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AN EXPERIMENTAL INVESTIGATION OF SOOTING CHARACTERISTICS OF A GAS TURBINE COMBUSTOR AND AUGMENTOR TUBE

by

Richard Howard Lindsay

September 1988

Thesis Advisor: D.W. Netzer

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Particle size variations within the combustor due to changing variables were documented. Effects of changing variables were dependent on inlet conditions and station. Fuel-air ratio had no effect on combustor or augmentor tube exhaust particle size. Raising inlet air temperature

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An Experimental Investigation of Sooting Characteristics of a Gas Turbine Combustor and Augmentor Tube

by

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Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1975

Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

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Particle size variations within the combustor due to changing variables were documented. Effects of changing variables were dependent on inlet conditions and station. Fuel-air ratio had no effect on combustor or augmentor tube exhaust particle size. Raising inlet air temperature did not significantly alter particle size within the combustor. The smoke suppressant, ferrocene, did not affect particle size uniformly within the combustor but significantly reduced the augmentor exhaust particle size, especially when combined with an increase in inlet air temperature.

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I. INTRODUCTION

The earth's atmosphere has been the recipient of man's technological wastes since the discovery of fire. Nature is able to cleanse combustion products from the air, but the process takes time. The industrial revolution increased the amount of particulate matter being expelled into the air. By the mid twentieth century, nature was no longer able to keep pace and public concern for the environment grew. The Environmental Protection Agency (EPA) has evolved from this early need to control the contaminants being emitted into the atmosphere. Its regulations and guidelines must be met by all industrial facilities.

Particulate and gaseous products of combustion are a major portion of the total source of pollutants or contaminants. Current Navy/Air Force engines all produce products that should be scavenged from the exhaust. Certain products such as soot can adversely affect engine life and reliability by collecting on internal surfaces, causing uneven heat distributions. Although the EPA's regulations only apply to ground engine testing of military engines, it would be advantageous to develop engines that emit less pollutants.

Periodic ground maintenance and testing of high performance engines requires facilities that provide realistic static test conditions. Most major shore facilities have several engine test cells and/or a hush house in which to conduct engine operations. Most test cells were originally designed to prevent re-ingestion of exhaust gases into the engine by passing them through an augmentor tube and into an exhaust stack and then into the atmosphere, cooling in the process. The facilities in use today were designed and built prior to current EPA regulations. They were not designed to remove pollutants from the exhaust and the cost of modifying them is often prohibitively expensive. One alternative solution is to put additives into the fuel that alter the combustion products.

Students at the Naval Postgraduate School began continuing research on the effects of fuel composition and additives on exhaust soot concentration in 1982. A full scale gas turbine combustor test facility has been developed. The combustor section of an Allison T-63-A-5A engine has been modified to allow the use of "IN SITU," nonintrusive, optical technique for combustion particle sizing. The combustor, complete with an aft pressure chamber, has three optical ports through which various lasers and light sources are transmitted. An instrumented augmentor tube, performing much like current test cell augmentor tubes, and an augmentor exhaust test stand provide particle size data and mass flow information.

One goal of this research has been to find suitable additives and test conditions that will significantly reduce the pollutants produced by gas turbine engines. In addition, the investigations have attempted to produce data which can be used to better identify how and where the additives work. Different fuels, additives, fuel-air ratios, air inlet temperatures and flow rates have been used in the test facility in order to explore their effects. This thesis effort was a continuation of the efforts of Grafton [Ref. 1], Young [Ref. 2], Urich [Ref. 3], and Jway [Ref. 4]. Previous work had not been able to obtain consistently accurate particle size correlation from the three-wavelength light transmittance and two-angle forward scattering measurements. In addition, determination of the changes in soot size and concentration through the engine and across the augmentor tube had received only limited attention. The following objectives were set as reasonably achievable within the timeframe allotted for the investigation.

(1) Accurately determine particle size within the T-63 combustor and aft pressure chamber by using three wavelength transmittance measurements.

(2) Determine the effects of various additives, inlet air temperatures, and fuel-air ratios on exhaust particle sizes.

(3) Determine the effects of the augmentor tube on particle growth.

II. EXPERIMENTAL APPARATUS

The apparatus used in this experiment consisted of an Allison T-63-A-5A Gas Turbine combustor (Figure 1), as modified by Grafton [Ref. 1]. Improved optical hardware were designed for more consistent data collection. The four inch diameter augmentor tube was modified so that augmentor tube exhaust pressure profiles and temperature data could be obtained.

A. COMBUSTOR

No major changes were made to the combustor utilized by Grafton. A new ignitor plug was obtained and installed prior to data runs. All optical port windows were removed, cleaned, checked for scratches and cracks, and replaced if required.

B. AIR SUPPLY

Compressed air to the main combustor and quench manifold system was provided from a 3000 PSI tank storage system (Figure 2). The system was extensively overhauled; all tanks were removed, scraped, painted, and hydrostatically tested prior to reassembly. Two pressure relief valves, one in each supply line, were installed prior to the main supply valve. Both banks of tanks had the relief valve set for 3200 PSI.

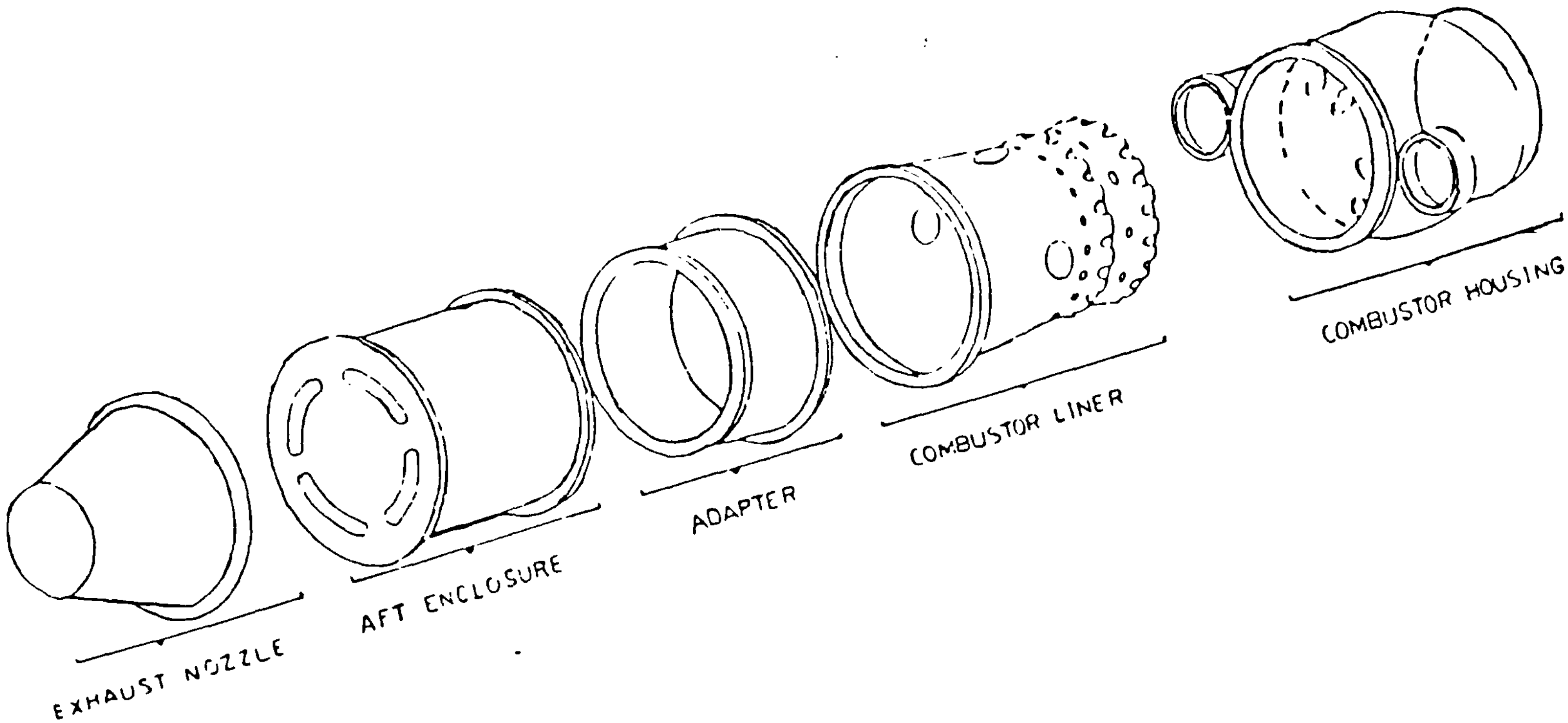


Figure 1. Schematic of T-63 Combustor Components [Ref. 1]

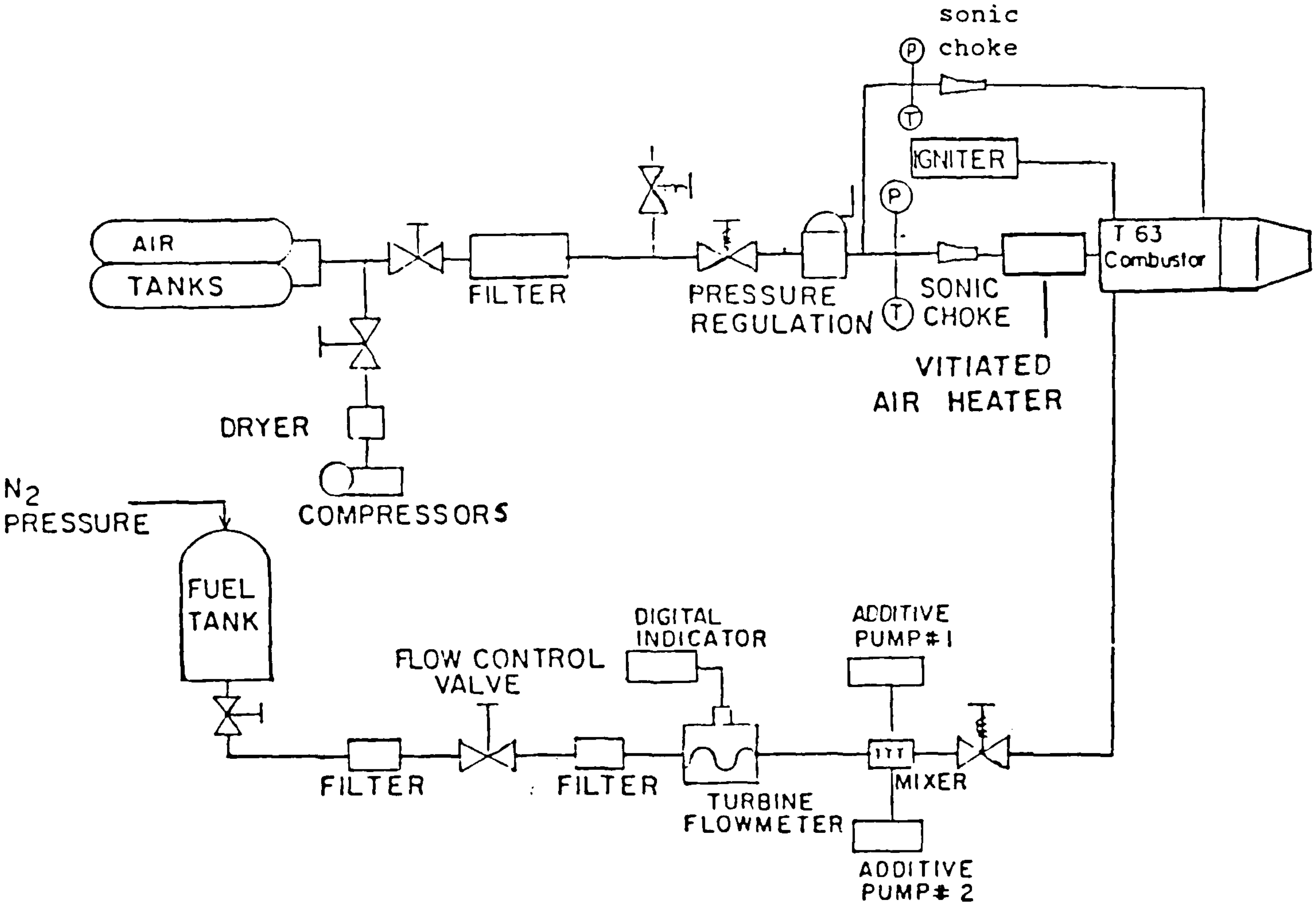


Figure 2. Schematic of Air and Fuel Supply Systems (Adapted from [Ref. 1])

A dome loaded pressure regulator, operated from the control room, provided a stable pressure through the main air sonic choke. Because the gas generator did not have a turbine, a downstream quench system was added by Grafton to simulate the temperature drop which results from work extraction by a turbine. The quench air system takeoff was prior to the main air sonic choke. The desired ratio of primary air flow rate to quench air flow rate was obtained by selecting the sonic choke areas which were supplied with a common upstream pressure. Temperature and pressure readings at these sonic chokes were used by the computer to calculate the mass flow rates. A hydrogen-fueled vitiated air heater with oxygen make-up was used to vary the combustor air inlet temperature.

A second compressor was installed in order to significantly reduce the time required to recharge the tanks between tests. An in-line air drier system effectively removed all moisture from the air. This greatly reduced the condensation which was observed in previous experiments.

C. FUEL SUPPLY

Metered fuel was supplied to the combustor through a fuel atomizer at the dome of the combustor (Figure 2). The fuel was stored in a pressure regulated tank that was controlled from the control room. Capacity of the tank was 20 gallons. Fuel flow rate, in gallons per minute, was read directly from a digital display of an in-line turbine flow meter and also recorded by the data acquisition system. The metered flow and additive pumps are discussed by Young. [Ref. 2] Ten different fuels (Table 1), designated by Naval Air Propulsion Center (NAPC), were available for study.

D. THERMOCOUPLES

The location and use of seven of the eight thermocouples utilized in this experiment are discussed in detail by Grafton [Ref. 1]. The eighth thermocouple was added to the aft portion of the augmentor tube so that augmentor exhaust total temperature data was available. All thermocouples were Chromel-Alumel and the computer was programmed to convert analog readings into temperatures for printout.

E. AUGMENTOR TUBE

In addition to the thermocouple, a small .050 inch diameter static pressure port was added to the aft end of the 4" diameter tube. The tube itself was six feet long and was securely mounted on a portable test stand. The stand was bolted in position whenever the engine was run. The augmentor test stand (Figure 3) was modified to accept a pressure rake to provide accurate stagnation pressures at the augmentor tube exhaust, and to mount a one inch diameter stainless steel tube used to direct the exhaust to a Malvern particle sizer.

TABLE 1

PHYSICAL AND CHEMICAL PROPERTIES OF FUELS [Ref. 6]

	1 (SUNTECH 1)	2 (SUNTECH 2)	3 (SUNTECH 3)	4 (SUNTECH 4)	5 Low Aromatic JP-5	6 Fuel Oil No. 2	7 Hydrocracked Gas Oil / JP-5	8 Diesel Fuel Marine / JP-5 50/50	9 High Aromatic JP-5	10 Oil Shale JP-5	Specif. MIL-T-5624L Requirement
API Gravity @ 15°C	38.9	37.8	41.3	41.6	41.8	37.1	35.6	38.9	40.5	43.7	37.0-48.0
Distillation (ASTM) IBP °C	163	168	171	180	181	153	193	180	190	184	---
Recovered 10%, max.	190	227	192	202	199	218	204	204	204	193	205
Recovered 20%	207	242	203	210	203	232	209	213	208	196	---
Recovered 50%	247	257	227	228	217	266	226	237	218	205	---
Recovered 90%	276	272	261	264	243	317	272	297	246	231	---
End Point, °C, max.	297	281	276	282	261	333	288	323	264	257	290
Residue (ml), max.	2.0	1.8	1.4	1.4	1.2	2.8	3.6	2.9	1.4	1.2	1.5
Loss (ml), max.	0.9	0.2	0.1	0.5	0.2	0.0	0.4	0.0	0.5	0.4	1.5
Composition Aromatics (vol%), max.	28.5	19.8	22.8	18.6	15.9	25.0	26.4	18.6	22.7	21.8	25.0
Olefins (vol%), max.	1.79	0.81	0.75	0.79	0.79	1.40	0.86	0.70	1.62	1.60	5.0
Hydrogen Content,(wt%), min.	13.36	13.48	13.66	13.82	13.79	13.22	12.83	13.54	13.49	13.70	13.50
Smoke Point, mm, min.	17.0	18.0	20.0	21.0	21.0	17.0	14.0	16.0	21.0	21.0	19.0
Aniline - Gravity Prod., min.	5,360	5,557	5,811	6,140	--	5,661	4,254	5,648	5,471	6,022	4,500
Freeze Point, °C	-30	-24	-34	-34.5	-50.0	-3.0	-31.0	-10.5	-53.0	-49.5	-46
Viscosity @ 37.8 °C, (cSt)	1.78	2.27	1.62	1.74	1.58	2.60	1.77	2.06	1.50	1.38	---
Temperature @ 12 cSt, (°C)	-30.6	-20.6	-35.6	-31.7	-35.5	-13.3	-30.6	-23.3	-35	-34.4	---

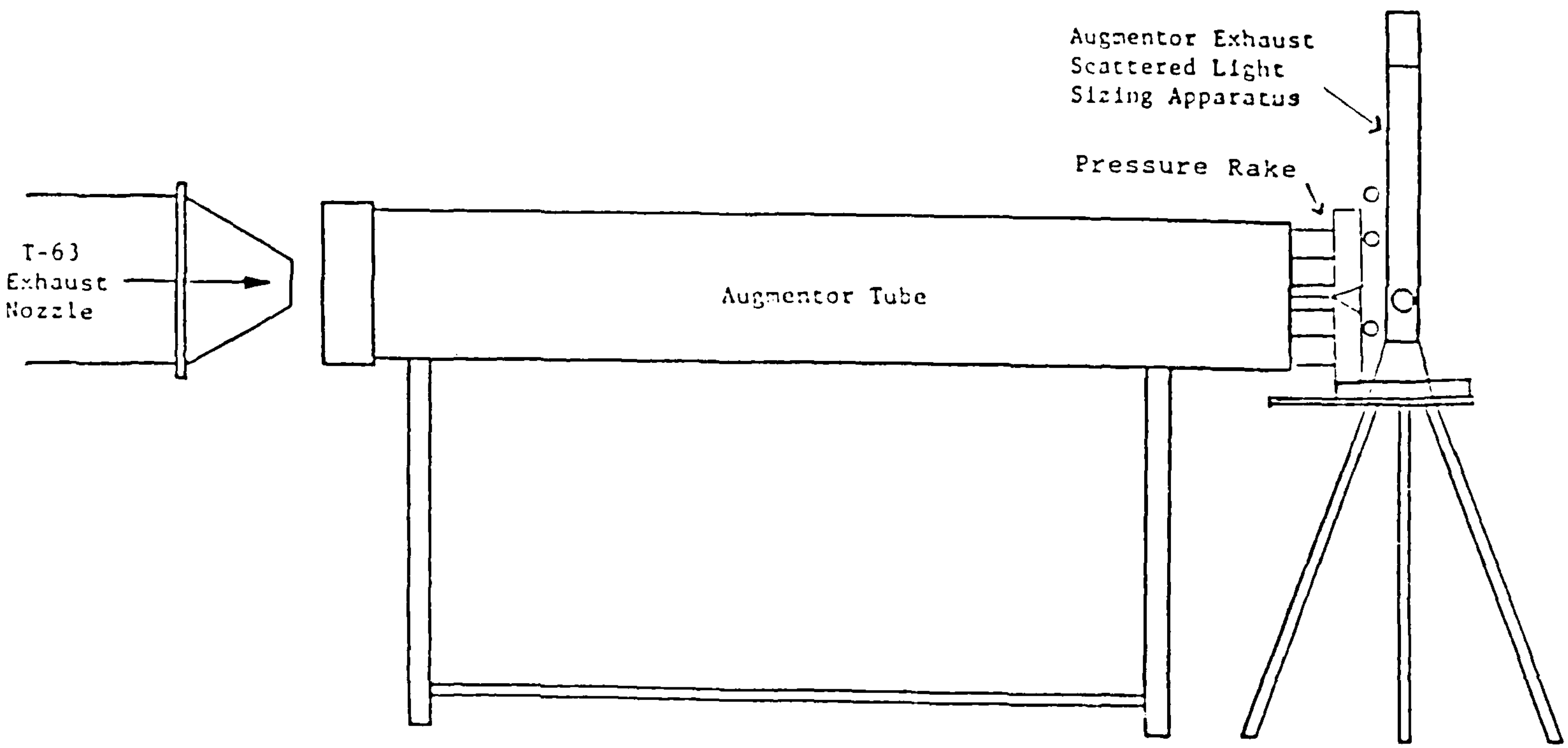


Figure 3. Side View of T-63 Augmentor Tube and Test Stand
(Adapted from [Ref. 1])

F. OPTICS

The optical measurement apparatus consisted of two three-wavelength light transmittance setups and three forward light scattering setups (Figure 4). The two combustor scattering measurement systems each used two scattering angles; the one used at the augmentor exit used three angles. Hardware details of each follow; theoretical development is contained in Chapter III.

1. Light Transmittance

Two different configurations of three-wavelength transmittance systems were installed. The forward combustion section utilized three separate laser sources (488, 632.8, and 1532 nm), each aligned and transmitted through the combustor can by the use of cube beamsplitters (Figure 4). The aft combustor transmittance system consisted of a white light source with a wavelength spectrum of 400 nm to approximately 1020 nm. Wavelengths of 450, 650, and 850 nm were utilized. The beam was collimated and reduced prior to being transmitted through the aft pressure chamber. Early experiments indicated that a reflection or interference was present from the large diameter collimated white light beam. A simple diaphragm was installed between the collimating lens and the engine window to reduce this beam.

The two light collection boxes (Figures 5 and 6) were nearly identical. Each box contained three photodiode

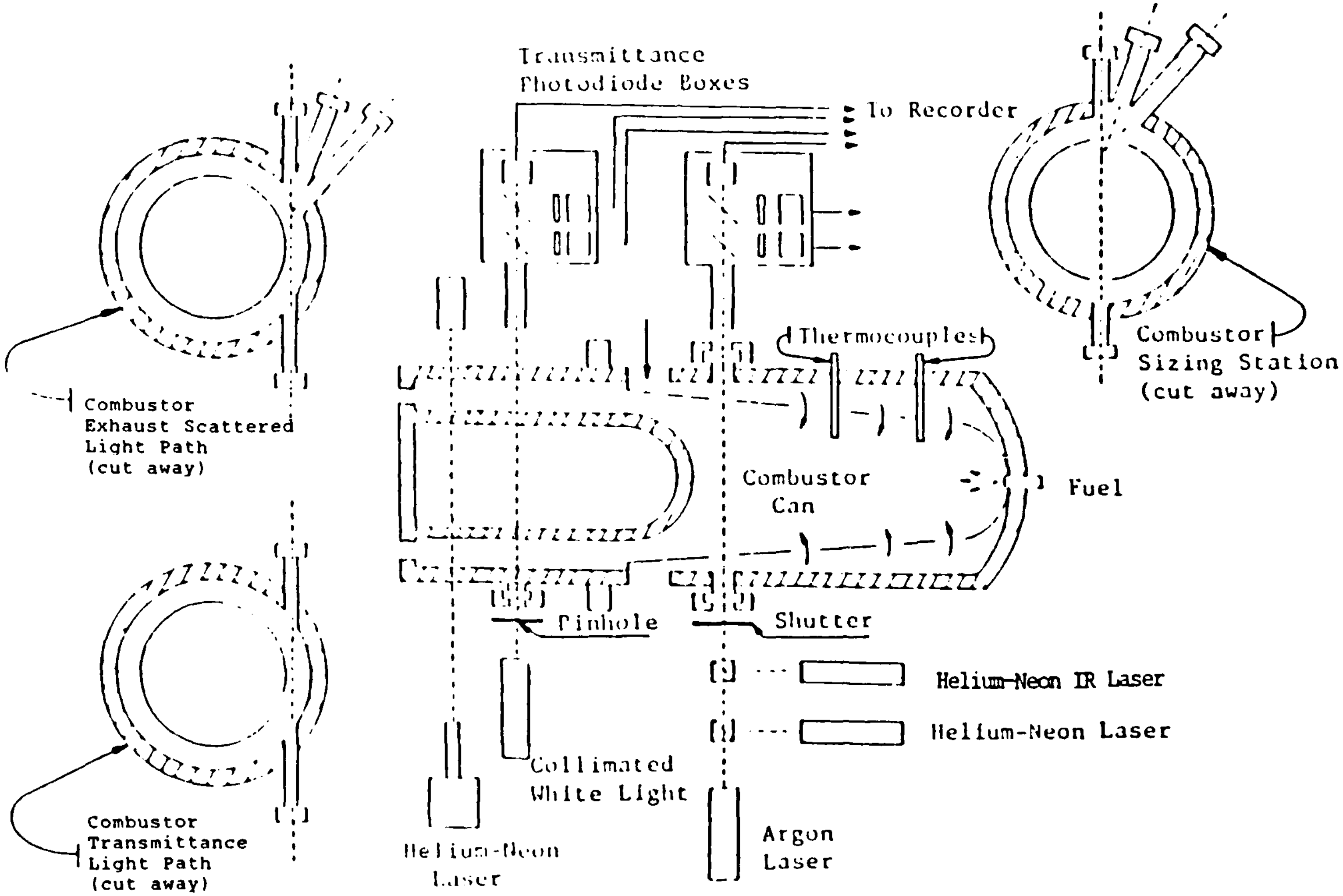


Figure 4. Schematic of T-63 Optical Test Apparatus
(Adapted from [Ref. 1])

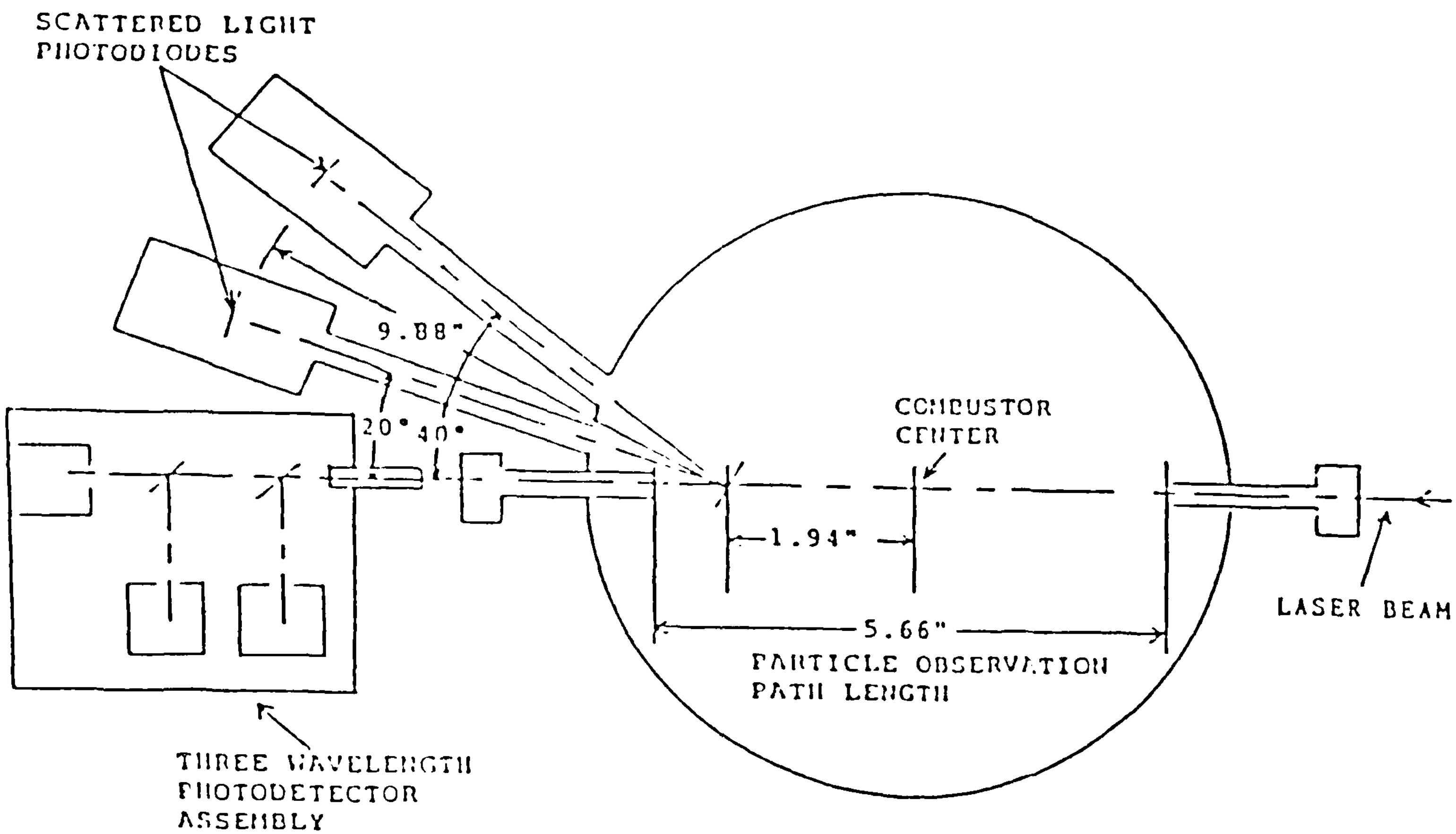


Figure 5. Diagram of T-63 Combustor Transmittance and Forward Light Scattering Apparatus (Adapted from [Ref. 2])

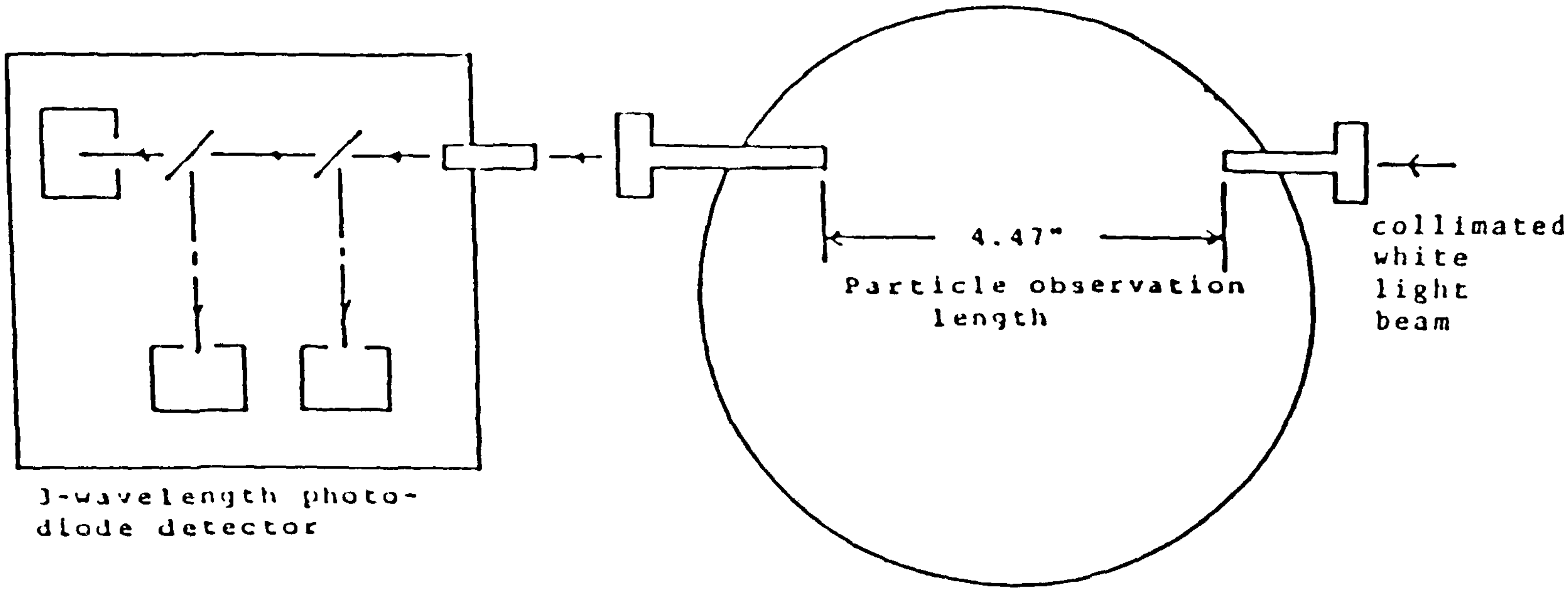


Figure 6. Diagram of T-63 Aft Chamber Transmittance Apparatus
(Adapted from [Ref. 2])

assemblies, each with its own narrow band filter. The incoming beam was directed onto the face of the diode by plate beamsplitters. Each photodiode detector, except the 1532 nm (IR) detector, had a preamplifier incorporated in the assembly. The amplifier for the 1532 nm signal was external to the box.

2. Light Scattering

The two-angle forward scattering system for the combustor (Figure 5) utilized the 632.8 nm wavelength laser source from the three laser transmittance set. Photodiode detector boxes were mounted at 20 and 40 degrees with a focal point in the laser beam 1.94 inches offset from the center of the combustion chamber. The aft pressure chamber scattering system also utilized a 632.8 nm laser source. The detector boxes were mounted at 20 and 40 degrees and focused on a laser beam transmitted through the outer (annular) volume of the chamber (Figures 4 and 7).

The third scattering system used a 488 nm laser source and three improved light collection tubes mounted at angles of -05, 10, 20 degrees. Each collection tube (Figure 8) had a 1.75 inch diameter lens that focused the scattered light through a .05 inch diameter diaphragm. These tubes replaced earlier tubes, of only .5 inches in diameter, that were not able to collect enough scattered light energy from the particles passing through the laser beam scattering volume. The larger tubes and lenses increased the capture

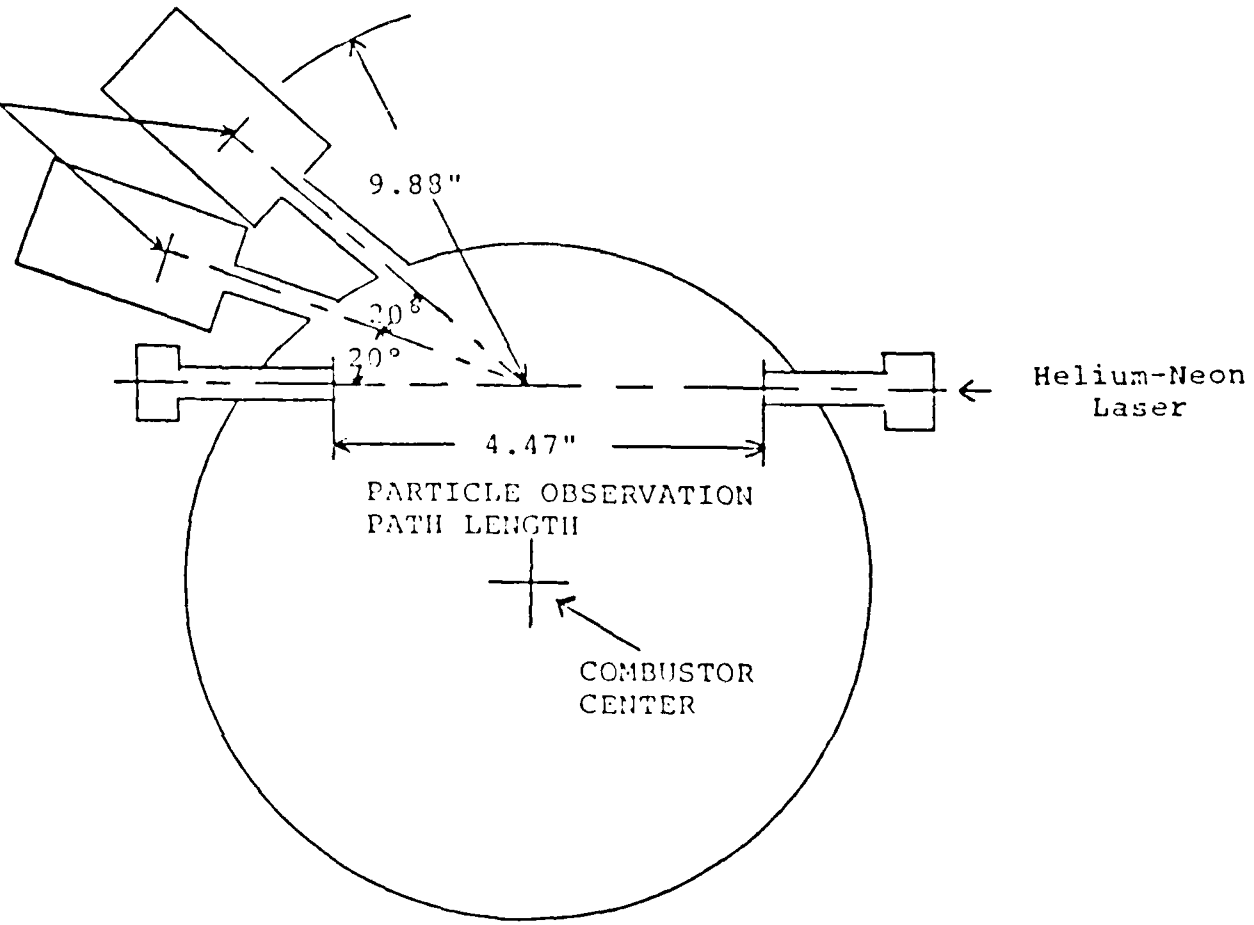


Figure 7. Diagram of T-63 Aft Chamber Forward Scattered Light Apparatus (Adapted from [Ref. 2])

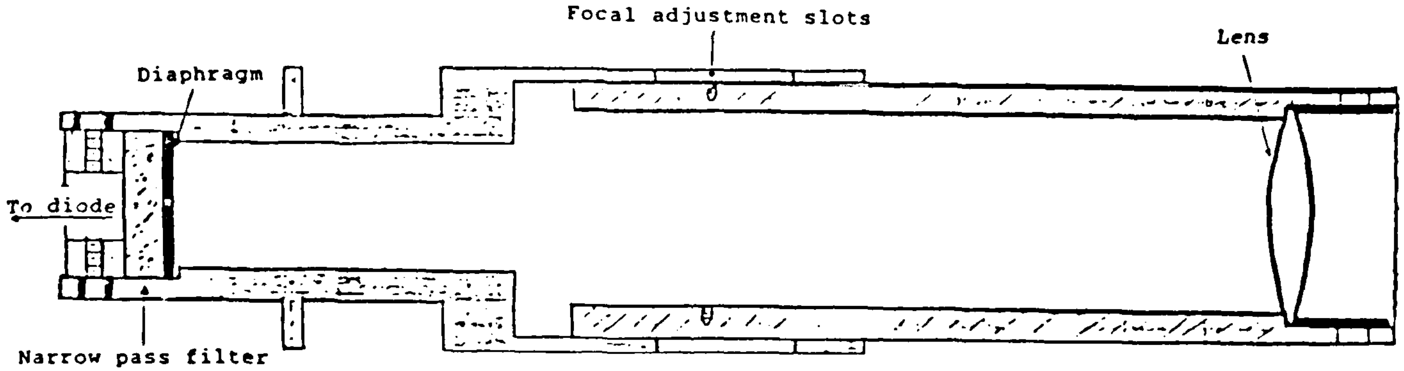


Figure 8. Diagram of Augmentor Scattered Light Collection Tube

volume and focused the total energy onto the photodetectors mounted directly to the aft end of each tube.

All three systems had a chopping capability designed to determine background light intensities. The combustion chamber system utilized an electrically actuated shutter that was programmed to close at varies times during data collection. The aft engine exhaust laser system did not incorporate a shutter, but rather cycled the laser off when background data was desired. The augmentor test stand shutter was not required and, therefore, not installed. The augmentor test stand is shown in Figure 9.

3. Malvern Particle Sizer

The Malvern 2600HSD particle sizer is a commercially produced particle sizing system capable of determining particles as small as .5 microns. The size range is determined by the installed lens, which for this experiment was a lens with a 63 mm focal length. Set-up and operation was in accordance with the operating and reference manuals provided by the manufacturer.

G. PURGE AIR

A positive pressure purge air system was used to ensure that all optical ports remained clear during engine operation. Earlier testing showed that small amounts of higher pressure air could be fed into the optical ports between the windows and the chamber and that this higher pressure would keep combustion products from collecting on

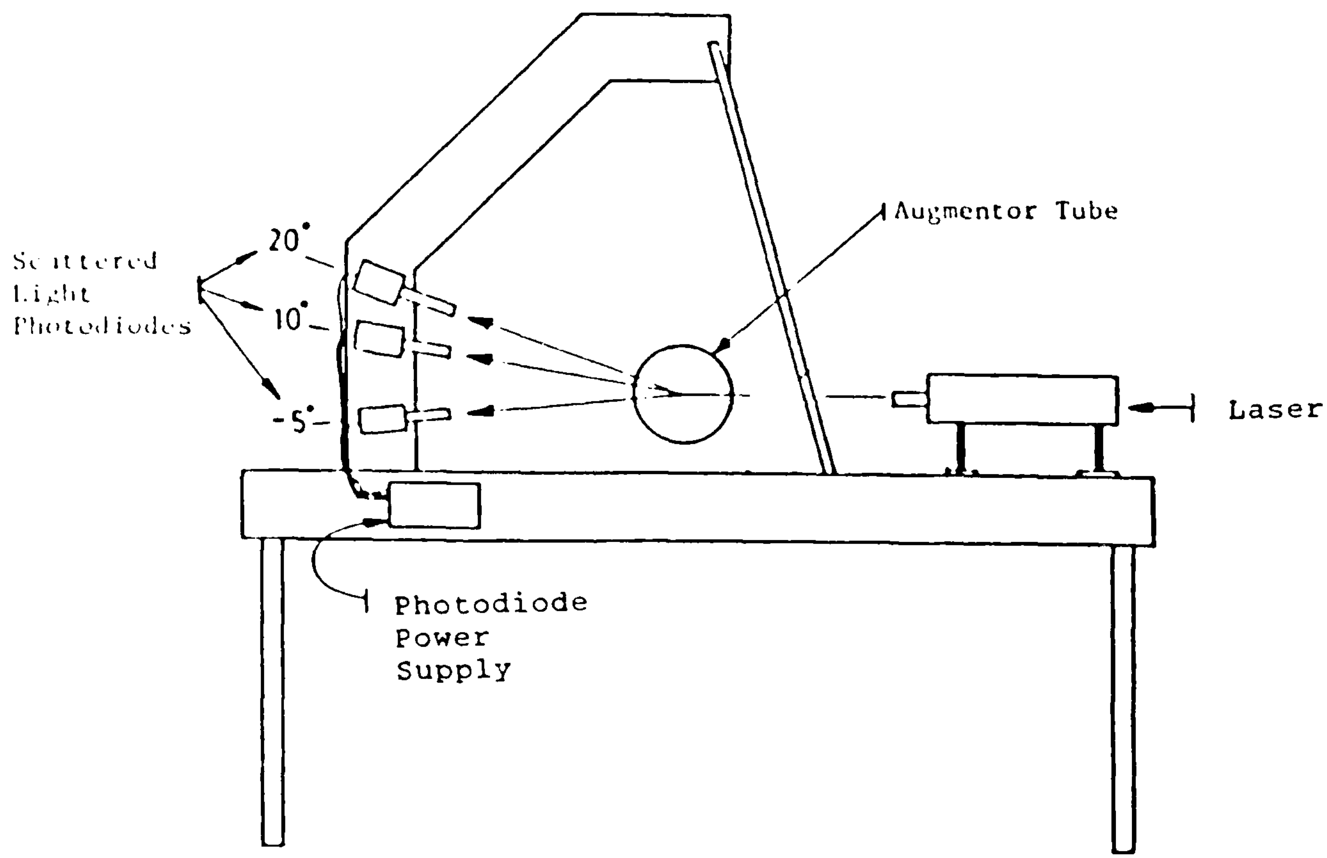


Figure 9. Front View of Augmentor Test Stand and Particle Sizing Apparatus (Adapted from [Ref. 1])

the windows during testing. Compressed air was controlled from the control room and was turned on prior to the main air, in case the chamber was filled with residual particles.

H. CONTROL ROOM

The control room as described by Grafton [Ref. 1] was not altered. Controls for the air, fuel, fuel additives, and the air heater were all mounted at the control panel. A window provided viewing of the cell during testing.

I. DATA COLLECTION

Data collection was accomplished through the use of a Hewlett-Packard data acquisition system. The programming language used was Basic 2.0. The program consisted of four sections: pre-ignition, hot run, hot run with additives, and post-ignition. Subroutines within the program collected pressures, temperatures, fuel flow rates, transmittances, and scattering data during each phase. Real time printouts of chamber temperature and transmittance voltages were also available from three strip charts located in the control room. A hard copy of all data was printed following completion of each run. Data reduction for particle sizing was accomplished by hand.

III. THEORY

This investigation used three optical techniques to determine the particle sizes at different sections of the combustor and augmentor tube. Both the three-wavelength transmittance systems and the forward scattering systems were non-intrusive, thereby eliminating collection probes. These methods did not disrupt the flow patterns and caused no additional agglomeration of particles due to obstructions. An overview of the theory of each system follows.

A. LIGHT TRANSMITTANCE TECHNIQUE

The three wavelength method described by Cashdollar [Ref. 5] was used both in the combustor and the aft pressure chamber. Bouguer's Law for transmittance through a polydispersion is:

$$T = \exp(-(3\bar{Q}C_m L/2\rho D_{32})) \qquad (1)$$

where

T = Transmittance at wavelength

$\bar{Q}$ = Average dimensionless extinction coefficient

C_m = Mass concentration

L = Path length

ρ = Density of particles

D_{32} = Volume to surface mean particle diameter.

Ratioing the logarithms of the transmittances for two wavelengths equates to the ratio of the dimensionless extinction coefficients.

$$\ln T_{\lambda_2}/\ln T_{\lambda_1} = \bar{Q}_{\lambda_2}/\bar{Q}_{\lambda_1} \qquad (2)$$

$\bar{Q}$ is a function of the complex refractive index (m) of the particles, the standard deviation (σ) of the size distribution and the wavelength (λ) of the illumination source. Graphs of extinction coefficient ($\bar{Q}$) versus volume to surface mean particle diameter (D_{32}) and ratios of extinction coefficients ($\bar{Q}_2/\bar{Q}_1$) versus mean particle diameter (D_{32}) were obtained (Figure 10) by using an Extinction Coefficient program obtained from the Pittsburg Mining Center, Bureau of Mines, written by Cashdollar. Different curves were obtained by varying the wavelengths, complex refractive index, and the standard deviation of particle size distribution. The two complex indices of refractions (1.95 - .66i and 1.80 - .60i) and two standard deviations (1.5 and 2.0) for a log-normal distribution used in this investigation were based on previous studies of carbon based soot particles. [Ref. 6]

The data reduction procedure for one measurement location consisted of obtaining three T_{λ} values from the

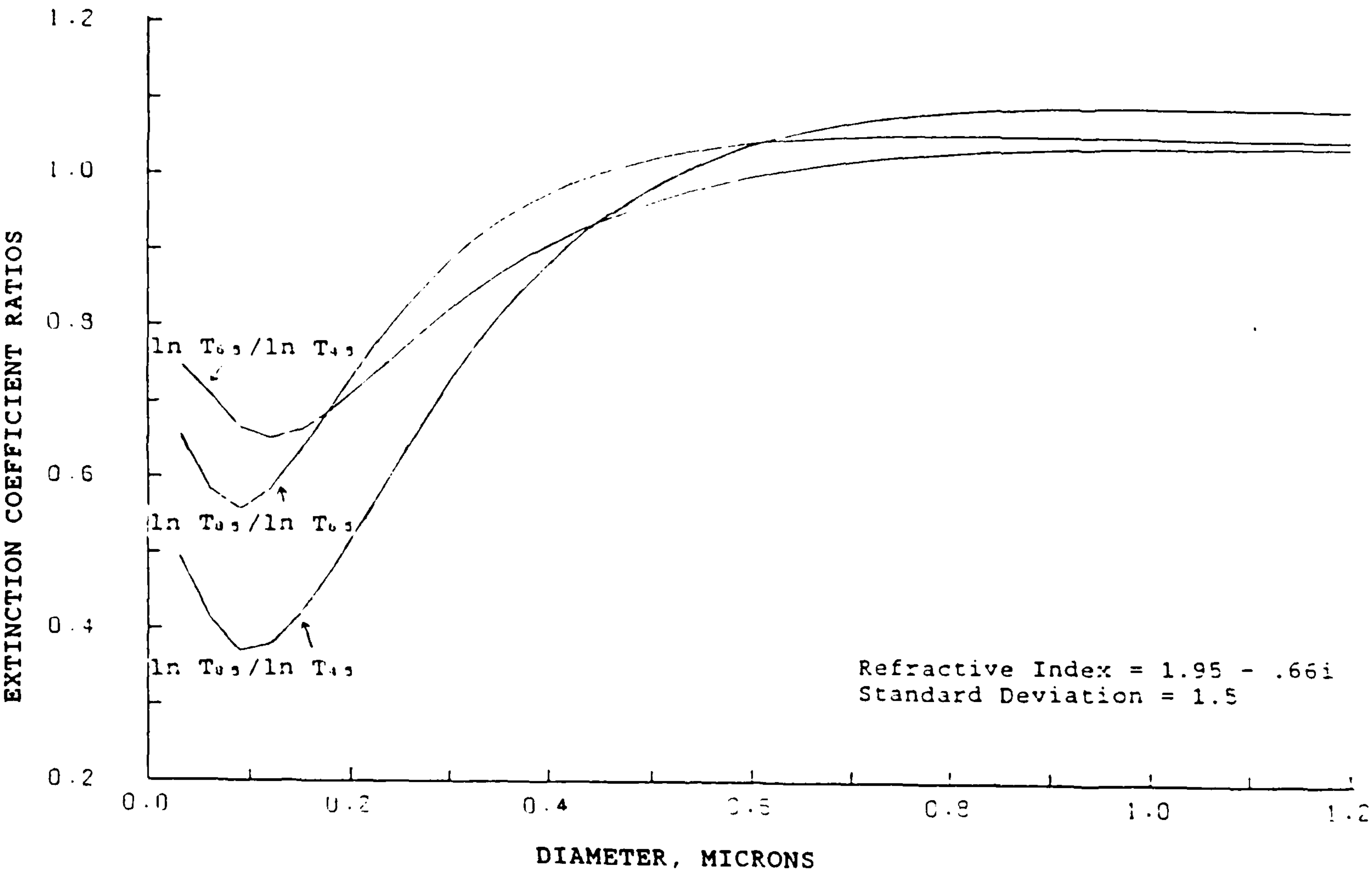


Figure 10. Extinction Coefficient Ratios vs. Particle Size (D_{32})

computer printout, corrected for zero voltage readings. By ratioing the logarithms of the three transmittances, three extinction coefficient ratios were obtained. Assuming the correct values of m and σ were used, the three ratios, when marked on the appropriate ratio curves, would align vertically over the correct D_{32} value. If they were not aligned, the ratio values were entered on curves obtained with different m or σ values.

There were several advantages to using three wavelength transmittance measurements within the engine. In addition to being non--intrusive, this method also provided an inexpensive, low power technique that required little data reduction. The measurements are also applicable to flows with low opacity. Continuous data measurements were also made in analog form to record diode voltage outputs on two separate strip charts. Each chart was used as a backup to the computer obtained data.

One disadvantage of this method was having to assume both an index of refraction (m) and a standard deviation (σ) of either 1.5 or 2.0. Each were also assumed to be constant over the range of wavelengths used in this investigation.

B. FORWARD LIGHT SCATTERING

Mean particle size can also be determined by measuring the scattered light at different scattering angles. Placing boundary conditions on the soot particle size parameter ($\alpha = \pi D_m/\lambda$) of approximately 4 allows the complicated MIE electromagnetic theory of light scattering to be reduced to Fraunhofer diffraction theory. If ratioing techniques are employed [Ref. 7] values of $\alpha = 1.0$ have resulted in good measurements. The method has been applied by Powell, et al. [Ref. 8] to measure soot particles of $D_{32} = 0.16$ microns with $\alpha = 1$ and $\lambda = 488$ nm. Fraunhofer diffraction thus gives: [Ref. 8]

$$I(\theta_1)/I(\theta_2) = F(\theta_1)/F(\theta_2) \tag{3}$$

where the Fraunhofer function is given by

$$F(\theta) = \int_0^1 1+\cos^2\theta[J_1(\alpha\theta\varepsilon)/\theta\varepsilon]^2 \exp[-(\delta \ln(\alpha\varepsilon/1-\varepsilon))^2]d\varepsilon/1-\varepsilon \tag{4}$$

In this expression

$\varepsilon = D/D_m$

D_m = maximum particle diameter

J_1 = 1st order Bessel Function

a and δ = upper limit distribution function parameters.

The Malvern particle sizer was the third technique used. It also is based on Fraunhofer diffraction theory and uses a semi-circular ringed array of photodetectors to gather forward scattered light. The system is said to be capable of sizing particles as small as .5 microns. Particle distributions can also be obtained from this system.

The forward scattering systems installed in the combustor did not utilize a third angle, as these systems were intended to validate the data obtained using measured transmittances. The additional augmentor tube scattering angle provided three ratios in order to significantly improve the confidence in size determination for particles exiting the augmentor tube.

Diffraction is caused by light passing near a particle, and should not be confused with either reflection or refraction. Thus, the ratios of diffractively scattered light intensities are insensitive to the particles refractive index or mass concentration [Ref. 8].

Assumming a monomodal distribution and fixing α, θ, a and δ, Fraunhofer functions (using Equation (4)) were computed by numerical integration. Typical a and δ values were used, i.e., $a = 1.13$ and $\delta = 1.26$ [Ref. 8]. Increments of integration were $d\varepsilon = 0.1$ and D_{32} ranged from 0.05 to 1.00 microns. Values for wavelengths of 488 nm and 6328 nm were ratioed and plotted versus D_{32} (Figures 11 and 12). The measured intensity ratios were equated to these F-ratio values, and were used to determine mean particle diameter.

The measured diode voltages at the exit of the augmentor tube did not have to be normalized to the equivalent capture volume because each collection tube captured the entire four inch width of the augmentor tube. Therefore, multiplying the diode voltage by the sine of the scattering angle was

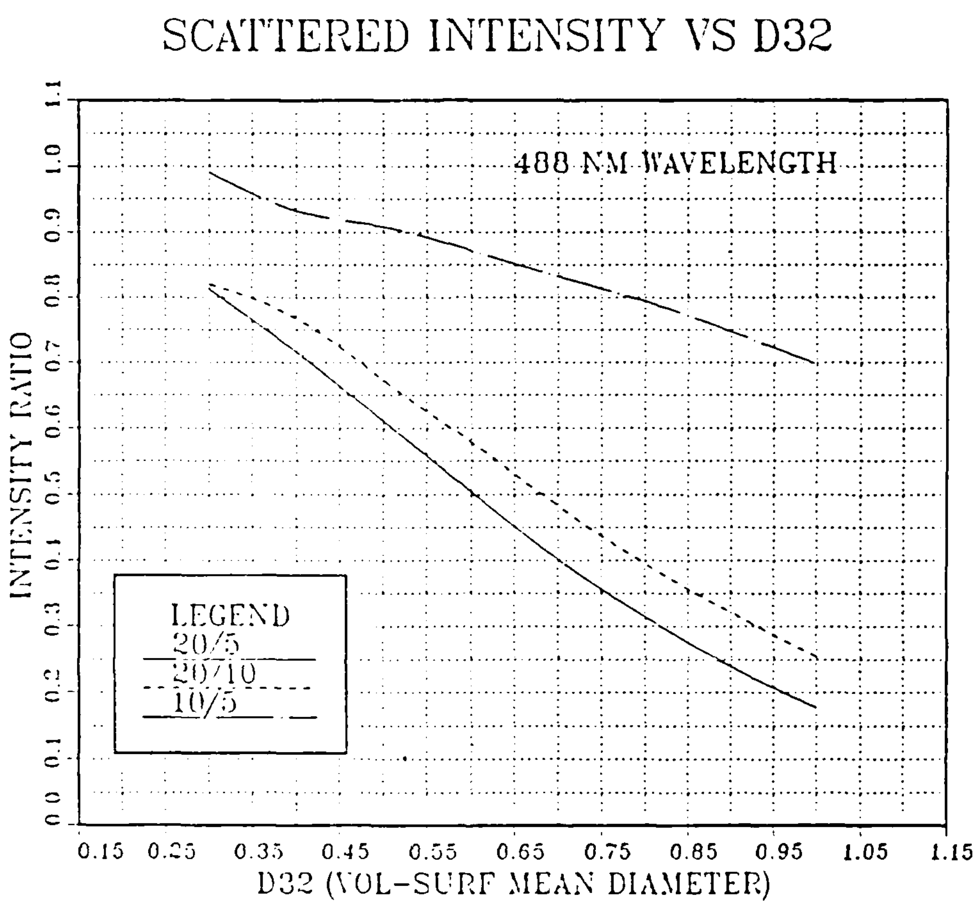


Figure 11. Three Angle Intensity Ratios vs. Particle Size (D_{32}) for 488 nm Wavelength Light

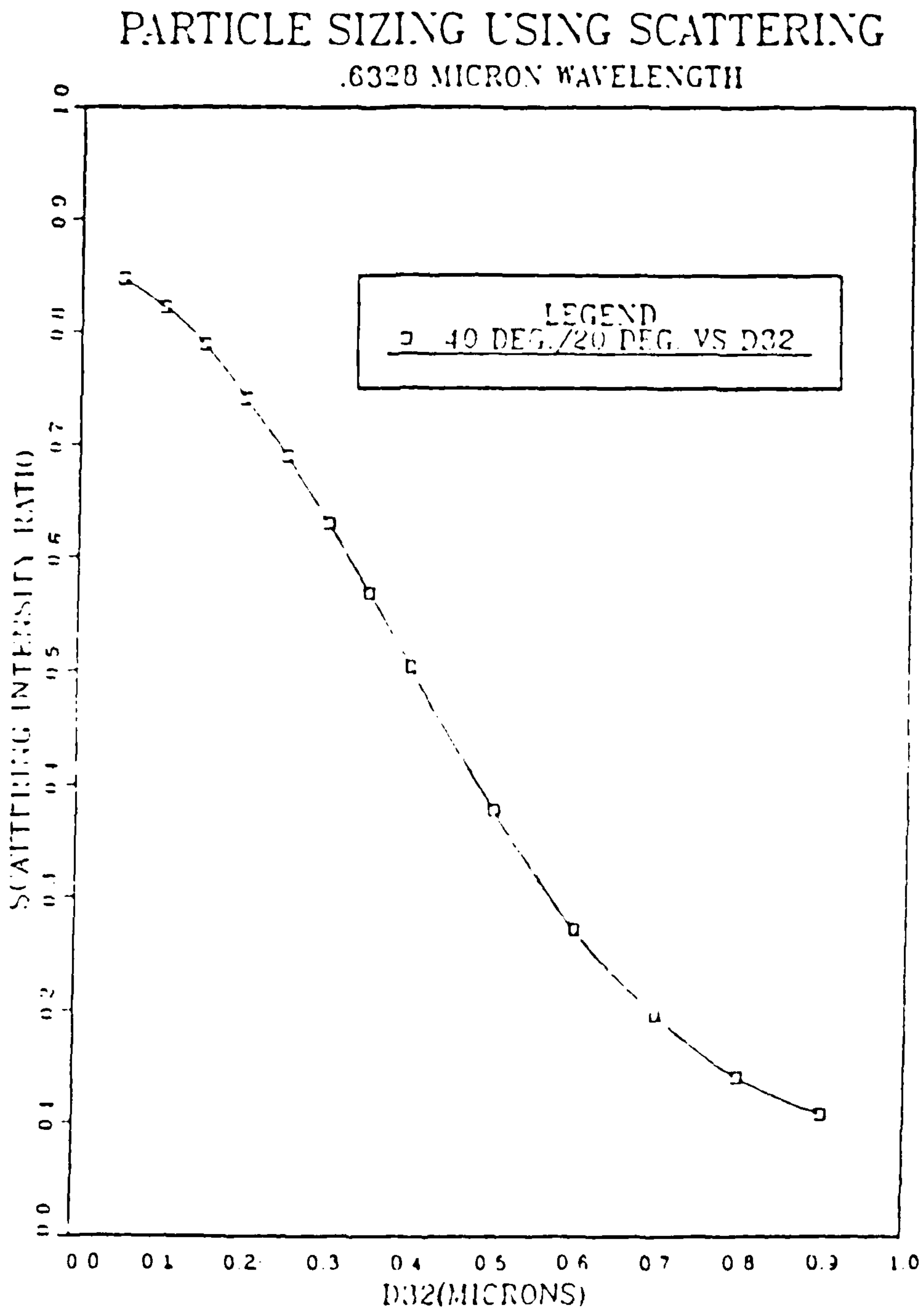


Figure 12. Two Angle Intensity Ratio vs. Particle Size (D_{32}) for 632.8 nm Wavelength Light [Ref. 1]

not required. Calibration constants, determined by ratioing voltages from a known power source, were originally used to relate voltages to intensities. Later, absolute intensity values were computed and then ratioed. Matching values to curves on Figures 11 or 12 identified the mean particle diameter.

The obvious advantage of this method is the independence of particle size on refractive index or mass concentration [Ref. 8]. Fraunhofer theory was applicable and values were easily calculated. However, these curves approached horizontal towards the limits for D_{32} and the curves were accurate over a limited middle range. Measurements at a minimum of three angles are required if accurate particle sizing is to be obtained from only forward light scattering.

Using both transmittance and forward scattering measurements significantly increases the confidence in the computed D_{32} values, and verifies the assumed refractive index used in the transmittance data reduction. A typical procedure is shown in Figure 13. Mass concentration can be determined from the extinction coefficient and measured transmittance at a particular wavelength, utilizing the steps found in Figure 13. Changes or variations of mass concentration could thus be determined at two separate locations within the combustor.

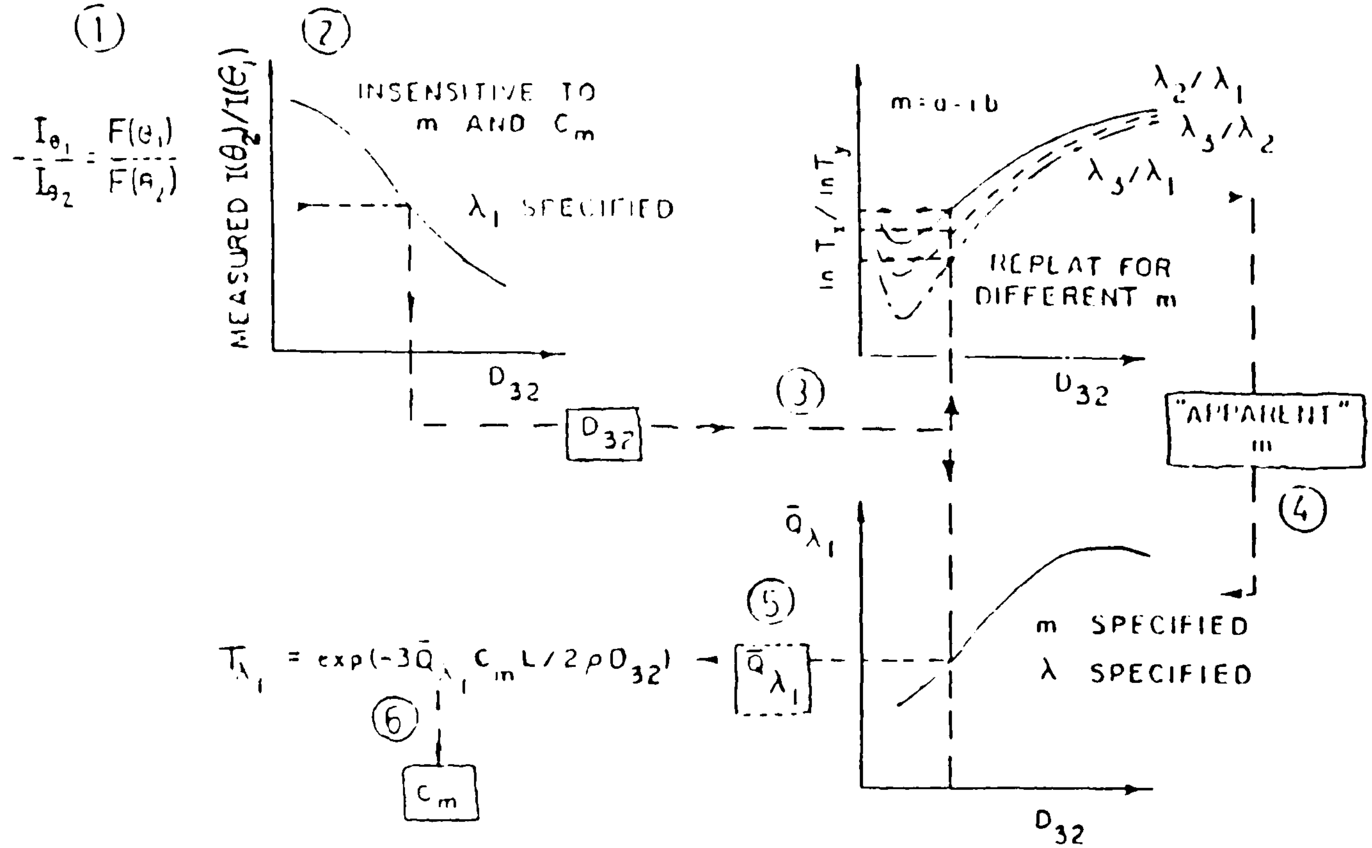


Figure 13. Determination of C_m [Ref. 1]

IV. EXPERIMENTAL PROCEDURE

The majority of the experimental procedures described in this section were repeated prior to each data collection run. The pressure transducers and photodiode boxes were periodically checked for calibration constant stability. Optical alignment proved to be the most demanding repetitive pre-run check, as minor alignment errors rendered data invalid.

Transducer calibration was accomplished by using a dead-weight tester and executing the calibration subroutine within the main T63 data acquisition program. Calibration was required on the main air, quench air, chamber pressure, and air heater fuel and oxygen transducers. Calibration values were manually updated in the main program.

The laser power and filter checks reported by Grafton [Ref. 1] were repeated except for the new 1532 nm InfraRed laser. Because differentials and ratios were used, exact power levels of each laser were not required. The voltage output of the IR photodetector was steady, thus the laser output was assumed to be steady.

Optical alignment of the three lasers of the combustor transmittance system was accomplished using two cube beamsplitters (Figure 4). The alignment of the 488 nm and 632 nm lasers could be visually checked against a flat black background. Coincident beams appeared as a bright white spot. The IR laser however, was much more difficult to align, requiring a hand held IR detector to indicate the beam positioning. Precision positioning of the IR laser was improved by mounting it on a traversing platform. Aligning the white light source through the aft exhaust chamber was comparatively easy. Proper alignment was assured when a reduced beam was aligned with cross hairs placed on each optical port.

The two transmittance boxes (Figures 5 and 6) were mounted on magnetic bases that gave good flexibility in positioning. They were also quite susceptible to accidental movement. Each box could be swiveled vertically and horizontally. Rotatable plate beamsplitters within the transmittance boxes directed the beams onto the face of the photodiodes. The photodiode boxes could be shimmed to ensure the incident beams were perpendicular to and aligned with the exact centers of the photodiodes.

Wooden covers were designed and built to house the lasers, white light source and optics. They proved successful in containing the laser energy, keeping the optics clean, and protecting that part of the system from accidental movement. Each cover was easily removable to allow for refined alignment. However, once the sources were aligned they tended to remain that way for some time.

Alignment of the three augmentor tube scattering diodes required the manufacture of a rotatable mirror that could direct a laser beam at any angle. Mounting the mirror such that the beam was bisected by the mirrored surface, small rotations of the mirror caused the beam to be directed (reflected) through .05 inch holes drilled in the scattering tube covers. Each tube was shimmed and aligned so that each was saturated when the beam passed through the lens cover. By ensuring the mirror was rotated about its centerline, the reflected beam originated from the same point in space and thus, each scattering tube was focused on that same point. Unfortunately, the laser used for the beam source could not be mounted permanently and the entire system required alignment prior to every run. Such exact alignment of the two engine mounted scattering systems was not possible. The stationary tubes were visually sighted on a laser beam utilizing blown smoke, but there was little assurance that both tubes of either system were aligned on the same point in space.

Strip chart recorders for the two transmittance systems were readied by covering the optical port of each transmittance box and setting the zeros on a base line. Full scale deflections were checked after uncovering the ports. Calibration was not required as differentials and ratios were used in data reduction. Zero values were also recorded using the acquisition system's DVM for later use in data reduction. One strip chart was capable of recording the augmentor scattering system data, providing an analog record of scattering voltages during certain developmental runs. Set up procedures were the same.

A pre-run check of air mass flow rate was done using a computer subroutine prior to any actual data run. Even though the engine was not going to be ignited, purge air was used to ensure residual particles, present within the engine, did not contaminate the windows. The computer recorded and printed both main and quench air flows. If the set values were acceptable the program was continued, otherwise the flow rates were changed and the check was repeated.

The T63 data acquisition and control program conducted the test in four major sections; pre-ignition, hot run, additive run and post-ignition. Within each of these sections data collection subroutines were called. The entire test was semi-automatic; prompts were displayed on the screen after each subroutine, requiring the operator to strike the continue key before proceeding.

All controls for the fuel, air, additives, and air heater were located in and operated from the control room. Engine ignition was accomplished by energizing the ignitor two seconds prior to turning on the fuel flow. A white cloud was emitted from the augmentor tube if the fuel failed to ignite. This occurred several times early in the experimental buildup and required replacement of the ignitor. Temperature stabilization was checked by observing the analog output reading before proceeding to collect the hot run data. The combustor was secured by first selecting the fuel switch off and then immediately continuing with the post-ignition data collection. Any differences between post-ignition data and pre-ignition data were attributed to accumulation of combustion products on the windows or possible optical movement during the test run. Post ignition data was crucial to accurate data reduction. Main air flow continued for a short period after this data was collected to cool the engine and augmentor tube. Window purge air was secured after the main air.

Data reduction was accomplished by hand, utilizing the steps outlined in Chapter III. Transmittance values were obtained from both the computer printout and the three-pen strip charts. The differential of laser-on and laser-off intensities was ratioed with the 100% air post-ignition value to obtain the transmittance for each wavelength. Natural logarithms of each were ratioed and the values were plotted on the extinction coefficient ratio graphs (Figure 10).

Scattering data from each station was printed as a voltage value and as a relative intensity value. The intensity value was obtained by normalizing from the photodiode calibration curves. Ratios of these intensity levels were matched to the Fraunhofer diffraction curves (Figures 11 and 12) to obtain mean particle size. Mass concentrations (C_m) could be obtained by using data as described in Chapter III.

The Malvern particle sizing apparatus was also used to attempt determination of the particle size distribution exiting the augmentor tube. A one-inch diameter stainless steel tube was placed in the exhaust flow and directed the captured flow to the Malvern system. With steady state conditions, the Malvern was activated and a particle size distribution was obtained. Remote activation was accomplished from the control room, but was not integrated into the T63 computer program.

V. RESULTS AND DISCUSSION

The three objectives of this thesis were to: 1) obtain consistent particle sizes using three wavelength transmittance measurements, 2) determine the effects of fuel composition, additives, fuel-air ratio, and inlet temperature on particle size, and 3) determine particle size at the augmentor tube exhaust utilizing forward light scattering. The test series began with numerous developmental firings and preliminary data collection runs using NAPC fuel #4 (Table 2). Procedures were developed and suitability of transmittance theory for particle sizing was validated during these initial runs.

The next 15 data collection runs were made using NAPC fuel #1; the first seven attempting to incorporate the Malvern 2600HSD Particle Sizer for determining augmentor tube exhaust particle size. The next eight runs used the three-angle forward scattering method. Four non-additive test runs were then made with a fuel with a lower hydrogen content, NAPC #7. Next, four runs were made using the vitiated air heater to raise air inlet temperature by as much as 305^{o} F. With the air heater still working, NAPC fuel #7, with a smoke-suppressant (Ferrocene) added, was next burned in the combustor. Instead of using the additive pumps, the smoke-suppressant was batch mixed (8 ml per gal)

TABLE 2

SUMMARY OF INITIAL TEST DATA (NAPC #4)

Date	f	T1.532	T.632	T.488	D32m	T.85	T.65	T.45	D32e	D32aug
mair=1.8										
mbp=0.6										
7-22	0.0212	---	---	---	---	0.805	0.784	0.705	.24-.25	---
7-26	---	---	0.465	0.264	0.47	0.84	0.801	0.748	.21-.26	---
mair= 1.8										
mbp= 1.0										
8-2	0.0215	0.376	0.277	0.218	.48-.61	0.899	0.8403	0.781	0.18	---
8-5#1	0.0212	---	---	---	---	0.89	0.863	0.835	.2-.32	---
8-8#1	0.0206	---	---	---	---	---	---	---	---	.5-.7
8-5#2	0.0205	---	---	---	---	0.88	0.847	0.787	.18-.24	1.2-1.3
8-8#2	0.0204	0.369	0.264	0.156	0.2	---	---	---	---	> 1.0

--- Data not available

with the fuel. This effectively reduced the length of each experimental run, thus allowing four test runs from a fully charged air supply system. The last two test runs were made with ferrocene added but the vitiated air heater secured.

A. DEVELOPMENTAL TESTS

Earlier thesis efforts at the Naval Postgraduate School produced results that gave a good indication of particle sizes expected at each station. The previous work gave guidelines and procedures to follow to obtain good data and were beneficial in completing the experimental buildup and validation phase. The procedures developed and lessons learned are presented here as they evolved from analyzing the results of developmental runs.

The first few runs in this phase were unsuccessful in that accurate sizing data was not obtained. Suspected causes were identified and the following changes were made:

(1) The IR photodiode preamplifier had a significant overshoot and slow response time, requiring removal from the circuit. Amplification of the diode output was made using an external Pacific amplifier, Model 8255, located in the control room.

(2) The collimated white light beam used through the aft exhaust chamber was too large and was impinging and reflecting off the optical port walls and edges. A diaphragm was added between the collimating lens and the optical port that reduced the beam diameter and eliminated the impinging and reflecting problem.

Calibration of the scattering system was attempted with the collection tubes and photodiodes mounted on the augmentor test stand, but their sensitivity required removal and calibration in a darkened room. Each tube and diode assembly was securely mounted on an optical stand with three degrees of movement for accurate adjustments of alignment. The laser beam power was reduced by neutral density, in-line filters and directed into the collection tube. Adjustments were made until a maximum voltage was obtained for each diode. Ratios were taken and calibration constants were input into the computer program for equating voltage ratios to intensity ratios. Unfortunately, early alignment procedures and ratio calibrations did not work and a better technique had to be developed. Early data analysis did, however, identify the need for a stronger incident beam in the augmentor exhaust and the 15mW HeNe (632.8 nm wavelength) laser was replaced with a 0.5 W Argon (488 nm wavelength) laser. The laser in-line filter in each collection tube was also changed to this new operating wavelength.

The evolution of calibration procedures spawned highly accurate alignment techniques, both in the calibration room and on the augmentor test stand. In order to insure proper alignment of the tube center during calibration, 0.05 inch holes were drilled in the center of each lens tube cap. The low power calibration beam was directed through the small hole and the tube's alignment was adjusted until saturation occurred. The calibration beam's power was then reduced using one or more additional neutral density filters until the diode was no longer saturated. Fine adjustments were then made to obtain a maximum value with the cap on. The cap was then removed and calibration was begun.

Initially, ratios were used to calculate calibration constants but the fluctuating output energy of the Argon laser required the addition of a power meter and direct measurement of both power and voltage outputs. The exceptional sensitivity of the photodiodes required extreme reduction of beam energy and a power meter capable of measuring into the nanowatt range. Power was varied using additional optical filters. Equations relating the diode voltages to light intensity were obtained by performing a least squares linear regression on calibration data. The equations were written into the T63 Data Collection program.

Accurate alignment on the augmentor test stand was just as important. The same fine adjustments were made on the test stand mounts while the beam was being directeu into the face of the tube by the rotatable mirror discussed in the Experimental Procedures section. Testing revealed that the alignment could be altered during a run and had to be checked prior to the next one.

Attempts to measure and record accurate scattered light intensities from the two-angle combustor and exhaust systems were abandoned because the above alignment procedures could not be followed within the engine. Visually sighting the laser beam passing through injected smoke did not provide the precision required to accurately determine particle size.

B. EXHAUST CHAMBER PARTICLE SIZING

Earlier experiments by Jway [Ref. 4] determined that the mean particle size at the motor exhaust decreased with increasing fuel-air ratio (f) when the mass flow of air was low (approximately 1.8 lbm/sec). However, when air flow was increased to 2.2 lbm/sec, D_{32} was not a function of fuel-air ratio. These results were obtained before the quench air capability was incorporated and, thus, the soot had a relatively long residence time (t_{res}) at high temperature. D_{32} values ranged from 0.2 to 0.35 microns. Later studies with quench air obtained the same range of particle sizes on several successful runs. Particles of similar size were expected during this experiment.

Developmental test results using Fuel #4 (Table 2) showed the difficulty in obtaining useful data on every run, and identified the problems discussed in the previous section. The nozzle entrance D_{32e} range of between 0.18 micron and 0.32 micron confirmed the results from earlier studies.

Data collection began after changing to a higher aromatic fuel, NAPC #1. Data collection runs 1 to 7 utilized an air mass flow of 1.8 lbm/sec and a quench flow of 1.01 lbm/sec. Results are tabulated in Table 3. Figure 14 is a plot of fuel-air ratio vs. combustor exhaust

TABLE 3

TABLE OF DATA

Run	f	Temp	Pc	T1.532	T.632	T.488	D32m	T.85	T.65	T.45	D32e	D32aug	Remarks
NAPC #1													mair=1.8 mbp=1.0
1	0.022	1201	93	0.322	0.349	0.192	< .20	0.818	0.769	0.732	.23-.37	---	
2	0.021	1266	90	0.382	0.186	0.145	0.28	0.866	0.825	0.753	.20-.21	---	
3	0.021	1307	95	0.344	0.165	0.115	0.25	0.859	0.819	0.736	.13-.21	---	
4	0.016	1117	110	0.348	0.168	0.132	0.26	0.780	0.732	0.649	0.21	---	mair=2.5 mbp=0.0
5	0.021	1227	96	0.344	0.286	0.256	0.38	0.842	0.810	0.740	.22-.25	---	
6	0.019	1107	94	0.364	0.271	0.260	0.38	0.856	0.814	0.751	.21-.22	---	
7	0.018	1027	93	0.395	0.335	0.316	0.35	0.853	0.810	0.749	.21-.22	---	
NAPC #1													mair=1.9 mbp=.59
8	---	1220	---	0.373	0.272	0.248	0.33	0.749	0.716	0.654	.26-.28	.52-.53	
8A	0.0193	1179	98	---	0.262	0.251	0.39	0.737	0.707	0.635	.25-.30	---	alignment
8B	0.0192	1192	97	0.360	0.241	0.209	0.31	0.802	0.767	0.691	.22-.25	---	sunlight
9	0.0178	1103	96	---	0.300	0.292	0.41	0.739	0.705	0.647	.275-.28	---	alignment
10	0.0176	1094	94	0.410	0.313	0.302	.38-.39	0.793	0.758	0.619	.23-.26	.60-.63	
11	0.0162	1014	92	0.466	0.338	0.322	0.38	0.830	0.793	0.725	.22-.23	.64-.655	
8C	0.0187	1158	95	0.378	0.237	0.264	.56-.65	0.825	0.786	0.712	.20-.23	.61-.63	
8D	0.0199	1222	98	0.353	0.195	0.234	.5-.7	0.814	0.773	0.705	0.23	---	sunlight
NAPC #7													
20	---	188	---	0.314	0.179	0.215	---	0.803	0.753	0.671	0.21	---	printout
20A	0.0195	1205	98	0.321	0.213	0.215	.54-.58	0.804	0.755	0.675	.20-.22	.66-.73	
21	0.0184	1142	96	0.334	0.216	0.196	.49-.55	0.810	0.760	0.670	.18-.22	.63-.75	
22	0.0168	1057	94	0.370	0.224	0.240	.5-.57	0.820	0.780	0.700	.18-.23	---	alignment
NAPC #7 with AIR HEATER													mair=1.98 mbp=.61
23	0.0182	1307	100	0.467	0.447	0.496	---	0.787	0.723	0.644	.21-.23	.56-.62	+200 F **
24	---	1192	---	0.518	0.441	0.498	.65-.72	0.705	0.665	0.591	.26-.27	---	+210 F printout
24A	0.0162	1175	99	0.523	0.471	0.21	.69-.78	0.689	0.648	0.579	0.265	0.58	+210 F **
NAPC #7 with AIR HEATER													mair=1.87 mbp=.57
25	0.017	1291	96	0.577	0.668	0.678	---	0.729	0.693	C.626	.26-.28	> .9	+305
NAPC #7 with ADDITIVE and AIR HEATER													mair=1.9 mbp=.59
26	0.0166	1230	96	0.544	0.475	0.622	.65*	0.75	0.73	0.691	.34-.36	.41-.45	+305 F ***
27	0.0169	1265	99	0.529	0.565	0.534	---	0.751	0.716	0.668	.28-.31	.41-.55	+265 F ***
NAPC #7 with ADDITIVE w/o AIR HEATER													
28	0.017	1074	93	0.401	0.373	0.325	.66-.73	0.856	0.821	0.744	.18-.22	.59-.62	***
29	0.0169	1074	92	0.444	0.389	0.372	.66-.72	0.705	0.667	0.572	.24-.27	.56-.63	***

* 1532/632.8 ratio
** 20/10 ratio
*** 20/5 and 20/10 ratios
--- Data not available or no correlation
Tair inlet = +15 F except as marked

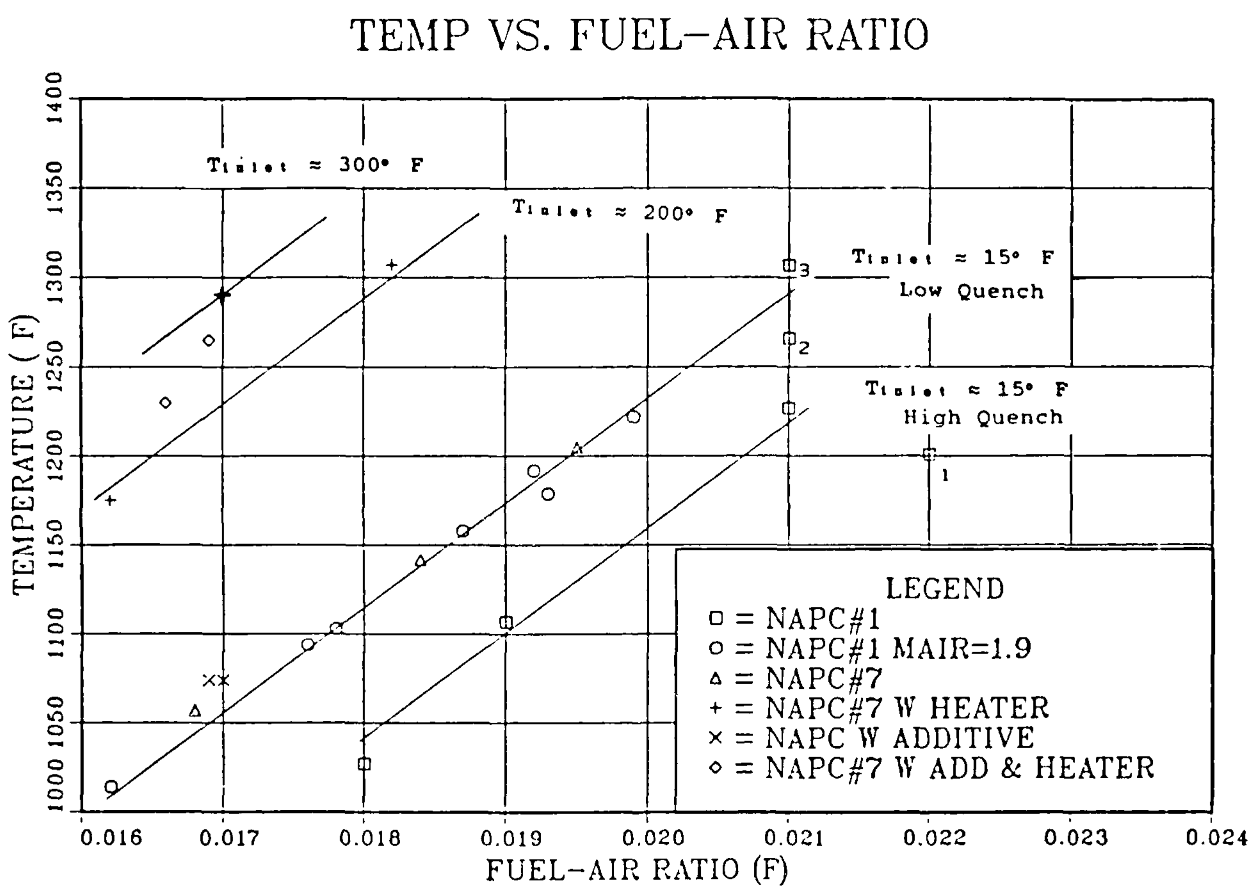


Figure 14. Combustor Temperature vs. Fuel-Air Ratio (f)

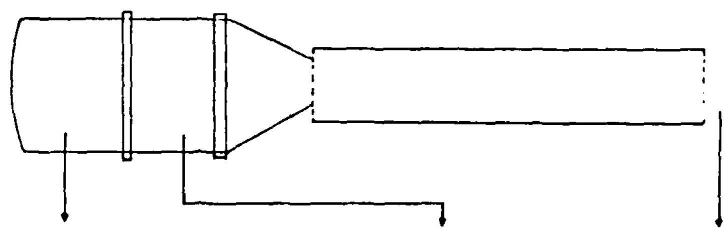
temperature, upstream of the injection location. From this figure it is apparent that the temperature varied linearly with the fuel-air ratio except for run numbers 1, 2, and 3. The particle size data from these three runs were, therefore, not used in the analysis of the results. The relatively consistent particle size of 0.21 microns at the exhaust station showed no dependence on fuel-air ratio (f). Data from Runs 8 through 11 are contained in Table 3 and summarized in Table 4. The quench air sonic choke was changed prior to these runs. The combustor air mass flow was increased to 1.9 lbm/sec while the smaller sonic choke reduced quench air flow to 0.59 lbm/sec. The average D_{32} value may have increased slightly with this changed test condition, but it was again not a function of fuel-air ratio. The reduced quench air increased the pre-quench gas temperature (Figure 14), indicating an upstream influence of the quench air.

Runs 20 through 22 were made using NAPC #7, lower in hydrogen content. The fuel-air ratio vs. temperature behavior was the same as for NAPC fuel #1 (Figure 14). Air mass flow rate and quench air remained the same. The exhaust D_{32} values were not significantly changed and still no sign of dependence on f was observed.

Data from Runs 23, 24, 24A and 25 were obtained utilizing the vitiated air heater to raise the air inlet temperature between 200^{o} and 305^{o} F. There was a detectable

TABLE 4

SUMMARY OF NAPC #1 RESULTS



FUEL NAPC # 1		COMBUSTOR	EXHAUST				AUG TUBE
mair =	1.9						
mbp =	0.59	D32	T45	T65	T85	D32	D32
f =	0.0193	0.39	0.635	0.71	0.74	0.25-0.30	.52-.53
f =	0.0192	0.31	0.691	0.767	0.802	0.22-0.25	.61-.63
f =	0.0178	0.41	0.647	0.705	0.739	.275-.28	align
f =	0.0176	.38-.39	0.691	0.758	0.793	.23-.26	.60-.63
f =	0.0162	0.38	0.725	0.793	0.83	.22-.23	.64-.655

rise in average particle size at this station with the elevated air inlet temperature when the fuel-air ratio was reduced from 0.0182 to 0.0162. Table 3 gives fuel-air ratios and mass flow rates for individual runs. Comparison of heater and non-heater D_{32} values at the same relative fuel-air ratio reflect a slight increase in D_{32} due to increasing air inlet temperature. Ferrocene had little effect on D_{32} with non-heated (cold) inlet air temperature. However, at low fuel-air ratios with heated inlet air, the ferrocene significantly increased D_{32}.

C. FORWARD COMBUSTOR PARTICLE SIZING

Previous experiments at the Naval Postgraduate School using light transmittances in the forward combustor produced varying degrees of success. Most particle size determinations made in this section were based on only one ratio of transmittance logarithms. Bennett et al. [Ref. 6] identified two possible causes for the "lack-of-correlation" [Ref. 6] between the three ratios. One was a possible bi-modal distribution of particle sizes within the combustor and the other was possible soot porosity. Not mentioned, was the possibility that the assumed shape did not approach spherical. Each of these would result in extinction coefficients quite different from the predicted values. In this section of the combustor the measurement volume traverses both an annular region, which flows into the turbine nozzle block, and a large recirculation zone.

To circumvent the wavelength separation problem discussed by Grafton [Ref. 1], the 1532 nm wavelength IR laser replaced the 513.5 nm Argon laser in the combustor transmittance system. After the initial response problem discussed earlier was corrected, the IR signal was as stable and consistent as the 632.8 nm and 488 nm signals. Unfortunately, the large variation in particle sizes (using NAPC fuel #1) was still present when all three ratios were plotted on Extinction Coefficient Ratio Curves.

In the past, reported values of D_{32} had been based on only one ratio. Most values found in Tables 3 and 4 were also based on the $\ln T_{632.8}/\ln T_{488}$ ratio; using the same particle index of refraction that was successful at the nozzle entrance. Reported particle sizes generally varied between .35 and .41 microns with NAPC fuel #1. A significant increase in size was observed when the lower hydrogen content fuel (NAPC #7) was used. Particle sizes of between 0.49 and 0.58 microns were found. However, fuel-air ratio had little effect on particle size for either fuel. For both of these fuels, the air mass flow was the same, 1.9 lbm/sec, and the quench flow rate was .59 lbm/sec. More significant than the increase in particle size, however, was the fact that all three transmittance ratios were used to determine D_{32} on Runs 20A, 21, and 22. This was the first time that all three ratios gave consistent size determination. The assumed index of refraction (m) was 1.95 - .66i and the assumed log normal distribution had a standard deviation (σ) of 1.5.

Of the four data collection runs with the air heater used, none had consistently usable particle size data from the forward transmittance system. A significant effect of the air heater was the rise in transmittance values at all wavelengths and most noticeably the 488 nm transmittance value. The D_{32} values in Table 3 were obtained using one or two of the ratios, but not all three. The limited data indicated that D_{32} increased with increasing air inlet temperature. Transmittance values obtained in the forward combustor with the air heater operating were often unusable in calculating D_{32} with this method.

The first two additive runs were done with the air heater operating and the same problems were encountered in sizing forward combustor particles. However, with the air heater secured, Runs 28 and 29 resulted in an acceptable range of between 0.66 and 0.73 microns for particle size from all three ratios. Compared to the D_{32} value reported for Run 22 these values were significantly greater (approximately 30%). Also noted was the reduced transmittance values when the air heater was not used. For example, T_{488} went from .534 on Run #27 to .325 on Run #28. These transmittance values were still larger than the non-additive transmittance values of Run #22 and can be attributed to the smoke suppressant. The limited data also indicated that ferrocene had much less effect on combustor D_{32} with hot air inlet temperatures.

D. AUGMENTOR TUBE EXHAUST PARTICLE SIZING

Bennett et al. [Ref. 6] present results from previous studies of augmentor tube exhaust particles. The earlier discussion on developmental tests associated with this experiment detailed the evolution of a successful three-angle forward scattering particle sizing system. Accurate particle sizes were not obtained with the Malvern 2600HSD particle sizer for two reasons:

(1) The obscuration must be greater than 5% in order for the Malvern to function properly. Transmittance values greater than 95% were reported across an eight inch augmentor tube in [Ref. 2]. Measured obscurations with the Malvern system installed were less than 4%.

(2) The Malvern system is advertised to size particles as small as 1 micron, with a subgroup to 0.5 microns. To accurately determine particles as small as 0.5 microns requires all particles to be within 55 mm of the 63 mm transform lens. This was not possible using the four inch augmentor tube. This required capturing only a portion of the augmentor exhaust, further reducing opacity.

The particle sizes obtained from the forward light scattering measurements ranged from 0.52 microns to 0.63 microns with NAPC fuel #1 (Table 4). There was no significant effect of fuel-air ratio on the exit particle size with NAPC #1. NAPC fuel #7 resulted in larger exhaust particles (.66-.75 microns), again with no significant effect of fuel-air ratio on particle size. Several runs resulted in saturation of the 05° and/or 10° photodiodes. The cause of this saturation has not yet been determined.

The lack of any significant effect of fuel-air ratio on D_{32} was in contrast to the results of Urich [Ref. 3] in which D_{32} increased with fuel-air ratio. The latter test condition had an augmentor tube diameter of 8", an augmentation ratio of .53 and no quench air. D_{32} values were between .33 and .42 microns. In the present investigation the augmentor tube was 4" in diameter, the augmentation ratio was .42 and quench air was used. Larger (approximately 0.6 microns) particles were observed. These results indicate that varying augmentor flow conditions can significantly affect the mean soot size.

D_{32} values were obtained from the 20°/10° intensity ratio for runs 23 and 24A. No data printout was available for Run 24 and the saturation of both the 05° and 10° photodiodes caused Run 25 data to be unusable. The effect of increasing inlet air temperature was to decrease the augmentor exhaust particle size at the same fuel-air ratio (with or without ferrocene added).

Prior to continuing with additive data collection runs, the augmentor tube was cleaned. This successfully eliminated the saturation problem at both the 05° and 10° photodiodes. The relatively consistent results are tabulated in Table 4. The reported values for Runs 26 through 29 were all based on only two ratios, 20/10 and

20/5. Inclusion of the 10/5 intensity ratios increased the particle size range by about 0.1 micron. Data from that ratio were not included in Table 3 for fuel #1, so only similarly obtained data were considered for fuel #7. The effect of including this ratio is discussed in the next paragraph.

Values from Runs 26 and 27 (hot air inlet temperature with ferrocene added) were compared with non-additive, heated air values from Runs 23 and 24A. The significant decrease in D_{32} at the augmentor tube exhaust, from .56-.62 microns to .4-.55 microns, was attributable to the smoke suppressant additive. As stated earlier, Runs 28 and 29 did not utilize the air heater. D_{32} values from these runs were compared with Runs 20A and 21. Although they did not have the same fuel-air ratio, they were the closest ones that also utilized NAPC fuel #7, and had augmentor exhaust particle size data. The .56-.63 micron D_{32} values with additive were smaller than the .63-.75 micron values determined without additive. Including the 10/5 intensity ratio data expanded the additive D_{32} value range into and including the .63-.75 micron non-additive range. Therefore, the true effect of the smoke suppressant additive without the air heater was not determinable.

E. AUGMENTATION RATIO

The augmentor tube exhaust velocity was determined using six horizontally arranged stagnation pressure port tubes on a rake. The average velocity was 1105 ft/sec. Mass flow calculations were made and the augmentation ratio of the four inch tube was determined to be 0.42.

F. SOOT CONCENTRATION AND MEAN PARTICLE SIZE SUMMARY

Soot concentrations in the forward combustor and at the exhaust nozzle entrance were estimated using average values for D_{32} and transmittances in Equation (1). The results are summarized in Table 5. Major observations were as follows:

(1) Fuel-air ratio had little effect on D_{32} values.

(2) Decreased hydrogen content (#1 -> #7 fuel) resulted in larger D_{32} in the combustor but no significant effect at the nozzle entrance.

(3) Ferrocene concentrations of 8 ml/gal of fuel (as recommended by the manufacturer) were not effective in reducing opacity.

(4) For the additive concentration and test conditions employed; ferrocene (a) significantly increased the particle size in the combustor with only a small decrease in concentration and (b) had no significant effect on concentration at the nozzle entrance but increased D_{32} at low fuel-air ratios.

(5) Using an average density of 1.5 gm/cm^3, soot particle concentrations were approximated as 0.3 mgm/l (5 x 10^7 particles/cm^3) at the nozzle entrance and 1-2 mgm/l within the forward combustor.

Since transmittance measurements were not made, the effect of the augmentor tube and augmentation ratio on soot concentration could not be determined. Effects of changing variables on D_{32} values, however, are summarized as follows:

(1) Significant soot agglomeration (D32 increased by a factor of 2 to 3) occurred across the exhaust nozzle-augmentor tube combination.

TABLE 5

MASS CONCENTRATIONS FROM AVERAGE VALUES

Soot density = 1.5 gm/cm

COMBUSTOR

Fuel#	Additive	Air Temp	T632.8	$\bar{Q}$	D32	Cm mgm/l
1	none	cold	.30	2.74	.37	1.1
7	none	cold	.22	2.85	.53	2.0
7	yes	cold	.38	2.80	.70	1.7
7	none	hot	.47	2.80	.70	1.3

NOZZLE ENTRANCE

Fuel#	Additive	Air Temp	T65	$\bar{Q}$	D32	Cm mgm/l
1	none	cold	.73	2.16	.23	.30
7	none	cold	.76	1.73	.20	.27
7	yes	cold	.74	2.16	.23	.28
7	none	hot	.68	2.22	.25	.38
7	yes	hot	.72	2.60	.32	.36

(2) At the same fuel-air ratio, increased combustor air inlet temperature slightly increased D_{32} at the nozzle entrance, but decreased D_{32} at the augmentor tube exhaust. The soot agglomeration process in the augmentor tube appeared to be slowed in the presence of higher temperatures.

(3) Ferrocene significantly reduced the particle size (i.e., agglomeration) at the augmentor tube exhaust.

(4) Raising combustor air inlet temperature increased the ability of Ferrocene to reduce D_{32} at the augmentor tube exhaust.

VI. CONCLUSIONS AND RECOMMENDATIONS

The modifications and improvements to the T-63 combustor and test facility produced data in good agreement with previous studies and supported several earlier conclusions. Two significant accomplishments made during this investigation were the validation of the three angle forward scattering sizing technique and correlation of three wavelength ratios within the combustor.

In particular, the latter is considered significant in that earlier studies chose to report the smaller value of particle size when three ratio correlations were not present. This study also tabulated the same smaller combustor particle size based on the $\ln T_{632.8}/\ln T_{488}$ ratio for NAPC fuel #1. However, when correlation was obtained using NAPC fuel #7, a larger particle size was found, casting doubt on the accuracy of the previous values. Sizing based on two ratios for tests using NAPC fuel #1, $\ln T_{1532}/\ln T_{632.8}$ and $\ln T_{1532}/\ln T_{488}$, generally produced particle sizes in the same range as for fuel #7, .55-.80 microns. It is possible that the particle sizes were in fact larger than reported. The large variation made determination of exact particle size difficult.

To check the accuracy of the three-wavelength system in the combustor, it is recommended that the three-laser system be used at the aft exhaust chamber to compare results with the white light source system. Good size correlation would validate the three laser system, in particular, the use of the IR wavelength. No evidence of signal contamination by combustion IR energy was observed, however, there was a proportionally larger "laser-off" signal at this wavelength than for the two lower wavelengths. Additionally, the cause of the significant reduction in consistent data when the vitiated air heater was used should be investigated.

The problems associated with three angle scattering measurements were mainly limited to calibration and alignment. The alignment problem was solved, but required extreme care and diligence prior to each test run. Calibration of the three photodiodes changes with time and operating temperature. To preclude recalibration of all three diodes, the following modification is proposed.

Remove the photodiode from each light collection tube assembly. Mount a fiberoptics cable just aft of the filter in each assembly such that it picks up the focused collected energy and transmits it to one photodiode. A trifurcated cable, fabricated such that only one input is received at a time, would eliminate the calibration requirement at low power as voltage outputs from the single diode could be ratioed directly.

Major findings from this investigation were:

(1) Fuel-air ratio had little effect on D_{32} values within the gas turbine combustor.

(2) Decreased hydrogen content resulted in larger D_{32} in the forward combustor but no significant effect at the nozzle entrance.

(3) Significant soot agglomeration occurred across the exhaust nozzle-augmentor tube combination.

(4) At the same fuel-air ratio, increased combustor air temperature slightly increased D_{32} at the nozzle entrance, but decreased D_{32} at the augmentor tube exhaust. Soot agglomeration appeared to be slowed in the presence of higher temperatures.

(5) Ferrocene concentrations of 8 ml/gal of fuel were not effective in reducing opacity.

(6) For the additive concentration and test conditions employed; ferrocene (a) significantly increased D_{32} within the combustor with only a small decrease in concentration and (b) had no significant effect on concentration at the nozzle entrance, but increased D_{32} at low fuel-air ratios.

(7) Ferrocene significantly reduced the particle size (i.e., agglomeration) at the augmentor tube exhaust.

(8) Raising combustor air inlet temperature increased the ability of ferrocene to reduce D_{32} at the augmentor tube exhaust.

(9) Soot particle concentrations were estimated to be 0.3 mgm/l at the nozzle entrance and 1-2 mgm/l in the forward combustor.

Time constraints did not allow a complete investigation into both the individual and combined effects of every variable. It is assumed that different combinations of variables might significantly alter the exhaust characteristics. Continued study on combined effects is recommended.

These follow-on studies need not be dedicated efforts, but rather could be part of a much larger NO_x investigation. Equipment designs for such an investigation are currently being finalized and initial buildup is anticipated in early 1989.

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