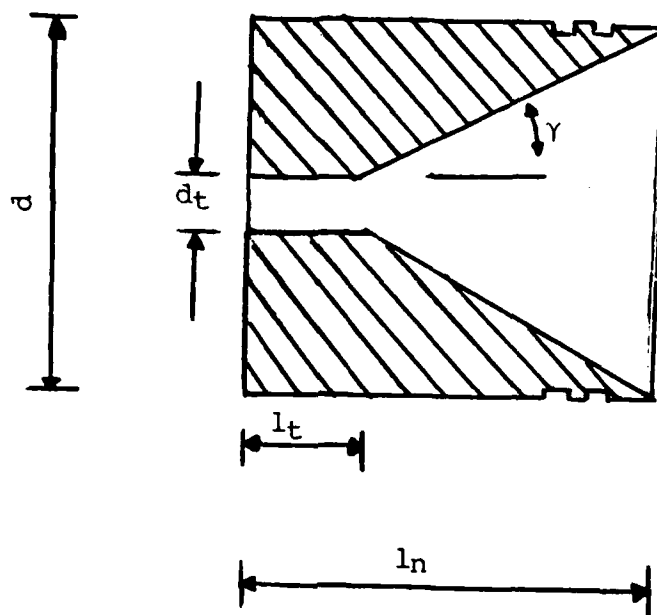
Specification of a series of values for θ_2 results in values for I_2 and, therefore, an I vs θ theoretical profile that passes through the experimental data at I_1 , θ_1 . If this curve does not fit the experimental data, then other values of D_{32} can be chosen and a new theoretical curve generated. A "best-fit" method is subsequently used to determine D_{32} . In summary, the method used for obtaining the mean particle size is based upon fitting an approximate (although quite accurate within specific angle restrictions) theoretical profile for a polydispersion to the unaltered profile obtained experimentally over a small range of scattering angles. The modified data reduction program is presented in the Appendix.

The second method was similar to the first and also used the above expression solved for D_{32} :

$$D_{32}^2 = -\ln(I_2/I_1) (\lambda/.57\pi)^2 / (\theta_2^2 - \theta_1^2)$$

The procedure used was to first select a starting angle, θ_1 , along with a θ_2/θ_1 ratio. A value of I_2 at θ_2 was obtained from the experimental data. This was repeated with increasing values of θ_2 and then again with different values of θ_2/θ_1 . The results were plotted graphically as particle size vs scattering angle for each angle ratio. A nearly constant value of D_{32} vs θ indicated a good correlation.

TABLE I



Description	Copper Nozzle	Copper Nozzle
Outside Diameter (d, inch)	2.125	2.125
Length (ln, inch)	1.25	1.25
Throat Diameter (dt, inch)	.28	.23
Slope (converging) Angle (γ , degree)	45	45

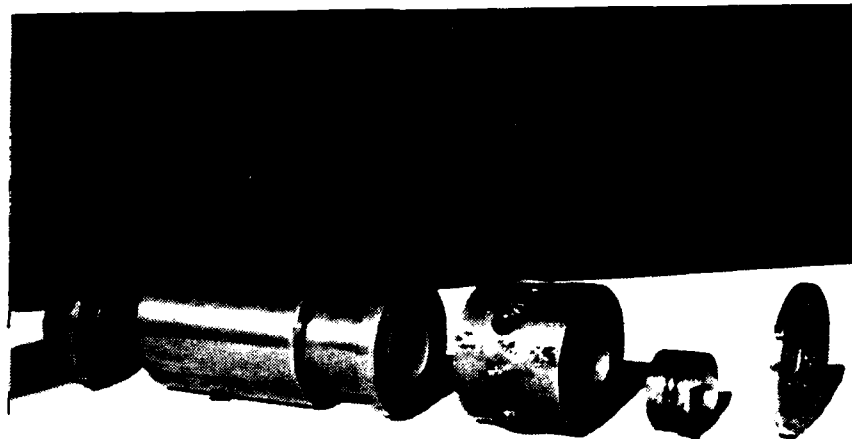


Figure 3.1. Motor Components



Figure 3.2. Installation of Rocket Motor

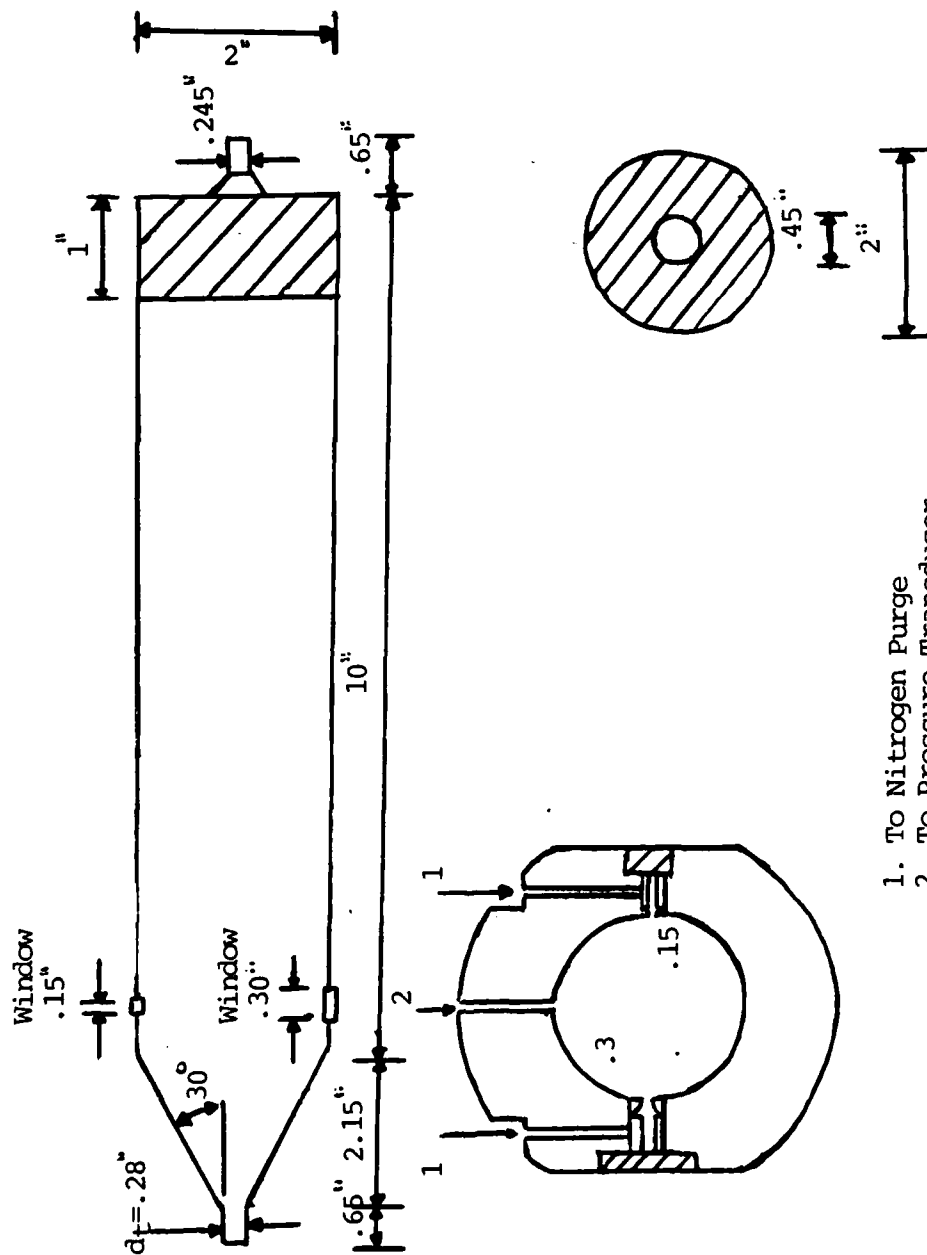


Figure 3.3. Schematic of the Motor

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Figure 3.4. Light Scattering Apparatus

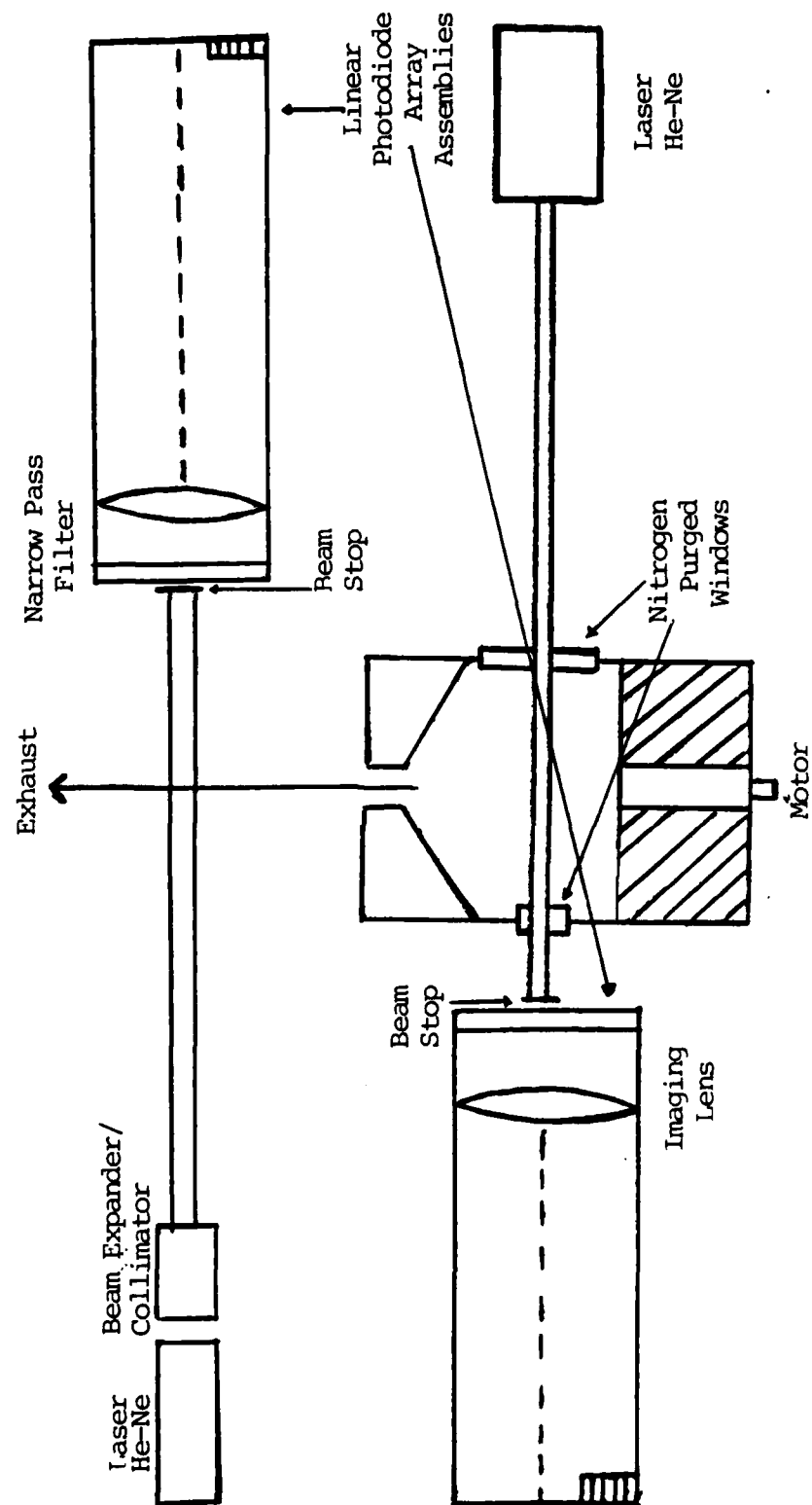


Figure 3.5. Schematic Diagram of Light Scattering Apparatus

TABLE II
LIGHT SOURCE SPECIFICATION

A. Helium-Neon Laser (Exhaust)

1. Manufacturer	Spectra-Physics
2. Model:	147
3. Type:	He-Ne Class IIIB
4. Output Power:	8 mWatt
5. Beam Diameter:	.92 mm
6. Beam Divergence:	.87 nrad.

B. Helium-Neon Laser (Motor Cavity)

1. Manufacturer:	Uni-Phase
2. Model:	1305P
3. Type:	He-Ne Class IIIB
4. Output Power:	5 mWatt
5. Beam Diameter:	.81 mm
6. Beam Divergence:	1.00 mrad.

IV. RESULT AND DISCUSSION

A. INTRODUCTION

The purpose of this study was to improve and validate the accuracy of the apparatus used for particle sizing in the rocket motor environment. Also, the experimental data will provide a basis to verify the particle size prediction model of the SPP.

The apparatus had been calibrated by Harris [Ref. 10] and Kertadidjaja [Ref. 11] using glass and polystyrene spheres in a suspension of water. Kertadidjaja [Ref. 11] also attempted to demonstrate the applicability of the apparatus to the combustion environment. This investigation continued the earlier studies with several refinements. Three propellant types were used in this investigation. All three utilized a GAP binder with ammonium perchlorate (AP) oxidizer. Each had varied aluminum content, with the percentages present being 0%, 2%, and 4.8%. The size of the aluminum powder was 20 microns. The major ingredient compositions for the 4.8% aluminized propellant were 14.7% GAP, 45.7% 200 μm AP, 24.6% 25 μm AP, 8.5% TEGIN and 4.8% 20 μm Al. The 0% and 2% aluminized propellants kept the same solids loading.

B. SYSTEM CALIBRATION

As previously mentioned, the apparatus was calibrated by both Harris [Ref. 10] and Kertadidjaja [Ref. 11]. The

apparatus was re-calibrated in this study as a result of the modifications that were made. The standard calibration procedure described in detail by Harris [Ref. 10] remained the same. The laser beam passed through a glass container holding a suspension of polystyrene spheres and water and was initially positioned on the number one diode. The linear diode array was then moved vertically down, with the aid of a dial indicator, such that the number one diode was one centimeter below the main beam. Since the diode array was 2.56 centimeters long and was 50 centimeters from the focusing lens, this arrangement allowed for a range of measuring angles from .02 to .07 radians. Therefore, the scattered light striking the diodes would not be affected by the main transmitted beam or the light diffracted by the beam stop as in the previous two studies. This arrangement was used both for the exhaust beam and the motor cavity beam.

Two polydispersion samples of polystyrene spheres, with D_{32} 's of 4.8 microns and 10.2 microns, were used for the calibration. These samples were chosen because the D_{32} was known and the expected D_{32} of the actual aluminum oxide particles during a motor firing was between 1 and 15 microns. The results are presented in Figures 4.1, 4.2, 4.3 and 4.4. These results were encouraging in regards to validating the modifications and the method for data reduction. Calibrations were also conducted within the motor cavity with the laser beam and scattered light passing through the motor windows. Figures

4.1 and 4.2 are representative of the results obtained. This indicated that the motor windows did not adversely affect scattering profile and, therefore, bias the results.

An initial point of concern was the narrow range of measuring angles which were employed in the present apparatus. Since large particles diffract most of the incident light at small angles and very small particles diffract most of the incident light at large angles, the range and minimum angle employed could not have resulted in sufficient sensitivity to particle size for the expected range of particle sizes. Also shown in Figure 4.1 are two additional theoretical profiles for D_{32} of 10 and 8.3 microns. It was apparent from the sensitivity of the slope change with D_{32} that the mean particle size could be determined with an uncertainty less than ± 0.5 microns.

The "upsweeps" in the curves at larger angles using the two angle method were the result of the increase in slope of the scattering profile due to the effect of truncation by the apparatus. These parts of the curves remain only to provide a reference to the angle ratios.

Another informative point in apparatus design is given by Hirleman [Ref. 18] in regards to placement of the focusing lens. Hirleman notes that truncation of the larger scattering angles, which is a function of the placement of focusing lens, will cause a biasing against the small particles. The expression given in this discussion is:

$$Z_c = (\pi d / 7.66 \lambda) D$$

where:

Z_c = critical distance in front of the focusing lens where significant energy diffracted by particles less than diameter D is truncated by the focusing lens

λ = wavelength of the incident light

For a given Z_c , all particles that are greater than D in size will have 84 percent of their diffracted energy pass through the focusing lens. In the exhaust configuration of the present apparatus Z_c was equal to 30.5 centimeters, d was 5.08 centimeters and λ was .6328 microns. This yields a D of 9 microns. Thus, according to this criterion, some of the scattered light from particles below 9 microns is truncated and, therefore, results in a bias towards larger particles. This type of biasing was small in the present apparatus down to particle sizes of approximately 3 microns (the smallest particles in the 4.8 micron D_{32} polydispersion) as evidenced by the good calibration results is shown in Figure 4.3. However, the apparatus could be improved by either moving the lens closer to the exhaust (at the risk of apparatus damage from the exhaust jet) or by using a larger diameter lens.

Transmittance effects were also investigated in conjunction with the calibration. As previously mentioned, transmittances above 90% are required to meet single scattering requirements. Calibrations were conducted using polystyrene

spheres with a D_{32} of 10.2 microns. Scattering data were recorded for transmittances of 85%, 70%, 60%, 50%, and 30%. The results are presented in Figures 4.5 through 4.14, and summarized in Table III. Both the curve fit and the two-angle methods resulted in very good agreement with the actual mean particle size with transmittances as low as 50%. Even a transmittance of 30% did not severely affect the measurement. These results indicate that particle sizing methods based upon single scattering theory can effectively be used in a multiple scattering environment with transmittances significantly less than 90%.

A test was then conducted to determine the transmittance in the actual motor exhaust using the 2% aluminized propellant. The procedure was the same as the one used in Reference 11. The transmitted beam was directed onto the diode array (with the appropriate filters to reduce the intensity) and the beam profile was recorded. The motor was then fired and the profile was again recorded. The results are presented in Figure 4.15. The results indicated a transmittance greater than 90%, with some beam spreading. There was also no apparent beam shift. Therefore, transmittance loss was determined not to be a debilitating factor in the motor exhaust jet.

The calibration curves have an apparent limit of approximately .04 radians for which scattered light can be recorded (for example, see Figure 4.3). However, it was stated that the apparatus was designed to record angles up to .07 radians.

This is due to the water-glass interface having an effective index of refraction of 1.39. Thus, the scattering angles are corrected for this high index of refraction, resulting in a corrected maximum angle of approximately .04 radians.

C. NOZZLE EXHAUST MEASUREMENTS

One test was conducted with a nonmetallized propellant. The results, presented in Figure 4.16, show no scattering. Therefore, the scattering observed by Kertadidjaja [Ref. 11] at smaller angles for a similar test was probably the result of beam broadening and diffraction around the beam stop.

Three tests were conducted with both the 4.8% and 2% aluminized propellants. The motor firing data and a summary of the particle size measurements are presented, respectively, in Tables IV and V. From light scattering measurements each propellant showed a similar result, one test with a D_{32} of approximately 5 microns and one with a larger value of D_{32} (7-12 microns). This test-to-test variation probably resulted from the very short burn times and the corresponding lack of a well-defined steady-state condition. These results are presented in Figures 4.17 through 4.28. Typical S.E.M. photographs are shown in Figure 4.29. The light scattering results were quite consistent with those obtained from the S.E.M. evaluation. Although the sample sizes from which the S.E.M. evaluations were based were relatively small (see Table VI), it still provided a good indication as to the validity of

the light scattering measurements. It should be noted that D_{32} , and to an even greater extent D_{43} , is strongly dominated by the larger particles. One or two large particles can significantly change D_{32} . Future S.E.M. evaluations should utilize much larger sample sizes.

The SPP equation for D_{43} (which is primarily a function of throat diameter) predicted much smaller values of D_{43} than observed in this limited set of data. The SPP model, however, is based on particulate data from motors with nozzle diameters greater than 1 inch.

D. NOZZLE ENTRANCE MEASUREMENTS

Light scattering measurements through the motor at the nozzle entrance were unsuccessful as a result of combustion light existing at the same frequency as the laser light. This was the case for both the helium-neon laser ($\lambda = .6328 \mu\text{m}$) and the argon laser ($\lambda = .488 \mu\text{m}$).

The analyses of the S.E.M. data for the nozzle entrance indicated a much larger D_{32} and D_{43} as compared to the nozzle exit measurements. Therefore, a significant reduction in size appears to have occurred to the larger particles across the exhaust nozzle.

TABLE III
EFFECT OF TRANSMITTANCE
ON MEASURED PARTICLE SIZE
(D₃₂ from Manufacturers Data Equals 10.2)

Transmittance (%)	Measured D ₃₂ (microns)
85	9.8
70	9.6
60	9.5
50	9.4
30	9.3

TABLE IV
SUMMARY OF MOTOR FIRINGS

Date of Test	Wt of Alum (%)	Press P_c (psig)	Press Max P_c (psig)	Burn Time (sec)	Residence Time (msec)	D_t (in.)
Oct 31, 85	0	350	366	3.8	-	.28
Oct 22, 85	4.8	312	328	2.9	10.9	.28
Oct 23, 85	4.8	328	359	2.8	11.3	.28
Oct 18, 85	4.8	333	340	2.8	11.3	.28
Nov 19, 85	4.8	450	466	.95	14.0	.25
Oct 30, 85	2.0	296	296	2.8	10.4	.28
Nov 26, 85	2.0	408	467	2.0	14.4	.28
Nov 25, 85	2.0	566	575	1.8	16.7	.25

Note: Pressure colume labeled P_c indicates pressure at which data was taken.

TABLE V
SUMMARY OF EXPERIMENTAL RESULTS

Wt of Alum (%)	Press P _c (psig)	D ₃₂ Light Sct. (psig)	D ₃₂ S.E.M. Ext./Mtr.	D ₄₃ S.E.M. Ext./Mtr.	D ₄₃ SPP Model
4.8	328	5.6	5.6/18.2	7.3/24.7	2.3
4.8	333	5.5	- / -	- / -	2.3
4.8	450	12.0	13.6/18.9	19.7/23.9	2.5
2.0	296	7.0	12.2/14.4	18.6/19.6	2.3
2.0	408	9.3	- / -	- / -	2.3
2.0	566	4.6	4.9/10.8	6.0/13.2	2.5

Note: (-) indicates sample was not taken for this run.
Diameters are in microns.

TABLE VI
S.E.M. PARTICLE DISTRIBUTION

	Size in microns															
	1	2	3	4	5	6	7	8	9	10	12	15	19	20	25	30
Oct 23 Ext.	53	22	16	11	7	4	2	1			1					
Oct. 23 Mtr.	50	21	22	13	9	6	8	4	1	2	1	1			1	2
Oct. 30 Ext.	45	42	11	13	21		2	2		1	1		1		1	
Oct. 30 Mtr.	24	15	3	6	28	3	7	13		6		3	1	2		1
Nov. 19 Ext.	64	35	31	7	6	1	1	1		2	1				1	1
Nov. 19 Mtr.	73	29	9	5	12	4	1	1	1	2	1	1	1		2	1
Nov. 25 Ext.	44	39	22	3	14	4	1	1		1						
Nov. 25 Mtr.	37	30	11	1	15	8	3	8		3	4	3			1	

CURVE FIT RESULTS INTENSITY VS. THETA

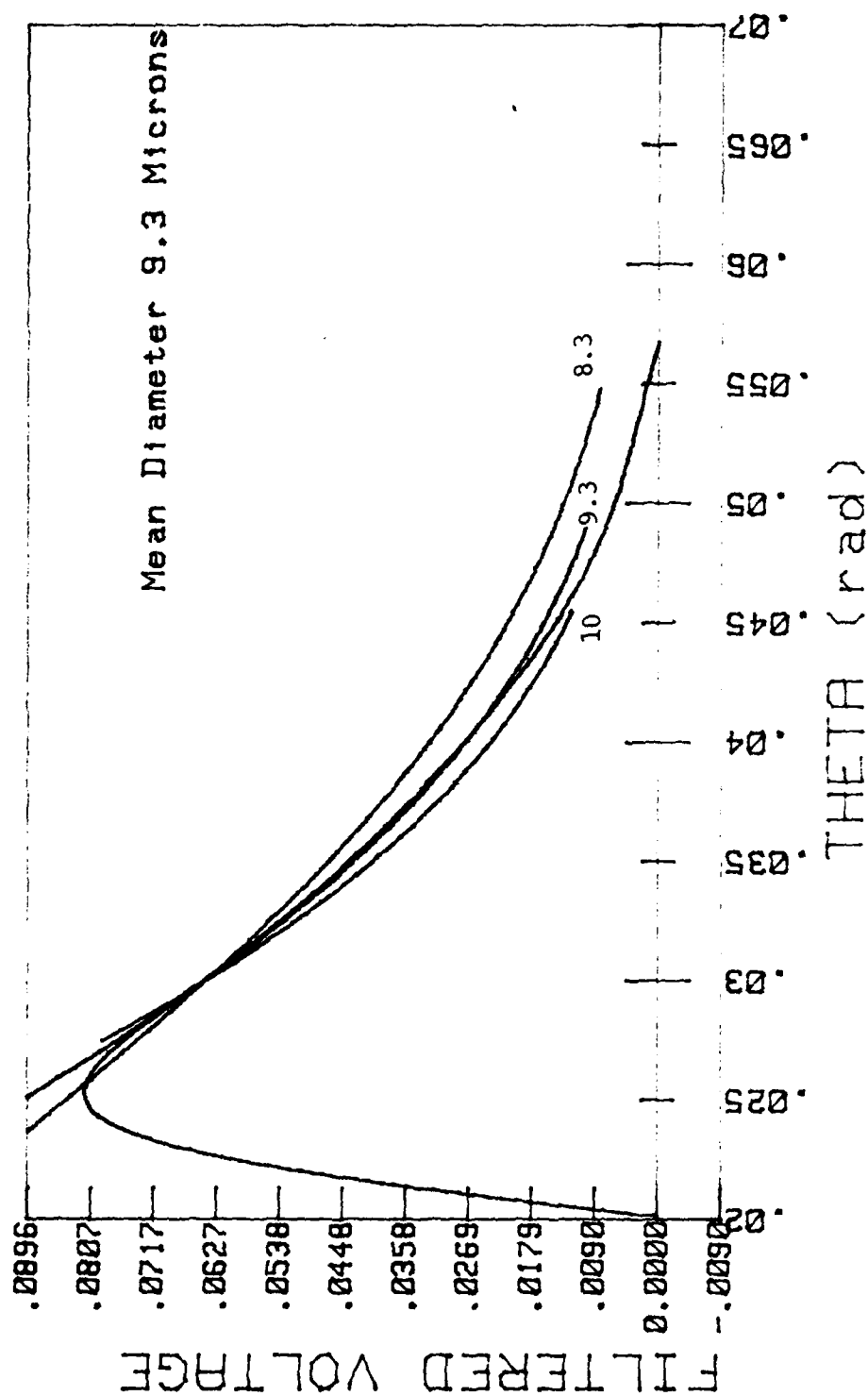


Figure 4.1 Calibration With 10.2 Micron Polystyrene Spheres

TWO-ANGLE METHOD For Various Angle Ratios

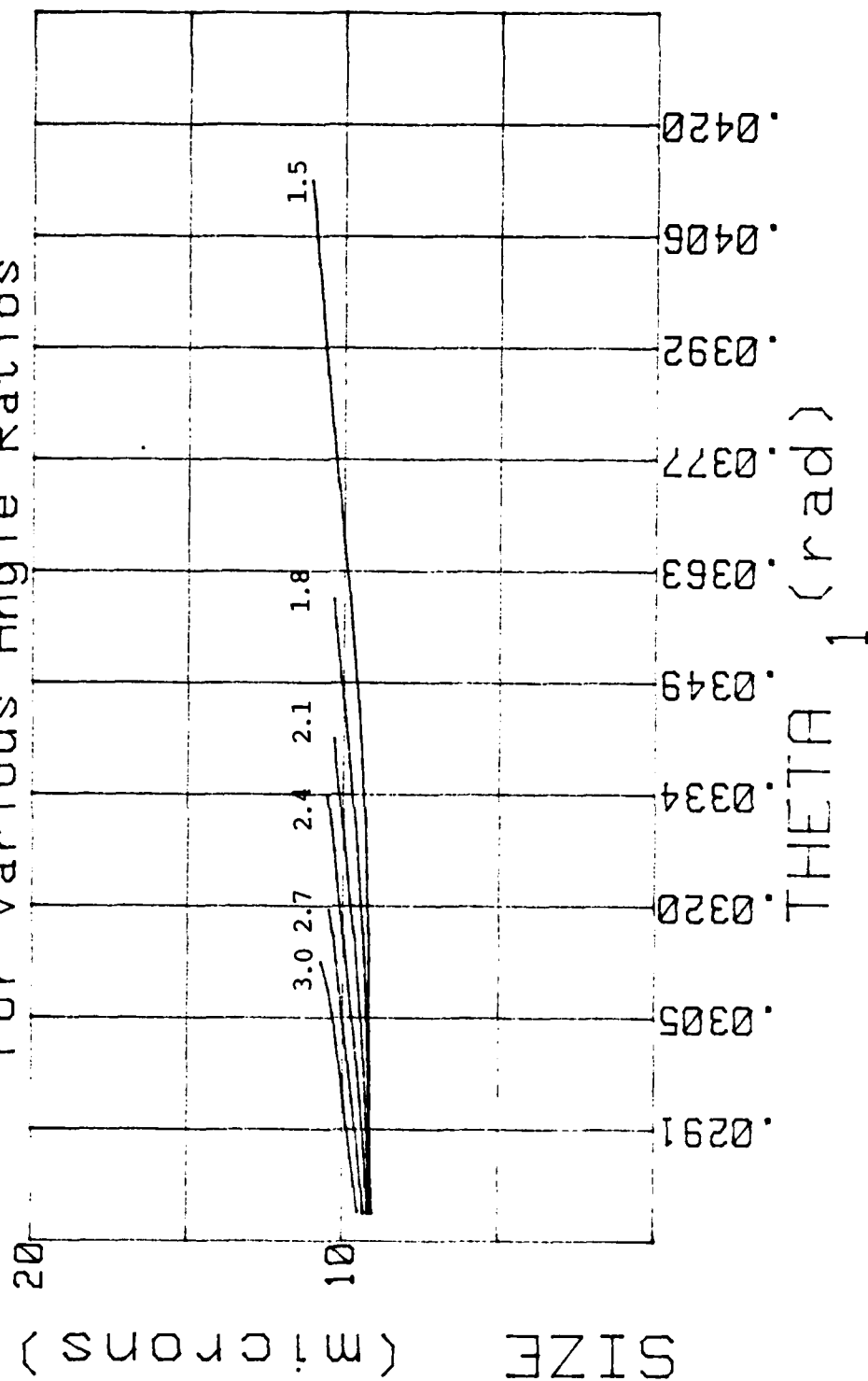


Figure 4.2 Calibration With 10.2 Micron Polystyrene Spheres

CURVE FIT RESULTS INTENSITY VS. THETA

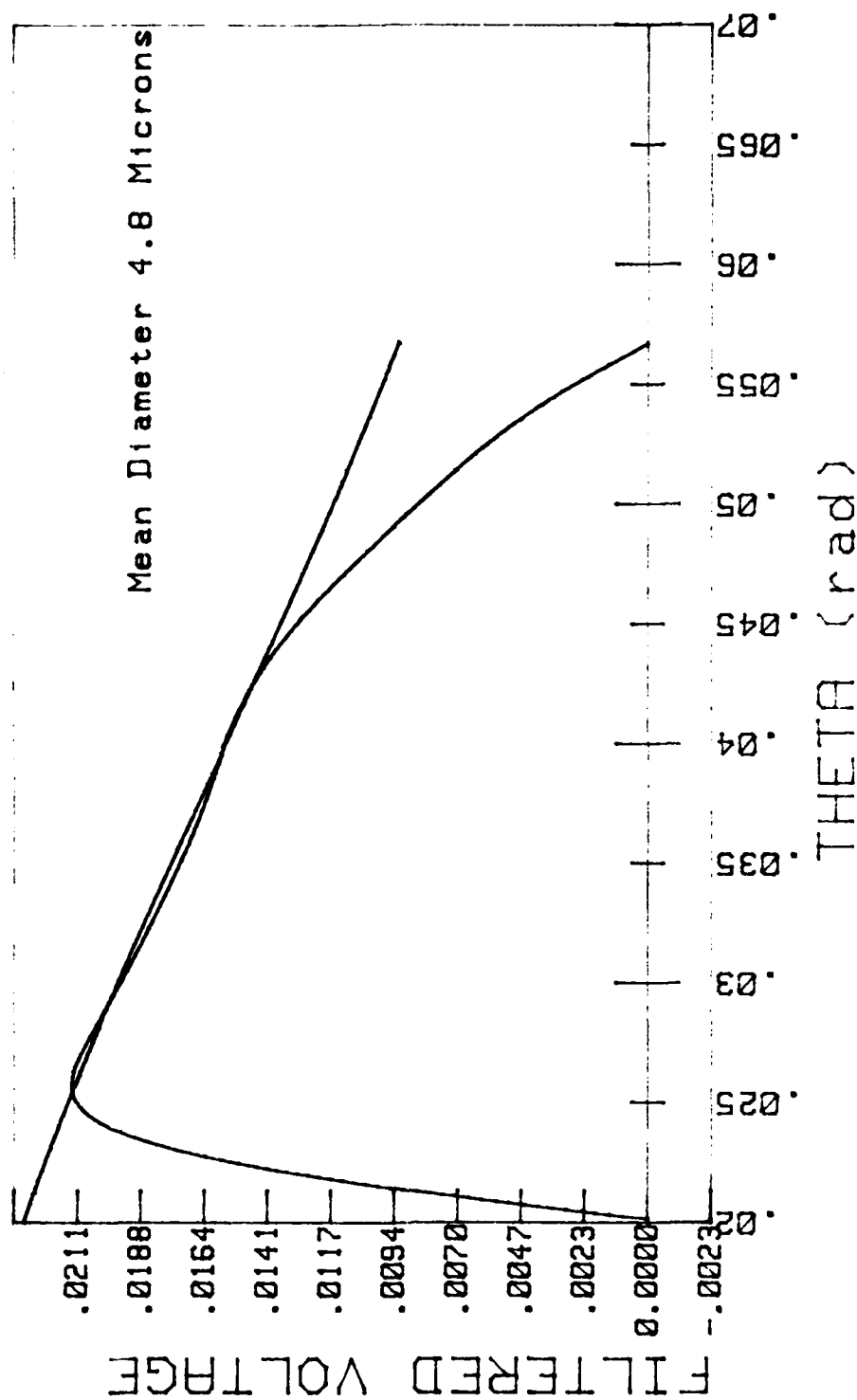


Figure 4.3 Calibration With 4.8 Micron Polystyrene Spheres

TWO-ANGLE METHOD For Various Angle Ratios

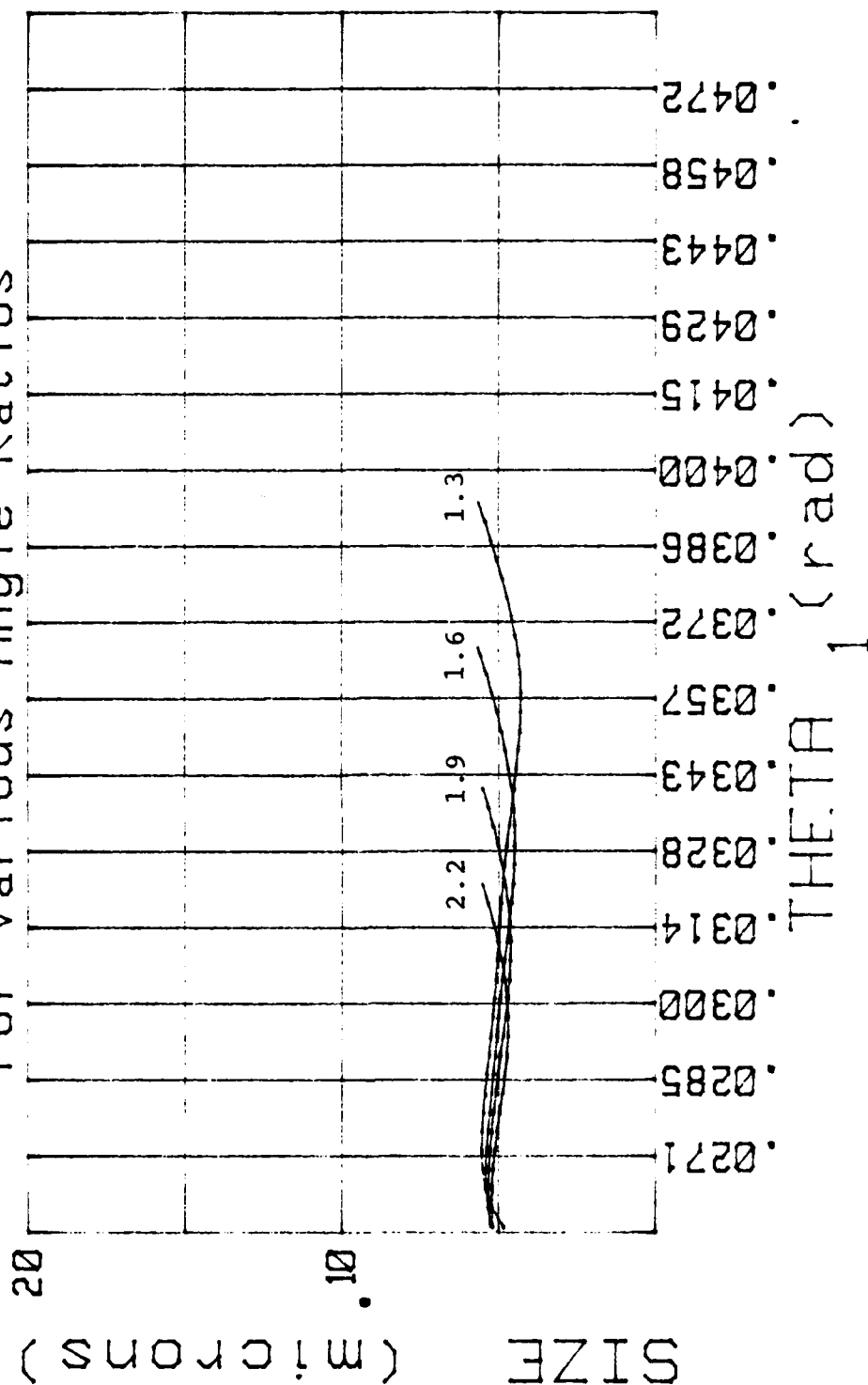


Figure 4.4 Calibration With 4.8 Micron Polystyrene Spheres

CURVE FIT RESULTS INTENSITY vs. THETA

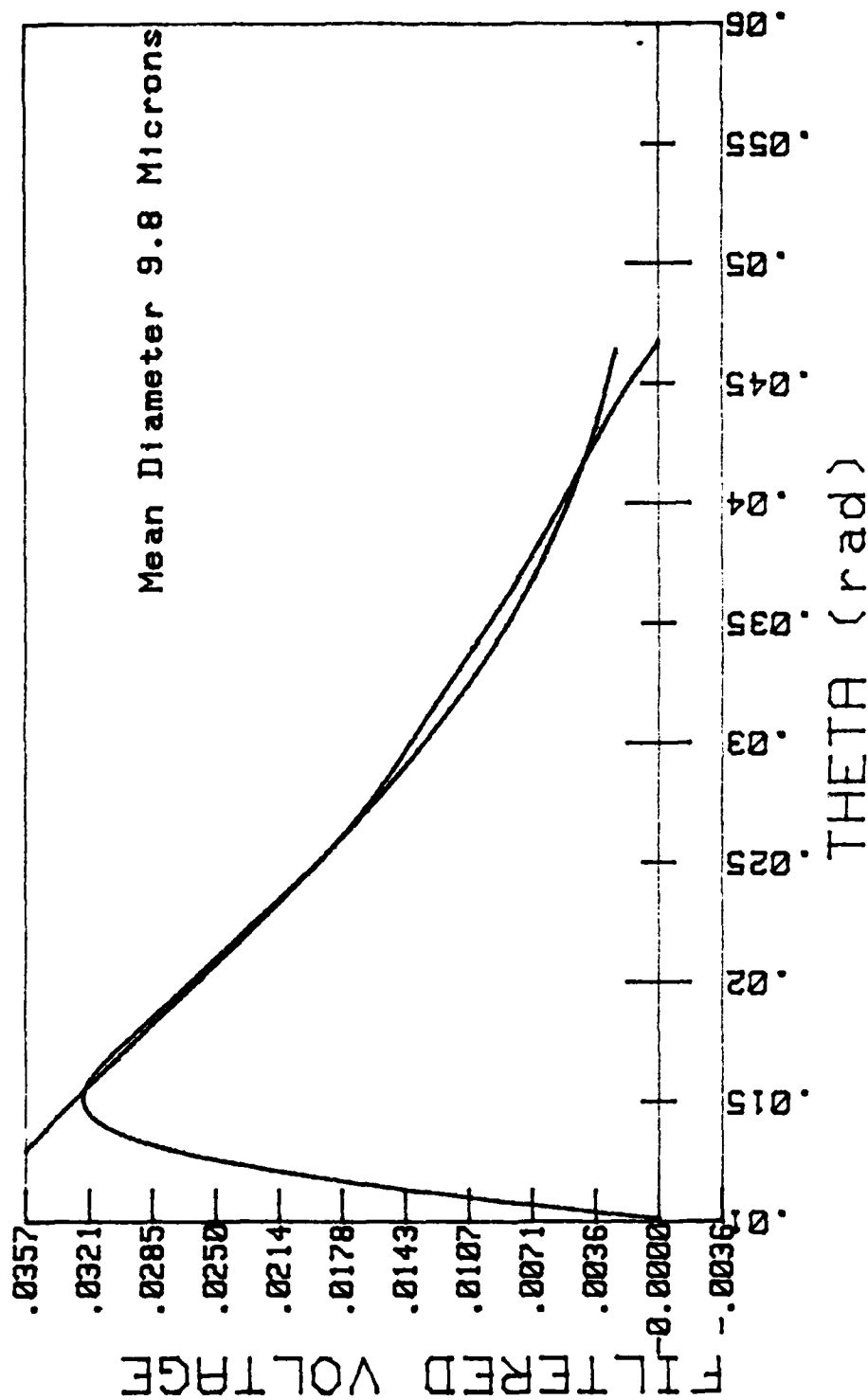


Figure 4.5 Curve Fit Method, 85% Transmitted Light

TWO-ANGLE METHOD For Various Angle Ratios

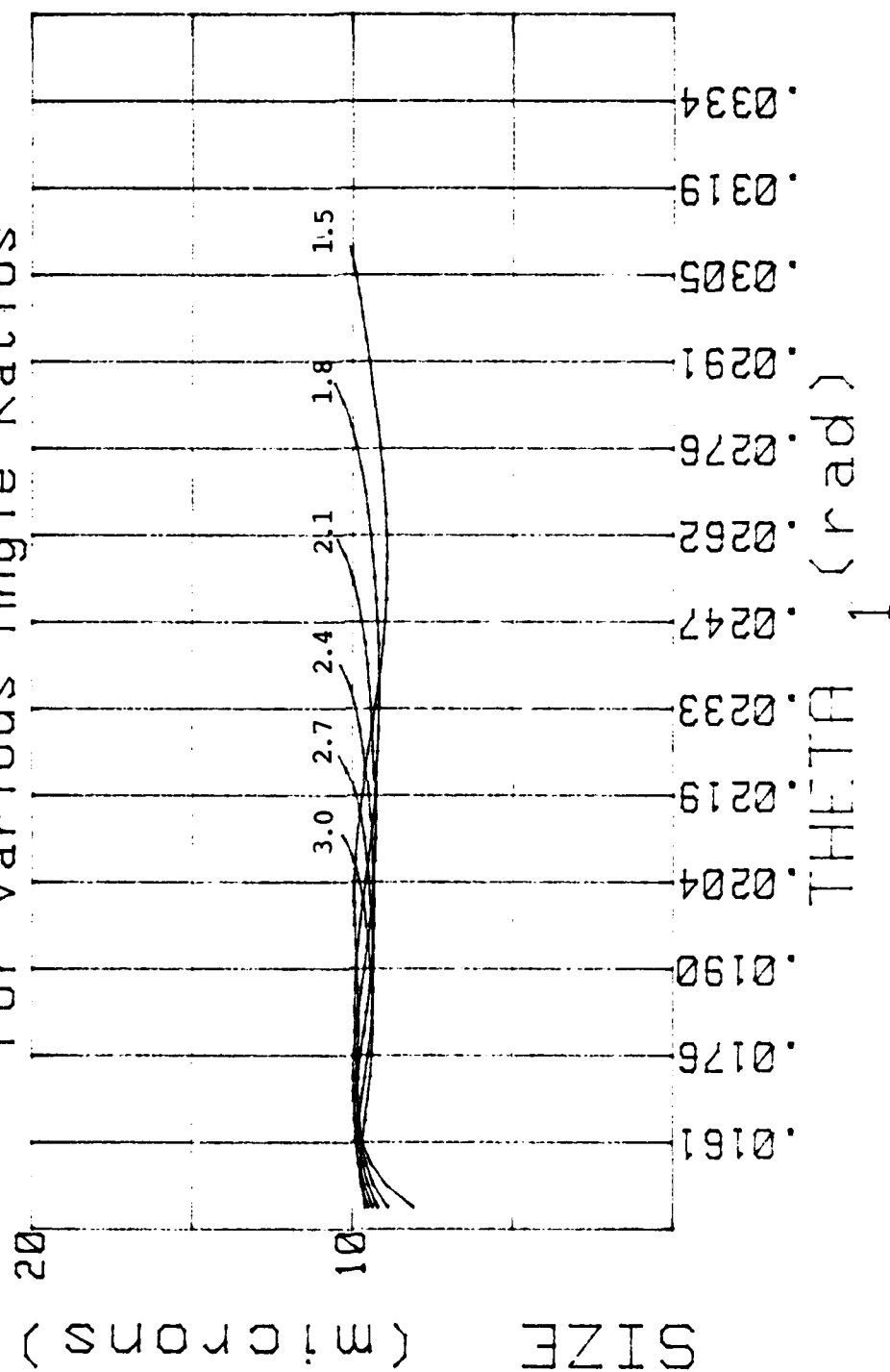


Figure 4.6 Two Angle Method, 85% Transmitted Light

CURVE FIT RESULTS INTENSITY VS. THETA

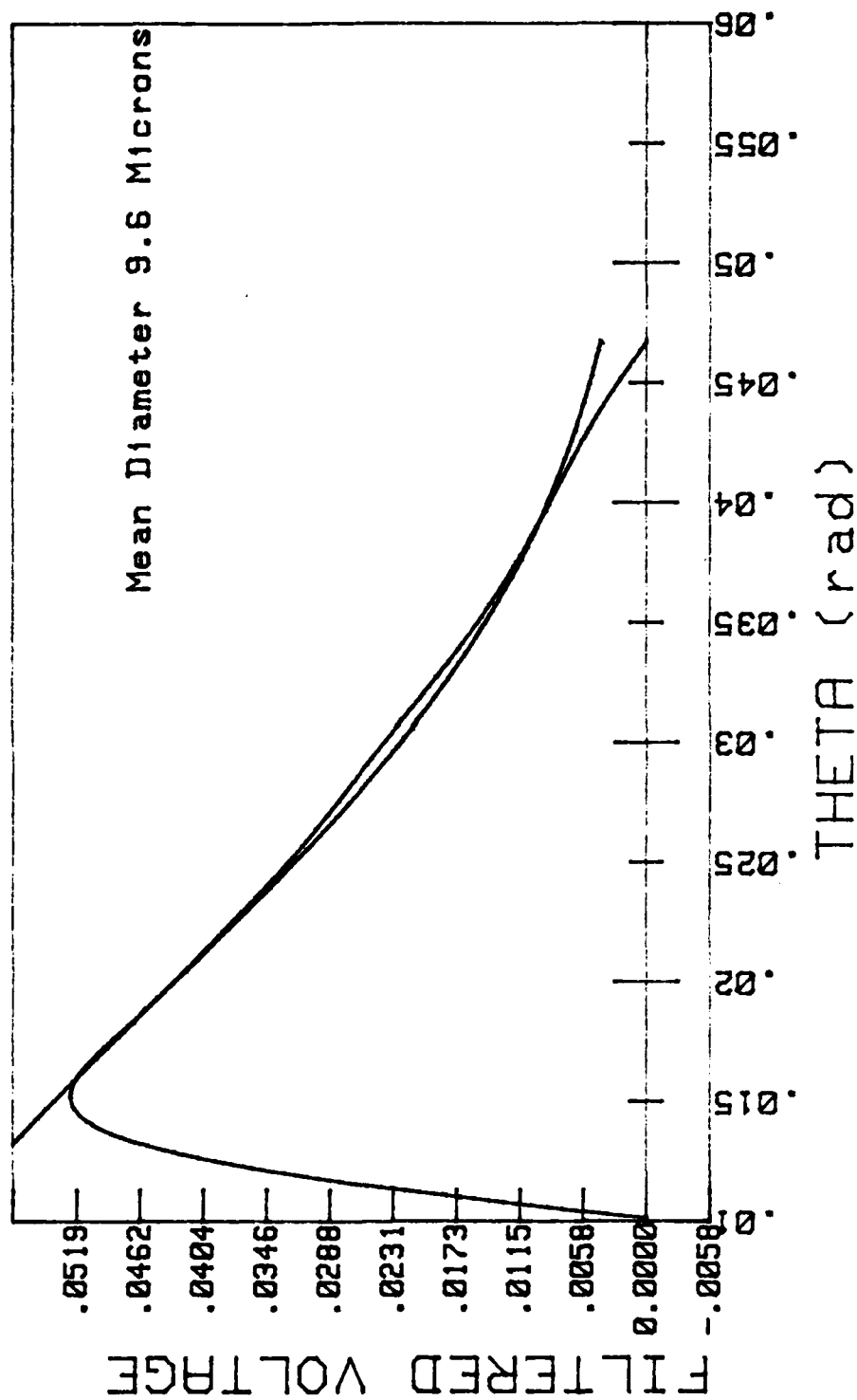


Figure 4.7 CurveFit Method, 70% Transmitted Light

TWO-ANGLE METHOD For Various Angle Ratios

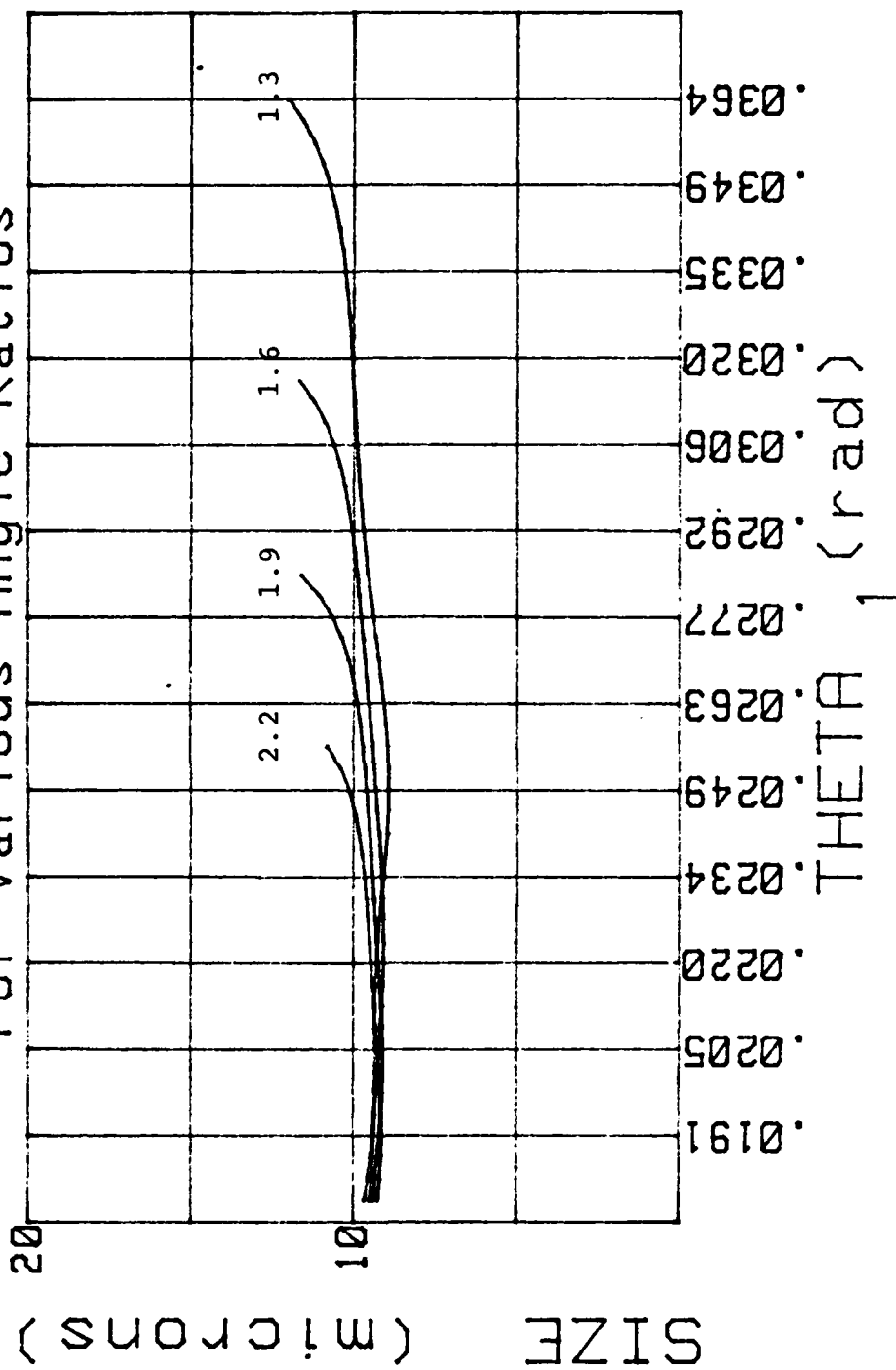


Figure 4.8 Two Angle Method, 70% Transmitted Light

CURVE FIT RESULTS INTENSITY VS. THETA

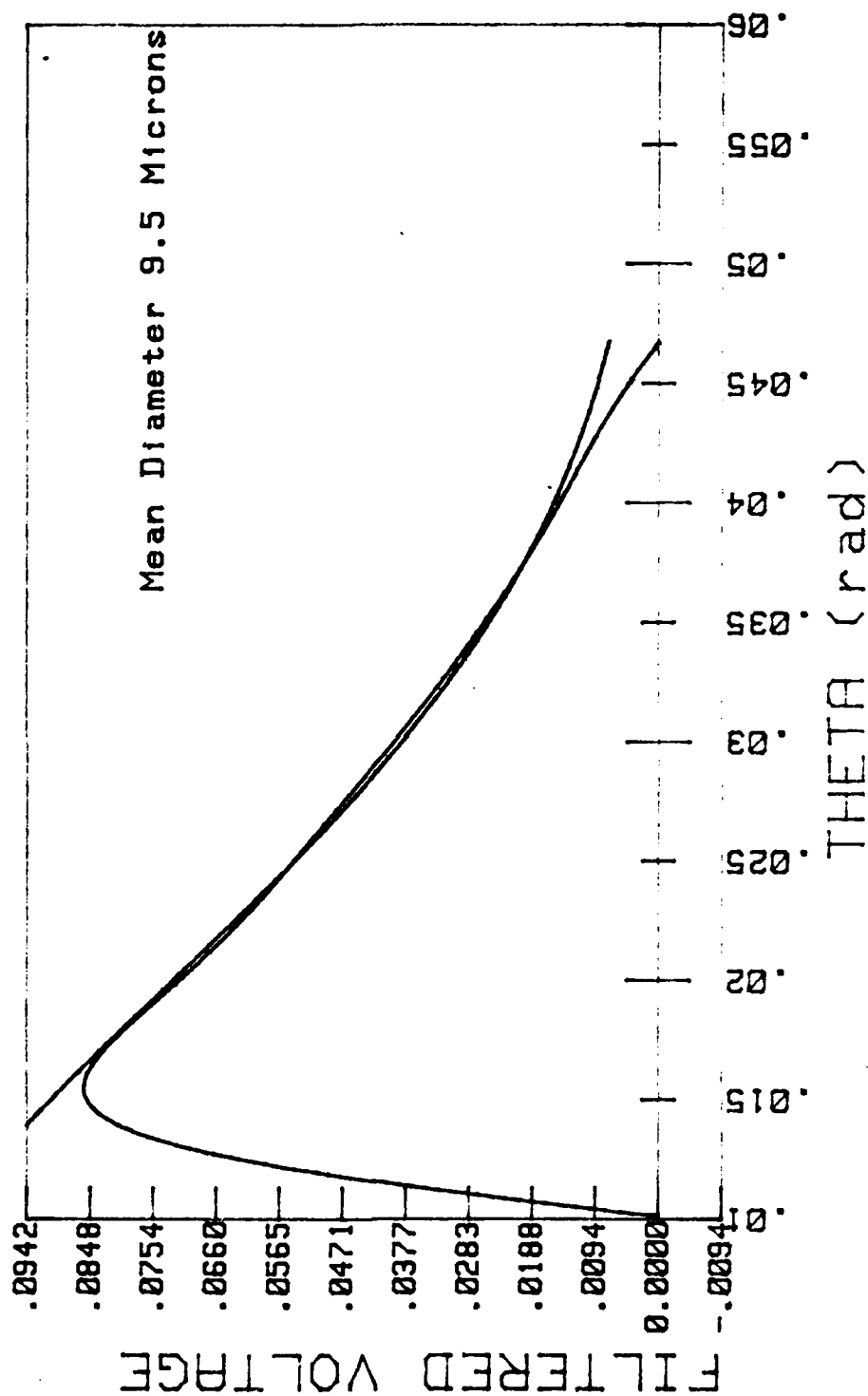


Figure 4.9 Curve Fit Method, 60% Transmitted Light

TWO-ANGLE METHOD For Various Angle Ratios

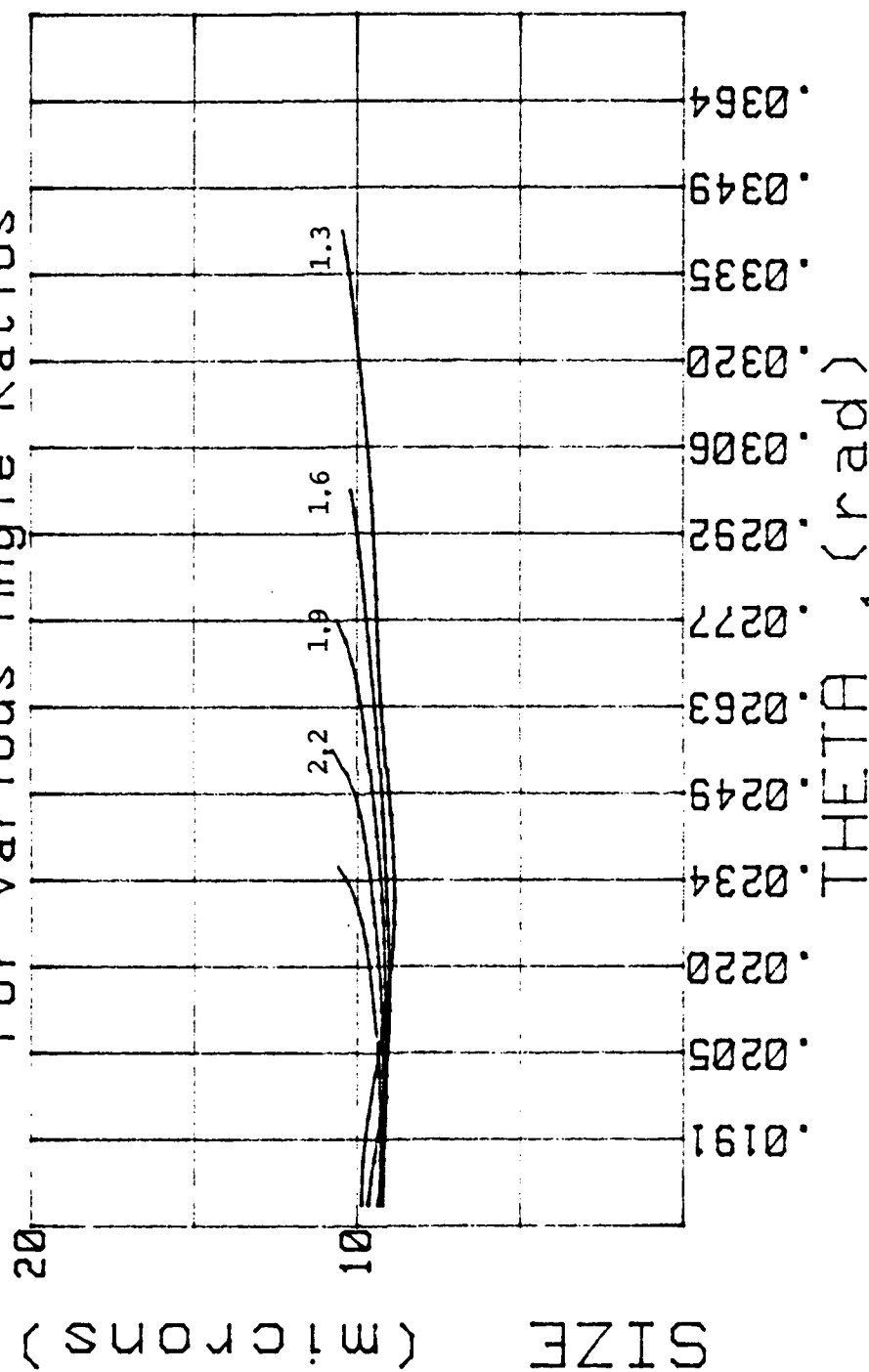


Figure 4.10 Two Angle Method, 60% Transmitted Light

CURVE FIT RESULTS INTENSITY vs. THETA

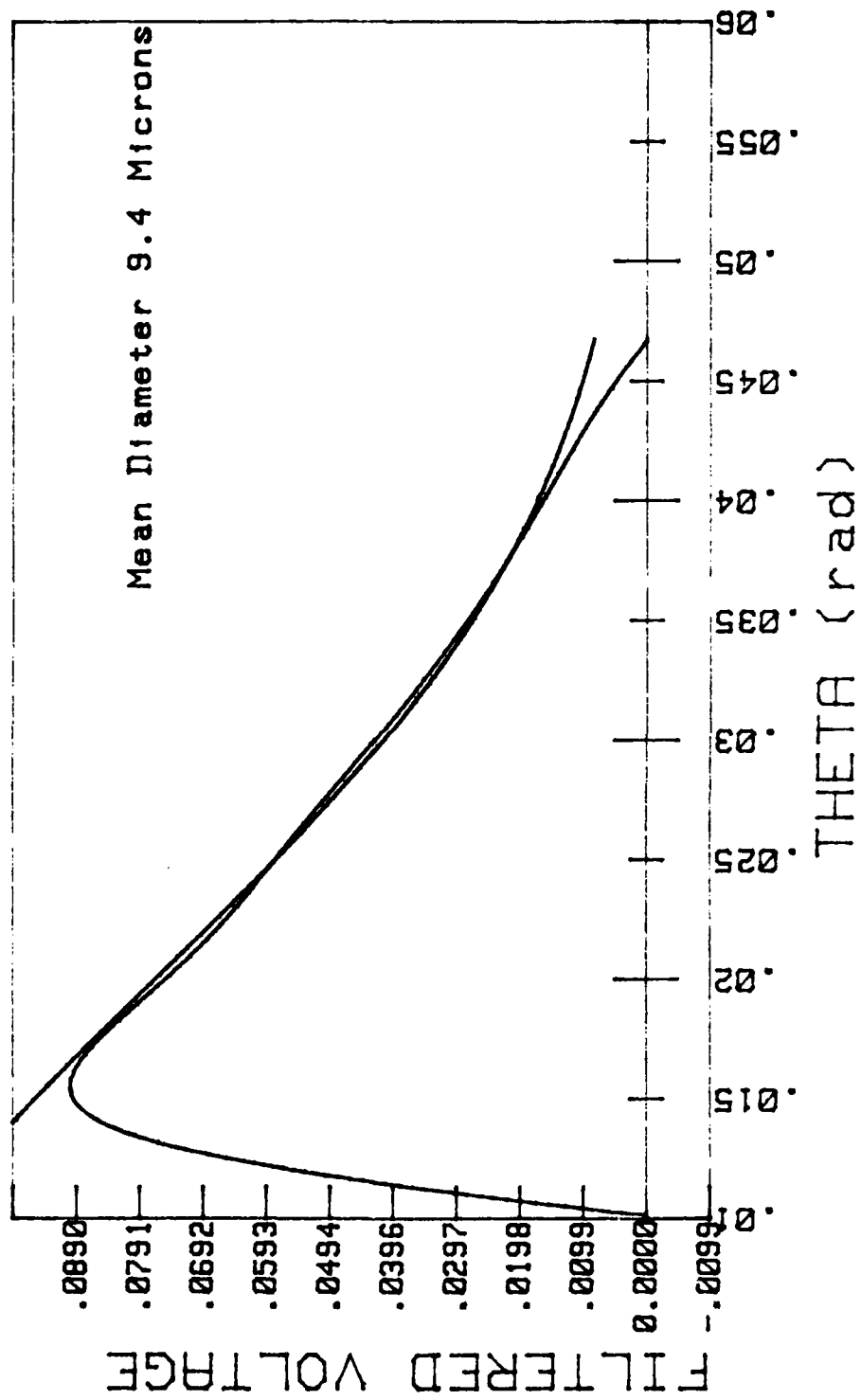


Figure 4.11 Curve Fit Method, 50% Transmitted Light

TWO-ANGLE METHOD

For Various Angle Ratios

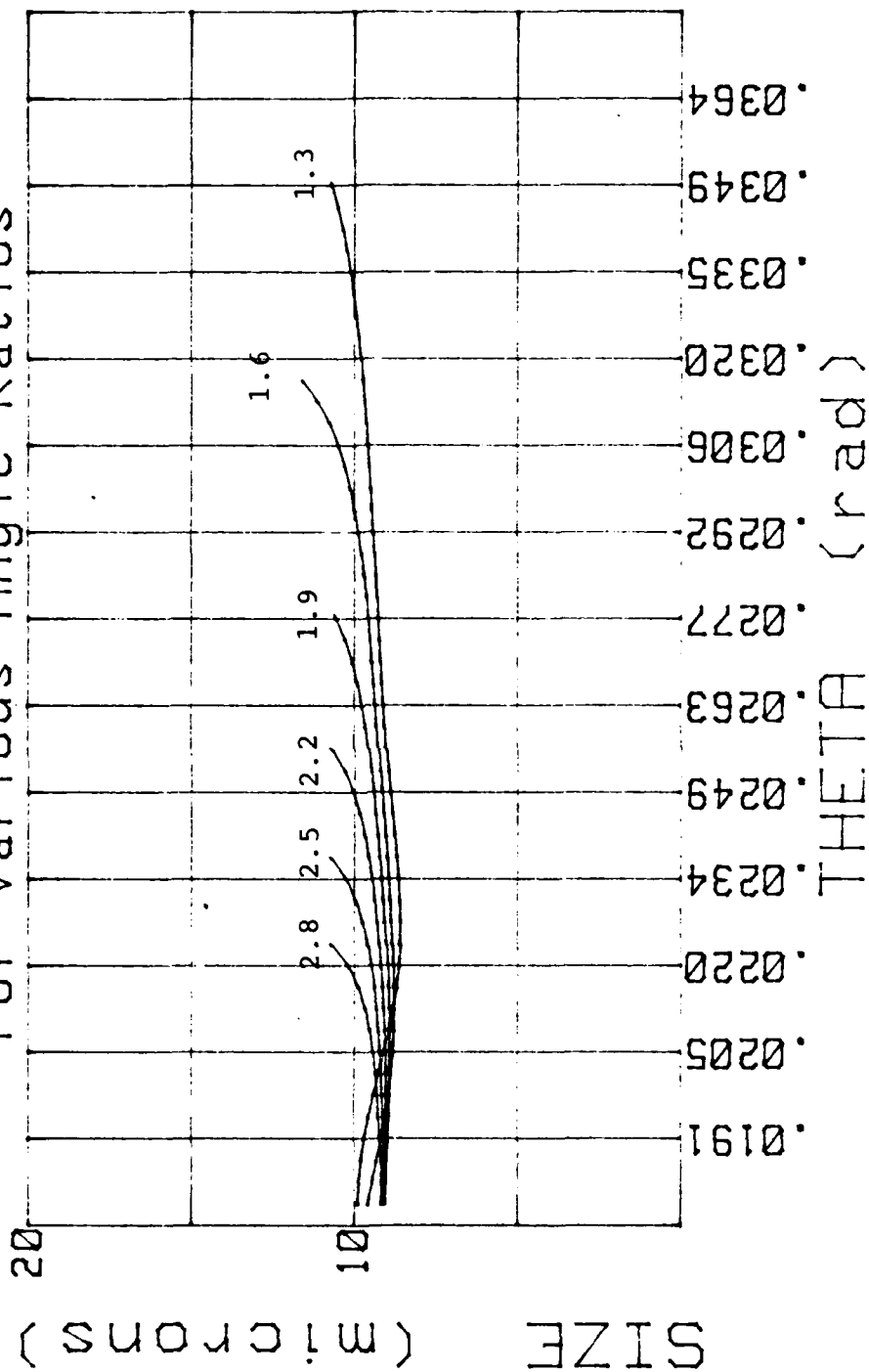


Figure 4.12 Two Angle Method, 50% Transmitted Light

CURVE FIT RESULTS INTENSITY vs. THETA

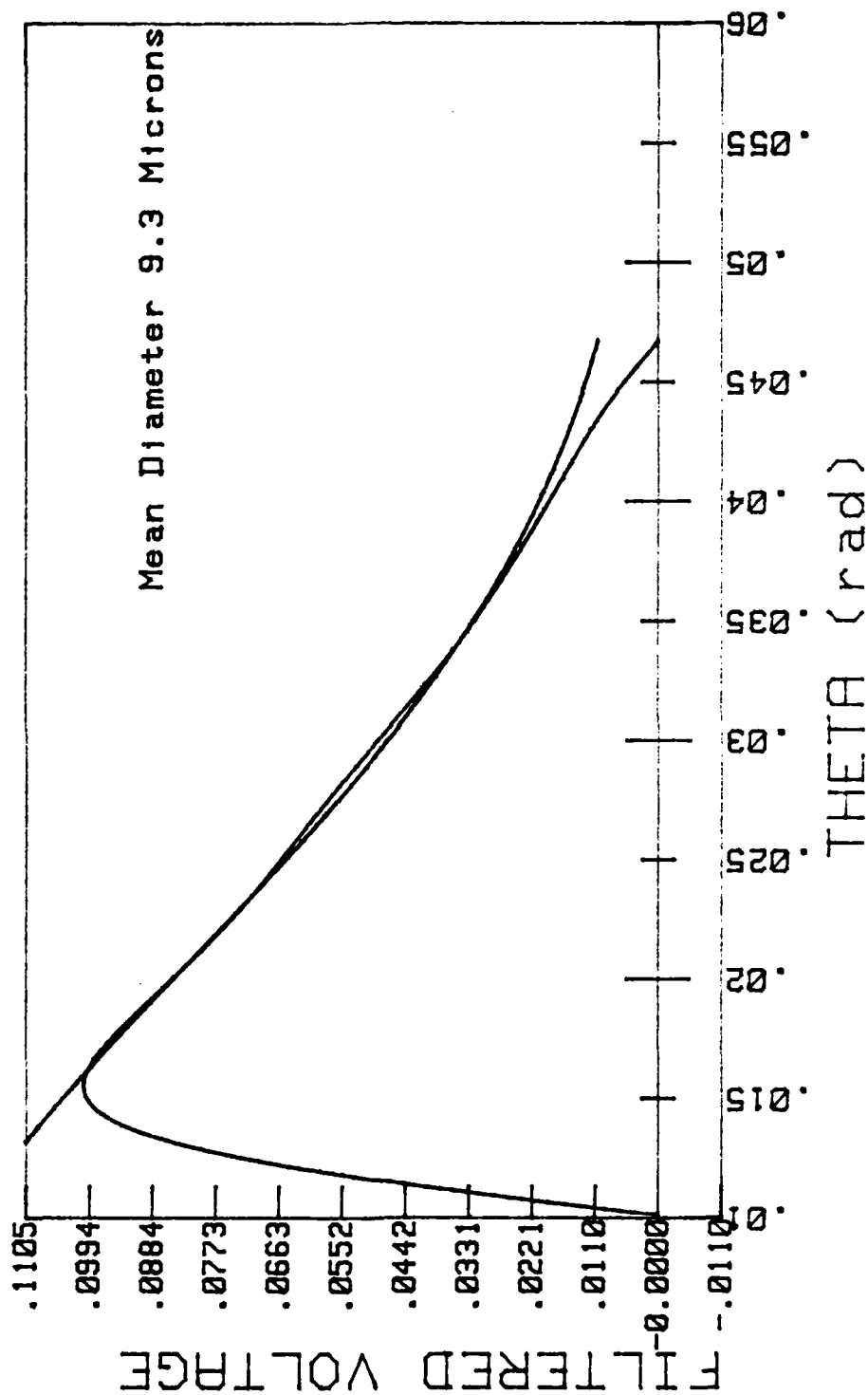


Figure 4.13 Curve Fit Method, 30% Transmitted Light

TWO-ANGLE METHOD For Various Angle Ratios

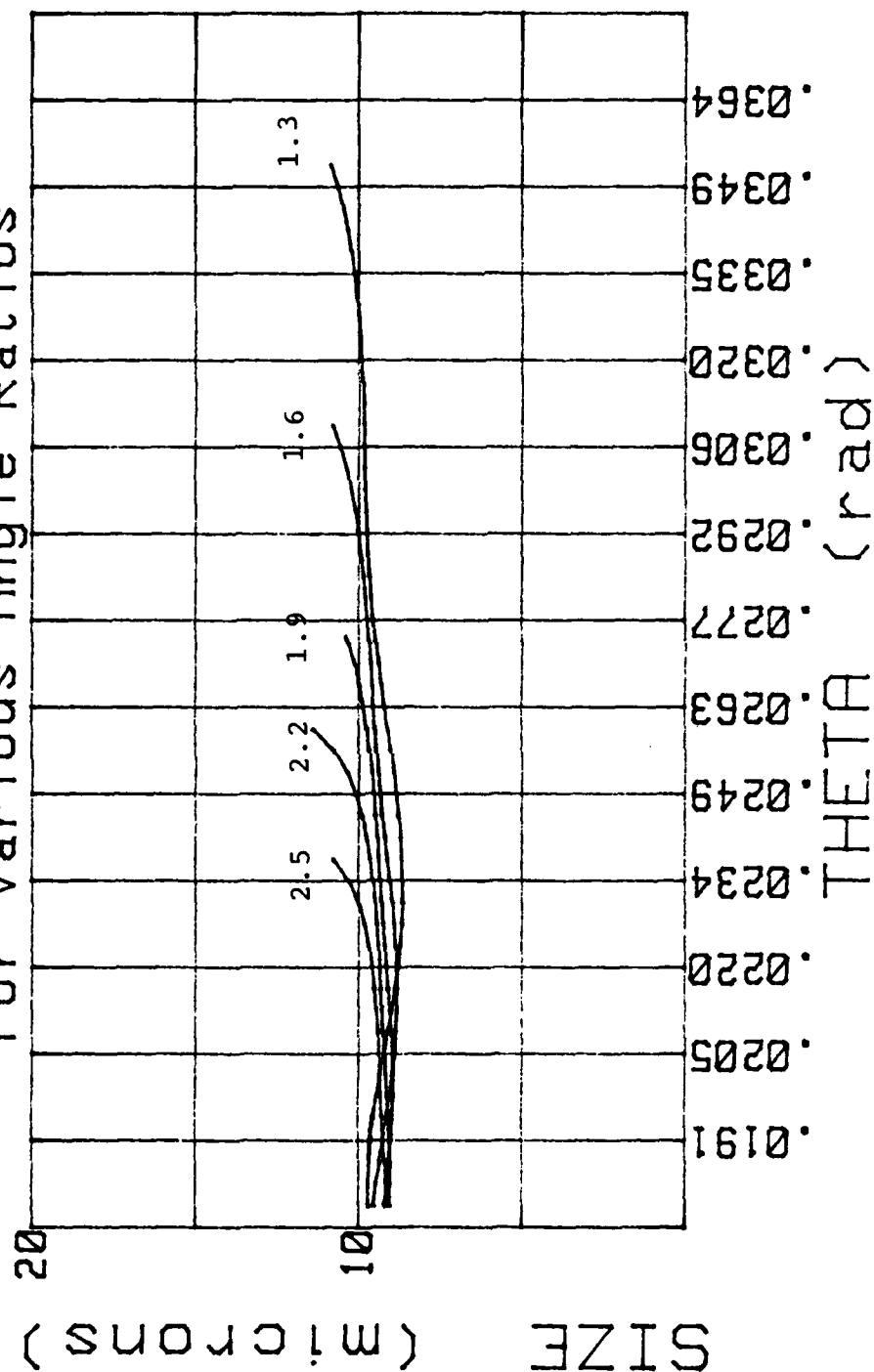


Figure 4.14 Two Angle Method, 30% Transmitted Light

RAW DATA VOLTAGE VS. DIODE

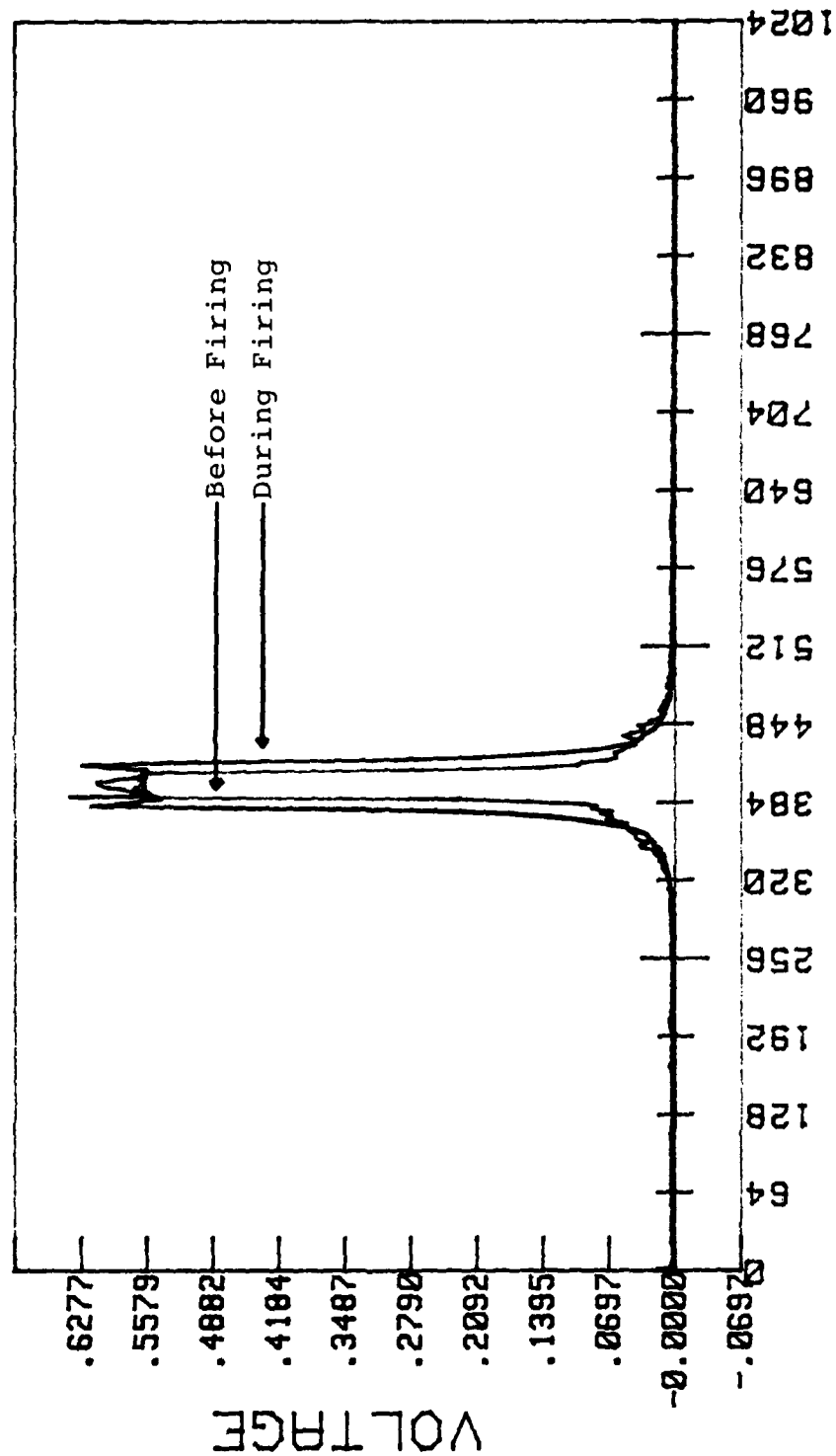


Figure 4.15 2% Aluminum Propellant, Less Than 90% Attenuation

VOLTAGE vs. DIODE

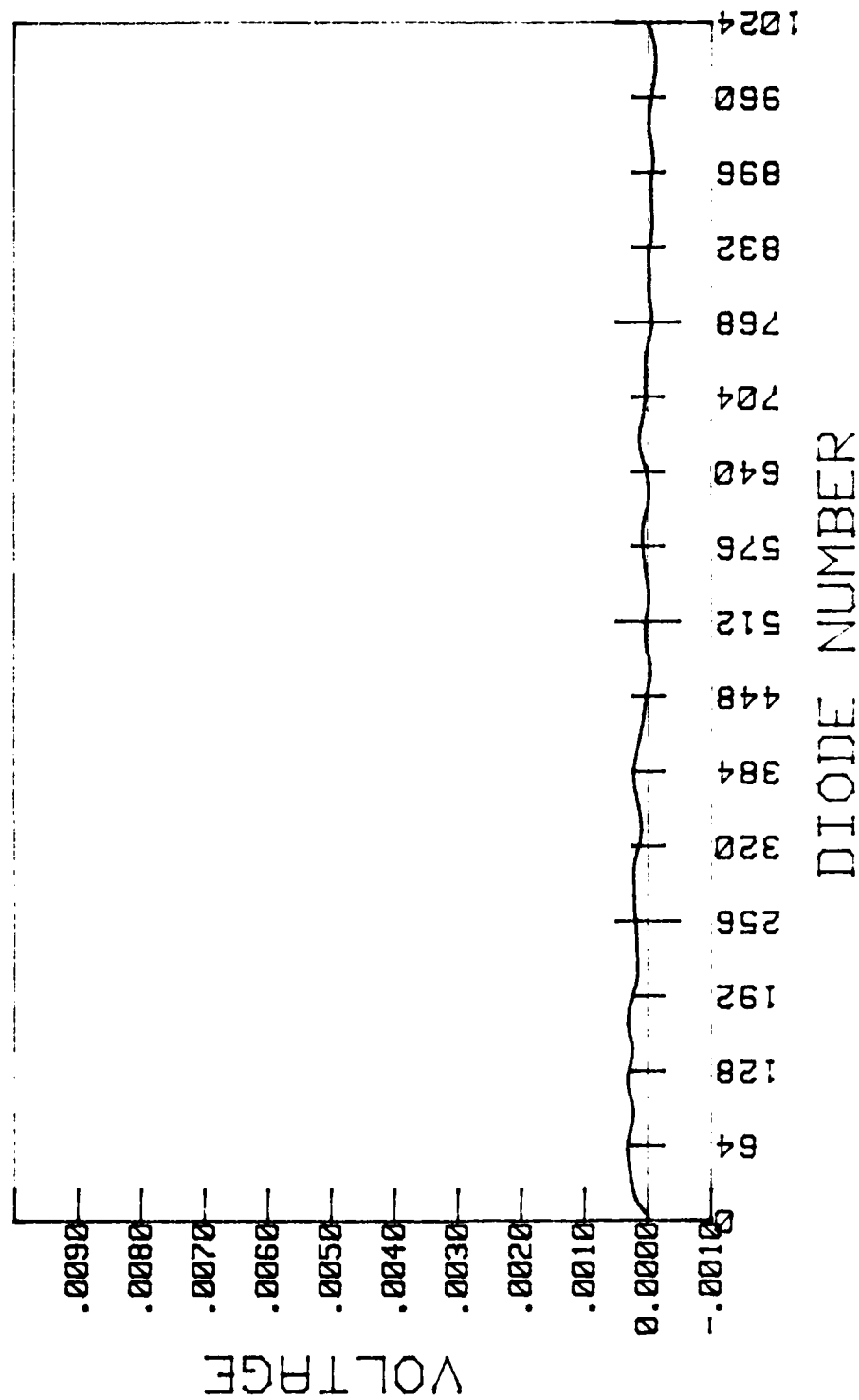


Figure 4.16 Non-Metalized Propellant, 22 Oct., Exhaust

TWO-ANGLE METHOD For Various Angle Ratios

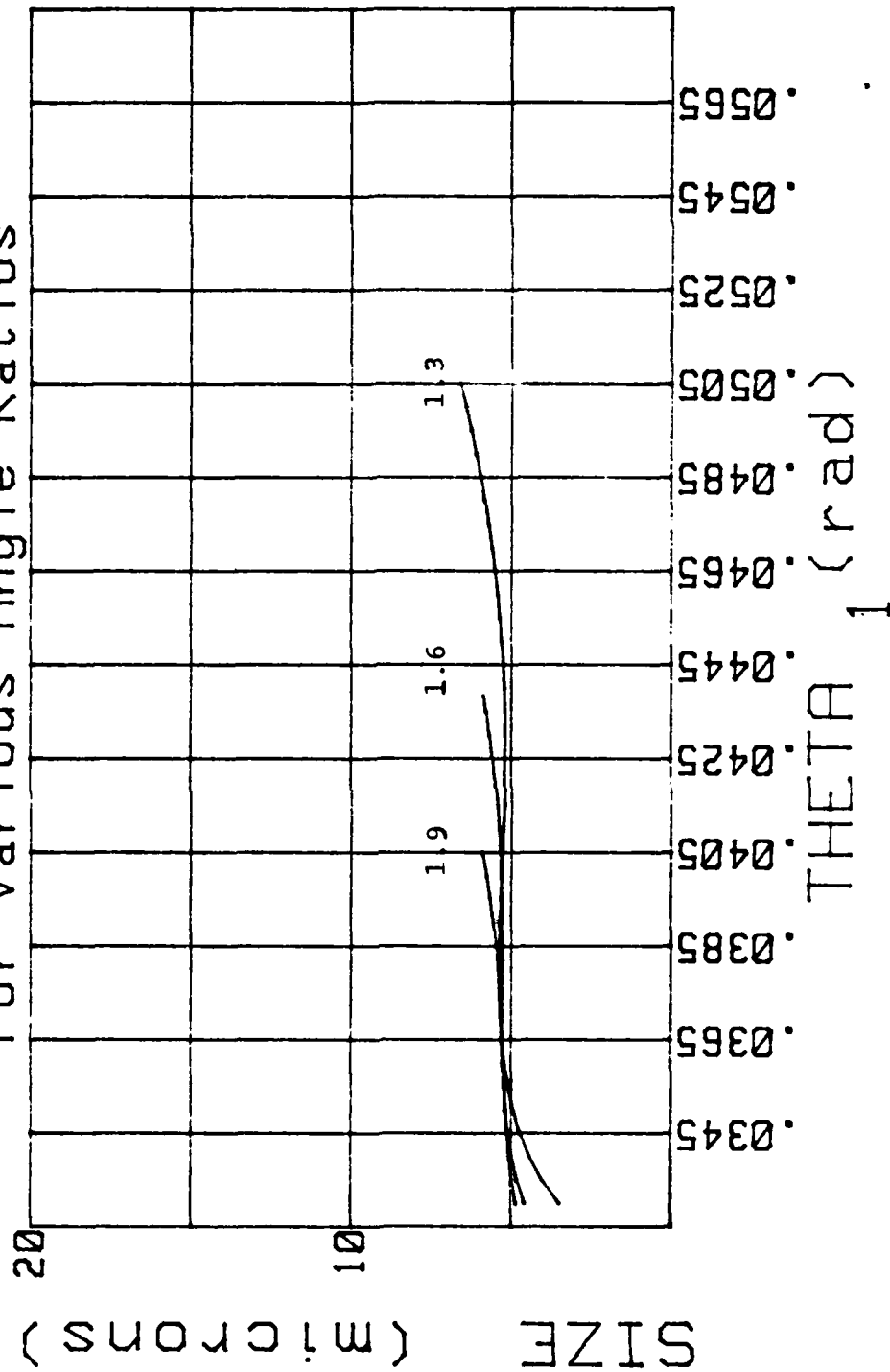


Figure 4.17 4.8% Aluminum Propellant, 18 Oct., Exhaust

CURVE FIT RESULTS INTENSITY VS. THETA

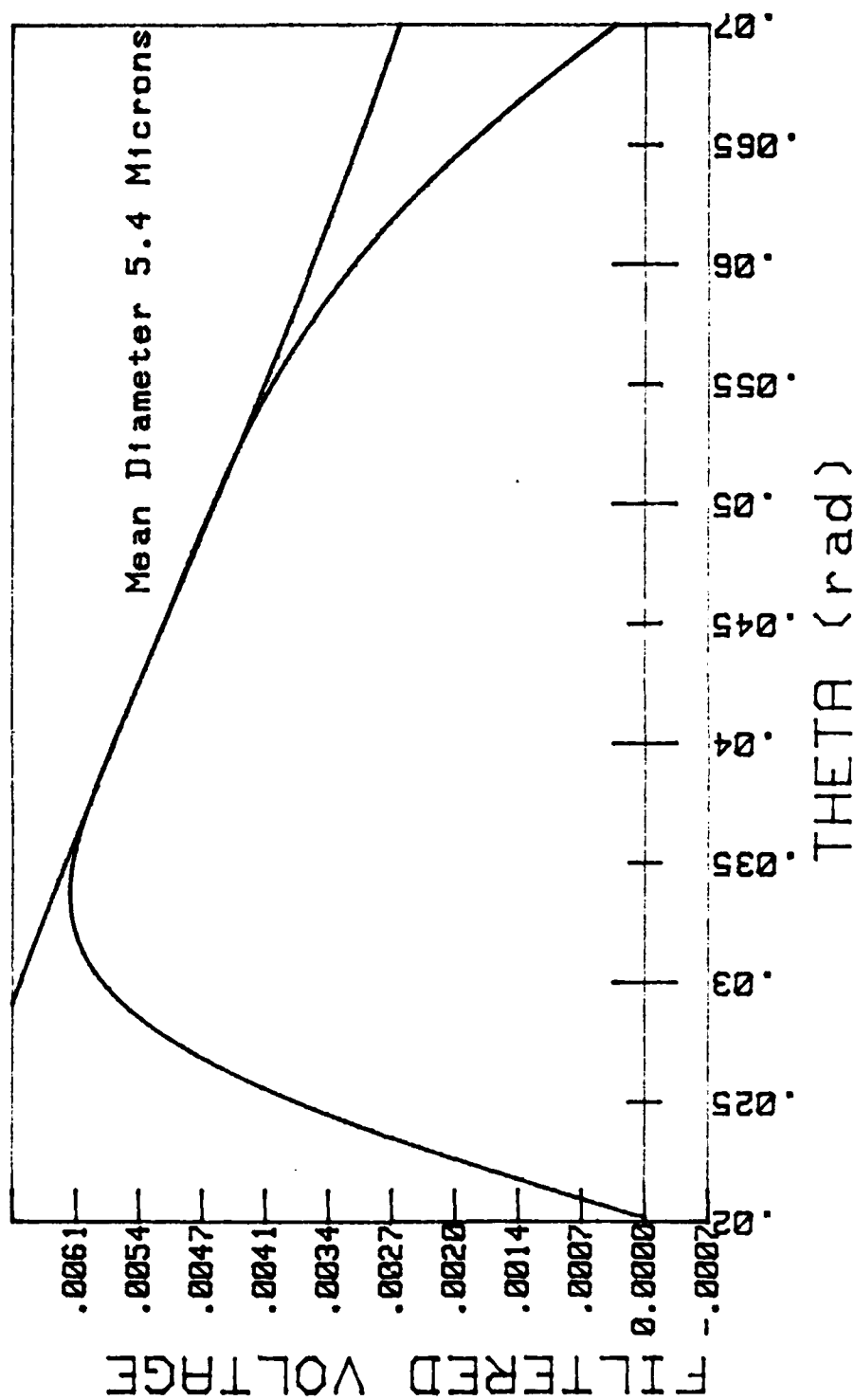


Figure 4.18 4.8% Aluminum Propellant, 18 Oct., Exhaust

CURVE FIT RESULTS INTENSITY vs. THETA

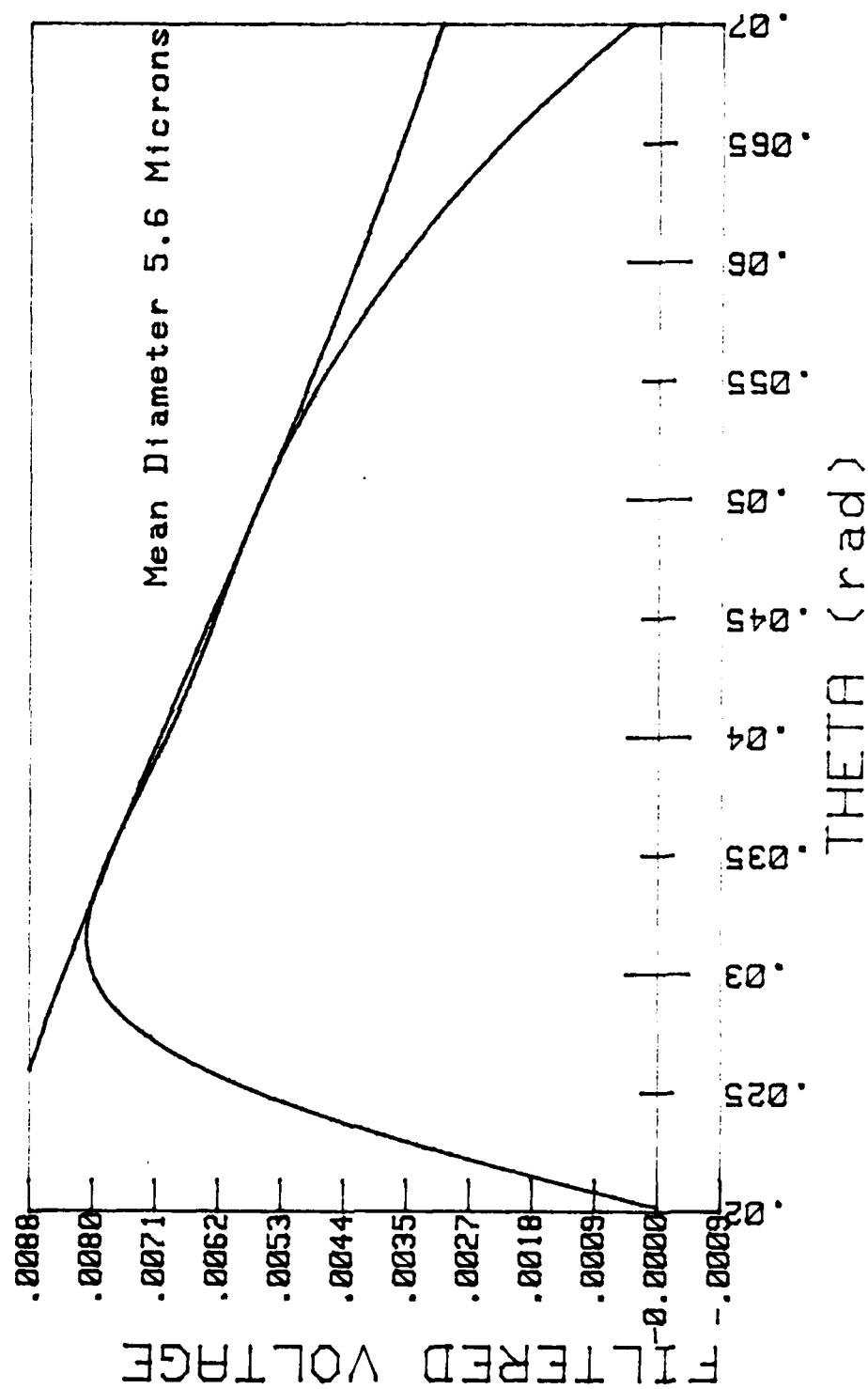


Figure 4.19 4.8% Aluminum Propellant, 23 Oct., Exhaust

TWO-ANGLE METHOD For Various Angle Ratios

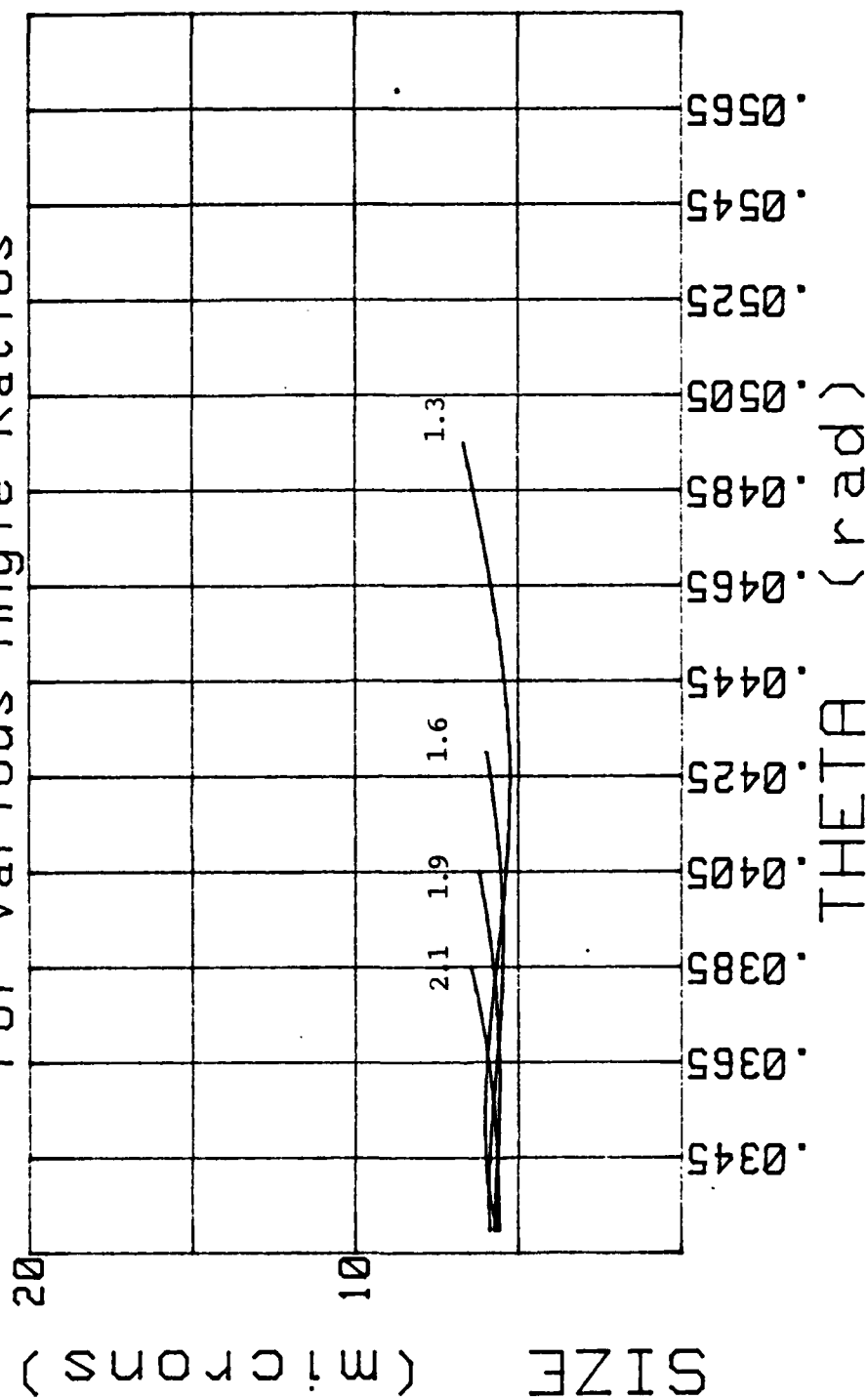


Figure 4.20 4.8% Aluminum Propellant, 23 Oct., Exhaust

CURVE FIT RESULTS INTENSITY VS. THETA

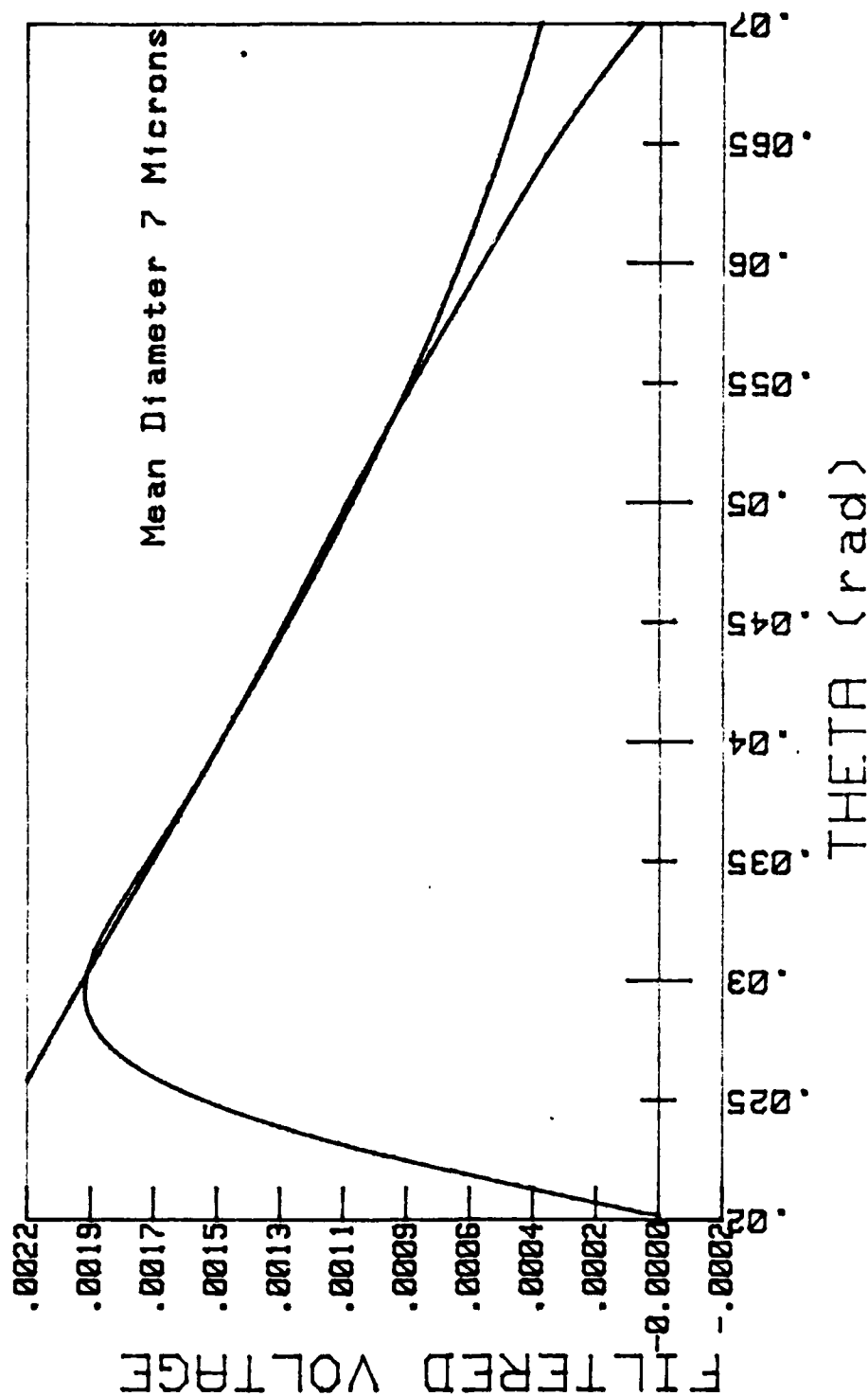


Figure 4.21 2% Aluminum Propellant, 30 Oct., Exhaust

TWO-ANGLE METHOD

For Various Angle Ratios

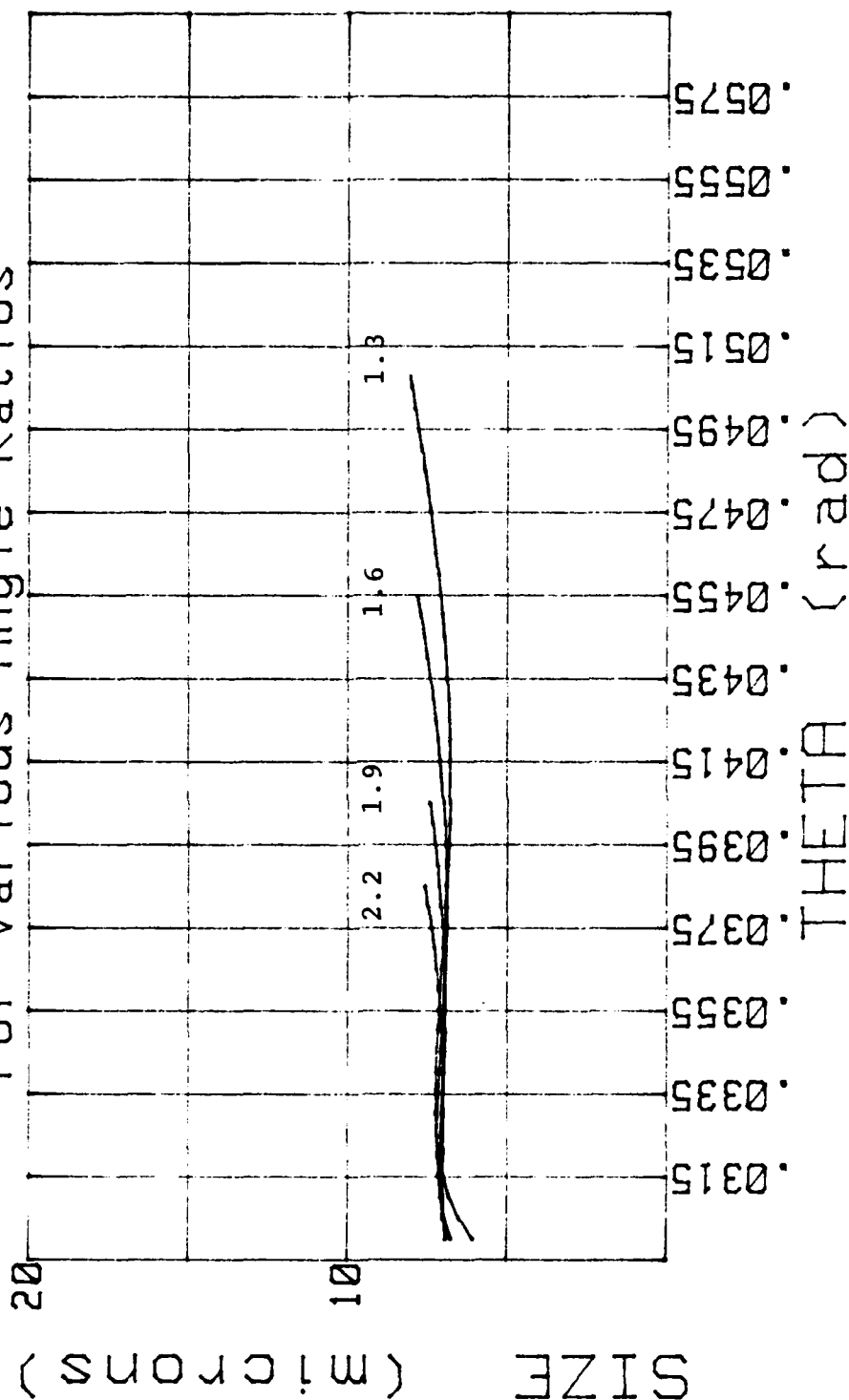


Figure 4.22 2% Aluminum Propellant, 30 Oct., Exhaust

CURVE FIT RESULTS INTENSITY vs. THETA

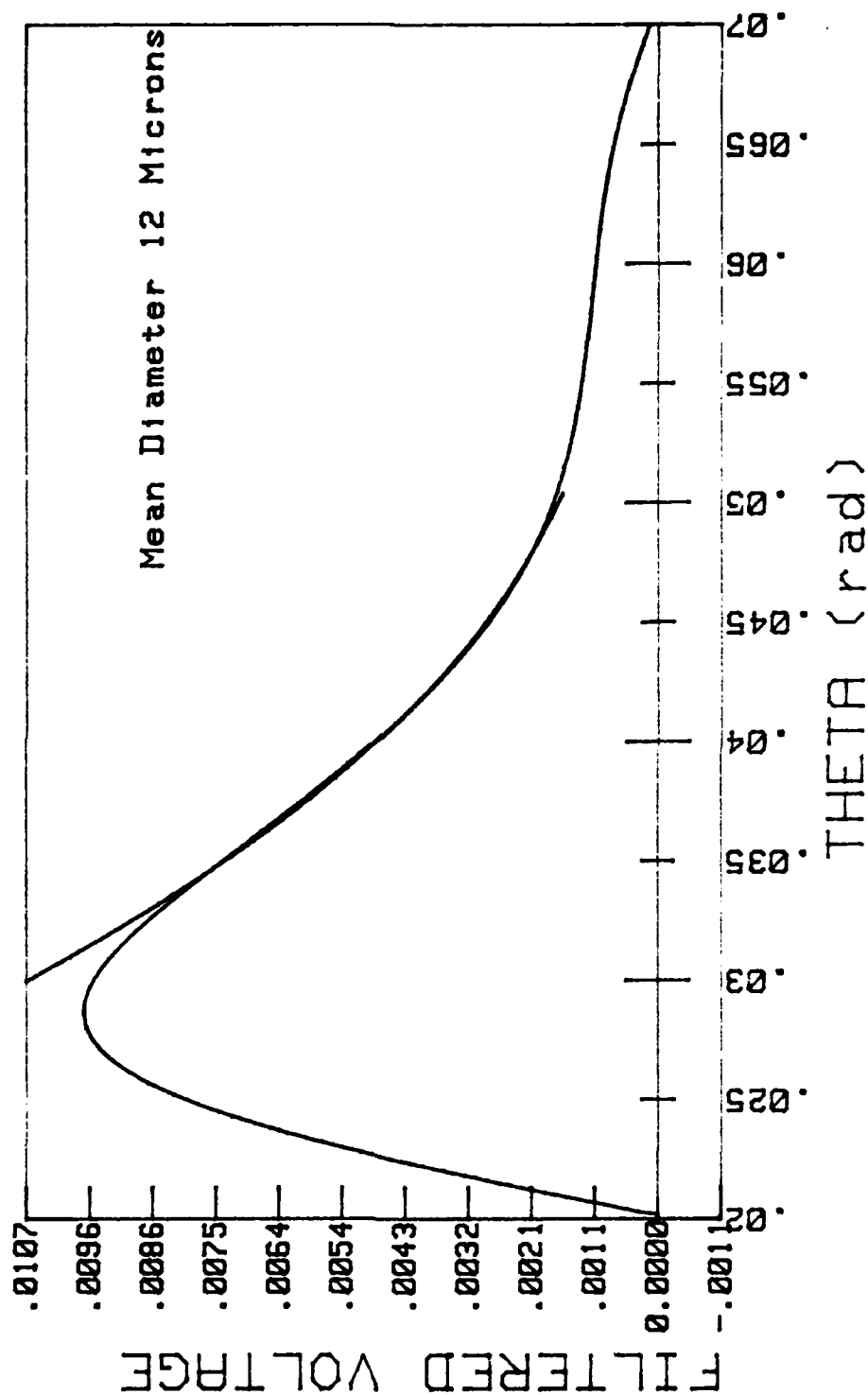


Figure 4.23 4.8% Aluminum Propellant, 19 Nov., Exhaust

TWO-ANGLE METHOD For Various Angle Ratios

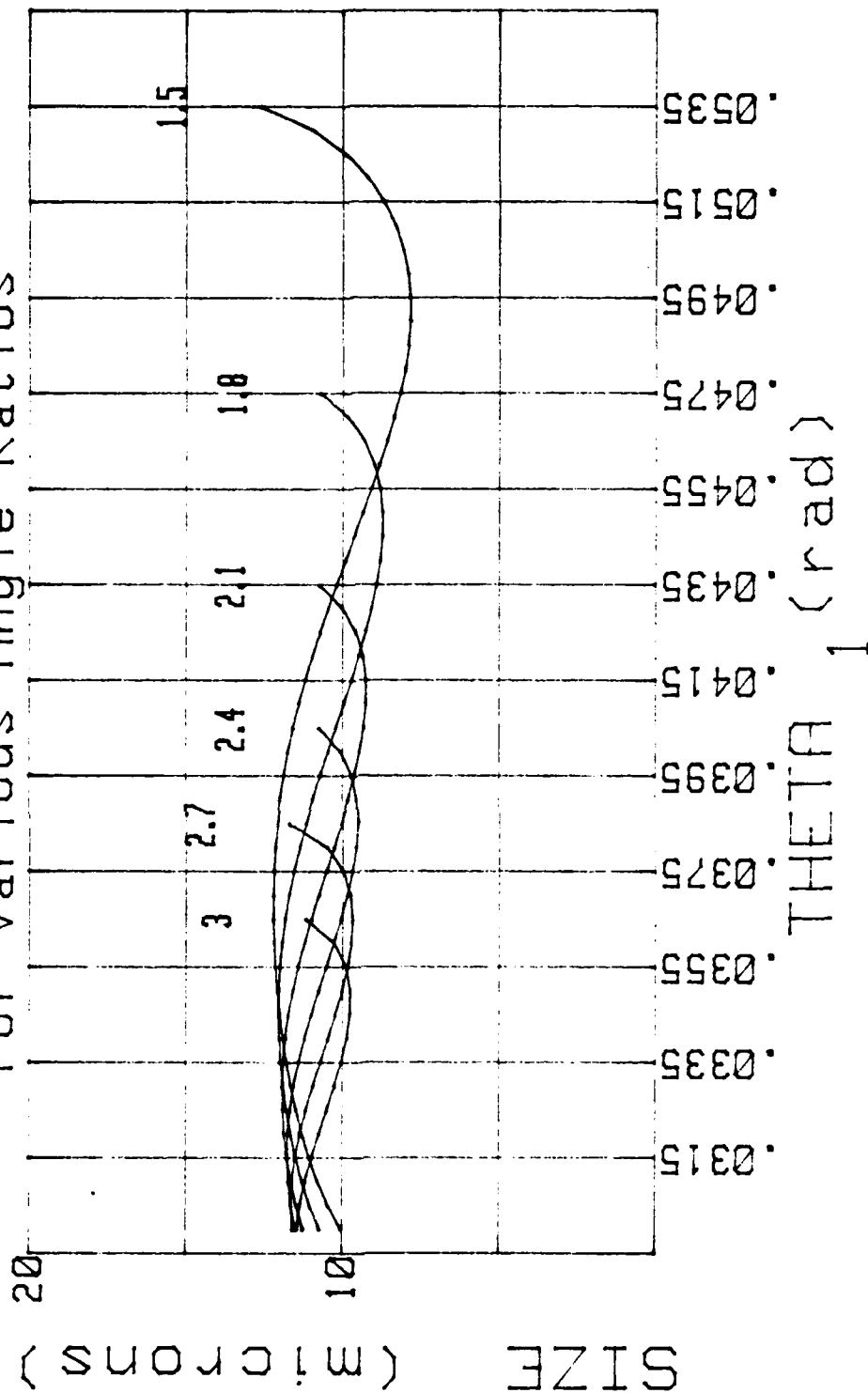


Figure 4.24 4.8% Aluminum Propellant, 19 Nov., Exhaust

CURVE FIT RESULTS INTENSITY VS. THETA

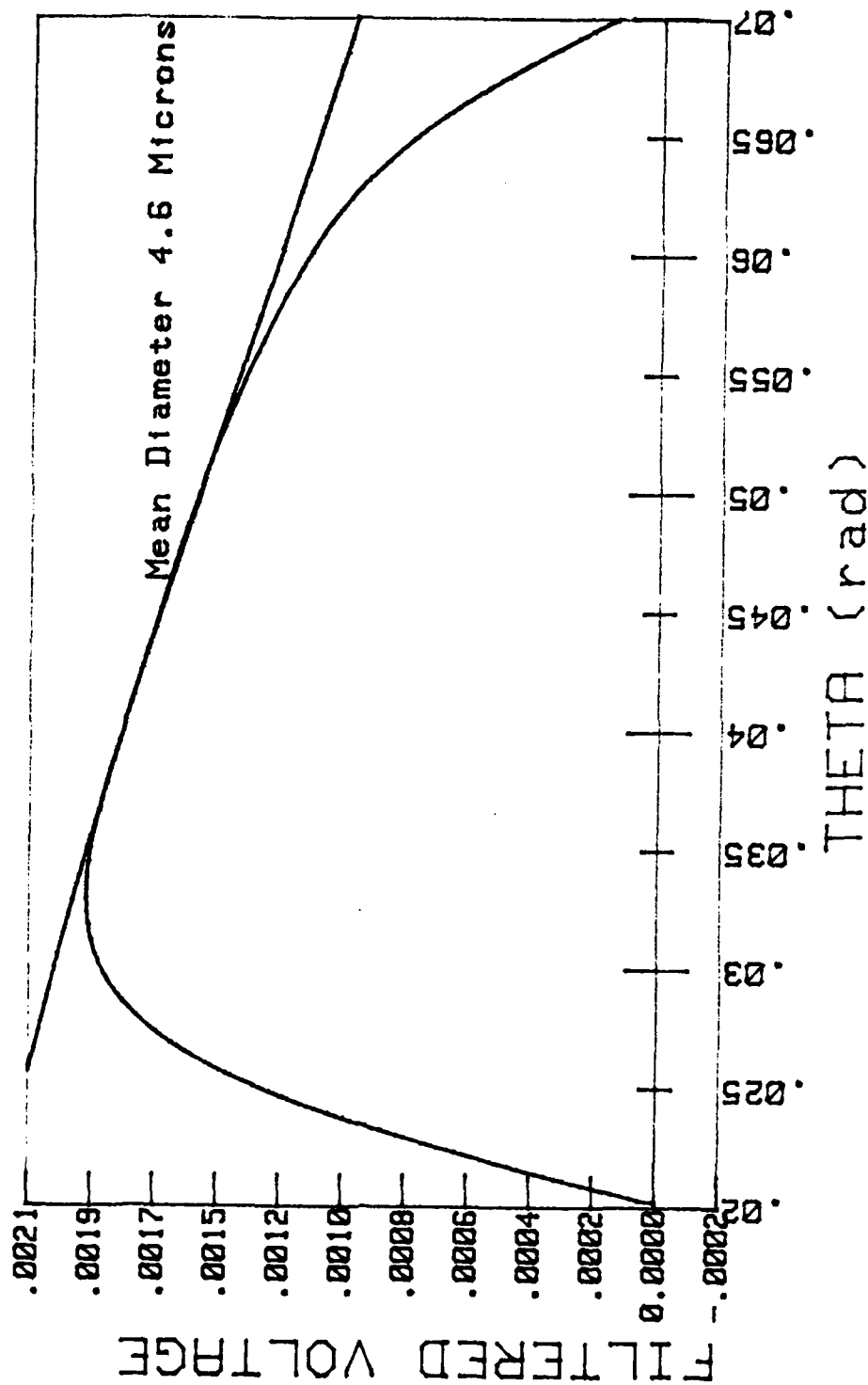


Figure 4.25 2% Aluminum Propellant, 25 Nov., Exhaust

TWO-ANGLE METHOD For Various Angle Ratios

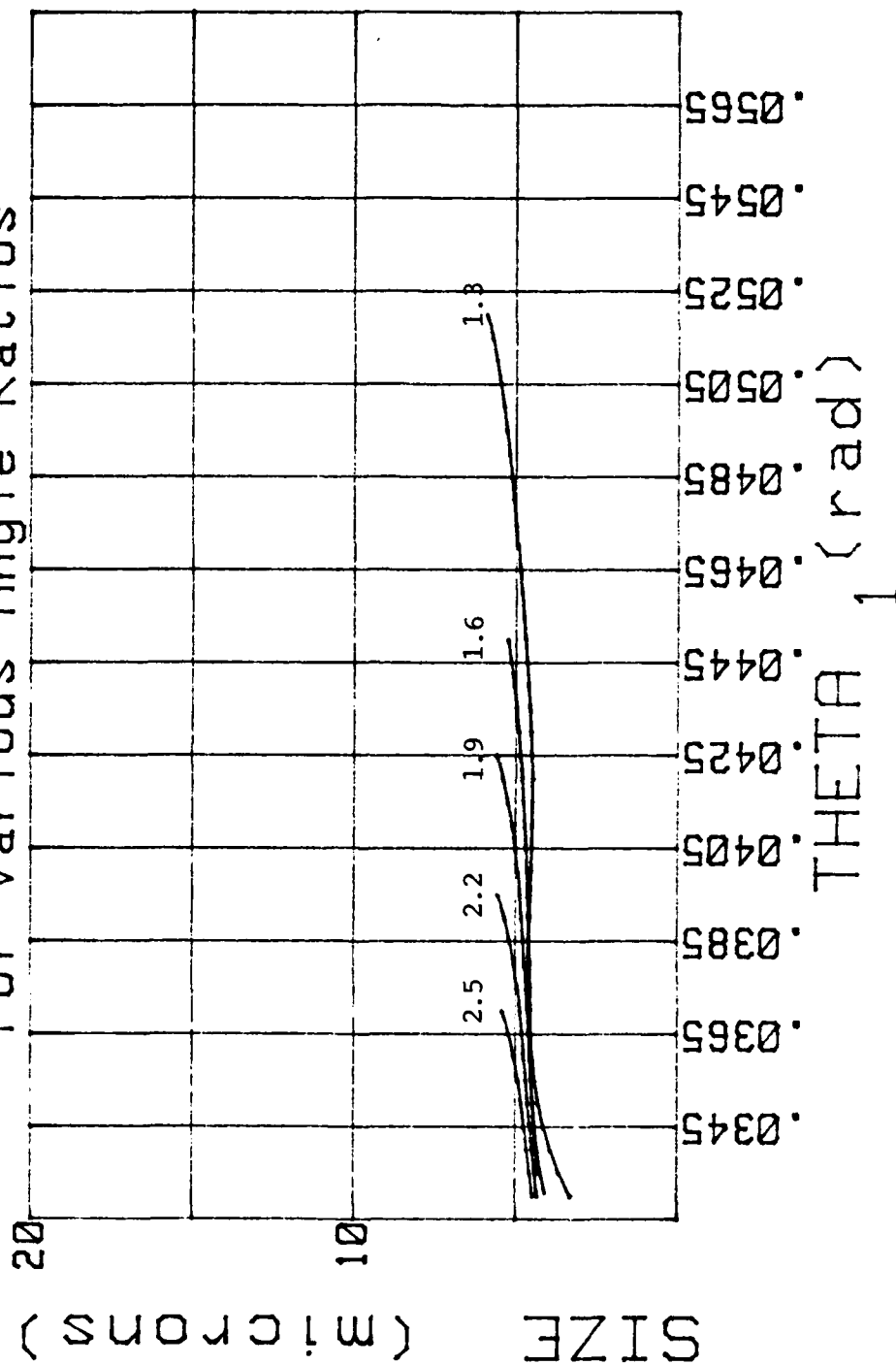


Figure 4.26 2% Aluminum Propellant, 25 Nov., Exhaust

CURVE FIT RESULTS INTENSITY VS. THETA

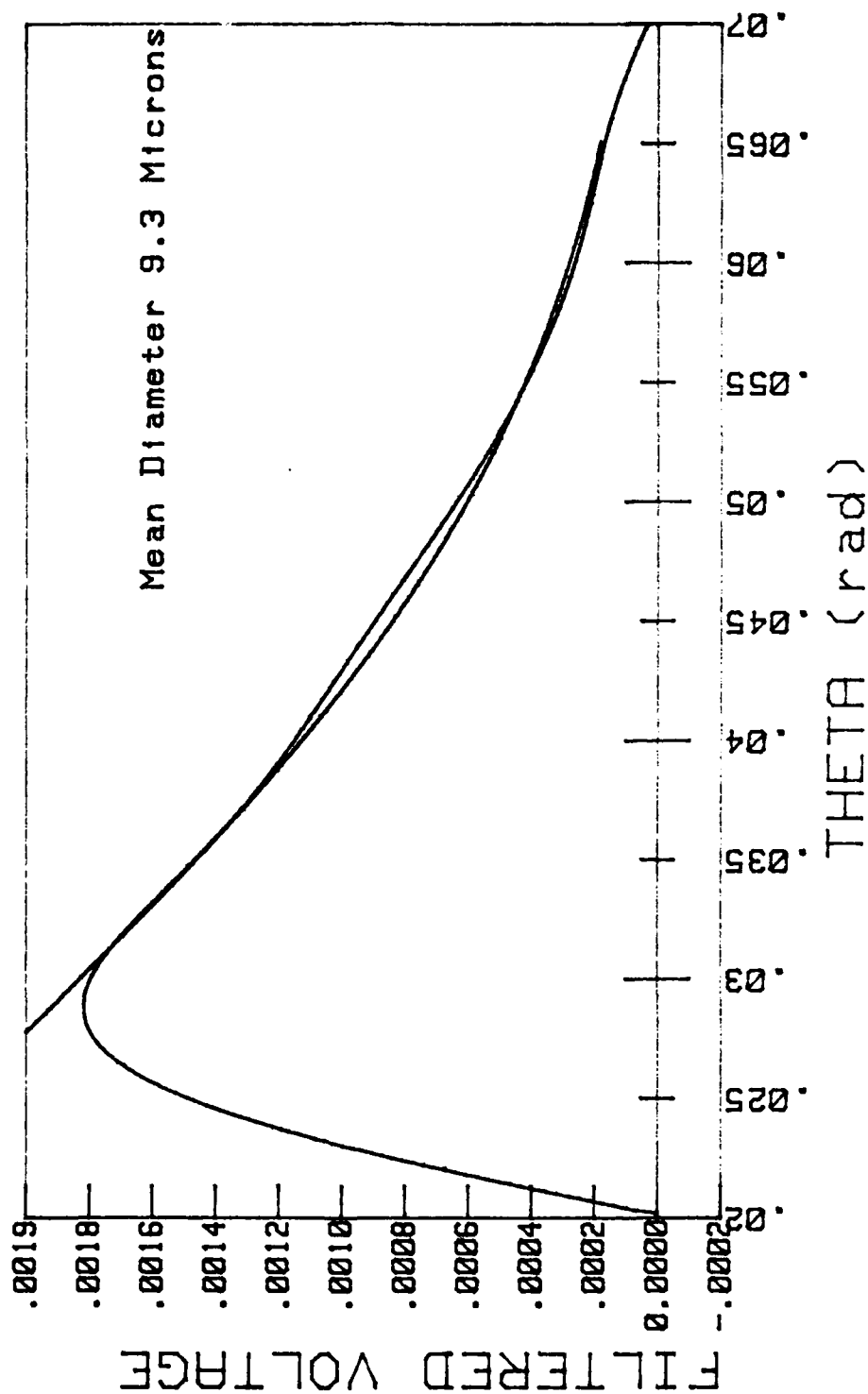


Figure 4.27 2% Aluminum Propellant, 26 Nov., Exhaust

TWO-ANGLE METHOD For Various Angle Ratios

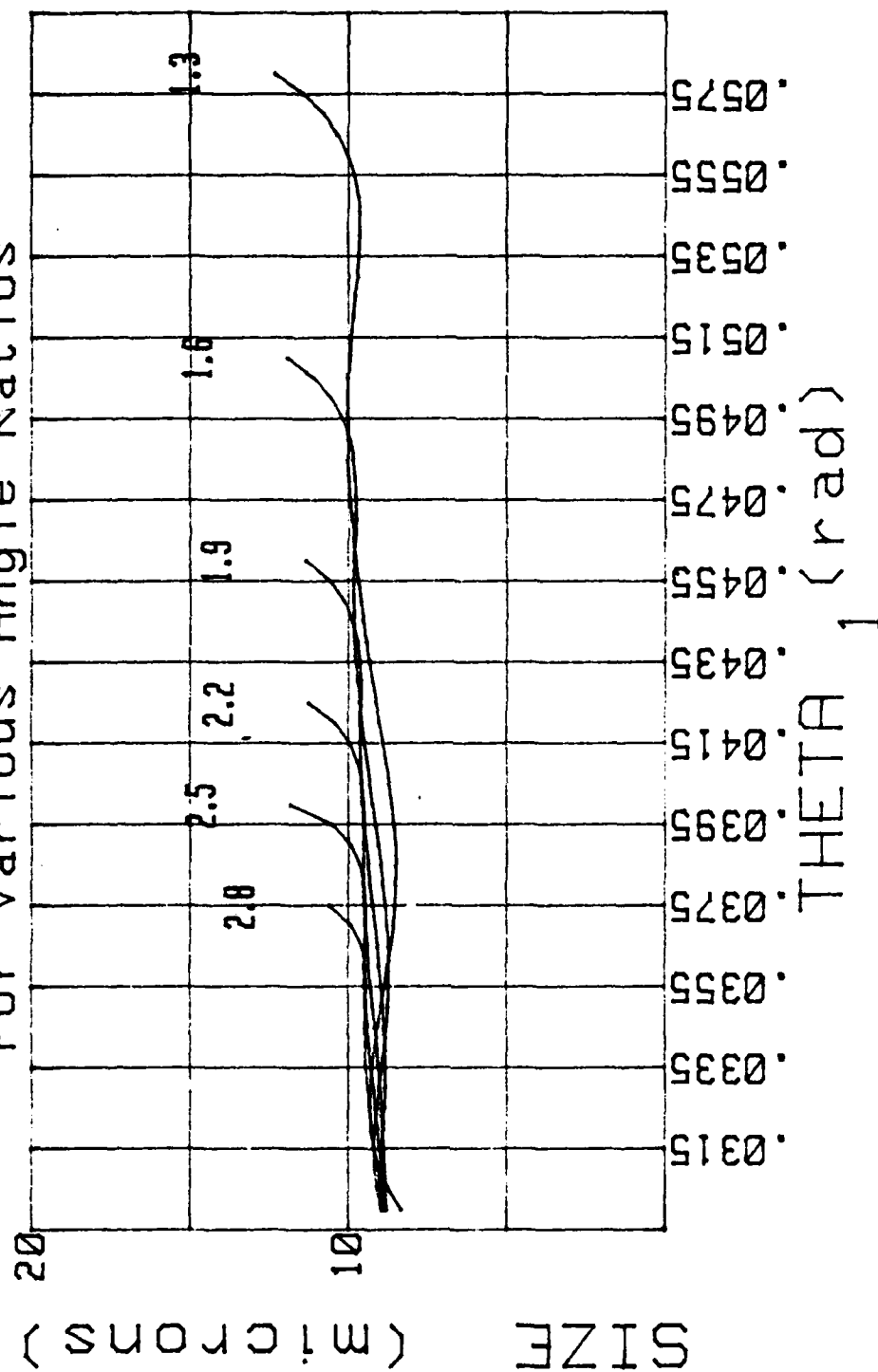
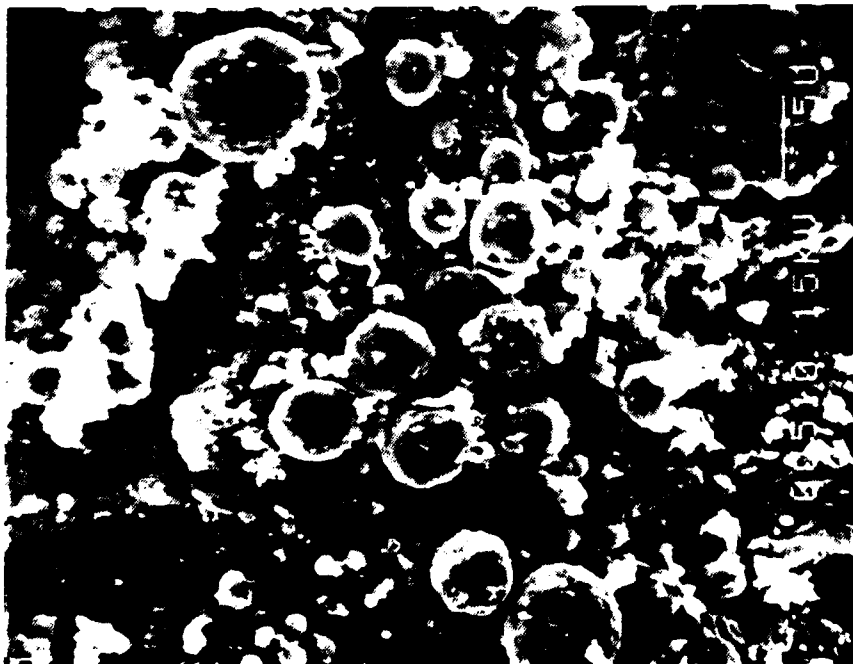
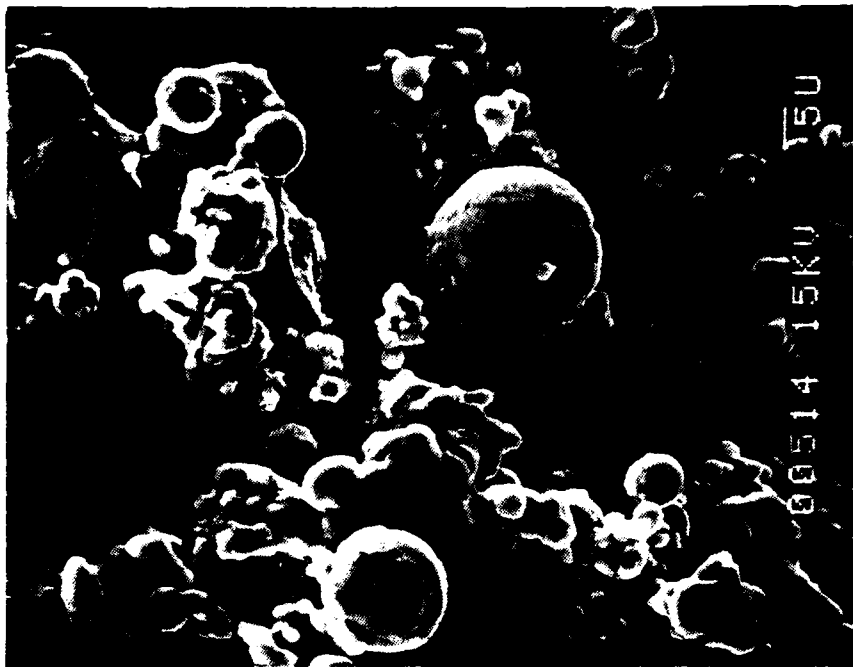


Figure 4.28 2% Aluminum Propellant, 26 Nov., Exhaust



Exhaust



Motor

Figure 4.29 SEM Eval., 2% Al Propellant

V. CONCLUSIONS AND RECOMMENDATIONS

The results of this study have shown that the measurement of D_{32} in rocket motor exhausts can be made using quite simple light scattering methods. Apparatus calibration results and S.E.M. evaluations of the collected motor exhaust products support this conclusion.

The SPP equation model underestimated D_{43} for this investigation. This indicated that the model predictions cannot be extrapolated to small motors with throat diameters less than one inch. The light scattering method, however, can be used to validate the SPP model for the larger motors upon which it was based.

In order to improve the signal to noise ratio in regards to the scattered light intensity, it is recommended that the laser beam be moved closer to the exit plane of the nozzle, where the particle density is greater. The laser beam for this study was 7.3 centimeters aft of the nozzle exit. To resolve the combustion light problem it may be necessary to use a different laser, such as a CO_2 that has a different wavelength than present in the combustion process. Also, other binder systems should be tested to determine if they significantly alter the light spectrum.

APPENDIX

PROGRAM LISTINGS

```

10 *****
20 ***** RDC *****
30 ***** PLOTS RAW DATA *****
40 ***** AVERAGES *****
50 ***** FILTERS *****
60 ***** DETERMINES MEAN DIAMETER *****
70 ***** BY INTERACTIVE GRAPHICS *****
80 ***** AND THE TWO-ANGLE METHOD *****
90 ***** Robert Kelly Harris 84 *****
100 ***** Revised, John S Rosa 85 *****
110 *****
120 OPTION BASE 1
130 COM /Hrdgans/ Av2(1024)
131 COM A2(1024) BUFFER
140 COM /Gauss/ T1(1024),L
150 COM /Max/ M7,M5,Xt,Yt,Xm,Ym,Xx
160 COM /Readata/ B,P,H,Q3$(20),Q4$(20),Zz$(20),Y1(8192) BUFFER,Y2(8192) BUFFE
R
170 COM /Two/ Av1(1024),M,M1,F
180 DIM Scans(R),X(1024)
190 COM /Plots/ P1$(20),P2$(20),P3$(20),P4$(20)
200 INTEGER Graf(1:12480) BUFFER
210 Choose: PRINT CHR$(12)
220 Old=0
230 PRINT " TO LOOK AT ANY DATA FILE THE PROGRAM NEEDS SOME STARTING INFORMATI
ON"
240 PRINT ""
250 PRINT " TO ACCOUNT FOR THE CHANGE IN WAVELENGTH IN THE MEDIUM"
260 PRINT ""
270 PRINT " ENTER THE INDEX OF REFRACTION OF THE MEDIUM"
280 PRINT ""
290 PRINT " WATER = 1.33"
300 PRINT " AIR = 1.0"
310 PRINT " ESTIMATE OF EXHAUST = 1.1"
320 BEEP
330 INPUT " THIS VALUE ADJUSTS THE COMPARISON CURVE TO THE MEDIUM",M1
340 PRINT CHR$(12)
350 PRINT " TO ACCOUNT FOR REFRACTION OF LIGHT AT BOUNDARIES BETWEEN"
360 PRINT ""
370 PRINT " THE MEDIUM AND AIR YOU MUST ENTER THE INDEX OF REFRACTION "
380 PRINT ""

```

```

390 PRINT "      OF THE COMBINATION OF THE MEDIUM AND ITS BOUNDARY"
400 PRINT ""
410 PRINT "      THIS VALUE IS APPLIED DIRECTLY TO THE DATA"
420 PRINT ""
430 PRINT "      AIR=1.0                PLEXIGLASS & WATER = 1.39"
440 PRINT ""
450 PRINT "ESTIMATE OF MOTOR CAVITY COMBUSTION PRODUCTS & WINDOW = 1.22"
460 PRINT ""
470 PRINT "      ESTIMATE OF ROCKET EXHAUST = 1.1 OR 1.0"
480 INPUT M
490 PRINT CHR$(12)
500 INPUT "      ENTER LASER WAVELENGTH (HeNe=.6328,Ar=.488)",L
510 INPUT "ENTER THE DESIRED PLOTTING INTERVAL OF DIODE ARRAY (2,4,6)",H
520 F=500                !mm FOCAL LENGTH OF OBJECTIVE LFNS
521 X(1)=1
522 T1(1)=.02
530 Diode=.025                !mm DIODE SPACING MAY BE .03
540   FOR I=1 TO 1023
550     X(I+1)=I+1                !CREATE AN ARRAY OF DIODE NUMBERS
560     T1(I+1)=ATN((I*Diode)/(F*M))+T1(1)    !CREATE AN ARRAY OF THETA
570   NEXT I
580 PRINT CHR$(12)
590 CALL Display(Old)                !JUST PRINTS INITIAL REMARKS ON CRT
600 IF Old THEN CALL Review(Av1(*))    !THESE TWO LINES ALLOW FOR
610 IF Old THEN GOTO Gauss            !REVIEWING REDUCED DATA FILES
620 REEP
630 INPUT "      INPUT TWO FILENAMES NOW (NO-PART ,PART)",Q3$,Q4$
640 INPUT "      ENTER '1' FOR 8 SCANS '2' FOR 4 SCANS",P
650 Z7$="INTERNAL,4,1"                ! USES LEFT DISK DRIVE FOR RAW DATA FILES
660 CALL Readata
670 CALL Shift
680 REEP
690 Screen: !
700 PRINT CHR$(12)                !CLEARS SCREEN
710 P1$="VOLTAGE"
720 P2$="DIODE NUMBER"                ! STRINGS FOR PLOTS
730 P3$="VOLTAGE vs. DIODE"
740 P4$="RAW DATA"
750 M5=1024
751 MR=0.
760 Xt=64                ! SET UP VALUES FOR PLOTS
770 Yt=.04
780 Xm=4
790 Yn=5
791 Xz=0
800 CALL Plot(Y2(*))                ! DRAWS AXES ,ETC...
810 GSTORE Graf(*)                ! STORES GRAPHICS DISPLAY JUST MADE
820 CALL Dataplot(B,Y1(*),H)        !PLOT NO-PARTICLES DATA
830 PRINT "      NO-PARTICLES PLOTTED"
840 PRINT ""
850 PRINT "      HOW MANY SCANS SEEN TO BE GOOD ?"
860 INPUT J

```

```

870 PRINT ""
880 PRINT " WHICH SCANS ARE GOOD ?...ie...1,2,4,5,7,INCLUDE LAST CO
WMA" !LAST COMMA IS REQUIRED OR YOU HAVE TO HIT CONT.. TWICE
890 INPUT Scans(1)
900 PRINT CHR$(12)
910 PRINT USING "/////////"
920 PRINT " AVERAGING THE SELECTED SCANS"
930 GRAPHICS OFF
940 CALL Average(J,Scans(1),Y1(1),Av1(1))
950 PRINT USING "@ "
960 GLOAD Graf(1) !LOADS GRAPHICS ARRAY RATHER THAN WASTE TIME RE-DRAWING
970 GRAPHICS ON
980 CALL Result(Av1(1),X(1),H) ! PLOTS 1024 ELEMENT ARRAYS
990 PRINT USING "/"
1000 PRINT " Average Intensity No-Particles"
1010 ON KEY 0 LABEL "AVERAGE1" GOTO Screen
1020 ON KEY 1 LABEL "PLOT-PARTICLES" GOTO 1060
1030 PRINT " PRESS KEY 0 TO RE-AVERAGE OR 1 TO CONTINUE"
1040 Standby: ! MANUAL CALLS THIS INTERRUPT DRIVEN PROGRAMMING
1050 GOTO Standby ! LOOPS, WAITING FOR USER TO DECIDE
1060 PRINT USING "@ "
1070 OFF KEY 1 !HELPS AVOID CONFUSION BY CLEARING THAT BOX
1080 CALL Dataplot(B,Y2(1),H) !PLOT PARTICLES DATA
1090 PRINT USING "/"
1100 PRINT " PARTICLE DATA PLOTTED"
1110 PRINT " FOR A HARD COPY OF THIS RAW DATA PRESS KEY 6"
1120 PRINT " "
1130 PRINT " OR TO CONTINUE PRESS KEY 1"
1140 ON KEY 6 LABEL "HARD & RAW" GOTO Raw
1150 ON KEY 1 LABEL "CONTINUE " GOTO Select
1160 GOTO Standby
1170 Raw: CALL Plot(Y2(1),1) ! THE ONE (1) IS AN OPTIONAL PARAMETER
1180 CALL Dataplot(B,Y2(1),H) ! WHICH IS USED TO GET HARD COPIES
1190 Select:
1200 OFF KEY 6
1210 OFF KEY 1
1220 PRINT CHR$(12)
1230 PRINT USING "/////"
1240 PRINT " HOW MANY SCANS SEEN TO BE GOOD ?"
1250 INPUT J
1260 PRINT " WHICH SCANS ARE GOOD ?...ie...1,2,4,5,7,INCLUDE
LAST COMMA"
1270 INPUT Scans(1)
1280 PRINT CHR$(12)
1290 PRINT USING "/////////"
1300 GRAPHICS OFF
1310 PRINT " AVERAGING THE SELECTED SCANS"
1320 CALL Average(J,Scans(1),Y2(1),Av2(1))
1330 PRINT USING "@ "
1340 P4$="AVERAGED SCANS"

```

```

1350 CALL Plot(Av2(#))
1360 GRAPHICS ON
1370 GSTORE Graf(1)
1380 CALL Result(Av2(#),X(#),H)
1390 PRINT USING "///"
1400 PRINT "                                     Average Scattered Intensity"
1410 ON KEY 2 LABEL "AVERAGE2" GOTO 1080
1420 ON KEY 3 LABEL "SUBTRACT" GOTO 1450
1430 PRINT "                                     HIT KEY # 2 TO RE-AVERAGE OR KEY # 3 TO
CONTINUE"
1440 GOTO Standby
1450 PRINT USING "0"
1460 OFF KEY 3
1470 MAT Av1= Av2-Av1                                     !SUBTRACTS NO-PARTICLES FROM PARTICLES
1480 GLOAD Graf(1)
1490 CALL Result(Av1(#),X(#),H)
1500 PRINT USING "///"
1510 PRINT "                                     Plot of the Difference Between Particles and N
o-Particles"
1520 PRINT "                                     KEY # 6 FOR HARD COPY"
1530 PRINT "                                     KEY # 1 TO CONTINUE "
1540 ON KEY 6 LABEL " HARD AVERAGE" GOTO 1570
1550 ON KEY 1 LABEL " FILTER " GOTO 1600
1560 GOTO Standby
1570 CALL Plot(Av1(#),1)
1580 CALL Result(Av1(#),X(#),H)
1590 PLOTTER IS 3,"INTERNAL"
1600 PRINT USING "///"
1610 PRINT "                                     ENTER THE NUMBER OF TIMES YOU WISH TO APPLY"
1620 PRINT "                                     THE DIGITAL FILTER FOR SMOOTHING"
1630 PRINT "                                     EXAMPLE***** 10"
1640 PRINT "                                     TAKES ABOUT 1.5 MINUTES"
1650 INPUT "                                     ZERO IS ALSO ACCEPTABLE",Fil
1660 IF Fil=0 THEN Gauss
1670 P4%="FILTERED DATA"
1680 CALL Filter(Av1(#),Fil)
1690 PRINT CHR$(12)
1700 CALL Plot(Av1(#))
1710 IF Fil THEN MAT X= T1
1720 CALL Result(Av1(#),X(#),H)
1730 PRINT "                                     Plot of the Difference Between Particles and N
o-Particles"
1740 PRINT "                                     AFTER APPLICATION OF A DIGITAL FIL
TER"
1750 PRINT "                                     for a HARD COPY "
1760 PRINT "                                     PREPARE the PLOTTER and"
1770 PRINT "                                     PRESS KEY # 8"
1780 PRINT "                                     OR"
1790 PRINT "                                     PRESS KEY # 9 TO NORMALIZE"
1800 ON KEY 8 LABEL "HARD FILTERED" GOTO 1830
1810 ON KEY 9 LABEL " NORMALIZE " GOTO Gauss

```

```

1820 GOTO Standby
1830 CALL Plot(Av1(*),1)
1840 CALL Result(Av1(*),X(*),H)
1850 OFF KEY 8
1860 Gauss: OFF KEY 2
1870 OFF KEY 8
1880 ON KEY 1 LABEL " FILTER " GOTO 1600 ! ALLOWS ONE TO SMOOTH OLD DATA
1890 ! WHEN REVIEWING REDUCED FILES
1891 Old=1 ! THIS ALLOWS FILTERING EVEN AFTER ENTERING GRAPHICS MODE, THE
1892 ! DIODE COORDINATES AREN'T NEEDED ANYMORE *SEE LINES NEAR CALL FILTER
1900 PRINT CHR$(12)
1910 !Av2 Array is Normalized BUT Av1(*) is Still Saved For Re-work if Needed
1920 MAT Av2= Av1 ! TO BEGIN WITH THE ARRAY IS ASSUMED TO BE NORMALIZED
1930 ! AND THE USER CHANGES THIS WITH INTERACTIVE GRAPHICS
1940 ! IN THE SUBROUTINE "Compare"
1950 P1$="FILTERED VOLTAGE "
1960 P2$="THETA (rad)"
1970 P3$="INTENSITY vs. THETA"
1980 P4$="CURVE FIT RESULTS"
1990 M5=.070
2000 X1=.005
2010 Y1=.1
2020 X2=2
2030 Y2=2
2031 X3=.02
2040 CALL Plot(Av1(*))
2050 CALL Result(Av1(*),I1(*),H)
2060 GSTORE Graf(*)
2070 CALL Compare(Av1(*),H,M,M1,Graf(*))
2080 GRAPHICS OFF
2090 ON KEY 4 LABEL "OTHER ARRAY" GOTO Choose
2100 ON KEY 5 LABEL " TWO-ANGLE " GOTO Buchele
2120 ON KEY 6 LABEL "STORE DATA" GOTO Storedata
2130 ON KEY 7 LABEL " QUIT " GOTO Quit
2140 CALL Menu1
2150 GOTO Standby
2160 Buchele: !
2170 CALL Twoangle
2180 CALL Menu1
2190 GOTO Standby
2200 Storedata: !
2210 CALL Store
2220 CALL Menu1
2230 GOTO Standby
2240 Quit: !
2250 END
2260 SUB Average(J,Scans(*),Y(*),Av(*)) !AVERAGES SELECTED SCANS
2270 MAT Av= (0) !INITIALIZES THE ARRAY LOCAL TO THIS ROUTINE
2280 FOR J=1 TO J STEP 1
2290 K=(Scans(J)-1)*1024+1
2300 L=Scans(J)*1024
2310 FOR I1=K TO L

```

! The 1 is for hard copy

!KEY 1 OPTION IS STILL VALID

!STRINGS FOR PLOTS

!SET UP VALUES
!FOR PLOTS

!PLOT OF NORMALIZED INTENSITY vs. THETA
! SAVES THE SCREEN IMAGE

! PRINTS OPTIONS ON THE SCREEN

! THIS COUNTER IS THE BEGINNING
! AND THIS ONE THE END OF BLOCKS
! OF 1024 IN THE OVERALL DATA

```

2320             I2=I1-K+1           ! THIS COUNTER IS ALWAYS BETWEEN
2330             Av(I2)=Av(I2)+Y(I1) ! 1 AND 1024
2340             NEXT I1
2350         NEXT I
2360     MAT Av= Av/IJ)
2370     SUBEND
2380 SUR DataPlot(B,Y(*),H)           ! B IS 4 OR 8 (THE NUMBER OF SCANS)
2390 COM /Max/ M7,M5,Xt,Yt,Xm,Ym,Xx
2400 LDIR 0
2410 LORG 4
2420     FOR J=1 TO B                 ! EACH SCAN
2430         MOVE 500+J*50,M7-.05     ! SEE NEXT LINE
2440         LABEL J;                 ! HELPS KEEP TRACK OF EACH SCAN AS IT APPEARS
2450         LINE TYPE 1
2460         K=(J-1)*1024+1           ! BEGINNING OF EACH SCAN AND
2470         L=J*1024                 ! THE END WITHIN THE TOTAL BLOCK
2480         MOVE 1,Y(K)              ! MOVE TO THE FIRST POINT
2490         FOR I=K TO L STEP H
2500             X=I-K+1              ! THIS GIVES 1 TO 1024 FOR ARCSISSA
2510             PLOT X,Y(I)
2520         NEXT I
2530     NEXT J
2540     PENUP
2541     M8=0
2550 SUBEND
2560 SUR Result(Iav(*),D(*),H)       ! THE AVERAGE INTENSITY IS PLOTTED
2570 CLIP ON
2580 MOVE D(1),Iav(1)
2590     FOR I=1 TO 1024 STEP H
2600         DRAW D(I),Iav(I)
2610     NEXT I
2620     PENUP
2630 SUBEND
2631 Sol: !
2640 SUB Plot(Y(*),OPTIONAL Hard)     ! IF THE OPTIONAL(Hard) IS RECEIVED
2650 COM /Max/ M7,M5,Xt,Yt,Xm,Ym,Xx ! THE FIGURE GOES TO THE PLOTTER
2660 COM /Plots/ P1$(20),P2$(20),P3$(20),P4$(20)
2670 M7=MAX(Y(*))*1.1                ! A SCALING VARIABLE
2680 M6=.1*M7                         ! ANOTHER SCALING VARIABLE
2700 GINIT                            ! GINIT IS JUST GOOD PRACTICE SO YOU KNOW
2710                                ! WHERE YOU ARE BEGINNING
2720 SELECT NPAP                      ! THIS DETECTS IF THE HARD COPY IS DESIRED
2730 CASE 1                          ! IT COULD BE DONE WITH IF THEN LOGIC
2740     PLOTTER IS 3,"INTERNAL"      ! BUT IS PRESENTED FOR FAMILIARIZATION
2750 CASE 2                          ! SINCE IT IS MORE POWERFUL IN COMPLEX
2760     PLOTTER IS 705,"HPGL"       ! SITUATIONS
2770 END SELECT
2780 GRAPHICS ON                      ! TO BE ABLE TO SEE THE PLOT
2790 CSIZE 5,.6
2800 DFC
2810 LDIR 0

```

```

2820 LOGC 5
2830 MOVE 75,95
2840 LABEL USING "K";P4$
2850 MOVE 75,90
2860 LABEL P3$
2870 MOVE 75,20
2880 LABEL P2$
2890 LDIR 90
2900 MOVE 18,60
2910 LABEL P1$
2920 VIEWPORT 30,125,30,85
2930 FRAME
2940 WINDOW Xx,M5,-M6,M7
2950 AXES Xt,M6,Xx,0,Xm,1,5
2960 LDIR 0
2970 CSIZE 3,.5
2980 LOGC 8
2990 CLIP OFF
3000     FOR I=-M6 TO M7 STEP M7/10
3010     MOVE Xx,I
3020     LABEL USING "I,M6.DDDD";I
3030     NEXT I
3040 CSIZE 3,.6
3050 LDIR 90
3060     LOGC 8
3070     FOR I=Xx TO M5 STEP Xt
3080     MOVE I,-M6
3090     LABEL USING "I,X";I
3100     NEXT I
3110     PENUP
3120 SUBEND
3130     SUB Compare(Av1(*),H,M,M1,INTEGER Graf(*))
3140     COM /Gauss/ T1(*),L
3150     COM /Hrdqaus/ Av2(*)
3160     COM /Max/ M7,M5,Xt,Yt,Xm,Ym,Xx
3201 Plot: !
3202     PRINT " INPUT REFERENCE ANGLE "
3203     INPUT Tt
3205     FOR N=1 TO 1024 STEP 1
3206     IF T1(N)=Tt THEN 3208
3207     NEXT N
3208     It=0
3209     FOR I=N-5 TO N+5
3210     It=It+Av1(I)
3211     NEXT I
3212     At=It/11
3220     OFF KEY
3230     ON KEY 3 LABEL "MENU" GOTO 4160
3240     PLOTTER IS 3,"INTERNAL"

```

! SCREEN UNITS FOR MARGINS
! DRAWS A BOX

! NUMBER THE Y AXIS

! NUMBER THE X AXIS

! GETS RID OF ALL LABELS ON KEYS

! IN CASE A HARD COPY WAS JUST MADE

```

3250      Hard=0                      ! (0) SO ONE DOESN'T EXIT TOO SOON
3260      Centerline=1                ! THE INITIAL NORMALIZING VALUE
3270      D=10.                      ! INITIAL PARTICLE MEAN DIAMETER IN MICRONS
3280 Change: CSize 4,.6
3290      PRINT USING "////////"
3300      PRINT "                      STAND BY FOR CURVE"
3310      MOVE 0,1
3320      CLIP ON
3331      DIM T(1:1024)
3340      FOR I=1 TO 1024 STEP H
3350          T(I)=A1*EXP(-D^2*((T1(I)^2-T1^2)*((M1*.57*PI)/L)^2)))
3370      DRAW T1(I),T(I)
3375      IF (T1(I)*((PI*D*M1)/L))>3.0 THEN 3440
3380      NEXT I
3440      PEMIP
3450      IF Hard THEN 3550             !EXITS ROUTINE IF A HARD COPY WAS JUST MADE
3460      PRINT USING "/////////"
3470      PRINT "                      USE THE KNOR TO VARY THE PARTICLE
SIZE"
3480      PRINT "                      OR HIT KEY # 6 FOR HARD COPY"
3490      PRINT " "
3500      PRINT "                      KEY # 9 ALLOWS YOU TO"
3510      PRINT "                      SELECT NEW REF ANGLE"
3520      PRINT " "
3530      PRINT "                      HIT KEY # 3 TO GET OUT"
3540      PRINT USING "////////"
3541      OFF KEY 0
3550      ON KEY 6 LABEL "HARD COPY" GOTO Hardgauss
3560      ON KEY 9 LABEL "NORMALIZE" GOTO Poot
3570      ON KNOR .05 GOTO Pulse
3580 Wait: GOTO Wait
3590 Pulse: PRINT USING "0"
3600      Strng1$="Mean Diameter "
3610      Strng2$=" Microns"
3620      Count=KNORX
3630      D=DROUND(D+Count/15,2)
3640      GLOAD Graf(*)
3650      LDIR 0
3660      LORG 8
3670      MOVE MS,.8*M7
3680      LABEL Strng1$&VAL$(D)&Strng2$
3690      GOTO Change
3700 Hardgauss:
3710      PRINT "                      PREPARE the PLOTTER"
3720      PRINT "                      PRESS CONTINUE for"
3730      PRINT "                      HARD COPY"
3740      PAUSE
3750      Hard=1
3760      CALL Plot(Av2(*),1)           ! SO THAT SUBEXIT OCCURS AFTER HARD COPY
                                      ! 1**HARD COPY

```

```

3770 CALL Result(Av2(*),T1(*),H)
3780 PRINT USING "e"
3790 LORG 8
3800 MOVE M5,,8*M7
3810 LDIR 0
3820 LABEL Strng1&VAL$(D)&Strng2$
3840 GOTO Change
4160 Subexit: !
4170 SUBEND
4180 SUB Manuel
4190 PRINT USING "e"
4200 PRINT " YOU CAN RE-NORMALIZE"
4210 PRINT "*****"
4220 PRINT " YOU CAN RE-AVERAGE (New Data Only)"
4230 PRINT "*****"
4240 PRINT " PRESS KEY # 4 TO LOOK AT OTHER DATA"
4250 PRINT " OLD OR NEW "
4260 PRINT " MOTOR / EXHAUST"
4270 PRINT "*****"
4280 PRINT " PRESS KEY # 5 "
4290 PRINT " FOR THE ' TWO-ANGLE ' METHOD"
4300 PRINT " OF PARTICLE SIZING"
4310 PRINT "*****"
4320 PRINT " TO STORE THE REDUCED DATA PRESS KEY # 6 "
4330 PRINT "*****"
4340 PRINT " TO END THIS SESSION PRESS KEY # 7"
4350 SUBEND
4360 SUB Display1(Old)
4370 PRINT " TO REDUCE NEW DATA PRESS KEY # 1"
4380 PRINT ""
4390 PRINT " TO REVIEW PREVIOUSLY REDUCED DATA PRESS KEY # 2"
4400 PRINT " "
4410 ON KEY 1 LABEL " NEW DATA" GOTO New
4420 ON KEY 2 LABEL " OLD DATA" GOTO Review
4430 Wait: GOTO Wait
4440 New: PRINT CHR$(12)
4450 PRINT " PUT THE DISK IN THE LEFT DRIVE IF IT IS NOT ALREADY"
4460 PRINT ""
4470 PRINT " ENTER THE NAMES OF THE FIRST AND SECOND FILES."
4480 PRINT ""
4490 PRINT " EACH FILE HAS DATA FROM BOTH DIODE ARRAYS."
4500 PRINT ""
4510 PRINT " FIRST IS NO-PARTICLES & NEXT IS PARTICLES ----D1$,D2$"
4520 PRINT ""
4530 Old=0
4540 SUBEXIT
4550 Review: Old=1 !THIS VARIABLE IS PASSED TO THE MAIN PROGRAM TO INDICATE
4560 !THAT THE DATA TO BE READ IS ONE (1) SCAN AND THAT
4570 !THE AVERAGING ROUTINES WILL NOT BE USED

```

```

4580          SUBEND
4590 SUB Readata
4600 COM /Readata/ B,P,H,Q3$(20),Q4$(20),Zz$(20),Y1(*) BUFFER,Y2(*) BUFFER
4610 Xyz=1          ! FILE POINTER VARIABLE
4620 R=8            ! NUMBER OF SCANS IN MOTOR DATA
4630 R1=65536       ! NUMBER OF BYTES OF MOTOR DATA
4640 IF P=2 THEN Xyz=4097 ! RECORD # WHERE 4 SCANS DATA BEGINS
4650 IF P=2 THEN R1=32768 ! NUMBER OF BYTES OF 4 SCAN DATA
4660 IF P=2 THEN R=4    ! NUMBER OF SCANS
4670 PRINT " "
4680 PRINT "          READING DATA FROM FILE ON DISK"
4690 ASSIGN @Disk1 TO Q3&Zz$
4700 ASSIGN @Disk2 TO Q4&Zz$          ! OPEN I/O PATHS
4710 ASSIGN @Buff1 TO BUFFER Y1(*)
4720 ASSIGN @Buff2 TO BUFFER Y2(*)
4730 CONTROL @Disk1,5;Xyz
4740 TRANSFER @Disk1 TO @Buff1;COUNT R1          ! READS NO-PARTICLE DATA
4750 WAIT FOR EOT @Disk1          ! NOT AN OVERLAPPING TRANSFER
4760 CONTROL @Disk2,5;Xyz          ! Xyz SETS DISK FILE POINTER TO
4770                                ! EITHER MOTOR OR EXHAUST DATA
4780 TRANSFER @Disk2 TO @Buff2;COUNT R1          ! READS PARTICLE DATA
4790 WAIT FOR EOT @Disk2
4800 ASSIGN @Disk1 TO *
4810 ASSIGN @Disk2 TO *
4820 ASSIGN @Buff1 TO *          ! JUST GOOD PRACTICE TO CLOSE
4830 ASSIGN @Buff2 TO *          ! I/O PATHS
4840 SUBEND
4850 SUB Plot2(E,D(*),X)
4860 DIM Title$(25),Theta$(20)
4870 GINIT
4880 IF X=1 THEN PLOTTER IS 705,"HPGL"
4890 DEG          ! DEGREES for LABEL DIRECTION
4900 GRAPHICS ON
4910 VIEWPORT 35,125,35,85
4920 Max=10*INT((MAX(D(*))+10)/10)
4930 WINDOW D(1,2),D(E,2),0,Max
4940 G=(D(E,2)-D(1,2))/(E-1)*4          ! AN X GRID LINE EVERY 4th POINT
4950 F=(INT(E/4)-1)*4
4960 IF F=0 THEN F=4
4970 CLIP D(4,2)-G,D(F,2)+2*G,0,Max          ! MAKES GRID UNIFORM
4980 GRID G,5,D(4,2)-G,0
4990 CLIP OFF
5000 LONG B
5010 LDIR 90
5020 CSIZE 4,.5
5030 FOR I=4 TO E STEP 4          ! PUTS NUMBERS ON X AXIS
5040     MOVE D(I,2),0
5050     LABEL USING ".DDDD";D(I,2)
5060 NEXT I

```

```

5070 LDIR 0
5080 LORG 9
5090 FOR I=10 TO Max STEP 10                                !NUMBER Y AXIS
5100     MOVE D(4,2)-G,I
5110     LABEL USING "#,K";I
5120 NEXT I
5130 CSIZE 6,.6
5140 Title$="TWO-ANGLE METHOD"
5150 Title1$="For Various Angle Ratios"                        !STRINGS FOR PLOTS
5160 Size$="SIZE (microns)"
5170 Thta$="THETA (rad)"
5180 Sub$="1"
5190 LDIR 90
5200 LORG 5
5210 B=D(4,2)-G-(D(E,2)-D(1,2))/10
5220 MOVE B,Max/2
5230 LABEL Size$
5240 LDIR 0
5250 A=(D(E,2)+D(1,2))/2
5260 MOVE A,-Max/4
5270 LABEL Thta$
5280 LORG 3
5290 MOVE A,-Max/4
5300 LABEL Sub$
5310 LORG 5
5320 MOVE A,Max*1.15
5330 LABEL Title$
5340 CSIZE 4.5
5350 MOVE A,Max*1.05
5360 LABEL Title1$
5370 PENUP
5380 SUBEND
5390 SUB Distribution(D(*),Tratio,E)
5400     LINE TYPE 1
5410     CLIP ON
5420     Tratio$=VAL$(Tratio)                                ! ANGLE RATIO
5430     MOVE D(1,2),D(1,1)
5440     FOR I=1 TO E
5450         DRAW D(I,2),D(I,1)
5460     NEXT I
5470     LORG 4
5480     LINE TYPE 1
5490     CSIZE 4,.3
5500     MOVE D(I-1,2),D(I-1,1)+2
5510     LABEL Tratio$
5520     PENUP
5530 SUBEND
5540 SUB Twoangle

```

!THIS SUBROUTINE PLOTS THE
!PARTICLE SIZES DERIVED USING
!VARIOUS ANGLE RATIOS APPLIED
!TO THE DATA OVER A RANGE OF
!ANGLES

```

5550 *****
5560 ***** SUBPROGRAM 'TWOANGLE' *****
5570 ***** PARTICLE SIZING BY *****
5580 ***** MEASURING THE RATIO *****
5590 ***** OF INTENSITY AT *****
5600 ***** TWO ANGLES *****
5610 *****
5620 OPTION BASE 1
5630 COM /Two/ Av1(1024),M,M1,F
5640 COM /Gauss/ T1(1024),L
5650
5660 DIM D(200,2)
5670 PRINT CHR$(12)
5680 PRINT USING "////////"
5690 PRINT " THIS SUBPROGRAM USES THE TWO-ANGLE METHOD DESCRIBED BY BUCHFLE"
5700 PRINT " "
5710 PRINT " TO CALCULATE PARTICLE SIZE FOR VARIOUS ANGLE RATIOS AND ANGLES."
5720 PRINT " "
5730 PRINT " IT IS HOPED THAT THE CURVES WHICH RESULT WILL SHOW "
5740 PRINT " "
5750 PRINT " WHICH SIZE IS THE MOST PROBABLE."
5760 PRINT " "
5770 PRINT "AFTER NOTING FROM THE RAW DATA WHICH ANGLES CONTAIN THE CENTER LOBE"
5780 PRINT ""
5790 PRINT " ENTER*****THE SMALLEST USEABLE ANGLE,"
5800 PRINT " THE SMALLEST ANGLE RATIO,AND"
5810 PRINT " THE STEP SIZE BETWEEN ANGLE RATIOS"
5820 PRINT " YOU WISH TO EXPLORE"
5830 PRINT " EXAMPLE***** .012,1.2,.4"
5840 INPUT " ENTER thetal,theta-ratio,theta-step",Q,A,B
5850 OFF KEY
5860 X=0
5870 Begin: !GRAPH WILL APPEAR ON SCREEN
5880 !Van De Hulst and Gumprecht & Sleepovich explain that the change in
5890 !wavelength of the beam is accounted for by dividing by the index
5900 !of refraction of the medium. *****L=L/M1 *****
5910 C=(L/M1/.57/PI)^2 !-----see page 15 of nasa tech paper 2156
5920 FOR N=1 TO 1024 !to see this is a convenient constant
5930 IF Q(T1(N)) THEN 5950 !FINDS POSITION OF MINIMUM AMPLGE
5940 NEXT N
5950 FOR Tratio=A TO 3 STEP B !VARIOUS ANGLE RATIOS
5960 FOR J=N TO 1010/Tratio STEP 10 !SETS THE RANGE OF POSSIBLE
5970 ! ANGLES (THETA 1)
5980 Thetal=T1(J)
5990 Theta2=T1(J*Tratio) ! THETA 2
6000 DeltaTheta=Theta2^2-Thetal^2
6010 I1=0
6020 I2=0

```

```

6030      FOR I=J-5 TO J+5
6040          I1=I1+Av1(I)
6050      NEXT I
6060          I1=I1/I1
6070      FOR I=INT(J*Tratio-5) TO INT(J*Tratio+5)
6080          I2=I2+Av1(I)
6090      NEXT I
6100          I2=I2/I1
6110      E=(J-N)/10+1
6120
6130
6140      IF I1<I2 OR I1=0 OR I2=0 THEN D(E,1)=0
6150      IF I1<I2 OR I1=0 OR I2=0 THEN GOTO Xcomp
6160      D(E,1)=SQR(-C/Deltatheta*LOG(I2/I1))
6170
6180
6190 Xcomp: D(E,2)=Thta1
6200      Spar=PI*D(E,1)*M1/L
6210      Tbar=Spar*Thta2
6220      IF Tbar>4 THEN J=1010/Tratio
6230      IF E=1 AND Tbar>3 THEN
6240      !the above line ends all calculation if
6250      !the first element (E=1) failed the test
6260      NEXT J
6270
6280
6290 PRINT CHR$(12)
6300      IF Tratio=A THEN CALL Plot2(E,D(*),X)
6310      CALL Distribution(D(*),Tratio,E)
6320 NEXT Tratio
6330      ON KEY 2 LABEL "HARD COPY" GOTO Hard
6340      ON KEY 3 LABEL "MENU" GOTO Subexit
6350 PRINT USING "/////"
6360 PRINT "
6370 PRINT "
6380 Standby:GOTO Standby
6390 Hard:X=1
6400      GOTO Pegin
6410 Subexit: GINIT
6420      GRAPHICS OFF
6430 SUBEND
6440 SUB Shift
6450 COM /Readata/ B,P,H,Q3$(20),Q4$(20),Zz$(20),Y1(*) BUFFER,Y2(*) BUFFER
6460 DIM E(1:R192)
6470 PRINT CHR$(12)
6480 PRINT USING "/////////"
6490 PRINT " RAW DATA IS BEING SHIFTED TO CORRECT FOR SMALL GAPS BETWEEN SCANS"
6500 PRINT ""
6510 PRINT "

```

!THESE 2 LOOPS AVERAGE A FEW
 !INTENSITIES IN THE HOPE
 !OF A STEADIER CALCULATION
 ! DONE HERE FOR THETA2 FOR
 ! THE GIVEN ANGLE RATIO
 !THIS IS A COUNTER FOR THE ARRAY CONTAINING
 !PARTICLE SIZE AND THETA1 FOR THE GIVEN
 !ANGLE RATIO
 !ALLOWANCE FOR IF THE DATA
 !IS NOT WELL BEHAVED
 !TWO ANGLE METHOD
 !VALUE OF DIAMETER based on INTENSITY RATIO
 !For a given ANGLE RATIO and ANGLE THETA1
 !THIS IS PI*D/LAMRDA -- THE SIZE PARAMETER
 !THETA BAR FOR THE LARGER ANGLE
 !THIS ENDS THE DO LOOP FOR THIS
 !ANGLE RATIO SINCE THE GAUSSIAN
 !IS NOT VALID WHEN Tbar > 3
 ! FIRST TIME THROUGH-- D HAS THE MOST ELEMENTS IT WILL HAVE
 ! SO SET UP THE GRAPH USING D's PRESENT PARAMETERS
 YOU CAN GET A HARD COPY BY PRESSING KEY # 2"
 OR EXIT THIS ROUTINE BY PRESSING KEY # 3"
 !A VARIABLE TO CONTROL PLOTTER

BE PATIENT, IT'S A LONG SET OF DO-LOOPS"

```

6520      !   THERE ARE SOME SMALL GAPS BETWEEN SCANS AND THIS SUBROUTINE
6530      !   SHIFTS THE DATA SO THAT THE FIRST DIODE DATA POINT IS MOVED
6540      !   TO THE VERY BEGINNING OF ITS 1024 BLOCK IN THE OVERALL ARRAY
6550      !   .THE FIRST SET IS RIGHT ON, THE NEXT IS ONE OFF,THE THIRD IS
6560      !   TWO OFF ,,SO FORTH. THIS MAY NOT MATTER WITH OUR RESOLUTION
6570      !   AND IS PROBABLY DUE TO THE MEMORY CARD CYCLING AT THE END OF
6580      !   SOME SCANS. SEE THE CIRCUIT TIMING DIAGRAM IN THE THESIS.
6590      SELECT B
6600      CASE 4                      !EXHAUST DATA HAS 4 SCANS
6610          M=3
6620      CASE 8                      !MOTOR DATA HAS 8 SCANS
6630          M=7
6640      END SELECT
6650      FOR K=1 TO 2
6660      IF K=1 THEN MAT E= Y1        !OPPERATES ON NO-PARTICLE AND PARTICLE SETS
6670      IF K=2 THEN MAT E= Y2
6680          FOR J=0 TO M
6690              IF M=7 AND J<=3 THEN 6800 !One 4096 Block Doesn't Need Shifting
6700                  FOR I=(J)*1024+1 TO (J+1)*1024      !BLOCKS OF 1024
6710                      IF M=3 THEN L=I+J                !Array B Has the worst
6720                          !Problem With Shifting Data
6730                      IF M=7 THEN L=I+1                !Array D is Always off by one
6740                      IF L>(J+1)*1024 THEN L=(J+1)*1024
6750                  !JUST TO AVOID PROGRAMMING ERROR AT THE END OF THE APRAY
6760                  E(I)=E(L)                            !THIS SHIFTS THE DATA
6770                  !DEPENDING ON 'I',ARRIVED AT
6780                  !BY OBSERVING RAW DATA
6790              NEXT I
6800          NEXT J
6810      IF K=1 THEN MAT Y1= E
6820      IF K=2 THEN MAT Y2= E
6830      NEXT K
6840      SUBEND
6850      SUB Store      ! THE LARGE ARRAY CONTAINING MULTIPLE SCANS HAS BEEN REDUCED
6860      ! TO A MEAN SCATTERING PROFILE BY AVERAGING AND FILTERING. IF
6870      ! YOU FEEL THAT STORING THIS DATA IS NECESSARY THIS ROUTINE
6880      ! DOES IT. IT SAVES DISK SPACE TO STORE THE RESULTS THEN
6890      ! ELIMINATE THE RAW DATA IF YOU FEEL CONFIDENT THAT THE
6900      ! REDUCTION IS THE BEST THAT CAN BE. IN OTHER WORDS,
6910      ! DO NOT PURGE A RAW DATA FILE UNLESS YOU ARE ABSOLUTELY SURE
6920      ! YOU WON'T WANT TO REDUCE IT AGAIN.
6930      COM /Hrdgaus/ Av2(*)          !Av2(*) IS THE REDUCED DATA
6940      DIM Data(1:1024) BUFFER      !BUFFER USED TO TRANSFER TO DISK
6950      MAT Data= Av2
6960      PRINT CHR$(12)
6970      PRINT USING "////////"
6980      PRINT "  A SUGGESTED METHOD OF NAMING REDUCED DATA FILES IS AS FOLLOWS"
6990      PRINT "  M-----MOTOR BEAM"
7000      PRINT "  X-----EXHAUST BEAM"

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7010 PRINT " C-----CALIBRATION , IF NO 'C' THEN AN ACTUAL FIRING IS ASSUMED"
7020 PRINT " G-----GLASS BEADS "
7030 PRINT " IF NO 'C' THEN 'G' STANDS FOR 'GAP' PROPELLANT"
7040 PRINT " A-----ALUMINUM OXIDE"
7050 PRINT " PPP-----CHAMBER PRESSURE FOR RUN OR OTHER...(NOZZLE TYPE)"
7060 PRINT " PARTICLE SIZE FOR CALIBRATION"
7070 PRINT " MMDD----MONTH,DAY OF RUN OR CALIBRATION"
7080 PRINT ""
7090 PRINT " EXAMPLE: MCA125JN12"
7100 PRINT ""
7110 PRINT " MOTOR BEAM CALIBRATION USING ALUMINUM OXIDE FROM 1 TO 25 MICRONS"
7120 PRINT " ON JUNE 12"
7130 PRINT " EXAMPLE: XGS50AU10"
7140 PRINT ""
7150 PRINT " EXHAUST BEAM DATA FOR GAP PROPELLANT AT 550 psi ON AUGUST 10"
7160 PRINT " PLACE A DISK IN THE RIGHT HAND DRIVE"
7170 PRINT " ENTER THE FILENAME YOU WISH TO USE FOR THIS REDUCED DATA"
7180 INPUT A$
7190 CREATE BDAT A$,512,16
7200 ASSIGN @Disk TO A$
7210 ASSIGN @Buff TO BUFFER Data(*)
7220 CONTROL @Buff,3;1,8192,1 !BUFFER IS FULL
7230 TRANSFER @Buff TO @Disk;COUNT 8192
7240 WAIT FOR EOT @Disk
7250 ASSIGN @Buff TO *
7260 ASSIGN @Disk TO *
7270 SUBEND
7280 SUB Review(Av1(*))
7290 DIM Data(1:1024) BUFFER
7300 PRINT " EACH REDUCED FILE CONTAINS ONE SCAN ONLY. YOU MUST KNOW IF IT"
7310 PRINT " IS EXHAUST , MOTOR CAVITY , OR CALIBRATION DATA."
7320 PRINT ""
7330 PRINT " THE DISK WITH THE REDUCED FILE SHOULD BE IN THE RIGHT-HAND DRIVE"
7340 PRINT ""
7350 PRINT " ENTER THE FILENAME OF THE REDUCED DATA"
7360 PRINT " TO BE REVIEWED"
7370 PRINT ""
7380 INPUT A$
7390 ASSIGN @Disk TO A$
7400 ASSIGN @Buff TO BUFFER Data(*)
7410 CONTROL @Disk,5;1
7420 CONTROL @Buff,3;1,0,1 !THIS IS AN EMPTY BUFFER
7430 TRANSFER @Disk TO @Buff;COUNT 8192 !1024*8=NUMBER OF BYTES
7440 WAIT FOR EOT @Disk
7450 ASSIGN @Disk TO *
7460 ASSIGN @Buff TO *
7470 MAT Av1= Data
7480 SUBEND
7490 SUB Filter(A(*),Fil)

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7500 DIM E(1:1024)
7510 PRINT CHR$(12)
7520 PRINT USING "/////////"
7530 PRINT "                                FILTERING THE SCATTERING PROFILE"
7540     FOR J=1 TO Fil
7550         FOR I=1 TO 1014
7560             B=I+1           !THIS IS A Symetric Moving Average
7570             C=I+2           !TYPE OF DIGITAL FILTER. EACH
7580             D=I+3           !DATA POINT IS EQUALLY WEIGHTED
7590             F=I+4           !IN THIS CASE BUT THIS CAN BE
7600             G=I+5           !CHANGED IF ONE DETERMINES THAT
7610             H=I+6           !FEWER POINTS WITH UNEQUAL WEIGHTS
7620             K=I+7           !WOULD BE FASTER OR GIVE BETTER
7630             L=I+8           !RESULTS. THIS TYPE OF FILTER WAS
7640             N=I+9           !USED SINCE IT INTRODUCES NO PHASE
7650             P=I+10          !LAG      (Angular Resolution).
7660             E(G)=(A(I)+A(B)+A(C)+A(D)+A(F)+A(G)+A(H)+A(K)+A(L)+A(N)+A(P))/11
7670             NEXT I
7680             MAT A= F
7690         NEXT J
7700 SUBEND

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