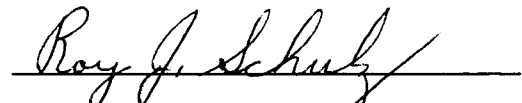
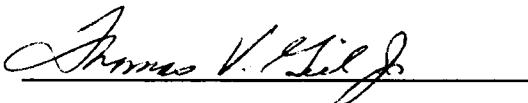
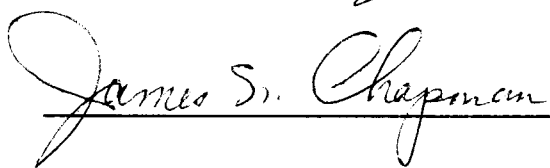


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SHADOW SPECTROMETER MEASUREMENTS OF PARTICLE SIZES
FROM AIR-ASSISTED ATOMIZING SPRAY NOZZLES

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Xiaoqing Qian
December 1988

DEDICATION

This thesis is dedicated to my friends and
my family members in China and in the United States.

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ABSTRACT

A major concern of industrialized nations is that power generation systems that burn hydrocarbon fuels release pollutants into the atmosphere that contribute to acid rain and other atmospheric environment problems. Therefore, an active program of research on exhaust gas pollutant control has been identified and funded by the United States Department of Energy (DOE). A part of this program is a project on direct sorbent injection for combined SO_2/NO_x removal funded by the United States Department of Energy at the University of Tennessee Space Institute (UTSI). In this project, a wet sorbent slurry is injected into an exhaust stream in a duct. The sorbent chemically reacts with the SO_2 and NO_x , and the exhaust gas SO_2 and NO_x are reduced.

The effectiveness of the SO_2 removal process depends significantly on the gas-droplet surface contact. Thus, the spray atomization performance of the slurry spray nozzles has to be investigated. Research was done, where four 1/4J-series air-atomizing nozzles (J22B, J22, J42, and J46) were characterized in atmospheric conditions, and one nozzle (J22) was characterized in a ducted hot gas, and two special, large flow-rate nozzles producing different spray patterns were investigated in the atmosphere. There were the SONIMISTTM Ultrasonic and CasterJetTM nozzles. An advanced, laser shadow spectrometer was used to measure the spray characteristics.

Results indicate that any of these nozzles (J22B, J22, J42, and J46) could produce a spray finely enough atomized for slurry sorbent injection for effective flue-gas clean up. The J22B nozzle operated satisfactorily between 2 gph and 10 gph; the other nozzles operated satisfactorily in the 5 to 20 gph range. In the

hot duct, the J22 nozzle worked very well in atomizing water, and its spray filled the hot gas duct but did not impinge on the duct walls to any measurable extent; about 99 percent of the spray water mass evaporated within 17 feet of the nozzle tip. The two special nozzles operated at much larger flow rates (2 - 6 times larger) than the 1/4J-series nozzles. However, because of their design, they produced sprays with Sauter-mean and volumetric-mean diameters comparable to the size ranges produced by the air-atomizing 1/4J-series of nozzles used in the cold flow and hot duct tests. But, the distributions of the liquid water content measured in these sprays showed that the spray clouds were spatially nonuniform.

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CHAPTER I

INTRODUCTION

1.1. Background

A major concern of industrialized nations is that power generation systems burn hydrocarbon fuels which release pollutants into the atmosphere that contribute to acid rain and other atmospheric environment problems. Retrofit of these systems with sulfur and NO_x capture technology would be less expensive than total replacement, assuming space is available for the scrubbers. But, with existing technology, costs are still very high. Also, sulfur capture systems impose an efficiency penalty along with increased operating costs for sorbent acquisition and disposal. Therefore, an active program of research on alternative methods for exhaust gas pollutant control has been identified and funded by the United States Department of Energy (DOE). A part of this program is a project on direct sorbent injection for combined SO_2/NO_x removal, funded at the University of Tennessee Space Institute (UTSI) wherein a wet sorbent slurry is injected into an exhaust stream with two results: first, through evaporation, water leaves the sorbent particle, and second, by phoresis and diffusion, pollutant materials such as SO_2 are absorbed on the wet surface of the sorbent particle. The pollutant species SO_2 is chemically reacted with the sorbent material, slaked lime (CaCO_3), to form CaSO_4 and CO_2 . Thus, the sorbent is chemically changed and the exhaust gas SO_2 is reduced.

In order to effect efficient SO_2 removal by a wet spray technology, an efficient slurry spray system must be developed and the efficiency of the spray cloud-flue gas interaction must be investigated. A key part of the performance of this tech-

nology for flue-gas pollutant control is the formation of sprays of very fine slurry particles, which are particles of C_aCO_3 enclosed by microscopic or micron-sized water droplets. It is obvious that the larger the sorbent's exposed surface area is, the more efficiently the process will work. The surface area of the sorbent exposed to the exhaust gas pollutants is given by

$$S = N_P \pi D_P^2, \quad (1)$$

where, if N_P is the number of sorbent particles per cubic meter of gas, and D_P is the particle diameter, in meters, then S is the surface area of exposed sorbent per cubic meter of exhaust gas. This parameter is similar in nature to the compactness criteria of indirect heat exchangers. It is easy to show that this surface area concentration is inversely related to particle diameter by rewriting equation (1),

$$S = 6\dot{M}_L / (\rho_L D_P V_P A), \quad (2)$$

where

$$\dot{M}_L = \rho_L V_P A N_P \pi D_P^3 / 6.$$

In equation (2), the parameters are the liquid slurry flow rate, $\dot{M}_L$, the density of the liquid slurry, ρ_L , the velocity of the particles, V_P , and the cross-sectional area of the spray, A . If the particles are injected at the speed of the gas flow, or, if they come to the speed of the gas flow, and the spray fills the duct cross-section, then the surface area concentration is

$$S = 6\dot{M}_L / (\rho_L D_P V_G A_D). \quad (3)$$

Clearly, smaller diameter particles result in larger surface area concentrations, for the other parameters remaining fixed. Thus, a good, efficient small-particle spray system with fine atomization is a necessity in the application and development of this flue-gas control process.

1.2. Purpose of the Thesis

The purpose of this research was to investigate and document the performance of several air-assisted atomizing water spray nozzles as part of the UTSI research program on direct sorbent injection for combined SO_2/NO_x removal. Some nozzles were supplied by other DOE direct sorbent injection contractors. The main instrument used in the present research was the shadow spectrometer developed by Particle Measuring Systems (PMS), Inc., which provided automated, near real time evaluations of droplets images. In order to document the spray cloud characteristics, the spray parameters were investigated using:

- (1) Water spray at two or more stations downstream of the spray nozzles.
- (2) Water spray at points along both vertical and horizontal traverses at each station (not included in the cold flow tests).
- (3) Water spray at all stations for different nozzle air pressures and water flow rates.
- (4) Water evaporation rates in ambient air.

The characterizing parameters for the spray cloud that were obtained in the present study include:

- (1) Droplets size distributions (size versus number density) at different stations for the various test conditions.
- (2) Characteristic droplet diameters including mass-median (D_{50}), volume-mean (D_{30}), and Sauter-mean (D_{32}) diameters which are important parameters in the description of the fluid dynamics of sprays and particulate clouds.
- (3) The flow numbers of the nozzles, which correlate with the characteristic sizes of the spray droplets.
- (4) Axial or radial liquid water content distributions of selected nozzle sprays.

The following sections of the study describe the instrumentation, the principles of measurement, experimental set-up, test procedures, the data reduction process, results and discussion, and conclusions.

CHAPTER II

INSTRUMENT DESCRIPTION

An aerosol particle can produce changes in four parameters associated with a scattered light wave: (1) Frequency and/or Phase; (2) Radiation Pattern; (3) Intensity Magnitude; and (4) Polarization. Based on these four parameters, existing optical techniques can use three measures to determine particle size: (1) measure differential optical frequency shifts; (2) measure scatter intensity characteristics; or (3) measure radiation pattern shapes. With the third method, there are several optical imaging systems used, such as photography, holography and shadow spectrometry. The major limiting factor of photography and holography is data reduction of large numbers of images. On the other hand, an automated shadow spectrometer collects the image data from each particle as it passes through a sample volume. Thus, shadow spectrometry greatly speeds up the data acquisition process. For this reason, a commercially available shadow spectrometer was chosen and acquired for particle characterization of the nozzle spray flows of this project.

2.1. The Shadow Spectrometer

The shadow spectrometer used was manufactured by Particle Measuring Systems, Inc., and was designated Model Number OAP-230X, or Optical Array Particle Size Spectrometer. This system included the following components: an optical system, a shadow detector photodiode array, a photodetector module, an input sensor, a strobe and reset generator module, a bulk area reject circuit, a size determination encoder, a size adder, output line driver, a depth-of-field strobe, and a power supply.

The optical arrangement of the shadow spectrometer is shown in Figure 1.* Particles flowing between the probe tips are illuminated by a He-Ne laser, of 2.0 mW beam power focused in the particle flow field. The illuminated particles cast shadows that are then imaged onto a linear photodiode array mounted transverse to the direction of particle motion. The detection system in the shadow spectrometer has 32 active photo-diode elements and is capable of discriminating particles in 30 size classes. The particle's size is determined from the number of diodes shadowed as each particle passes through the sample volume; hence, the size distribution measurable depends on the optical system arrangement. When a shadow is detected, a flip-flop memory element is switched from 0 to 1 for each shadowed element. Any particle which shadows either end element on the top and bottom photodiodes is rejected, since an unknown portion of the particle is out of view and its size can not be determined. Electronic logic is incorporated into the device which allows the rejection of images crossing the end diodes, to prevent fractional images from being counted. A probabilistic correction table based on the geometries of the system is used to correct the particle sizing logic for rejected particles to achieve good number counts. So, within the 32 element array, particles small enough to shadow one element, and large enough to shadow as many as 30 elements can be differentiated. The instrument was set up with optical geometry such that a $10\text{ }\mu\text{m}$ particle shadowed a single element; thus, the range of measured particle sizes was from $10\text{ }\mu\text{m}$ to $300\text{ }\mu\text{m}$, with $10\text{ }\mu\text{m}$ resolution. In addition to the system described above, there is included in the sizing system a bulk area reject circuit (BARC). This circuit allows a one-dimensional PMS imaging probe to detect and reject particle measurements which were caused by the probe viewing two or more particles at one time, i.e., a coincidence event. The BARC was not

* All figures are in the Appendix.

in service during the test series.

When the spectrometer detects and sizes a particle, it places a binary code on parallel output lines and issues a pulse on a "strobe" line. Then, a data processor accepts this parallel binary output and generates a particle size data point. The data accumulates during a measurement period to result in particle size distribution obtained by the PMS "smart-probe".

2.2. The Smart ProbeTM

The "smart probe" consists of four 4.5" × 4.0" printed circuit cards housed in a small enclosure separated from the spectrometer and containing all the necessary power supplies. The particle measurement data signals are sent from the spectrometer to the probe through a standard PMS data cable. The probe has two general modes of operation: printing, and plotting. In either case, the program accumulates particle data for a period of time, referred to as the sample interval. For printing, a report is generated at the end of each interval listing the particle counts for each size (channel) for the interval. For plotting, a near real-time histogram is generated and displayed on a CRT terminal.

CHAPTER III

EXPERIMENTAL METHODS

3.1. Cold Flow Spray Tests

3.1.1. Calibration of the Shadow Spectrometer

In order to insure correctly measured particle number counts in the appropriate size range, the shadow spectrometer had to be calibrated. This was accomplished with pre-sized glass beads. These beads are recommended by the manufacturer of the shadow spectrometer and were purchased from Particle Information Services. The beads come in different size ranges. The first size range used was 75-105 μm which checks the middle sized particles. The second set of beads tested for correct system response in the 210-250 μm range. The method for checking the correctness of the array response was simply to drop the beads through the laser beam, making sure to drop beads across the entire area between the probe tips. The beads cannot go through too fast or too slow, or at an angle, or the calibration check can be skewed or otherwise misrepresented. It was found that the analyzer was well calibrated in the upper range, obtaining correct readings in the 210-250 μm range. The smaller size range was also within calibration specification with readings of 70-130 μm , with most readings falling within the 75-105 μm range expected.

The PMS probe uses nitrogen purge flow to keep the optics clean. When the purge flow was set at approximately 20 standard cubic feet per hour (scfh), small effects were observed on large size beads (see Table 1). In Table 1, the first number on each column is the rejection count, i.e., within the sampling time interval, all rejected data goes to this count. The second number correspond to the 0-10 μm

Table 1

Mean Calibration Data of Large Size Beads

Channel No.	D_j (μm)	No Purge* (No. Count)	20 SCFH Purge* (No. Count)
reject channel	—	112.	74.
1	0-10	0.	0.
2	10-20	0.	0.
3	20-30	0.	0.
4	30-40	0.	0.
5	40-50	0.	0.
6	50-60	0.	0.
7	60-70	0.	0.
8	70-80	0.	0.
9	80-90	0.	0.
10	90-100	0.	0.
11	100-110	0.	0.
12	110-120	0.	0.
13	120-130	0.	0.
14	130-140	0.	0.
15	140-150	0.	0.
16	150-160	0.	0.
17	160-170	0.	0.
18	170-180	0.	0.
19	180-190	0.	0.
20	190-200	0.	0.
21	200-210	3.	3.
22	210-220	6.	3.
23	220-230	6.	3.
24	230-240	1.	2.
25	240-250	2.	1.
26	250-260	0.	0.
27	260-270	0.	0.
28	270-280	0.	0.
29	280-290	0.	0.
30	290-300	0.	0.
reject channel	—	0.	0.

* Time interval is 5 seconds.

size count; that is, within the sampling time interval, all the particles with sizes smaller than or equal to $10\text{ }\mu\text{m}$ are included in this count or bin. Other sizes are likewise counted. The thirty-first bin is for sizes in the $290\text{--}300\text{ }\mu\text{m}$ range. The last number is always zero, since the corresponding channel is not used. For the small size beads, the purge tended to turn the very smallest beads in the direction of the purge flow. As a result, with purge flow, the size distribution is shifted to larger sized particles as shown in the data (see Table 2). The nozzle spray flows investigated did not show particle size shifts because of the purge flow, as shown by repeated testing with and without the purge flow. Thus, the purge effects were not significant in the actual spray evaluation.

3.1.2. Experimental Set-Up

The shadow spectrometer was installed in a vertical position on the bed of a lathe to provide flow traversing capabilities. Each nozzle tested was installed in a test stand with its spray axis aligned horizontally, and supplied with water and air (see Fig.2). The water flow rate was set using a flow meter. Gauge meters were used to show the individual pressures of the water and air of the nozzle. A nitrogen purge line was attached to the spectrometer to reduce water build-up on the probe tip mirrors. During the tests, a purge of 50 scfh was used at all the times (explained in section 3.1.4.). The Smart ProbeTM was used to transfer the test data and to record them on a Zenith microcomputer.

3.1.3. Test Procedure

Four nozzles were operated and their sprays characterized. These nozzles were classified as 1/4J air-atomizing nozzles, manufactured by Spraying Systems Company. Each nozzle is capable of generating a certain type and flow of particles. The nozzle models used were J22, J42, J46 and J22B. The J46 is a wide angle,

Table 2

Mean Calibration Data of Small Size Beads

Channel No.	D_j (μm)	No Purge* (No. Count)	20 SCFH Purge* (No. Count)
reject channel	—	101.	94.
1	0-10	0.	0.
2	10-20	0.	0.
3	20-30	0.	0.
4	30-40	0.	0.
5	40-50	0.	0.
6	50-60	0.	0.
7	60-70	4.	2.
8	70-80	12.	6.
9	80-90	26.	18.
10	90-100	30.	29.
11	100-110	22.	21.
12	110-120	11.	12.
13	120-130	3.	7.
14	130-140	1.	6.
15	140-150	1.	3.
16	150-160	1.	1.
17	160-170	1.	1.
18	170-180	1.	1.
19	180-190	1.	1.
20	190-200	0.	1.
21	200-210	0.	1.
22	210-220	0.	1.
23	220-230	0.	0.
24	230-240	0.	0.
25	240-250	0.	0.
26	250-260	0.	0.
27	260-270	0.	0.
28	270-280	0.	0.
29	280-290	0.	0.
30	290-300	0.	0.
reject channel	—	0.	0.

* Time interval is 5 seconds.

round spray nozzle. The J22, J22B and J42 are round spray nozzles (see Fig.3); they provide the same basic spray characteristics, but with different flow rate ranges. The J22B generates half the flow of the J22. The J42 generates much more flow than the J22's for similar supply pressures. The J22 was said to have a "greater atomization ability" than the others.

The spray of each nozzle was measured along its centerline. The profiles of the nozzle sprays are symmetric, but if aligned horizontally, gravity will eventually cause the droplets to fall and the spray becomes non-symmetric about the centerline. The nozzle centerlines were determined by aiming the nozzle orifice at the center of the laser beam. Each nozzle was tested under a variety of air and water flow rates and measurements were taken at various axial distances downstream from the nozzle tip.

3.1.4. Purge Effects on Particle Sizing

The effect of the purge used to keep the probe clear was measured using the J42 nozzle. The conditions tested were 18 gph water flow rate, 50 psi air pressure, and a distance of 5 feet from the nozzle. The purge flow was set at 50 scfh, 30 scfh, and 10 scfh, respectively. Figure 4 shows particle number density (i.e., particle number per cubic millimeter) versus particle size (μm). There were no measurably significant differences, with or without the purge. The effects of the purge between 10 scfh to 50 scfh are very small, so in all of the other nozzle spray tests, purge effects were neglected. The purge was set at 50 scfh for all tests.

3.1.5. Test Matrix

Each spray station was examined for nearly one minute at 5 second intervals. Table 3 presents a typical test matrix. The data obtained from the PMS shadow

Table 3
Cold Flow Test Conditions

Nozzle	Water Flow Rate (GPH)	Air Pressure (PSI)	Distance (FT)
J22	24,20,18,15,10,5,2,1	40, 60, 80	3, 5
J22B	12.5, 10, 8, 5, 3, 2	40, 60, 80	3, 5
J42	27,24,20,18,15,10,5,2	40, 60, 80	3, 5
J46	20, 15, 10, 5	40, 60, 80	3, 5

spectrometer are the particle number counts in 10 μm size intervals in the range of 10-300 μm . The measurement distances were chosen by visual and instrumental inspection of the spray. In each nozzle test, conditions were found where the spray appeared to be most stable and well atomized, i.e., no pulsing and no obvious agglomeration of droplets falling to the ground. These conditions were then used for the rate of evaporation testing.

Another phase of the testing was done to obtain evaporation rates of the sprays. The J22, J42, and J46 were used to measure evaporation by being measured at axial distances of 1.5', 3', 6', 8', and 10' from the nozzle only on the centerline. The main measurement difficulty at the longer distances was the fact that the axis of symmetry of the spray moves down vertically from the centerline as the axial distance increases, because of gravity effects on the spray drops. Test conditions in this phase are given in Table 4.

Table 4

Clod Flow Evaporation Test Conditions

Nozzle	Water Flow Rate	Air Pressure	Water Pressure
J22	18 GPH	80 PSI	72 PSI
J42	15 GPH	60 PSI	45 PSI
J46	10 GPH	40 PSI	28 PSI

3.2. Hot Gas Duct Tests

3.2.1. Introduction

After successful cold flow testing of four candidate spray nozzles, the J22B, J22, J42, and J46, the next phase of the project was to select a nozzle and perform hot gas testing. The J22 nozzle was selected for this phase of the testing because it provided an adequate liquid flow rate, and, in addition, it produced a single, narrow, cone-shaped spray of acceptably fine atomized particles.

In this part of the test program, the spray nozzle was installed in a duct in which hot air was flowing. The nozzle was operated with water as the spray liquid. The hot gas tests were set up, conducted, and results were obtained as described in the following sections of the study.

3.2.2. Experimental Method

The main instruments used in the hot gas testing was the shadow spectrometer with the Smart ProbeTM. The principles and techniques for using these

instruments were already explained and will not be repeated here.

The shadow spectrometer and Smart ProbeTM were calibrated before the hot duct tests. The same kind of glass beads, with size ranges 75-105 μm and 210-250 μm , were used. The calibration data were very similar to those obtained in the cold flow calibrations. Thus, the instruments were verified to be working properly before hot flow testing.

The test section of the hot duct is 37 feet long. The diameter of the duct is 16 inches. The gas composition and temperature inside the duct can be adjusted to simulate flue-gas conditions desired. During the tests, the duct inlet temperature was set around 250 °F. The ducting was wrapped with a single layer of 3" thick foil-backed insulation, and sealed with Silastic RTV90TM and aluminum tape. The test section mating flanges were sealed with removable rubber bands fabricated from high temperature silicone rubber. The section duct pieces were supported with fabricated saddles positioned over the rubber seals which were in turn suspended from chains attached to structural supports overhead, as shown in Figure 5. The test section incorporated several individual two foot long sections. A one foot long section was used to install the PMS instrument. The shadow spectrometer was installed on the bed of a lathe fixed to this duct section. The lathe bed permitted the shadow spectrometer to traverse the duct flow from the center of the duct to about a half inch from the duct wall. To make a complete top-to-bottom survey of the duct flow, the shadow spectrometer was first used to measure flows in the top half part of the duct, i.e., from the center line of the duct to within 0.5" of the top of the duct wall. Then the section containing the Shadow spectrometer was rotated 180 degrees to measure flows in the bottom part of the duct from center line to within 0.5" of the bottom wall.

There is another one foot long duct spacer section that permitted various sections of the test duct to be replaced for the insertion of shadow spectrometer section. This allowed measurements to be obtained at one foot intervals downstream of the nozzle for testing, see Figure 5.

The nozzle was installed at the center of the duct. Measured flows of water and air were supplied to the nozzle. Inside the duct, simulated flue-gas (heated-air) was flowing at 10 meters per second in the direction of the sprays (concurrent flow). A nitrogen purge line was attached to the spectrometer to reduce water build-up on the probe. Purge effects on particle sizing were found to be negligible during cold flow testing at flow rate up to 50 scfh, so during the hot gas test, the purge rate was set at 50 scfh.

3.2.3. Test Procedures

In the hot duct tests, the J22 nozzle spray performance was investigated under a variety of water and air flow rates. Radial traverses of the sprays were obtained at various axial distances from the nozzle. Table 5 presents a typical test matrix.

In order to determine different spray densities at different axial and radial positions in the hot duct, up to 5 different axial stations were examined. Data was obtained by using different sampling-time intervals, of 5 seconds, 10 seconds or 15 seconds as required to obtain statistically "steady" data. That is, the tests done with different sampling times were used to make sure that a sufficiently large number of samples were obtained for statistical confidence. For each sample period, at least 5 sets of data were collected. These data represent the number counts of particles with diameters ranging from 10 to 300 μm , in 10 μm intervals, which was the same set up used for the cold flow tests.

Table 5

Hot Duct Test Conditions for J22 Nozzle

Distance from Nozzle Tip	Radial Position* of Vertical Axis (INCHES)	Water Flow Rate (GPH)	Air Pressure (PSI)
2 FT	$\pm 0.5, \pm 0.8, \pm 1.8, \pm 2.8,$ $\pm 3.8, \pm 4.8, \pm 5.8, \pm 6.8, \pm 7.8,$	10,15,20	60,80,90
3 FT	$\pm 0.5, \pm 0.8, \pm 1.8, \pm 2.8,$ $\pm 3.8, \pm 4.8, \pm 5.8, \pm 6.8, \pm 7.8,$	10,15,20	60,80,90
7 FT	$\pm 0.5, \pm 0.8, \pm 1.8, \pm 2.8,$ $\pm 3.8, \pm 4.8, \pm 5.8, \pm 6.8, \pm 7.8,$	10,15,20	60,80,90
11 FT	$\pm 0.5, \pm 0.8, \pm 1.8, \pm 2.8,$ $\pm 3.8, \pm 4.8, \pm 5.8, \pm 6.8, \pm 7.8,$	10,15,20	60,80,90
17 FT	$\pm 0.5, \pm 0.8, \pm 1.8, \pm 2.8,$ $\pm 3.8, \pm 4.8, \pm 5.8, \pm 6.8, \pm 7.8,$	10,15,20	60,80,90

* Top wall = -0.0; Centerline = ± 7.8 ; Bottom = +0.0

3.3. Large Flow-Rate Nozzle Characterization Tests

3.3.1. Introduction

After cold flow tests of the air-atomizing J22B, J22, J42, and J46 nozzles, and the hot duct tests of the J22 nozzle, two other nozzles were tested and characterized. They were a CasterJetTM Nozzle developed by Spraying Systems Company, model 19930, and a SONIMISTTM Ultrasonic Spray Nozzle developed by Heat Systems-Ultrasonics, Inc., model HSS-900. The unique feature of the CasterJetTM nozzle is that it provides a flat, fan-shaped spray pattern. The droplets are finely atomized even at fairly high water flow rates. The SONIMISTTM Nozzle incorporates within it a high energy, gas driven sonic generator that creates sound waves that chop the liquid into small drops. Then, the drops are further atomized by a co-flowing air stream. Closer control of droplet size is achieved with this system, it is claimed, than is possible with conventional high pressure air-atomizing nozzles or spinning disc systems.

For these tests, the same PMS system was used as before. The nozzles were set up to spray into the atmosphere, like the cold flow tests. The PMS shadow spectrometer was fixed in position and the nozzles were moved vertically and horizontally. Thus, in these tests, both vertical and horizontal traverses of the sprays were obtained.

3.3.2. Test Procedure

In the tests, the CasterJetTM and SONIMISTTM nozzle sprays were investigated under a variety of water flow rates but with a fixed air pressure of 100 psi. Vertical and horizontal traverses of the spray were obtained at various axial distances from the nozzles. Table 6 presents a typical test matrix for the CasterJetTM nozzle, and Table 7 for the SONIMISTTM nozzle. For the CasterJetTM nozzle,

Table 6

Test Conditions for CasterJetTM Nozzle

Distance from Nozzle Tip	Horizontal Axis* (INCHES)	Vertical Axis** (INCHES)	Water Flow (GPH)
41"	$\pm 2, \pm 4, \pm 6, \pm 8, \pm 10,$	$\pm 0, \pm 2, \pm 4, \pm 6, -8,$	45, 90, 180,
54"	$\pm 2, \pm 4, \pm 6, \pm 8, \pm 10,$	$\pm 0, \pm 2, \pm 4, \pm 6, +8,$	45, 90, 180,

* Above the centerline and left side of centerline (looking toward the nozzle) is negative.

** Below the centerline and right side of centerline (looking toward the nozzle) is positive.

Table 7

Test Conditions for SONIMISTTM Nozzle

Distance from Nozzle Tip	Horizatal Axis* (INCHES)	Vertical Axis** (INCHES)	Water Flow (GPH)
13"	$\pm 2, \pm 4, \pm 6,$	$-0, \pm 2, \pm 4, \pm 6, +8,$	15, 30, 45,
41"	$\pm 2, \pm 4, \pm 6,$	$-0, \pm 2, \pm 4, \pm 6, \pm 8, -10,$	15, 30, 45,
54"	$\pm 2, \pm 4, \pm 6, \pm 8, \pm 10,$	$-0, \pm 2, \pm 4, \pm 6, \pm 8, -10,$	15, 30, 45,

* Above the centerline and left side of centerline (looking toward the nozzle) is negative.

** Below the centerline and right side of centerline (looking toward the nozzle) is positive.

the spray at 13" is too dense to analysis.

The sample collection time intervals were set at 5 seconds for each nozzle. The N₂ purge flow was turned on all the time. For each sample position, at least 10 sets of 5 second sampling time data were collected. These data sets were added and averaged for presentation. The basic data represented the number counts of particles with diameters ranging from 10 to 300 μm , in 10 μm intervals; this, too, is the same as for the other nozzle tests reported.

CHAPTER IV

METHODS OF DATA REDUCTION

The recorded data were transferred to mass storage on a hard disk as particle number counts grouped in size in intervals of 10 μm over the range of 10-300 μm . The data were blocked in fixed measurement time intervals, for each sample set. For data reduction, the UTSI VAX 11/785 system was utilized. To obtain averaged data, all the data blocks for a given measurement position or point in the spray were added together and divided by the total number of the measurements. What resulted were the average count numbers for each measurable particle size at each condition. Then, different characteristic particle sizes were determined for data presentation.

4.1. Particle Number Density

In order to characterize a spray cloud, the analysis must start with the particle size versus number density distributions. For the PMS system, the number densities for each size particle are given by:

$$N_d(I) = N_c(I) / [TA(I)V] \quad (4)$$

$$(I = 1, 2, 3, \dots, 30)$$

In Eq.(4), I is the particle size channel number, from 1 to 30. $N_d(I)$ are the number densities (number of particles of size range I per cubic millimeter of measurement volume). $N_c(I)$ are the number counts (a pure number). T is the measurement time interval. For different testing conditions, it was set as 5, 10, or 15 seconds. V is the spray velocity; specifically, for the data reduction, V was 10 meters per second, i.e., 10000 mm/sec. A(I) are the probable sample areas for each

particle size range which were determined and supplied by the PMS Company, shown in Table 8. These sample areas are not the actual physical sampling areas shadowed by the particles. They are calculated from the physical sampling areas but corrected to count for particle rejection events, [Ref.2].

4.2. Mean Diameters and Characteristic Lengths of Sprays

The known characteristics of a spray from a nozzle are: 1) the flow rate of liquid put into the spray; 2) the supply pressures of the water and air; 3) and spray geometrical parameters such as spray cone angle and whether the spray is a solid or hollow cone configuration. However, the most important characteristics of the spray are usually not known, such as the spray particle size distributions, the particle velocities, the evaporation rates of the spray, and the chemical or thermal interaction of the spray with the surrounding environment. However, with modern instrumentation such as the laser shadow spectrometer, some of this information can be obtained by measuring fundamental data, such as the particle number density versus size distribution. From these measurements, mean and characteristic parameters can be calculated and then compared for each spray. A discussion of the most commonly defined and used spray parameters is presented below because the data obtained from the measurements reported herein are displayed in terms of them. The nomenclature used in the definitions of the mean and characteristic spray quantities is presented first.

Let N_j be the number of particles of size range j per cubic millimeter of measurement volume; that is, N_j is the number of particles with diameter in the range $D_j - \delta D \leq D_j \leq D_j + \delta D$, where δD is an arbitrary allowable excursion about D_j . In the present study, δD of 5 μm resulted from the PMS set-up.

Table 8

Sampling Area Chart for Size Resolution

Channel Number	Probable Sample Area (mm ²)
1	0.028
2	0.217
3	0.632
4	1.177
5	1.734
6	2.364
7	3.050
8	3.787
9	4.600
10	5.393
11	6.133
12	6.903
13	7.652
14	8.360
15	9.012
16	9.150
17	8.540
18	7.930
19	7.320
20	6.710
21	6.100
22	5.490
23	4.880
24	4.270
25	3.660
26	3.050
27	2.440
28	1.830
29	1.220
30	0.610

The total number of particles per cubic millimeter of measurement volume is then

$$N_t = \sum_{j=1}^{N_{max}} N_j, \quad (5)$$

where N_{max} is the index of the largest size particles measured. In the present study, $N_{max} = 30$, corresponding to particles in the size range

$$290\mu m \leq D_{max} \leq 300\mu m.$$

The number fraction of each particle size range is defined as

$$\lambda_j = N_j / N_t. \quad (6)$$

Thus, λ_j corresponds to a mass fraction (or volume fraction for constant density particles) of the particles in size range j . In other words, λ_j represents the fraction of the total spray mass measured in the measurement volume that is contained in particles with diameters in the range $D_j - \delta D \leq D_j \leq D_j + \delta D$. With this nomenclature, characteristic and mean quantities that characterize a given spray (or point in a spray) can be defined.

4.2.1. Mean Surface Area Particle Diameter

The diameter of a particle in a uniform spray (having only one particle size) having the same total number of particles as the measured spray, and having the same total surface area as the measured spray is defined as D_{20} , where

$$N_t \pi D_{20}^2 = \sum_{j=1}^{N_{max}} (N_j \pi D_j^2). \quad (7)$$

Hence,

$$D_{20} = \left(\sum_{j=1}^{N_{max}} \lambda_j D_j^2 \right)^{1/2}. \quad (8)$$

Clearly, then, D_{20} is the surface-area-mean diameter of the measured spray.

4.2.2. Volume-Mean (or Mass-Mean) Particle Diameter

In the same way, the volume-mean particle size of the measured spray can be defined as

$$D_{30} = \left(\sum_{j=1}^{N_{max}} \lambda_j D_j^3 \right)^{1/3}. \quad (9)$$

4.2.3. Number-Mean Particle Diameter

The ratio of the volume to the surface area of a specific size particle is

$$l_j = (Vol._j / Area_j) = (\pi D_j^3 / 6) / (\pi D_j^2) = D_j / 6. \quad (10)$$

Thus, the number-averaged, surface-to-volume length scale of the spray is defined as $L_{V/A}$, by the equation

$$N_t L_{V/A} / 6 = \sum_{j=1}^{N_{max}} N_j l_j = \sum_{j=1}^{N_{max}} N_j D_j / 6, \quad (11)$$

giving,

$$L_{V/A} = \sum_{j=1}^{N_{max}} \lambda_j D_j. \quad (12)$$

Thus, $L_{V/A}$ is a length scale characterizing the number-mean volume to surface area particle. If $L_{V/A}$ is very large compared to, for example, D_{30} , then the spray has a significant fraction of large particles. Hence, $L_{V/A}$ can tell whether the spray has numerous or few particles. However, this parameter is not generally used because it is difficult to interpret. Instead, a volume-to-surface diameter called the Sauter-mean diameter is widely used.

4.2.4. Sauter-Mean Diameter

Another characteristic length scale of the spray is the Sauter-Mean diameter (SMD). It is not a true mean quantity. The Sauter-Mean Diameter is defined as

$$D_{32} = \frac{\sum_{j=1}^{N_{max}} \lambda_j D_j^3}{\sum_{j=1}^{N_{max}} \lambda_j D_j^2} = D_{30}^3 / D_{20}^2. \quad (13)$$

Also, if V_t is the total volume contained in all the measured particles and S_t is their total surface area, it is easy to show that

$$D_{32} = 6V_t / S_t. \quad (14)$$

4.2.5. Mass-Median Diameter

A final characteristic diameter to define is the mass-median diameter. This diameter is defined as that diameter (or diameter-range size class) such that 50 percent of the total mass of the measurement is contained in all particles of diameter less than or equal to the mass-median diameter. Thus, if the total mass of the measurement is

$$M_t = \sum_{j=1}^{N_{max}} N_j \rho_l \pi D_j^3 / 6, \quad (15)$$

then 50 percent of this mass is M_{50} , or

$$M_{50} = M_t / 2 = \sum_{j=1}^{N_{50}} N_j \rho_l \pi D_j^3 / 6. \quad (16)$$

In this sum, N_{50} represents the class index of that diameter particle, $D_{j=N_{50}}$, such that the sum represents half of M_t . Thus, D_{50} , as it is often denoted, is the mass-median diameter.

4.3. Usage and Meaning of the Mean, Median, and Characteristic Lengths and Diameters

It is beyond the scope of this study to identify and discuss the uses and/or applications of the characteristic length-scales or mean diameters to industrial processes based on sprays or particulate clouds. Instead, in the present study,

such data is used to show and attempt to explain the relative differences between the sprays produced by the nozzles selected and tested.

4.4. Data Reduction Equations in the Computer Program

The actual equations used to calculate D_{30} , D_{32} , and D_{50} from the measured $N_d(I)$ and $D(I)$ were as follows.

Sauter mean diameter (SMD):

$$D_{32} = \frac{\sum_{I=1}^{30} N_d(I) D(I)^3}{\sum_{I=1}^{30} N_d(I) D(I)^2} \quad (17)$$

Eq.(17) was used to compute the SMD from measured diameters and number densities. I is the channel number representing each ten μm interval. $N_d(I)$ is the number density (No./ mm^3) of the particle sizes falling in channel (I), i.e. the number density of the particle diameter between $(I-1) \times 10$ and $I \times 10$. $D(I)$ is the particle diameter (in μm) associated with channel (I); $D(I)$ ranged from 10 μm to 300 μm . In the calculations, particle diameters used were in the middle of the size classes, that is they ranged from 5 μm to 295 μm . SMD's were computed for each nozzle at each flow rate, for each measurement position.

Volume mean diameter:

$$D_{30} = \left(\frac{\sum_{I=1}^{30} N_d(I) D(I)^3}{\sum_{I=1}^{30} N_d(I)} \right)^{1/3} \quad (18)$$

Eq.(18) was used to compute the volume-mean diameter. D_{30} was computed for all the conditions for which the SMD was computed.

Mass median diameter:

$$M(J) = \sum_{I=1}^J \pi \rho_l N_d(I) D(I)^3 / 6 \quad (19)$$

$M(J)$ is the integrated particles' mass accumulation (gram per cubic meter of measurement volume) up to size class J . ρ_l is the water density, i.e., 1 gram per

cubic centimeter of particle volume. From Eq.(19), mass $M(J)$ can be computed from the smallest diameter, $J=1$, up to the largest diameter, $J=30$. The mass-median diameter was determined as the diameter where $M(J)$ was half of $M(30)$. This diameter is then D_{50} . Again, it means that half of the total spray mass is in all droplets which have diameter less than or equal to D_{50} . D_{50} was computed for all spray conditions for which D_{32} and D_{30} were computed.

4.5. Nozzle Flow Numbers

The nozzle flow number is F_N , defined as:

$$F_N = (FlowRate) / \sqrt{\Delta P_l} \quad (20)$$

Where ΔP_l is the liquid supply gauge pressure. Since the volume flow rate is

$$\dot{V} = VA, \quad (21)$$

and we have Bernoullis' equation for the liquid leaving the nozzle,

$$P_0 = P + \rho_l V^2 / 2, \quad (22)$$

then

$$\Delta P_l = P_0 - P = \rho_l V^2 / 2. \quad (23)$$

Hence

$$F_N = \dot{V} / \sqrt{\Delta P_l} = (AV) / \sqrt{\rho_l V^2 / 2} = A \sqrt{2 / \rho_l}. \quad (24)$$

Where ρ_l is the liquid density; A is the area of the nozzle orifice. Since ρ_l is considered to be a constant, then $F_N \propto A$, i.e., if A is larger, then F_N is larger. The nozzle with larger flow number will generate the larger size droplets, since drop size must scale with the orifice area of the nozzle, A .

4.6. Liquid Water Content

The liquid water content (LWC) or spray mass, in units of grams of liquid per cubic meter, also can be computed for each measurement position. The equation for LWC is

$$LWC = \sum_{I=1}^{30} \left(N_d(I) \pi \rho_l D(I)^3 / 6 \right). \quad (25)$$

Again, I is the channel number. $N_d(I)$ is number density (No./mm³) of channel (I). ρ_l is liquid density. $D(I)$ is particle diameter corresponding to channel I.

CHAPTER V

RESULTS, DISCUSSIONS AND CONCLUSIONS

5.1. Cold Flow Spray Tests

5.1.1. Presentation of the data

This section presents a brief discussion of the type of cold flow spray experimental data obtained and the purpose for which it was obtained and used.

5.1.1.1. Initial Test Comparisons. The nozzles selected for testing were the J22, J22B, J42 and J46 nozzle listed in the Spray Systems Co. catalog. Each nozzle operates over a range of water flow rate and atomizing air pressures. Therefore, for initial comparisons, nominal operating conditions were selected for each nozzle that were thought to represent approximately the typical atomizing performance for each nozzle. Table 9 lists these conditions for each nozzle.

Table 9

Nominal Conditions for the J22, J22B, J42 and J46 Nozzles

Nozzle	Water Flow Rate	Air Pressure	Nozzle Flow No.
J22B	5 GPH	60 PSI	0.80
J22	15 GPH	60, 80 PSI	2.08, 1.82
J42	20 GPH	60 PSI	2.83
J46	15 GPH	60 PSI	2.19

The nozzles were tested and measurements of their sprays were obtained for these nominal operating conditions. The data from these tests include the fundamental number-density versus droplet-size distributions and also the derived mean and characteristic diameters at each measurement position, including D_{30} , D_{50} , and D_{32} . In order to relate the mean and characteristic diameters, their ratios can be calculated for each measurement position; the ratio calculated for the present study was D_{32}/D_{30} .

5.1.1.2. Parametric Testing. After the nozzles were tested at their nominal operating conditions, they were then tested over a wide range of flow rates and driving air pressures. This testing permitted the actual "best" nozzle operating conditions to be experimentally determined for each nozzle. For the purpose of this research program, "best" operating conditions mean those flow rates and air pressures that result in the most stable and finely atomized spray. The reason for this definition is that the nozzles are candidates for the wet-slurry sorbent application to flue gas clean-up. The best clean-up conditions will occur for the highest spray evaporation rates and greatest flue gas contact with the sorbent particles. Both of these conditions are fulfilled when a spray operates by producing the most finely atomized spray; that is, creates a spray with the smallest Sauter-mean diameter, D_{32} , or area-mean diameter, D_{20} . However, besides being able to get the most finely atomized spray, the nozzle must also be able to inject a sufficient amount of spray mass into the flow for adequate flue gas cleanup. Therefore, there will be a design trade-off between the number of spray nozzles and their flows and atomization characteristics. Having a system based on more, smaller nozzles means having to deal with increased nozzle plugging by the slurry particles and very complex plumbing that supplies the liquid flow and atomizing air. Hence, for

an application or design engineering task based on spray characteristics, choosing appropriate nozzles is a complex task.

Thus, it is extremely important to characterize the sprays of a series of potentially usable nozzles over a wide range of flows and air pressures. For this reason, the bulk of the data reported herein contains this type of information for the J22B, J22, J42 and J46 nozzles.

In addition to the characteristic spray parameters such as D_{30} , D_{20} , D_{32} , and D_{50} , the liquid flow of the spray is also important. Having the fundamental particle number density versus particle size distributions, it was also possible to compute the total liquid spray mass measured at the selected locations in the spray. Thus, liquid water content (LWC, gm/m^3) distributions were also computed and plotted for some of the sprays. This kind of information gives insight about spray evaporation and spray symmetry or asymmetry, and also can be used to check the PMS instrument to see if it is measuring liquid flow rates comparable to the flow rate supplied to the nozzle. That is, a mass conservation check is provided by the LWC distributions.

5.1.2. Data from the Nominal Operating Conditions

Typical distributions of particle number density versus particle diameter are presented in Fig.6-15 for the J22B, J22, J42 and J46 nozzle, respectively.

Figures 6 and 7 present data from the J22B nozzle at 3' and 5' from the nozzle exit on the centerline of the spray. Figures 8-11 present the data from the J22 nozzle for the same distances and positions. Figures 12 and 13 present similar data for the J42 nozzle, and Figs.14 and 15 represent the data from the J46 nozzle tests. All of these distributions have the same shape except for the J46 nozzle at 5', which appears bimodal. In terms of numbers, all of the sprays generated

the greatest numbers of the droplets having the smallest diameter. More than 90 percent of the particles generated had diameters less than or equal to $50\text{ }\mu\text{m}$. Thus, the spray nozzles were operating as expected. The smallest flow number nozzle generated the highest number of the smallest particles which was also expected. Note that the data for the J46 nozzle at 5' the data may be wrong, since this data is an order of magnitude larger and shows the bimodal distribution, different from all the other data, for comparable flows and operating pressures. However, Fig.8 and Fig.14 show that the J46 at 3' gives almost an identical distribution to the J22 nozzle at 3', for the same flow rate and driving air pressures. This also indicates that the data of Fig.15 may show the results of either an instrumentation problem or a nozzle operating problem.

5.1.3. Data from the Parametric Testing Program

5.1.3.1. Mean and Characteristic Diameters. Figures 16 through 27 show the Sauter-mean (D_{32}), the volume-mean (D_{30}), and the mass-mean diameter (D_{50}) of the measured sprays from the J22B, J22, J42 and J46 nozzles, at 3' and 5' from each nozzle, for a very wide range of water flow rates and for three atomizing air pressures. These measurements were obtained on the geometrical centerline of the nozzle. Each data point, on the curves displayed on each figure, represents a particle number density versus particle size distribution. Because these distributions are essentially the same in appearance as those in Figs. 6-15, they are not presented in this report.

Figures 16, 20, and 24 present D_{32} , D_{30} , and D_{50} for the J22B nozzle. Figures 17, 21, and 25 give the same respective data for the J22 nozzle; Figs.18, 22, and 26 provide this data for the J42 nozzle; And, finally, Figs.19, 23, and 27 give the data for the J46 nozzle.

Figures 16 through 19, displaying the SMD variations with operating conditions for the various nozzles, also present the data points that corresponded to the "nominal" operating conditions, Table 9. For each nozzle it is apparent that these "nominal" operating conditions do not produce the smallest SMD sprays. For every nozzle, the spray conditions corresponding to the smallest SMD occurred at the minimum water flow rate through the nozzle. Choosing 3' as the measurement position, Table 10 lists the smallest SMD at the smallest flow rate for each nozzle.

Table 10

Smallest SMD for the Smallest Flow Rate

Nozzle	Smallest SMD	Smallest Flow Rate	Air Pressure	Nozzle Flow No.
J22B	9 μm	2 GPH	80 PSI	0.309
J22	13 μm	2 GPH	80 PSI	0.316
J42	17 μm	2 GPH	80 PSI	0.295
J46	25 μm	5 GPH	80 PSI	0.700

Thus from Table 10 it is seen that all of the nozzles produce a fairly fine spray particles when the flow rate of water is just a few (2-5) gallons per hour. However, it was found that when the water flow rates were in this range, the sprays were not stable; the spray flashed, or pulsed. From the tests, for J22, J42 and J46 nozzles, pulsing started when flows were 5 gph, or less, while for the J22B nozzle, pulsing started around 2 gph. Also these flow rates are far from the nominal flow rate that are required from these nozzles for use in gas clean up activities. Therefore,

Table 11 presents the value of SMD for each nozzle operating at its nominal flow rate and air pressure; also taken at 3' from the nozzle for consistency of comparison.

Table 11

SMD at Nominal Flow Rate and Air Pressure

Nozzle	SMD	Nominal Flow Rate	Air Pressure	Nozzle Flow No.
J22B	46 μm	5 GPH	60 PSI	0.80
J22	134 (126) μm	15 GPH	60 (80) PSI	2.08 (1.82)
J42	155 μm	20 GPH	60 PSI	2.83
J46	139 μm	15 GPH	60 PSI	2.19

Table 12 shows that, basically, the J22, J42, and J46 produce about the same size SMD sprays, at essentially comparable flows and driving pressures. Also, according to the each nozzle's flow number, the larger flow numbers result in the larger mean droplet sizes, and smaller flow numbers result in smaller mean droplet size; this was expected. Mean droplet sizes scale with the size of the nozzle orifice flow area, for each type nozzle.

The variation of SMD with flow rate and air pressure is, of course, observably different for each nozzle. Similar information can be gleaned from Figs.20-23, in terms of volumetric-mean diameters and in Figs.24-27 in terms of mass median diameters, of the sprays. For all nozzles, the mean and characteristic diameters increase rapidly as the water flow rate goes from 2 to 20 gph, and as the air pressure increases, they all decrease.

Table 12

SMD for Each Nozzle at the Same 10 GPH Flow Rate

Nozzle	SMD	Water Flow Rate	Air Pressure	Nozzle Flow No.
J22B	113 μm	10 GPH	60 PSI	1.40
J22	99 μm	10 GPH	60 PSI	1.51
J42	117 μm	10 GPH	60 PSI	1.54
J46	130 μm	10 GPH	60 PSI	1.58

It is worthwhile noting that at a comparable flow rate for all nozzles, for example, at 10 gph, all of the nozzles produce sprays with approximately equal SMD's. Table 12 shows this, where SMD is displayed for each nozzle at 10 gph flow rate, 60 psi driving pressure, and at 3' from the nozzle.

Therefore, purely from the basis of comparing spray SMD values at representative measurement positions and for equal operating conditions, it may be concluded that any of these nozzles can be used in an application to flue-gas cleanup. The nozzle to pick will be the one that exhibits the least fouling and plugging, provides a spray with a satisfactory spread rate or cone angle, and yields a liquid water content distribution that is acceptably uniform in the ducting downstream of the spray (that is, uniformly covered the ducted flue-gas flow). Note, however that the 10 gph flow rate is about the largest flow rate for which the J22B can operate. For J22B at its maximum flow rate, the spray was not formed very well. Observations showed that the spray contained solid fluid streams or unbroken

liquid jets issuing from part of its periphery. Thus, J22B must be used for flow rates under 10 gph.

The next interesting observation is that the volume-mean diameter for each nozzle is significantly smaller than either the SMD or the mass-median diameter. This means that the surface area-mean diameter, D_{20} , is significantly smaller than the volume-mean diameter, D_{30} , and also that a significantly large fraction of the total spray mass is contained in a relatively few large droplets.

Figures 28 through 31 show this plainly, where for each nozzle, the diameter ratio D_{32}/D_{30} is plotted for the range of operating conditions. Note that for each nozzle, at the lowest flow rates, D_{32}/D_{30} is roughly about 1.3 to 1.5, meaning that the spray has a fairly narrow number density distribution; that is the bulk of the droplets are all about the same size, and the size is in the 20-30 μm range, or less. However, at the highest flow rates, D_{32}/D_{30} ranges from about 2.0 to 2.5, meaning that the distribution of sizes has broadened, and further, the mass distribution in the spray has shifted toward the largest sized particles. It is also noted that the data of Fig.31, which was obtained by testing the J46 nozzle, is significantly different in character, although not in magnitude, from the corresponding data of the other nozzles. Therefore, it can be anticipated from the spray measurements that the J46 must be different qualitatively from the other nozzles. As Fig.3 showed, the J46 nozzle is wide angle, round spray nozzle, which made it differ from the other narrow angle, round spray nozzles, like J22B, J22 and J42.

5.1.3.2. Spray Evaporation. Figures 32, 33, 34 and 35 show, in different ways, the rate of evaporation of the sprays from the J22, J42, and J46 nozzles, for operation at the chosen conditions. Figure 32 shows particle number density versus size distributions obtained on the centerline of the nozzles at various axial positions

downstream of the nozzles. The distributions show that the smaller particles are evaporating; their number densities are decreasing significantly as axial distance increases. Figures 33, 34, and 35 show the changes in Sauter-mean, volumetric-mean, and mass-median diameters, respectively, with axial distance from the nozzles. These figures all show the same trend; the drop sizes are rapidly decreasing with axial distance from the spray, indicating intense evaporation is occurring in the spray.

Figure 36 shows the same information displayed in the form of axial distributions of liquid water content for each nozzle. This data shows that indeed the sprays are evaporating; not just spreading out. Note that the LWC values at $X = 1.5'$ are not realistic. The value of LWC at $X = 3'$ are within 20 percent of values that can be calculated for this axial position using a simple spray theory. Hence, at $X = 1.5'$, the PMS instrument response was "saturated" by the presence of too many particles in the spray. In other words, the sprays were "dense phase" in this region and the PMS system could not obtain correct LWC values.

5.1.4. Conclusions

The conclusions from testing the J22B, J22, J42, and J46 nozzles under cold flow conditions are as follows.

(1). All of the nozzles tested could produce either small ($10\text{-}20\ \mu\text{m}$) mean diameter sprays at low ($2\text{-}5\ \text{gph}$) water flow rates, or large ($100\text{-}150\ \mu\text{m}$) mean diameter sprays at the higher water flow rates ($10\text{-}20\ \text{gph}$).

(2) When correctly used, so that no spray instability occurred, such as spray flashing or spray pulsing, each nozzle was capable of producing sufficiently atomized sprays. The J22B nozzle operated satisfactorily between $2\ \text{gph}$ and $10\ \text{gph}$; the other nozzles operated satisfactorily from $5\ \text{gph}$ to $20\ \text{gph}$ or even higher.

(3) The volume-mean, Sauter-mean and mass median diameters of the sprays from each nozzle increase with increasing flow number, and increasing water flow rate; the diameters decrease with increasing air pressure.

(4) Since all four nozzles are 1/4J air atomizing nozzles, for equal flow rates and air pressures, all of the nozzles produced sprays with about the same volume-mean and Sauter-mean diameters provided that the flow rates did not produce unstable spray.

(5) Both liquid water content measurements and mean diameter measurements indicate that the sprays evaporated significantly as the distance from the spray nozzle increased. The Sauter-mean diameters measured on the centerline of the spray decreased with increasing axial distance.

(6) The main conclusion from the cold flow testing is that any of these nozzles (J22B, J22, J42, and J46) could produce a spray finely enough atomized for slurry sorbent injection for flue-gas clean up. The selection of the appropriate nozzle will thus depend on which nozzle gives

- (a) the proper slurry flow rate;
- (b) a satisfactory spray coverage (cone angle, depth of penetration, etc.);
- (c) the least plugging, fouling and spray instability;
- (d) the easiest plumbing configuration (permits the fewest nozzles to be utilized in the application).

(7) For the hot duct slurry tests at UTSI, the diameter of the hot duct is 16", and a 15-18 gph slurry flow rate and 60-100 psi air pressure are required. J46 is wide angle round spray nozzle; its spray will imping on the duct wall. And J22B is suitable for only 2-10 gph flow rate. Therefore, neither of them were used in the slurry tests. From the cold flow spray tests, for the air pressure around 60-80 psi, the J22 nozzle works better than J42 at 15-18 gph flow rate (J42 nozzle works

better at higher flow rates). So, the J22 nozzle was picked up for the hot duct spray tests using water as the spray medium for further characterizations.

5.2. Hot Gas Duct Tests

5.2.1. Results and Discussions

The hot duct experiments using water as the liquid medium were done so that the results could be compared to corresponding, actual slurry sprays measured also in the hot duct. Since, for the slurry tests, the supply air pressure was 95-100 psi, and the slurry flows ranged from 15 gph to 18 gph, the data from the hot tests using water that are of interest are for the conditions in Table 13. The data obtained in the hot gas tests with water as the liquid medium, for the test conditions listed in Table 13, are presented in the thesis.

Table 13

Hot Test Conditions for Water Spray for Comparison to Slurry Tests

Condition	Water Flow Rate	Air Pressure	Positions*	Nozzle Flow No.
1	15 GPH	90 PSI	90 DEG	2.023
2	15 GPH	90 PSI	270 DEG	2.023
3	20 GPH	90 PSI	90 DEG	2.550
4	20 GPH	90 PSI	270 DEG	2.550

* Top part of the duct = 90 DEG.; Bottom part of the duct = 270 DEG.

5.2.1.1. Particle Number Density Distributions. Figures 37 to 40 present distributions of measured particle number densities versus particle sizes as a function of radial position in the hot gas duct at various distances from the nozzle. Fig.37 is for J22 nozzle with the chosen conditions at 3 feet. Figures 38, 39, and 40 show the J22 nozzle at the same conditions, but at 7 feet, 11 feet, and 17 feet, respectively, from the nozzle. All of these figures show the following.

(1) For each condition, the centerline flow in the duct was mixed with a great many more particles than at the walls. The particle number densities decrease from the center of the duct to the wall.

(2) The largest numbers of particles were in droplets sized smaller than 50 μm .

(3) When the water flow rate was increased from 15 gph to 20 gph, with fixed air pressure, 90 psi, the particle number densities increased; i.e., more particles at all sizes were measured. By comparing these figures, it is clear that particles number densities decrease dramatically with increasing distance from the nozzle. This means that lots of particles disappeared, some of them reaching the wall of the duct, but most of them evaporating.

5.2.1.2. Spray Liquid Water Content Distributions. Figures 41 and 42 show the radial distributions of the liquid water content at various axial distances from the J22 nozzle. Fig.41 is data from sprays at 20 gph water flow rate and 90 psi air pressure. Fig.42 is data from sprays at 15 gph water flow rate and 90 psi air pressure. These two figures show that the spray LWC in the hot duct gradually becomes uniform with increasing distance from the nozzle. At three feet, the highest LWC was slightly above the centerline; that is, more LWC was observed above the centerline. Essentially no LWC was obtained at the duct wall, most

was concentrated on the center line. At seven feet from the nozzle, the highest LWC was about equally distributed about the centerline, taking both Fig.41 and 42 into account. However, the magnitude of the LWC decreased by a factor of 10. Also, in general, the LWC profile was broadened. A few droplets were present near the duct walls. At eleven feet, the LWC profile has broadened again, and the curves become flatter, meaning that the LWC distributions in the duct became more uniform, even with the sharp peaks in the profiles. At seventeen feet, similar trends were observed. The LWC is about the same in both the upper and lower halves of the duct flow. In all, these figures present that: first, from three feet to seven feet, the highest LWC shifted from the top part of the duct to the center or the bottom part; second, the farther the measurements were taken from the spray, the more uniform the LWC became.

5.2.1.3. Mean and Characteristic Diameter Distributions. Figures 43, 44, and 45 present D_{32} , D_{30} , and D_{50} for the J22 nozzle at three feet, seven feet, eleven feet and seventeen feet from the nozzle, respectively, for two water flow rates and the same air pressure.

Figure 43 displays the variations in Sauter-mean diameter, or D_{32} , with radial position at the test conditions listed in Table 11. At three feet, as Figure 43 shows, the diameter distribution of the spray is fairly symmetric, although the SMD at the top half part of the duct is a little bit larger than at the bottom half part. Smaller SMD particles are observed at the edge of the spray near the walls. However, since most SMD's are around 40 to 50 μm , the spray is well atomized, and the J22 nozzle gives good atomizing performance.

Considering the accuracy of the instrumentation, about all that can be said concerning the data in Figure 43 is that the SMD of the spray stays fairly uniform

in the 35 to 60 μm range, from 3 feet to 17 feet from the nozzle. The spatial variations result from evaporation, gravitational effects, duct flow turbulence, and other effects, perhaps even droplet collisions and agglomerations. However, since the mass of the spray is decreasing (as Figs. 41 and 42 show), it is very interesting that the SMD remains so fairly constant.

Figure 44 presents the same type of data as is in Figure 43, only for Figure 44 the volumetric mean diameter, D_{30} , is presented in radial distributions at different axial positions for two water flow rates. Exactly the same trends are observed in Figure 44 as are shown in Figure 43. However, the volume-mean diameter ranges from 20 to 30 μm , somewhat less than the SMD's 40 to 50 μm average range.

The corresponding distributions of mass-median diameter, D_{50} , are displayed in Figure 45. Except for a shift in magnitude, these distributions are also similar to those presented for the SMD. The mass median diameter ranges from 20 to 80 μm at 3 feet and 7 feet, but drops to the 40 to 45 μm range at 11 and 17 feet. This means that the drop-size distributions nearest the spray are broad; that is, a wide range of particle sizes occurs. However, as distance increases, the drop size distribution is becoming narrow; that is, all drops are tending to the same size.

In order to show the relationship between the characteristic diameters of the J22 nozzle sprays in the hot gas duct experiments, the ratios of the Sauter-mean diameter to the volumetric mean diameters were computed. These ratios, which correspond to the data presented in Figs. 43 and 44, are plotted in Figure 46. These distributions show that at 3 feet, D_{32}/D_{30} ranges from 1.0 to about 2.3, while at 7 feet the range has reduced to about 1.6 to 2.0. Progressing to 11 feet, D_{32}/D_{30} varies from about 1.4 to 1.8, and finally, at 17 feet, the ratio appears fairly constant at about 1.4. These data show in another way that the sprays had a wider range of particle sizes at 3 feet and 7 feet, than at 11 feet and 17 feet. Thus,

the sprays are becoming much more uniform in droplet size as distance increases. The size distribution has become narrower; the remaining droplets are becoming fewer in numbers but more uniformly sized. Similar trends were encountered in the cold flow tests.

5.2.2. Conclusions

The conclusions from the hot duct tests are as follows.

(1) The J22 nozzle worked very well in atomizing water and creating the type of sprays desirable for slurry testing. The sprays generated filled the hot gas duct but did not impinge on the duct walls to any measureable extent.

(2) The sprays from the J22 nozzle produced the most spray liquid water content in the center of the duct flow. Although the sprays were slightly asymmetrical, with greater LWC above the centerline within 7 feet of the nozzle, and with greater LWC below the centerline at distances exceeding 7 feet from the nozzle, in general, the sprays' LWC distribution became essentially uniform at about 11 feet from the nozzle.

(3) The liquid water content of the sprays decreased rapidly as distance from the nozzle increased, dropping by a factor of 100 between 3 feet and 17 feet from the nozzle. Therefore, 99 percent of the spray evaporated in the first 17 feet of travel.

(4) Although the sprays were rapidly evaporating, the Sauter-mean diameters, and, hence, the volume-mean and mass-median diameters, became fairly uniform spatially, both transverse to and along the length of the flow. Sauter-mean diameters were in the 35 to 60 μm range with most between 40-50 μm ; volume-mean diameters were in the 25 to 30 μm range; finally, mass-median diameters were

initially in the 20 to 80 μm range, with the majority tending toward the 40 to 45 μm range farther downstream.

(5) The interpretation of the data was as follows:

The sprays are rapidly evaporating; about 99 percent of the spray mass evaporated within 17 feet of the nozzle, and the numbers of droplets are decreasing. The drop sizes are all approaching a uniform size. Further, this size is uniform spatially, that is, it is uniform across the flow. Thus, at the farthest distance from the nozzle, 17 feet, the evaporation is essentially complete, the residual evaporation rate is approaching a slow, steady value, and residual drops are uniform in size, for example, the SMD's are approaching 35-45 μm , and uniform in space across the duct.

5.3. Large Flow-Rate Nozzle Characterization Tests

5.3.1. Results and Discussions

For each nozzle, one set of data corresponding to a specific flow rate was chosen for analysis, as requested. For the CasterJetTM 19930 nozzle, data obtained at a water flow rate of 90 gph will be presented. For the SONIMISTTM HSS-900 nozzle, data taken with a 30 gph water flow rate is presented. For both of these cases, the air pressure was 100 psi, as noted previously.

Figures 47-49 present data obtained from testing the SONIMISTTM Ultrasonic Spray Nozzle. Vertical and horizontal distributions of Sauter-Mean diameter (SMD or D_{32}), volume-mean diameter (D_{30}), and the ratio of Sauter-mean to volume-mean diameter (D_{32}/D_{30}) are presented in Figures 47, 48, and 49, respectively. Figures 50-52 present the same data, in the same order, for the CasterJetTM nozzle.

5.3.1.1. SONIMISTTM Ultrasonic Nozzle Results. For the SONIMISTTM nozzle, the SMD's are of the same order of magnitude as those produced by the air-atomizing 1/4J-series of nozzles, with the largest sized particles in the center of the spray. As distance from the nozzle increases, from 13 inches to 54 inches, the SMD's tend to increase. The smaller size particles are evaporating completely, leaving only the larger sizes to contribute to the particle-size statistics of the spray cloud. The SMD distributions are asymmetric, to a degree, meaning that the sprays generated are non-symmetric. However, comparing the data in Fig.47 at 13, 41, and 54 inches, it is clear that the sprays are tending to axial symmetry. This same trend shows up in Fig.48, and 49, obviously. The ranges in the diameters are as follows. Sauter-mean diameters range from about 10 to 110 μm , at $X=13''$, to 25 to 140 μm at $X = 54''$. Mean volumetric diameters range from about 10 to 45 μm , at $X = 13''$, to 15 to 65 μm at $X = 54''$.

The distributions of the ratio D_{32}/D_{30} for the SONIMISTTM Ultrasonic nozzle sprays show that D_{32}/D_{30} approaches unity (1.0) near the outer edges of the sprays and values from 2.0 to nearly 4.0 in the center of the spray, at $X = 13''$. However, progressing downstream, the distributions of the ratios of D_{32}/D_{30} tend to reverse, with larger values on the outer limits of the spray, in the range 2.0 to 2.8, and smaller values of D_{32}/D_{30} near the centerline, tending to about 2.2. Thus, this types of nozzle appears to generate a spray with a broad size distribution (particle number density versus size), and this tends to be maintained even as distance from the nozzle is increased. A slightly more uniform drop size distribution is provided in the central regions of the spray at distances of 41'' and farther.

5.3.1.2. CasterJetTM Nozzle Results. Distributions of Sauter-mean diameter are provided in Figure 50 for the CasterJetTM nozzle obtained at 41" and 54" from the nozzle. The size range in SMD varies from about 45 μm up to about 145 μm . The results for these sprays are essentially symmetric from left to right, or horizontally, and significantly asymmetric from top to bottom, or vertically. This is easily explained because the CasterJetTM nozzle provides a flat, fan-shaped spray. The "flattened" part of the spray was horizontal in the tests reported here. Thus, the spatial non-uniformity of the spray measurements around the nozzle axis of mechanical symmetry are understood in terms of the shape of the spray cloud produced by the nozzle.

Figure 51 provides the same information as Figure 50, but the data presented are distributions of volumetric-mean diameters. Figure 52 presents the corresponding distributions of the ratios of Sauter-mean diameter to volume-mean diameter. Again, the distributions were essentially uniform in the horizontal plane where the flat part of the spray resided, and were nonuniform in the vertical plane. Mean volumetric diameters ranged from 15 to 60 μm . The ratios D_{32}/D_{30} ranged from about 1.5 to 3.0 in various parts of the spray. Generally, the distribution within the main body of the spray, that is, horizontally, were much more uniform than in the vertical distributions which captured conditions at the edges of the horizontally flat spray.

5.3.2. Conclusions

Both the SONIMISTTM Ultrasonic Spray Nozzle, at 30 gph, and the CasterJetTM nozzle, at 90 gph, were capable of providing reasonably well-atomized sprays. The Sauter-mean and volumetric-mean diameters measured in their respective sprays were within the size ranges produced by the air atomizing 1/4J-

series of nozzles used in the cold flow and hot gas duct tests. The spray from the CasterJetTM nozzle was asymmetric about the center line of the nozzle body, clearly, because this nozzle was designed to produce a flat spray.

Both sprays operated at much larger flow rates than the 1/4J-series of nozzles; for example, the SONIMISTTM nozzle operated at about twice the flow rate and the CasterJetTM operated at six times the flow rate of the J22 nozzle. Despite this, they both appear to provide acceptable atomization, at least comparable to all of the other nozzles tested in this study.

CHAPTER VI

SUMMMARY AND RECOMMENDATIONS

6.1. Summary

A series of experimental investigations were conducted of the finely atomized water sprays produced by two sets of air-assisted spray nozzles. The investigations were done in order to characterize the atomization and spray cloud characteristics of the nozzles, which were candidates for a slurry sorbent injection, flue-gas clean up program. The investigations were done using a commercially available shadow spectrometer instrument that collected data on the statistics of particle sizes in the instrument probe volume immersed in the measured sprays. The data gathered included mean and characteristic spray diameters, and liquid water contents.

The research showed that all of the nozzles produced finely enough atomized sprays for the flue-gas cleanup program. Thus, the basis for selecting a spray nozzle for application to slurry injection from among the candidater can be based on the flow rate desired, the spray cone necessary for coverage of the flue-gas, and the plugging and fouling characteristics of the nozzles. Note that the CasterJetTM nozzle produced a fan-shaped spray; the SONIMISTTM Ultrasonic nozzle produced a spray with a broad particle size range; the J46 is a wide-angle round spray nozzle; and the J22B, J22 and J42 are round spray nozzles.

Besides the practical conclusions obtained from this study, the research showed that a large amount of data characterizing spray clouds of particles can be obtained quickly and economically with commercially available instrumentation.

6.2. Recommendations

For future work, more detailed research can be done in order to get more information about the nozzle performances, such as:

(1) For cold flow spray tests, do horizontal and vertical axial traverses of the spray cloud so that more data can be obtained for comparison with the data from the hot duct tests. This would clarify the effects of the surrounding gas temperature and velocity.

(2) Measure the spray droplet velocities, so that more accurate results can be reached by accounting for differences or variations in that parameter.

(3) Modify the test bed and ducting that contain the instrument set-up. Perform vertical and horizontal traverses of the spray while keeping the flows fixed. This avoids the problem of having to survey part of the spray first, then stop all flows, rotate the ducting or nozzle, and restart the flows to do the other parts of the spray. This would permit more consistent data to be obtained.

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APPENDIX

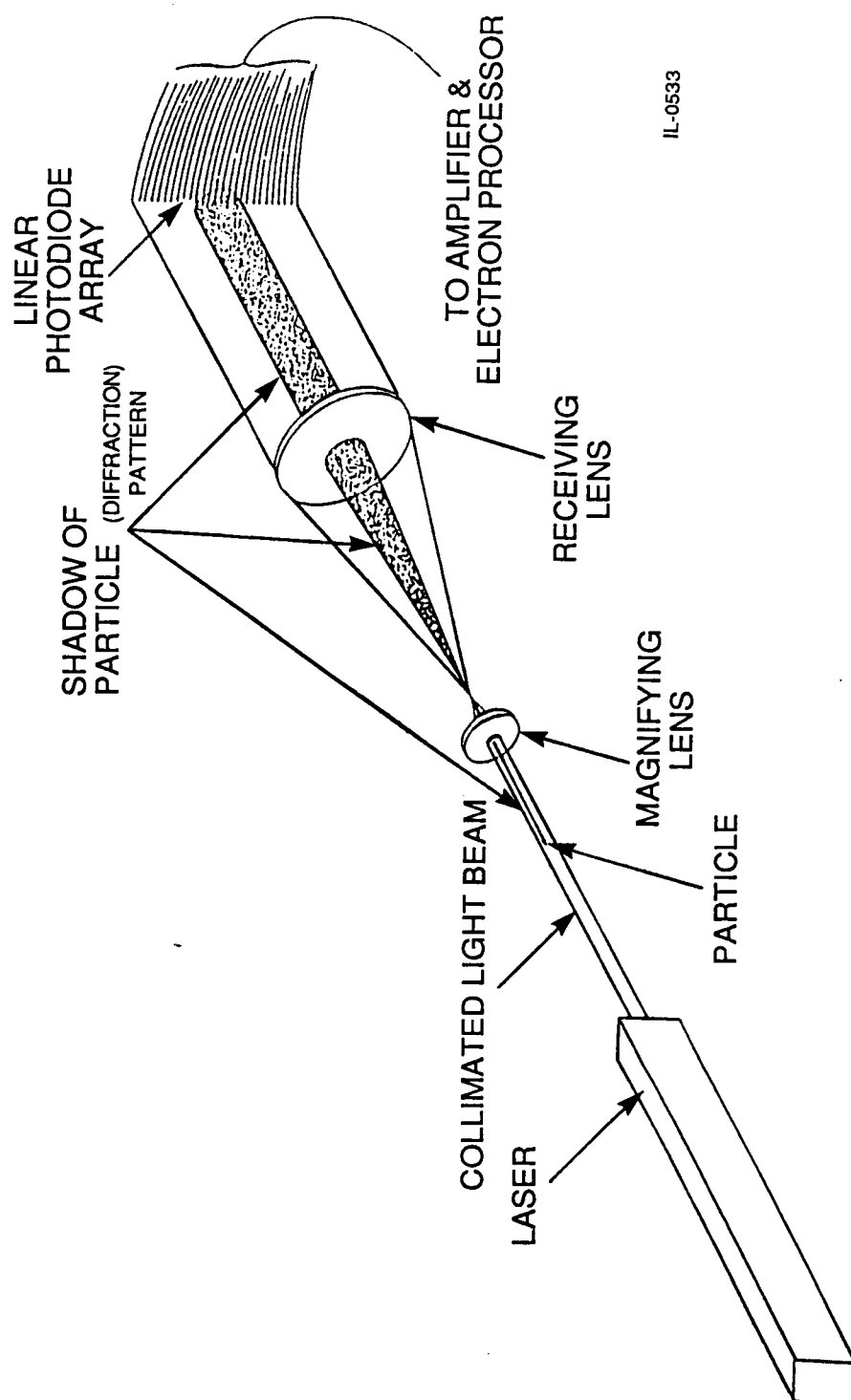


Figure 1. Particle Sizing Shadow Spectrometer

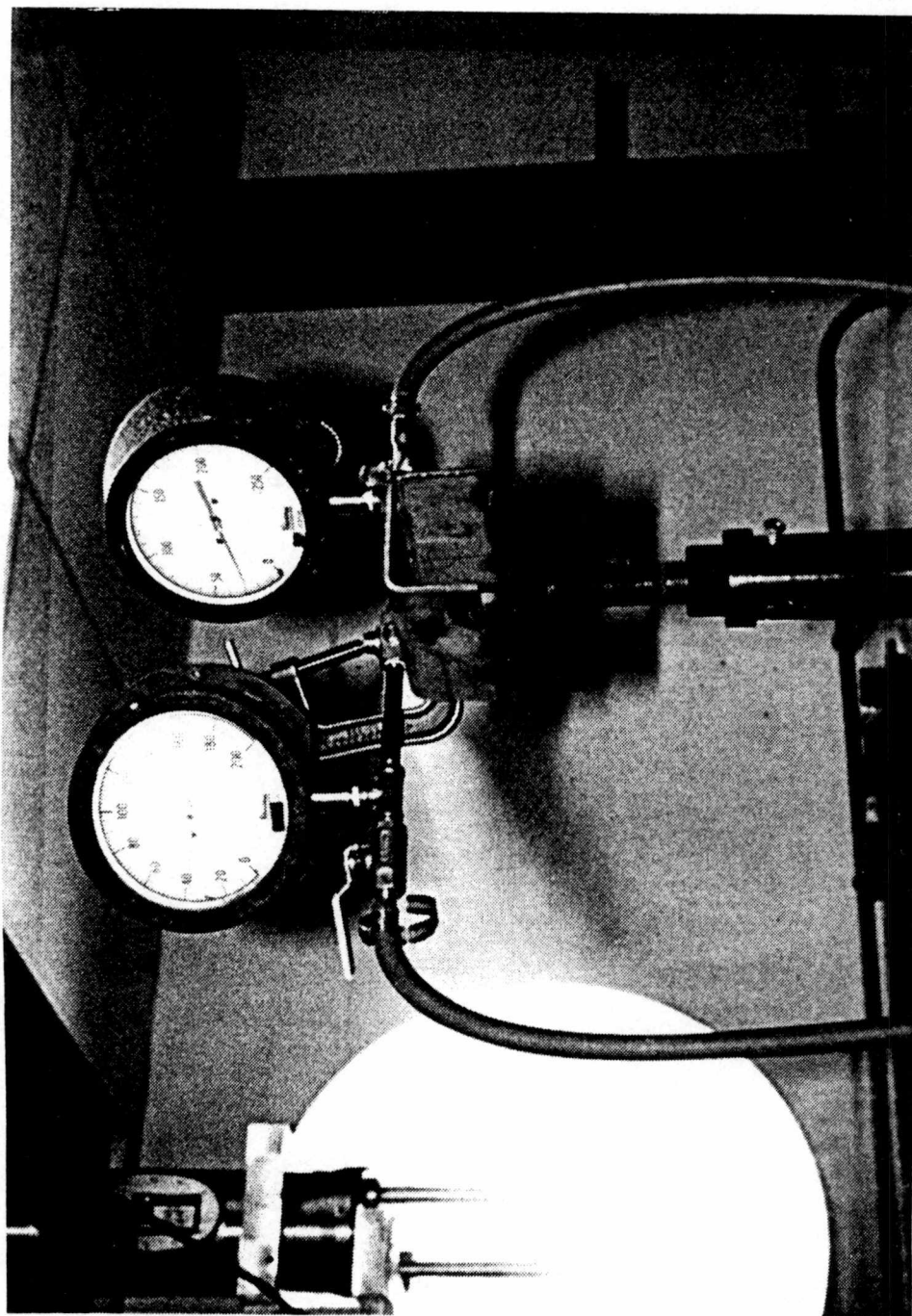


Figure 2. Schematic of Cold Condition Experimental Set-Up

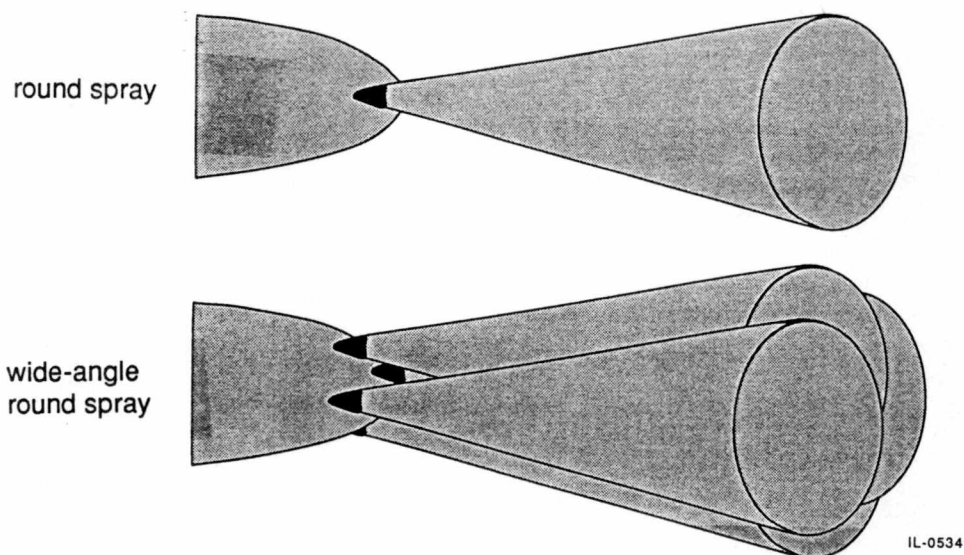


Figure 3. Schematic of Single Cone, Round Spray Nozzle and Multiple-Cone, Wide-Angle Round Spray Nozzle

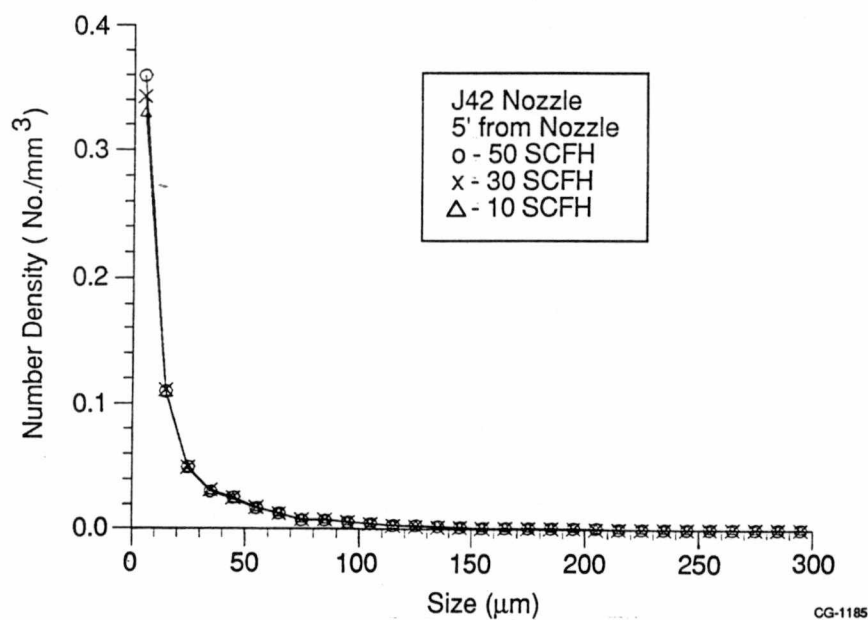


Figure 4. Effect of PMS Nitrogen Purge Flow on Measured Particle Size Distributions

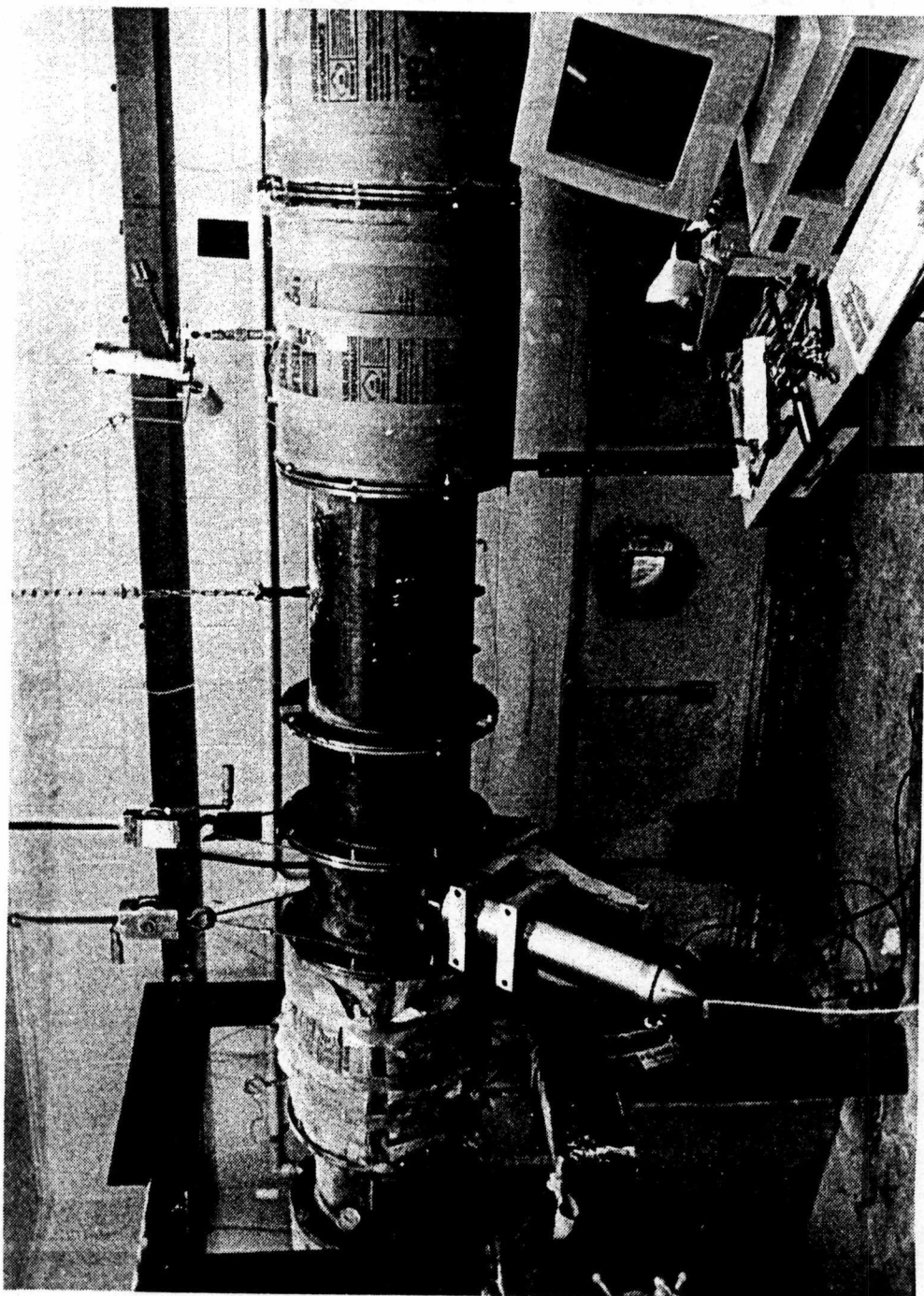


Figure 5. Schematic of Hot Duct Test Experimental Arrangement

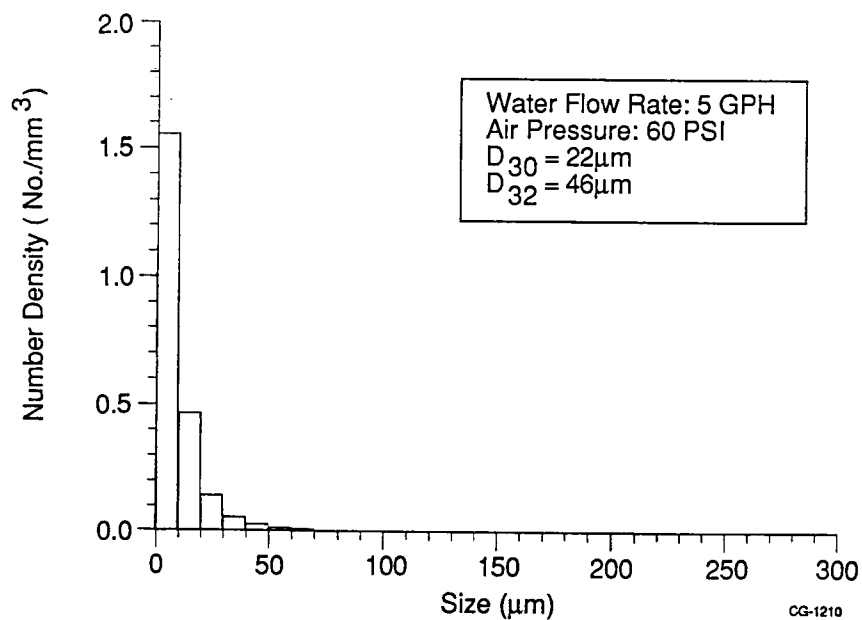


Figure 6. Particle Number Density Distribution for J22B Nozzle at Nominal Operating Conditions; 3' from Nozzle

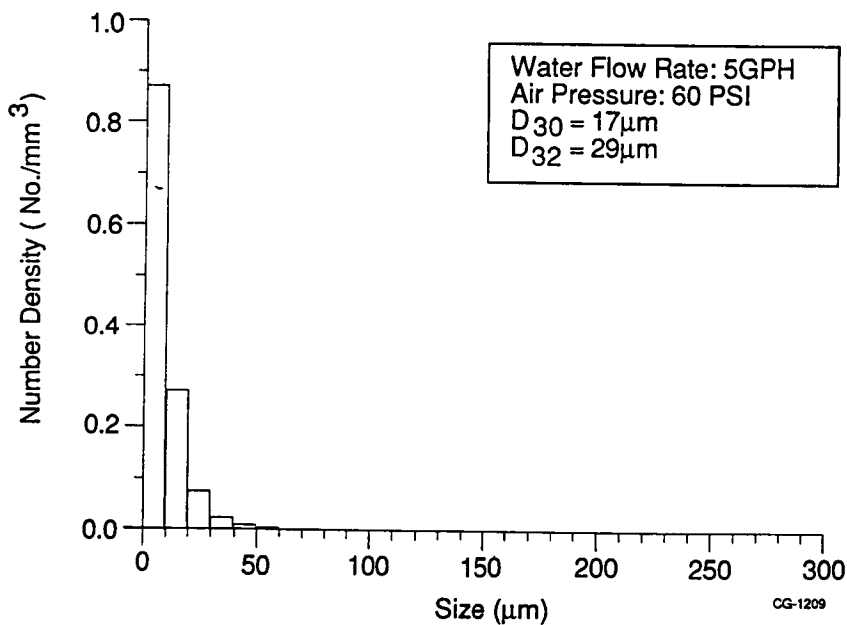


Figure 7. Particle Number Density Distribution for J22B Nozzle at Nominal Operating Conditions; 5' from Nozzle

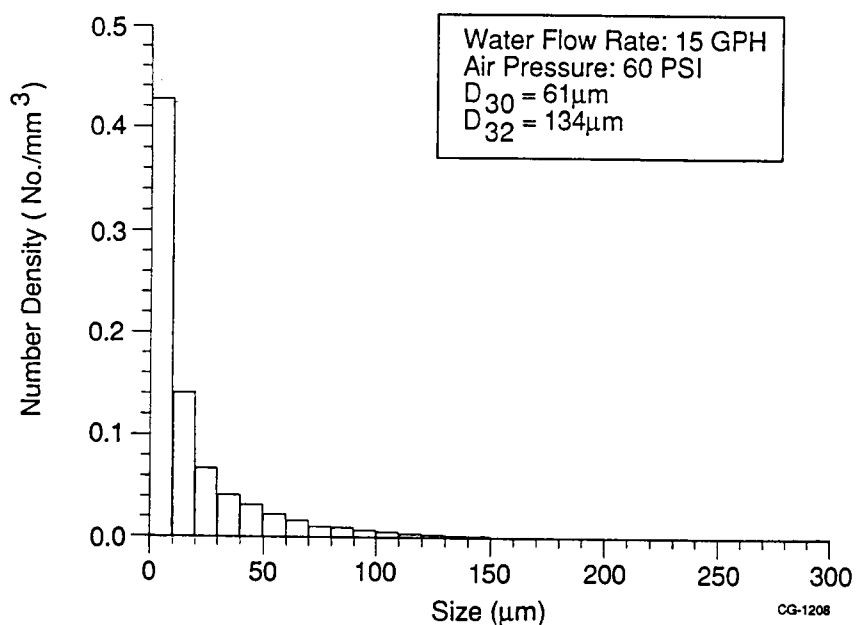


Figure 8. Particle Number Density Distribution for J22 Nozzle at Nominal Operating Conditions; 3' from Nozzle

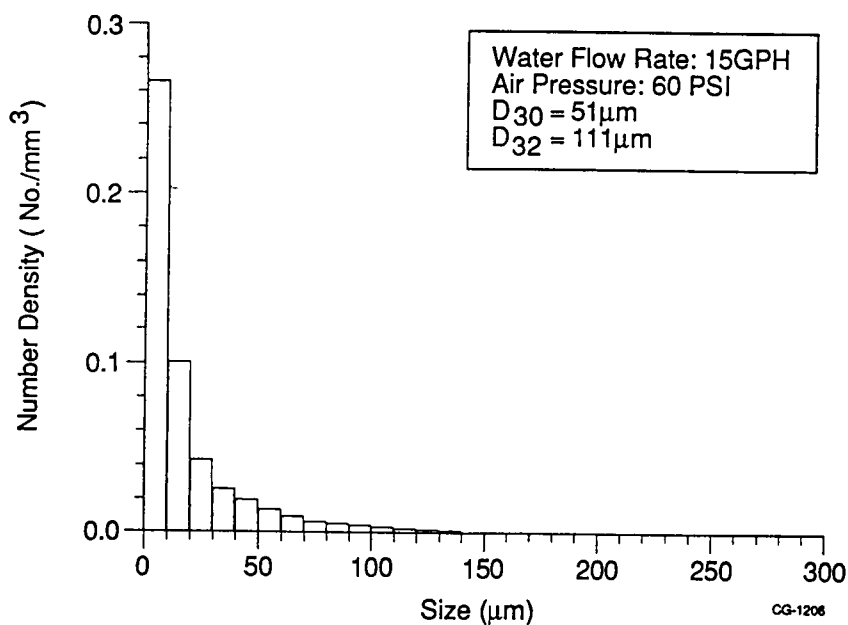


Figure 9. Particle Number Density Distribution for J22 Nozzle at Nominal Operating Conditions; 5' from Nozzle

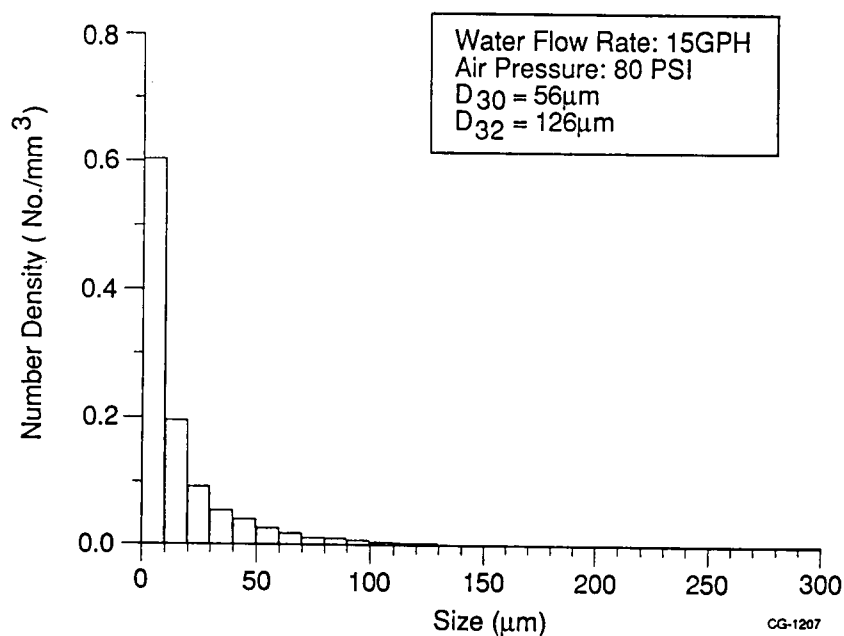


Figure 10. Particle Number Density Distribution for J22 Nozzle at Other Nominal Operating Conditions; 3' from Nozzle

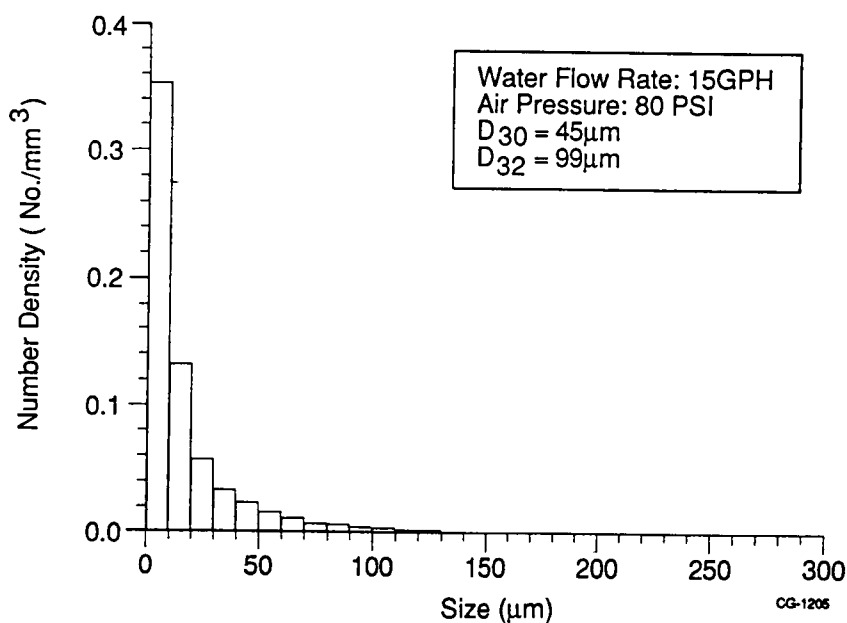


Figure 11. Particle Number Density Distribution for J22 Nozzle at Other Nominal Operating Conditions; 5' from Nozzle

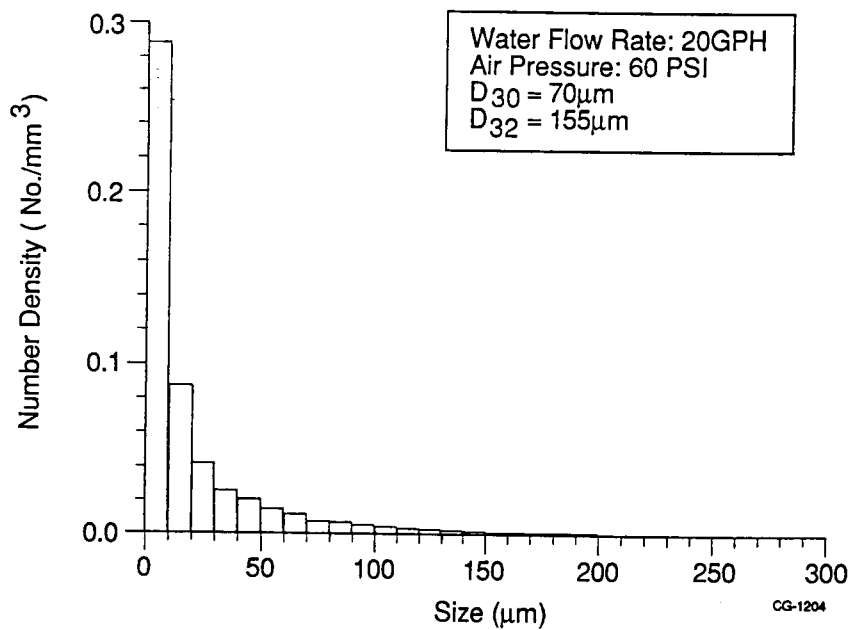


Figure 12. Particle Number Density Distribution for J42 Nozzle at Nominal Operating Conditions; 3' from Nozzle

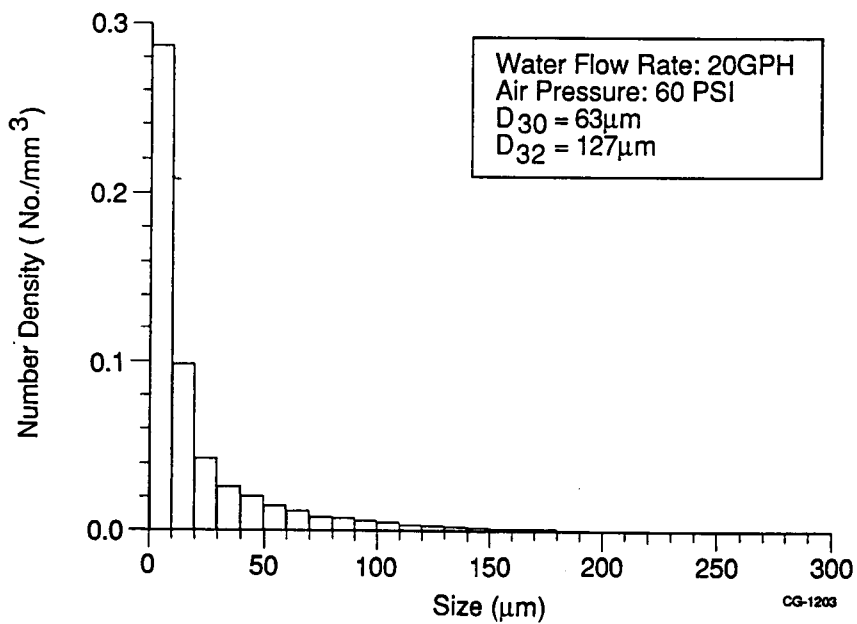


Figure 13. Particle Number Density Distribution for J42 Nozzle at Nominal Operating Conditions; 5' from Nozzle

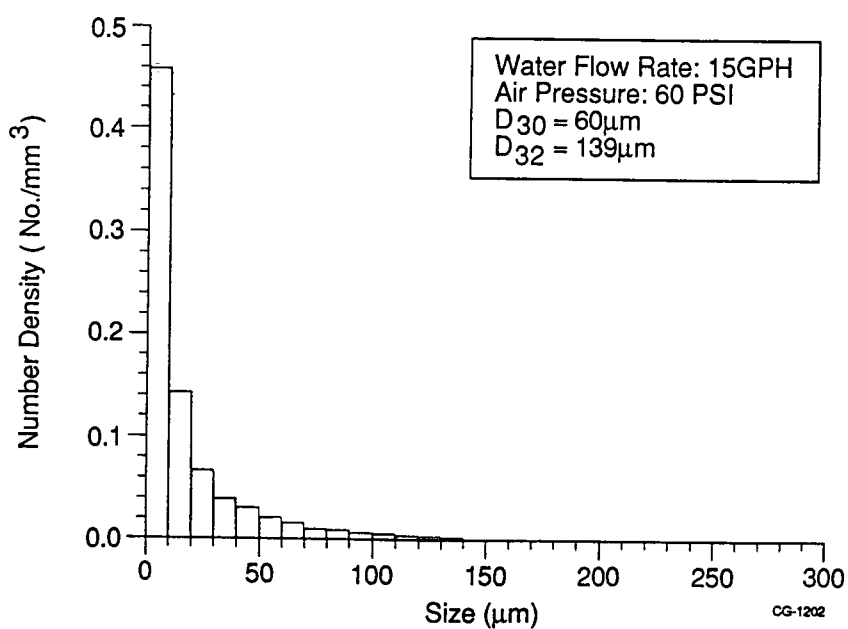


Figure 14. Particle Number Density Distribution for J46 Nozzle at Nominal Operating Conditions; 3' from Nozzle

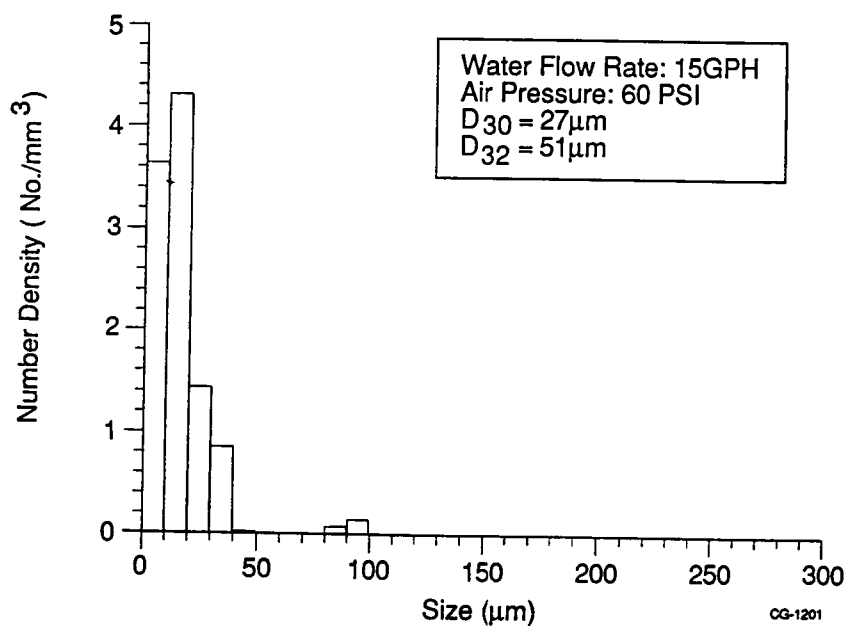


Figure 15. Particle Number Density Distribution for J46 Nozzle at Nominal Operating Conditions; 5' from Nozzle

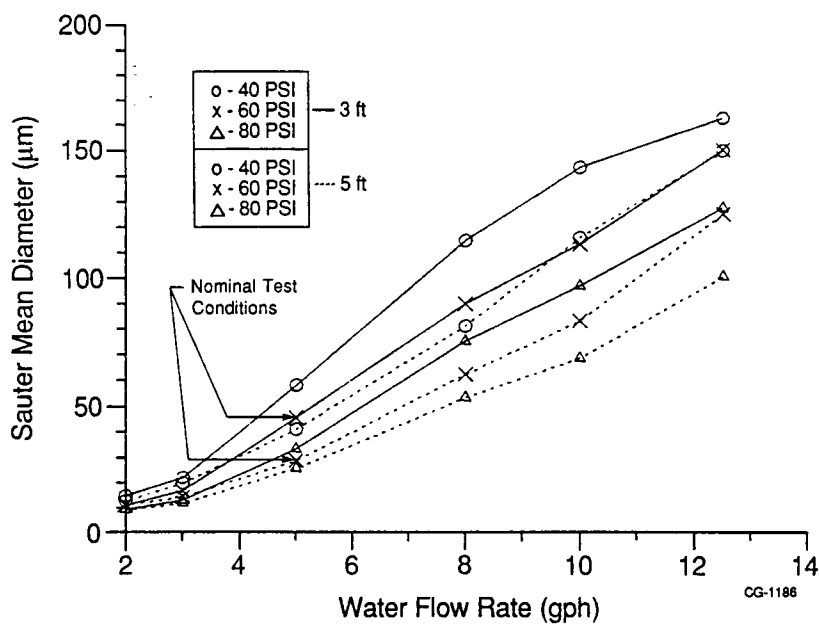


Figure 16. Sauter-Mean Diameter for J22B Nozzle as a Function of Flow Rate and Operating Air Pressure

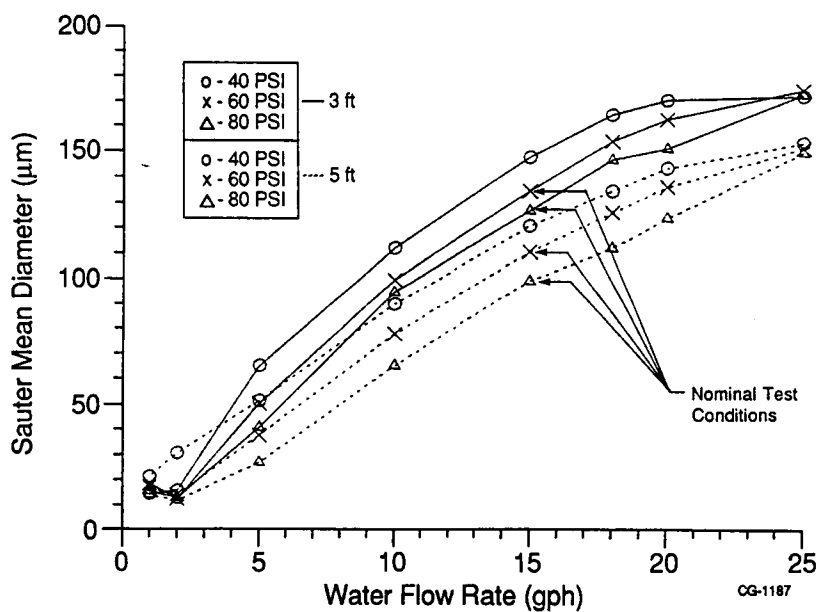


Figure 17. Sauter-Mean Diameter for J22 Nozzle as a Function of Flow Rate and Operating Air Pressure

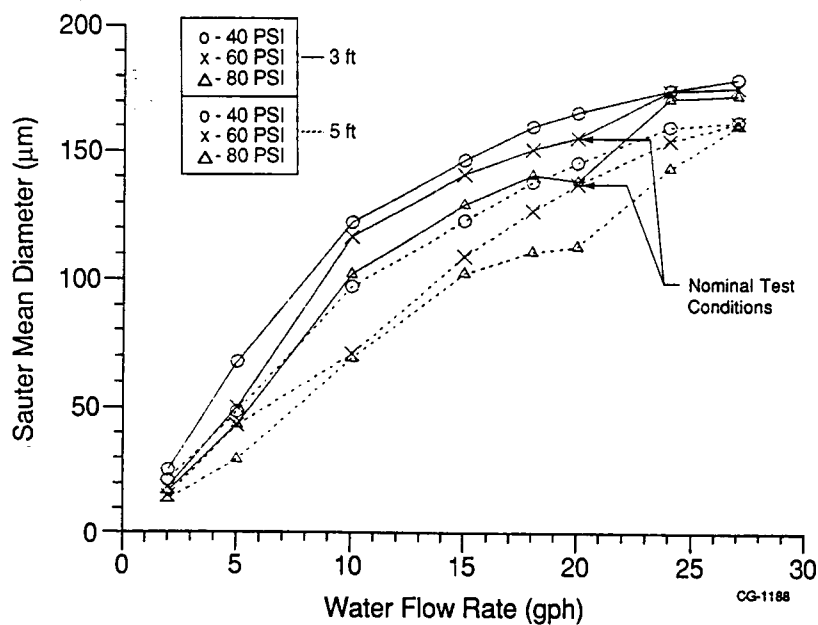


Figure 18. Sauter-Mean Diameter for J42 Nozzle as a Function of Flow Rate and Operating Air Pressure

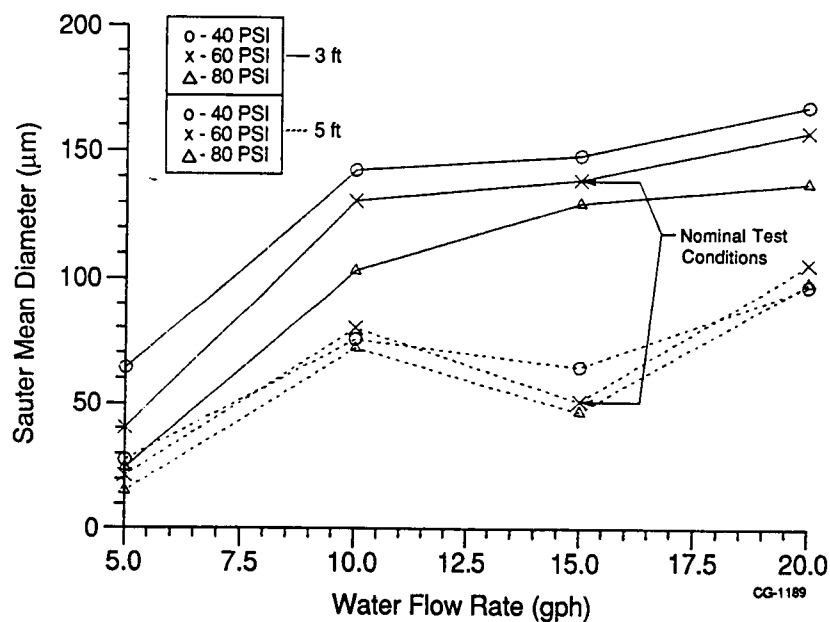


Figure 19. Sauter-Mean Diameter for J46 Nozzle as a Function of Flow Rate and Operating Air Pressure

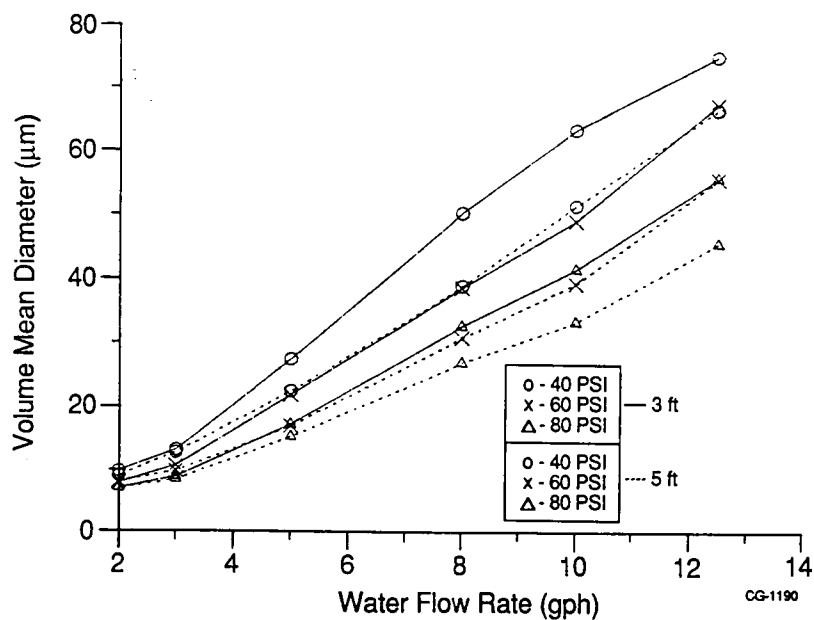


Figure 20. Volume-Mean Diameter for J22B Nozzle as a Function of Flow Rate and Operating Air Pressure

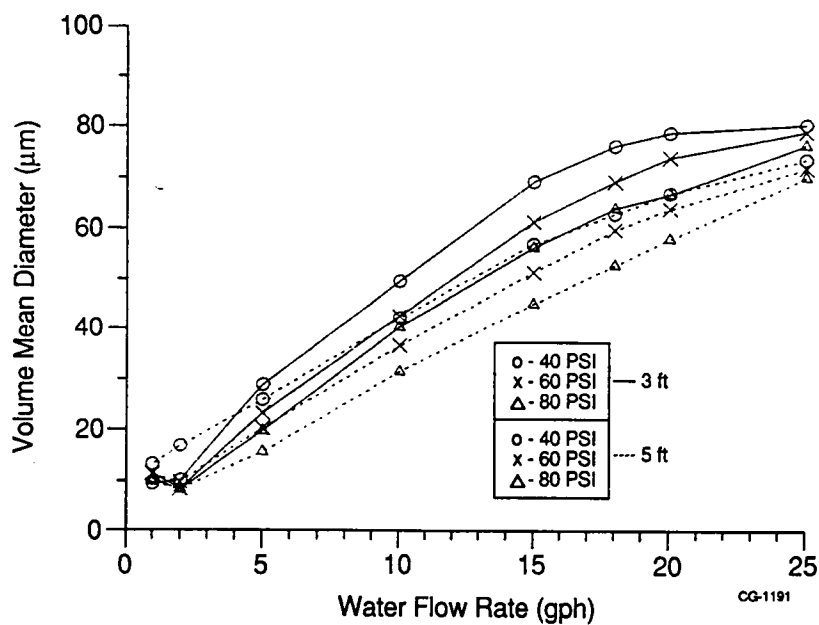


Figure 21. Volume-Mean Diameter for J22 Nozzle as a Function of Flow Rate and Operating Air Pressure

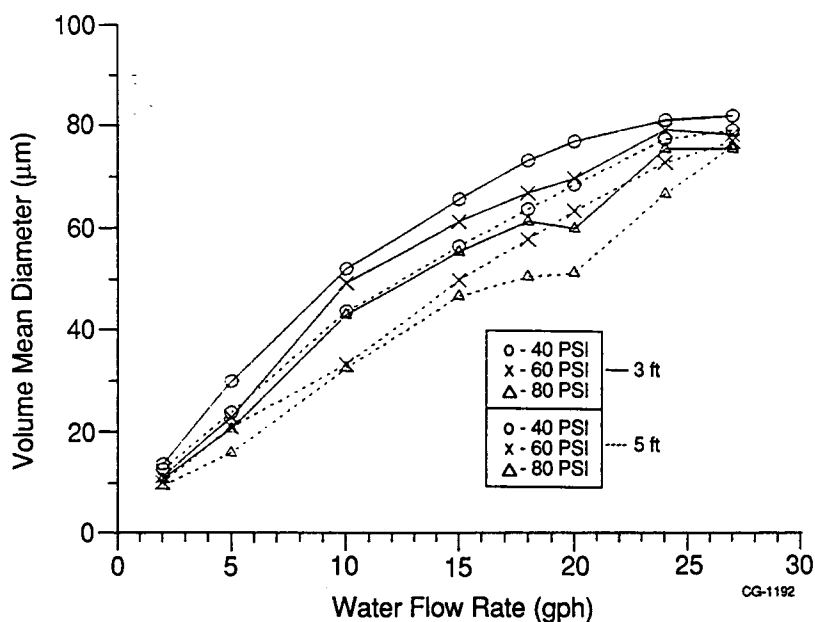


Figure 22. Volume-Mean Diameter for J42 Nozzle as a Function of Flow Rate and Operating Air Pressure

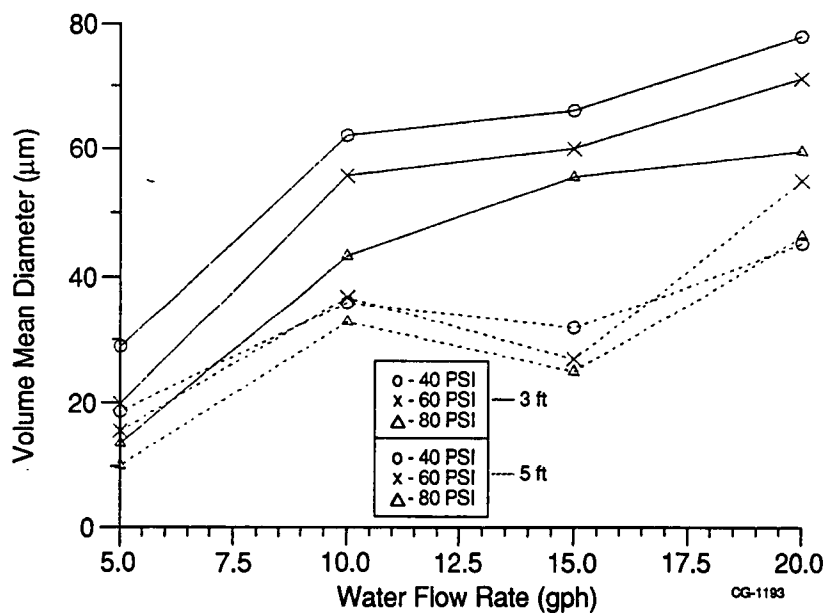


Figure 23. Volume-Mean Diameter for J46 Nozzle as a Function of Flow Rate and Operating Air Pressure

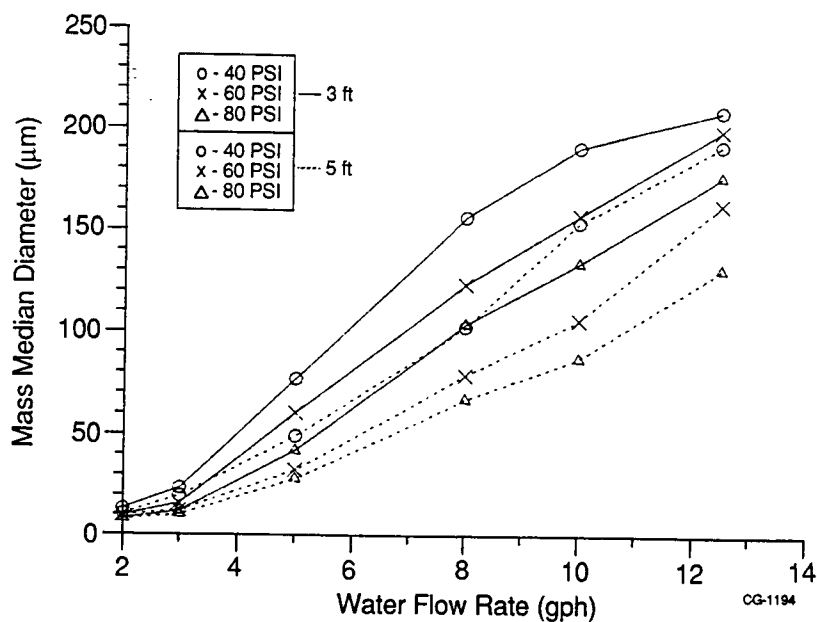


Figure 24. Mass-Median Diameter for J22B Nozzle as a Function of Flow Rate and Operating Air Pressure

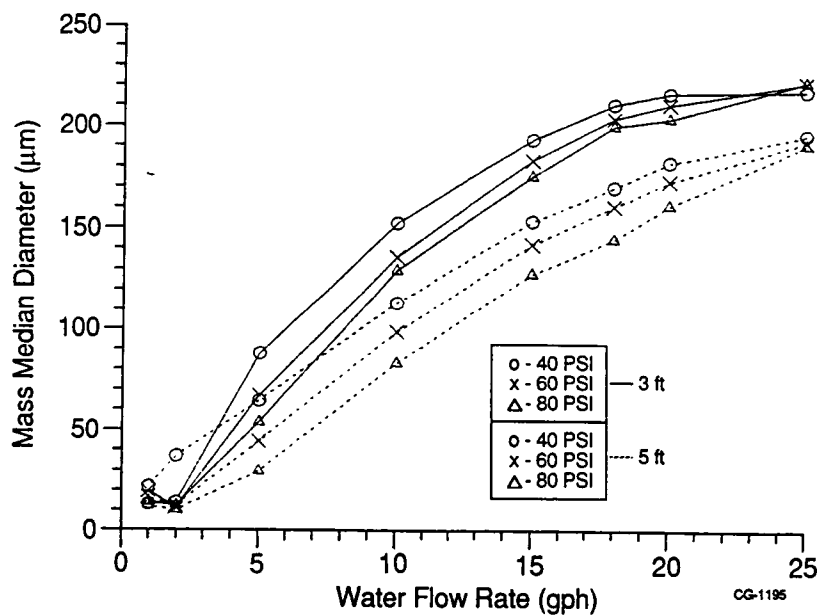


Figure 25. Mass-Median Diameter for J22 Nozzle as a Function of Flow Rate and Operating Air Pressure

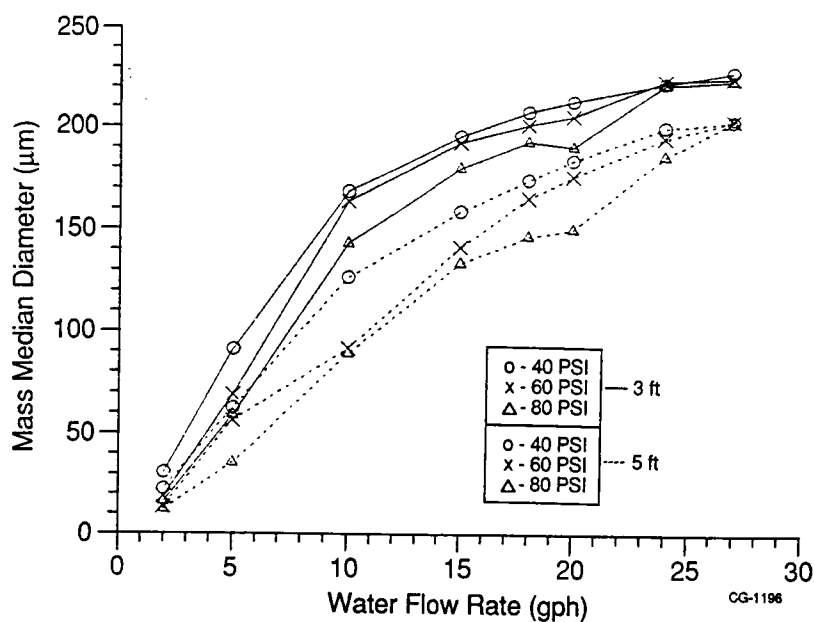


Figure 26. Mass-Median Diameter for J42 Nozzle as a Function of Flow Rate and Operating Air Pressure

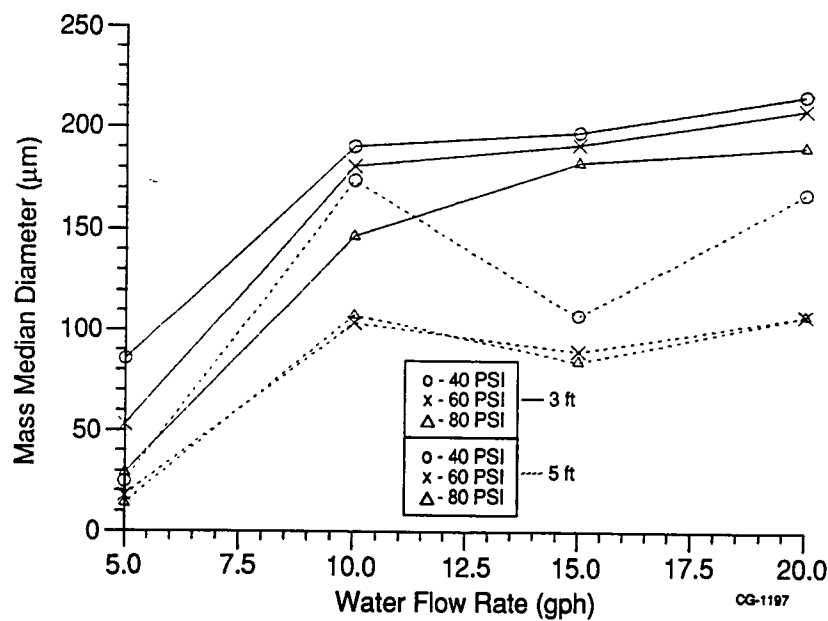


Figure 27. Mass-Median Diameter for J46 Nozzle as a Function of Flow Rate and Operating Air Pressure

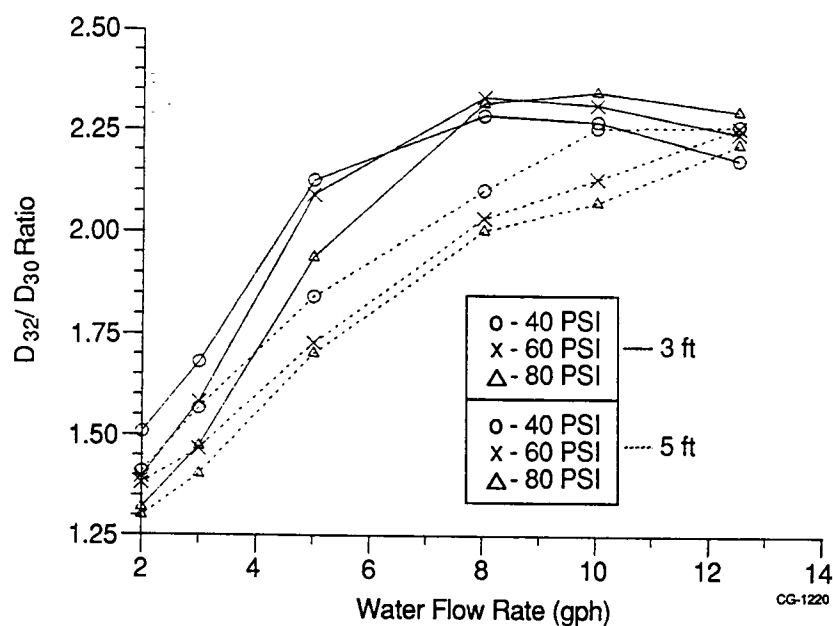


Figure 28. Ratio of Characteristic Spray Diameters for J22B Nozzle as a Function of Flow Rate and Operating Air Pressure

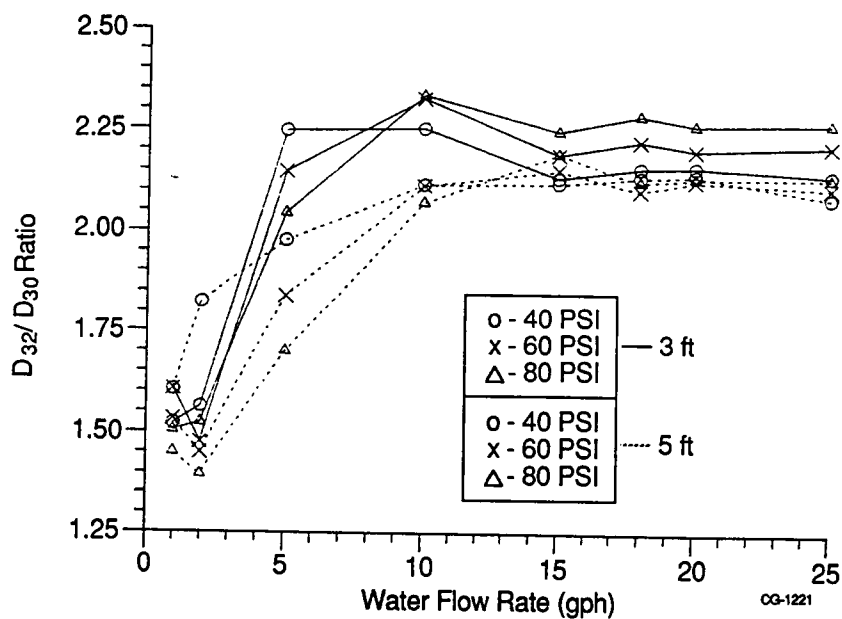


Figure 29. Ratio of Characteristic Spray Diameters for J22 Nozzle as a Function of Flow Rate and Operating Air Pressure

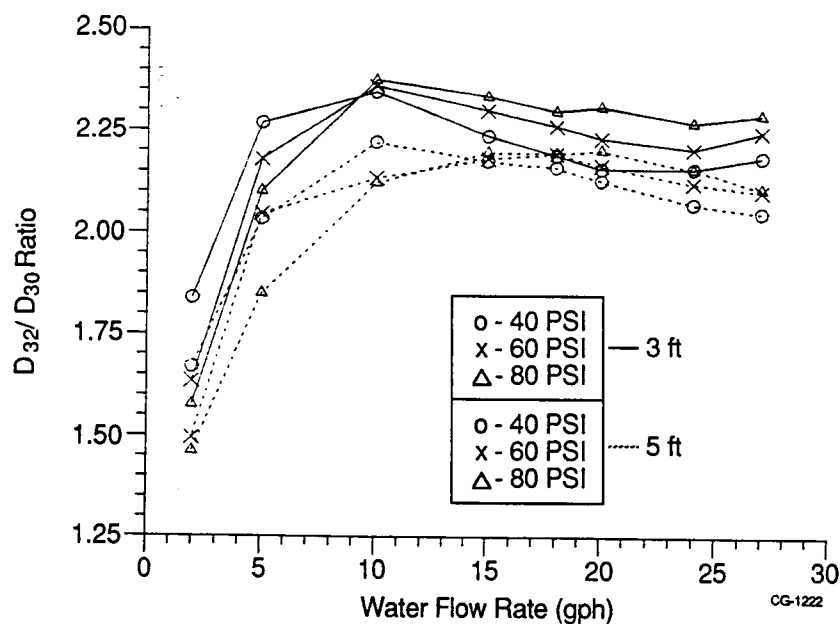


Figure 30. Ratio of Characteristic Spray Diameters for J42 Nozzle as a Function of Flow Rate and Operating Air Pressure

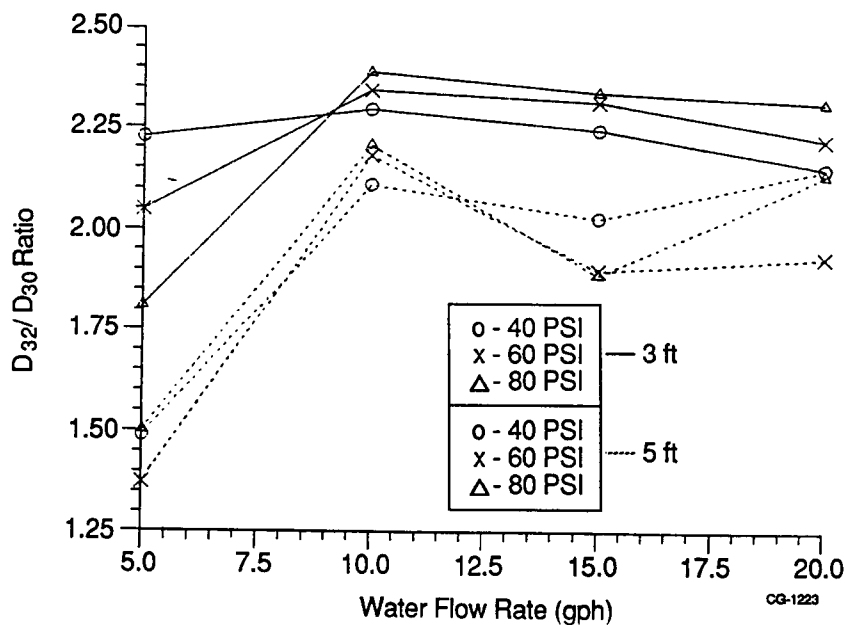


Figure 31. Ratio of Characteristic Spray Diameters for J46 Nozzle as a Function of Flow Rate and Operating Air Pressure

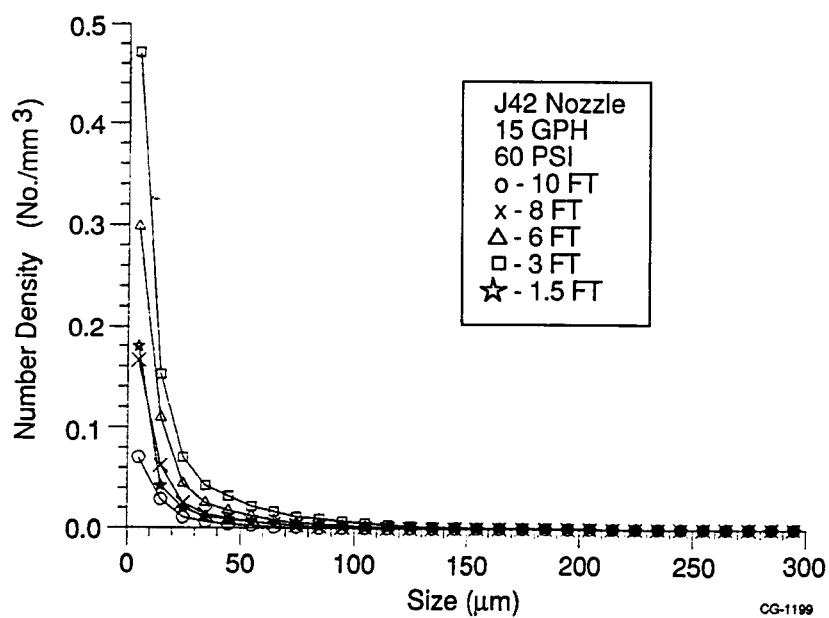
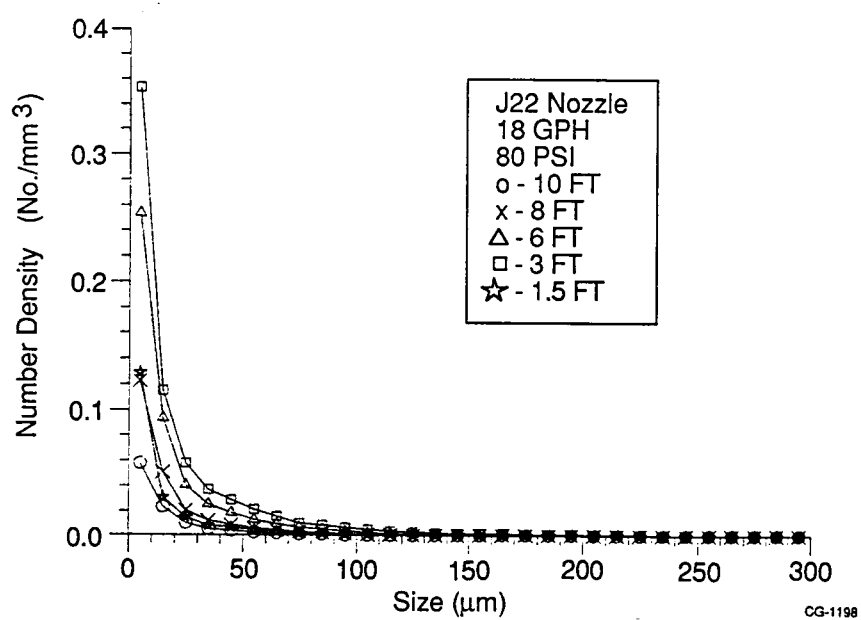


Figure 32. Change in Particle Size Distributions with Axial Distance from the Nozzle

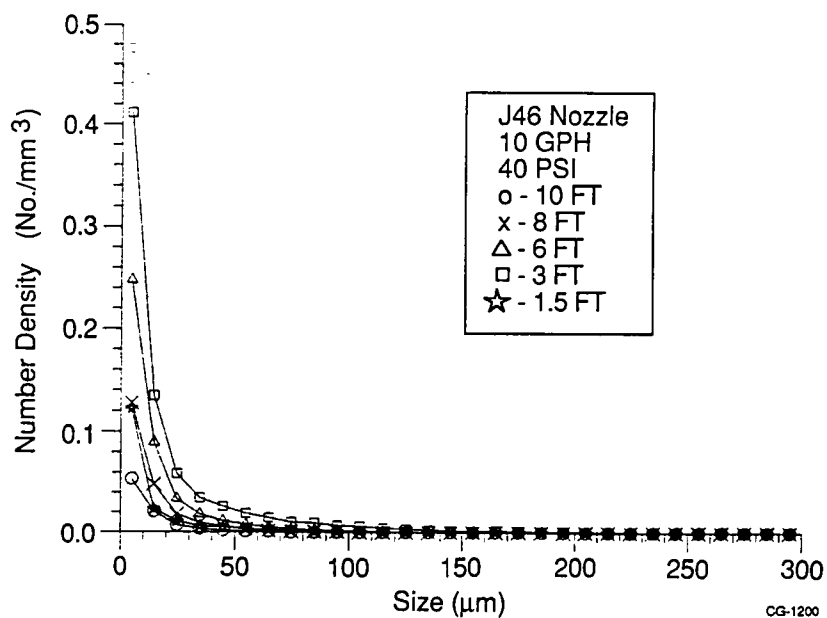


Figure 32. (Continued)

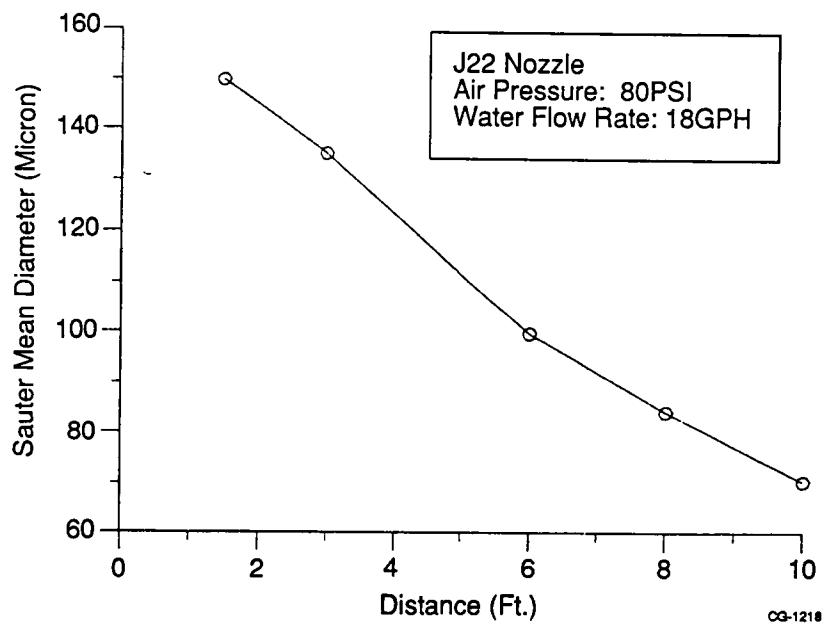


Figure 33. Change in Sauter-Mean Diameter with Axial Distance from the Nozzle

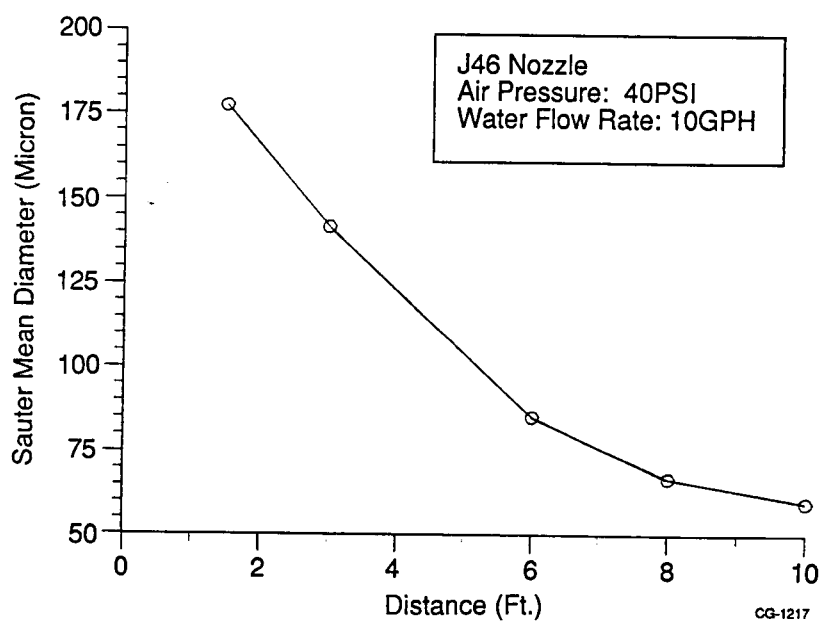
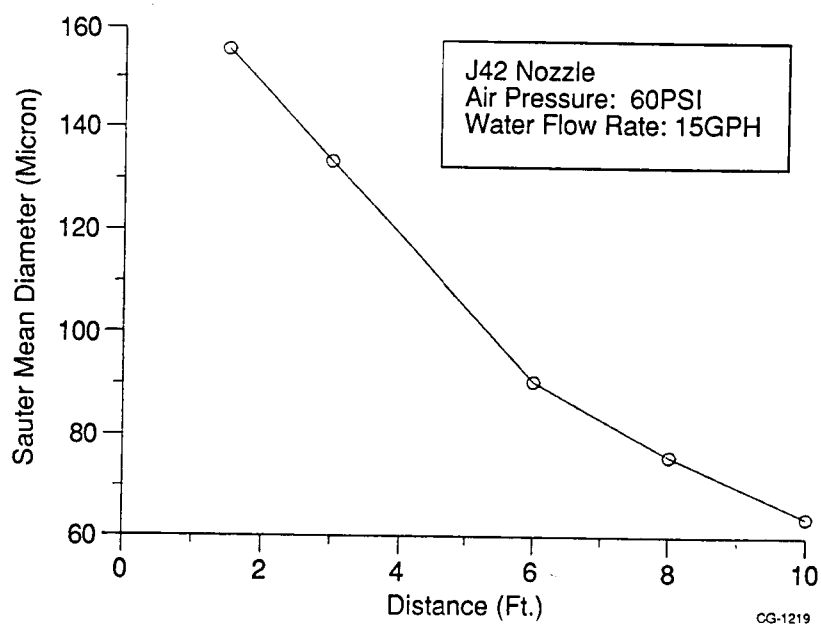


Figure 33. (Continued)

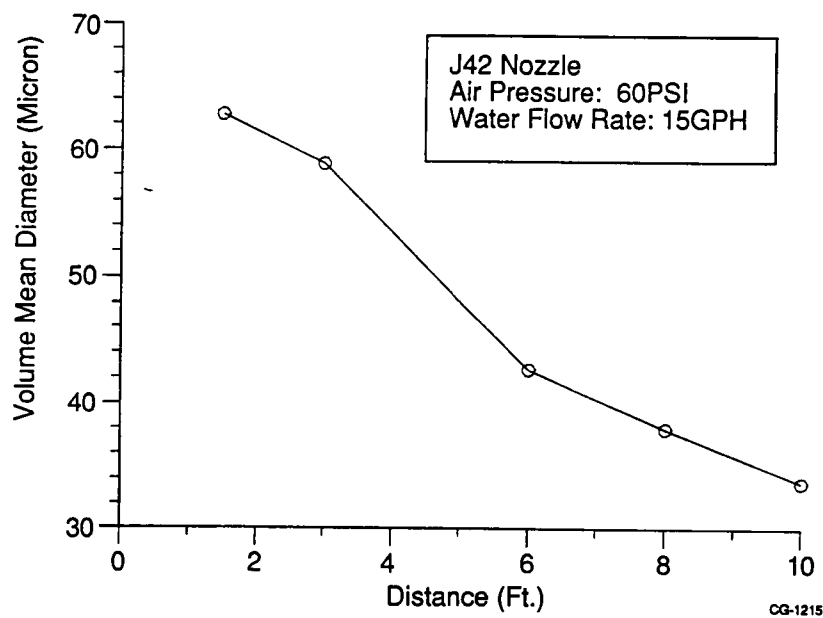
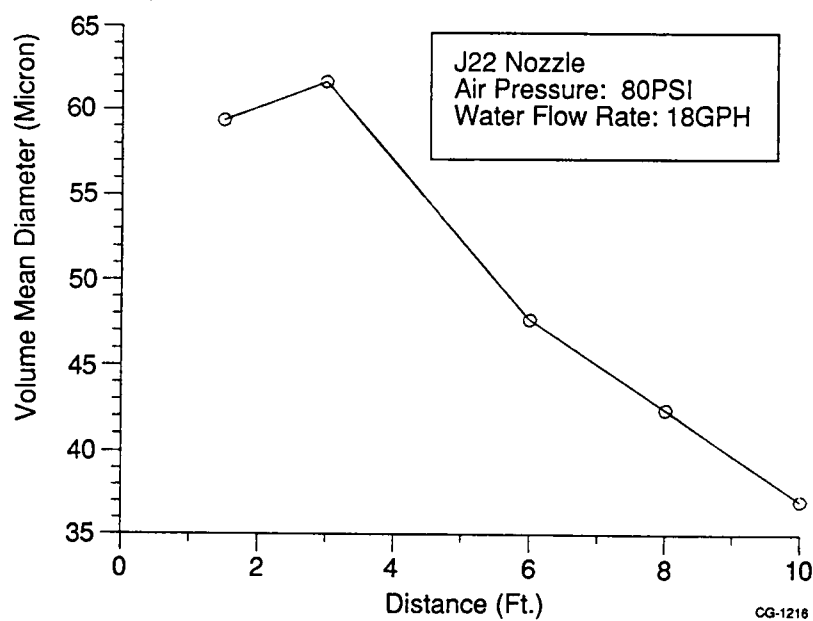


Figure 34. Change in Volume-Mean Diameter with Axial Distance from the Nozzle

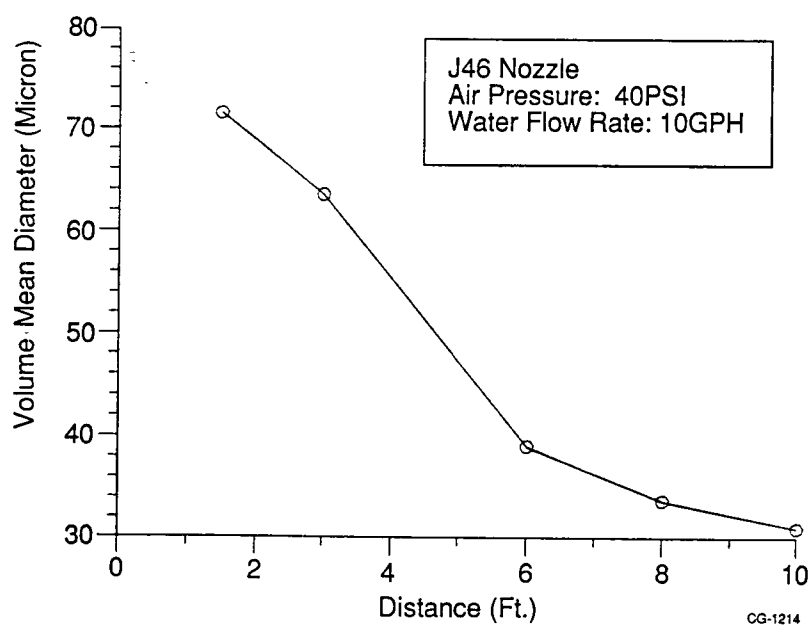


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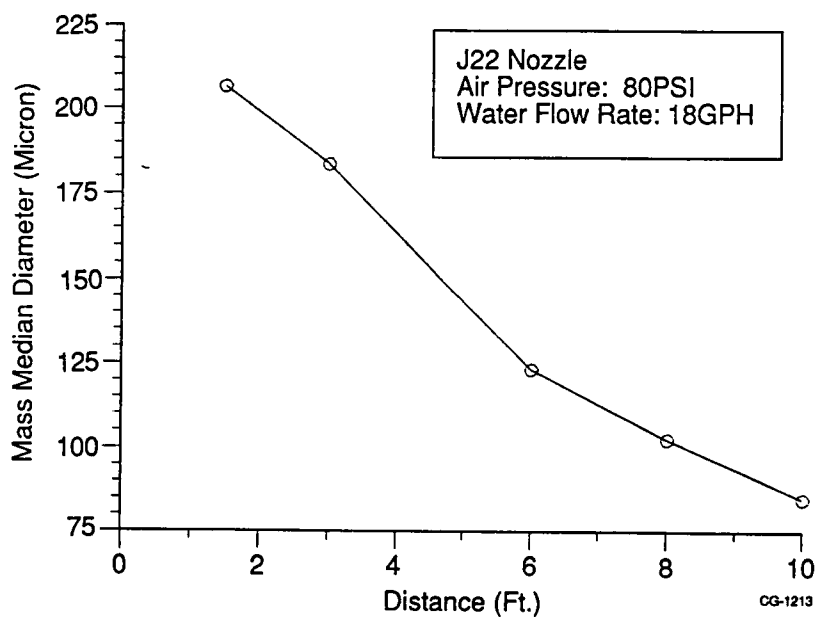


Figure 35. Change in Mass-Median Diameter with Axial Distance from the Nozzle

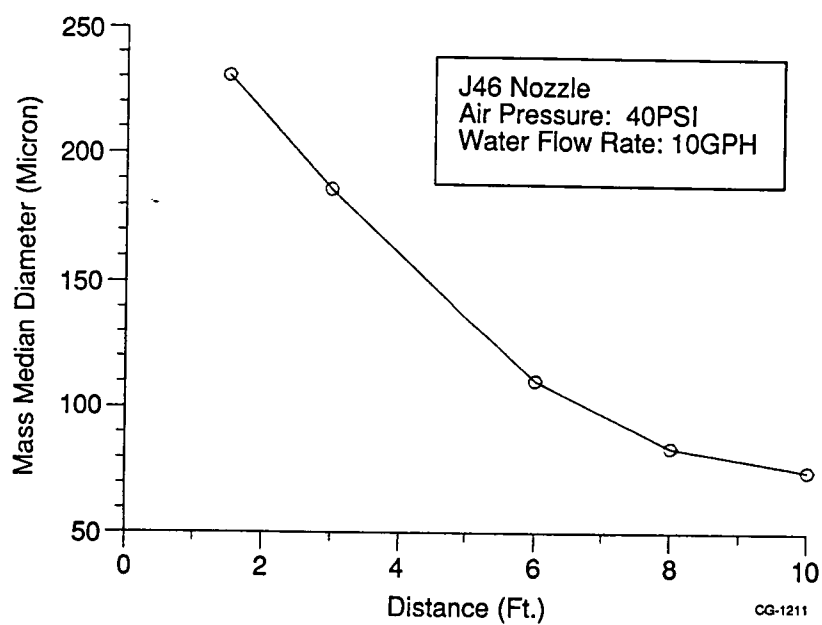
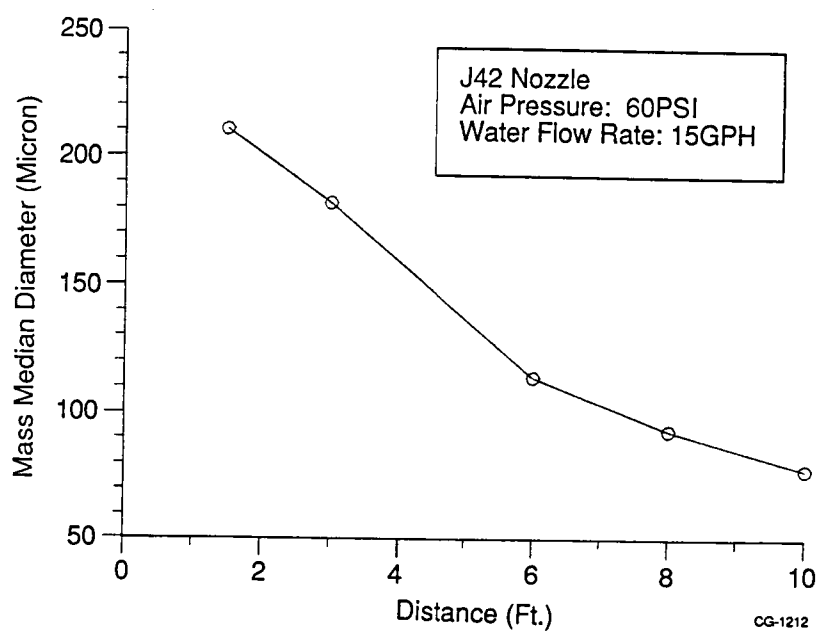


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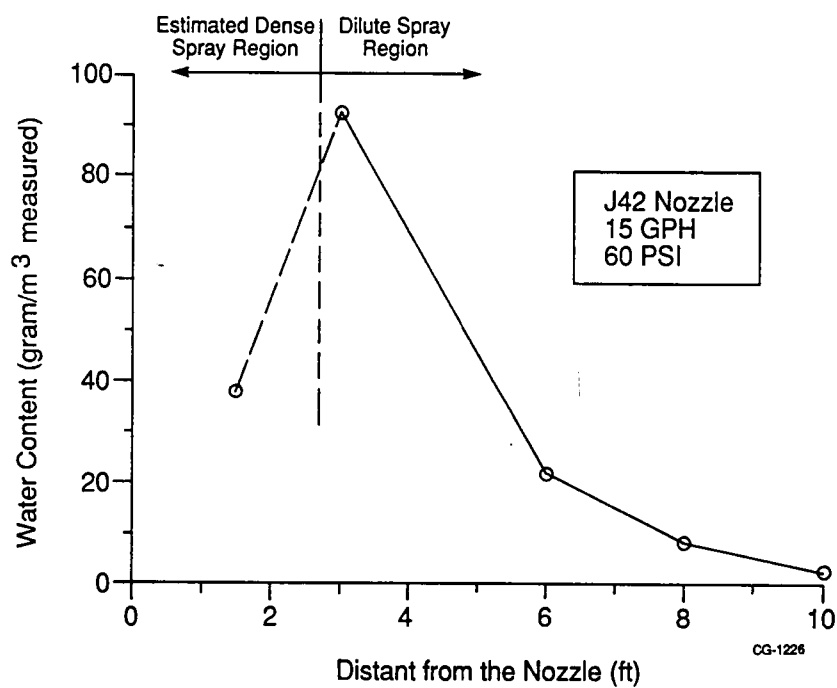
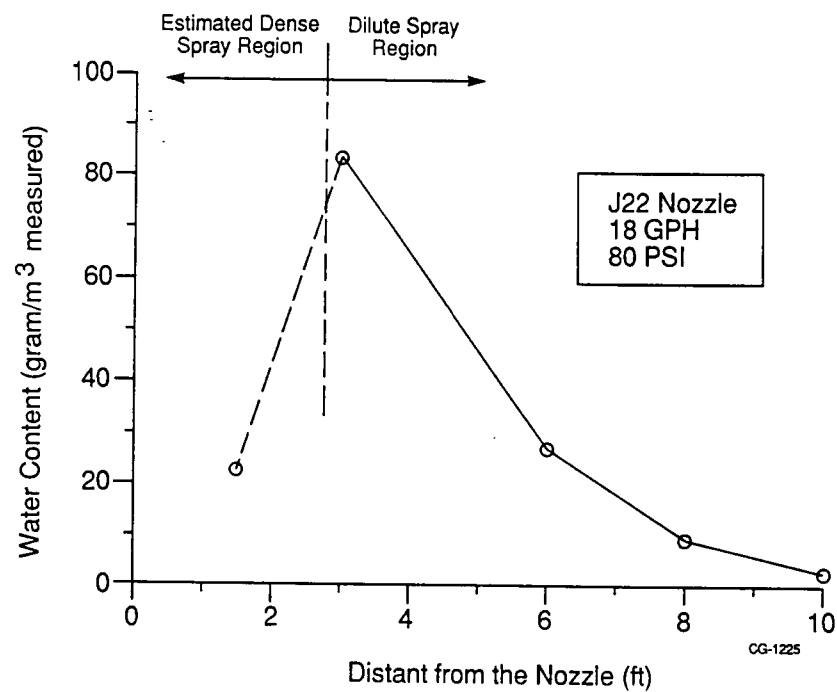


Figure 36. Axial Distribution of Liquid Water Content Distribution on Centerline of Nozzle

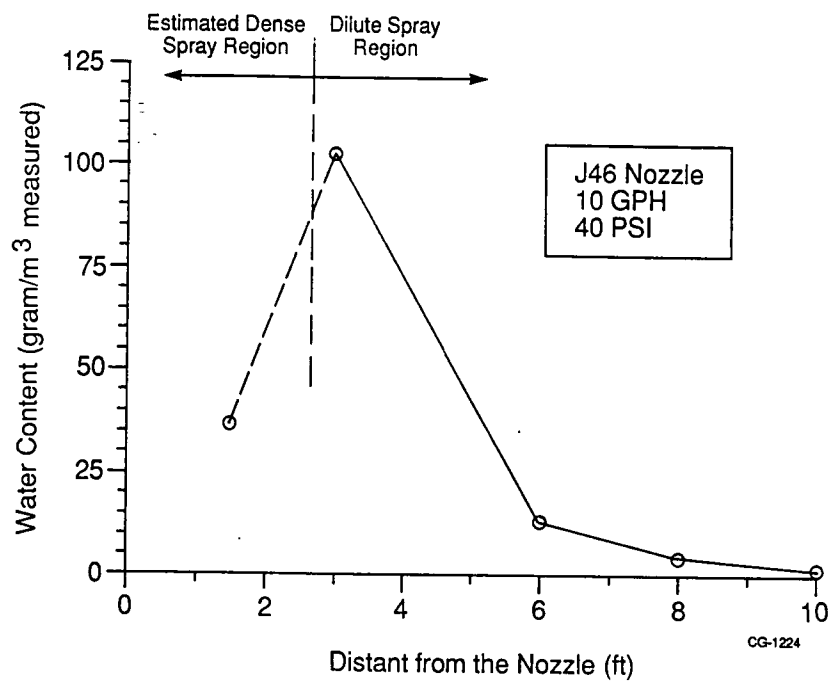


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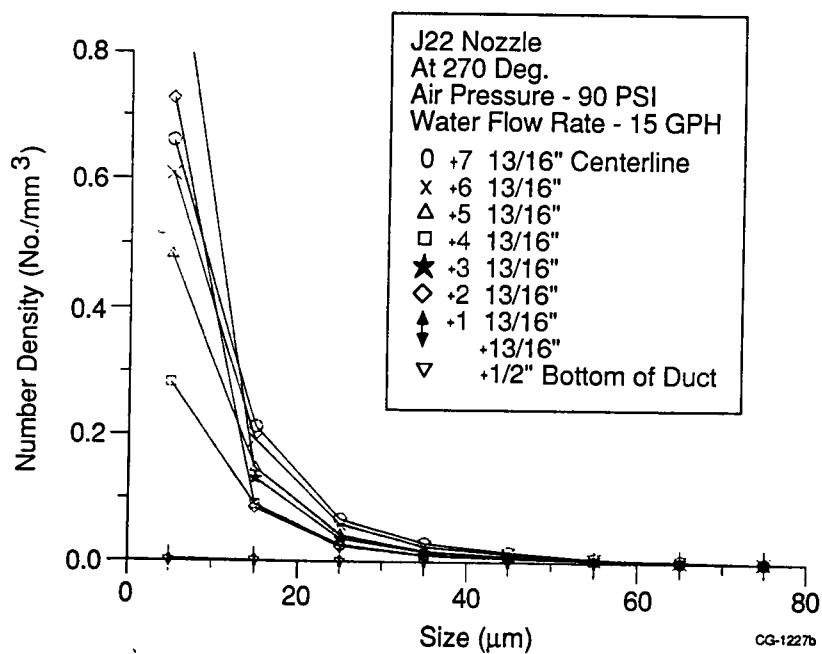
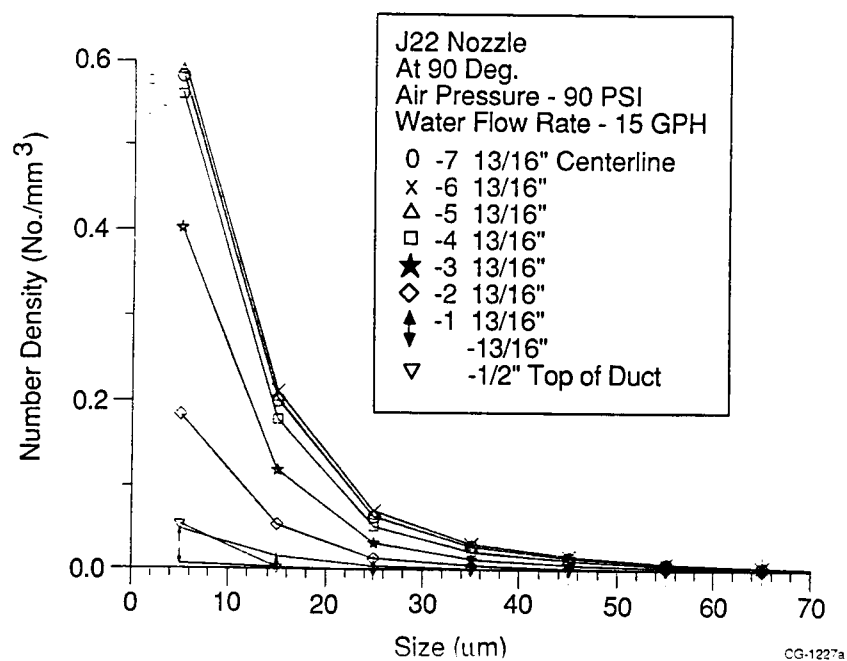


Figure 37. Distributions of Measured Particle Number Densities Versus Particle Sizes as a Function of Radial Position in the Hot Gas Duct; 3' from Nozzle

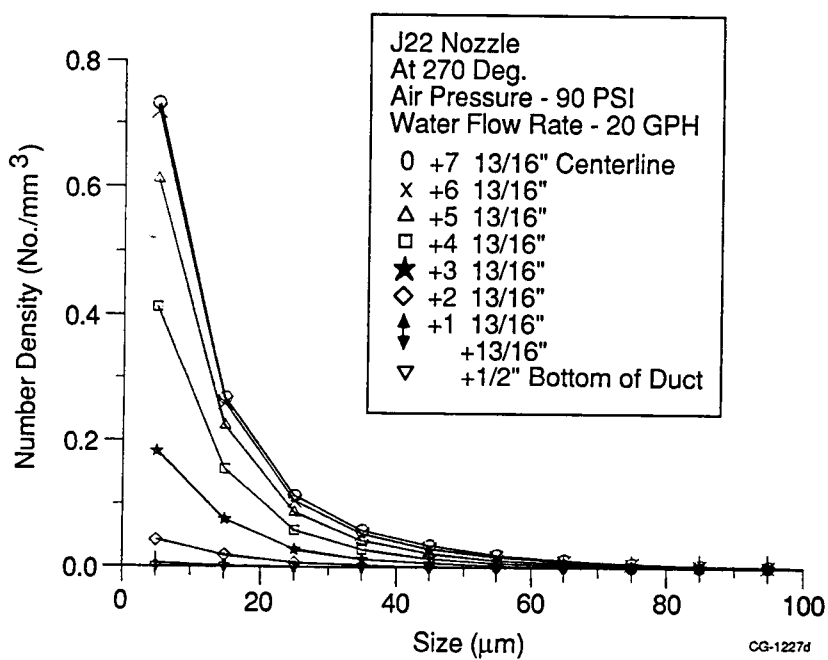
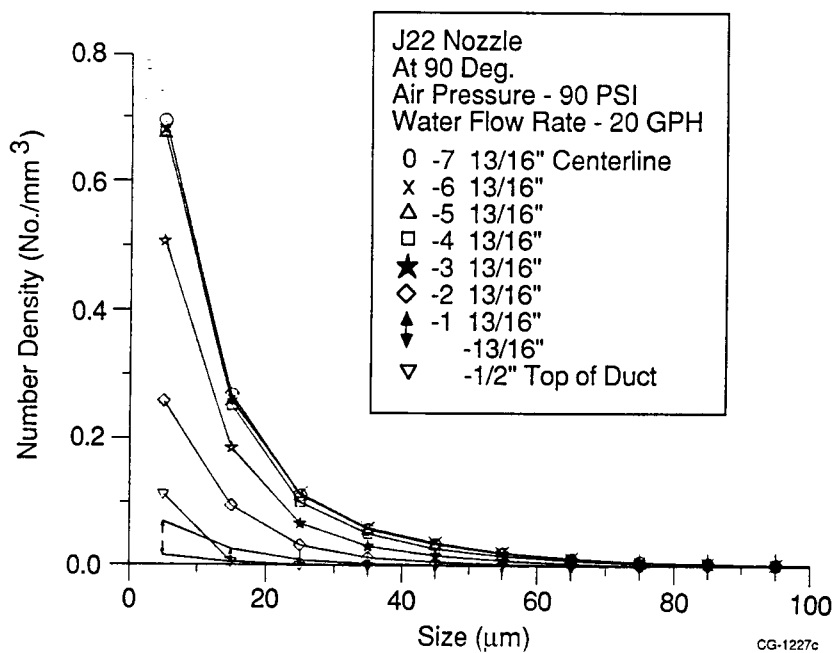


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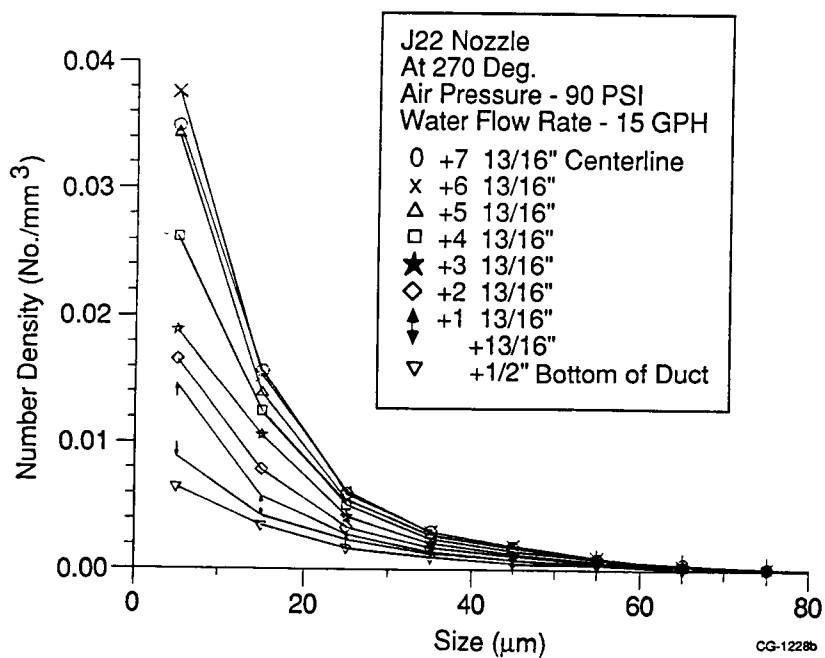
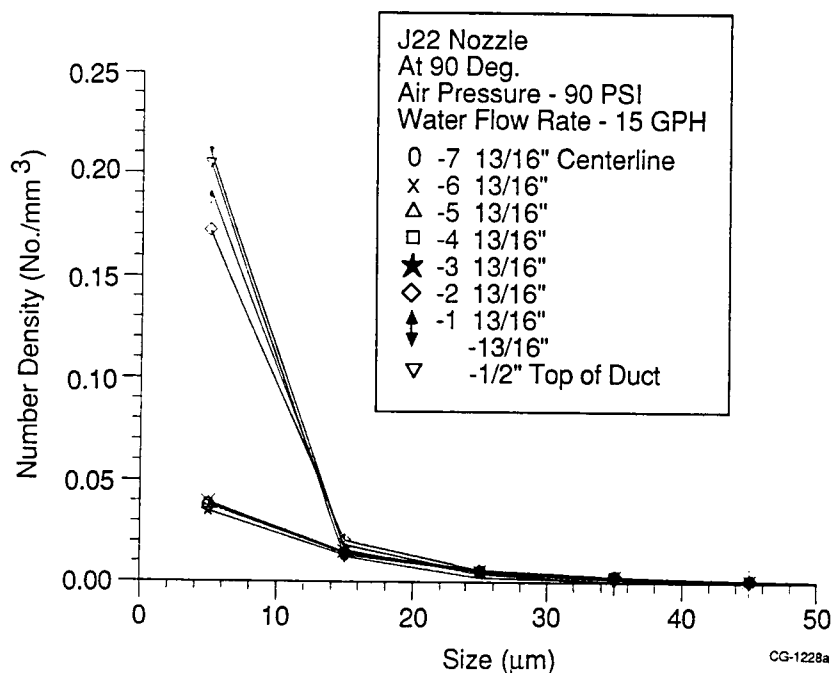


Figure 38. Distributions of Measured Particle Number Densities Versus Particle Sizes as a Function of Radial Position in the Hot Gas Duct; 7' from Nozzle

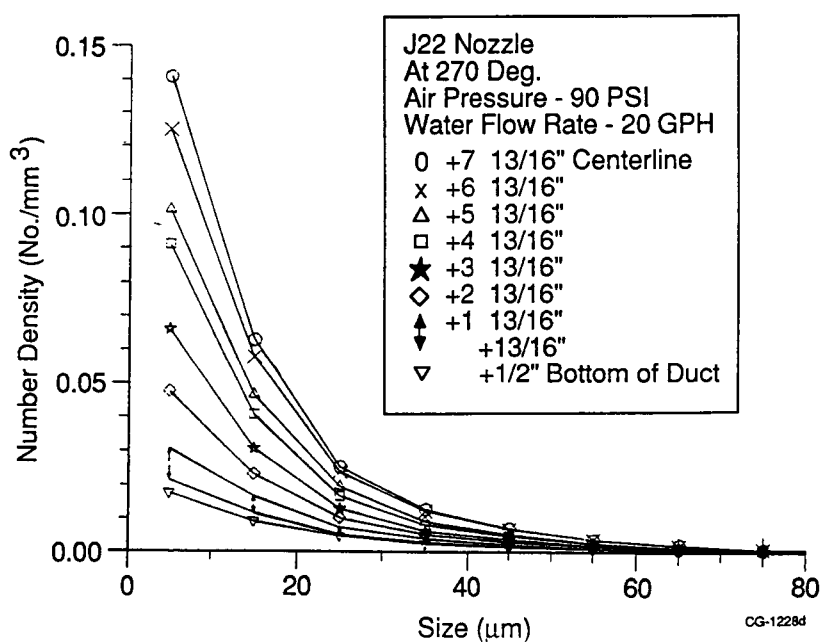
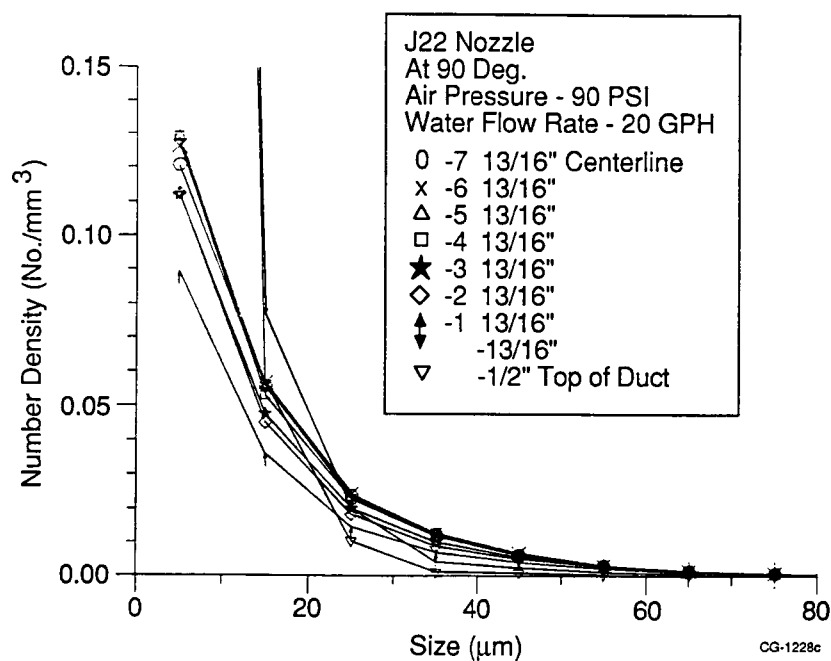


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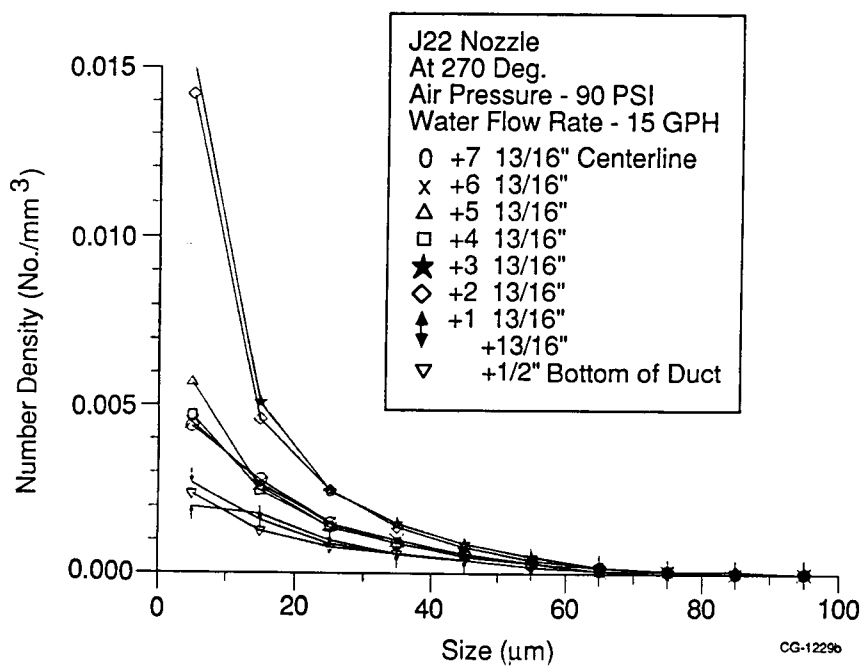
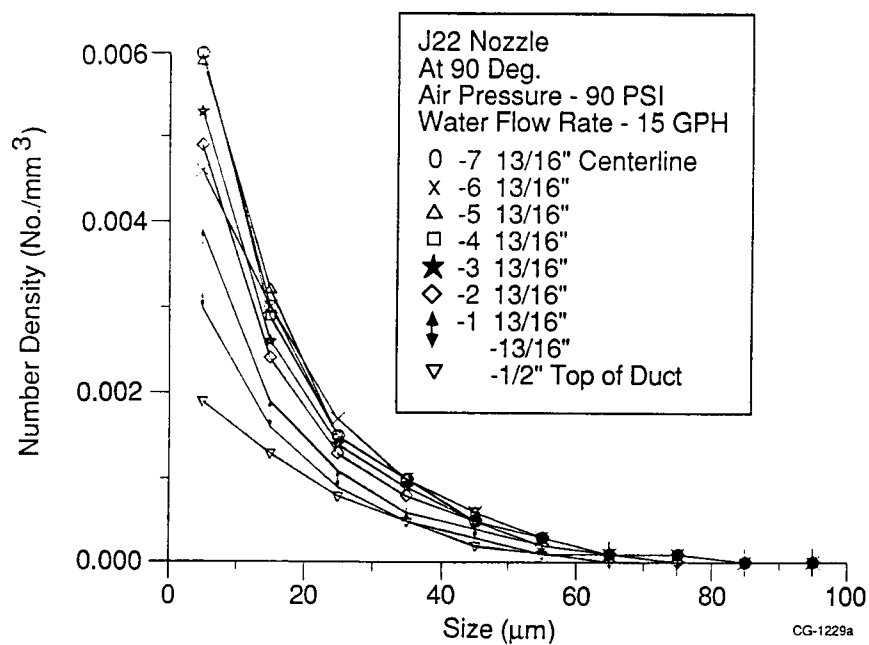


Figure 39. Distributions of Measured Particle Number Densities Versus Particle Sizes as a Function of Radial Position in the Hot Gas Duct; 11' from Nozzle

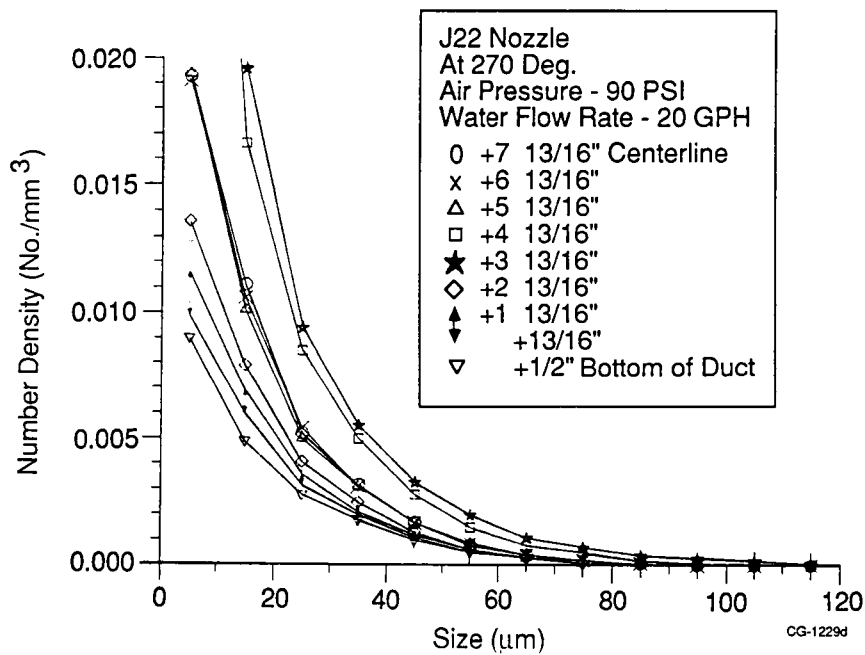
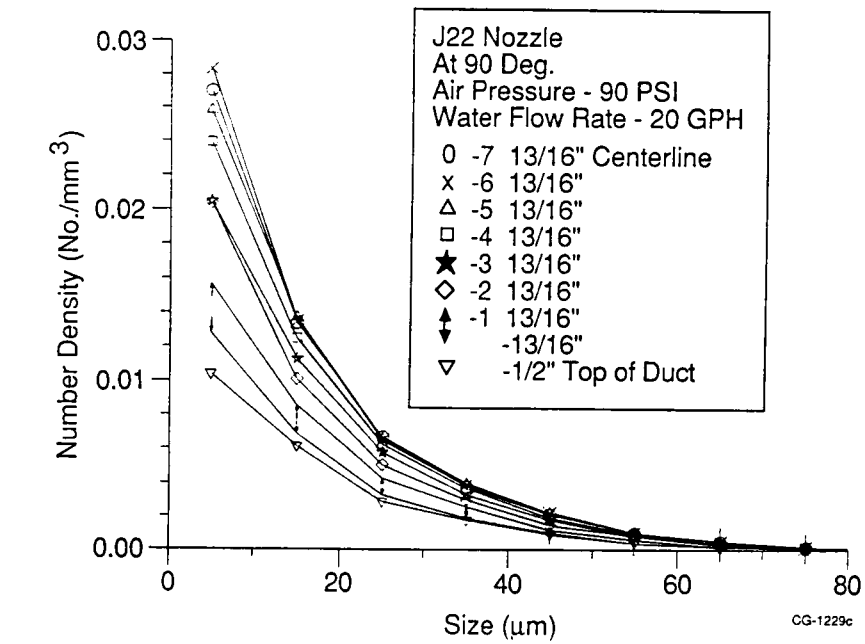


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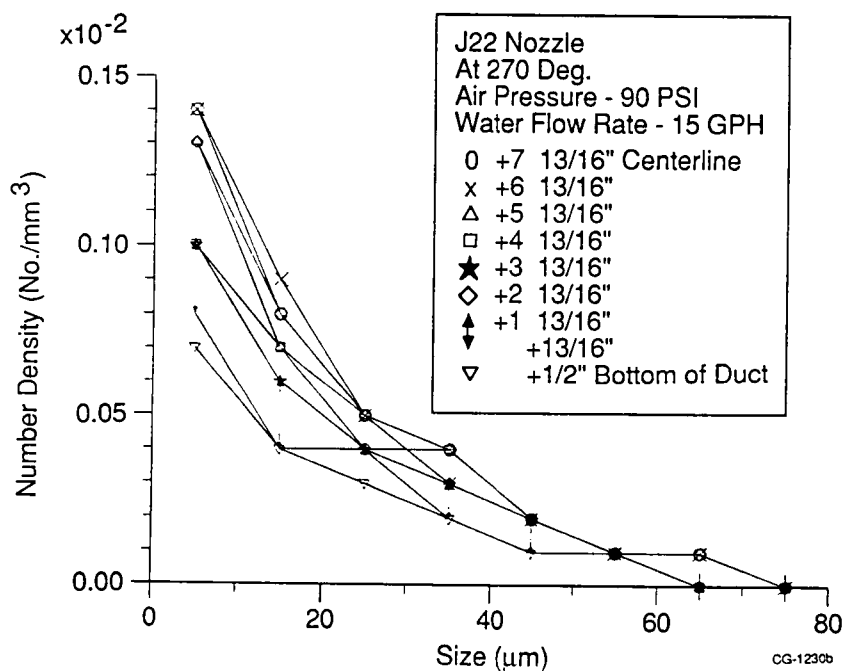
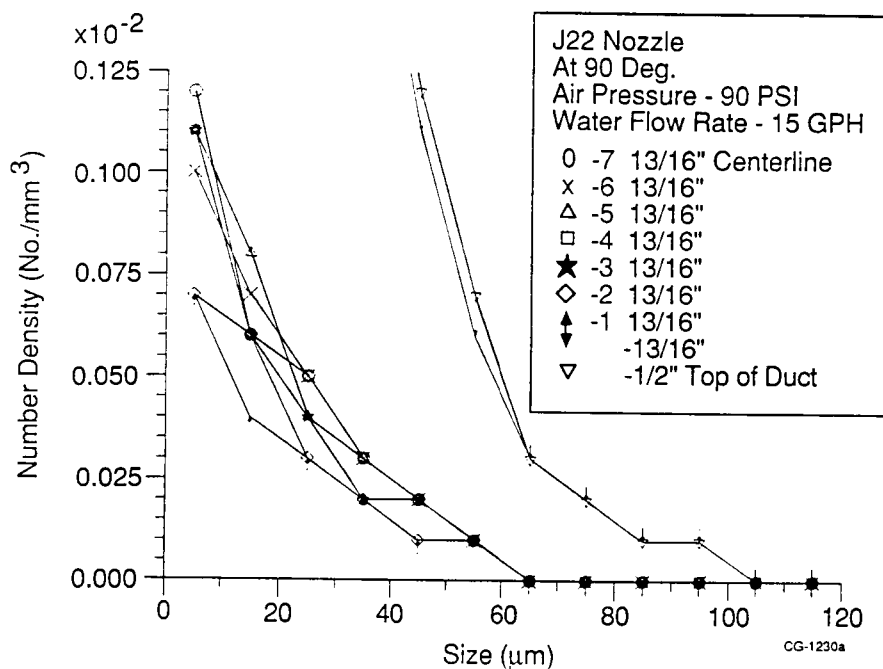


Figure 40. Distributions of Measured Particle Number Densities Versus Particle Sizes as a Function of Radial Position in the Hot Gas Duct; 17' from Nozzle

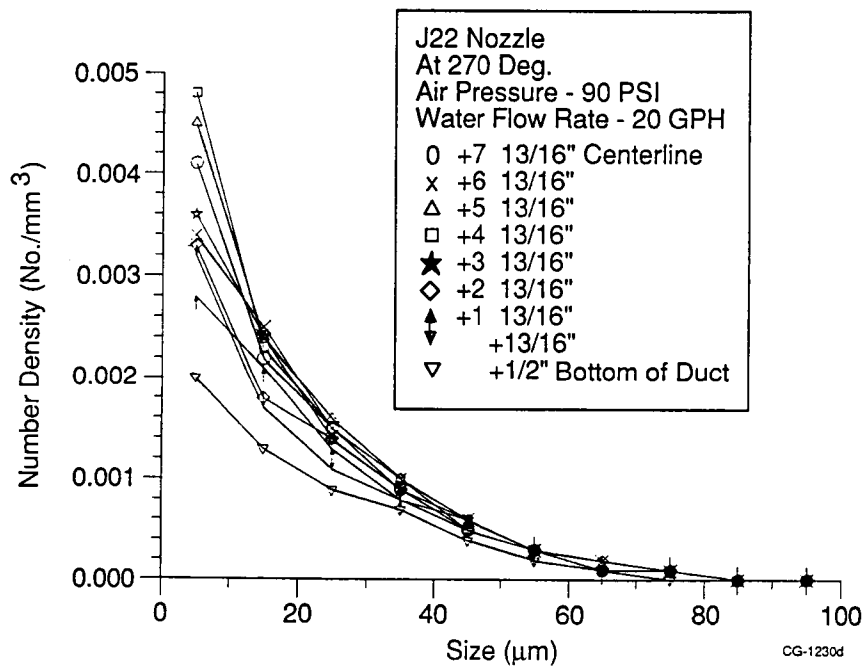
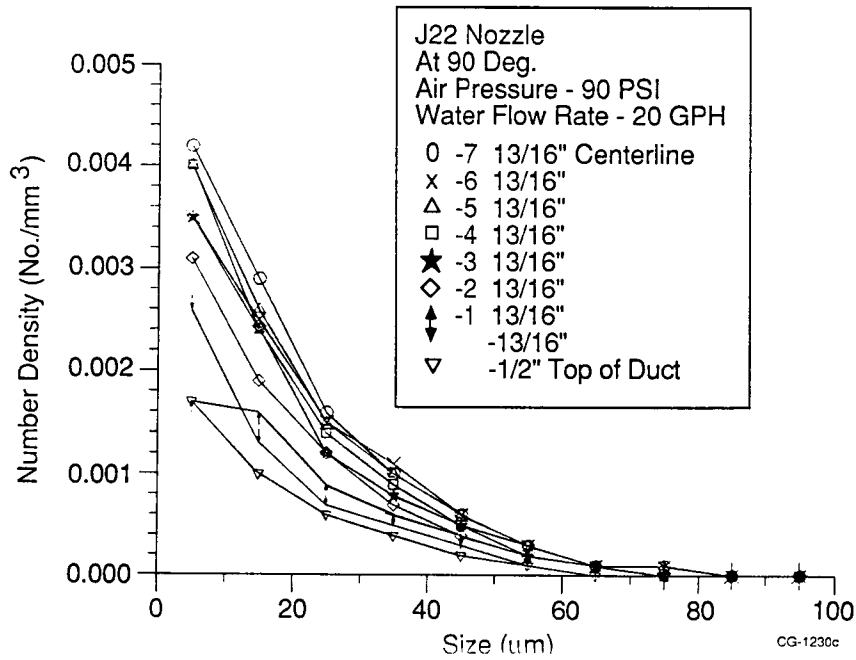


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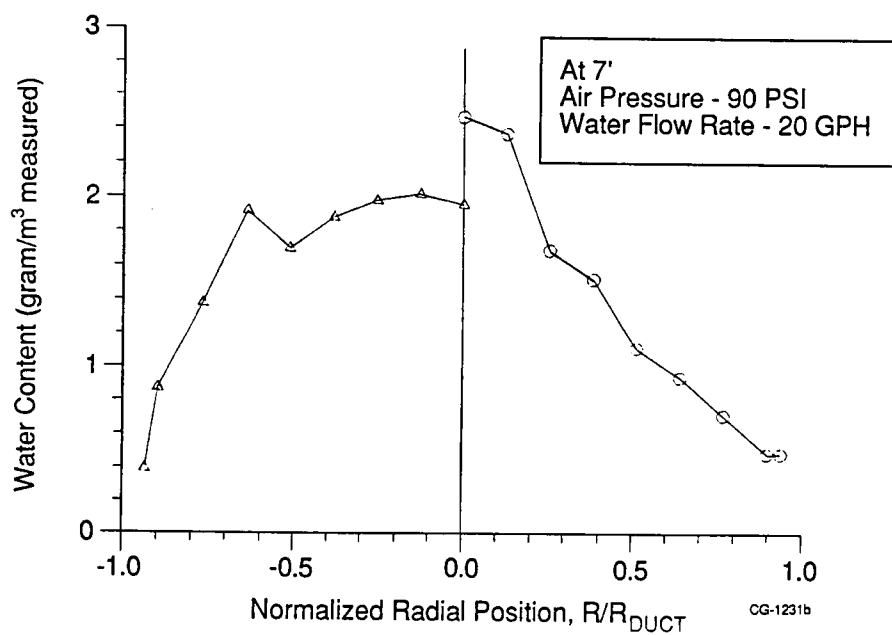
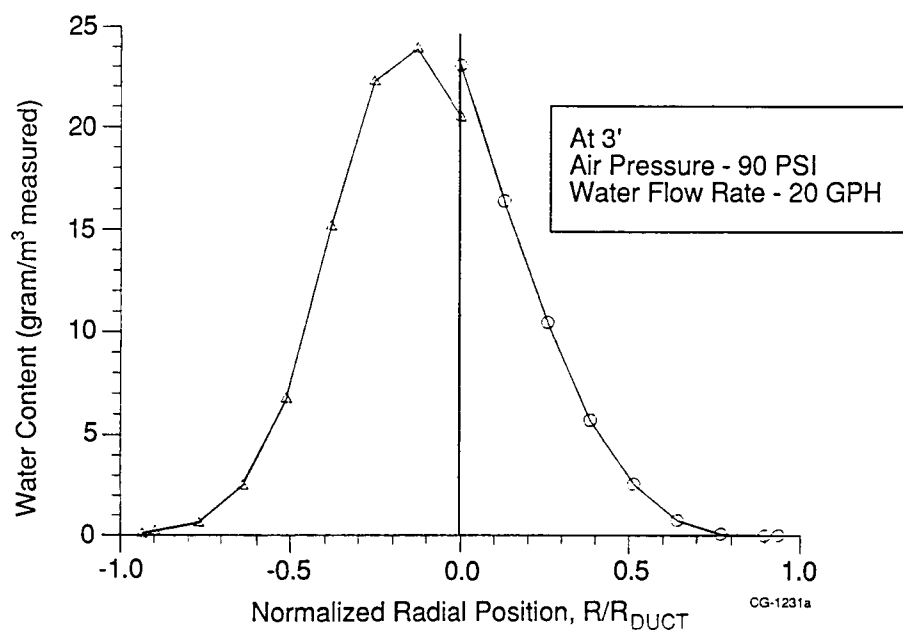


Figure 41. Radial Distribution of Spray Liquid Water Content for J22 Nozzle as a Function of Axial Distance in the Hot Gas Duct; 20 GPH Flow Rate

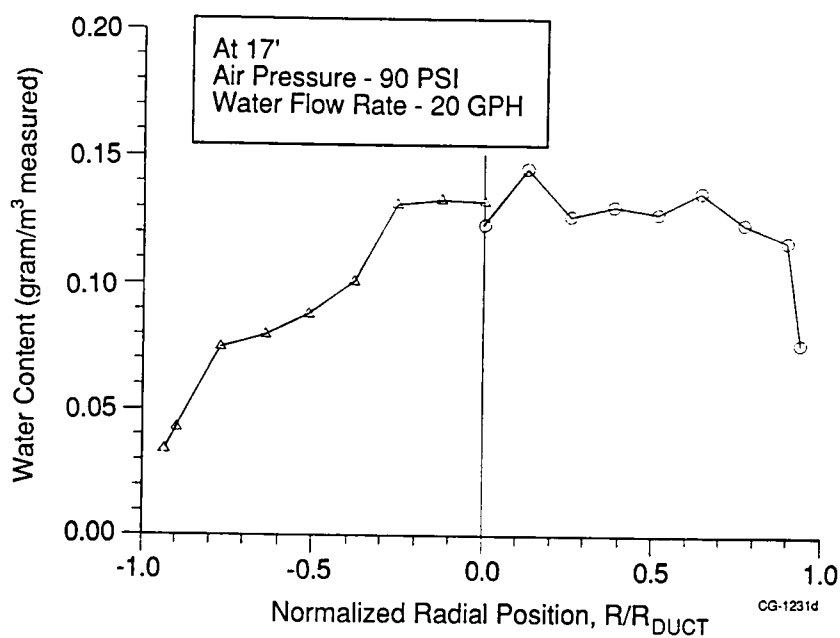
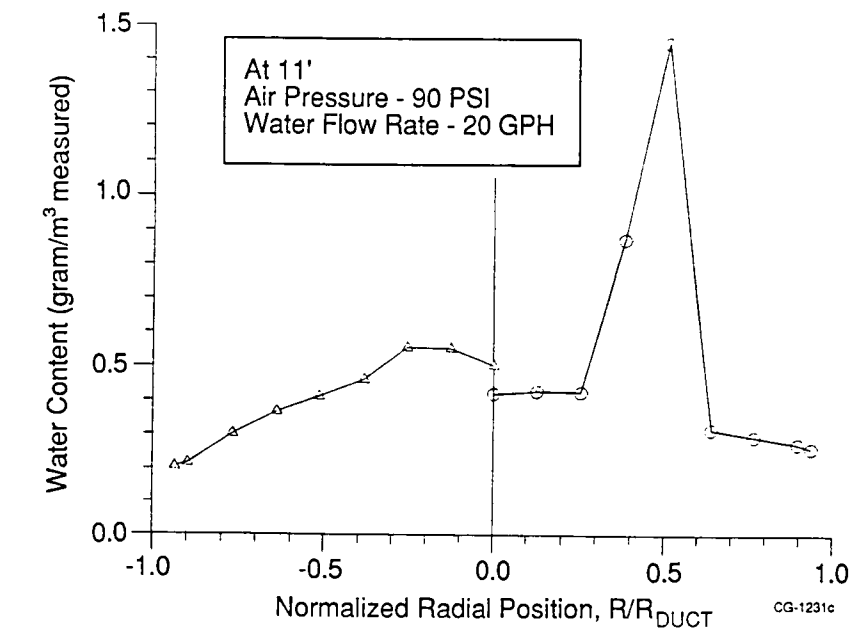


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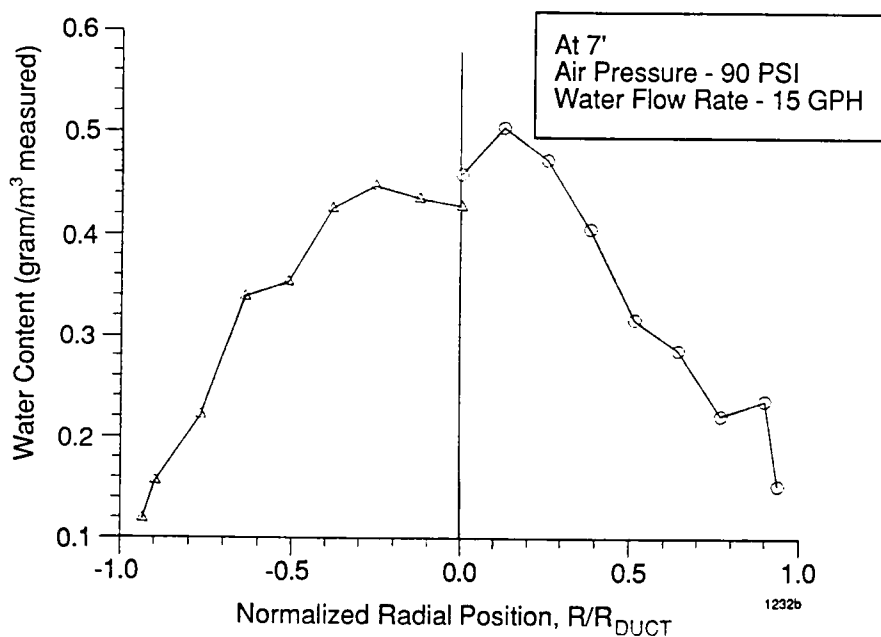
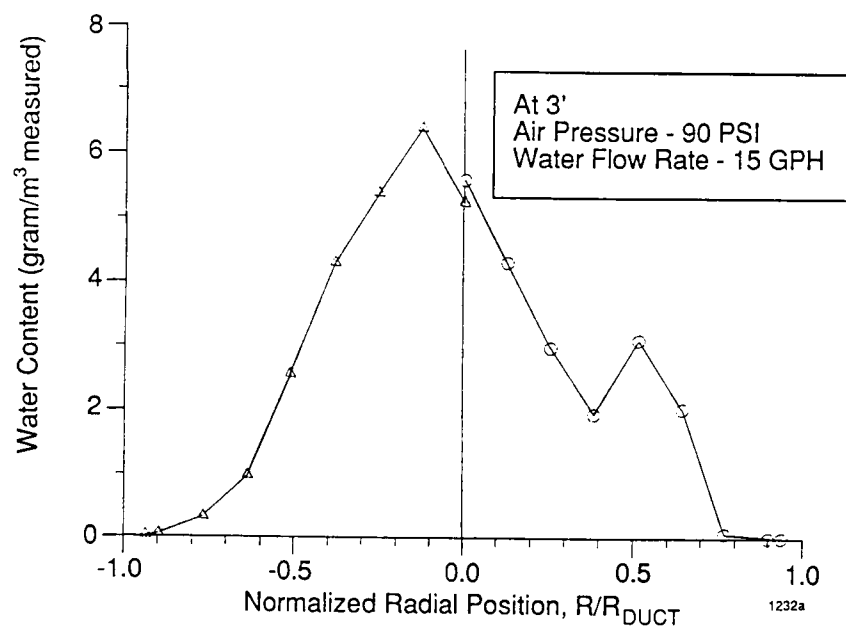


Figure 42. Radial Distribution of Spray Liquid Water Content for J22 Nozzle as a Function of Axial Distance in the Hot Gas Duct; 15 GPH Flow Rate

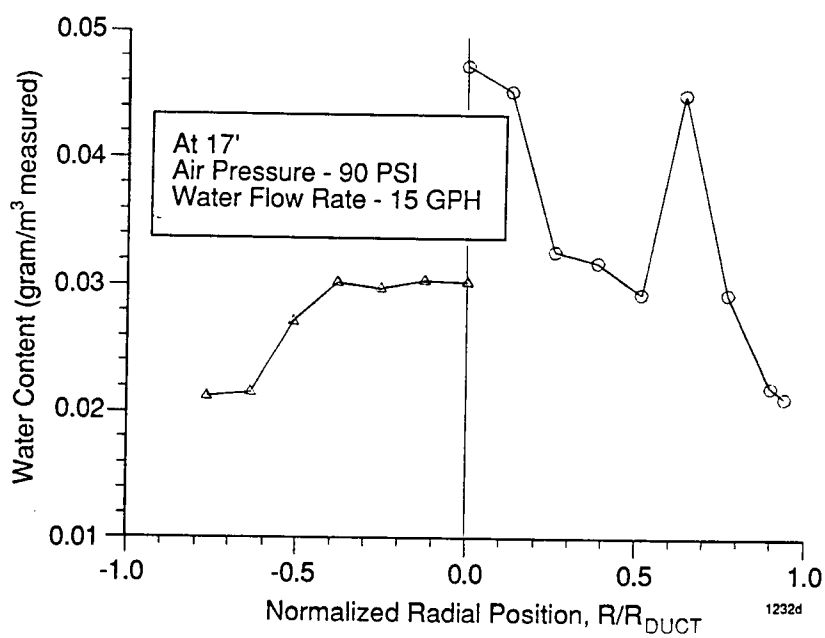
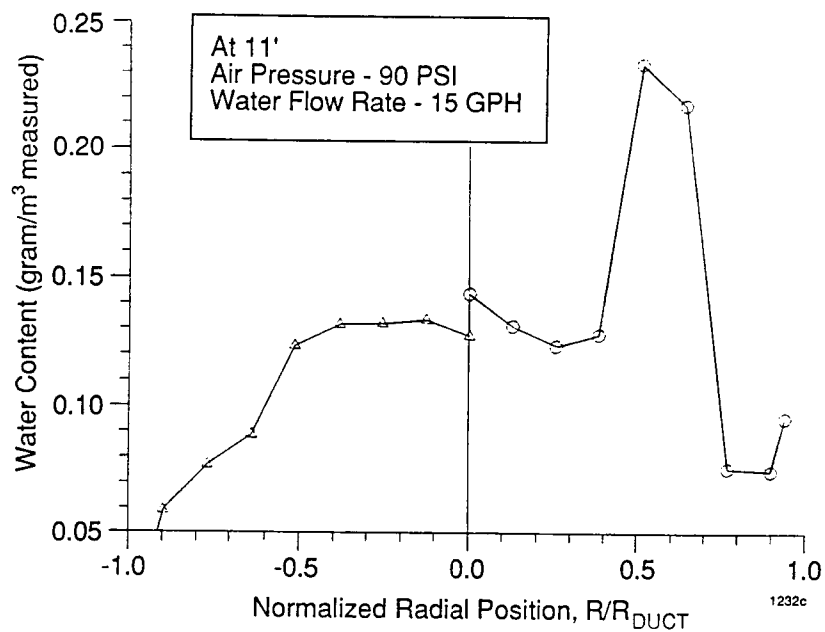


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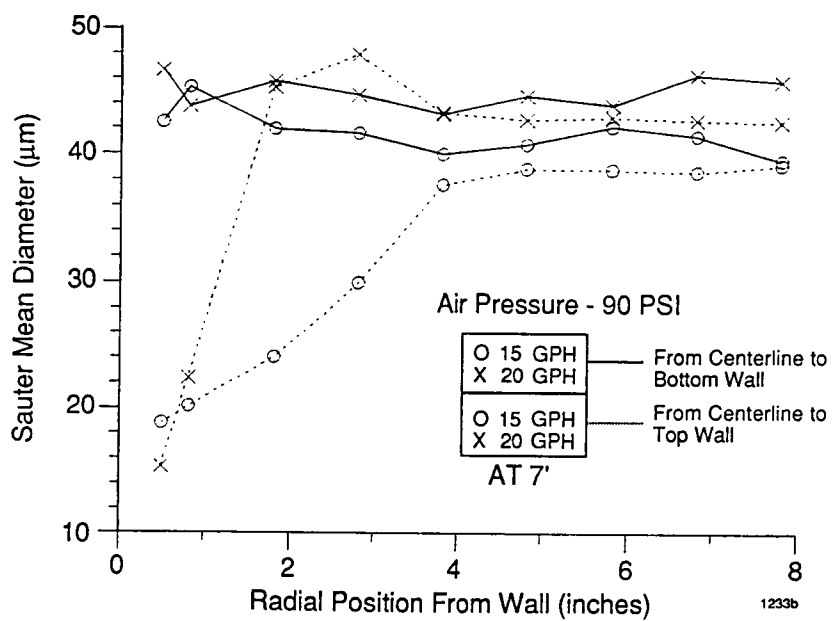
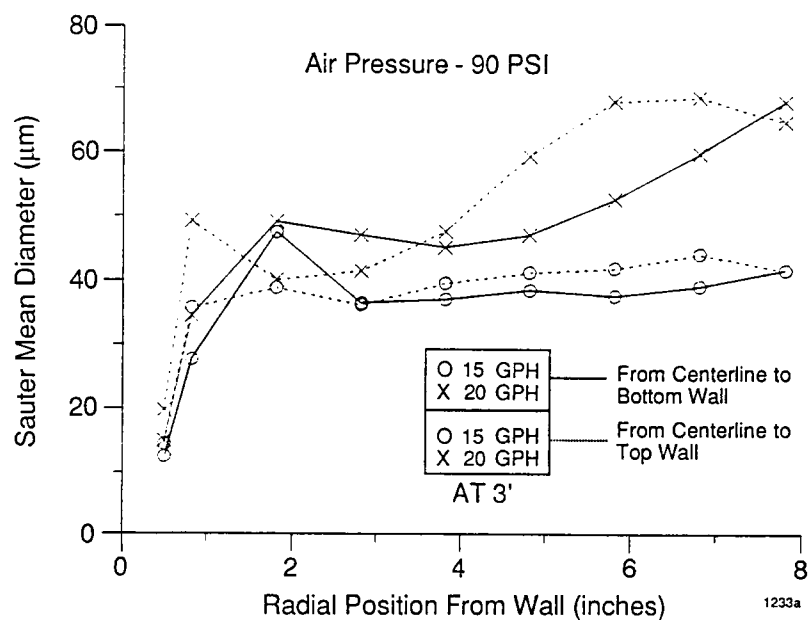


Figure 43. Radial Distributions of Sauter-Mean Diameter for J22 Nozzle as a Function of Axial Distance in the Hot Gas Duct Tests for Two Nozzle Flow Rates

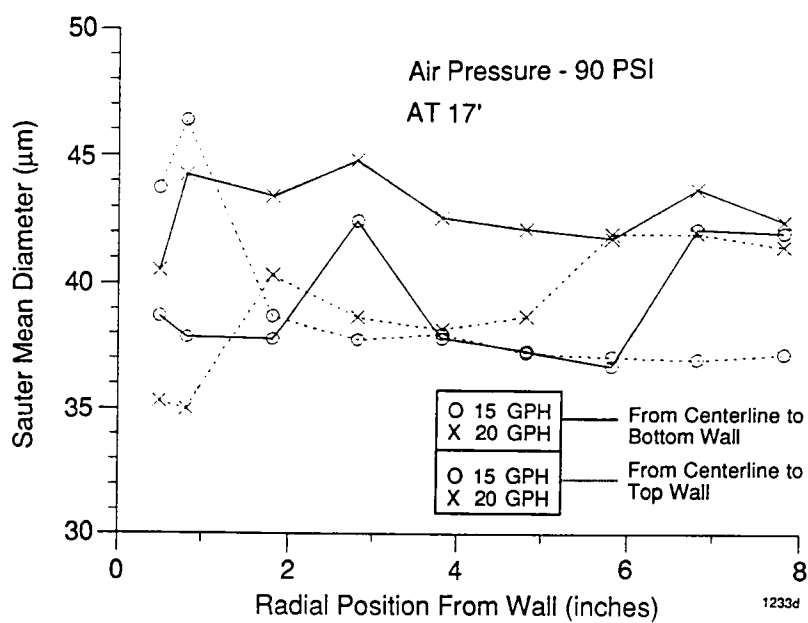
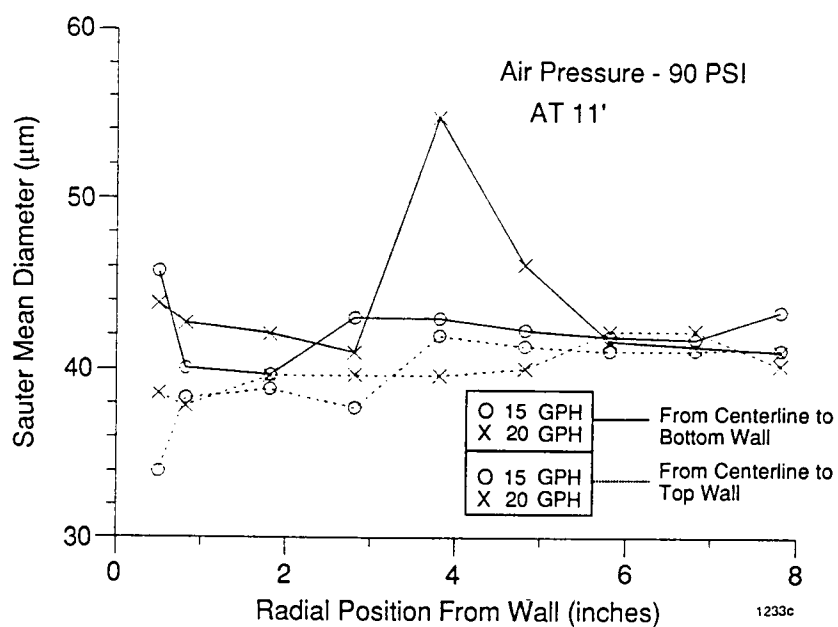


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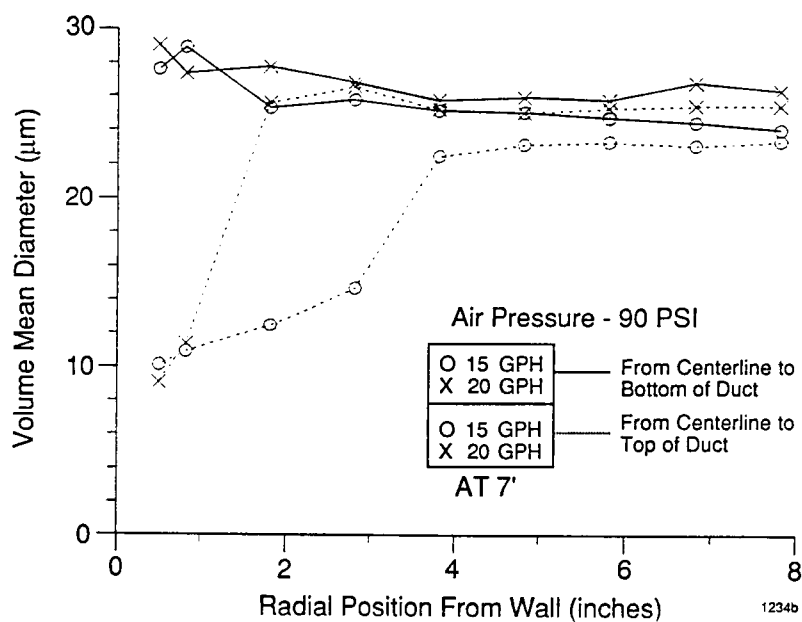
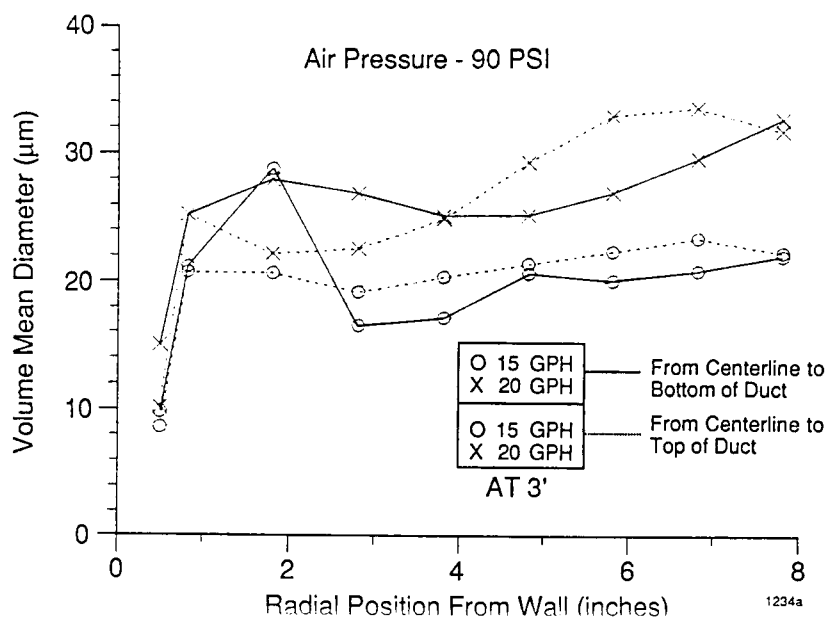


Figure 44. Radial Distributions of Volume-Mean Diameter for J22 Nozzle as a Function of Axial Distance in the Hot Gas Duct Tests for Two Nozzle Flow Rates

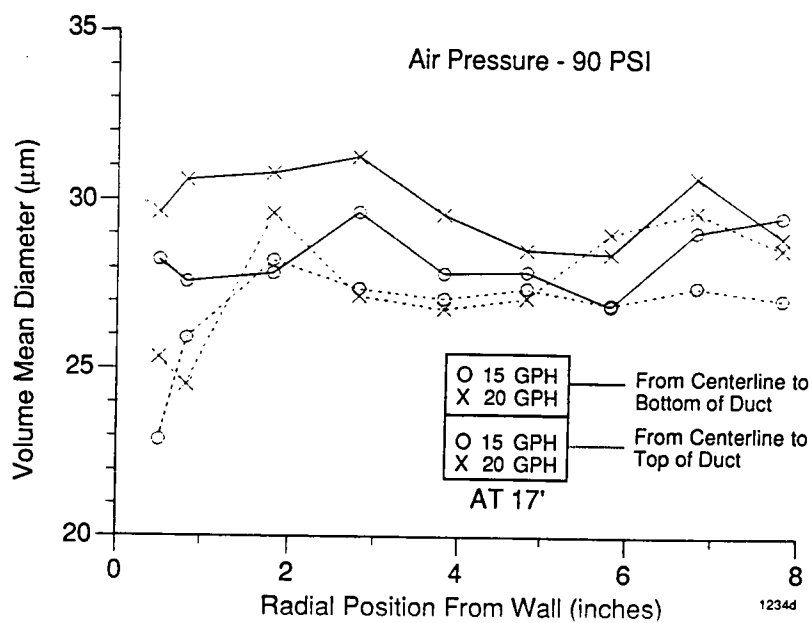
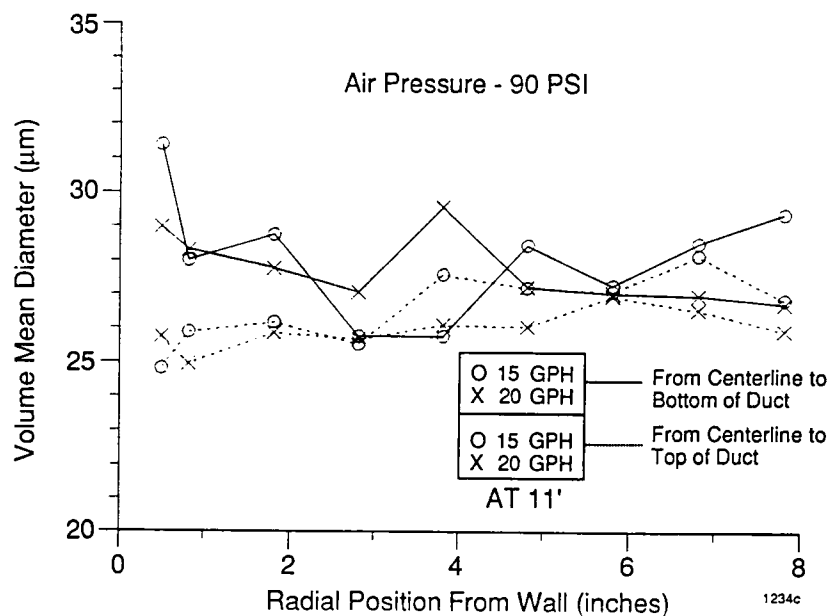


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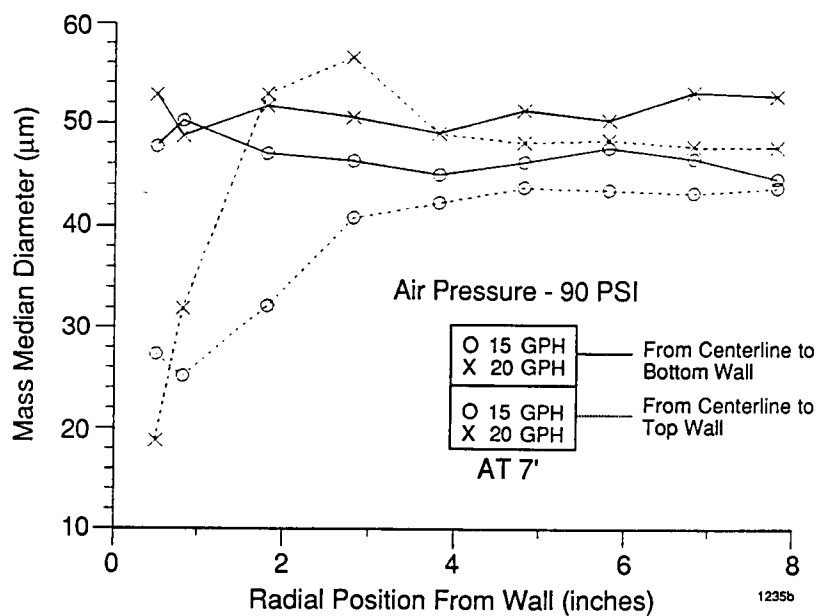
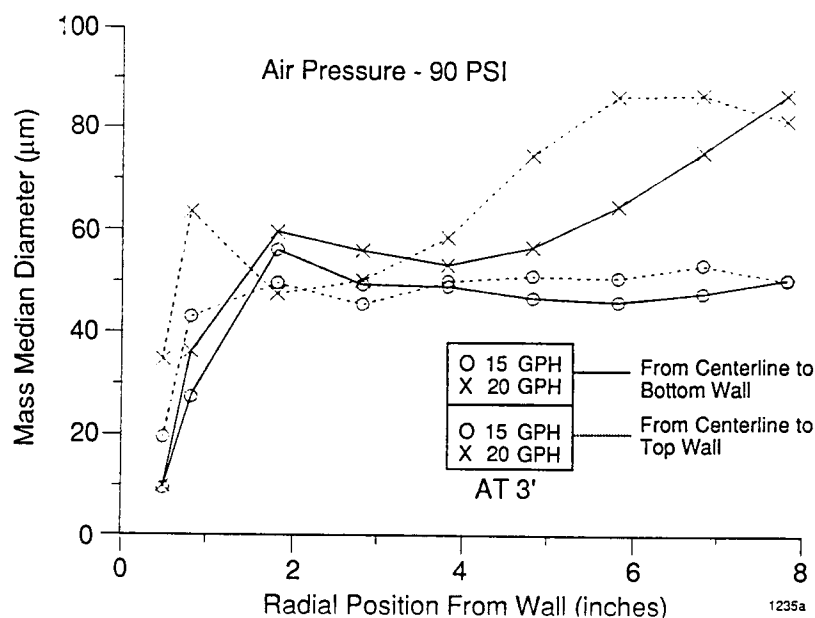


Figure 45. Radial Distributions of Mass-Median Diameter for J22 Nozzle as a Function of Axial Distance in the Hot Gas Duct Tests for Two Nozzle Flow Rates

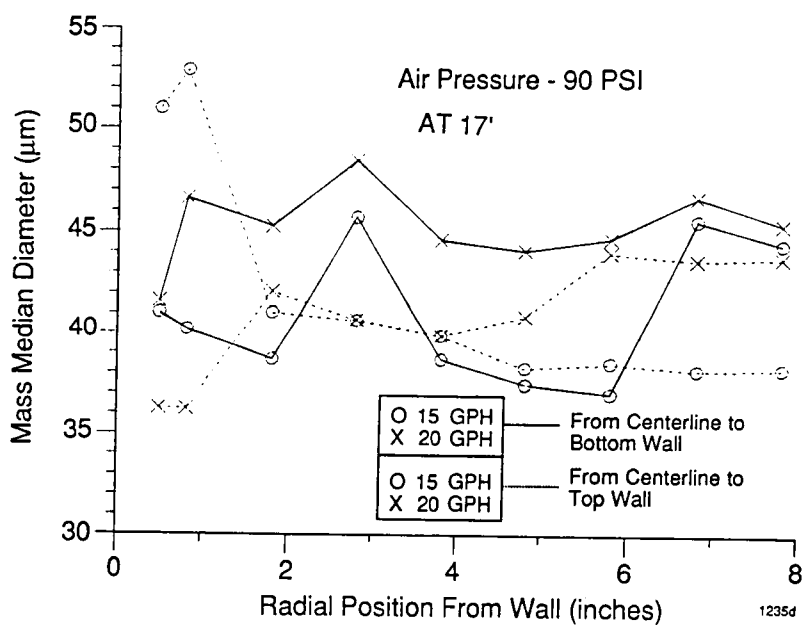
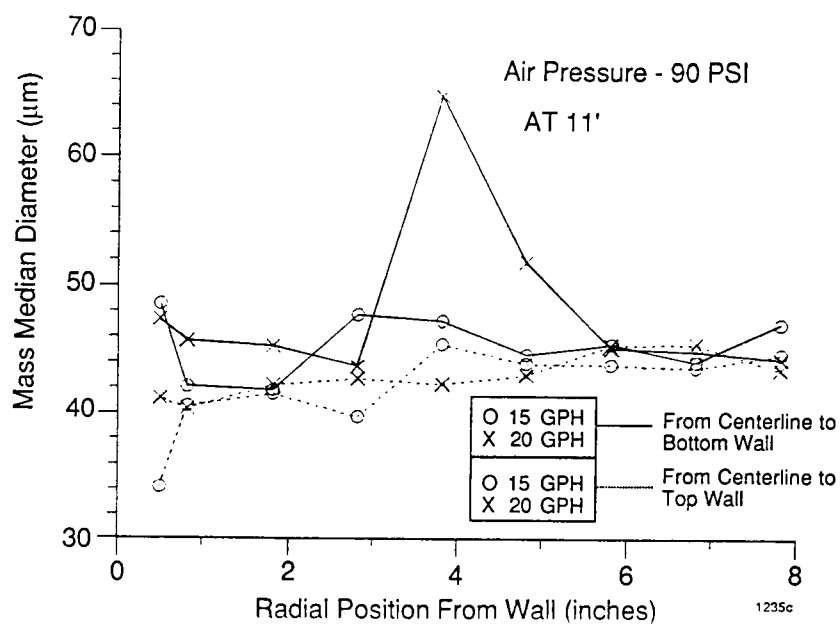


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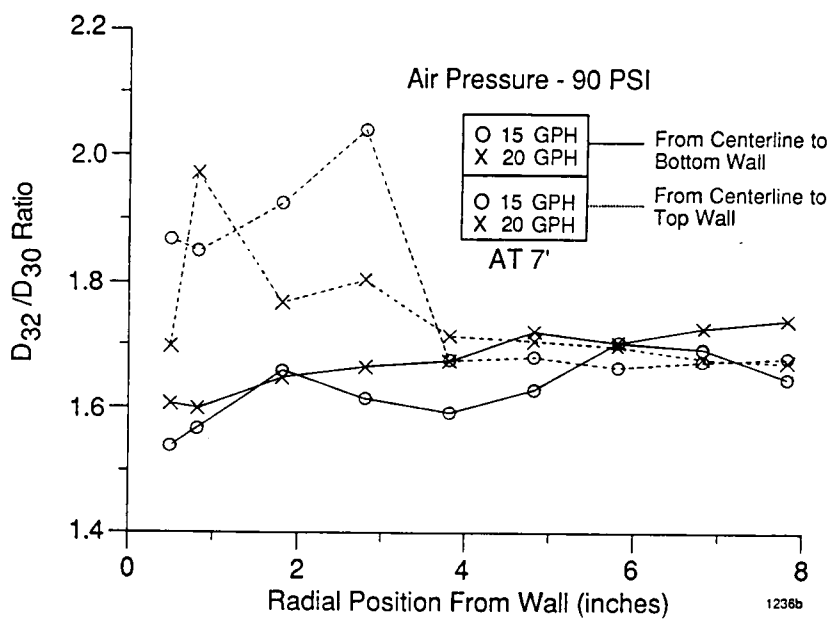
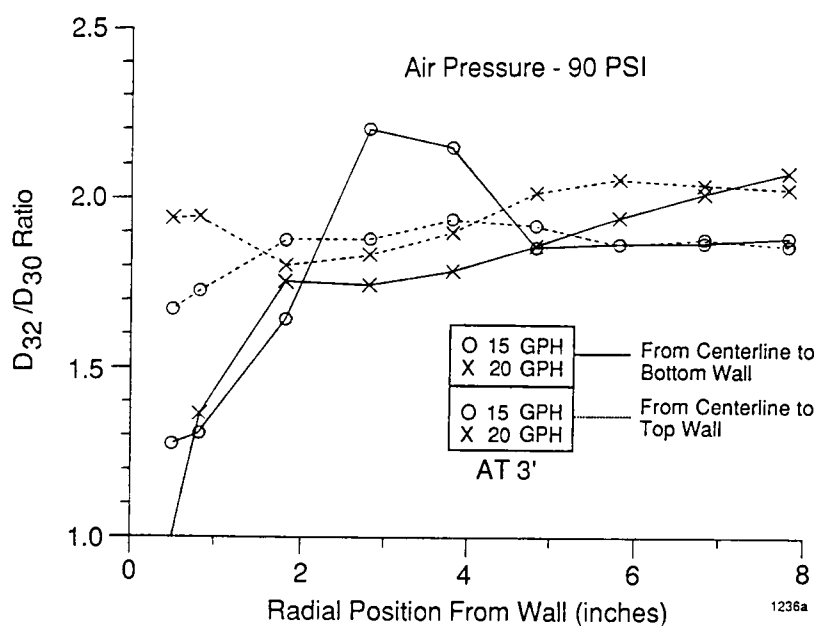


Figure 46. Radial Distributions of the Ratio of Characteristic Diameters for J22 Nozzle as a Function of Axial Distance in the Hot Gas Duct Tests for Two Nozzle Flow Rates

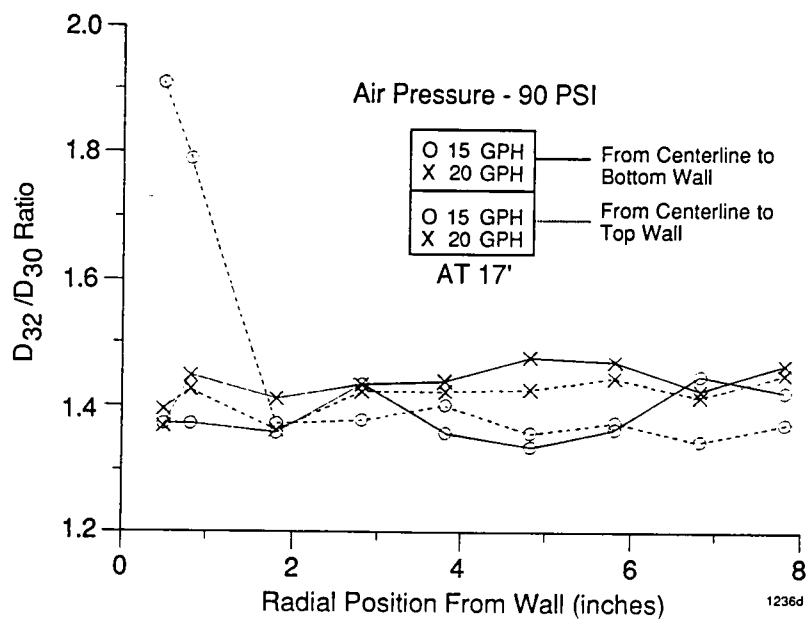
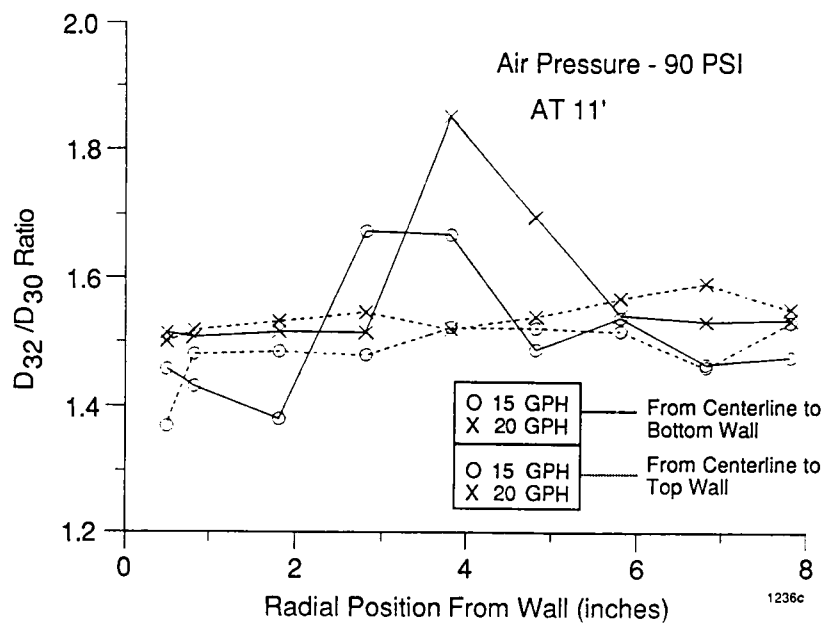


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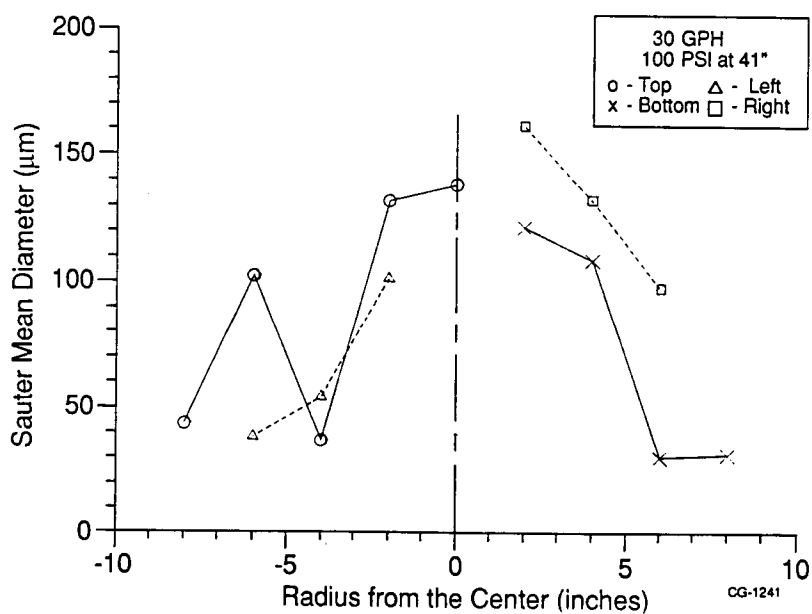
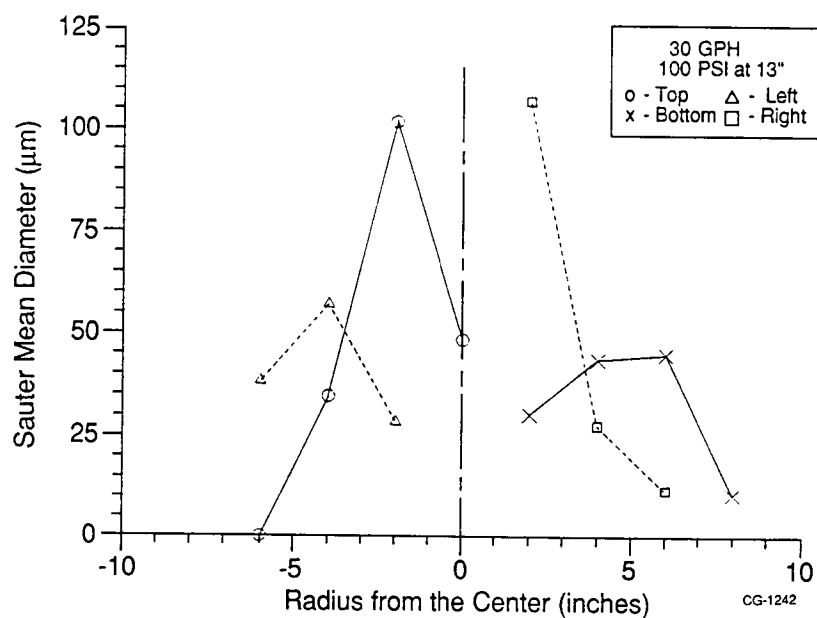


Figure 47. Vertical and Horizontal Distributions of Sauter-Mean Diameter for SONIMISTTM Ultrasonic Nozzle as a Function of Axial Distance

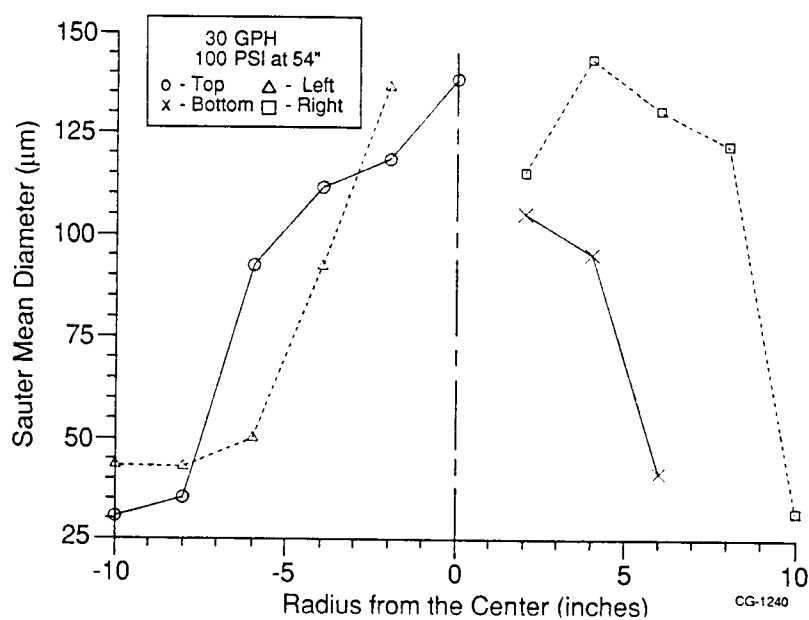


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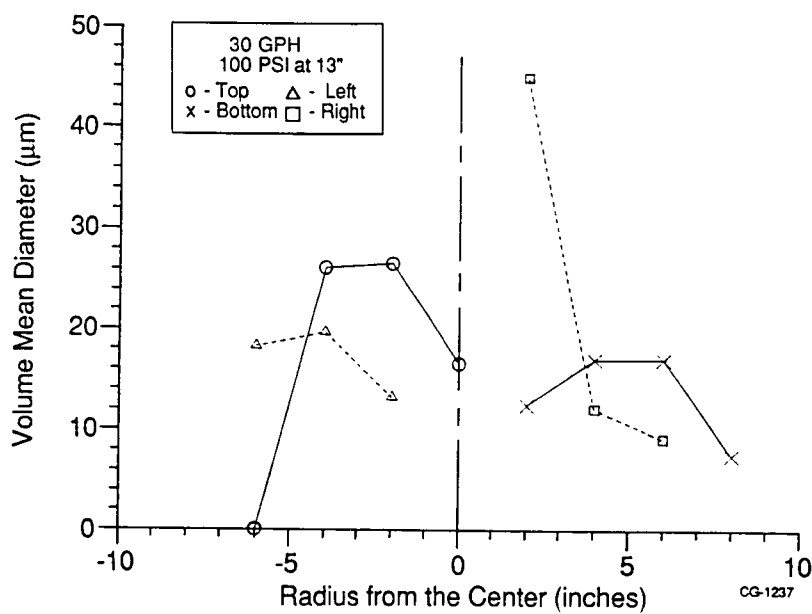


Figure 48. Vertical and Horizontal Distributions of Volume-Mean Diameter for SONIMIST™ Ultrasonic Nozzle as a Function of Axial Distance

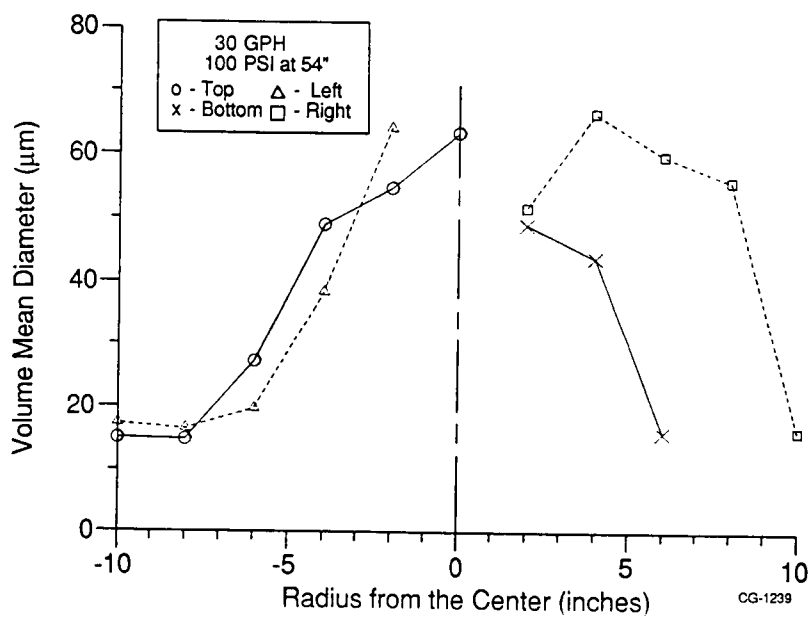
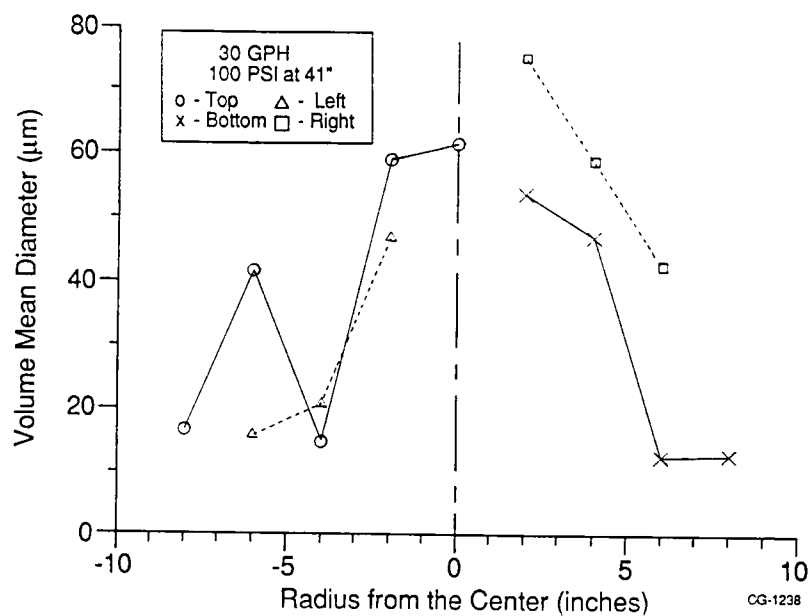


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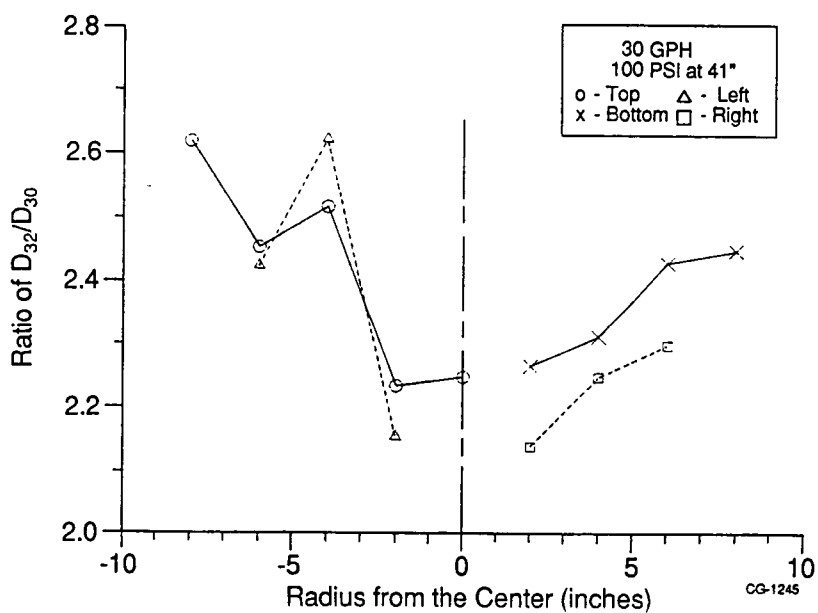
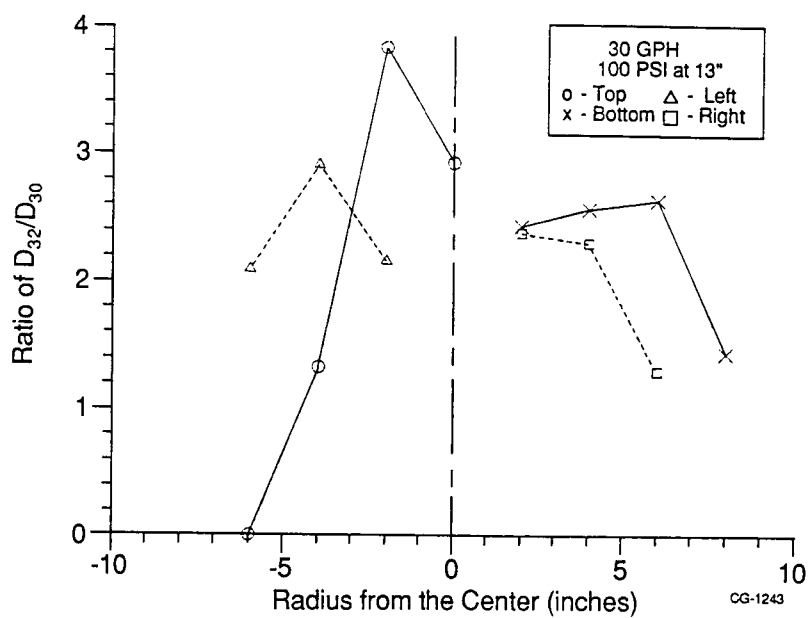


Figure 49. Vertical and Horizontal Distributions of the Ratio of Sauter-Mean Diameter to Volume-Mean Diameter for SONIMISTTM Ultrasonic Nozzle as a Function of Axial Distance

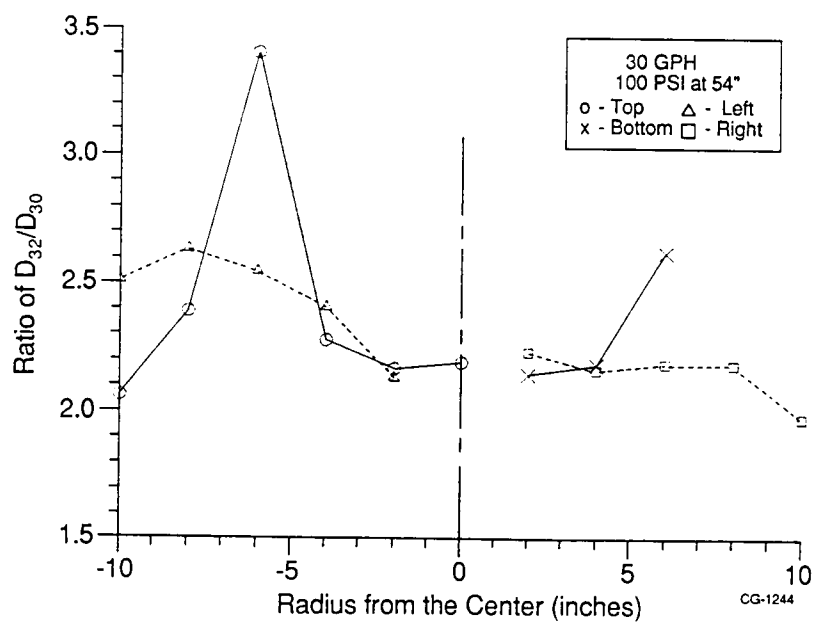


Figure 49. (Continued)

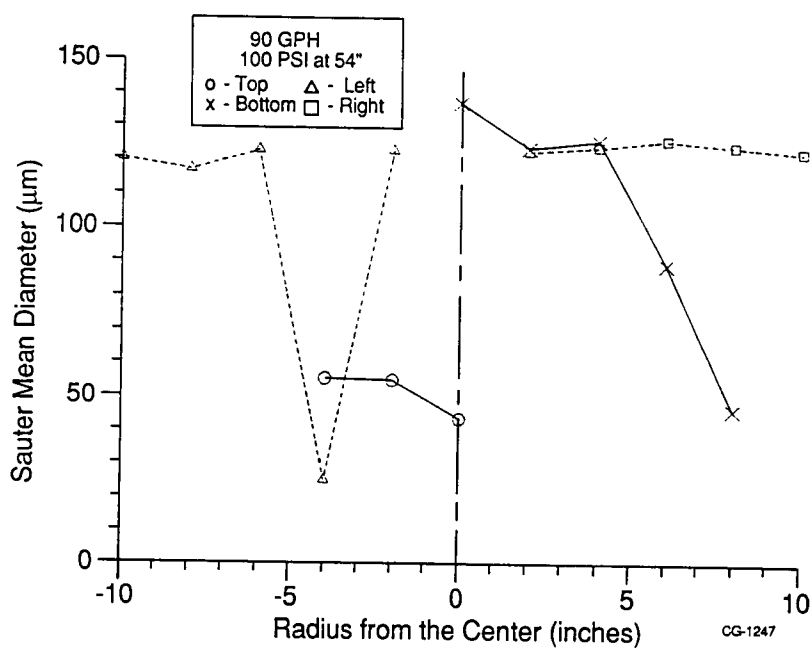
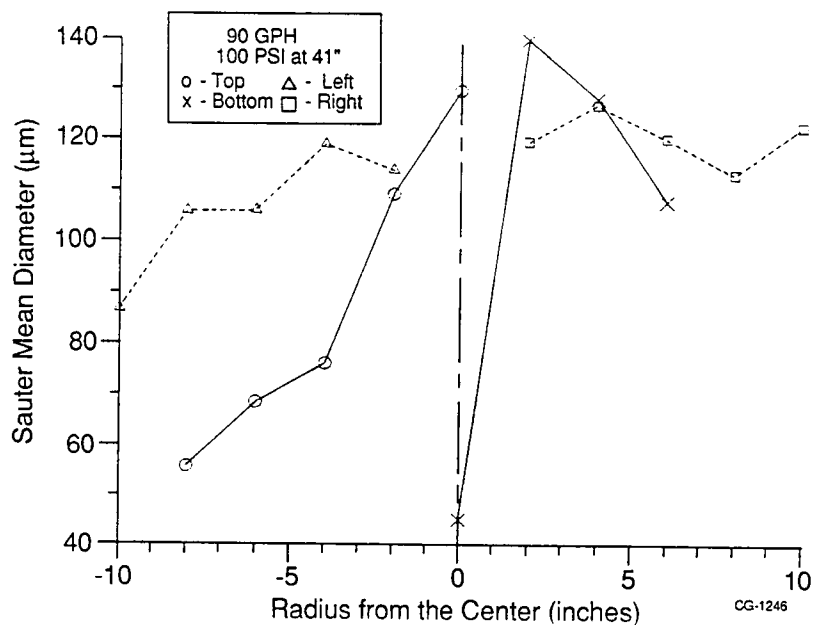


Figure 50. Vertical and Horizontal Distributions of Sauter-Mean Diameter for CasterJetTM Nozzle as a Function of Axial Distance

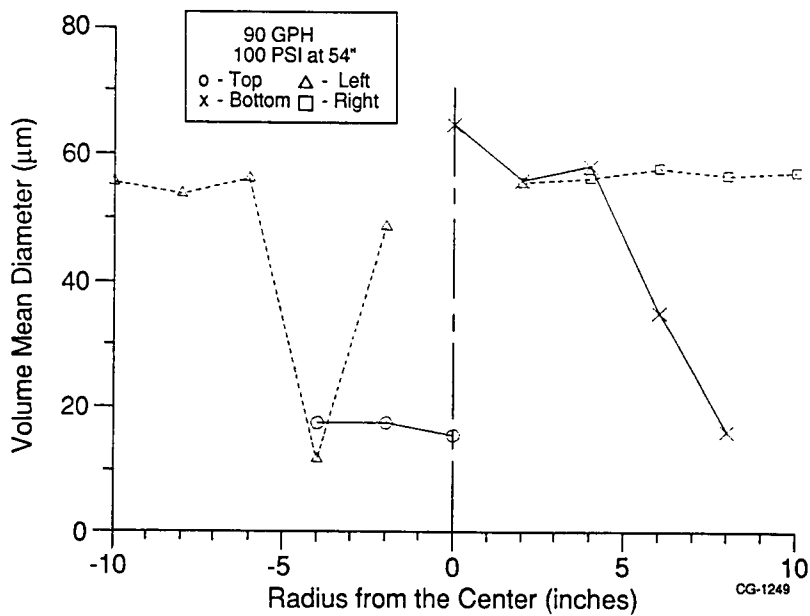
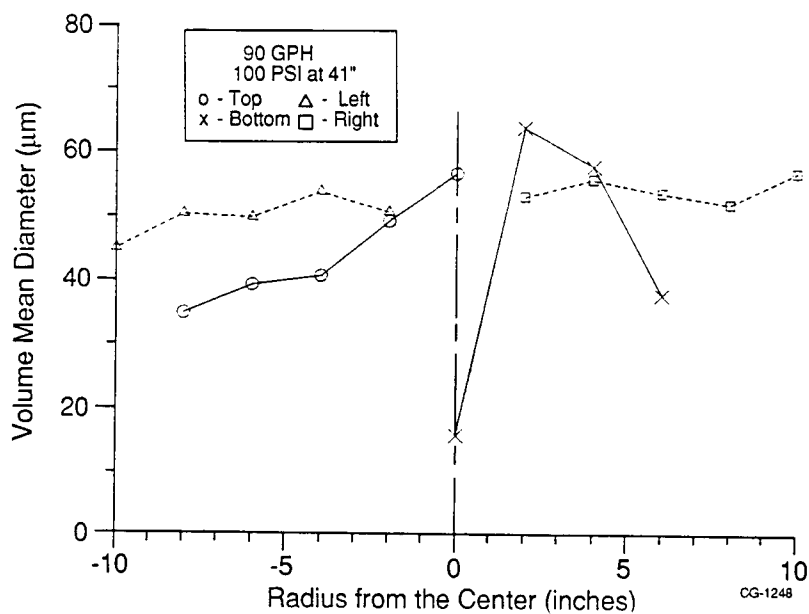


Figure 51. Vertical and Horizontal Distributions of Volume-Mean Diameter for CasterJetTM Nozzle as a Function of Axial Distance

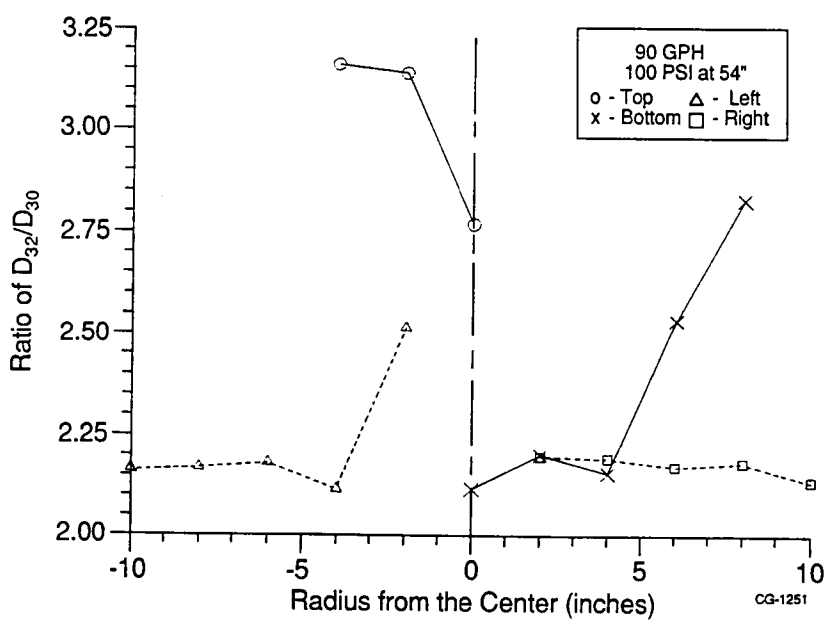
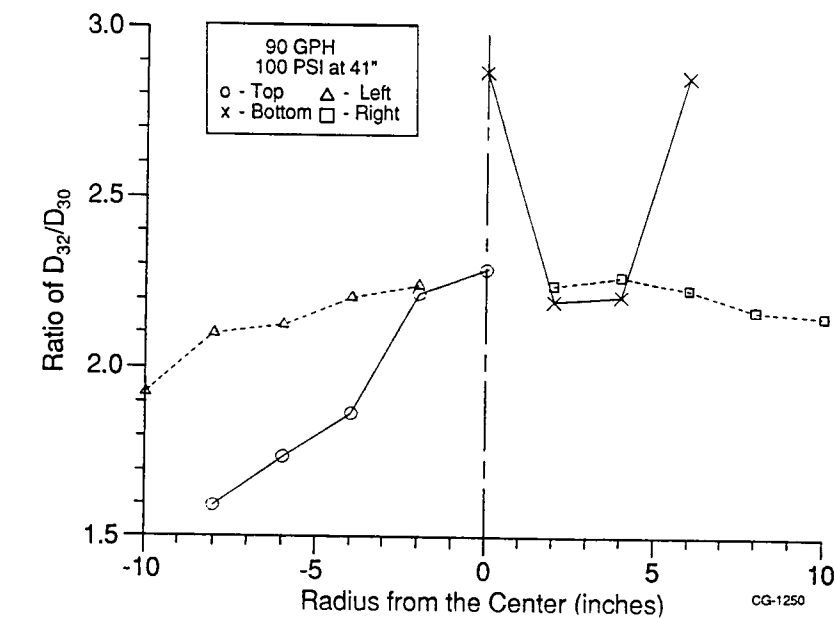


Figure 52. Vertical and Horizontal Distributions of the Ratio of Sauter-Mean Diameter to Volume-Mean Diameter for CasterJetTM Nozzle as a Function of Axial Distance

VITA

Xiaoqing Qian was born in Beijing, China on April 6, 1964. She received her elementary and high school education in Beijing, China. In July 1985 she graduated from the Beijing University of Aeronautics and Astronautics, Beijing, China, where she received her Bachelor of Science degree with a major in Aerospace Engineering. After graduation, she entered the Graduate School of Beijing University of Aeronautics and Astronautics, worked on her Master Degree with the major in aerospace engineering for one year.

In September 1986, she came to The University of Tennessee Space Institute as a graduate research assistant. In December 1988 she received the Master of Science degree in Aerospace Engineering.