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## Monterey, California



# THESIS

OPTICAL SIZING OF SOOT IN GAS TURBINE  
COMBUSTORS AND EXHAUST AUGMENTOR TUBES

by

Mark F. Young

March 1987

Thesis Advisor:

D.W. Netzer

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Optical Sizing of Soot in Gas Turbine  
Combustors and Exhaust Augmentor Tubes

by

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B.S., United States Naval Academy, 1979

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requirements for the degree of

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## ABSTRACT

An experimental investigation was conducted to examine optical sizing techniques in gas turbine combustors and exhaust augmentor tubes. The two primary objectives of this thesis were to improve the accuracy of optical particle sizing in the combustor and across the augmentor tube, and to verify the improved capabilities with a test series. Multiple wavelength light transmittance and light scattering techniques were used. Particle sizes were found to be .15 to .17 microns in the combustor, increasing in size to .35 to .45 microns in the aft can, and 1.5 to 1.6 microns at the exit of the augmentor tube. Also a MALVERN 2600 HSD particle sizer was used to verify the accuracy of the T-63 optical system. A number of recommendations for improving the system were discussed.

TABLE OF CONTENTS

I.	INTRODUCTION AND BACKGROUND -----	9
II.	THEORY -----	12
	A. LIGHT TRANSMITTANCE TECHNIQUE -----	12
	B. FORWARD LIGHT SCATTERING TECHNIQUE -----	14
III.	DESCRIPTION OF EXPERIMENTAL APPARATUS -----	22
	A. COMBUSTOR -----	22
	B. AIR SUPPLY -----	22
	C. FUEL SUPPLY -----	25
	D. AIR HEATER -----	25
	E. ADDITIVE PUMPS -----	25
	F. THERMOCOUPLES -----	25
	G. DATA REDUCTION SYSTEM -----	28
	H. CONTROLS -----	28
	I. LIGHT TRANSMITTANCE APPARATUS -----	28
	J. FORWARD LIGHT SCATTERING APPARATUS -----	29
IV.	EXPERIMENTAL PROCEDURE -----	35
V.	DISCUSSION OF RESULTS -----	37
VI.	CONCLUSIONS AND RECOMMENDATIONS -----	45
	LIST OF REFERENCES -----	48
	INITIAL DISTRIBUTION LIST -----	49

LIST OF TABLES

1. PROPERTIES OF NAPC #9 FUEL ----- 38

LIST OF FIGURES

1.	Extinction Coefficient versus D32 -----	15
2.	Extinction Coefficient Ratios versus D32 -----	16
3.	Extinction Coefficient versus D32 -----	17
4.	Extinction Coefficient Ratios versus D32 -----	18
5.	Intensity Ratio versus D32 -----	21
6.	T-63 System Schematic -----	23
7.	T-63 Combustor Schematic -----	24
8.	Side View of T-63 Thermocouple Locations -----	26
9.	End View of T-63 Thermocouple Locations -----	27
10.	Schematic of T-63 Test Apparatus -----	30
11.	Schematic of T-63 Aft Can Transmittance Apparatus -----	31
12.	Schematic of T-63 Combustor Transmittance and Light Scattering Apparatus -----	32
13.	Augmentor Tube Scattering Photodiodes -----	34
14.	MALVERN Augmentor Tube Sampling Data -----	42
15.	MALVERN Exhaust Nozzle Sampling Data -----	44

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## I. INTRODUCTION AND BACKGROUND

At present there is a great deal of interest in the study of soot formation in gas turbine engines. In the operational environment, soot production directly affects the engine service life, reliability, and combat survivability. Soot is also one of the key contributors to the gas turbines' negative impact on environmental air quality.

Routine maintenance and overhaul of gas turbines is carried out in test cells located at various shore-based installations. These test cells are required to meet all federal standards issued by the Environmental Protection Agency concerning air pollution. The test cells must also meet any applicable local state laws which tend to be more demanding. These regulations apply to the engine when it is operating in the test cell environment, not when installed on the aircraft or while airborne.

Two approaches are available for the test cells to meet their operational requirements. First, the exhaust from the test cell could be "scrubbed," but this approach tends to be prohibitively expensive if applied to all test cells. The second approach is to modify or treat the fuel with fuel additives and/or smoke suppressants with the result being a "cleaner" exhaust product at a reasonable cost.

The long-term goal of this research is a significant reduction in the in-flight pollutants from a gas turbine. Present efforts are more concerned with sooting characteristics in the test cell environment.

The objectives of current research at the Naval Postgraduate School are to determine the effects of different fuel compositions and smoke suppressants on:

- soot size and concentration
- NOx concentration, and
- heat release rates.

These effects will be measured both within the combustor and the exhaust augmentor tube.

This thesis was a continuation of the efforts of Hua [Ref. 1] and Urich [Ref. 2]. A number of modifications were made to the T-63 Test Apparatus to improve the capabilities of the system. Modifications were as follows:

- Enlarging of the exhaust nozzle to meet combustor design flowrate at combustor design pressure.
- Design and installation of a rigid test stand behind the augmentor tube for accurate light scattering measurements at three forward angles.
- Installation of a smaller augmentor tube to reduce cold air induction and increase soot concentration at the exit.
- Installation of an additional argon laser for transmittance and scattering measurements within the main burner.
- Installation of new optics and associated equipment to improve data acquisition.

The first objective of this thesis was to design and construct improvements to the transmittance and light scattering measurement equipment. This was needed to increase accuracy in particle sizing in the combustor and across the augmentor tube. The second objective was to demonstrate the improved capability of the system during an actual combustor test.

## II. THEORY

There are two basic methods available for the study of the sooting characteristics in gas turbine combustors and in test cells. One approach is the withdrawal of a soot sample for analysis. The other approach is referred to as "in situ" [Ref. 3] optical analysis and utilizes light transmittance and forward light scattering techniques. This second approach was employed for this thesis.

### A. LIGHT TRANSMITTANCE TECHNIQUE

This technique incorporates the use of three different wavelengths of light for continuous transmittance measurements through a gas containing soot particles. The values of transmittance are then ratioed to each other and the particle size can then be calculated from MIE SCATTERING theory.

This procedure was successfully applied by K.L. Cashdollar [Ref. 3] to measure the mass concentration and particle size of a cloud of smoke. The transmission of light through a cloud of uniform particles is given by BOUGUER'S LAW [Ref. 3]:

$$T = \exp(-QAnL) = \exp[-(3QCmL/2\rho d)] \quad (1)$$

where:

T = fraction of light transmitted  
 Q = dimensionless extinction coefficient  
 A = cross-sectional area of particle  
 n = concentration of particles  
 L = path length of the light beam  
 C<sub>m</sub> = mass concentration of particles  
 ρ = density of particles  
 d = diameter of particles.

For a polydisperse system of particles, which is more characteristic of soot, Dobbins [Ref. 4] revised BOUGUER'S LAW to the following:

$$T = \exp[-3\bar{Q}C_m L / 2\rho D_{32}] \quad (2)$$

where:

$\bar{Q}$  = average extinction coefficient  
 D<sub>32</sub> = volume-to-surface mean particle diameter.

$\bar{Q}$  is a function of the complex refractive index (m) of the soot, the standard deviation of the particle size distribution (σ), particle size (D<sub>32</sub>), and the wavelength of the light (λ). Equation (2) can be put into a more useful format by taking the natural log of both sides, yielding the following equation:

$$\ln T = \bar{Q}[-3C_m L / 2\rho D_{32}] \quad (3)$$

Equation (3) could be referenced to any wavelength. The ln ratio of the transmissions at any two wavelengths is equal to the ratio of the calculated extinction coefficients for the same wavelengths [Ref. 3]:

$$\frac{\text{LN } T(\lambda_1)}{\text{LN } T(\lambda_2)} = \frac{\bar{Q}(\lambda_1)}{\bar{Q}(\lambda_2)} \quad (4)$$

These ratios were used with a computer program provided by Cashdollar. This program generated curves for the extinction coefficient ( $\bar{Q}$ ) and the extinction coefficient ratios ( $\bar{Q}(\lambda_1)/\bar{Q}(\lambda_2)$ ) versus D32. Different shapes for the curves were obtained by varying the complex refractive index ( $m$ ) of the soot and the standard deviation of the particle size ( $\sigma$ ). If the complex refractive index and standard deviation were correct, all three ratios would yield the same particle size (D32). If the value for D32 was not consistent, then either the refractive index or the standard deviation size, or both, could be varied. Using previous experience, a refractive index of  $m = 1.95 - .66i$  and a standard deviation of  $\sigma = 1.5$  gave the most consistent results. Figures 1 through 4 show plots from the program.

#### B. FORWARD LIGHT SCATTERING TECHNIQUE

The other approach to "in situ" measurements to determine D32 is referred to as Forward Light Scattering. Using this technique, the ratio of intensities at two scattered angles (i.e.,  $20^\circ$  and  $40^\circ$ ) will give a measurement

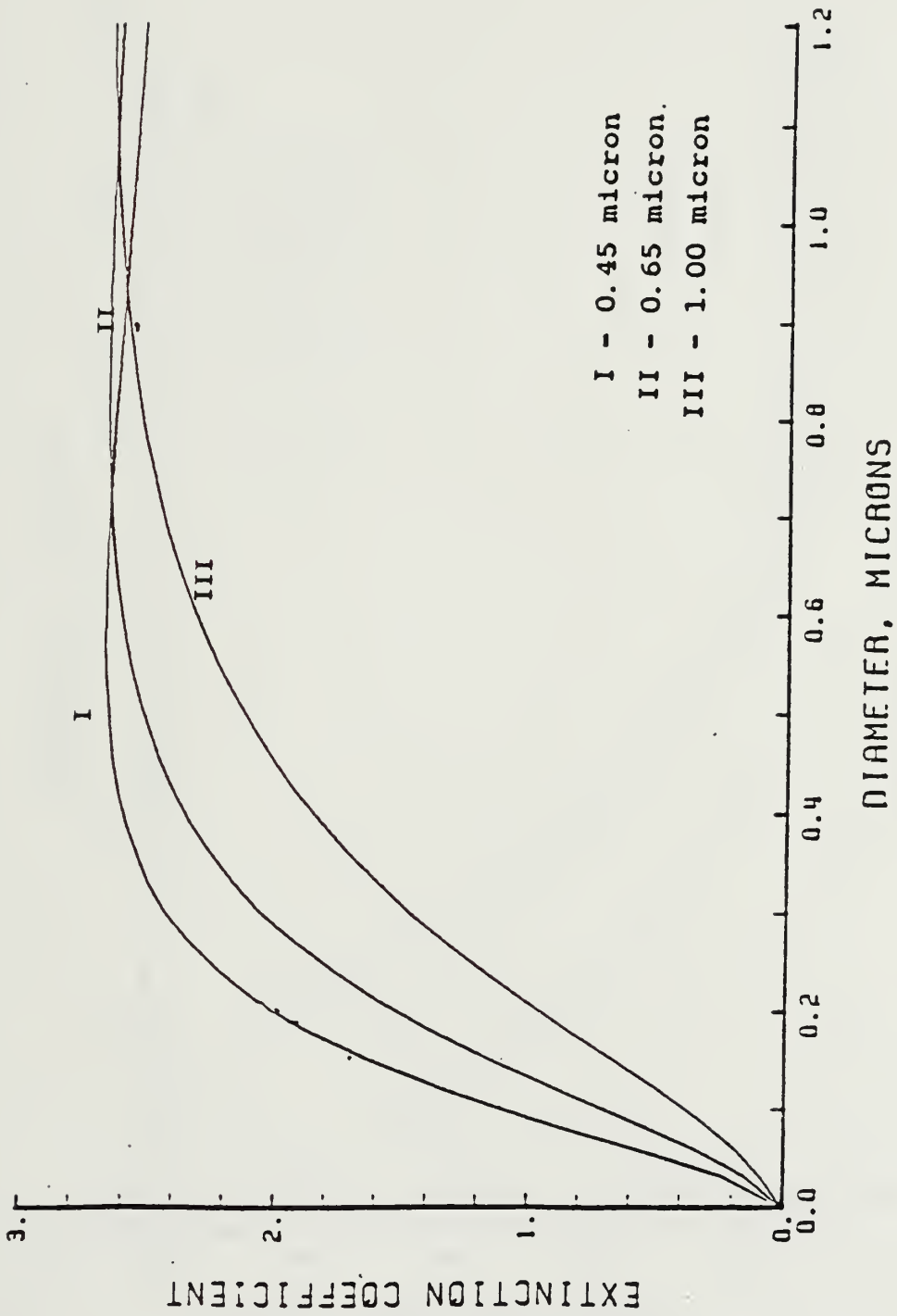


Figure 1. Extinction Coefficient versus D32

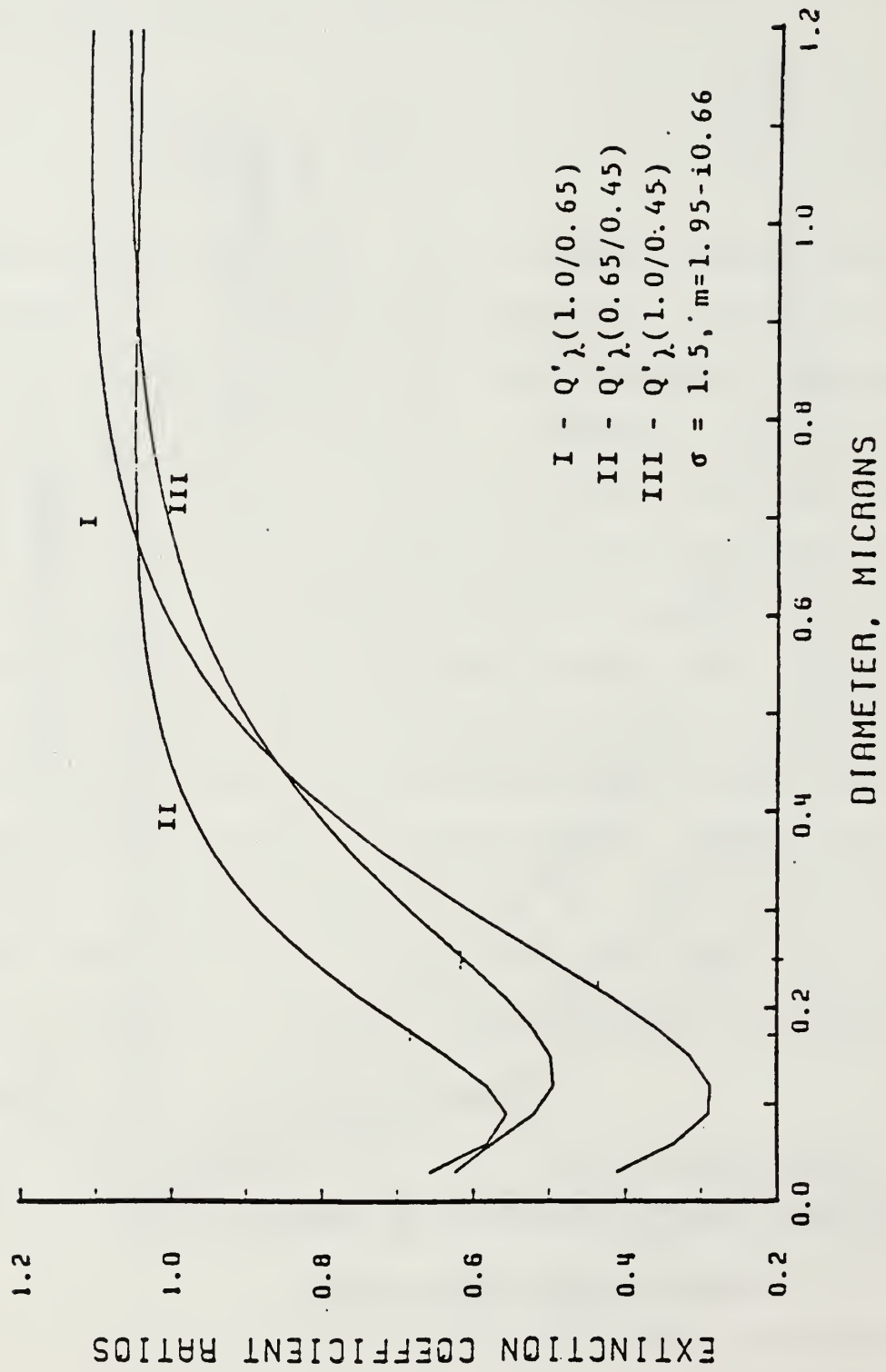


Figure 2. Extinction Coefficient Ratios versus D32

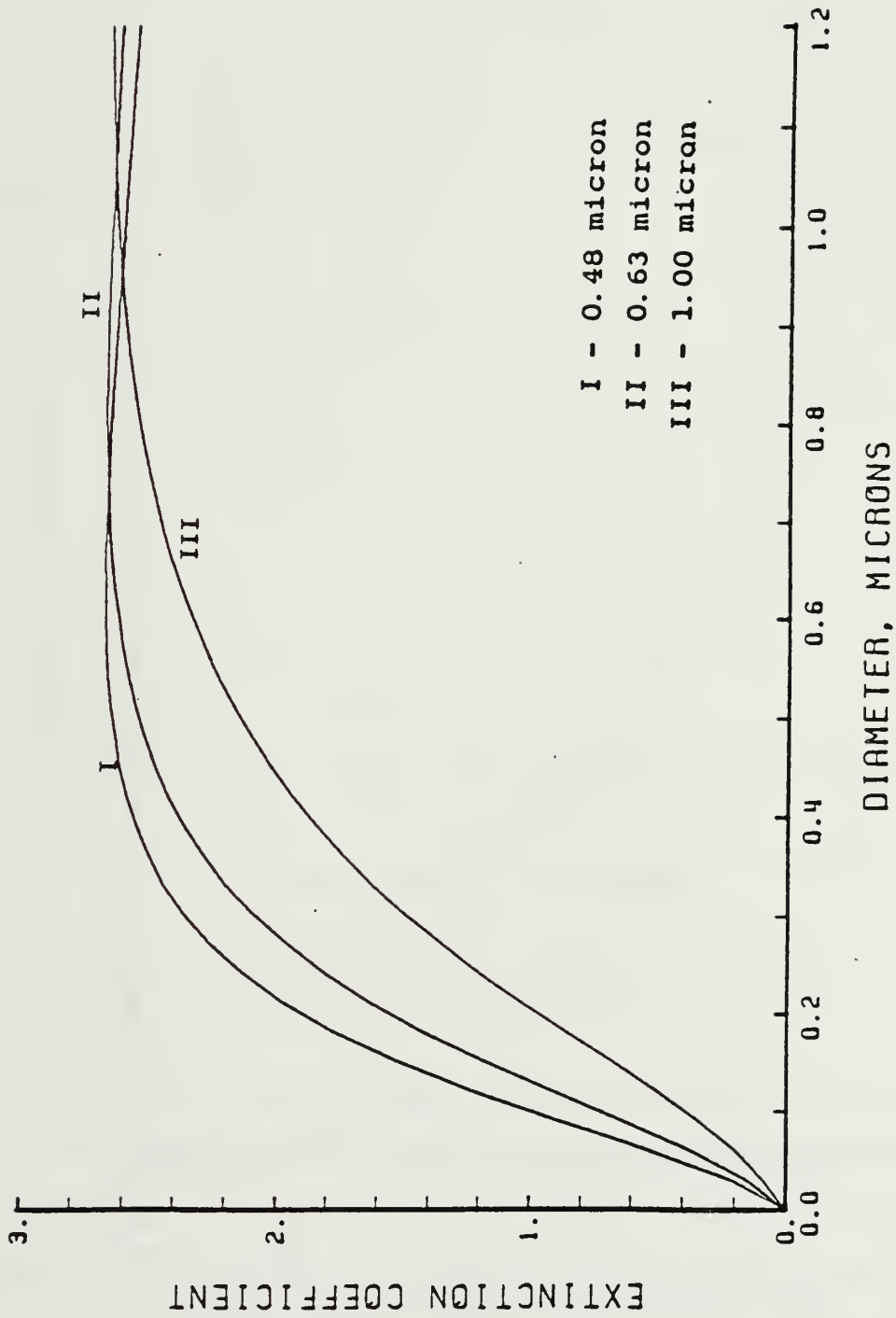


Figure 3. Extinction Coefficient versus D32

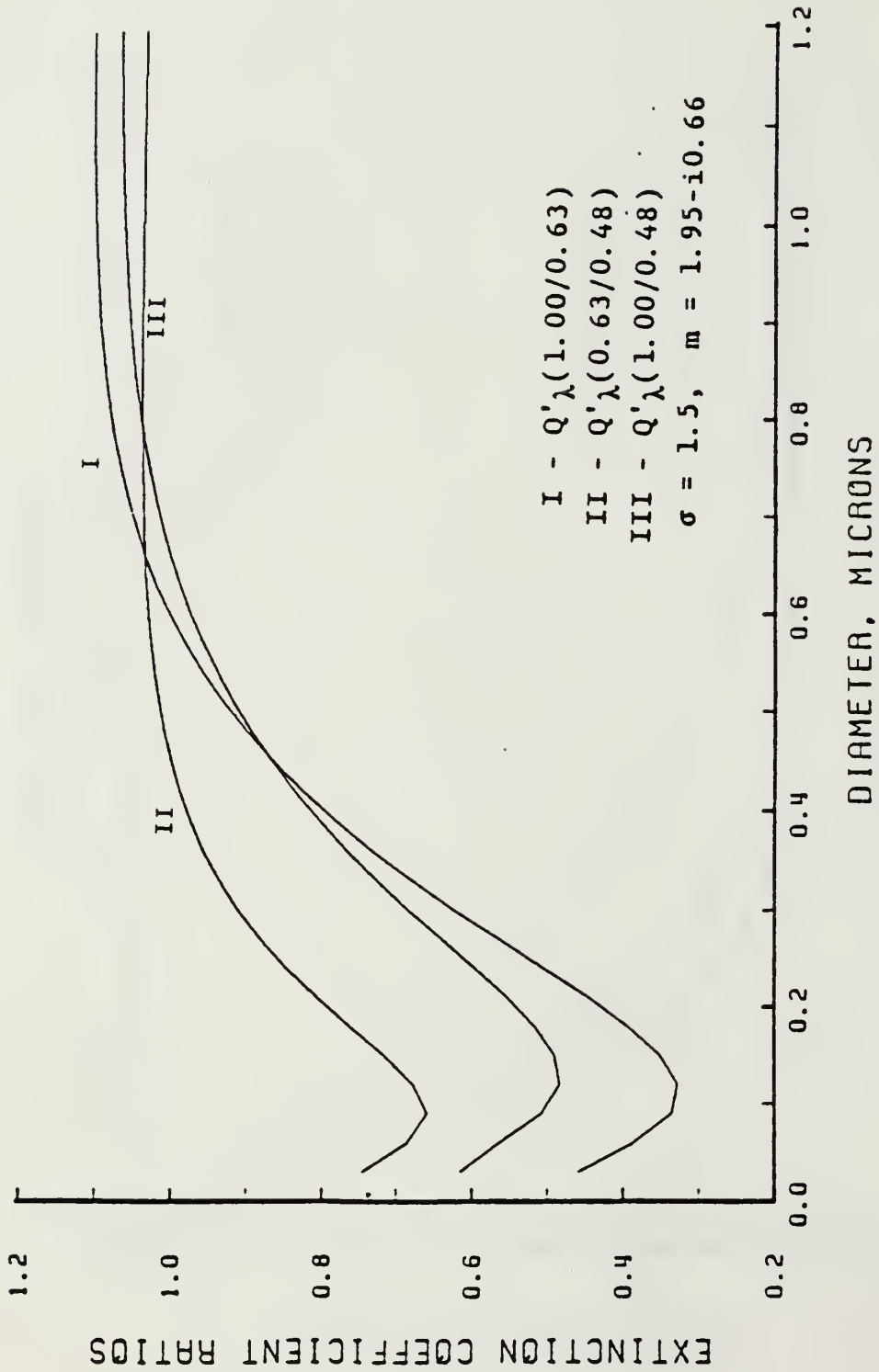


Figure 4. Extinction Coefficient Ratios versus D32

of the particle mean diameter. Assuming a polydisperse cloud, the ratio of intensities at any two forward scattering angles is given by the following equation:

$$I(\theta_1)/I(\theta_2) = F(\theta_1)/F(\theta_2)$$

Powell and Zinn [Ref. 5] developed the following equation for  $F(\theta)$ :

$$F(\theta) = \int_1^2 (1+\cos^2\theta) [J_1(\alpha\theta\varepsilon)/\theta\varepsilon]^2 \exp -[\delta \ln(a\varepsilon/1-\varepsilon)]^2 d\varepsilon/1-\varepsilon \quad (5)$$

where:

$$\alpha = \pi D_m / \lambda = \text{size parameter}$$

$$D_m/D_{32} = 1 + (a \exp(1/4 \delta^2))$$

$$a = \text{size distribution parameter} = 1.13$$

$$\delta = \text{size distribution parameter} = 1.26$$

$$D_m = \text{maximum particle diameter}$$

$$\varepsilon = \text{particle diameter divided by } D_m$$

$$J_1 = \text{Bessel function of order one.}$$

This equation only considers Fraunhofer diffraction.

Since the forward lobe is made up of mostly Fraunhofer diffraction, the ratio of scattered light intensities is insensitive to particle refractive index and concentration.

Using Equation 5, a plot of intensity ratios versus particle size (D32) can be produced. So that the intensities are referenced to the same scattering volume, each intensity must be multiplied by the SIN of its respective scattering angle. Using this ratio as an entry to the plot, a value of D32 can be determined. A plot of intensity ratio versus D32 is included as Fig. 5.

INTENSITY RATIO VERSUS D32

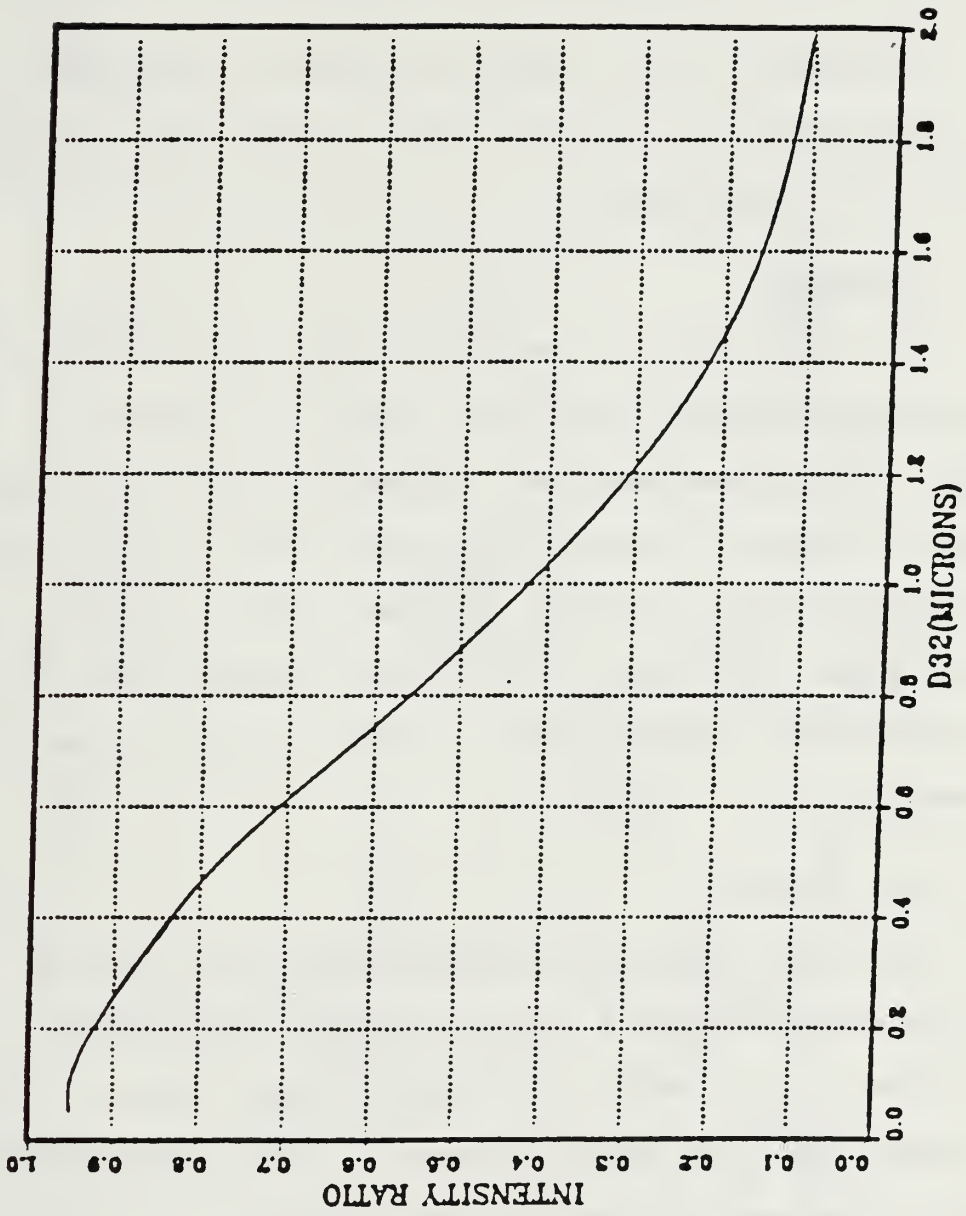


Figure 5. Intensity Ratio versus D32

### III. DESCRIPTION OF EXPERIMENTAL APPARATUS

A summary of the separate pieces of equipment that make up the system is included below. Figure 6 is a descriptive layout for the system.

#### A. COMBUSTOR

The combustor was the combustion section of an Allison T-63 gas turbine. The power turbine and compressor were not used. Included with the combustion can were the ignitor plug, combustor housing and the turbine nozzle block. A stainless steel exhaust chamber with converging exhaust nozzle was added aft of the turbine nozzle block to maintain the desired pressure level. Figure 7 is a schematic of the combustor.

#### B. AIR SUPPLY

With the compressor removed from the combustor, air had to be supplied from a remote source. In this case, air was provided by a 3000 PSI tank storage system. This air entered into the engine through the two ducts that originally received air from the compressor.

The desired flowrates were achieved using a pressure regulator and solenoid on/off valve. A sonic choke was used together with measurements of the temperature and pressure for calculation of the flow rate.

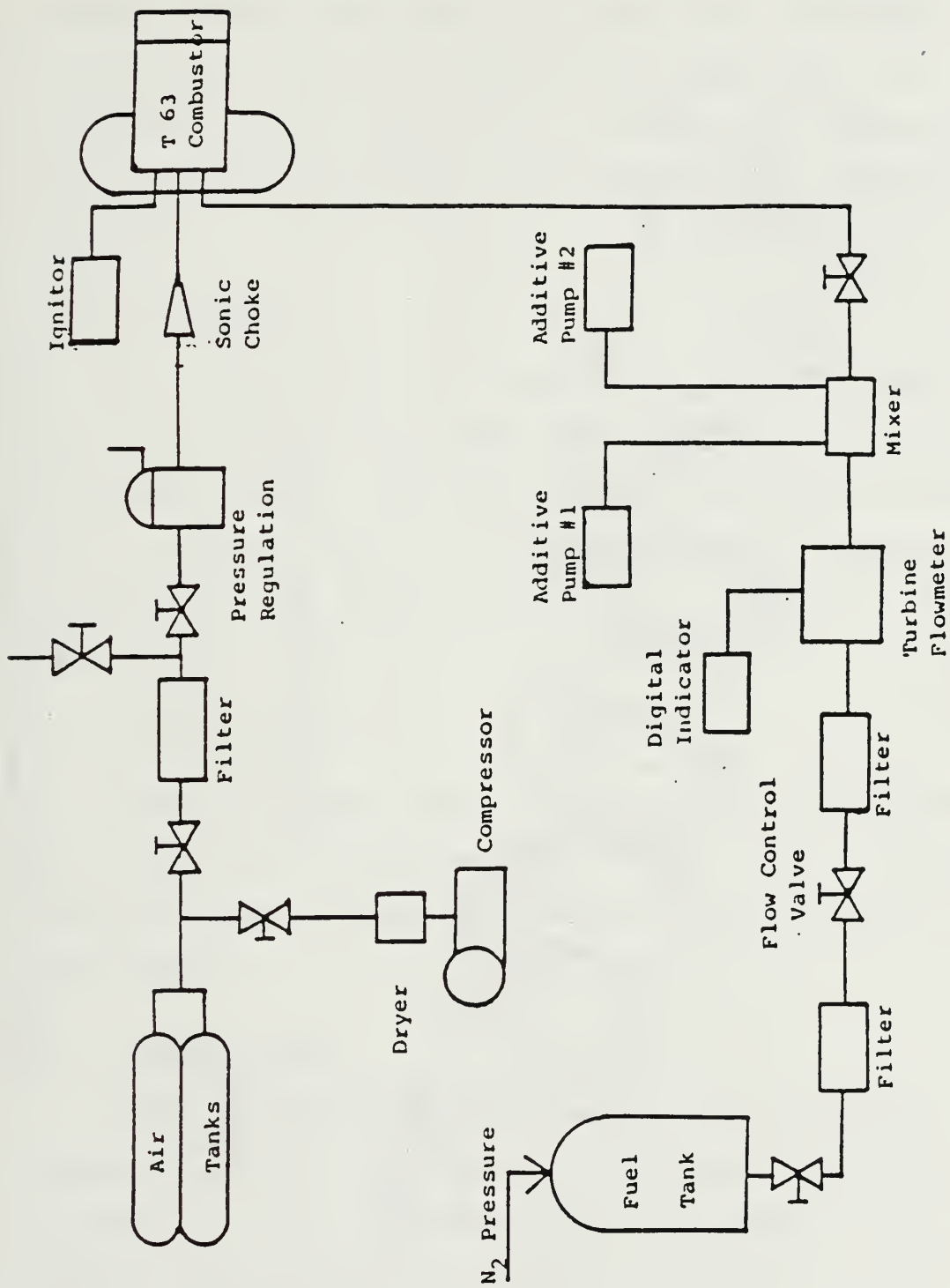
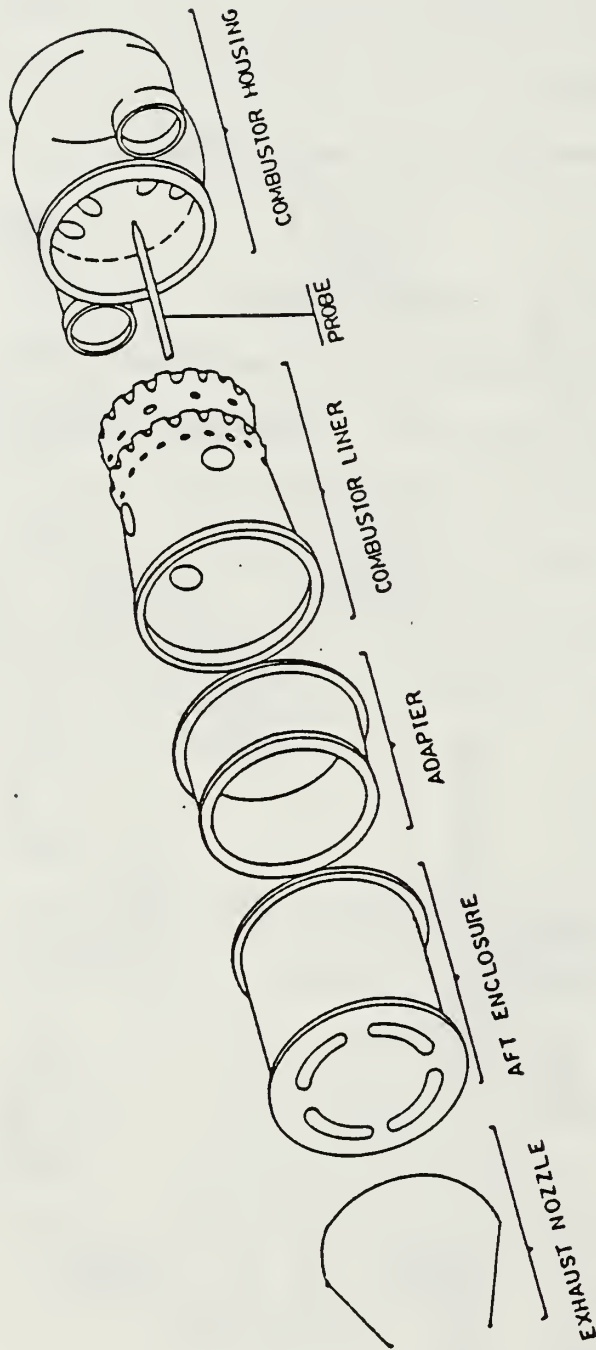


Figure 6. T-63 System Schematic [Ref. 6]



Schematic of T-63 Combustor Components

Figure 7. T-63 Combustor Schematic [Ref. 6]

### C. FUEL SUPPLY

The fuel was delivered to the engine from a pressurized twenty gallon fuel tank. The fuel went through a manual throttling valve, a turbine flow meter and an electric solenoid on/off valve prior to reaching the combustor. The fuel tank was pressurized and pneumatically controlled with nitrogen.

### D. AIR HEATER

A hydrogen fueled air heater was installed and could be used to increase the temperature of the inlet air to more realistic levels. Additional oxygen was added to the heated air to adjust for that consumed with the hydrogen. The ignitor and gas controls for the air heater were located in the control room.

### E. ADDITIVE PUMPS

Two Eldex pumps were mounted on the test stand and were remotely operated by switches in the control room. The mixing of the fuel and the additive was done using a swirl-type mixer.

### F. THERMOCOUPLES

Five thermocouples were located in the combustor. Their exact locations are depicted on Figures 8 and 9. The outputs of these thermocouples were sent to the Hewlett-Packard data acquisition system.

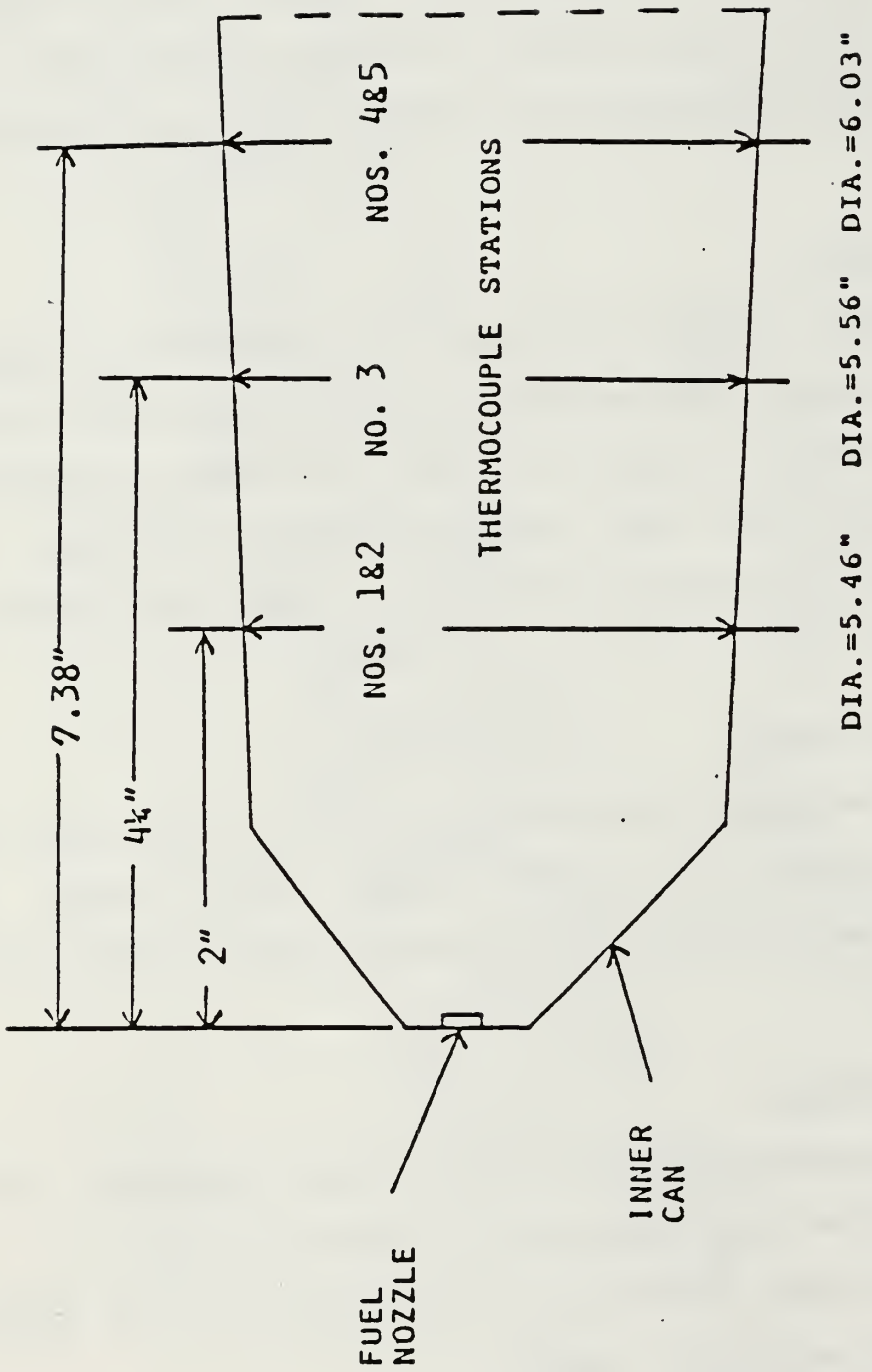
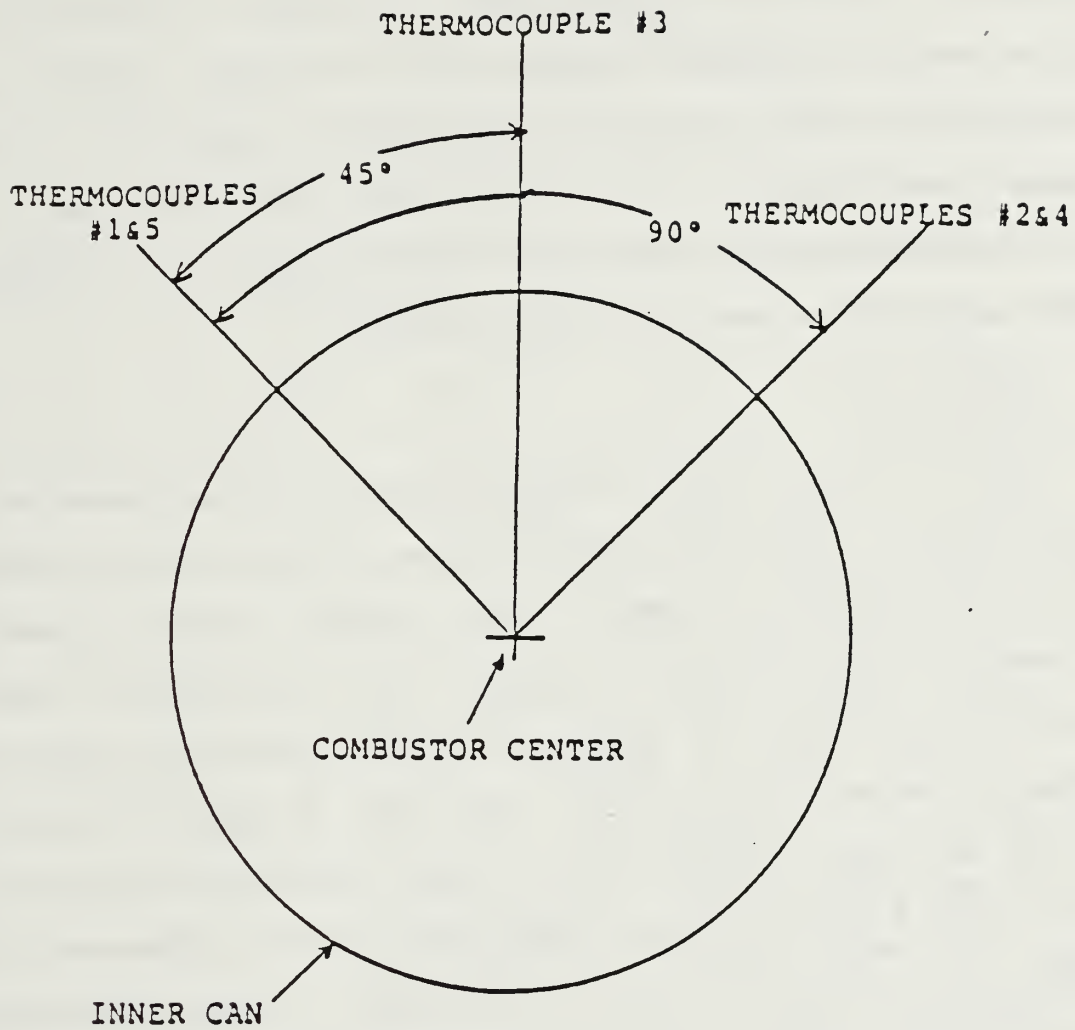


Figure 8. Side View of T-36 Thermocouple Locations [Ref. 1]



DISTANCE OF THERMOCOUPLES FROM COMBUSTOR CENTER

#1	2.23"
#2	1.73"
#3	2.28"
#4	2.01"
#5	NOT USED

Figure 9. End View of T-63 Thermocouple Locations [Ref. 1]

#### G. DATA REDUCTION SYSTEM

Data was recorded using a Hewlett-Packard computer system. Pressures, temperatures, flowrates, and transmittance and scattering voltages were recorded during each portion of motor operation. The exhaust temperature of the engine was displayed on either a strip chart recorder or a digital display to determine "steady-state" for computer data acquisition and as a safety backup.

#### H. CONTROLS

All controls were situated such that the experiment could be run from the control room. There was a control valve for setting the desired air pressure and an electric solenoid on/off switch to initiate and terminate air flow. Controls for the fuel system included a control valve and pressure gauge for the fuel tank and an electric on/off switch to control fuel flow. A flow control valve for the fuel with digital readout from the turbine flowmeter was installed adjacent to the control panel. There was also an electric vent valve to vent pressure from the fuel tank.

#### I. LIGHT TRANSMITTANCE APPARATUS

Light transmittance measurements were taken at the aft end of the combustion can and in the aft pressure enclosure. In the combustion can two argon lasers and one helium-neon laser were used. The wavelengths for the lasers were .488(blue), .5145 (green), and .6328(red) microns

respectively. To filter out combustion light, a light chopper on the input beams was used to provide a 90 Hz reference signal to phase-lock amplifiers, which also received the inputs from the photodiodes. From the phase-lock amplifier the signals were sent to the computer.

As previously mentioned, light transmittance measurements were also taken in the aft pressure enclosure. A less complicated white-light source was used here since combustion light was not present. After passing through the exhaust gases the white-light was divided into three different beams using beam splitters. Each beam was passed to an individual photodiode which was preceded by a specific wavelength filter. The outputs of the three photodiodes were sent directly to the computer. The voltage signals from these diodes were also recorded on strip charts in the control room to provide a "hard-copy" of transmittance variation during an experiment. These strip charts also proved helpful in determining the proper time for computer data sampling. Figures 10, 11 and 12 show the geometry of the transmittance equipment as installed on the T-63.

#### J. FORWARD LIGHT SCATTERING APPARATUS

Light scattering measurements were taken both in the combustor and at the exit plane of the augmentor tube. In the combustor, the measurements were taken at  $20^\circ$  and  $40^\circ$  using the 250 mW argon laser as a source. The outputs of the two diodes were sent through phase-lock amplifiers and

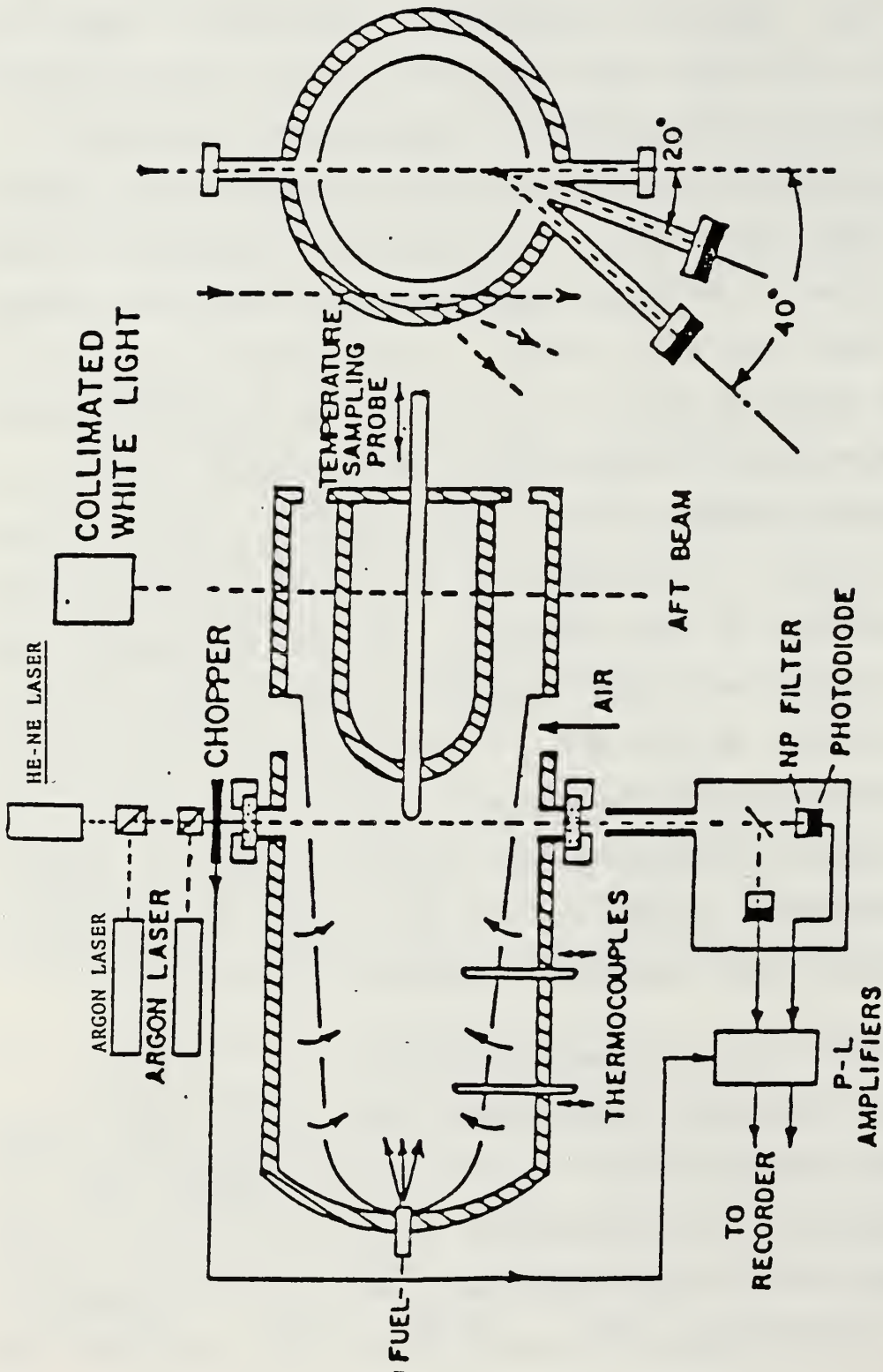


Figure 10. Schematic of T-63 Test Apparatus (Adapted from [Ref. 6])

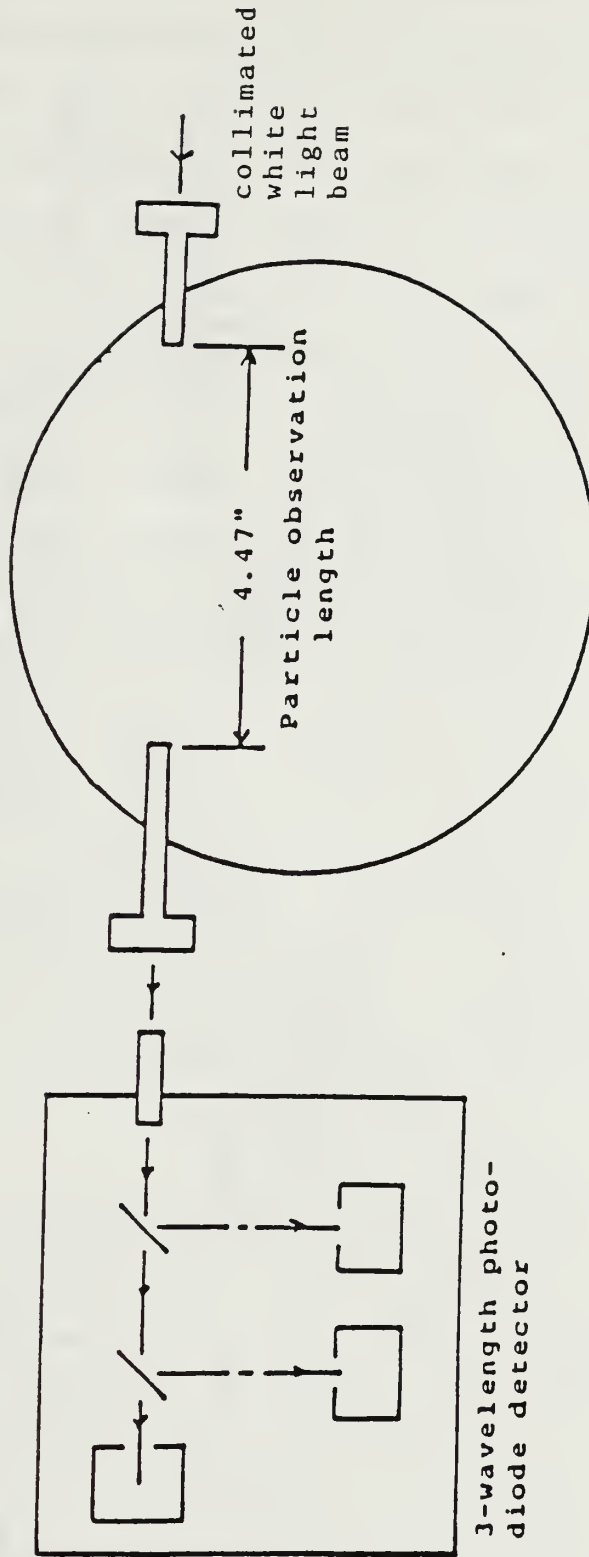


Figure 11. Schematic of T-63 Aft Can Transmittance Apparatus (Adapted from [Ref. 1])

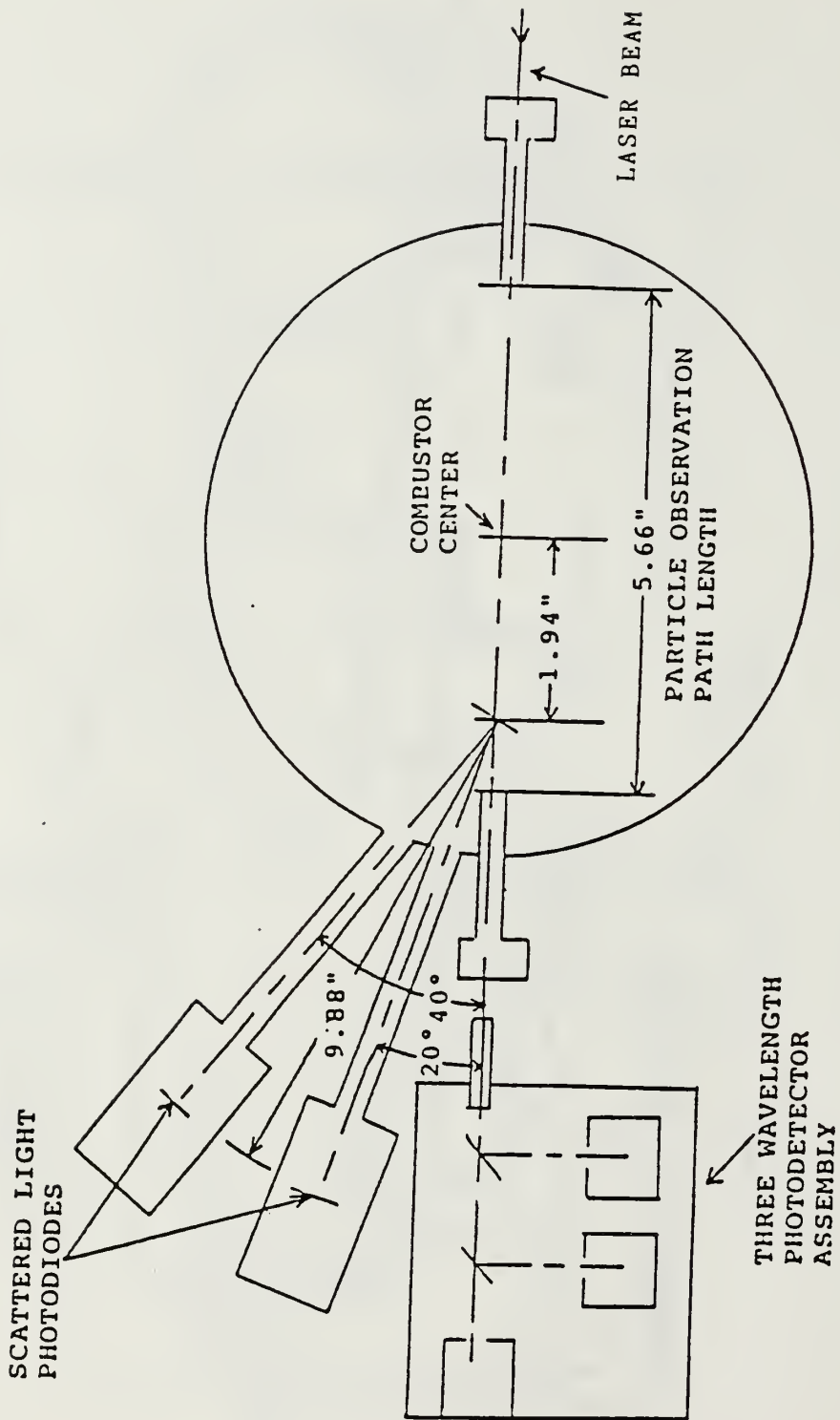


Figure 12. Schematic of T-63 Combustor Transmittance and Light Scattering Apparatus (Adapted from [Ref. 6])

then to the computer for data reduction. Figures 10 and 12 show the mounting configuration for the scattering diodes.

For collecting scattering data from the augmentor tube, a mounting bracket and test stand were constructed. This bracket and test stand allowed for scattering angles of  $0^{\circ}$  to  $90^{\circ}$  in increments of  $10^{\circ}$ . In this investigation, the configuration for collection of scattering data was either  $10^{\circ}$ ,  $20^{\circ}$  and  $40^{\circ}$  or  $10^{\circ}$ ,  $20^{\circ}$  and  $30^{\circ}$ . With the absence of combustion light in this area, the outputs from these photodiodes were sent directly to the computer. Figure 13 shows the mounting configuration for the diodes.



Figure 13. Augmentor Tube Scattering Photodiodes

#### IV. EXPERIMENTAL PROCEDURE

Prior to conducting a test, a number of equipment calibrations and procedural checks were required. All lasers were turned on and allowed to warm up and their alignment with the photodiodes was rechecked. This same alignment check was followed with the white-light and its diodes. All other electrical equipment such as power supplies in the test cell, and electronic racks and control panels in the control room were turned on to ensure proper operation.

Manual shut-off and control valves for the combustor air and fuel supplies had to be checked for proper positions. Nitrogen bottles used for pressurizing the fuel tank and operating the pneumatic controls were connected and their proper operation was checked from the control room.

Before the test, the data acquisition and reduction program was loaded into the computer. After loading, the computer "asked" the user a series of questions so that the program would be set for the proper combustor configuration for that test. The program collected four different sets of data during any one run. These data sets were:

- Pre-Ignition Air Only Data
- Hot Run (No Additive) Data
- Additive Hot Run Data
- Post-Ignition Air-Only Data.

The Pre-Ignition data were taken with the Main Air on, but without fuel flow and ignition. Hot Run Data were taken with the engine operating in a steady-state condition after light-off. Additive data were taken with an additive mixed with the fuel or this data could be used as another non-additive run if desired. Post-Ignition data were taken after fuel flow to the engine had been secured, but with the Main Air still on.

During each run the following data were recorded/calculated by the computer:

- air flow rate
- fuel flow rate
- fuel-air ratio
- air pressure
- air temperature
- combustor pressure
- combustor exhaust temperature
- main combustor temperature (5 probes)
- signal voltages for transmitted light
- signal voltages for scattered light.

## V. DISCUSSION OF RESULTS

The original objective of this thesis was to improve the accuracy of the particle sizing techniques utilized with the T-63 and to demonstrate the improved capabilities with a test series. The test series consisted of four runs utilizing the T-63 Data Acquisition system with the instrumentation discussed above, and two additional runs using a MALVERN 2600c particle sizer to verify some of the data from the first four tests.

All of the tests were made using NAPC 9 fuel (high aromatic JP-5, Table I). No additives were used, but tests were made at two different fuel-to-air ratios. The first test used a fuel-to-air ratio of .0159. All other tests were made at a higher ratio of .0179.

Data reduction for the first test yielded a particle size ( $D_{32}$ ) of .45 microns in the aft can. All three transmittance ratios gave very consistent results using the MIE-SCAT program with  $m$  at 1.95--.3i and  $\sigma$  set to 2.0. Very low (less than 5%) transmittances were obtained in the combustor. This indicated that the low fuel-to-air ratio produced an extremely soot-laden flow. No particle size could be determined.

For the first test, the augmentor scattering apparatus was configured with photodiodes at  $10^\circ$ ,  $20^\circ$  and  $40^\circ$ . The

TABLE I  
 PROPERTIES OF NAPC #9 FUEL

	NAPC #9
API Gravity @ 15°C	40.5
Distillation (ASTM)	
IBP °C	190
Recovered 10% Max	204
Recovered 20%	208
Recovered 50%	218
Recovered 90%	246
End Point, max	264
Residue (ML), Max	1.4
Loss (ML), Max	0.5
Composition	
Aromatics (Vol %), Max	22.7
Olefin (Vol %), Max	1.62
Hydrogen Content (Wt %), Min	13.49
Aniline--Gravity Prod., Min	5471
Freeze Point, °C	-53.0
Viscosity @ 37.8 °C, (cSt)	1.50
Temperature @ 12 cSt, (°C)	-35

initial data reduction showed some scattering at  $10^\circ$  and  $20^\circ$ , but nothing at  $40^\circ$ . Dominant scattering at the lower angles indicated that large particles were exiting the augmentor tube. Prior to the third test, the augmentor scattering diodes were recalibrated to determine more accurate calibration constants (voltage outputs for fixed intensity input) for each diode. When the corrected calibration constants were applied to the  $I(\theta = 20^\circ)/I(\theta = 10^\circ)$  raw data from the first test, a mean particle size ( $D_{32}$ ) of 1.50--1.52 microns was determined.

The second and all subsequent tests were made at the fuel-to-air ratio of .0179. This higher ratio resulted in a particle size in the aft can of .35 microns. This decrease in  $D_{32}$  with increased fuel-to-air ratio was in agreement with the behavior observed by Jway [Ref. 1]. The transmittances in the combustor improved from those obtained at low fuel-to-air ratios, to 10.8% for the He-Ne (red) laser and 30.6% for the argon (blue) laser. This result was inconsistent with theory, since the higher wavelength (red at .6328 microns) should have had a higher transmittance than the lower wavelength (blue at .488 microns).

Again, the augmentor photodiodes showed scattering at  $10^\circ$  and  $20^\circ$ , but nothing at  $40^\circ$ . When the data was reduced using the correct calibration constants, a particle size of 1.55 microns was obtained. This was in good agreement with the results from test one.

The third test failed to produce any accurate particle sizing data in the aft can. The transmittance values obtained for the combustor were 17.9% for the He-Ne laser (red) and 30.5% for the argon laser (blue), again in reverse order to what should have been observed.

The augmentor tube photodiodes were changed to  $10^\circ$ ,  $20^\circ$  and  $30^\circ$  in an attempt to obtain data at three angles. Again, only the  $10^\circ$  and  $20^\circ$  diodes recorded measurable intensities. This test resulted in a particle size of 1.52 microns.

It was observed in the first three tests that the high power of the argon laser, coupled with small misalignment of the windows, resulted in many reflections along the optical path. In an attempt to see if this was the cause for the incorrect transmission intensities, a fourth test was conducted in which the high-power argon laser (250 mW) was replaced with a smaller (8 mW) argon laser. A beam splitter was also removed which increased the intensity of the He-Ne laser. The result was a transmittance of 17.3% for the red, and 7.3% for the blue laser. This result agreed with theory. This one ratio yielded a particle size of .15-.17 microns in the combustor for  $m = 1.95 - .66i$  and  $\sigma = 1.5$ .

The very large  $D_{32}$  measured at the augmentor tube exhaust was not expected, thus the selection  $10^\circ$ ,  $20^\circ$  and  $30^\circ$  or  $40^\circ$  degrees for scattering angles. For  $D = 1.5$ ,  $30^\circ$  is approximately the end of the Fraunhofer center lobe,

where accuracy of the theory is questionable. It was decided to use another measurement device, which used smaller angles, to check the accuracy of the approximately 1.5 microns mean size discussed above. The fifth and sixth tests were conducted using a MALVERN 2600 HSD particle sizer to determine the particle size distribution at the exit of the augmentor tube and at the exit of the T-63 combustion can nozzle. No combustor data were taken by the computer during either of these runs. With the MALVERN set at the augmentor tube exit, it yielded 80% of the particles with diameter between 1.4 and 1.9 microns and a  $D_{32}$  of 1.9 microns. Data from this test are included as Fig. 14. This was in good agreement with the data from the first three tests. In order to measure particles as small as 0.5 microns, the MALVERN had to be operated with a 63 mm lens, the least accurate configuration. Also, the optimum condition would be for the MALVERN sample volume to be within one focal length of the lens. This was not possible due to the diameter of the augmentor tube.

Data from the sixth test confirmed the particle size obtained earlier for the aft can. During this test, the MALVERN was positioned to determine the particle size distribution at the exit of the exhaust nozzle (i.e., the entrance to the augmentor tube). The result was that 10% of the particles had diameters between 1.4 and 1.6 microns, 42% between 1.2 and 1.4 and 41% between 0.5 and 1.2 microns.

Malvern Instruments MASTER Particle Sizer M3.0 Date 25-02-87 Time 14-32

Size microns	under	% in band	Size microns	under	% in band	Result source=Sample Record No. = 0 Focal length = 63 mm. Experiment type pia Number distribution Beam length = 75.0 mm. Obscuration = 0.0523 Volume Conc. = 0.0021 % Log. Diff. = 6.10 Model indep
118.4	100.0	1.7	11.1	83.2	0.0	D(v, 0.5) = 1.7 µm
102.1	98.3	4.0	9.6	83.2	0.0	D(v, 0.9) = 77.1 µm
88.1	94.4	4.8	8.3	83.2	0.0	D(v, 0.1) = 1.6 µm
76.0	89.5	4.2	7.2	83.2	0.0	D(4, 3) = 14.9 µm
65.6	85.3	2.1	6.2	83.2	0.0	D(3, 2) = 1.9 µm
56.6	83.2	0.0	5.3	83.2	0.0	Span = 43.7
48.8	83.2	0.0	4.6	83.2	0.0	Spec. surf. area = 0.07 sq. m. / cc.
42.1	83.2	0.0	4.0	83.2	0.0	
36.3	83.2	0.0	3.4	83.2	0.0	
31.3	83.2	0.0	3.0	83.2	0.0	
27.0	83.2	0.0	2.6	83.2	0.0	
23.3	83.2	0.0	2.2	83.2	0.1	
20.1	83.2	0.0	1.9	83.1	60.6	
17.4	83.2	0.0	1.6	22.5	20.0	
15.0	83.2	0.0	1.4	2.6	0.0	
12.9	83.2	0.0	1.2	2.6	0.2	

Sample details:-Test data 03-06-1986. R.J.H.J.

Figure 14. MALVERN Particle Size Data for Augmentor Tube Exit

$D_{32}$  was 1.2 microns. Data are included as Fig. 15. This indicated that the particles were agglomerating as they passed through the converging nozzle and through the augmentor tube.

The MALVERN was used to verify the data that were being obtained from the three-angle measurement apparatus. In both cases, the result was in very close agreement with data from the previous runs, especially when the less than optimum operating conditions for the MALVERN were taken into account.

Malvern Instruments MASTER Particle Sizer M3.0 Date 25-02-07 Time 15-10

Size microns	under	% in band	Size microns	under	% in band	Result source=Sample Record No. = 0 Focal length = 63 mm. Experiment type pia Number distribution Beam length = 51.0 mm. Obscuration = 0.0218 Volume Conc. = 0.0009 % Log. Diff. = 5.73 Model indp
110.4	100.0	0.0	11.1	99.8	0.0	D(v, 0.5) = 1.2 µm
102.1	100.0	0.0	9.6	99.8	0.0	D(v, 0.9) = 1.4 µm
88.1	100.0	0.0	8.3	99.8	0.0	D(v, 0.1) = 1.0 µm
76.0	100.0	0.1	7.2	99.8	0.0	D(4, 3) = 1.4 µm
65.6	99.9	0.1	6.2	99.8	0.0	D(3, 2) = 1.2 µm
56.6	99.8	0.0	5.3	99.8	0.0	Span = 0.3
48.8	99.8	0.0	4.6	99.8	0.0	Spec. surf. area 0.07 sq.m./cc.
42.1	99.8	0.0	4.0	99.7	0.0	
36.3	99.8	0.0	3.4	99.7	0.2	
31.3	99.8	0.0	3.0	99.6	0.2	
27.0	99.8	0.0	2.6	99.4	0.2	
23.3	99.8	0.0	2.2	99.2	0.6	
20.1	99.8	0.0	1.9	98.6	1.5	
17.4	99.8	0.0	1.6	97.1	10.1	
15.0	99.8	0.0	1.4	87.0	41.7	
12.9	99.8	0.0	1.2	45.3	41.4	

Sample details:--Test data 03-06-1986. R.J.H.J.

Figure 15. MALVERN Particle Size Data for Exhaust Nozzle

## VI. CONCLUSIONS AND RECOMMENDATIONS

The successful outcome of the test series indicates that the T-63 system had been significantly improved. Accurate data for transmittances and particle size in the aft can and scattering data in the augmentor tube were obtained, and proved to be consistent. Transmittance measurements in the combustor were improved and particle size data were obtained, but could not be verified with other ratios at different wavelengths. The MALVERN also proved to be an excellent means for data verification.

The one major problem still remaining seems to be with data acquisition. In its current form, the computer only takes data when instructed by the operator. The operator must have an accurate and reliable means to determine when a steady-state condition has been achieved for data acquisition. It is recommended that the use of strip-charts be continued since they offer the only viable current method for determining the steady-state condition. It is also recommended that a program change be made so that the more critical data (i.e., that dealing with transmittance and scattering) would be taken immediately when the computer is cued by the operator. Other data, such as temperatures, pressures, etc., could be taken afterwards without any degradation of data accuracy.

The results from the augmentor tube scattering data indicated that the augmentor tube photodiode geometry should be changed. The present configuration of  $10^\circ$ ,  $20^\circ$  and  $40^\circ$  or  $10^\circ$ ,  $20^\circ$  and  $30^\circ$  would be proper for small particles (less than .5 microns), but not for large ones. Consideration should be given to a  $5^\circ$ ,  $10^\circ$  and  $15^\circ$  diode configurations for collection of augmentor tube scattering data.

To improve accuracy for particle sizing, consideration should be given to make use of the complete MIE equations for generating the scattered light intensity distribution. This would account for absorption, refraction, reflection and diffraction. Presently, only diffraction is considered. The result would be an intensity profile that would account for all four phenomena.

The last recommendations concern the use of the high power (250 mW) argon laser. When the laser was operated at high power, the values for transmittance in the combustor did not agree with theory. This was apparently caused by the scattering associated with the beam as it passed through the combustor and windows. When the low power (8 mW) argon laser was used, the transmittance values in the combustor agreed with theory and particle size ( $D_{32}$ ) could be measured. If the use of the high power argon laser is to continue, it should be used on the minimum power setting. The low power argon laser could be used at a different wavelength (.5145 microns), which would give three

transmittance ratios for particle size determination in the combustor.

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