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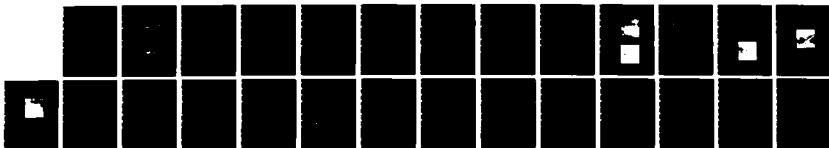
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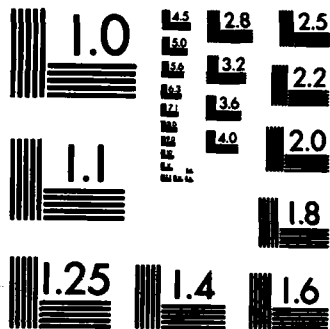
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Analysis of Particulates in the Exhaust Plume of a J52-P3 Turbojet Engine at Military Power

by
J. H. Johnson
E. D. Erickson
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MARCH 1985

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FOREWORD

Particulate matter (smoke) in the exhaust plumes of military aircraft is a highly visible pollutant that has caused frequent complaints from the public. The work described in this report will be combined with data obtained at the North Island Naval Air Station, San Diego, Calif., to develop an understanding of particle growth in the aircraft exhaust plume. Such an understanding should enable the Navy to engineer solutions to reduce the quantities of particulate matter released to the environment by military aircraft engines.

This report describes work performed at the Naval Weapons Center during fiscal year 1984. The work was performed using Pollution Abatement Research funds, Program Element Number 62765N, NAVAIR Task Area SF65-559-002 under the sponsorship of A. F. Klarman.

Approved by
E. B. ROYCE, *Head*
Research Department
10 January 1985

Under authority of
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Released for publication by
B. W. HAYS
Technical Director

NWC Technical Publication 6618

Published by Technical Information Department
Collation Cover, 12 leaves
First printing 270 copies

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NWC TP 6618	2. GOVT ACCESSION NO. AD-A157840	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ANALYSIS OF PARTICULATES IN THE EXHAUST PLUME OF A J52-P3 TURBOJET ENGINE AT MILITARY POWER		5. TYPE OF REPORT & PERIOD COVERED Interim October 1983-September 1984
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J. H. Johnson, E. D. Erickson, and D. J. Knight		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Weapons Center China Lake, CA 93555-6001		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS PE 62765N Task SF65-559-002
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Weapons Center China Lake, CA 93555-6001		12. REPORT DATE March 1985
		13. NUMBER OF PAGES 22
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution is unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Aircraft engine Exhaust Particulates Pollution		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) See back of form.		

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(U) This report presents particulate concentration, emission index, and size distribution data in the exhaust plume of a J52-P3 turbojet engine, run at military power in the open air. Recommendations are listed for future tests.

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ACKNOWLEDGMENT

We are indebted to Larry A. Mathews and Harold E. Cronin for their technical advice and their help in reducing the data from the TSI aerosol analyzer.

INTRODUCTION

The analysis of particulates in the exhaust plume from jet engines is one project in a large program to study the pollution caused by military aircraft. Sampling high power jet engine exhaust for pollutants is difficult, and several techniques are being employed to obtain a realistic picture. Also, the reduction in visibility due to particulate emissions is of considerable interest.

In the analytical method currently in use in industry, particulate sampling is conducted over the exhaust exit plane of a jet engine test cell stack (References 1 and 2). Although the stack temperatures may exceed 150°C at the sampling point, the total mass of particulate per sample volume at ambient temperature (20°C) can be obtained. This is accomplished by drawing the stack gas through a heated glass fiber filter (maintained at a temperature of 120°C), and then by drawing the stack gas through an ice cooled impinger train (maintained at a temperature of 20°C). Particulates that would exist at ambient temperature include the solids collected at 120°C and those collected as condensable matter at 20°C. This measurement is repeated at a matrix of sampling points throughout the cross section of the stack. Appropriate calculations yield an emission index (EI).

Particle size distribution data, taken from a test cell stack, may not be representative of the exhaust aerosol that is allowed to grow in the open air. In the open air, entrainment of atmospheric air causes rapid cooling of the exhaust plume. The particles grow due to condensation of hydrocarbon from the gaseous stream as the temperature decreases in addition to the normal particle growth from collision.

The objective of our work was to sample and analyze the plume of a military jet engine in the open air to determine the particle size distribution and total particulate concentration. Gas samples were collected for monitoring combustion gases and for calculating quantities of fuel consumed. These data were then to be compared to those taken in test cells where samples were collected at temperatures above 150°C. Eventually, these data will supplement particle size distribution measurements made by new optical methods being developed by the University of Tennessee Space Institute, Tullahoma, Tenn., as part of the program of the Naval Air Propulsion Center, Trenton, N.J.

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Pollution abatement work is underway at the Naval Weapons Center (NWC) to understand the pollutants produced by ordnance. This analytical technology has been adapted to study the exhaust of Navy aircraft.

In this report, a study of particulate concentration, size distribution, and fixed gases in the exhaust of a J52-P3 turbojet engine is presented. A refinement of sampling technique, based on preliminary work (Reference 3), and on this project, is proposed for future studies.

Funds were not received in time to do the experiments in the spring when the winds and temperatures were more predictable. When the wind speed and direction are changing constantly, temperature fluctuations and sample dilution occur, and it is impossible to get a representative gas or particulate sample. The wind speeds for tests 7 and 8 were within a reasonable limit. The wind speed and direction for each test are shown in Figure 1.

Even though the tests were made as early as possible in the morning, the ambient temperature would rise so quickly, we could not predict the test temperature with any accuracy. Tests 7 and 8 were to be made at 70 and 50°C, respectively. Actually, the temperatures obtained were 75 and 62°C.

EXPERIMENTAL SECTION

The open air Weapons Survivability Laboratory site at NWC was used for the tests. A J52-P3 turbojet engine was mounted on a concrete platform so that the center of the exhaust port was approximately 1.8 m above the ground (Figure 2). The ground was covered with a concrete pad and a steel sheet extending several hundred feet behind the engine. Sampling equipment was placed behind barricades on a platform in the exhaust plume as shown in Figure 3.

LOCATION OF SAMPLING POINTS

The sample collection apparatus was to be set up at three different points behind the engine, at distances where the temperature would be 70°C, 50°C, and one point further back at a distance to be determined later. This was in order to observe particulate growth with a decrease in temperature. We noticed during these tests that at the 50°C point, 100 ft from the engine, the plume was starting to rise from the pad. This made it impractical to do any tests at a greater distance from the engine. Figure 4 shows the location of the sampling points.

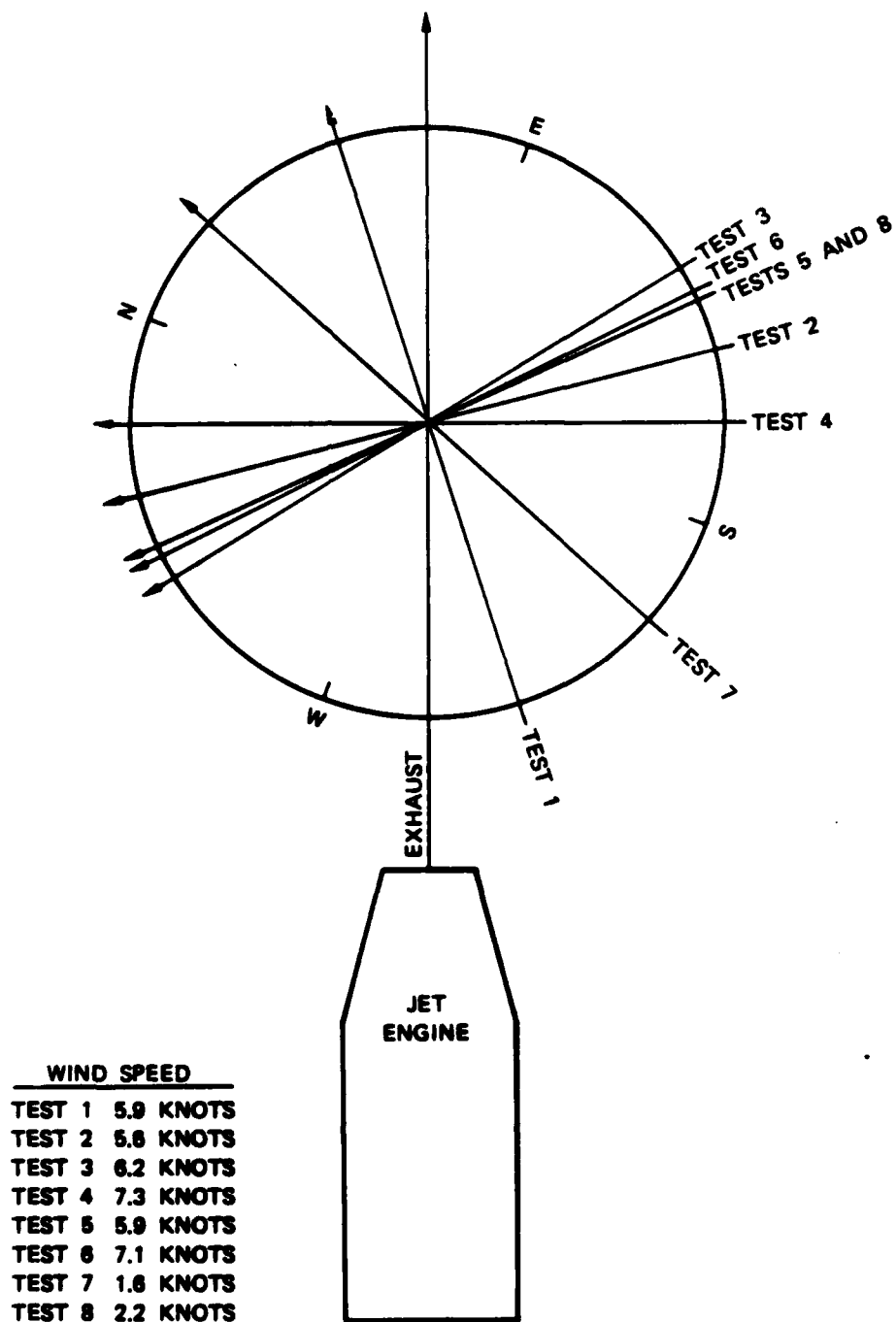


FIGURE 1. Wind Speed and Direction.



FIGURE 2. Side View of J52-P3 Turbojet Engine Positioned on Test Pad.

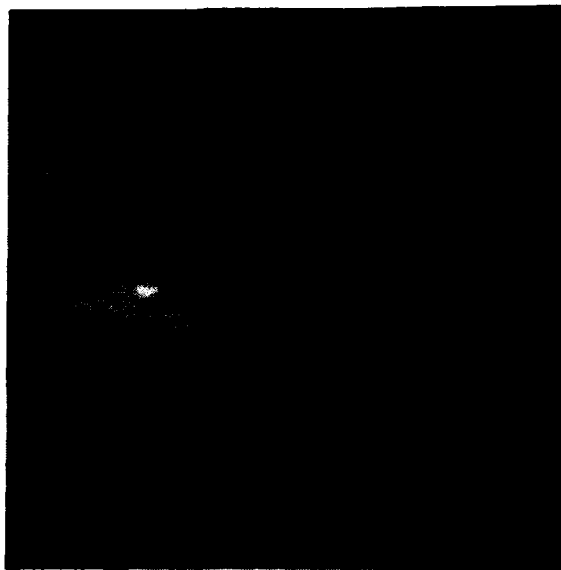


FIGURE 3. J52-P3 Turbojet Engine and Sampling Equipment in the Background.

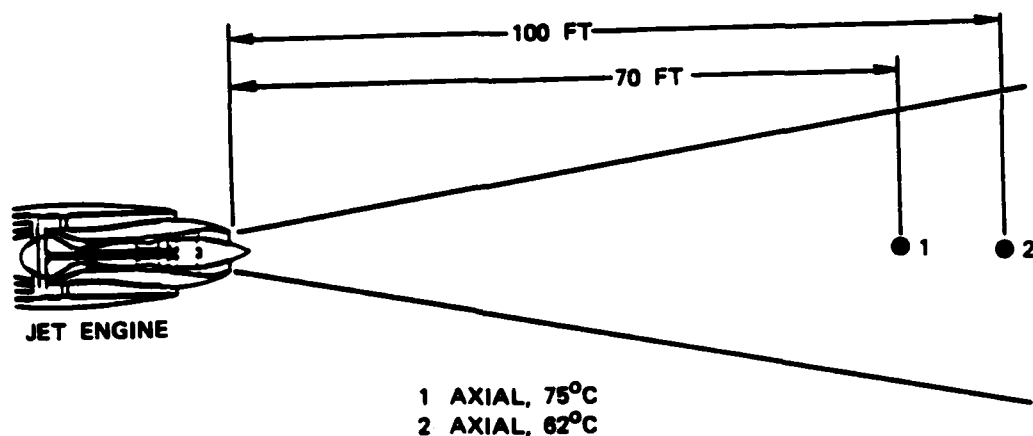


FIGURE 4. Location of Sampling Points with Temperatures of 62 and 75°C as Viewed From Above.

SAMPLING APPARATUS

Gas Sampling Apparatus

A gas sampling system was designed and built to collect eight gas samples, in pairs, sequentially. (The schematic is shown in Figure 5.) In this figure, the pump solenoids are labeled 1, and the sample solenoids are labeled 2. Prior to the test, the pump solenoids were opened to evacuate the flask. During the test, the pump solenoids were closed and the sample solenoids were opened for 10 seconds to collect each gas sample. After sampling, both solenoids were closed to isolate the gas sample. When it was safe to approach the sampling system, the manual valve on the sample flasks was closed. The sample flasks were then removed from the sampling system and transported to the laboratory for analysis.

Particle Sampling Apparatus

Two different types of sampling apparatus were utilized. One of them served to make total particle collections. It consisted of a 100-mm diameter, type A, glass fiber filter contained in a Sierra model 710 stainless steel, filter housing. The other collectors were particle size analyzers: an Anderson 14-stage low pressure impactor (LPI) and a Thermal Systems Inc. (TSI) electrostatic aerosol size analyzer.

The particle collectors and pumps were mounted to the platform behind the shielding barricade. This set up is shown in Figure 6. The particle laden air was drawn to each particle collector through

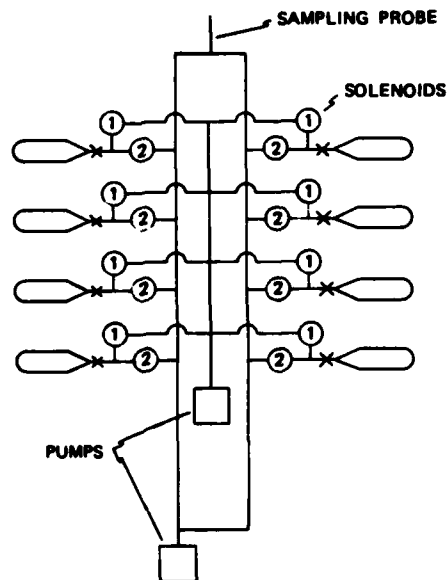


FIGURE 5. Schematic of Gas Sampling Apparatus.

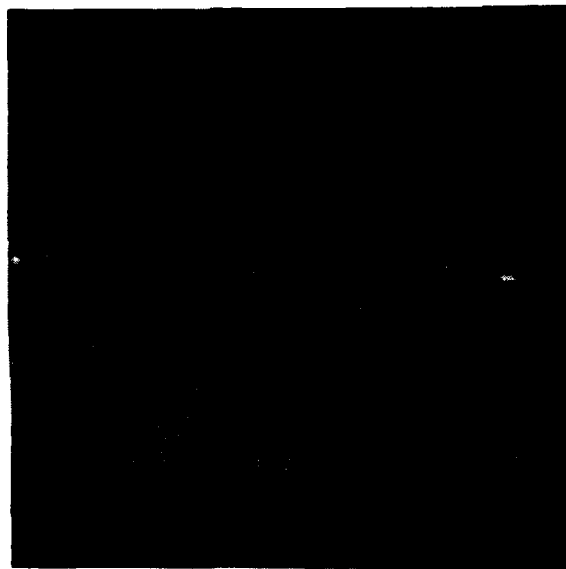


FIGURE 6. Particle Sampling Apparatus Located Behind Protective Shield. The turbojet engine exhaust port can be seen in the background.

stainless steel probes about 2.5 m in length and 1.3 cm inner diameter. Isokinetic nozzles were placed on the end of each probe facing into the plume (Figure 7). The intake probes were located on the platform approximately 1.8 m above ground level and were located away from surfaces that might cause flow stagnation. The average flow rate through the LPI sampler was 2.4 L/m for all the tests, and the average flow rate through the TSI sampler was 1.4 L/m for all the tests. The average flow rate through the 100-mm-diameter filter used to capture a total particulate sample was 74.0 and 79.5 L/m at sampling points 1 and 2, respectively.

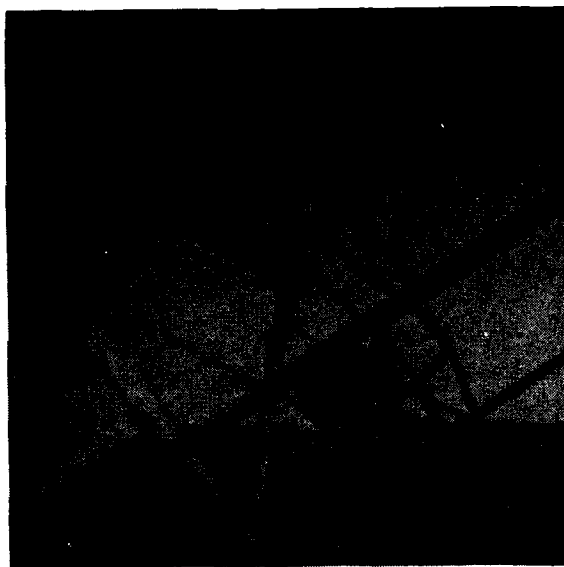


FIGURE 7. Isokinetic Probes Facing Into the Plume.

Particle Size Distribution Measurement

Initially, particle size distributions were to be determined by both an Anderson 14-stage LPI and a TSI electrostatic aerosol size analyzer. However, since particles could not be found on any of the stages of the Anderson impactor, we decided not to use the impactor on tests 7 and 8. The TSI analyzer was much too sensitive for this application. To prevent the analyzer's amplifier from overloading, a tee had to be put in the sample probe line to dilute the sample (see Figure 8).

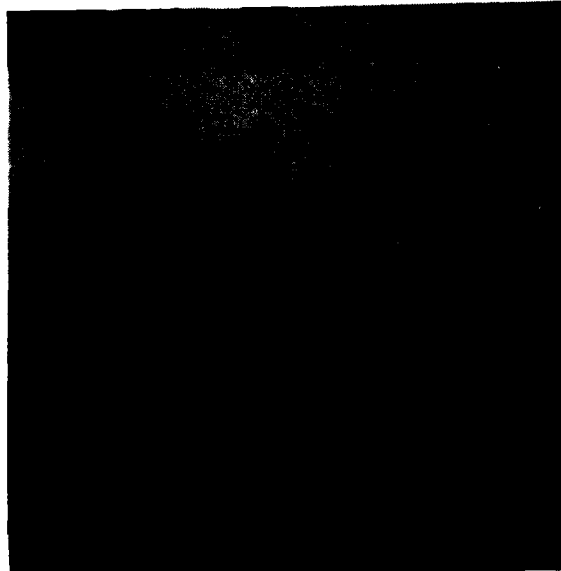


FIGURE 8. TSI Electrostatic Aerosol Analyzer and Tee.

Six runs were made before the correct dilution was arrived at to keep the recorder trace on scale. The total particle collector was also checked and only one-sixtieth as much sample was found for this engine compared to the TF30-P1 jet engine.

SAMPLING TECHNIQUE

Tests with the engine at military power were made at each of the two sampling points to determine the concentration and size distribution of particulates. The sampling time for each run was 10 min. The jet engine was run for 5 min prior to sampling to allow the engine to stabilize.

All filters and substrates were desiccated and weighed before and after sampling to determine the mass of particulate collected. The filters and substrates were stored in large petri dishes before and after sampling.

DATA PRESENTATION

FIXED GASES

Samples collected for fixed gas analysis were analyzed using a Perkin-Elmer Sigma 2000 gas chromatograph with a 6-ft by 1/8-inch Spherocarb column. This chromatograph is equipped with a catalyst which makes it possible to use a flame ionization detector for the detection of CO and CO₂.



Carbon monoxide and CO₂ can be monitored to levels as low as 0.3 parts per million (ppm). Concentrations of CO and CO₂ are listed in Tables 1 and 2. These data were used to approximate the quantity of fuel which had been burned to produce the particulates which we collected at each position (see Appendix).

TABLE 1. Gas Samples from the Exhaust of a J52-P3 Turbojet Engine. (Test 7 at a distance of 70 ft.)

Time sample taken, min	CO ppm	Average CO ppm ^a	CO ₂ ppm	Average CO ₂ ppm ^{b,c}
2	1.13	1.09	2133	1711
2	1.05	...	2154	...
4	0.98	0.99	2145	1730
4	0.99	...	2178	...
6	1.12	1.09	1989	1555
6	1.06	...	1985	...
8	1.94	1.96	2229	1832
8	1.98	...	2298	...

^aAverage CO for 10 minutes = 1.28 ppm.

^bAverage CO₂ for 10 minutes = 1707 ppm.

^cCorrected for CO₂ in air.

TABLE 2. Gas Samples from the Exhaust of a J52-P3 Turbojet Engine. (Test 8 at a distance of 100 ft.)

Time sample taken, min	CO ppm	Average CO ppm ^a	CO ₂ ppm	Average CO ₂ ppm ^{b,c}
2	1.13	1.20	1596	1232
2	1.27	...	1723	...
4	0.77	0.75	1705	1292
4	0.72	...	1734	...
6	0.57	0.59	1718	1249
6	0.60	...	1636	...
8	0.63	0.64	1521	1127
8	0.64	...	1589	...

^aAverage CO for 10 minutes = 0.80 ppm.

^bAverage CO₂ for 10 minutes = 1225 ppm.

^cCorrected for CO₂ in air.

TOTAL PARTICULATE CONCENTRATIONS

The total mass of particulate collected was determined to be the difference between the tare and final weights of the 100 mm glass fiber filter. The filters yielded 1.2 and 1.5 mg of particulates for tests 7 and 8, respectively. The total concentrations for tests 7 and 8 were calculated to be 1.62 and 1.89 mg/m³, respectively. These data also were used to calculate the particulate emission index (Appendix).

PARTICLE SIZE DISTRIBUTION

The mass of particulate collected for each size range was determined from the data collected by the TSI electrostatic aerosol size analyzer. Thus, the mass percent of particulate in each size range was found. These data are plotted as bar graphs in Figures 9 and 10.

DATA ANALYSIS AND DISCUSSION

Figures 9 and 10 indicate that with the engine running at military power all of the particulate mass was found in the 0.10 to 1.0 μm range. The mass median aerodynamic diameters for the above size distributions

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TEST NO. 7

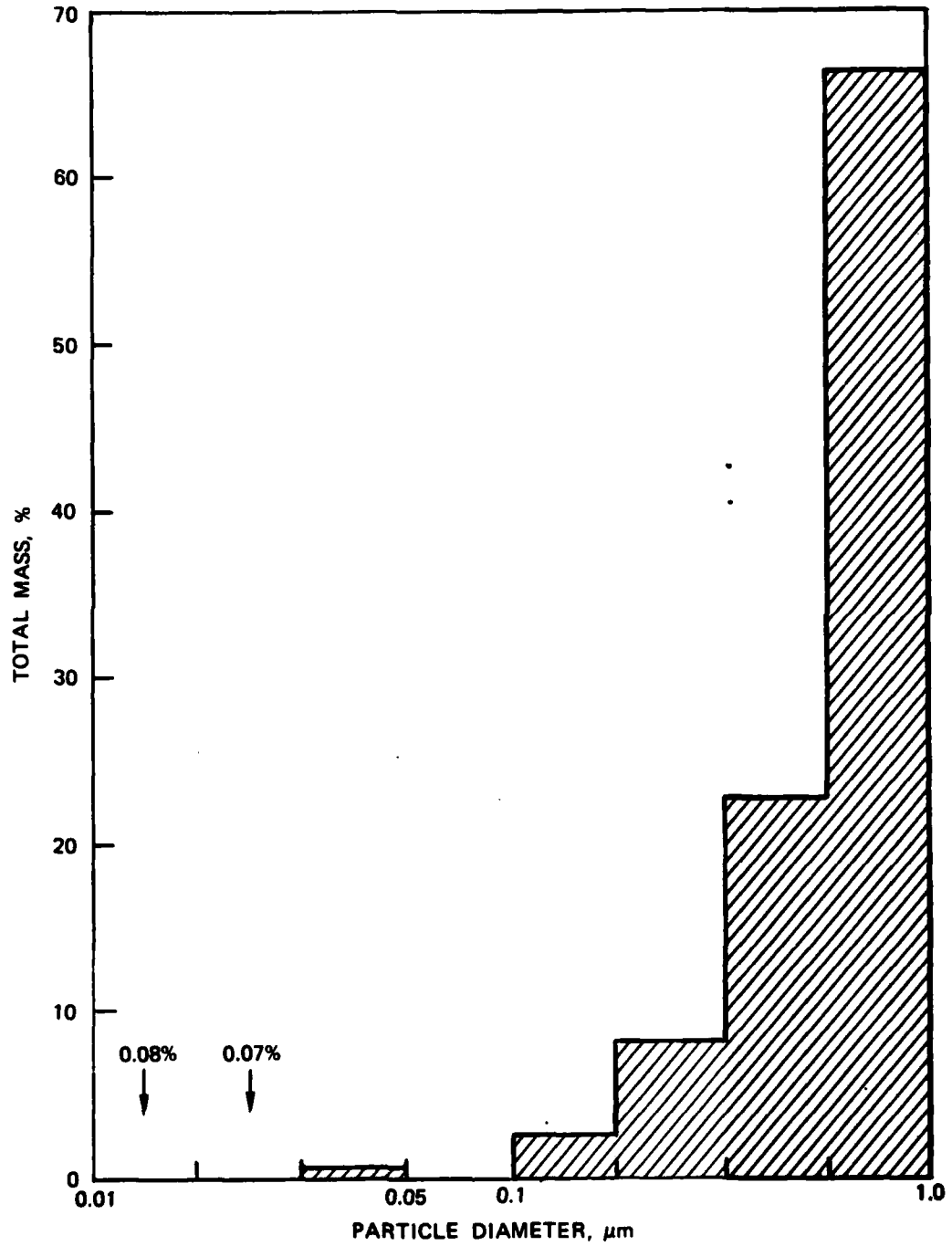


FIGURE 9. Mass Percent Versus Particle Diameter for the Test Sampling Point 1.

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TEST NO. 8

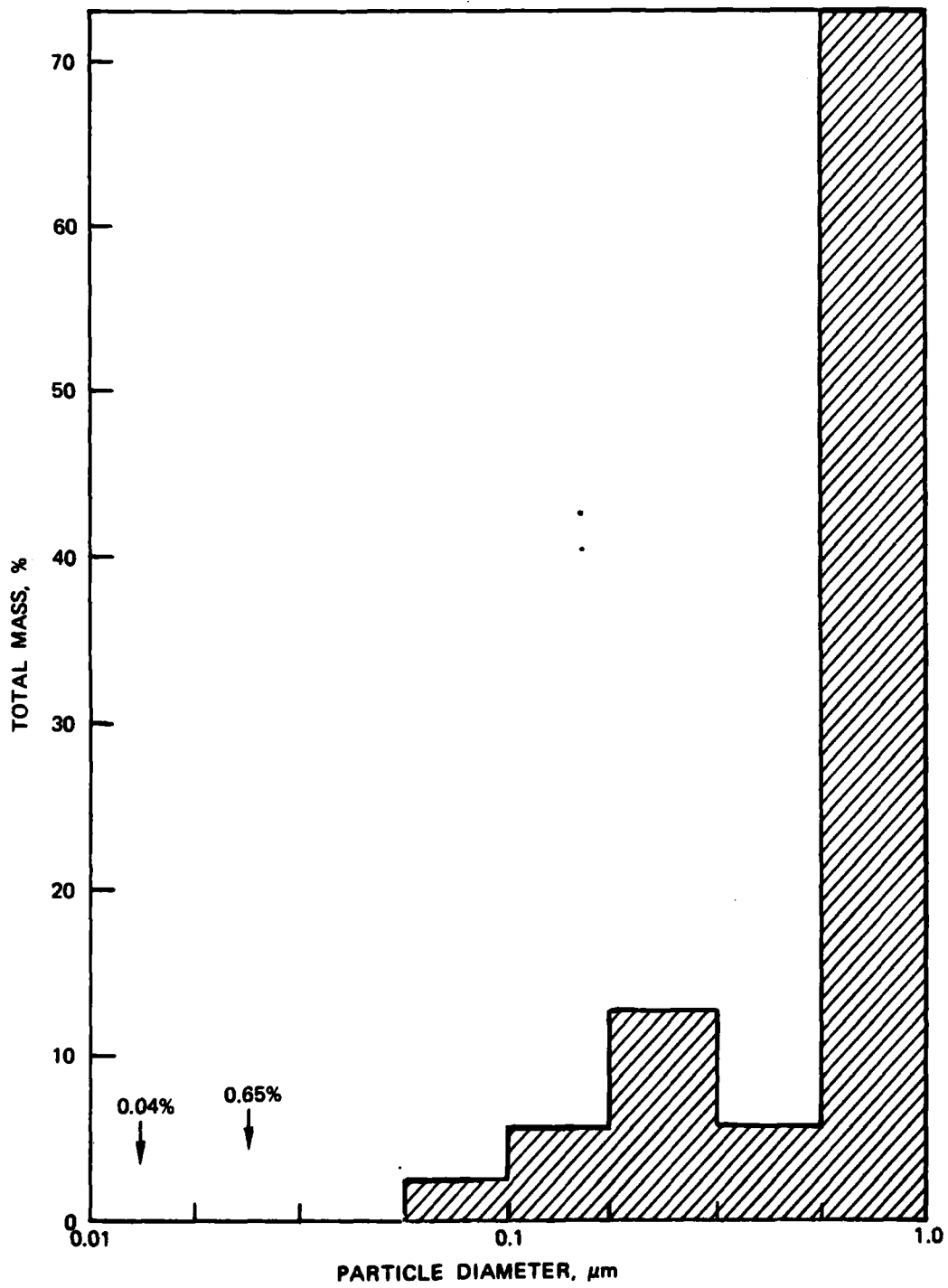


FIGURE 10. Mass Percent Versus Particle Diameter for the Test at Sampling Point 2.

were 0.67 and 0.70 μm for sampling points 1 and 2, respectively. These data are very high compared to the data taken from a TF30-P1 engine last year in which the mass median diameters were 0.19 and 0.27. Size distribution data obtained in a test cell of the exhaust from a TP30-P414 engine at military power yielded 0.13 μm as a mass median diameter (Reference 4).

Since we were not able to use the 14-stage Anderson impactor on these two tests, we do not have a check on the accuracy of the TSI analyzer in the configuration that it was used. The amount of sample going to the TSI analyzer was diluted by a factor of 38:1 to keep from overloading the amplifier and having all the peaks go off scale on the recorder. This dilution was attained by using a tee in the sample probe line and drawing air into the analyzer from 80 ft off to the side and ahead of the sampling devices, Figure 11.

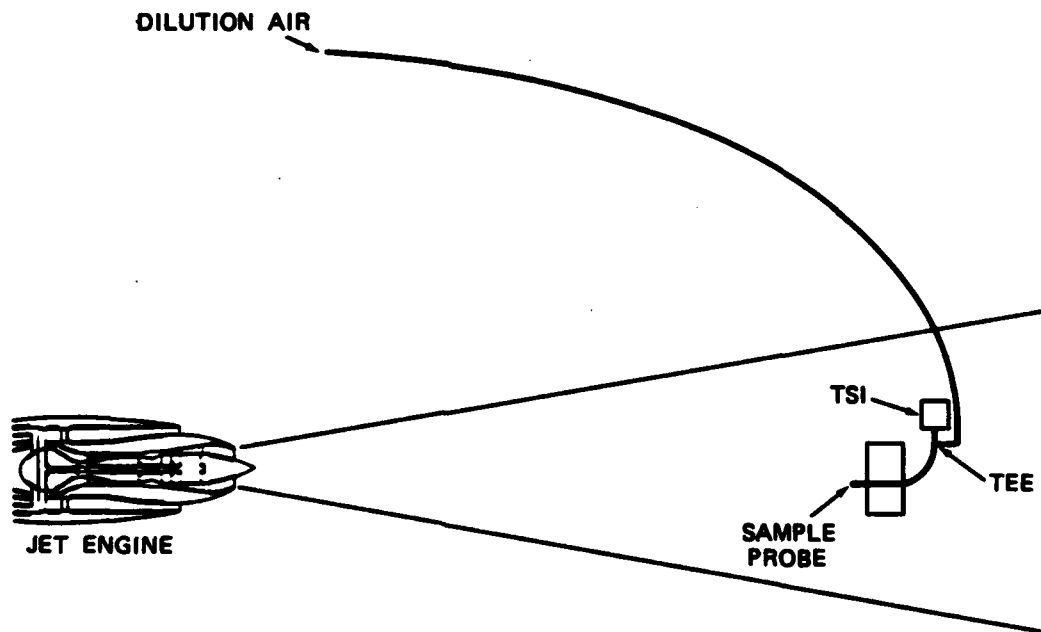


FIGURE 11. TSI Electrostatic Aerosol Size Analyzer Showing Tee Location.

We feel that the reason the mass median diameter was so high was because the plume from the engine was causing a vortex that eventually reached the dilution air intake. This vortex contained dust particles which had a much larger mass median diameter than the particulates from the engine. If this were true, the volume of dust particles would have covered up any particulates from the engine.

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The total particulate concentration increased from 1.62 mg/m³ at 75°C to 1.89 mg/m³ at 62°C along the plume axis. A decrease would have been expected due to entrainment of ambient air and spreading of the plume with increased distance from the jet engine. The increase we observed could be due to increased condensation occurring on very small particles or Aitken nuclei.

The particulate EI, expressed as mass of particulates per 1000 mass units of fuel consumed, was calculated from the CO₂ and total particulate data (Appendix). The values of the EI calculated for each sampling point are shown in Table 3. These values might be lower if the calculation were to include uncondensed hydrocarbon gases which we did not monitor during the work. The measured values of EI compare very well with those reported for rebuilt TF30-P414 engines, run at military power in test cells. Such rebuilt engines produced EIs that ranged from 2.2 to 3.7 (Reference 2).

TABLE 3. Calculated EIs.

Test No.	Distance from exhaust port, ft	Exhaust temperature, °C	EI
7	70.0	74.9	2.06
8	100.0	61.8	3.25

CONCLUSIONS

The particle size distribution data show that the mass median aerodynamic diameter of the particulates is in the range of 0.67 to 0.70 μm compared to an average diameter of 0.13 μm for test cell data. It is difficult to ascertain whether the particle growth is influenced by external contaminants such as dust, redispersion of particles which had previously adhered to engine surfaces, or condensation. The TSI aerosol analyzer is much too sensitive to use for this type of work. We may have to increase the engine run time so that we can use the Anderson 14-stage impactor to obtain the particle size distribution data.

The open air plume test data for a J52-P3 turbojet engine yielded EI data that compared very well with the test cell data for a rebuilt TF30-P414 engine. Both engines were tested at military power. The EI data were calculated from material balances of carbon dioxide and total particulate matter; however, the J52-P3 turbojet engine EI values would be smaller if uncondensed hydrocarbon gases were present and had been included in the calculations.

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From the experiences with these tests, we have developed some recommendations for future tests.

1. We need to be able to raise and lower the sampling rack to keep the probes in the center of the exhaust plume.

2. The test duration needs to be 10 times longer (100 minutes) to collect representative samples on the total particulate filter and on the Anderson 14-stage impactor.

3. Wind speeds should be no more than 2 to 3 knots.

4. An optical particle counter with a range of 0.5 to 10.0 μm should be used to monitor the dust.

5. Total particulates, as well as velocity and temperature, should be sampled at four or more points in a cross section of the plume to obtain concentration and velocity profiles. Such information will allow a calculation of the degree of entrainment and, thus, the dilution effect on the EI.

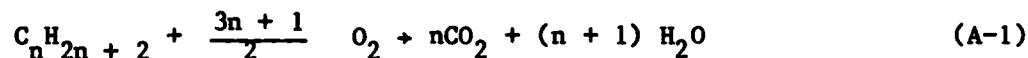
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4. Personal Communication with Everett L. Douglas of the Aircraft Environmental Support Office, Naval Air Rework Facility, Naval Air Station, North Island, San Diego, Calif., 18 October 1983.

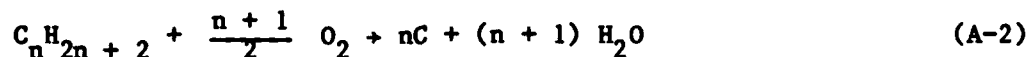
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Appendix
EMISSION INDEX CALCULATION

The EI for particulates is defined as the mass of particulates emitted per 1000 mass units of fuel consumed. An approximate EI can be calculated from the limited amount of data at a sampling point. The mass of carbon dioxide in the gas volume sampled for particulates is calculated, and the mass of fuel burned to produce that mass of carbon dioxide is found from a material balance of the assumed equation for combustion



Also, assume that the particulates sampled are composed only of carbon. The mass of fuel burned to produce that mass of carbon is found from a material balance of the assumed equation for its formation,



The EI is calculated by dividing the mass of particulate sampled by the mass of fuel burned and multiplying the ratio by 1000.

Using the data from test 7:

T = 74.9 °C
 P = 702 torr = 0.924 atm
 0.17 vol % CO₂ in gas sampled
 M_p = 0.0012 g particulates collected
 V = 743 L of gas sampled

The calculation is as follows

$$\text{The partial volume of CO}_2, V_{\text{CO}_2} = (0.0017) (743) \text{ L} = 1.26 \text{ L}$$

Using the ideal gas law for partial volumes,

$$V_{\text{CO}_2} = \frac{n_{\text{CO}_2} RT}{P} = \frac{M_{\text{CO}_2} RT}{44 P} \quad (\text{A-3})$$

where

P = total pressure of gas = 0.924 atm
 T = temperature of gas = 347.9 K
 R = gas constant = 0.0821 atm-L/g-mole K
 n_{CO₂} = gram moles of CO₂, and
 M_{CO₂} = mass in grams of CO₂

Transposing equation A-3, and substituting the above values, we get $M_{CO_2} = 1.79$ g.

From a material balance of equation A-1, the mass of fuel burned to form CO_2 is

$$M_a = \frac{14.2 M_{CO_2}}{44.0} \quad (A-4)$$

if the predominant molecular species in the fuel is $C_{12}H_{26}$.

$M_a = 0.58$ g upon substitution of M_{CO_2} .

From a material balance of equation A-2, the mass of fuel burned to form carbon is

$$M_b = \frac{14.2}{12.0} M_p \quad (A-5)$$

$M_b = 0.0014$ g upon substitution of M_p . The total fuel consumed to form CO_2 and carbon is $M_{fuel} = M_a + M_b = 0.581$ g.

The EI

$$EI = \frac{M_p}{M_{fuel}} \times 1000 \quad (A-6)$$

is found to be 2.06 upon substitution.

These calculations assume that the above material balances account for the fuel consumed. However, the calculations ignore uncondensed hydrocarbon gases.

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1 Naval Energy and Environmental Support Activity, Port Hueneme
2 Naval Explosive Ordnance Disposal Technology Center, Indian Head
Code RD (1)
Technical Library (1)
1 Naval Intelligence Support Center (NISC-60, Library)
3 Naval Ocean Systems Center, San Diego
Code 513
S. Yamamoto (1)
A. Zirino (1)
Code 5131, M. H. Salazar (1)
2 Naval Ordnance Station, Indian Head
Code E, Pollution Abatement Program Manager (1)
Technical Library (1)
3 Naval Research Laboratory
Code 4300 (1)
Code 6100 (1)
Library (1)
3 Naval Ship Weapon Systems Engineering Station, Port Hueneme
Code 5711, Repository (2)
Code 5712 (1)
2 Naval Amphibious Base, Coronado
SDV Team 1 (1)
SEAL Team 5 (1)
5 Naval Surface Weapons Center, Dahlgren
G-51
J. Bromfield (1)
D. Knudsen (1)
R. Gibbs (1)
Code 651, D. Rowe (1)
Technical Library (1)
5 Naval Surface Weapons Center, White Oak Laboratory, Silver Spring
Code R11 (2)
Code R16, J. Hoffsommer (1)
Code R17 (1)
Code R141, G. Young (1)
1 Naval Underwater Systems Center, Newport (Code 364, R. Kronk)
1 Naval War College, Newport
1 Naval Weapons Station, Concord (Code 321, M. Bucher)
2 Naval Weapons Station, Yorktown
Code 203, M. West (1)
Code 50 (1)
6 Naval Weapons Support Center, Crane
Code 3025, D. Burch (1)
Code 50C, B. E. Douda (1)
Code 505, J. E. Short (1)
NAPEC (1)
R&E Library (2)
4 Office of Naval Technology, Arlington
-MAT-0716 (1)
MAT-072 (1)
MAT-0723 (1)
MAT-0724 (1)
1 Pacific Missile Test Center, Point Mugu (Code 2145)
1 Theatre of Nuclear Warfare Project Office (TN-20A, G. Patton)
1 Army Armament Munitions & Chemical Command, Rock Island Arsenal

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