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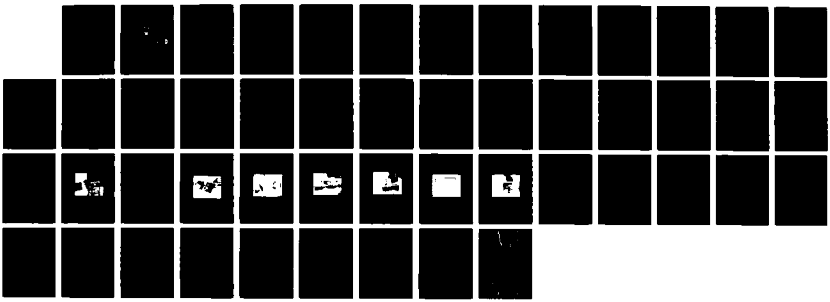

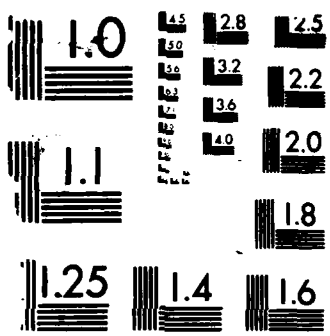

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THESIS

A PARAMETRIC INVESTIGATION OF SOOT BEHAVIOR
AND OTHER EMISSIONS IN A GAS TURBINE COMBUSTOR

by

Joseph Dickson Weller

June 1984

Thesis Advisor: David W. Netzer

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An investigation was conducted to determine the effects of operating characteristics and fuel additives in a gas turbine combustor on particulates (soot) and other gaseous emissions (NOx, NO). The principles of Mie theory and three-wavelength light transmittance have been utilized in this investigation to determine particulate size and mass concentration. Using an Allison T63 turboshaft engine combustor, five experimental fuels of varying chemical composition were analyzed from an emissions standpoint. There was no

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A Parametric Investigation of Soot Behavior and Other Emissions in a Gas Turbine Combustor

by

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Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1973

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 1984

Author: ______________________________

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Thesis Advisor

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Chairman, Department of Aeronautics

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Dean of Science and Engineering

ABSTRACT

An investigation was conducted to determine the effects of operating characteristics and fuel additives in a gas turbine combustor on particulates (soot) and other gaseous emissions (NOx,NO). The principles of Mie theory and three-wavelength light transmittance have been utilized in this investigation to determine particulate size and mass concentration. Using an Allison T63 turboshaft engine combustor, five experimental fuels of varying chemical composition were analyzed from an emissions standpoint. There was no apparent relationship between particulate size and either fuel composition or combustor exhaust temperature. Nitric oxide levels were indifferent to fuel composition but did show a characteristic upward trend with exhaust temperature. Visible spectrum transmittance did indicate an inverse relation to increasing exhaust temperature. Though only two fuel additives were tested on one fuel, there was no manifestation of improved transmittance with their use.

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I would like to thank Dr. David Netzer, Professor of Aeronautics, for his unflagging assistance and total dedication to graduate research. Without his vast experience and abundant energy, many difficult questions and problem areas would have greatly impeded this study. His personal interest and time devoted are deeply appreciated. Special thanks also to Kenneth Graham, Adjunct Professor to the Aero Department from NWC, China Lake, and to Mr. Patrick Hickey, Aeronautical Engineering Technician, for their help and assistance throughout the duration of the experimental work. Finally, I thank my family, particularly my wife, for the inspiration they provided.

I. INTRODUCTION

For the past thirty-five years the U.S. Navy has been flying jet aircraft. Due to the progressive sophistication as well as the diversity of naval aircraft turbojets, and later turbofans, several engine overhaul facilities were required to maintain safe and efficiently operating engines aboard fleet aircraft. Only with such dedicated facilities could engines be reworked, monitored in a controlled environment, and modified for improved performance. Since the establishment of the first such naval facility, the engines had been tested under the emissions veil that protected operational military aircraft. More recently, however, violations of both Federal and local community emission control guidelines has been cited in view of the exhaust emissions of the jet engine test cells at various rework facilities. Resulting lawsuits have made it necessary for the facilities to comply with local pollution standards. The solution desired is one which will allow the uninterrupted testing (i.e. without major and expensive overhaul of the existing test cells) throughout an engines normal operating spectrum while complying with all emission regulations. The present objective is to not only contribute to cleaner combustion of aviation fuels but also to determine some characteristics of the emitted particulates. Questions arise as to how and where in the combustion process soot particulates form, are consumed, and to what extent are soot and other emissions affected or perhaps controlled by engine operating temperature, pressure, fuel/air ratios, fuel composition and fuel additives. Both the Naval Air Propulsion Center (NAPC) [Ref. 1-2] and the Naval Postgraduate School (NPS) [Ref. 3] have previously performed evaluations of smoke suppressant fuel additives. Further studies of soot/emissions behavior in gas turbine combustors were conducted more recently at NPS as part of a research program for NAPC. Using an Allison T63-A5A (T63) engine combustor, Krug [Ref. 4] and Dubeau [Ref. 5] initiated an investigation of particulate formation, and size distribution utilizing extractive probes and three-wavelength light transmittance techniques. Much additional experimental work was required, however, due to limited results of the initial investigaton. Saturation of light detectors by combustion "noise" of the same wavelength rendered much of the initial data inconclusive. In addition, temperature and gas sampling probes were used only at the aft end of the combustor to verify probe integrity.

The diagnostic techniques involving three-wavelength light transmission measurements have proven successful in past studies and were again utilized in this investigation to further study the effects of fuel composition and smoke suppressant additives on particulate size and concentration. Subsequent verification of these results/data is planned utilizing a traversing extractive probe which will provide sampling data at various locations along the combustor centerline axis.

In this investigation the allison T63 combustor was used as a representative of actual gas turbine engine combustors. Its size, operating characteristics, and simplicity are all very advantageous as well as the fact it does not require an inexhaustive air supply system. The experimental apparatus initially constructed by Dubeau and Krug [Ref. 4-5] had to be modified to further enhance data acquisition and analysis. Its primary function remains as a source from which combustion particulate sizing and fuel additive effectiveness can be determined. In this investigation soot size and concentration was measured at only one location in the combustor (the aft end) and NOx/NO samples were extracted from an area closer to the exhaust ports.

Initial screening of ten experimental fuels provided by NAPC was to be performed to determine the "cleanest" and "dirtiest" burning compositions. The deciding factors for "clean" or "dirty" were particulate (soot) size and concentration, opacity (or transmittance), and levels of nitric oxides. These fuels and their associated physical and chemical characteristics are presented in Table I [Ref. 6]. Initial testing of these same fuels has been accomplished by NAPC. Using an Allison T63-A-5A engine, NAPC designed their tests to investigate the effects of the fuel properties on engine exhaust and smoke gaseous emission levels and engine performance [Ref. 6]. Their findings included, among others, the following relationships:

1) increases in fuel hydrogen content contributed to:
   a) decreases in engine smoke number at high power settings
   b) no significant changes in oxides of nitrogen emissions
2) increases in fuel aromatic content contributed to:
   a) increases in engine smoke number at high power settings
   b) no significant changes in oxides of nitrogen emissions
3) increasing operating temperature which was a linear function of fuel flow and engine power contributed to:
   a) increases in oxides of nitrogen
   b) increases in engine smoke number

These trends were to be compared with the results of the present investigation in which measurements were made within the combustor rather than at the engine exhaust. Another difference between the tests performed by NAPC and NPS involves the diagnostic techniques. NAPC uses flame ionization analysis and chemiluminesence (for nitric oxides) while NPS uses light extinction (or transmittance) for particle sizes and chemiluminesence for the nitric oxides.

Following initial NPS "screen" testing, the lowest and highest emitting fuels were to be further analyzed in the combustor to determine the influence on the particulates and emissions by varying fuel/air ratio (operating temperature), pressure, and additions of smoke-suppressant fuel additives.

The objectives of this thesis were:

1) to determine particulate size and mass concentrations within the combustor by use of Mie theory and three-wavelength light transmission measurements [Ref. 7].
2) to accurately measure other emissions, particularly NOx/NC formed in the combustion process.
3) to develop trends relating fuel composition to emission levels and particulate sizes and concentration.
4) to gather information enhancing knowledge of the mechanisms of soot formation in the combustion process, i.e. where it is formed, and how it may be affected by operating parameters or fuel additives.
5) to compare the results as much as possible with the previously reported T63 engine test data.

II. EXPERIMENTAL APPARATUS

The experimental apparatus as shown in Figures 1-3 had a significant impact on the very nature of this work and underwent several modifications and improvements for enhanced operation. Since a complete description of the components may be extracted from earlier reports [Ref. 4-5], only a brief synopsis of each subsystem and the instrumentation shall be provided here.

A. COMBUSTOR

An Allison T63-A-5A (T63) turboshaft engine combustor was used as the primary test component (Figure 4). Advantages of the T63 include the simplicity of a single chamber, igniter, and fuel nozzle; reasonable size yet realistic operating characteristics, and convenience provided for optics due to its reverse flow design.

B. AIR SUPPLY SYSTEM

An air supply system consisting of a bank of fourteen (19.49 cu ft) high pressure air tanks maintained suitable air mass flow rates when charged to nearly 3000 psi. Tank pressurization was provided by a 3500 psi Joy compressor. The air supply line included a nitrogen-controlled dome pressure regulator and a 0.57 inch diameter sonic choke. The latter was used in conjunction with a thermocouple and pressure transducer to calculate exact air mass flow rates.

C. FUEL SUPPLY SYSTEM

Fuel flow was similarly provided by a nitrogen-controlled and nitrogen-pressurized, 20 gallon JP fuel tank. Exact metering of the fuel to the electrically controlled solenoid valve and fuel nozzle was accomplished with a calibrated standard line turbine flowmeter located just upstream of the additive injection point in the fuel line. Fuel flow rate could be controlled from 0.00 to 0.50 gallons per minute (±0.005 gpm). A hand-operated valve and a digital rate indicator located at the main control panel permitted immediate adjustment of fuel flow in order to attain desired values of combustor temperature, fuel/air ratio, or flow rate (Figure 3). Additionally, two Eldex (model E) precision metering pumps (Figure 5) were located downstream of the turbine flowmeter to control fuel additive injections during the parametric study. Proper additive and fuel mixing was accomplished with a swirl-type mixer. Additive flow rate could be controlled between the preset limits of 0.2 and 5.0 ml per minute. Actuation via separate pump switches was performed at the main control panel.

D. OPTICAL DETECTOR SYSTEM

The three-wavelength light transmission measurement technique used in this investigation is but one means of obtaining particulate data while maintaining undisturbed flow conditions. The procedures utilized previously by Dubeau [Ref. 5], and Krug [Ref. 4] have been retained with modifications primarily related to "noise" filtering, improved fuel flow metering, enhanced data collection/reduction routines, and utilization of only one source/detector system located in the combustor, aft of the "primary zone".

The apparatus depicted in Figure 1 consisted of the following components mounted on free-standing, non-vibrating tables:

1. A projector with a 750 watt incandescent bulb served as the white light source. Uniform intensity light was provided by placing a piece of diffuse glass between the lamp and projector lens.
2. The beam was collimated by subsequently passing it through a 0.04 inch diameter pinhole to a 31.5 mm (diameter) achromatic lens with an 80 mm focal length (Figure 6).
3. Viewports were located on either side of the combustor in the most rearward position possible along the engine centerline.
4. The detector box containing the three wavelength detection filters and photodiodes (Figure 7) was mounted on a separate, adjustable table. The transmitted "light" exiting the combustor viewport then entered a 10 inch long blackened tube which minimized detection of forward scattered light. To enhance the linearity of the diode outputs at all wavelengths and to prevent detector saturation, the rear of the tube was reduced in size using a small orifice, 0.1 inch in diameter. Upon exiting the tube, the light then passed through two beam splitters which redirected the three resulting beams to photodiodes via narrow pass filters. The filters utilized were 8500, 6500, and 4560 Angstroms. These particular values were selected in an attempt to minimize the superposition of combustor "noise" and to provide spread in the wavelengths for accuracy in determining mean particle sizes.

E. INSTRUMENTATION

All instruments pertinent to the experiment were monitored within the confines of the control room. Strategically located thermocouples and pressure transducers enabled determinations of air mass flow rate, combustor temperature and pressure and fuel/air ratio. Guage air pressure was measured just upstream of the sonic choke and recorded on a Honeywell 1508B visicorder. Combustor chamber operating pressure was similarly recorded on the Honeywell. Strip chart recorders were utilized to record air and combustor temperatures and turbine flow meter data, as well as the transmittance signal outputs of the photodiodes.

F. NITROGEN OXIDES ANALYZER

A Monitor Labs model 8440E analyzer (Figure 8) which is a gas phase chemiluminescence detection device, was utilized with a strip chart recorder to provide a real-time permanent trace of both NOx and NO (oxides of nitrogen). It operates on the principle of chemiluminescence of an activated NO_2 species produced by a reaction between ozone (O_3) and NO. NO_2 (nitrogen dioxide) could be calculated simply as the difference between NOx and NO.

III. EXPERIMENTAL PROCEDURE AND ANALYSIS

A. EQUIPMENT SET-UP/WARMUP

In order to achieve a consistent test environment, all necessary equipment was allowed a nominal warm-up period of 30 minutes. This included all electronic recording devices (strip chart recorders, visicorder), thermocouples, the optical system (projector, photodiodes, voltage surge surpressor), and the NOx analyzer. During this warm-up cycle, main air supply valves, fuel tank pressurization lines and valves, and control panel nitrogen control valves were opened. Pressure transducers were calibrated using a dead weight tester. Following system warm-up, optics were checked for proper alignment and detector voltage output. Also, zero and 100% transmittance readings were taken at this time with the light source off and on respectively. "Set" values for air and fuel line pressures were then adjusted to desired levels using hand loading valves at the control panel.

B. TEST RUN

Following appropriate safety precautions which included warning horns, visual clearance, and flashing light, the main air switch was activated first. Readings were obtained for 100% transmittance with air flow in order to account for any opacity due solely to particulates in the dry air. Then the igniter and fuel switches were activated simultaneously to complete the light-off. Immediately upon light-off the operator in the control room could monitor and adjust fuel flow via the digital readout and control valve.

Upon reaching steady-state transmittance for all three wavelengths, as well as steady NOx/NO levels and combustor exit gas temperature, the light source was then extinguished and steady-state transmittances were again obtained as combustion continued. Then the light source was reactivated and original steady-state conditions were reestablished. If fuel additives were being tested, the pumps would then be activated singularly or together in order to observe any change in transmittance. Again the steady-state values with both the light on and off would be recorded. Upon shutdown, zero and 100% transmittance values were rechecked in order to detect any system deviation during the test run.

C. DIAGNOSTIC TECHNIQUES

1. Particulate Sizing/Mass Concentration

The recorded values of transmittance for the three wavelengths were utilized to find the following in order:

1) Mean particle size
2) Mass concentration

The optical detector system is the primary focal point of this analysis. Collimated light must be maintained in order to ensure that only light directly from the source is transmitted through the combustion zone while absorption and scattering by the particulates accounts for the fraction not detected by the diodes. A ratio of transmitted light with particulates present to that without particulates is then formed. Bouguer's Law for the fractional transmission of light through a cloud of fine uniform particles may be expressed as follows:

$$T = \exp(-QAnL) = \exp[-(3QC_m L/2\rho d)] \qquad (1)$$

where T= fraction of light transmitted

Q= dimensionless extinction coefficient

A= cross-sectional area of a particle

n= number concentration of particles

L= path length which light beam traverses

C_m= mass concentration of particles

ρ= density of an individual particle

d= particle diameter

Previous work by Dobbins [Ref. 8] indicated that good correlation of experimental data could be obtained if equation (1) is modified to account for a distribution of particle sizes such that:

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

where $\bar{Q}$= average extinction coefficient

d_{32}= volume-to-surface mean particle diameter

The natural log of equation (2) for a given wavelength of light provides:

$$\ln T_\lambda = \bar{Q}_\lambda \, (-3C_m L/2\rho d_{32}) \qquad (3)$$

A ratio of the logarithms of the transmittances for any two selected wavelengths then yields:

$$\frac{\ln T_{\lambda_1}}{\ln T_{\lambda_2}} = \frac{\bar{Q}_{\lambda_1}}{\bar{Q}_{\lambda_2}} \qquad (4)$$

since particle size, mass, and density are all constants.

Application of Mie light scattering theory to determine values of $\bar{Q}$ as a function of λ, d_{32}, 'm' (a complex refractive index), and σ (the standard deviation) has been demonstrated by K. L. Cashdollar [Ref. 7]. A computer program was utilized for the three wavelengths (8500, 6500, and 4660 Angstroms) and appropriate values of m (1.95-.66i; 1.9-.35i) and σ (1.5;2.0) for carbon particles [Ref. 7] to generate graphical output of particle size versus extinction coefficients ($\bar{Q}_\lambda$) and their ratios (Figure 9). Since three wavelengths were utilized, three ratios of the coefficients may be calculated to correlate one particle size. If all three ratios do not yield nearly the same d_{32}, then either σ and/or 'm' are in error. Various realistic [Ref. 7] values of and 'm' were used until good correlation was attained. Mass concentration may be determined next by combining the newly attained value of d_{32} and $\bar{Q}$ with equation (3):

$$C_m = -2/3[\rho d_{32}/\bar{Q}_\lambda L]\ln T_\lambda \qquad (5)$$

Again, three well-correlated transmittance values can be used to verify one value for mass concentration.

IV. DISCUSSION AND RESULTS

A. GENERAL

The purpose of this investigation was to analyze the effects of varying fuel composition, operating characteristics, and fuel additives on the production, consumption, and general behavior of soot and other emissions such as NOx and NO. Comparison then could be made with NAPC data obtained from tests of the same fuels in a T63 engine. The feasibility of using Mie theory and three-wavelength light transmission measurements to obtain data on particulate size and mass concentration had already been proven, although the application of the technique to the T63 had been successful on only a limited basis. Therefore refinement of techniques and analysis were among the first objectives.

B. APPARATUS REFINEMENTS

A careful selection of detector wavelength was made at the outset in order to reduce combustor "noise" superimposed on the visible and infra-red transmittances. Electronic low-pass filters were also applied for similar reasons to the visible and IR signals. Exact alignment of the collimated light source and the detector apparatus was seemingly the most crucial factor affecting the reliability of results. Therefore careful alignment was performed before a test run with zero and 100% transmittances recorded both before and after the run. In addition to the improved optical detection apparatus, a standard line turbine flow meter was installed to enhance monitoring and control of the fuel flow and combustor exhaust temperature. The calibrated flowmeter and digital rate indicator enabled the setting of desired and repeatable run conditions. This capacity was critical to performing a controlled parametric study of temperature or fuel/air ratio effects on the particulates.

C. PARAMETRIC RESULTS

Despite plans to initially screen all ten experimental fuels obtained from NAPC, only five fuels were actually screened. These included the two fuels which were highest (fuel 1) and lowest (fuel 5) in aromatics as well as three other representative fuels of various compositions. Parametric studies were completed on fuels 1, 5, and 7 while more limited data was obtained on fuels 2 and 9. The run conditions and results of twenty-nine tests involving these five fuels are summarized in Tables II and III.

As depicted in Figures 10 and 11, the mean particle diameter of soot did not vary appreciably with aromatics or hydrogen content. Also manifest in Figure 12 is a similar indifference to exhaust temperature. The relatively constant mean diameter of approximately 0.2 to 0.25 microns corroborates data presented in references 3 and 9.

The trends for NOx levels versus temperature are clearly evident in Figure 13. Although the increase in NOx with exhaust temperature was expected and correlates with the T63 engine test trends, the NOx levels and sensitivity to temperature were approximately 100 times greater in the NAPC engine tests [Ref. 6]. Possible reasons for the different NOx levels and sensitivity to exhaust temperature are 1) the lower mass air flow in the NPS combustor and 2) the lower air temperature at the inlet of the NPS combustor and its effect on the "primary zone". Trends such as these related to exhaust temperature could be similarly related to fuel/air ratio. Figure 14 reveals no direct correlation of fuel composition (i.e. aromatics) to NOx levels.

Figure 15 depicts a general decrease in visible transmittance with increasing temperature for fuels 1, 5, and 7. Similarly, Figure 16 shows a trend of increasing mass concentration with increasing combustor exhaust temperature (or fuel/air ratio). The results of the T63 engine investigation by NAPC [Ref. 6] also revealed an increase in engine smoke number (which increases with particulate mass concentration) with increasing temperature. However, data from reference 9 indicated a cleaner burn in a combustor at higher temperatures. A possible explanation for this difference is the fact that the T63 combustor utilized in this study has a lower residence time and does not provide the time-at-temperature necessary for any appreciable soot consumption. Similar findings in the T63 engine tests further indicate this trend may be a result of T63 design geometry and residence time and not a function of air inlet temperature.

Since the screen tests showed fuel 1 (Figure 15) to have a lower visible transmittance (as well as corroboration from reference 6, which indicated that fuels high in aromatic content had higher smoke numbers), the decision was made to use fuel 1 to test the effectiveness of two smoke suppressant fuel additives. On successive test runs utilizing Ferrocene and 12% Cerium Hex-cem at concentrations of approximately 20 ml per gallon of fuel, only very slight changes were detected in the visible spectrum transmittance. These transmittance improvements of less than 5% are considerably smaller than those found at the exhaust of a combustor for similar additive flow rates [Ref. 3]. Again the short residence time within the T63 combustor may account for this small effect or it may have been due to the low inlet air temperature and/or mechanisms by which the fuel additives operate within a combustor. These results indicate that the two additives investigated are effective in enhancement of the soot oxidation process rather than in the soot formation mechanisms.

D. PROBLEM AREAS

The determination of particulate size using three-wavelength light transmittance techniques requires particularly close attention to optical line-up as well as careful selection of detector frequencies (wavelengths) and refractive index chosen for final correlation. Attempts were made to use light deflection devices (mirrors, prisms) to facilitate test cell operation, however these further reduced the reliability of results. Several graphs (Figure 9, for example) were created to find the most suitable match of refractive index and actual test transmittances at the selected wavelengths. The optimum selection for 'm' appeared to remain (as in previous investigations) at 1.95-.66i (σ= 1.5) for the wavelengths of 8500, 6500, and 4660 Angstroms.

NOx analysis was hindered occasionally by fouling of the sample line due to soot build-up or saturation with liquid fuel which occurred during initial ignition at very high fuel flow settings. Other malfunctions were primarily related to faulty strip chart mechanisms or inability of the air supply to maintain adequate air mass flow rate.

V. CONCLUSIONS AND RECOMMENDATIONS

The application of three wave-length light transmission techniques for particle sizing in the T63 gas turbine combustor was proven feasible. Repeated tests with several fuels indicated reasonable and well-correlated soot particle diameters from 0.21 to 0.26 microns. NOx analysis of the fuels further indicated temperature dependent values ranging from 12 to 24 ppm.

Parametric studies were made on three of the five fuels tested. In all respects the different fuels manifested the same trends. Fuels 1, 5, and 7 exhibited 1) increasing NOx levels with increasing combustor exhaust temperature or fuel/air ratio; 2) decreasing transmittance with increasing combustor exhaust temperature or fuel/air ratio; 3) increasing mass concentration with increasing combustor exhaust temperature or fuel/air ratio; and 4) constant particulate size with changing fuel composition and exhaust temperature. The decreasing transmittance was a function of the increasing mass concentration since particulate size was found not to vary as a function of temperature.

The results for particle size, NOx analyses, and mass concentration were in qualitative agreement with the results presented in reference 6. It is felt that the apparent increase in mass concentration (decreasing transmittance) with higher exhaust temperature was the result of a greater production of soot within the combustor while a short residence time in the T63 inhibited the usual subsequent consumption of that soot which has been formed.

During separate fuel-additive tests on fuel 1 (in which Ferrocene and 12% Cerium Hex-cem were added at a concentration of 20 ml/gallon to the fuel flow), there was no noticeable change in any of the particulate characteristics. Additionally, NOx levels remained relatively constant whenever additives were introduced. Again, the results with the additives indicated that there possibly was not enough residence time within the combustor for the additives to significantly effect the particulate characteristics.

It is recommended that additional tests be conducted in the T63 gas turbine combustor utilizing both light transmittance techniques and sampling probe data to examine and further corroborate the transmittance and mass concentration trends. It is further recommended that the incoming air to the combustor be heated in order to determine the effects, if any, of a higher and more realistic operating temperature.

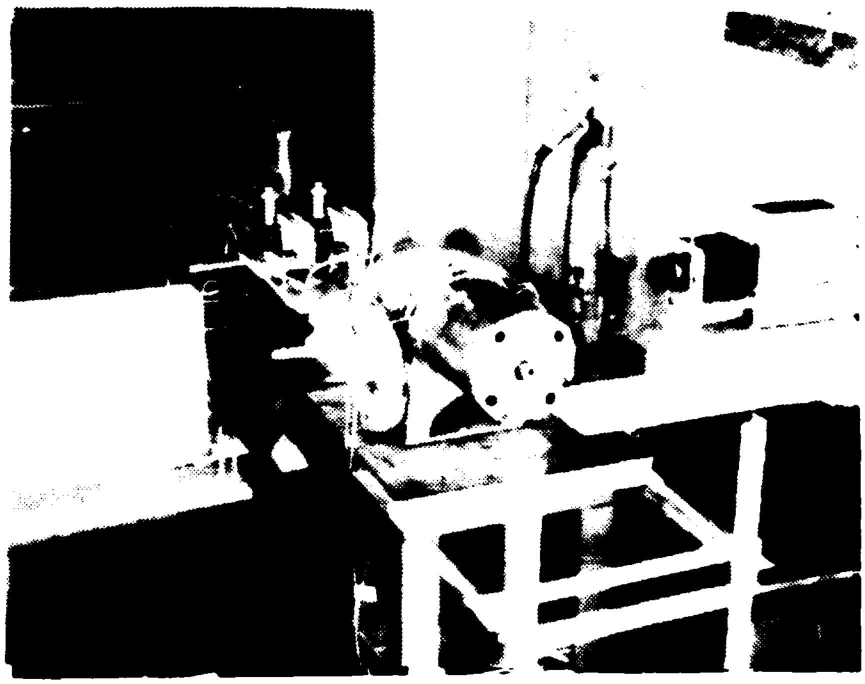


Figure 1 Test Cell Facility.

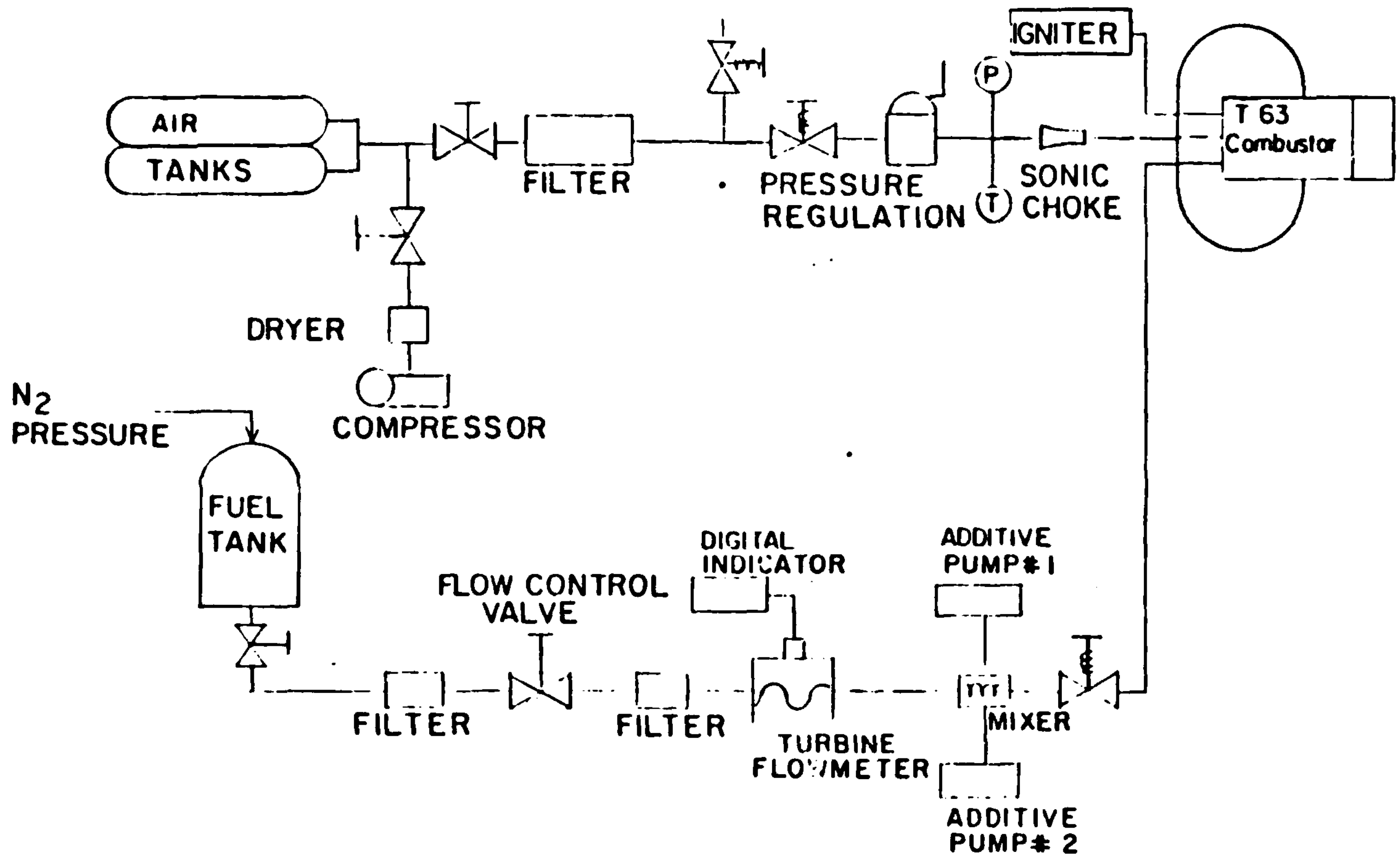


Figure 2. Schematic of T63 Test Cell Facility

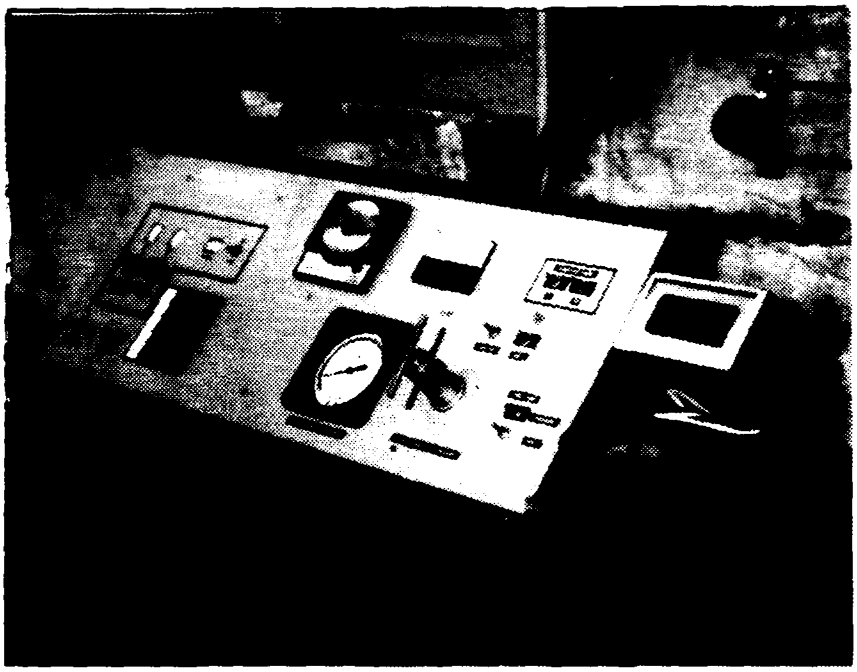


Figure 3. T63 Control Panel.

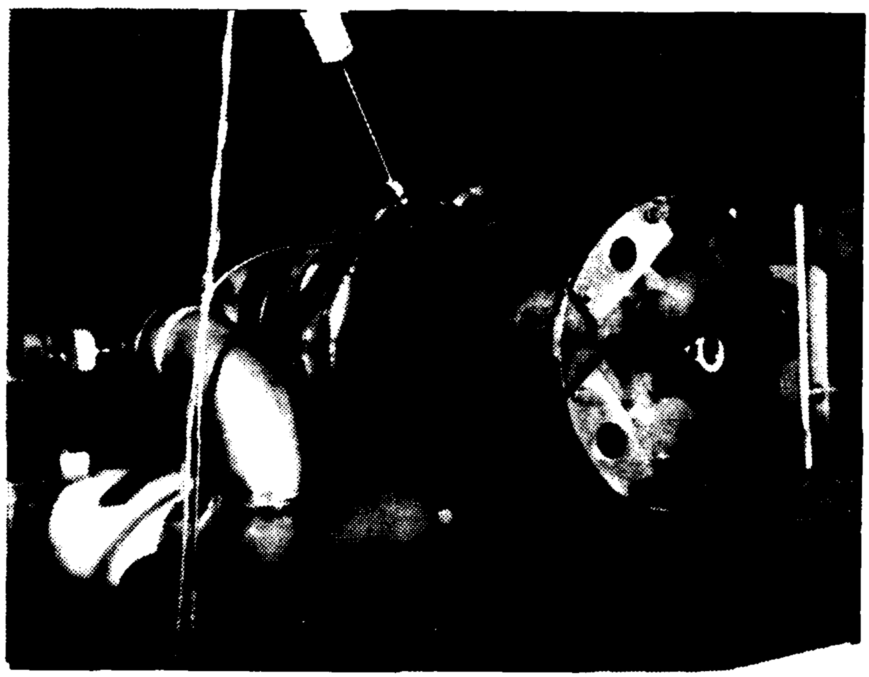


Figure 4 T63 Combustor.

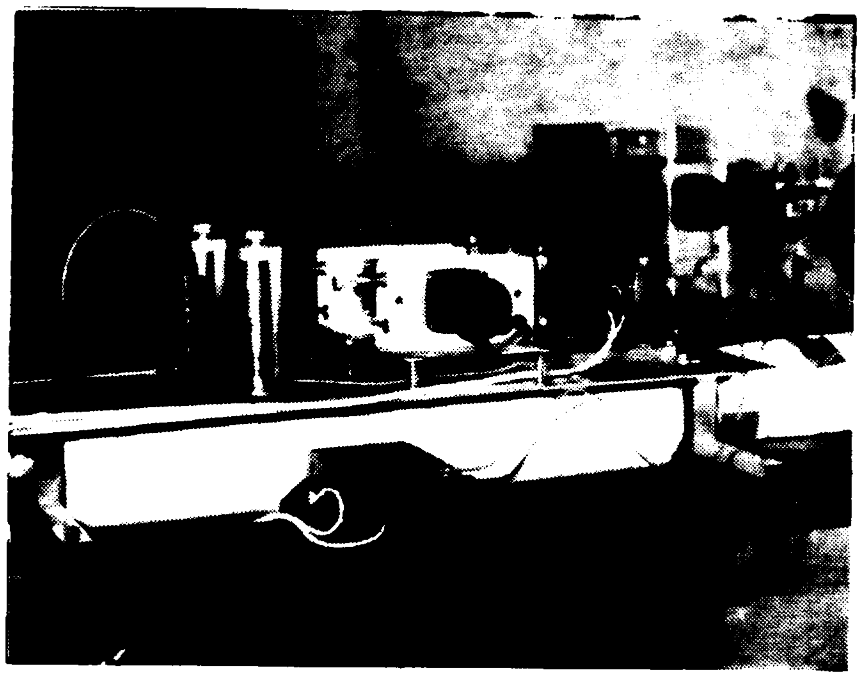


Figure 5. Turbine Flowmeter and Precision Metering Pumps

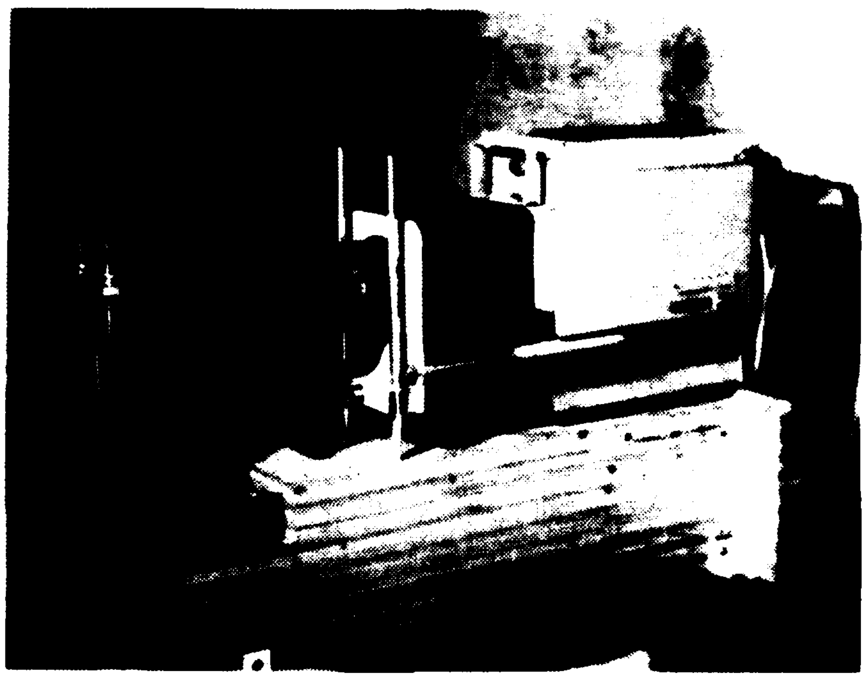


Figure 6 Collimated White Light Source.

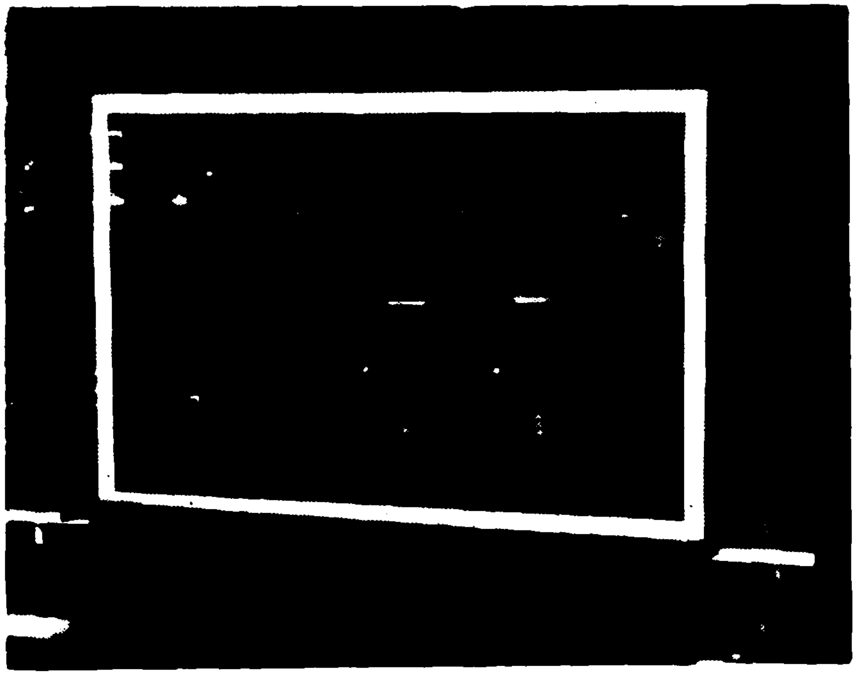


Figure 7. Three Wavelength Optical Detector.

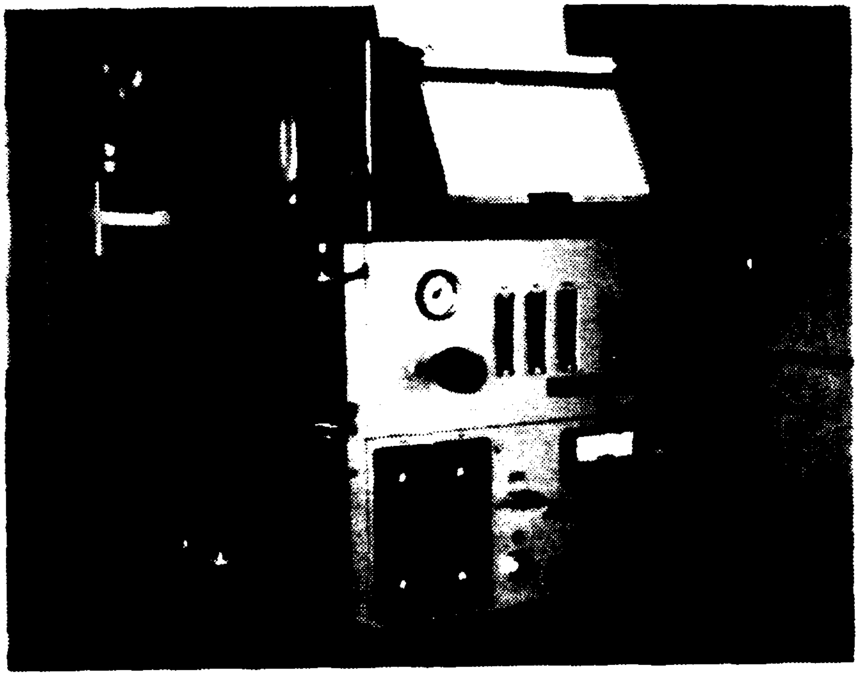
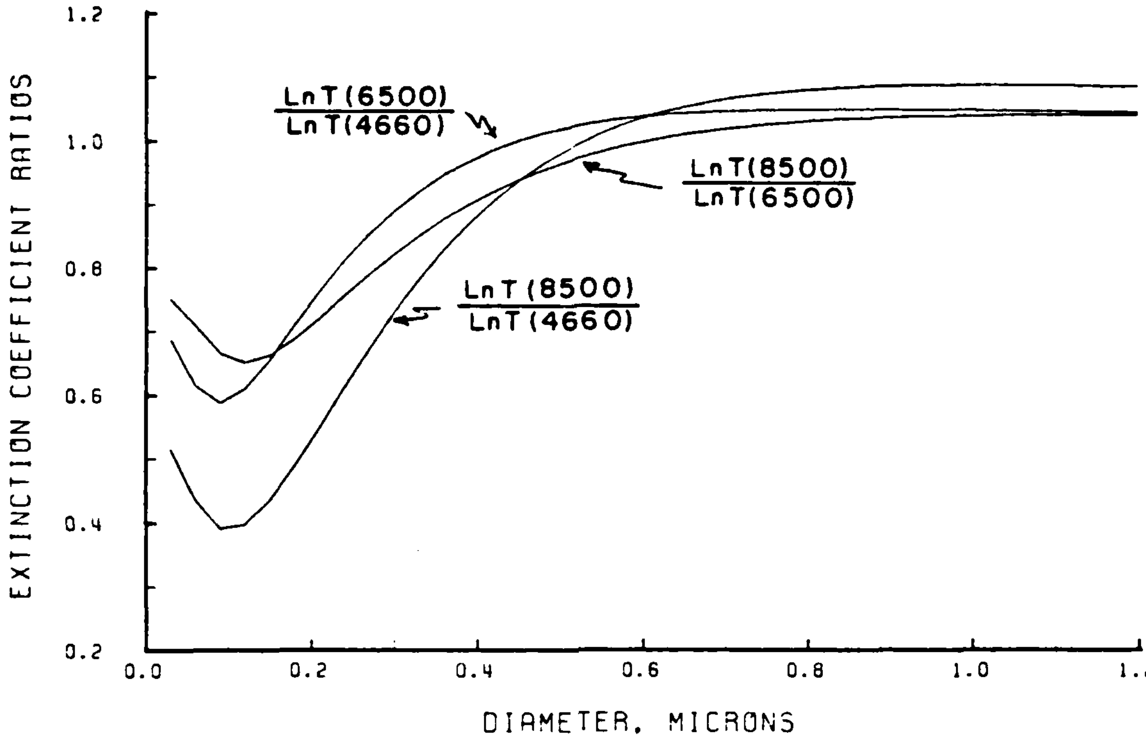


Figure 8. Nitrogen Oxides Analyzer.



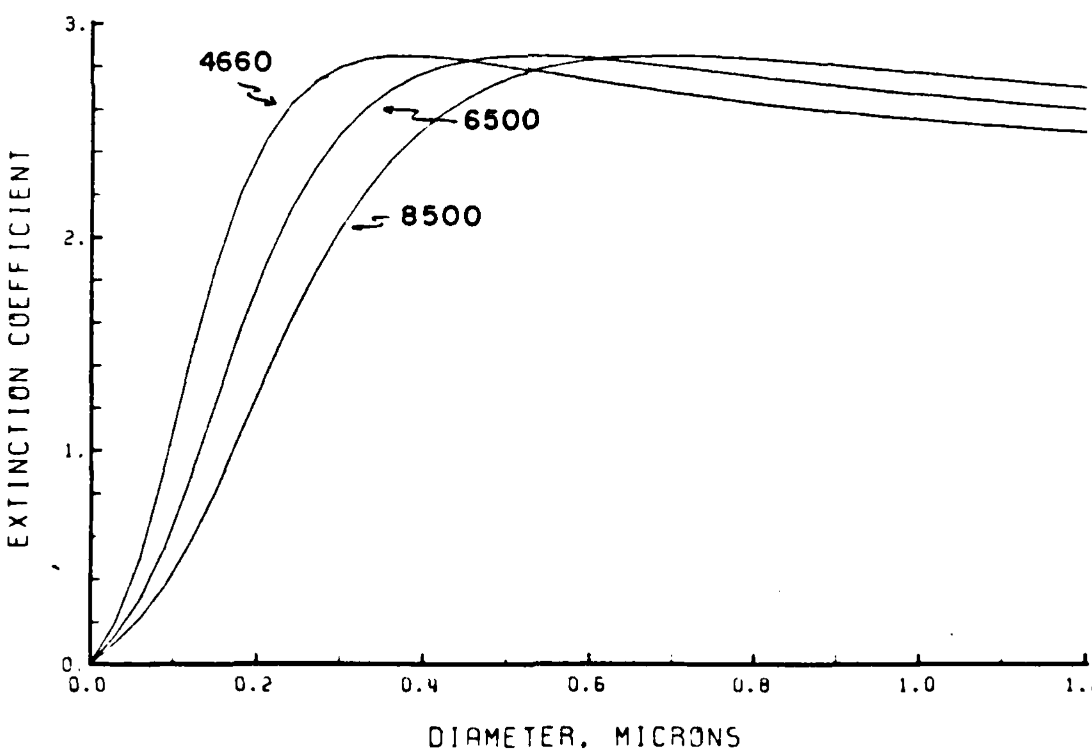


Figure 9 Extinction Coefficients and Coefficient Ratio Graph.

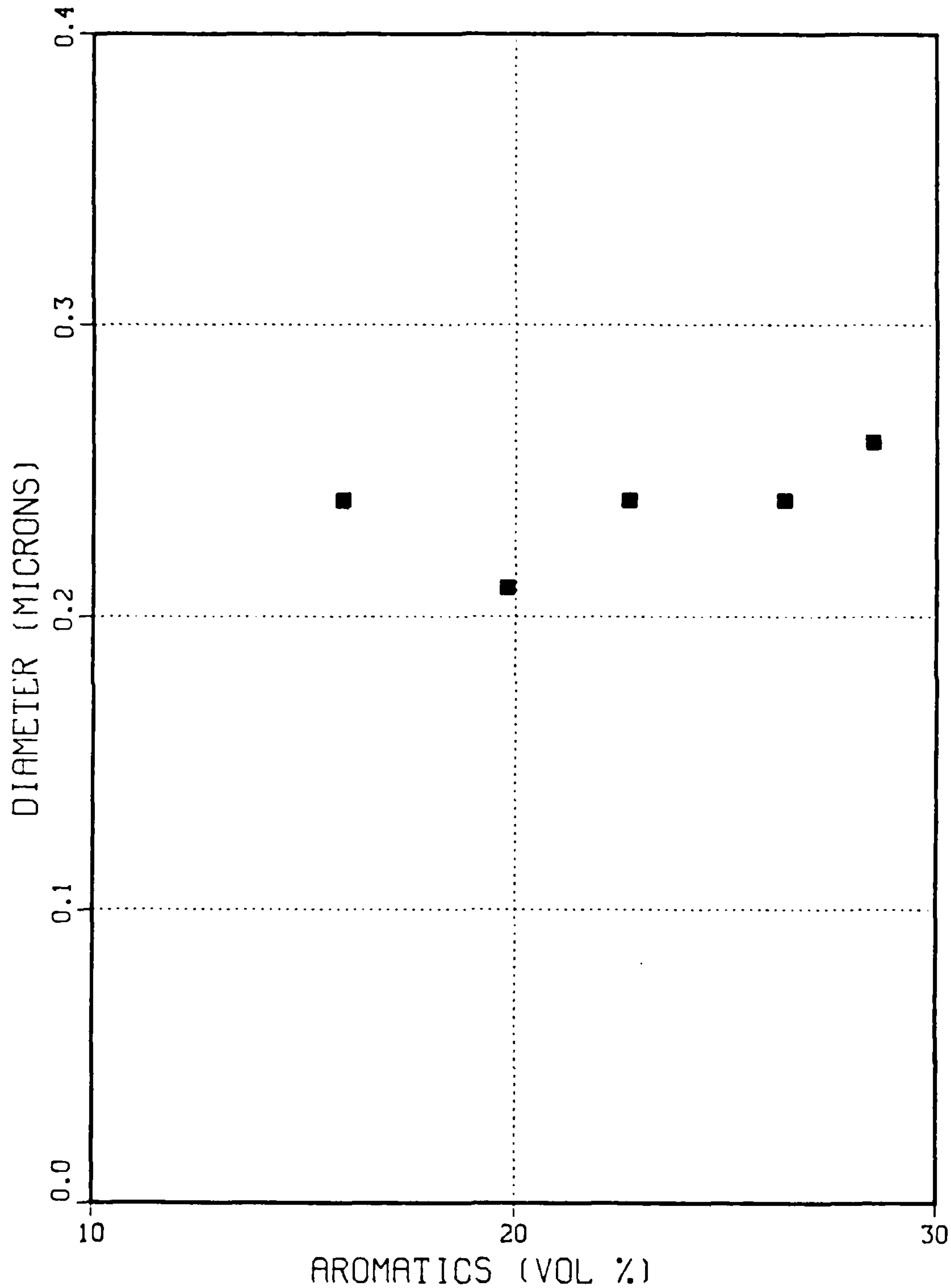


Figure 10. Particle Size vs. Aromatics Content

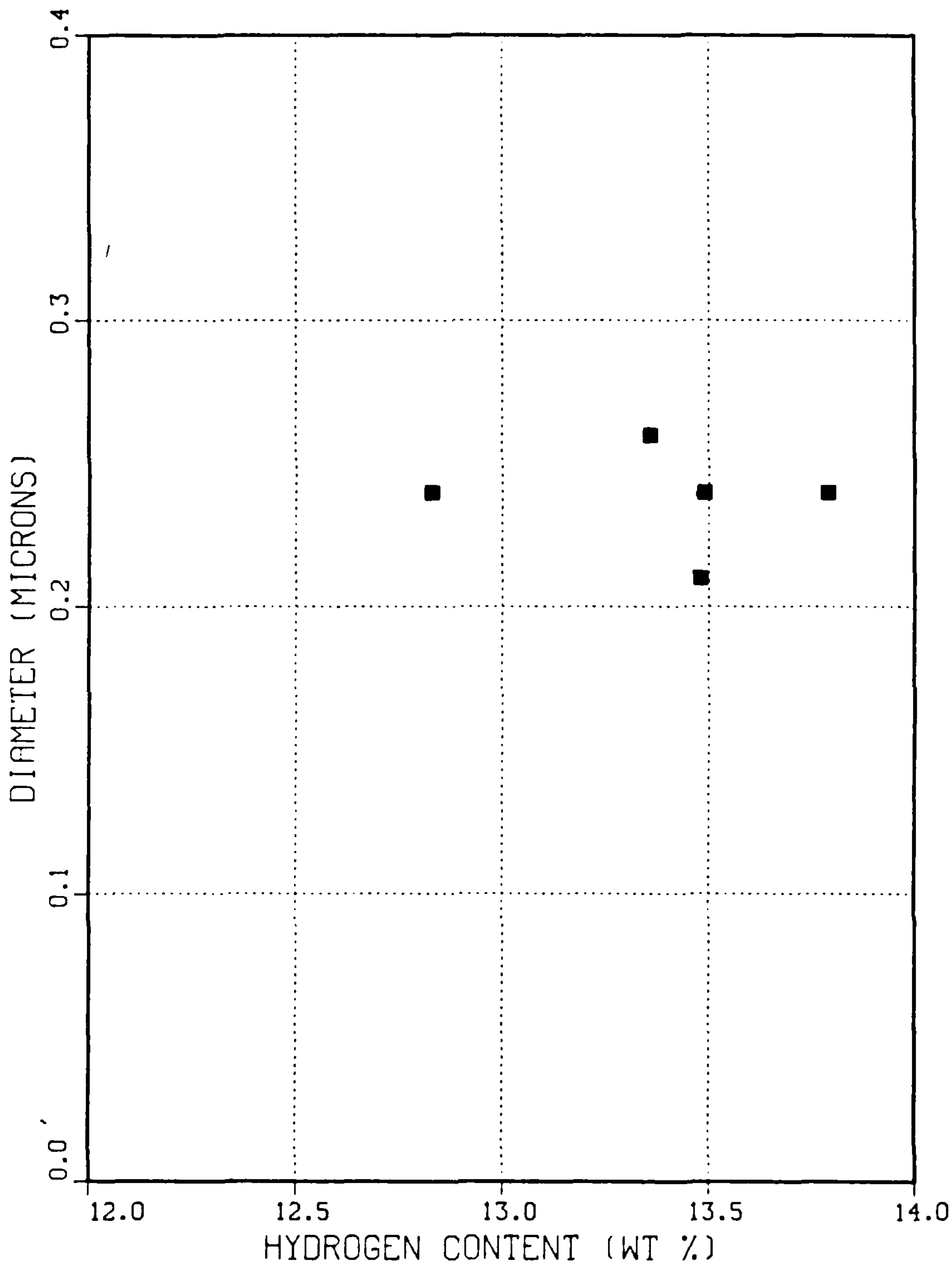


Figure 11. Particle Size vs. Hydrogen Content

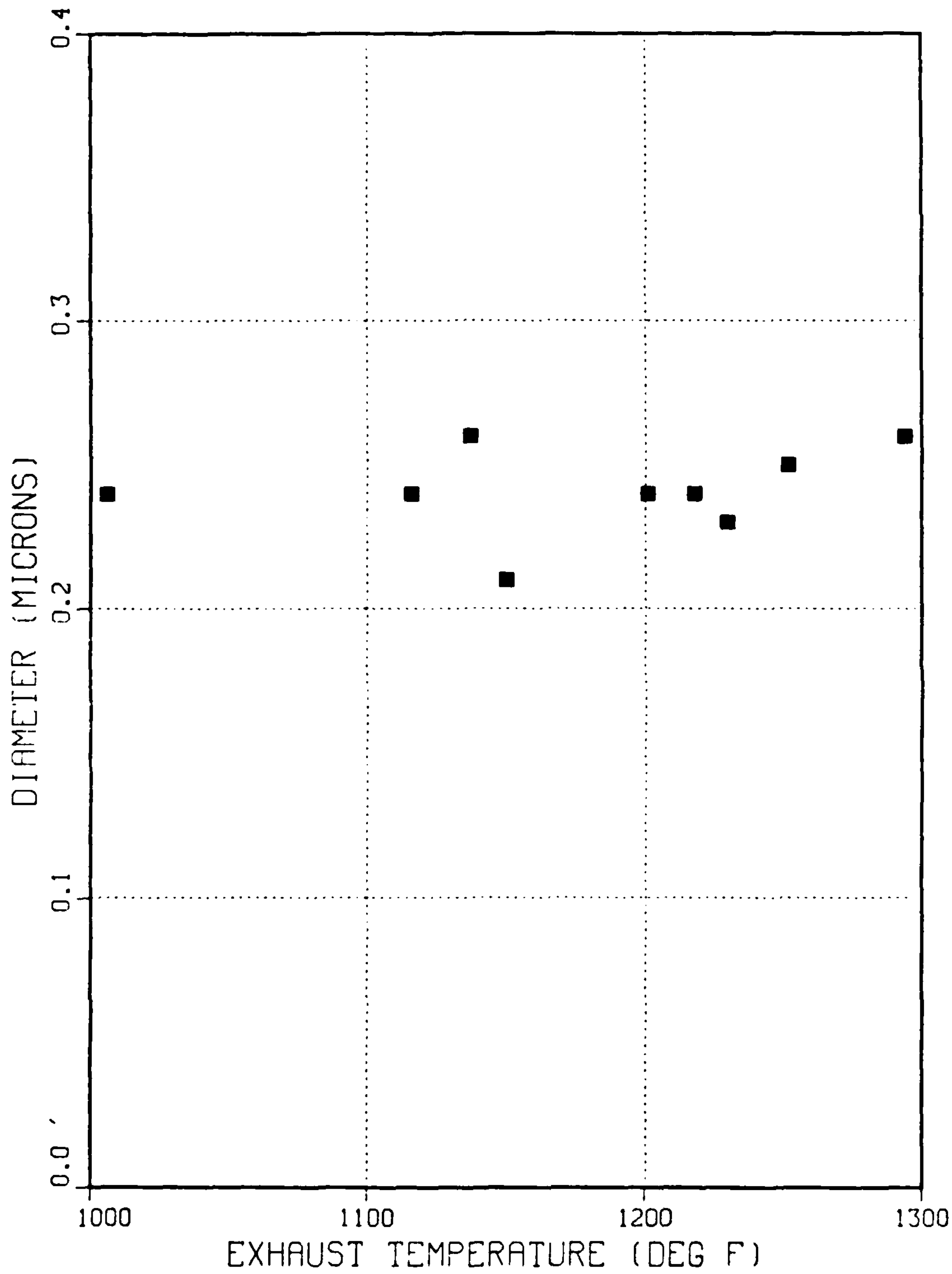


Figure 12. Particle Size vs. Exhaust Temperature

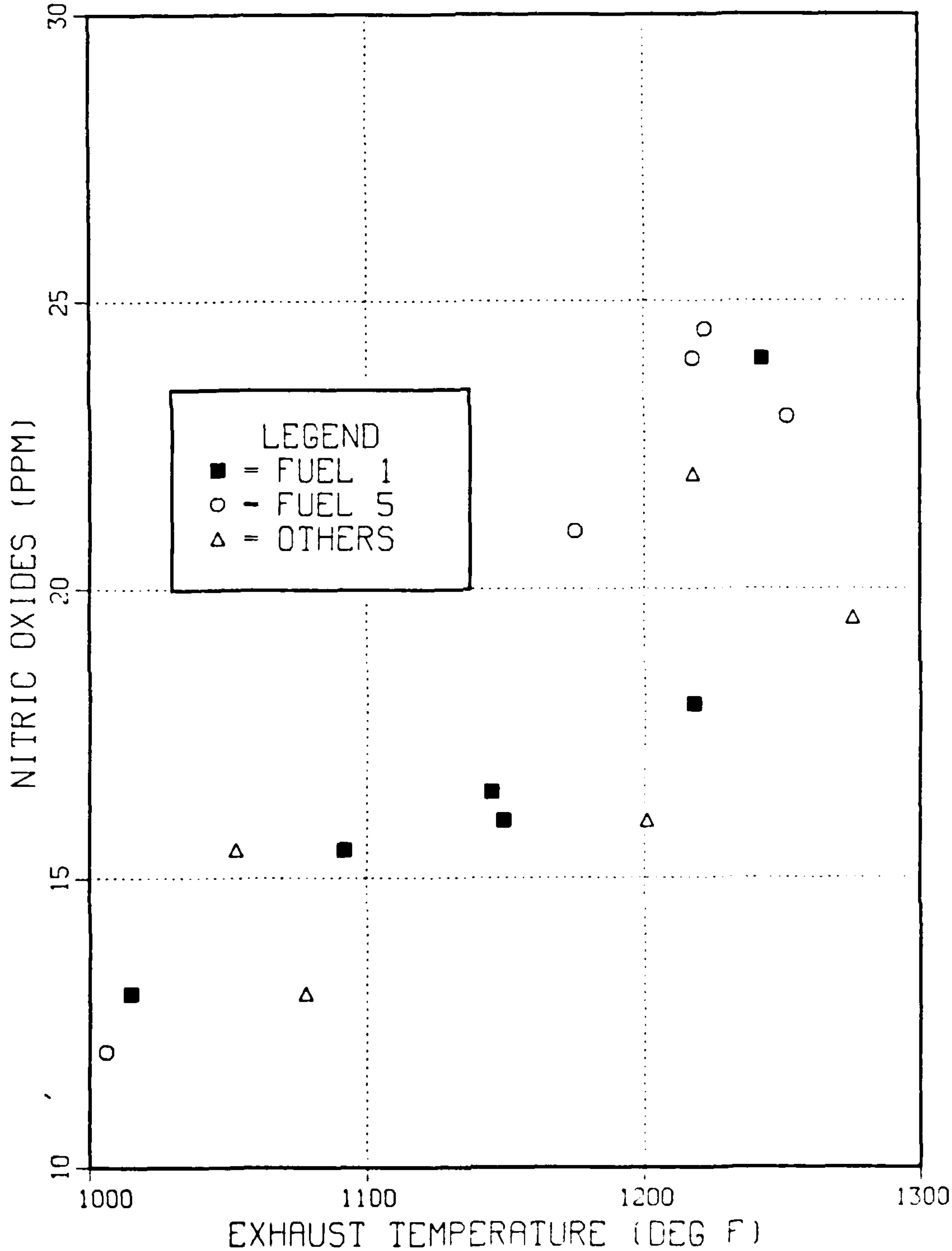


Figure 13. Nitric Oxides vs. Exhaust Temperature

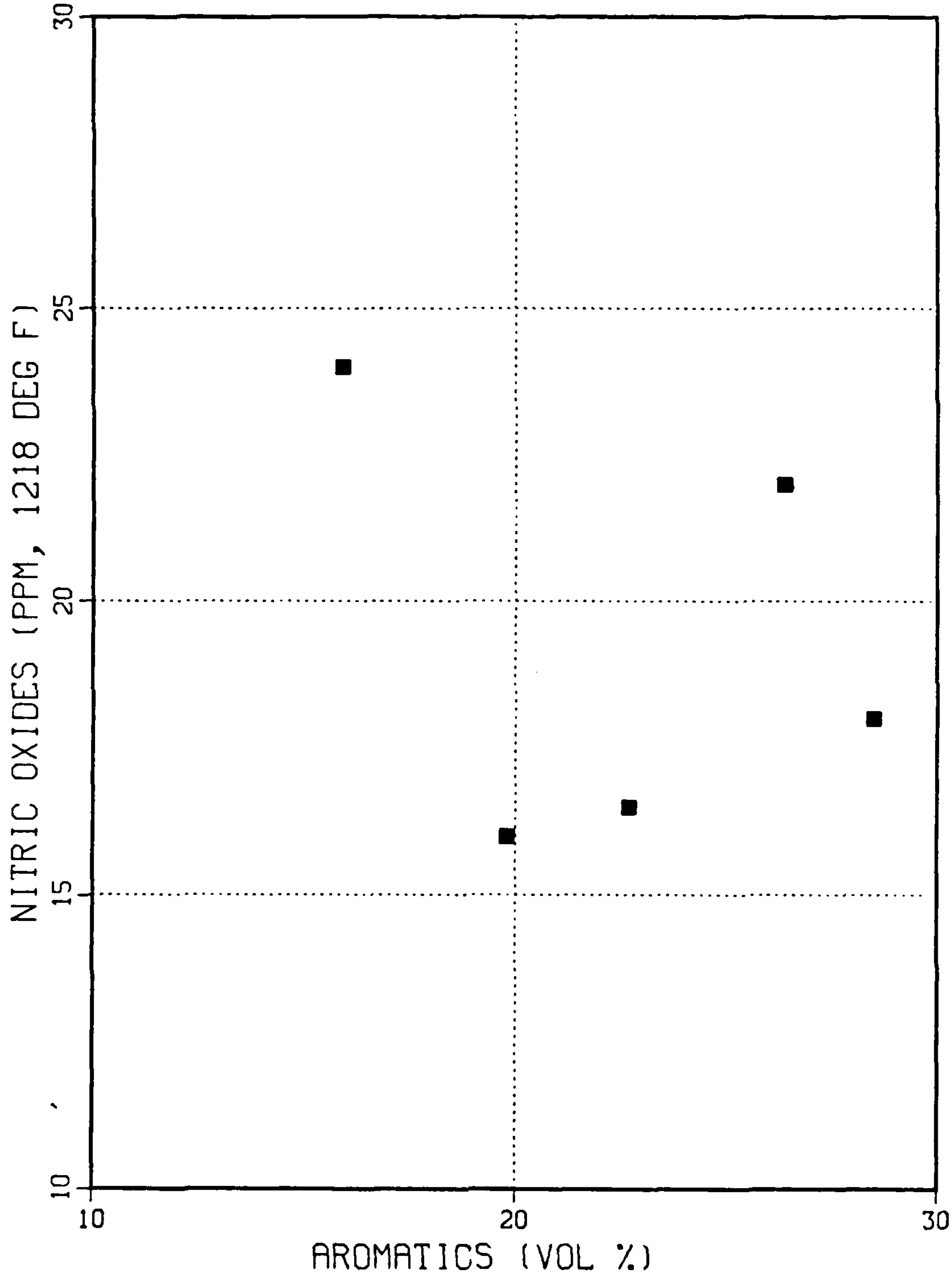


Figure 14. Nitric Oxides vs. Aromatics.

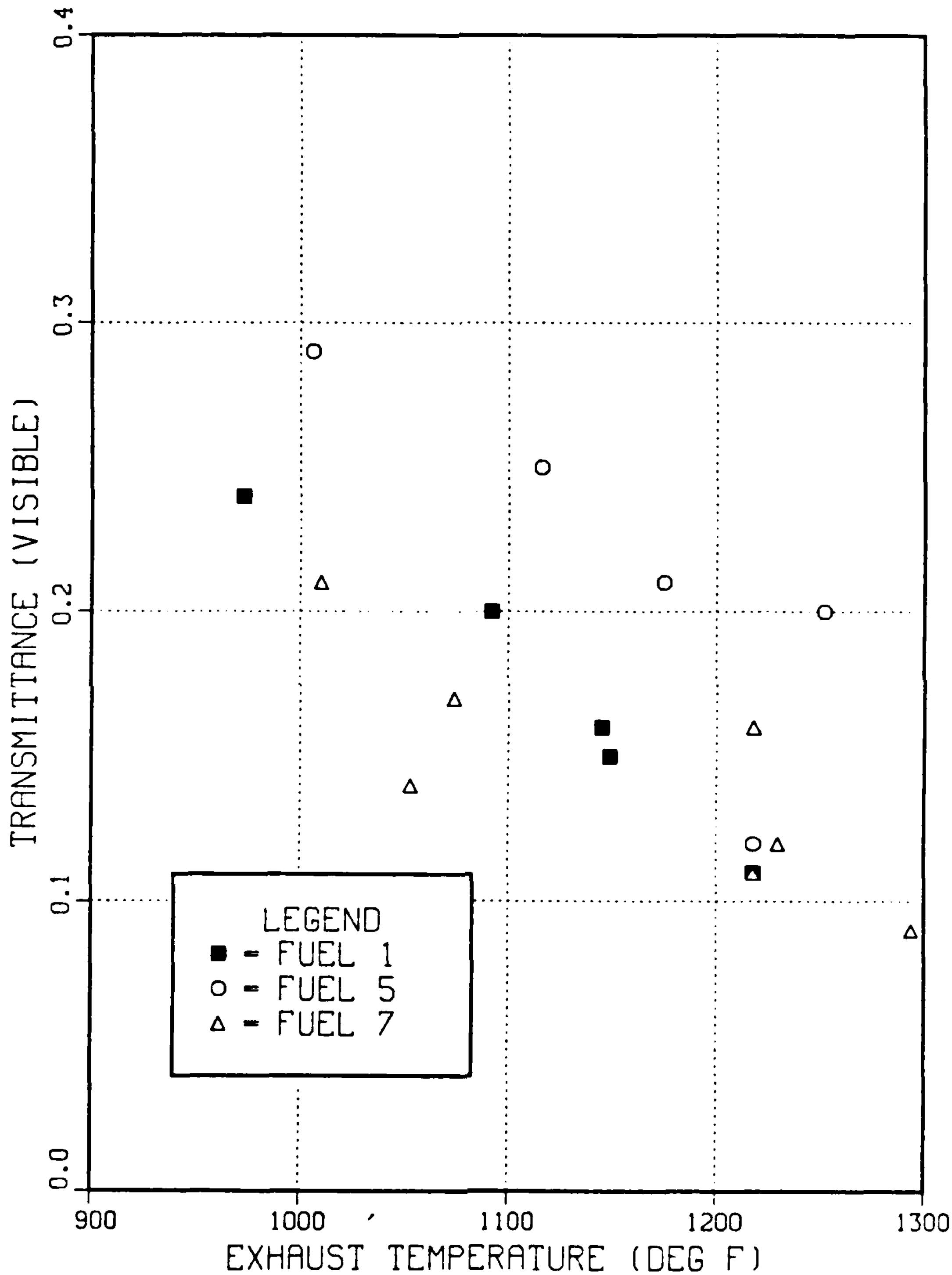


Figure 15. Visible Transmittance vs. Exhaust Temperature

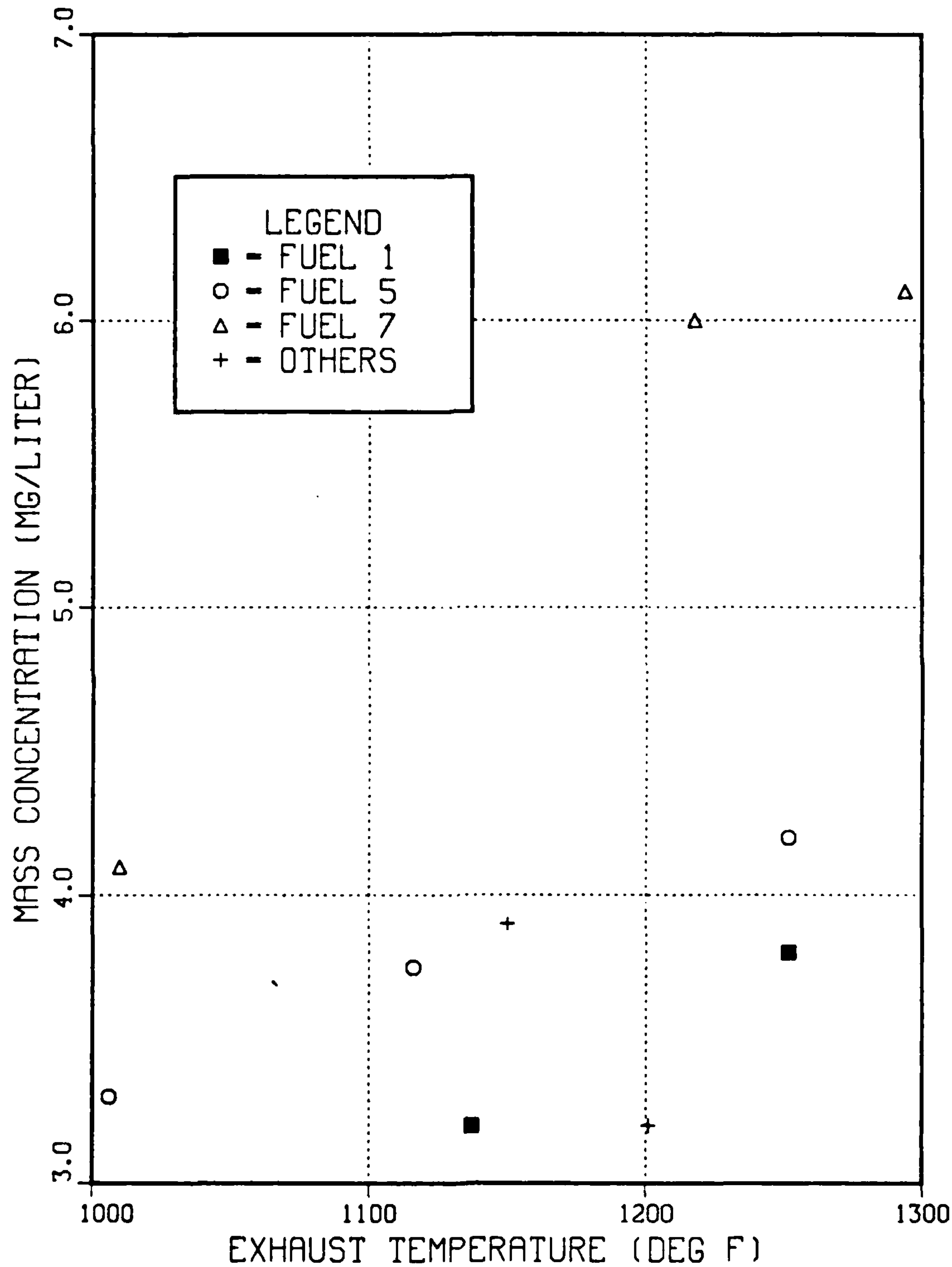


Figure 16. Mass Concentration vs. Exhaust Temperature.

TABLE I

Physical and Chemical Properties of Fuels

	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	---

TABLE II

T63 Test Conditions

Fuel no.	Run no.	Tair (°R)	Texh (°R)	Pc (psia)	$\dot{M}$air (lb/s)	$\dot{M}$fuel (lb/s)	'f'
1	1	464	1597	99	2.643	.0379	.0143
	2	488	1552	104	2.667	.0442	.0166
	3	486	1605	107	2.702	.0465	.0172
	4	492	1609	106	2.697	.0468	.0174
	5	498	1433	100	2.687	.0385	.0143
	6	495	1678	106	2.660	.0487	.0183
	7	494	1475	101	2.686	.0414	.0154
	8	501	1703	104	2.632	.0493	.0187
	9	483	1678	105	2.693	.0476	.0177
	10	485	1802	109	2.735	.0550	.0201
	11	487	1712	105	2.693	.0493	.0183
2	6	465	1610	101	2.714	.0381	.0140
5	1	492	1678	108	2.650	.0482	.0182
	2	492	1682	109	2.674	.0496	.0186
	3	499	1678	106	2.602	.0481	.0185
	4	497	1576	105	2.654	.0442	.0167
	5	497	1466	100	2.690	.0408	.0152
	6	497	1635	105	2.643	.0470	.0178
	7	497	1712	107	2.643	.0496	.0188
7	2	477	1660	100	2.619	.0380	.0145
	3	474	1450	--	2.597	.0380	.0146
	4	474	1515	106	2.609	.0410	.0157
	5	475	1678	109	2.570	.0460	.0180
	8	476	1690	113	2.742	.0490	.0179
	9	476	1754	112	2.670	.0500	.0187
	10	499	1470	101	2.637	.0385	.0146
	11	478	1538	106	2.707	.0431	.0159
	12	488	1534	107	2.679	.0431	.0161
9	1	464	1661	99	2.625	.0390	.0149

TABLE III

T63 Test Results

Fuel no.	Run no.	T8500	T4660	T6500	d32 μm	NOx ppm	NC ppm
1	1	.390	.170	.290	.26	15	7
	2	.264	.160	.196	.30*	15.5	14
	3	.200	.137	.159	.37*	16.5	16
	4	.194	.137	.151	.36*	16	14.5
	5	.241	.200	.242	--	12	8
	6	.124	.091	.113	--	18	17.5
	7	.187	.140	.161	.36*	13	9.5
	8**	.134	.097	--	--	24	23
	11***	.315	.176	.232	.26	20.5	17.5
2	6	.470	.172	.293	.21	12	9
5	3	.175	.142	.196	--	24	22
	4	.335	.171	.247	.25	--	--
	5	.381	.214	.292	.25	12	9.5
	6	.259	.156	.214	.31*	21	18
	7	.284	.139	.205	.25	23	20.5
7	4	--	--	--	--	15.5	12.5
	5	.196	.069	.110	.24	22	19
	8	.201	.066	.120	.23	--	--
	9	.157	.064	.094	.26	--	--
	10	.297	.140	.207	.26	--	16
	11	.146	.103	.150	--	13	9.5
	12	.203	.112	.166	.31*	--	--
9	1	.430	.180	.320	.24	16	8

*questionable correlation (±.05 micron)
**ferrocene additive @ 20 ml/gallon fuel
***12% Cerium Hex-cem additive @ 20 ml/gallon fuel
Other runs invalidated/aborted

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