EPA-650/2-75-055

May 1975

Environmental Protection Technology Series

DETERMINATION OF AIRCRAFT TURBINE ENGINE PARTICULATES

U.S. Environmental Protection Agency
Office of Research and Development
Washington, D. C. 20460

EPA-650/2-75-055

DETERMINATION OF AIRCRAFT TURBINE ENGINE PARTICULATES

by

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Contract No. 68-02-1236
ROAP No. 26ACU-31
Program Element No. 1AA010

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U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF RESEARCH AND DEVELOPMENT
WASHINGTON, D.C. 20460

May 1975

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Publication No. EPA-650/2-75-055

ABSTRACT

The objective of this twelve-month program was to develop measurement techniques for particulate emissions from aircraft gas turbine engines. The ultimate goal was to establish optimum representative sampling procedures, parameters, devices, and instruments to estimate the mass of these particulates emitted from gas turbines as they exist in the open atmosphere.

A series of tests with a turboprop engine, Garrett/AiResearch Model TPE331, was used as a basis for determining the feasibility of gravimetrically measuring the particulate emissions from aircraft engines. Limited tests were also conducted with two turbofan engines, the Garrett/AiResearch Model TFE731-2 and the Pratt & Whitney Model JT8D-9.

Several different filter materials were tested to determine the one most suitable for the particulate measurements. DM450 Metricel filter material (a copolymer of acrylonitrile and polyvinyl chloride) was selected.

It was concluded that satisfactory correlations between particulate mass emissions and smoke number can be obtained with a given engine operating at given conditions, but that correlations obtained under different operating conditions even with the same engine have substantially different slopes. Thus, reflective smoke numbers do not seem to accurately assess the particulate emission rate of a significant variety of aircraft gas turbine engines.

It was determined that the particulate mass emission rate from the engines varies intermittently with time and that ambient dust levels can have a significant effect on measured results. Deposits of particulate matter in the sampling probe and transfer line were not significant.

A uniform distribution of particulate concentrations was measured at the exhaust plane of the TPE331 Engine. However, samples obtain from the JT8D Turbofan Engine indicated a significant variation in particulate concentration at the exhaust plane of this engine. The cause for this variation was not determined. Data from both the JT8D-9 and TFE731-2 engines indicated significant variations during the initial portion of the tests and subsequently stabilized at a relatively constant level.

It was difficult to compare the results of gravimetric measurements of engine particulate emissions with the conventional smoke number. The latter is principally affected by small carbon particles whereas the former can be affected by both ambient dust ingested at the engine inlet and relatively large particles which form as carbon deposits on the walls of the combustor and are intermittently dislodged and discharged from the engine.

It is recommended that a combination of the two methods be the subject of further research, in order to relate gas turbine particulate emissions to air quality standards.

This report was submitted in fulfillment of Contract No. EPA 68-02-1236 by AiResearch Manufacturing Company of Arizona under the sponsorship of the Environmental Protection Agency. Work was completed in July 1974.

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ACKNOWLEDGEMENTS

This report was prepared by the AiResearch Manufacturing Company of Arizona, a division of The Garrett Corporation, under EPA Contract Number 68-02-1236.

The period of performance of this program was 29 June 1973 through 30 June 1974. The AiResearch Program Manager was Keith M. Johansen. Emerson L. Kumm was the Principal Investigator and Peter C. Amundsen was responsible for all engine tests and emissions data acquisition.

All tests with the TPE331 and TFE731 Engines were run at the AiResearch Test Facilities in Phoenix, Arizona. An additional series of tests with a JT8D-9 Engine were conducted on subcontract at Aviation Power Supply (APS) in Burbank, California. The cooperation of Allen R. Stokke, Manager, and John C. Bogena, Foreman of Engine Test Facilities at APS during these tests is gratefully acknowledged.

The EPA Project Officer was Dr. Ronald L. Bradow. His technical direction and assistance during the program provided significant contribution.

I. CONCLUSIONS

General conclusions from this program were as follows:

- Accurate gravimetric measurements of gas turbine engine particulate emissions can be obtained.

- Smoke number (reflectance) measurements do not correlate with gravimetric measurements of engine particulate emissions.

- As with smoke number (reflectance) measurements, it is difficult to relate gravimetric measurements of engine particulate emissions to ambient air quality standards.

- For the engines tested, a reduction in particulate mass emission concentration was noted at higher engine power levels, even though the smoke number increases.

- The carbon deposits in the sampling probe and transfer lines were typically less than 5 percent of the material collected by the filters. Also, there was not a significant trend between transfer line length and measured particulate emissions.

- The cost of obtaining gravimetric measurements of production engine particulate emissions would be substantially higher than the conventional smoke number measurements.

The background, data and measurement techniques presented in this report permits considerably more accurate tests and measurements to be made of gas turbine particulate emissions than was previously possible.

The gravimetric measurement data presented herein indicates that the particulate concentration (emission rate) varies intermittently during engine operation and that significant stratification of the particulates can exist at the exit plane of some engines. It was assumed that small carbon particles are produced at a relatively uniform rate in fuel-rich zones within the combustor. Larger particulates are probably derived indirectly from ambient dust ingested at the engine inlet and from carbon deposits which form within the combustor.

The conventional smoke number measurement depends chiefly on the very small carbon particulate material for which the atmosphere has a long retention time, but the gravimetric measurement includes the larger particles which do not remain suspended in the atmosphere. Hence, it is difficult to relate gravimetric measurement of particulate mass emissions measurements to ambient air quality standards. The situation is complicated by the many variables that influence the combustion of fuel and the variety of combustion chambers that are used in gas turbine engines.

Accurate gravimetric measurements can be obtained if the sample gas volume is 0.028 M^3 or larger. Within the range of parameters tested, probe flow-rate and filter flow-rate did not significantly effect the test results.

The particulate size measured from the TPE331 Engine was shown to be somewhat uniformly distributed from large material (over 9 microns) to very small materials (approximately 0.3 microns).

II. RECOMMENDATIONS

It is recommended that the sampling apparatus and techniques developed in this program be used for additional research to attempt to correlate particulate emissions with smoke number and to relate this data to ambient air quality standards. This would include further testing to study the effects of nonisokinetic sampling (and its effect on probe sampling efficiency), dilution, ambient dust ingested at the engine inlet, stratification of particulate concentrations in the engine exhaust plane, nonconstant particulate emission rates, and particle size distribution.

The use of DM450 Metricel filter material for engine smoke number measurement is recommended since it provides a more accurate reflectance measurement than the Whatman No. 4 material currently used.

III. INTRODUCTION

BACKGROUND

The standards[(1)]* for the control of air pollution from aircraft gas turbine engines established by the Environmental Protection Agency specifically regulate emissions of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and smoke. Smoke is defined as the particulate matter in the engine exhaust that obscures the transmission of light.

The convention in the formulation of the air quality standards has been to specify primary and secondary standards for particulates as mass per unit volume of air (refer to Table 1). However, the current method of dealing with determinations of gas turbine particulate emissions is to specify a smoke number that is an indicator of the relative visibility of the exhaust gas.

The procedure used for determining this smoke number involves a measurement of the optical reflectivity of the particulates collected on a specific type of porous filter element by the passage of a known volume of engine exhaust gas through the filter. The difficulty in attempting to use this procedure as an indicator of the particulate mass emitted is that the reflectivity is largely a function of the relative size of the particulates collected, and may not necessarily be related in any discrete manner to the total mass of the sample, particularly since particle sizes

*Superscript numbers in parenthesis designate references presented in Section VIII of this report.

Table 1. NATIONAL AMBIENT AIR QUALITY STANDARDS.

(Federal Register, April 30, 1971)

Pollutant	Standard Description
Carbon monoxide (Primary and secondary)	(a) 10 milligrams per cubic meter (9ppm), maximum 8-hour concentration not to be exceeded more than once per year.
	(b) 40 milligrams per cubic meter (35 ppm), maximum 1-hour concentration not to be exceeded more than once per year.
Hydrocarbons (Non-methane) (Primary and secondary)	(a) 160 micrograms per cubic meter (0.24 ppm), maximum 3-hour concentration (6 to 9 am) not to be exceeded more than once per year. For use as a guide in devising implementation plans to meet oxidant standards.
Nitrogen dioxide (Primary and secondary	(a) 100 micrograms per cubic meter (0.05 ppm), annual arithmetic mean.
Particulate matter (Primary)	(a) 75 micrograms per cubic meter, annual geometric mean.
	(b) 260 micrograms per cubic meter, maximum 24-hour concentration not to be exceeded more than once per year.
(Secondary)	(a) 60 micrograms per cubic meter, annual geometric mean, as a guide to be used in assessing implementation plans to achieve the 24-hour standard.
	(b) 150 micrograms per cubic meter, maximum 24-hour concentration not to be exceeded more than once per year.
Photochemical oxidants (Primary and secondary)	(a) 160 micrograms per cubic meter (0.08 ppm), maximum 1-hour concentration not to be exceeded more than once per year.
Sulfur dioxide (Primary)	(a) 80 micrograms per cubic meter (0.03 ppm), annual arithmetic mean.
	(b) 365 micrograms per cubic meter (0.14 ppm), maximum 24-hour concentration not to be exceeded more than once per year.
(Secondary)	(a) 60 micrograms per cubic meter (0.02 ppm), annual arithmetic mean.
	(b) 260 micrograms per cubic meter (0.1 ppm), maximum 24-hour concentration not to be exceeded more than once per year.*
	(c) 1300 micrograms per cubic meter (0.5 ppm), maximum 3-hour concentration not to be exceeded more than once per year.**

Note: Primary standards provide for protection of public health; secondary standards for prevention of other undesirable effects on public welfare.

*Change to 100 micrograms per cubic meter as of August 1974 - EPA.

**Change to 700 micrograms per cubic meter as of August 1974 - EPA.

in gas turbine exhausts can be nonhomogenous. There may also be a great variation in particle size that changes with operating mode for a given engine, and varies with different types of engines. An additional consideration is that the smoke number and plume visibility of a high-bypass-ratio, exhaust-mixing turbofan engine may be much lower than that of a nonbypass type (i.e., turbojet or turboshaft) engine that has essentially identical-mass emissions per unit operating time. This difference is due to the dilution effect of the bypass air on the sample.

Research by Champagne[2] indicates that the smoke number index can be identical for two particulate emission samples that differ in total mass by a factor of as much as two. The smoke number is primarily influenced by the reflectivity of the smaller particles on the filter paper. The larger particles will have little effect on the reading obtained, irrespective of their mass quantity.

It is necessary to sum the operating-time weighted emission rates from each of the pertinent engine operating modes in order to obtain a complete indication of the effect of the engine on environmental quality. However it is not possible to make this kind of assessment with accuracy through the use of conventional smoke number reflectance data. A direct mass (gravimetric) measurement of engine particulate emissions was therefore considered a means to provide a more accurate assessment of gas turbine engine contribution to ambient air concentrations without the requirement to extrapolate from optical density measurements.

OBJECTIVE

The objective of the two-phase, 12-month program was to assess the feasibility of gravimetric measurement technique for determining particulate emissions from gas turbine engines. The goal of the program was to establish optimum sampling procedures, parameters, devices, and instruments to estimate the mass of these particulates emitted from aircraft gas turbines as they exist in the open atmosphere.

SCOPE

Particulate emission data was obtained from three different gas turbine engine types for this program:

(1) TPE331-5-251 - A single-shaft turboprop engine rated at 840 shaft horsepower.

(2) TFE731-2 - A two-spool turbofan engine rated at 3500 pounds thrust.

(3) JT8D-9-A - A two-spool turbofan engine rated at 14,500 pounds thrust.

The TPE331 Engine (Serial No. X-21) was used for the majority of the tests. All TPE331 Engine tests were conducted with the inlet air temperature controlled to 15°C. During Phase I, gaseous and smoke* emissions from this engine were measured to verify that the emission characteristics of this engine was representative of other engines of the same model. A test was also conducted with several candidate filter materials to select a suitable material for gravimetric measurement of engine

*Conventional smoke number per EPA Standards (Reference 1) particulates. In addition, the exhaust plane of this engine was mapped with a single-point probe to determine particulate inhomogeneities and thus, the applicability of using a 12-point averaging probe for subsequent tests.

During Phase II, several series of tests were conducted with the TPE331 Engine to assess effects of the various sampling and engine operating parameters including probe-flow rate, filter-flow rate, sample volume, line length, dilution ratio, and engine power. Additional TPE331 Engine tests with an Andersen Cascade Impactor were conducted to determine particulate size and distribution as a function of engine power. Tests with a TFE731-2 Engine were conducted to determine the requirement for isokinetic sampling.

Particulate emissions data were obtained from a JT8D-9 Engine in order to determine whether or not there are significant particulate inhomogeneities in the engine exhaust and, if present, whether these inhomogeneities can be related to the can-annular combustor configuration used in the engine. (The TPE331 and TFE731 Engines have annular, reverse-flow combustor configurations.)

A statistical analysis of the data was conducted to assess the suitability of the gravimetric method for gas turbine engine exhaust particulate measurements and to define optimum test procedures and conditions.

IV. TEST EQUIPMENT AND EXPERIMENTAL TECHNIQUES

TEST EQUIPMENT DESIGN

The testing in this program for particulate emissions from gas turbine propulsion engines resulted in some modifications of the 12-point probe pickup and lines as specified by the EPA[1] for measurement of smoke exhaust emissions. These modifications resulted in reducing the amount of particulate deposited in the probe and sample transfer line to a very small percentage of the amounts collected on the filters. Figure 1 shows the location of the sampling probe at the exit plane of the TPE331 Engine. Figure 2 shows the EPA specified sampling system. Details of the final 12-point probe used with the TPE331 and the TFE731 Engines in this investigation are given in Figure 3. The EPA specifications were used to locate the 12-point probe relative to the exhaust nozzle for sampling the exhaust particulate emissions. Steady-state flow was established using the bypass around the filter before switching to the filter element.

The exit plane of the TPE331-5-251, used as the reference engine in this program, was also examined by a single-point traversing probe. A sketch of the single-point traversing probe inlet is given in Figure 4.

The 12-point averaging probe used on the JT8D-9 Engine required a special support to withstand the force of the exhaust gas flow. A photograph of the installation is shown in Figure 5 and illustrates the special stiffeners for supporting the probe orifices.

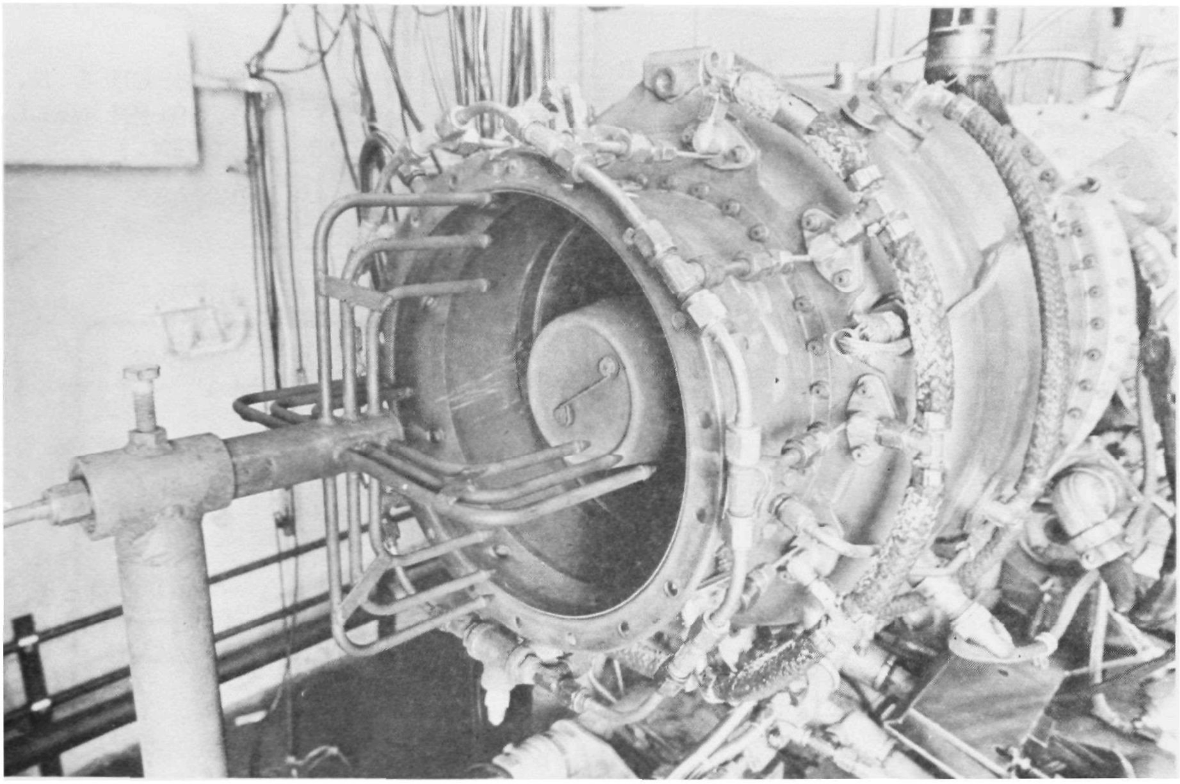


Figure 1. TPE331-5-251, S/N 21 with 12-point sampling probe.

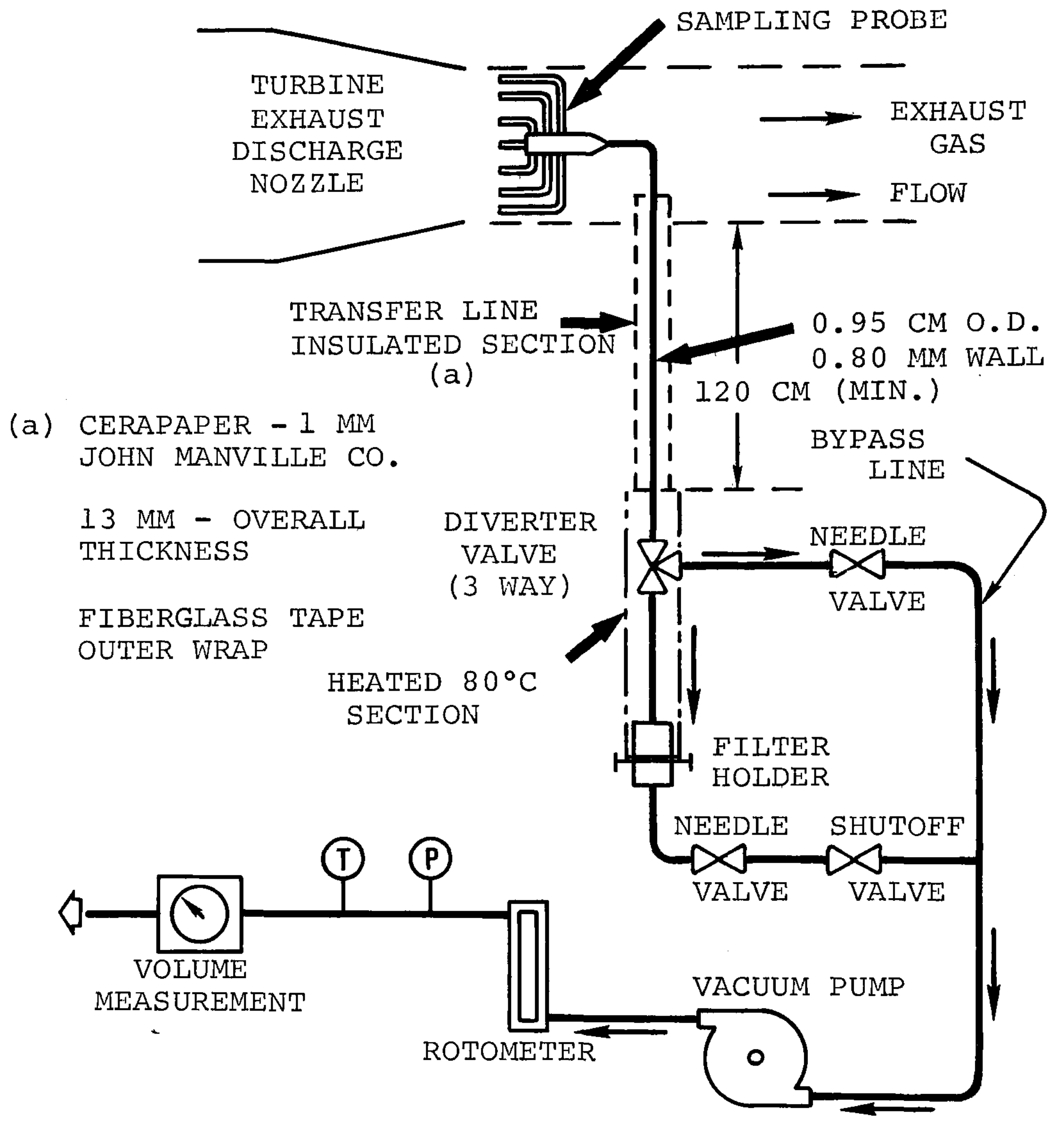
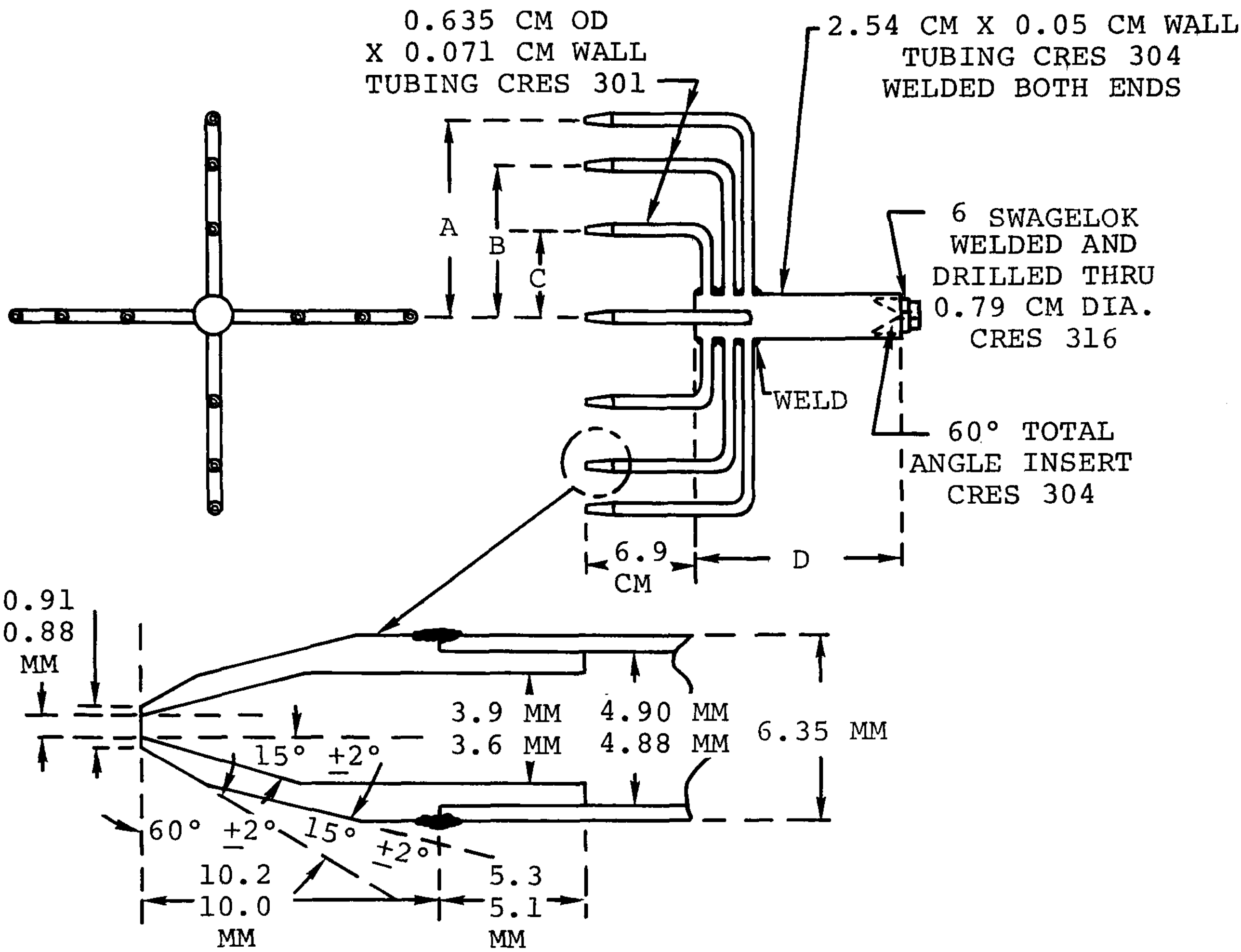


Figure 2. Particulate sampling system for gas turbine engines.



DIMENSION	PAP223080-1 TFE731	PAP223080-3 TPE331
A (mm)	128.0	110.0
B (mm)	99.0	84.0
C (mm)	74.0	45.0
D (mm)	255.0	128.0

Figure 3. Twelve-point averaging probe for particulate sampling.

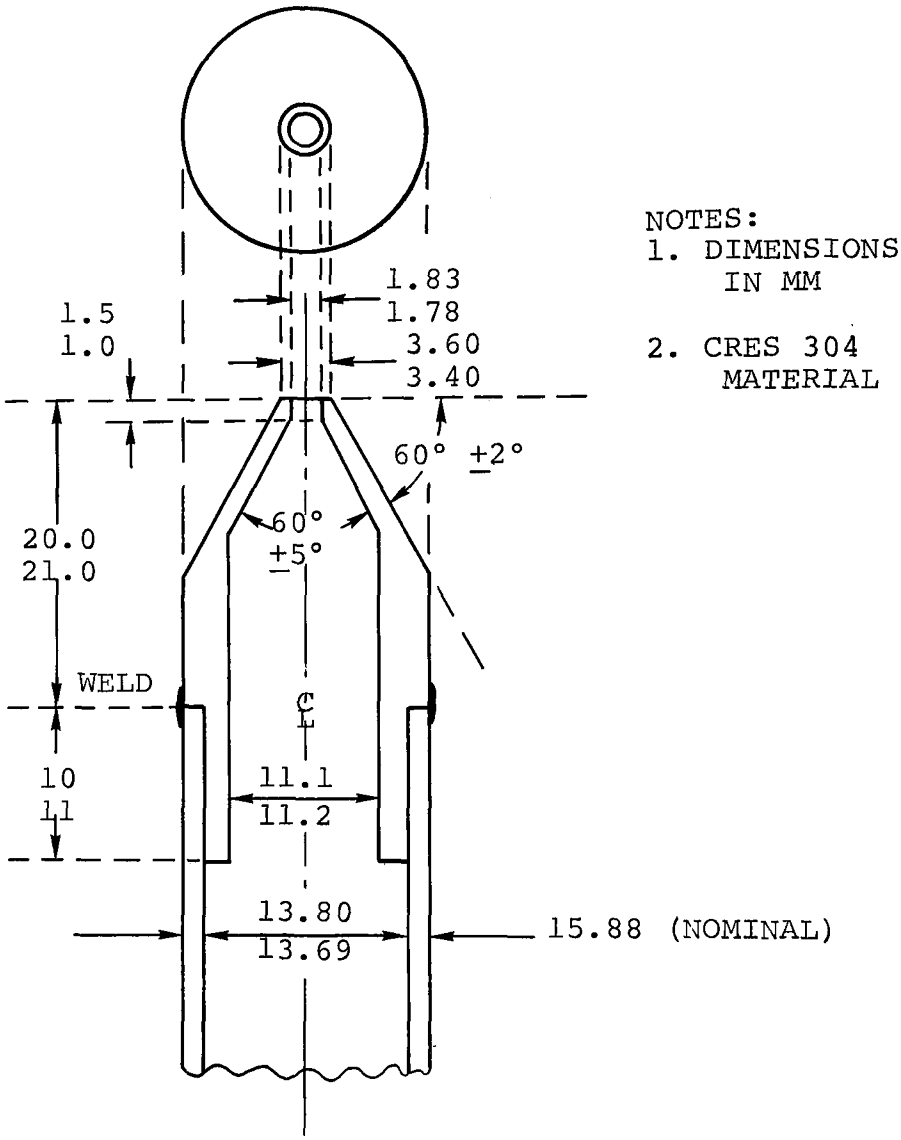


Figure 4. Single point traversing probe inlet.

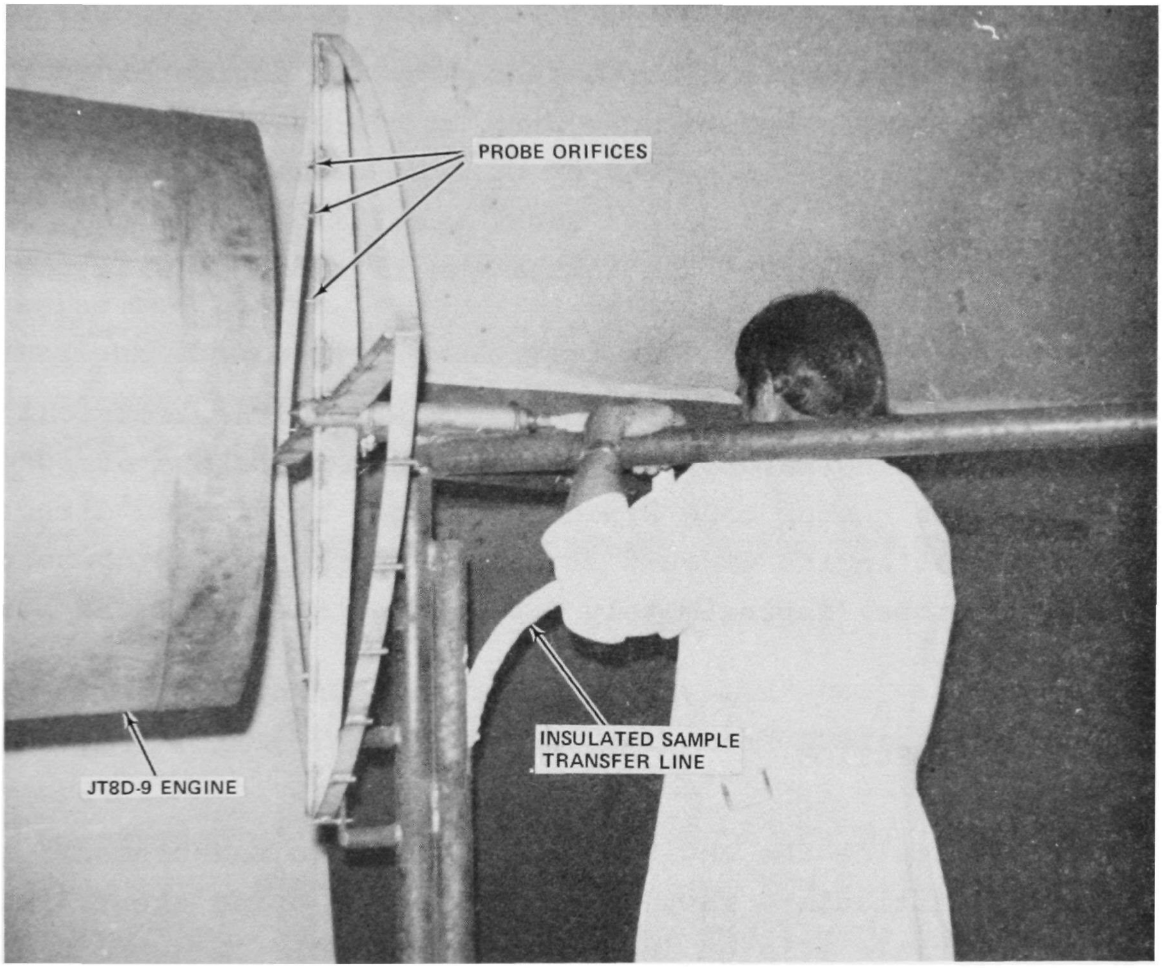


Figure 5. Twelve-point averaging probe mounted behind the JT8D-9 engine.

The vacuum pump adequately provided the required flow rate of 0.85 m^3/hr used initially in the program. (The effect of different sample flow rates was subsequently investigated as discussed in Section VI.) The probe orifice pressure loss was counter balanced by the engine exhaust dynamic head. The pressure drop in the stainless-steel sample transfer line (0.64 cm outside-diameter, 0.08 cm wall thickness, and 9.14 meters long) was 7.4 cm of Hg and the pressure drop across the filter was 15 cm of Hg with the flow of 0.85 m^3/hr (STP).

The sample transfer line was heated with electrical heater tape to maintain a minimum gas temperature of 80°C. Since this heater tape would be damaged if exposed directly to the hot engine exhaust stream, a short section downstream of the probe (approximately 0.5 m long) was insulated but unheated.

FILTER SELECTION

Following the engine gaseous emission measurement tests, particulate samples were obtained using the following materials (listed in the order tested):

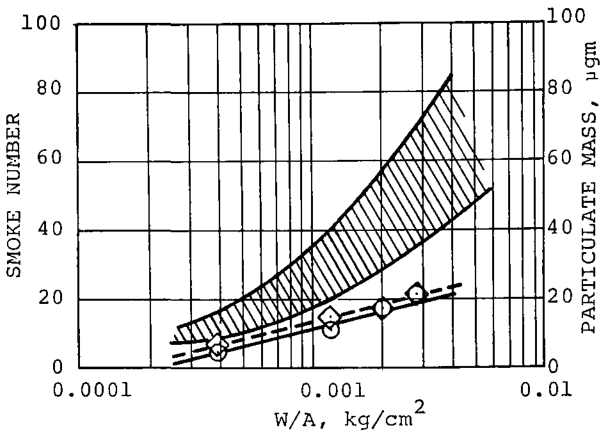
(1) Whatman No. 4
(2) DM450 Metricel - Gelman Instrument Company
(3) DM800 Metricel - Gelman Instrument Company
(4) Versapor - Gelman Instrument Company
(5) AA Millipore - Millipore Corporation

The tests were run in compliance with the EPA regulations. Particulate samples were obtained at four engine power points: taxi/idle, 30-, 90-, and 100-percent corrected rated power. After setting the engine on power, four samples (flow volumes of 0.0028, 0.0085, 0.0142, and 0.0198 m^3) of each filter type were taken. Additional tests using Whatman No. 4 were conducted following the AA Millipore tests at taxi/idle and 100 percent power to determine repeatability.

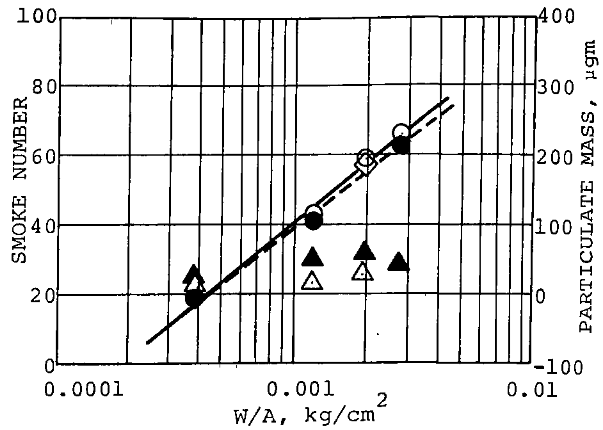
Typical results of the particulate data analysis are presented in Figure 6. Smoke number* measurements were obtained from all the filter specimens at each of the four engine conditions. The smoke number data resulted in straight line correlations on a semi-log grid. The Whatman No. 4 material produced lower smoke numbers than the other materials. Good correlation of the data (from the Whatman No. 4 material) taken before and after the test indicated no change in engine performance during the test sequence.

The four candidate filter materials were measured gravimetrically for all engine operating conditions. The correlation given by D. L. Champagne[2] was used to obtain a comparison of particulate weight from the four candidate filter materials and smoke number from the Whatman No. 4 filters. For an initial evaluation see Figure 6(a).

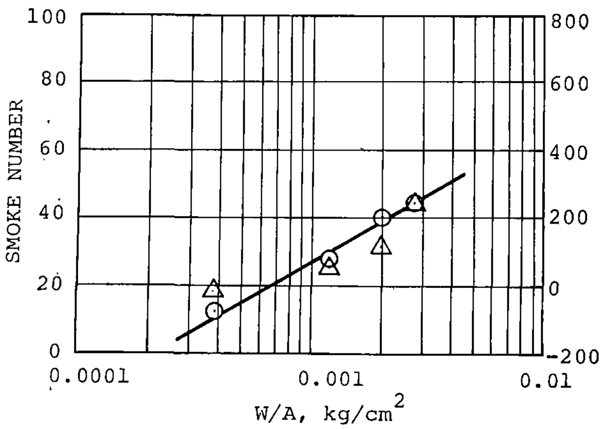
*The term "smoke number" is defined by Reference (1) as a specific analysis of smoke spot reflectance with Whatman No. 4 filter material and at an exhaust gas sampling of 0.023 lb. per square inch of filter area (1.62×10^{-3} Kg/cm^2). However, the smoke number data presented in this report were obtained from reflectance analysis of samples of several filter materials and at various exhaust gas volume flow rates, and therefore are not all smoke number measurements by the conventional definition.



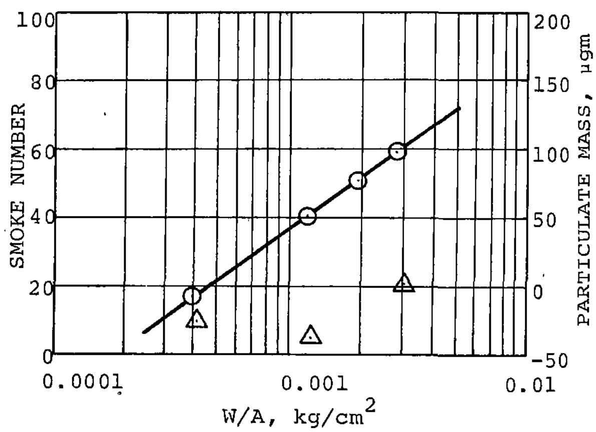
(a) Whatman #4 Filter Material



(b) Metricel Filter Material
Open symbols - DM450
Closed symbols - DM800



(c) Versapore Filter Material



(d) Millipore AA Filter Material

○ Smoke Number
△ Particulate Mass

Figure 6. Smoke number and particulate mass versus weight flow per unit filter area for candidate filter materials (100% power).

It was subsequently shown that the weighing procedures used for filter material screening were inadequately controlled and thus produced inaccurate results. However, the Metricel material (DM450 and DM800) produced the most consistent smoke number and gravimetric results. It was evident also that the particulate deposit on the filters was not proportional to the sample gas volume even though there was good correlation with the smoke number. This phenomena will be discussed in detail later in this report (see "Repeatability Tests" pages 29 through 42).

The Metricel filters are rated by Gelman for a maximum operating temperature of 77°C. A brief test was conducted with sample gas temperatures of 150°C and 80°C to determine whether the higher temperature would adversely effect the filtering characteristics of the material. The filters from the tests with high gas temperatures showed no visible evidence of deterioration and the smoke numbers from both tests were identical. The DM450 Metricel filter was chosen for all subsequent testing.

FILTER WEIGHING PROCEDURE

A significant effort in the program was devoted to the development of a practical system for weighing the filters to the desired accuracy (± 5 micrograms). Items influencing the weighing accuracy include:

(a) Static charge on the filter.

(b) Changes in local humidity (the variation in the weight of a filter that is caused by changes in the ambient humidity was found to be significant as compared to the particulate weight being measured).

(c) Standardization (zero and calibration) of balance.

Weighings were conducted initially in a "Clean Room" with and without a glove box. Although the humidity was accurately controlled in the "Clean Room", air currents induced electrical charges which also influenced the accuracy of the balance.

It was subsequently determined that repeatable weighing of the filter elements (weighing about 60 mg each) could be made with an electrobalance* (absolute accuracy is specified to be ±1 microgram) in a metal and glass glove box as shown in Figure 7. Plastic Petri dishes were used to hold and catalog the individual filter elements before and after tests.

Since it was not possible to maintain the same absolute humidity in the glove box for the pre- and post-test filter weight measurements, the filters were grouped in batches of ten with two reference (untested) filters in each batch. The filters were calibrated inside the sealed glove box in open trays for 24 to 36 hours before weighing.

Initially, weighings were made in the glove box with a hot plate and water beaker using a relative humidity controller to evaporate water and maintain a humidity above the room humidity. This was subsequently shown to be unnecessary.

The average mean deviation of 63 reference filters was determined to be 5.5 micrograms. By applying the average mean deviation of the reference filter weight to the mean

*Cahn Electrobalance Model 4100 - Cahn Instruments/Division of Ventron, Paramount, California 90723.

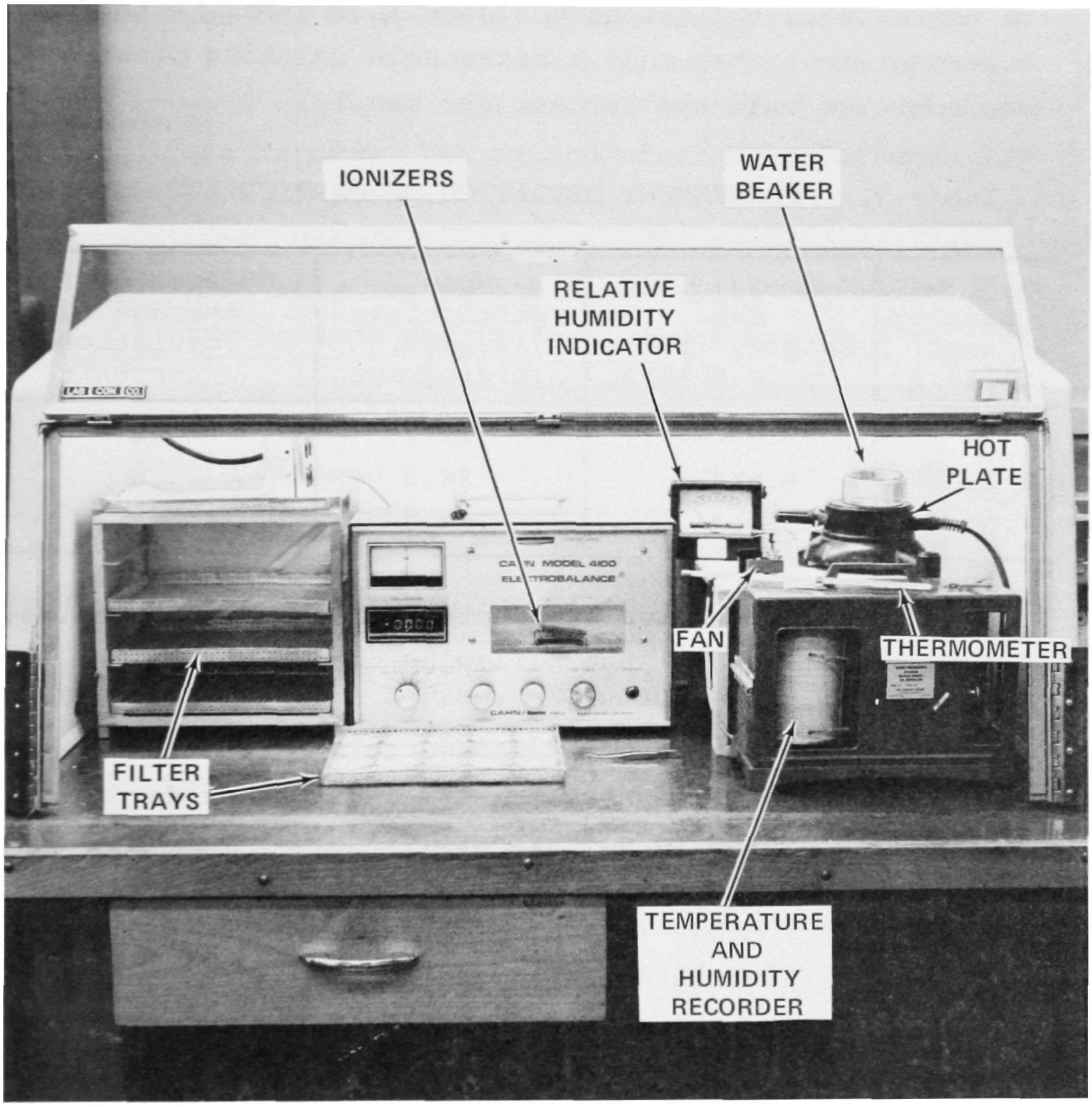


Figure 7. Glove box used for weighing filters.

MP-46817

particulate weights for the three gas sample volumes, the percentage effect of the weighing error on the actual weight measurements was determined. This is shown in Table 2. The standard mean deviation of the weighings of the reference filters as a percent of the particulate weighings is shown to decrease as the gas sample size increases. A value of 5-percent indicates that a reasonable weighing precision was achieved with the largest gas sample.

Table 2. MEASUREMENT DEVIATION OF PARTICULATE OR FILTERS

Quantity test filters	Gas sample, (STP) cubic meters	Mean particulate weight, micrograms	Reference filter average mean deviation, percent
22	0.0085	52.2	10
23	0.014	86.0	6
23	0.020	109.7	5

The procedure finally adopted to achieve the desired accuracy consisted of the following steps:

(a) The filters were exposed to a constant relative humidity and temperature environment for at least 24 hours to equilibrate.

(b) An ionizer (a radio-active source) was placed inside the weighing chamber of the balance to remove the static charge from the filters, walls of the chamber, and the weighing pans. Both sides of the filter were exposed to the ionizer for approximately 1 minute before being weighed.

(c) Ten filters were weighed as a group (this typically required 15 minutes).

(d) The first filter was then reweighed and the balance zeroed. If the first filter weight or balance zero setting changed by more than 2 micrograms, the ten filters were weighed again.

(e) The relative humidity and temperature in the glove box, (or in the proximity of the balance when weighing in the open laboratory environment) was recorded before and after weighing each lot of ten filters.

(f) When weighing in the open laboratory environment, the balance and filters were located in an area where there was a minimum of air currents (i.e., away from an air conditioning vent) in order to minimize exposure to local humidity changes and airborne dust.

PROBE AND LINE DEPOSITS

After each test series, the probes and lines were flushed with a solvent* and the filtrate was weighed. The filtrate was also examined under a high power microscope to determine the approximate percentage of carbon in the probe and line deposits. From the test results discussed in a later section, the large center support tube acted to separate and collect material grossly larger than obtained on the filter elements.

The test arrangments using the Andersen Cascade Impactor and an EPA furnished Gas Diluter are discussed in the sections relating to those tests.

*Dow Clean (1,1,1 trichloroethane)

V. TPE331 ENGINE EMISSION CHARACTERISTICS

GASEOUS AND SMOKE EMISSIONS

The TPE331 Engine (S/N X21) was used for the major portion of the tests in this program and was therefore designated to be the reference engine. Gaseous and smoke emissions measurements were obtained from this engine to demonstrate that it was typical of production engines. The emission measurements were conducted in compliance with EPA regulations[(1)] using commercial aviation (ASTM D1655-71T, Jet A) fuel and constant temperature (15°C) inlet air. The inlet air relative humidity was 32 percent. The particulate concentrations are reported in terms of micrograms per gram of exhaust gas since the exhaust gas sample was calculated in grams. Micrograms per cubic meter (STP) may be obtained by multiplying the micrograms per gram by 1225.4

Emission data was taken at four power settings:

- o Taxi/idle (5 percent power, 65 percent speed)
- o 30 percent corrected rated power
- o 90 percent corrected rated power
- o 100 percent corrected rated power

The resultant gaseous emissions and smoke number data and the production baseline range for this engine model is summarized in Table 3. The data indicated that while the gaseous emissions are typical of TPE331 Engines, the smoke number is relatively low. The conventional smoke number (SN) is taken at the semi-log graph extrapolated value of gas weight flow to filter area ratio of 0.0230 lbs/in^2 or 0.00162 Kg/cm^2.

Table 3. TPE331 ENGINE EMISSIONS

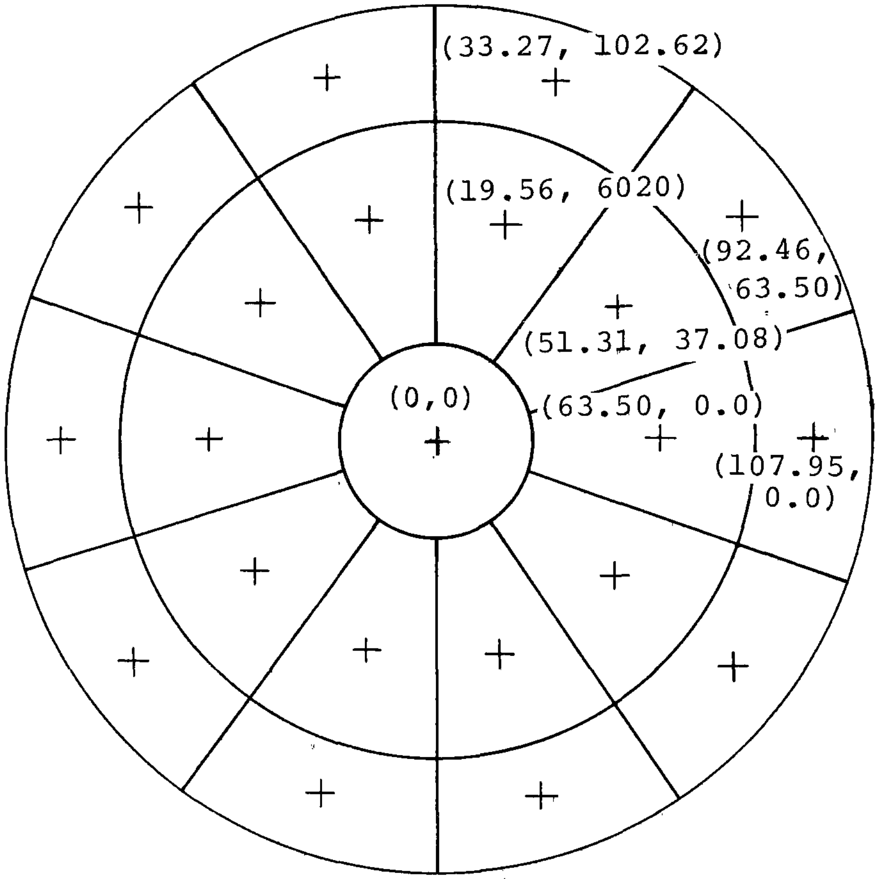
Engine	Gaseous emission, kg pollutant per 1000 hp-hr cycle			Smoke number
	HC	CO	NO_x	
TPE331-X-21	27.4	19.1	3.5	16
Production baseline range	24-34	18-25	3.2-4.1	14-23

In order to assess particulate mass and smoke number inhomogenieties at the reference engine exhaust plane, an exhaust-plane map was obtained. The exhaust plane of the engine was divided into twenty-one equal areas as shown in Figure 8. With the use of a single-point probe, two samples were obtained at the centroid of each of these areas for each of the four engine power conditions.

The resulting maps are presented in Figure 9. The smoke numbers for a given power setting do not vary significantly across the exhaust plane except near the edges (primarily at the top). It was believed that lift forces on the probe may have caused some displacement resulting in external air ingestion.

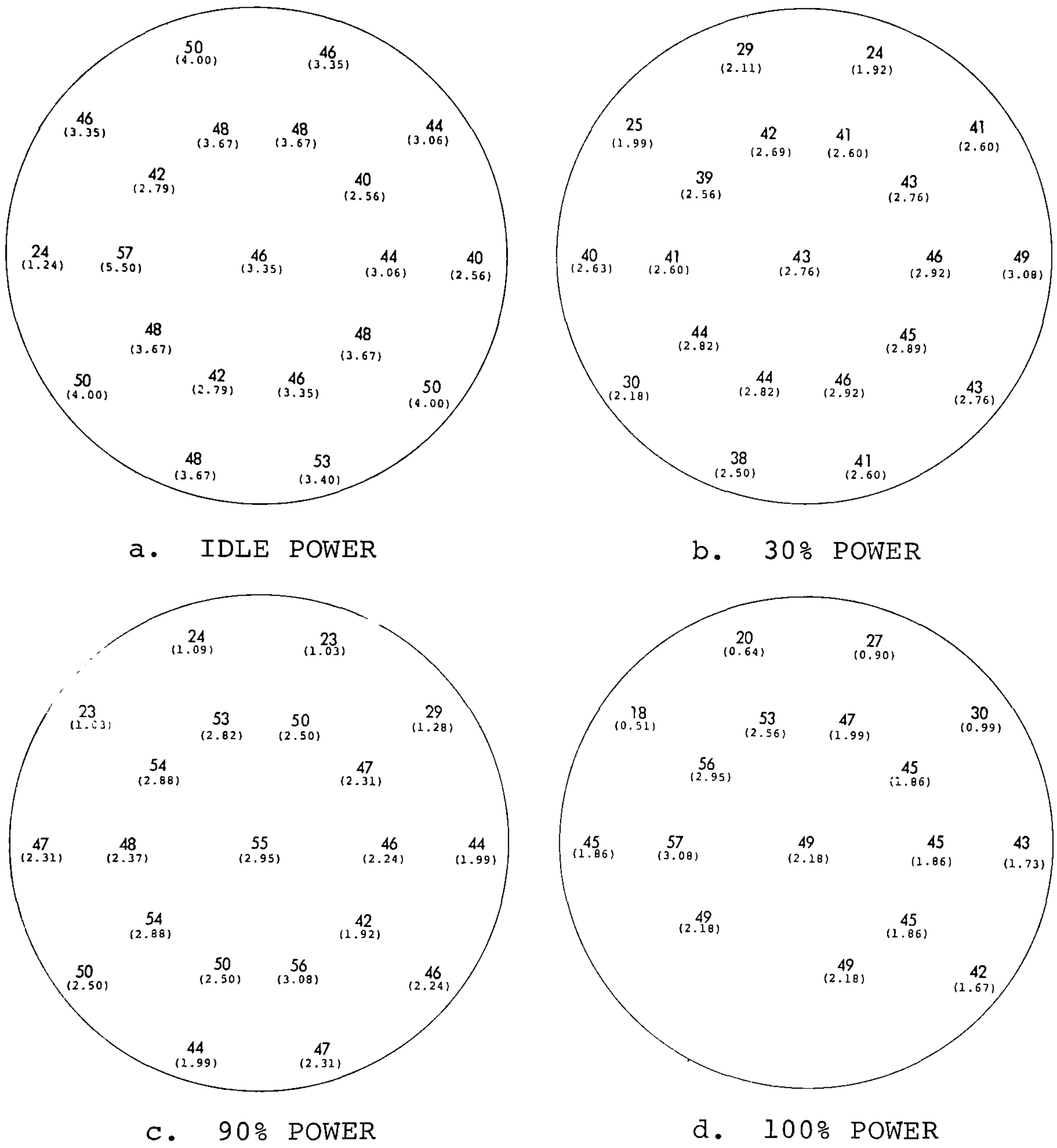
The numbers in parenthesis on Figure 9 are approximations of particulate concentrations determined from measured smoke number at each point. These approximations were obtained from plots of DM450 Metricel particulate mass versus smoke number as shown in Figure 10. Since there was considerable scatter* on these plots, a group of tests was conducted to investigate the repeatability of

*Attempts by Champagne(2) and Shaffernocker(3) to correlate engine particulate mass emissions and smoke numbers have produced similar results.



DIMENSIONS - MILLIMETERS
X, Y COORDINATES
QUADRANTS ARE SYMMETRICAL

Figure 8. TPE331 equal area mapping diagram.



NOTES:

1. PARTICULATE-TO-GAS WEIGHT RATIO, μg/g, GIVEN IN PARENTHESIS.
2. FILTER MATERIAL - DM450 METRICEL.

Figure 9. TPE331 Exhaust mapping smoke number.

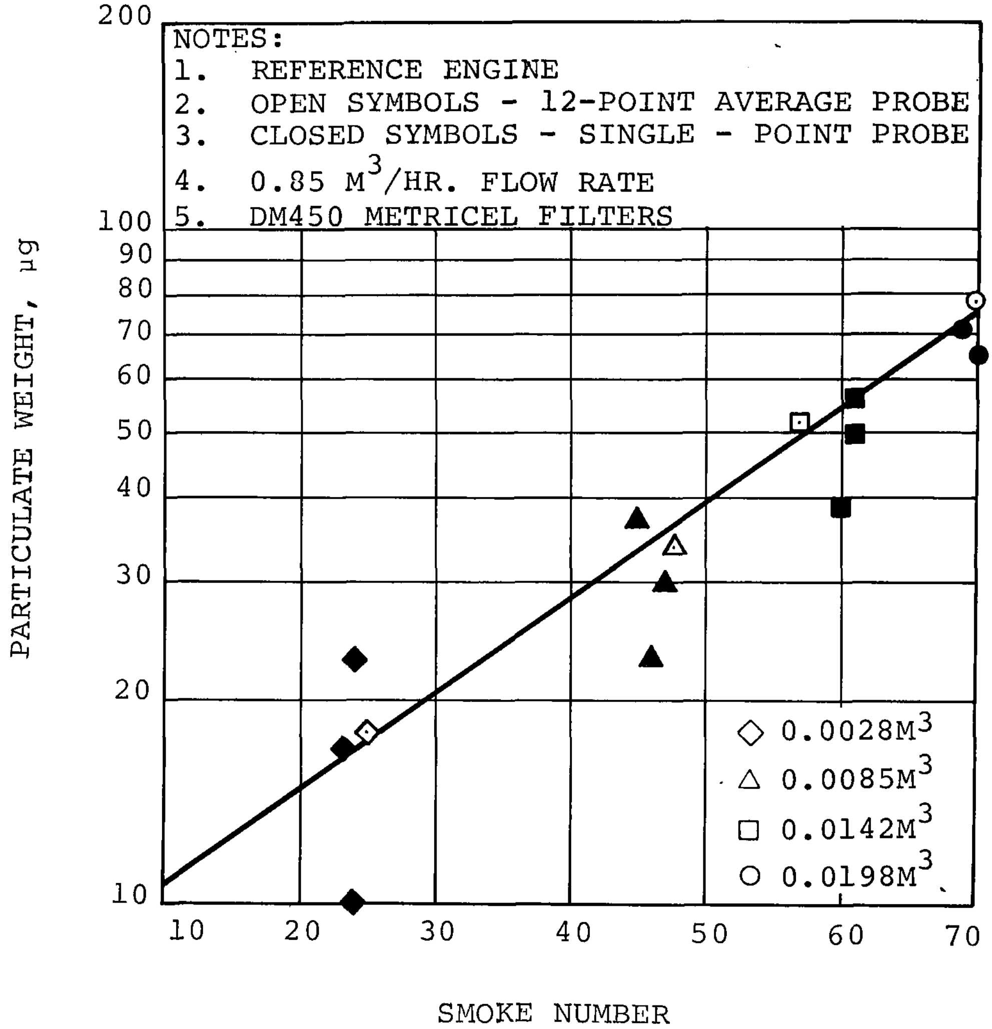


Figure 10. Weight increase versus smoke number at 90-percent power.

gravimetric data. These tests are discussed in the following section.

REPEATABILITY TESTS

Considerable scatter was noted in the particulate mass measurements under constant test conditions and procedures. Initially, the scatter was thought to be attributed to inaccurate filter weight measurements. However, subsequent investigations showed weight measurements of the filters to be accurate within ±5 micrograms and therefore not a major contributor to the data scatter. Other possible sources of error that were also investigated and discounted included sampling line leakages and instrumentation inaccuracies. Therefore several series of tests were conducted to determine whether the rate of particulate emission from the engine was constant.

In the first test, 92 samples were obtained consecutively (to eliminate ambient changes) using the four engine power conditions* and four sample gas volumes (0.0028 m^3, 0.0085 m^3, 0.0142 m^3, and 0.0198 m^3). For some of these samples, two filters were placed in series in order to determine if some of the particulate mass was passing through the filters. For these samples, the indicated mass concentration was assumed to be the total mass collected by the two filters.

As a result of the typical ±5 micrograms weighing inaccuracy, the 16 filters of the 0.0028 m^3 sample volumes exhibited very large variations in measured particulate

---

*The major portion of the tests was at 30 percent power.

weight concentration and were, therefore, not included in the analysis.

The test results plotted in Figure 11 show that the particulate concentration varies significantly from one test sample to the next. However, the smoke numbers (reflectance readings) of the DM450 Metricel filters (shown in Figure 12) are relatively uniform.

From these results, it was tentatively concluded that particulate mass was emitted from the engine at a non-constant rate. Apparently carbon deposits that accumulate on the combustor wall occasionally (and erratically due to engine vibration) break off and are discharged through the engine exhaust. These would generally be larger particles and would tend to produce significant scatter in the measured mass emissions. Since these would be relatively large particles but few in number, the measured smoke number would not be significantly effected.

Further, it was anticipated that as the sample volume is increased (with a constant sample flow rate), the data scatter would be reduced since longer sampling times would be required and this would tend to provide a better average of the erratic particulate mass emissions. The particulate concentrations measured for three sample volumes at the four engine power settings are summarized in Table 4. As expected, a reduction in the particulate concentration standard mean deviation occurs with increasing sample volume for the tests at 30-percent power.

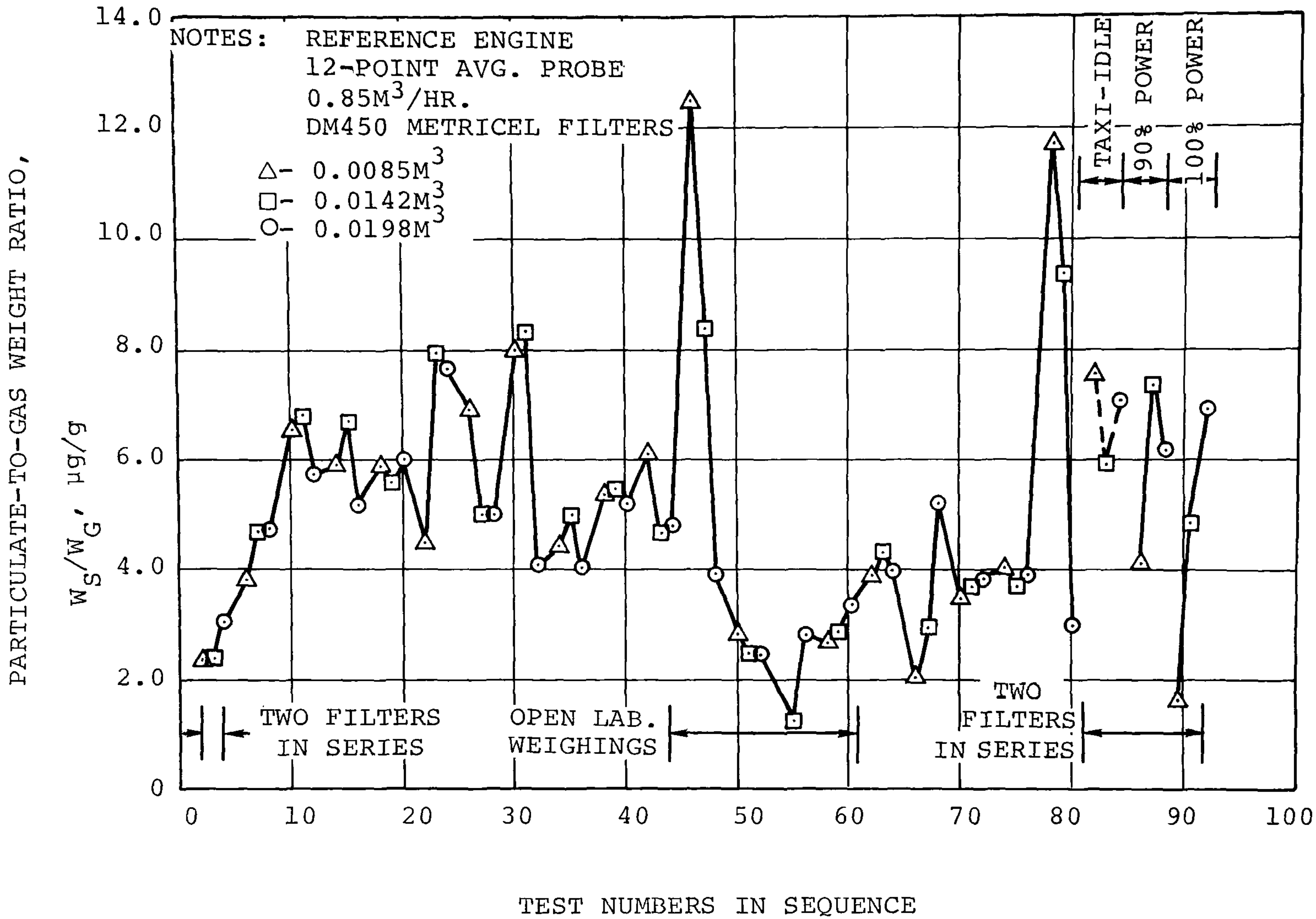


Figure 11. Particulate emissions of engine repeated tests.

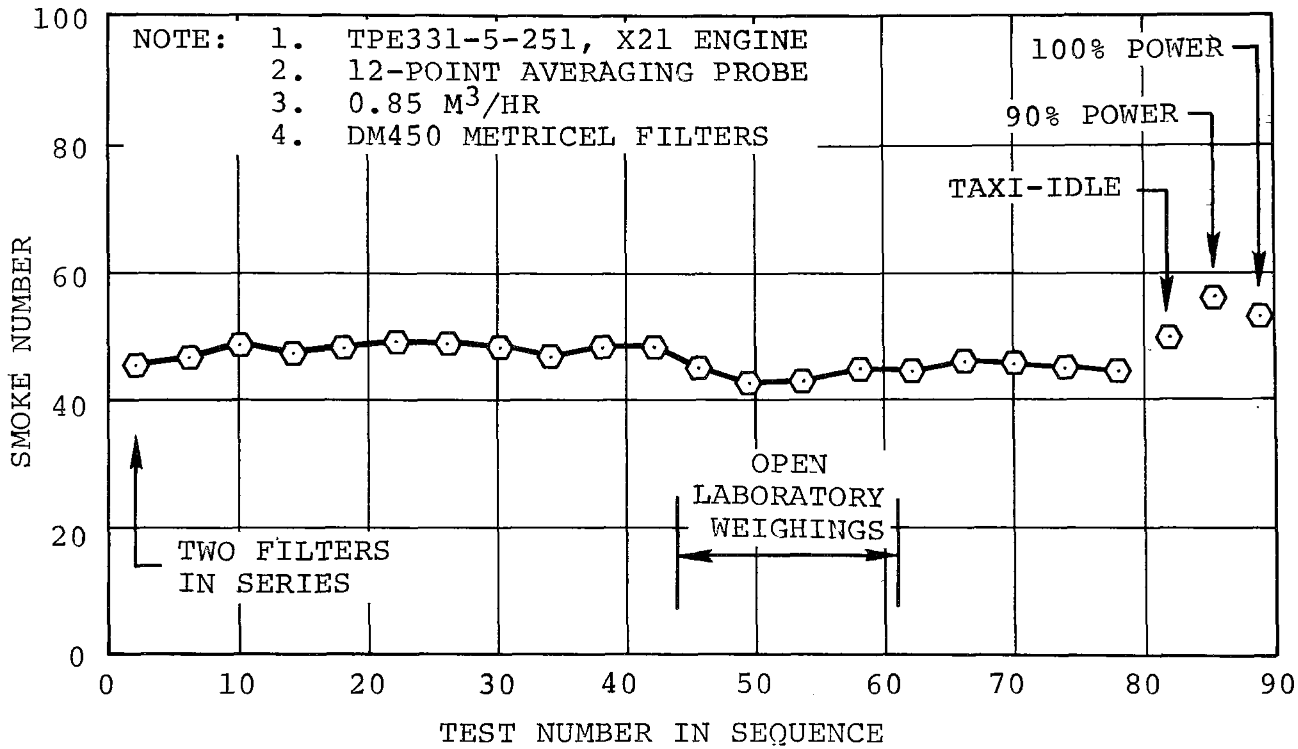


Figure 12. Smoke number of engine repeatability tests.

Table 4. REPEATABILITY TEST RESULTS

Number of tests	Engine power, %	Sample size, m^3	Particulate concentration µg/g	Particulate concentration standard mean deviation, µg/g
19	30	0.0085 (Group A)	5.43	2.89
20	30	0.0142 (Group A)	5.09	2.27
20	30	0.0198 (Group A)	4.40	1.25
Total 59	30	Group A	4.96	2.23
6	taxi/idle	Group A	5.64	1.43
9	90	Group A	3.95	1.74
9	100	Group A	3.75	1.98

Although not directly related to repeatability, it is important to note from the data presented in Table 4, that the particulate concentration decreases at higher engine power levels even though the smoke number increases. This trend as well as the level of particulate concentrations differ significantly with results reported by Champagne.[(2)] By using a value of 1225.4 grams of air (dry) to a cubic meter (standard sea level conditions), Champagne's results were replotted and are illustrated in Figure 13. As shown, the data from the reference TPE331 Engine (Table 4) shows a different trend and higher particulate concentrations than are indicated in Champagne's curves. The discrepancy between this data and the data reported by Champagne may be attributable to the fact that the TPE331 Engine is a single-spool turboshaft engine configuration whereas Champagne's data is predominantly from a two-spool turbojet engine (J79).

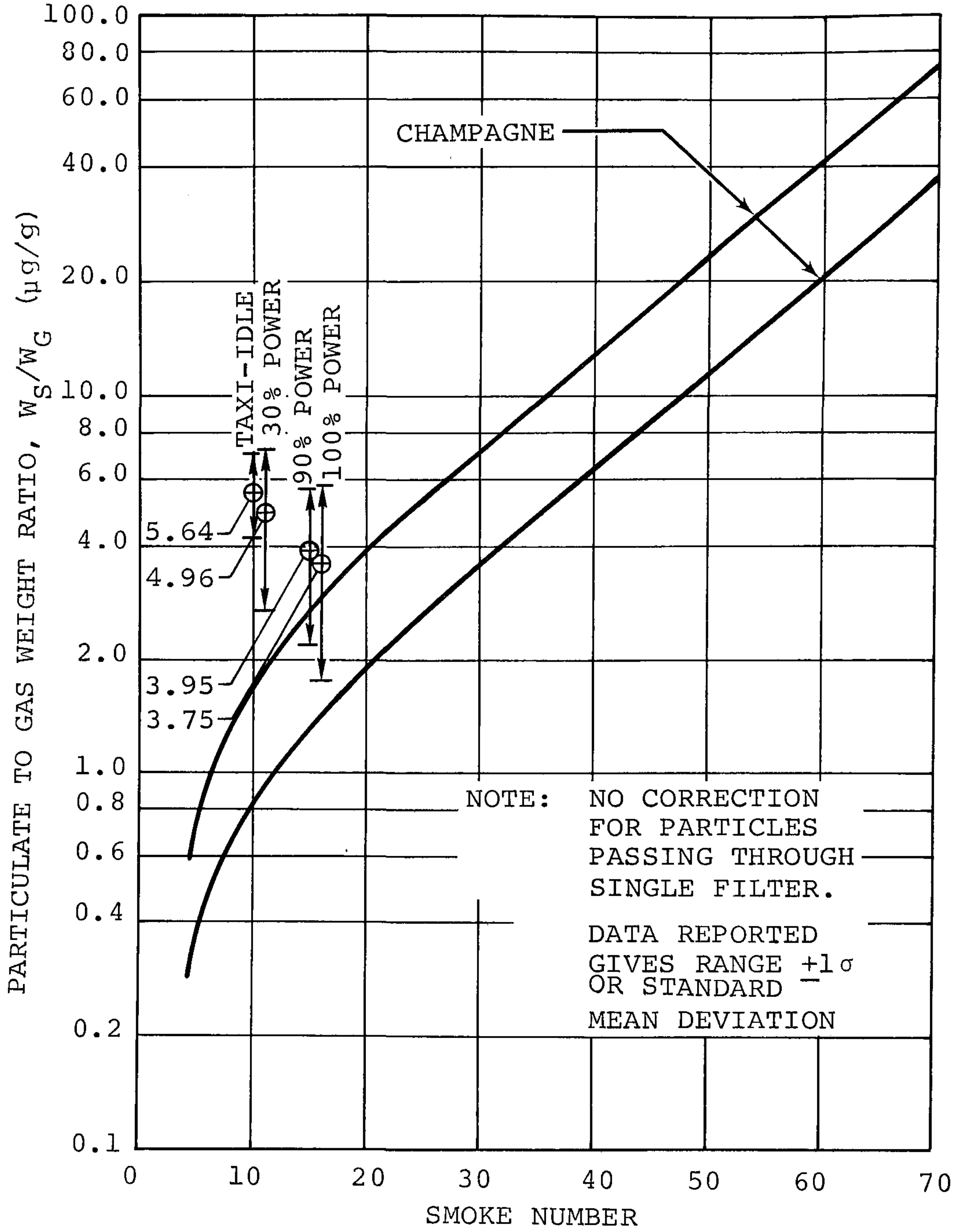


Figure 13. Smoke number versus particulate concentration for Champagne results.

In order to further investigate the possibility that data scatter would be reduced at larger sample volumes (longer sampling time), additional samples were obtained at the 30 percent power and sample volumes of 0.0198 m^3, 0.0283 m^3, and 0.0340 m^3.

The results are shown in Figure 14 reaffirms that engine exhaust gas particulates can vary significantly during the test sequence even through little or no change is noted in the smoke number. Figure 14 also presents the measurement of the ambient dust taken at the engine exhaust, both with and without the engine windmilling. The ambient dust loading is higher than was previously assumed and it is evident that future tests should sample such dust during the test series, preferably at the engine inlet and simultaneously with the exhaust gas sample so that each measurement can be corrected for dust ingestion.

These results, as well as previous results, indicate that gravimetric measurements of exhaust gas particulates are susceptible to considerable scatter. However, the smoke number as given by the DM450 Metricel filters appear to be consistent and relatively constant for each engine power setting and/or sample volume. The smoke number variation of the reference engine with power setting from taxi-idle to 100% power is readily discernible with the DM450 Metricel filters but very little absolute change is perceived on the conventional Whatman #4 filter. The higher sensitivity of the DM450 Metricel filter to smoke number measurement as compared to the Whatman No. 4 filters indicates that this material should be given more general useage. Figures 15 and 16 show how consistent the measurements are from a series of reference engine tests conducted to obtain the smoke number for the standard reference W/A = 0.0230 lb. gas sample/sq. in. of filter area (0.00162 Kg/cm^2).

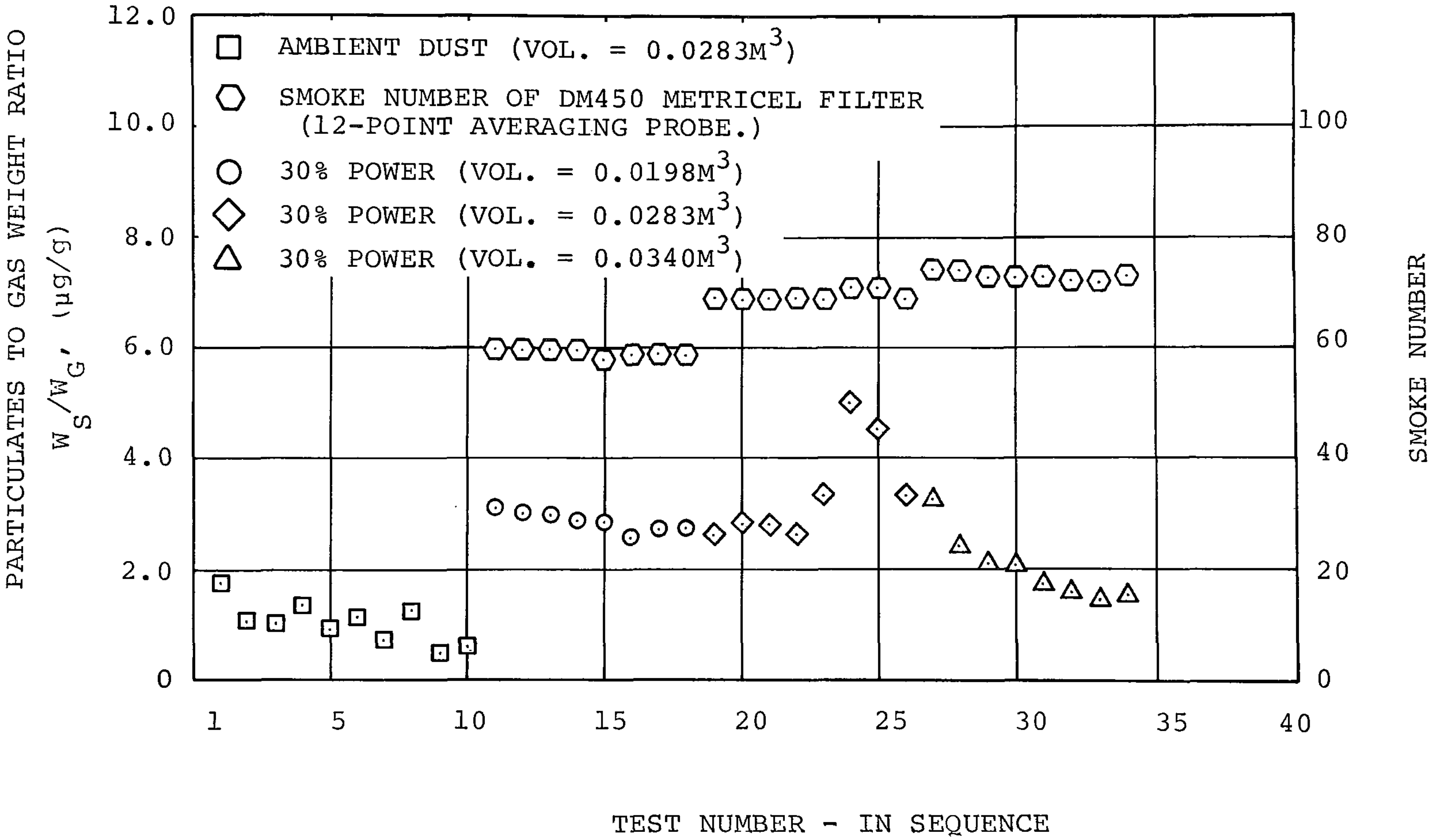


Figure 14. TPE331, dust and smoke measurements.

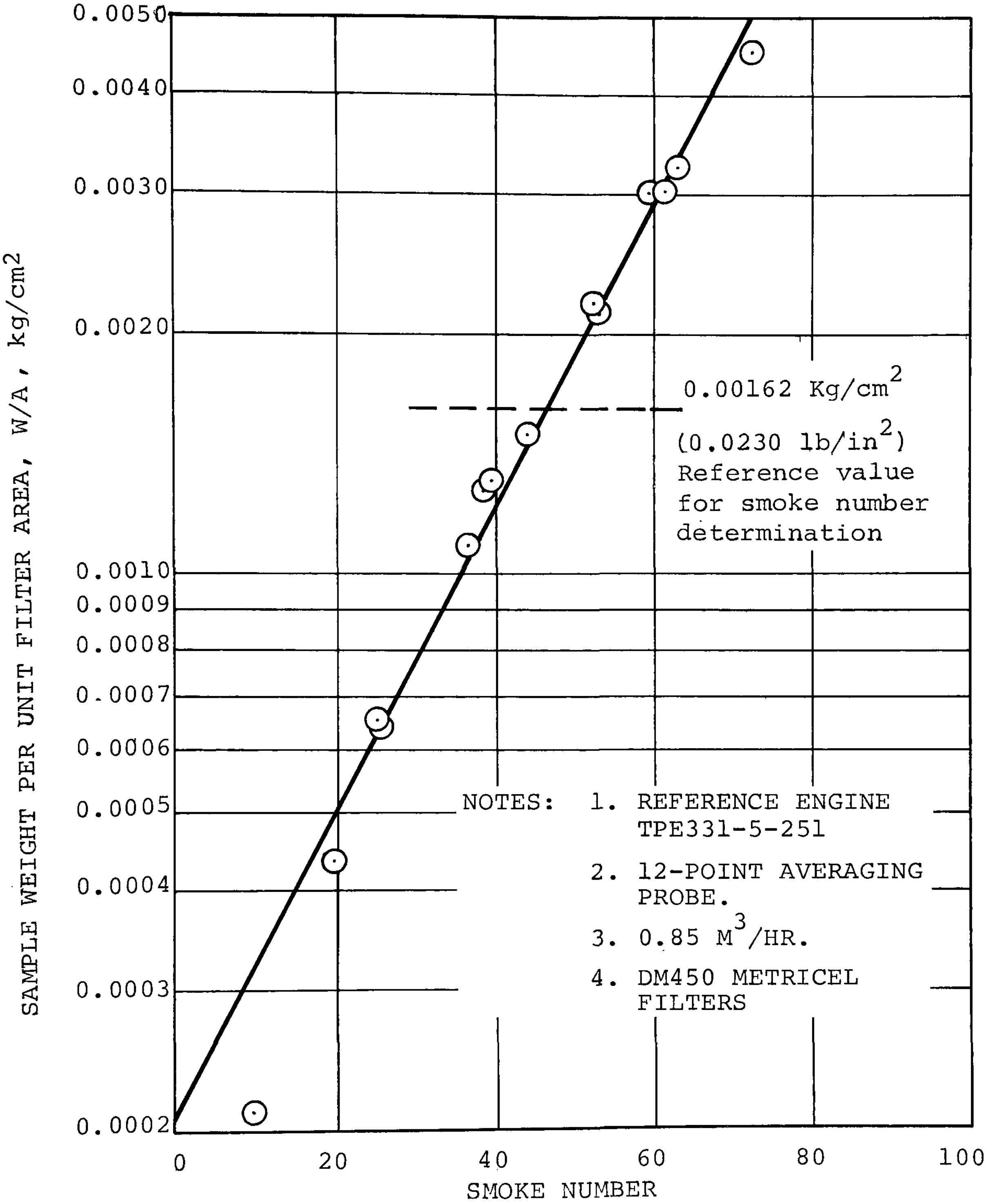


Figure 15. Smoke number correlation at taxi-idle condition.

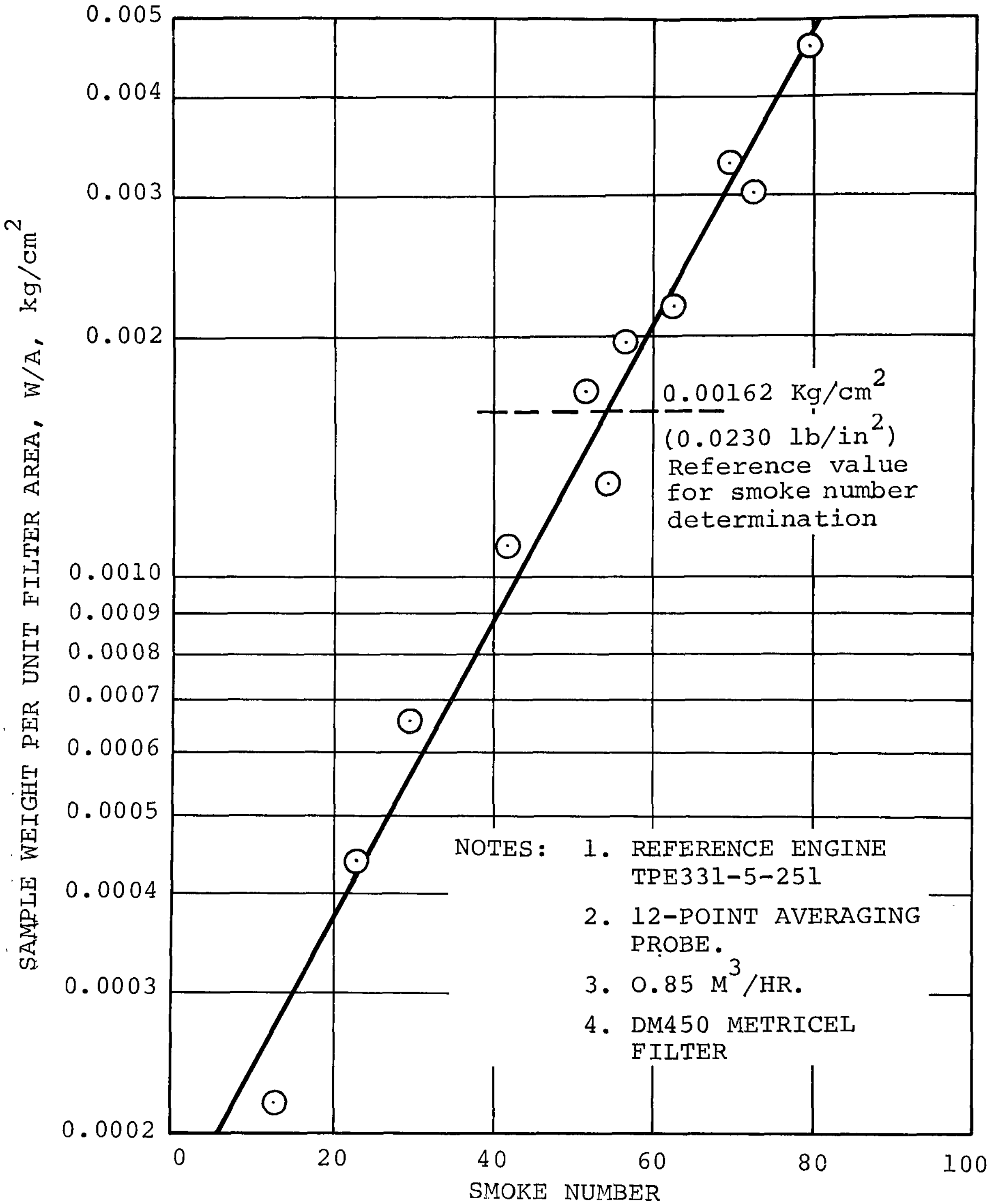


Figure 16. Smoke number correlation at 100 percent power.

The standard reference value can be obtained from a flow sample of approximately 0.01 m^3 with the 47 mm filter diameter. The filter has an exposed (filter) area of 7.81 cm^2. The DM450 Metricel filter has not been used for turbine engine smoke number measurement evidently because with engines of smoke number greater than 35, the spot saturates with respect to reflectance measurements, before the reference volume/area (0.0016^2 kg/cm^2) sample can be achieved.

A check on the conventional smoke number of the reference engine was obtained with Whatman No. 4 to determine what measureable change in engine smoke emission may have occurred over the test program (10 months). The data, shown in Figure 17, was taken at the taxi/idle operating condition and compared to previous data. The engine smoke number was unchanged from the value of 10.0. This indicates the overall engine emissions over the test period were quite constant.

With improvement in filter weighing techniques as previously described, additional repeatability tests were conducted with the TPE331 reference engine at 30-percent power in a continuing effort to define the factors influencing the data scatter. Data derived from these tests is presented in Figure 18. The particulate concentrations measured in these tests were nearly constant; the mean particulate concentration was 1.49μg/g with a standard deviation of 0.09μg/g.

Ambient dust measurements made with the twelve-point averaging probe in normal test position in the exhaust plane with the engine windmilling at 20-percent speed

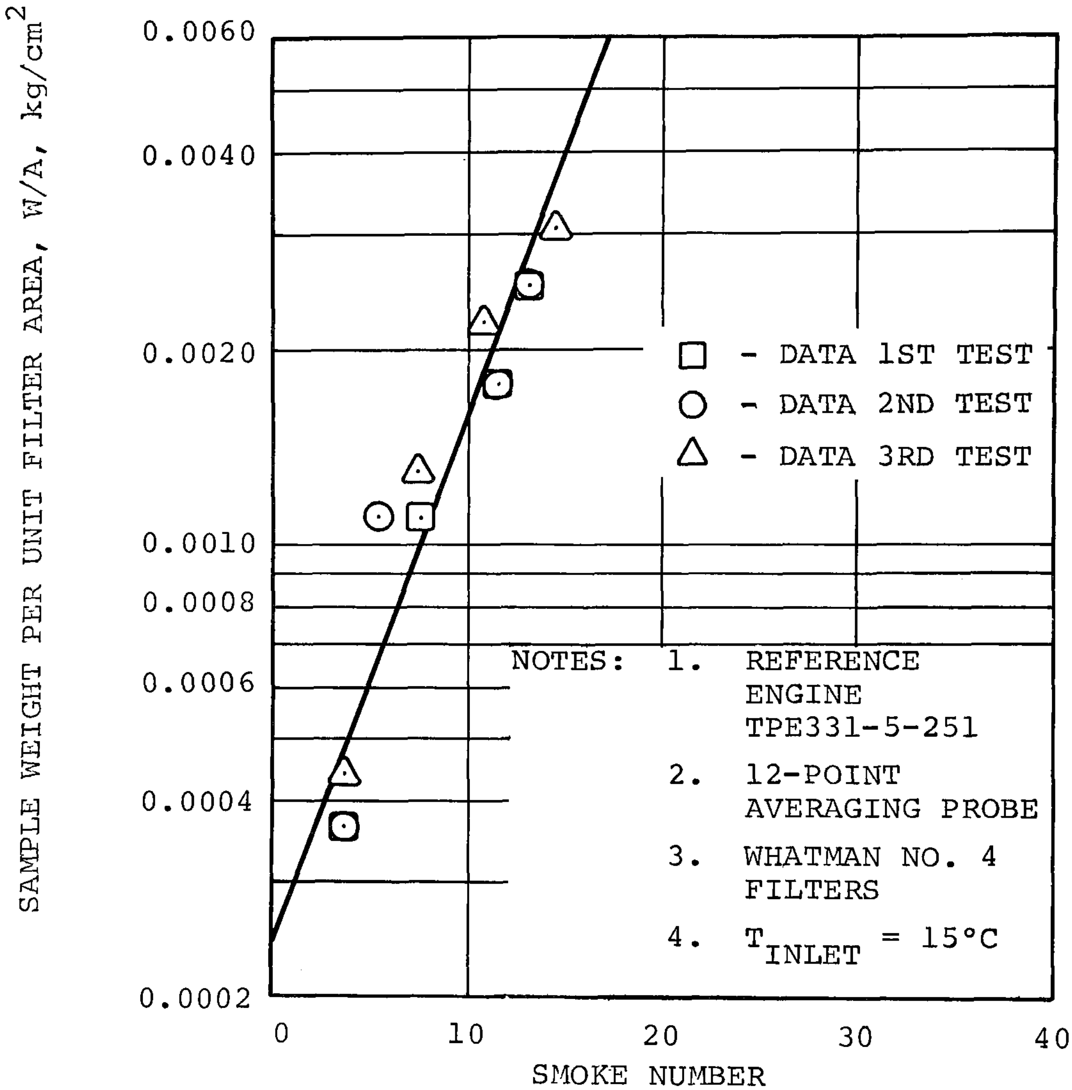


Figure 17. Weight flow versus smoke number at taxi-idle condition.

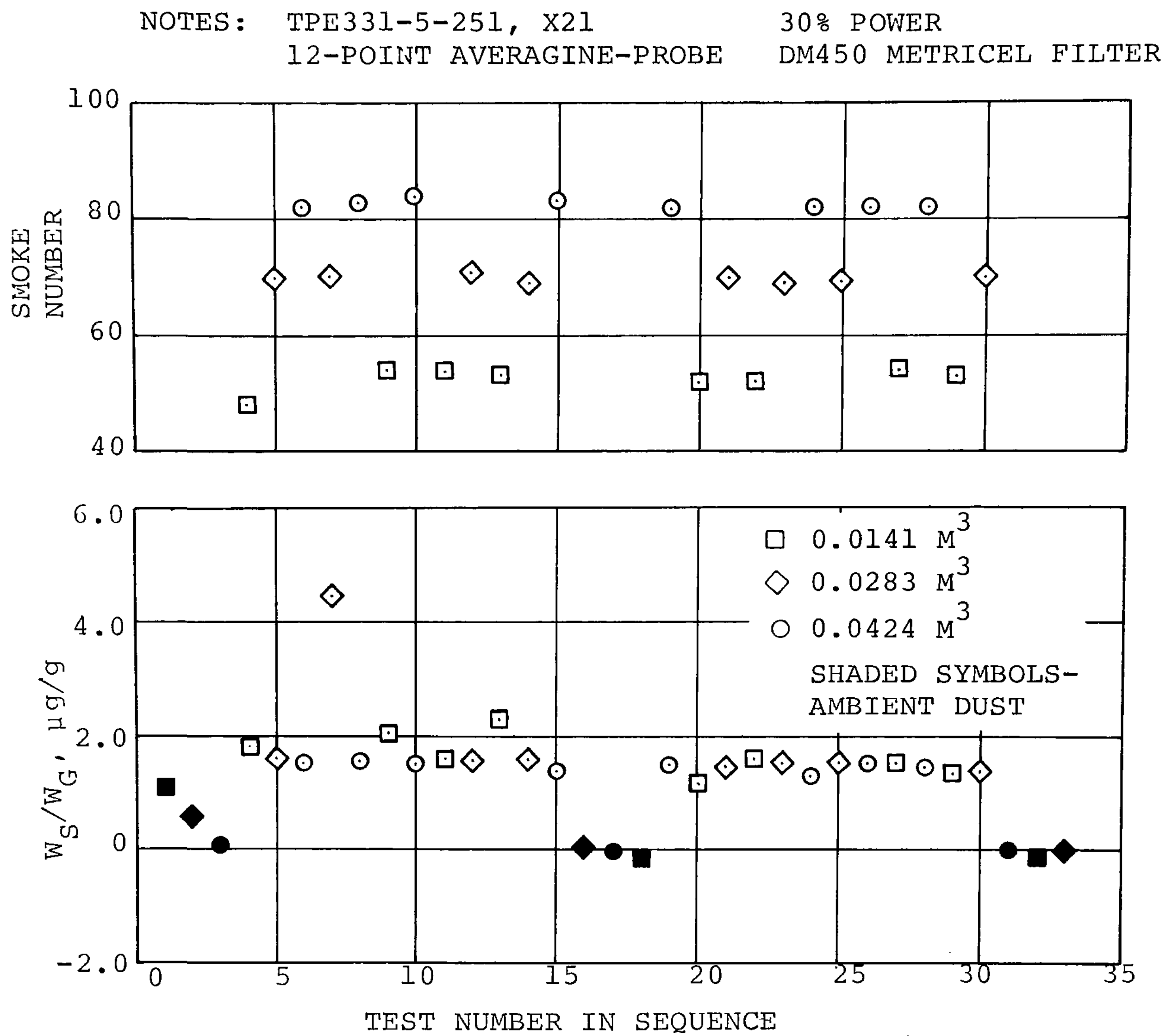


Figure 18. TPE331 dust and smoke measurements.

showed insignificant concentrations. In the previous test, Figure 14, measured values ranged nominally from 1.5 to 3.0 μg/g with several points exceeding 3.0 μg/g while ambient dust concentration measurements ranged from 1.0 to 2.0 μg/g. These represent extraordinarily high concentrations of ambient dust (1000 to 2000 $\mu g/in.^3$) and presumably they were at least partially the result of local traffic and turbulence in the vicinity of the test facility. It is apparent however, that ambient dust can have a significant effect on the measured particulate concentration. In order to quantitatively separate the effect of particulates aspirated through the engine at a specific data point from those resulting from other variables that may contribute to the observed scatter (i.e., variation in engine carbon particulate production), it would be necessary to measure inlet particulates with a separate filter system.

A review of all the repeatability data obtained resulted in the following conclusions:

(a) Filter weighing, instrumentation, and test errors did not significantly contribute to the observed scatter.

(b) The particulate concentrations emitted by the engine and ambient dust can vary irregularly with time.

(c) The smoke number was relatively constant for each sample volume in spite of the observed particulate weight scatter.

SECTION VI. PARTICULATE MEASUREMENT METHOD DEVELOPMENT

EFFECT OF SAMPLING PARAMETERS

The test arrangement shown in Figure 19, was used to test the variable parameters shown in Table 5. The reference engine with the 12-point averaging probe was used. A Graeco-Latin parameter test square[4] using the symbol designations of Table 5 resulted in a test formulation for varying the probe and filter flow rates and sample volumes as follows:

GRID I

	a	b	c
1	Aα	Bγ	Cβ
2	Bβ	Cα	Aγ
3	Cγ	Aβ	Bα

GRID II

	α	β	γ
A	1a	2c	3b
B	2b	3a	1c
C	3c	1b	2a

The results are given in terms of particulate weight to gas flow weight ratio as determined by weighing the filters and by measuring the DM 450 Metricel smoke number. Due to the variable test results previously obtained, three series of tests were made of each grid. The data was statistically analyzed by regressing sample volume (X_1), probe-flow rate (X_2), and filter-flow rate (X_3) on particulate concentration and smoke number. Table 6 summarizes the results.

With the use of the Student "t" test[4], it is evident that the sample volume has a high level of significance (99.95 percent probability) in the linear relationship with

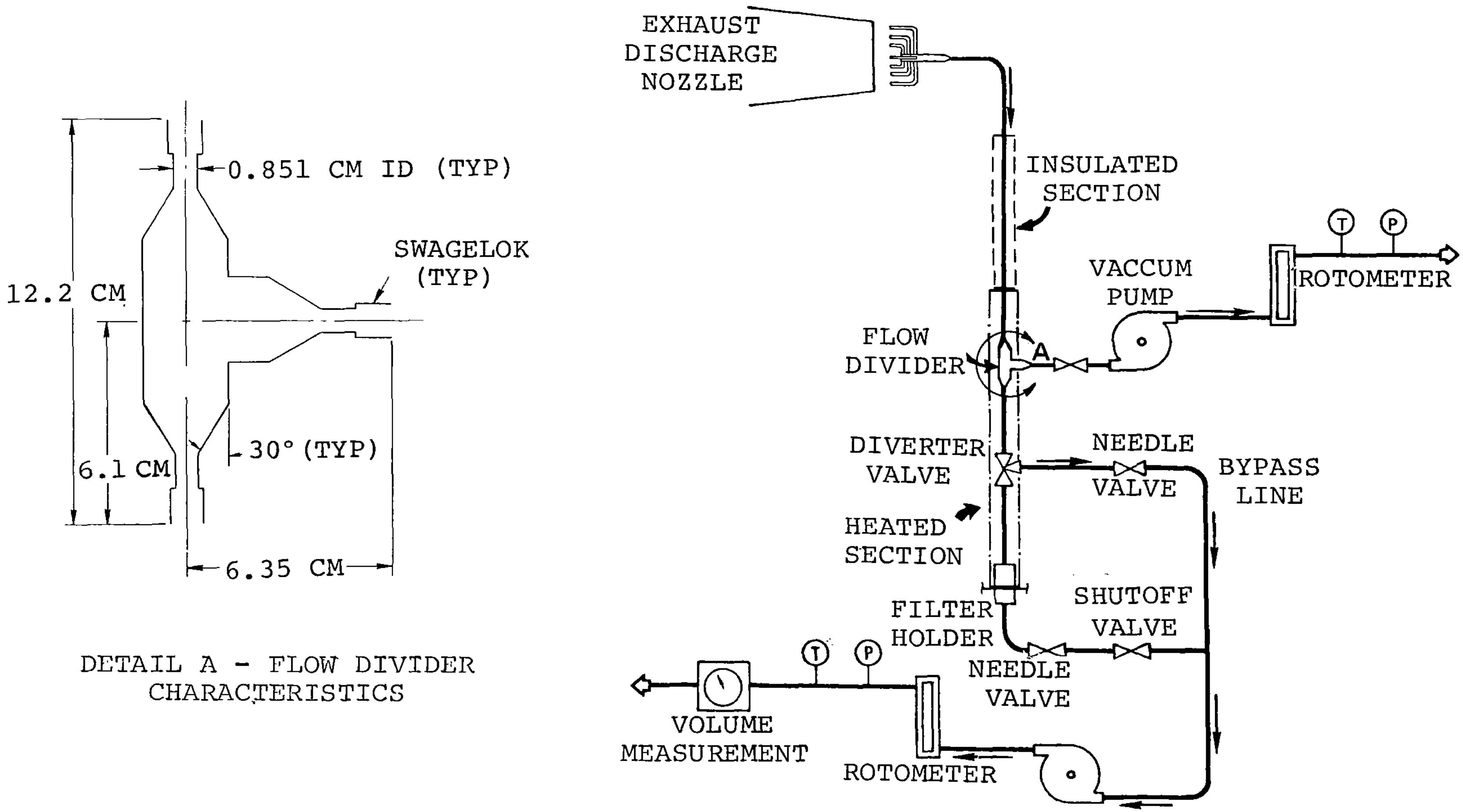


Figure 19. Particulate sampling system for gas turbine engines.

Table 5. VARIABLE PROBE/FILTER FLOW RATES - TPE331

Block:	Engine - TPE331-5-251, S/N X21 Probe transition line - 1.9 meters insulated Temperature controlled line - 11.3 meters, 80°C No sample dilution Sample flow diagram - Figure 19	
Variable parameters:	Engine operating conditions	a = taxi-idle b = 30% power c = 90% power
	Probe flow rate	A = 0.85 m^3/hr B = 1.70 m^3/hr C = 2.55 m^3/hr
	Filter flow rate	α = 0.425 m^3/hr β = 0.638 m^3/hr γ = 0.85 m^3/hr
	Gas sample volume	1 = 0.0198 m^3 2 = 0.0283 m^3 3 = 0.0425 m^3

smoke number. Table 6 also shows that the relationship between volume and particulate concentration at 30- and 90-percent power has a lower level of significance, (60 to 75 percent) than at taxi/idle (99.57 percent). The coefficients of correlation between these variables are shown in Table 7. There is the expected good correlation of sample volume with smoke number and a low level of significance between volume and particulate concentration.

It had been postulated that low probe-flow rates should provide erroneously high measured particulate concentrations (and perhaps smoke number). The analysis of the variable probe-flow rate data and variable filter-flow rate data does not provide a strong substantiation for this postulate. At 90-percent power, there is a good correlation of probe- and filter-flow rate with smoke number; however, at the lower power conditions there is a low correlation. At all power conditions, there is a low to moderate correlation between flow-rate and particulate concentration.

As expected and observed previously, the data also indicated that the prediction error is reduced at large sample volumes. Therefore, the data obtained at the largest gas sample volume [0.0425 m^3] was analyzed over the complete power range to further investigate the significance of probe-flow rate and filter-flow rate on particulate concentration and smoke number. The analysis of variance table for this data is presented in Table 8. It is observed that the coefficients of correlation are very low (0.11 and 0.14) and the Student "t" test shows a low level of significance (below 75 percent) with respect to smoke number. Thus, it was concluded that the range of variations in probe-flow and filter-flow rates used during the test do not affect the

Table 6. SUMMARY OF ANALYSIS OF RELATIONSHIP OF VARIABLES FROM MULTIPLE REGRESSION BY THE STUDENT "T" TEST.

Dependent variable	Power level	Student "t" test for significance of relationship		
		Volume	Probe flow rate	Filter flow rate
		(0.0198, 0.0283, 0.0425 m^3)	0.85, 1.70, 2.55 m^3/h	(0.425, 0.638, 0.85 m^3/h)
Smoke number	90%	$t=19.828>t_{(17)}=3.965$ at 99.95% level	$t=-8.658<t_{(17)}=-3.965$ at 99.95% level	$t=4.910<t_{(17)}=-3.965$ at 99.95% level
	30%	$t=5.978>t_{(17)}=3.965$ at 99.95% level	$t=0.351>t_{(17)}=0.257$ at 60% level	$t=0.214<t_{(17)}=0.257$ below 60% level
	Idle	$t=9.772>t_{(17)}=3.965$ at 99.95% level	$t=-0.789<t_{(17)}=-0.689$ at 75% level	$t=0.367>t_{(17)}=0.257$ at 60% level
Concentration of particulate	90%	$t=0.936>t_{(17)}=0.257$ at 60% level	$t=0.518>t_{(17)}=0.257$ at 60% level	$t=2.474>t_{(17)}=2.110$ at 97.5% level
	30%	$t=1.292>t_{(17)}=0.689$ at 75% level	$t=2.056>t_{(17)}=1.740$ at 95% level	$t=2.162>t_{(17)}=2.110$ at 97.5% level
	Idle	$t=-3.259<-2.898$ at 99.5% level	$t=0.921>t_{(17)}=0.689$ at 75% level	$t=-2.325<t_{(17)}=2.110$ at 97.5% level

Table 7. SUMMARY OF ANALYSIS OF RELATIONSHIP OF VARIABLES BY COEFFICIENTS OF CORRELATION.

Dependent variable	Power level	Correlation coefficient		
		Volume (0.0198, 0.0283, 0.0425 m^3)	Probe-flow rate 0.85, 1.70, 2.55 m^3/h	Filter-flow rate 0.425, 0.638, 0.85 m^3/h
Smoke number	90%	0.983 High correlation	-0.918 High correlation	-0.795 High correlation
	30%	0.848 High correlation	0.093 Low correlation	0.057 Low correlation
	Idle	0.934 High correlation	-0.206 Low correlation	0.098 Low correlation
Concentration of particulate	90%	0.243 Low correlation	0.145 Low correlation	0.552 Moderate correlation
	30%	0.326 Low correlation	0.482 Low correlation	0.500 Moderate correlation
	Idle	-0.657 Moderate correlation	0.239 Low correlation	-0.528 Moderate correlation

Table 8. ANALYSIS OF VARIANCE OF REGRESSION AGAINST SMOKE NUMBER AT 0.0425 CUBIC METERS GAS SAMPLE VOLUME.

Coefficient of determination	0.0521
Multiple corp. coefficient	0.2282

Sum of squares attributable to regression	15.62083
Sum of squares of deviation from regression	284.37917

Variance of estimate	18.95861
Std. error of estimate	4.35415

Intercept (a value)	87.77083

Analysis of variance for the multiple linear regression

Source of variation	D.F.	Sum of squares	Mean squares	F value
Due to regression............	2	15.62083	7.81042	0.4120
Deviation about regression...	15	284.37917	18.95861	-
Total....	17	300.00000	-	-

Variable no.	Mean	Std. deviation	Reg. coeff.	Std. error of rfg. coe.	Computed T value	Partial corp. coe.	Sum of sq. added	Prop. var. cum.
1	0.81667	0.46177	1.08333	2.51387	0.43094	0.11059	9.93103	0.03310
2	0.41667	0.08587	-6.63333	12.10840	-.54783	-.14005	5.68980	0.01897
3	86.00000	4.20084	-	-	-	-	-	-
Comp. check on final coeff.			-6.63333					

X_1 - Probe flow rate

X_2 - Filter flow rate

X_3 - Smoke number

measured particulate concentration or smoke number significantly over the complete engine operational range.

An attempt was made to correlate smoke number with particulate concentration at different power levels and gas sample volumes. For this analysis, the effects of probe-flow rate and filter-flow rate were ignored and only the larger sample volumes were considered. The resulting correlation is presented in Figure 20. Two curve fits were made because the data at taxi/idle was acquired at 65-percent engine speed, whereas at the other power conditions, the engine speed was 100 percent. Therefore, the curve between taxi/idle and 30-percent power is considered an interpolation, while the data between 30- and 90-percent power may be represented quite accurately by the curve.

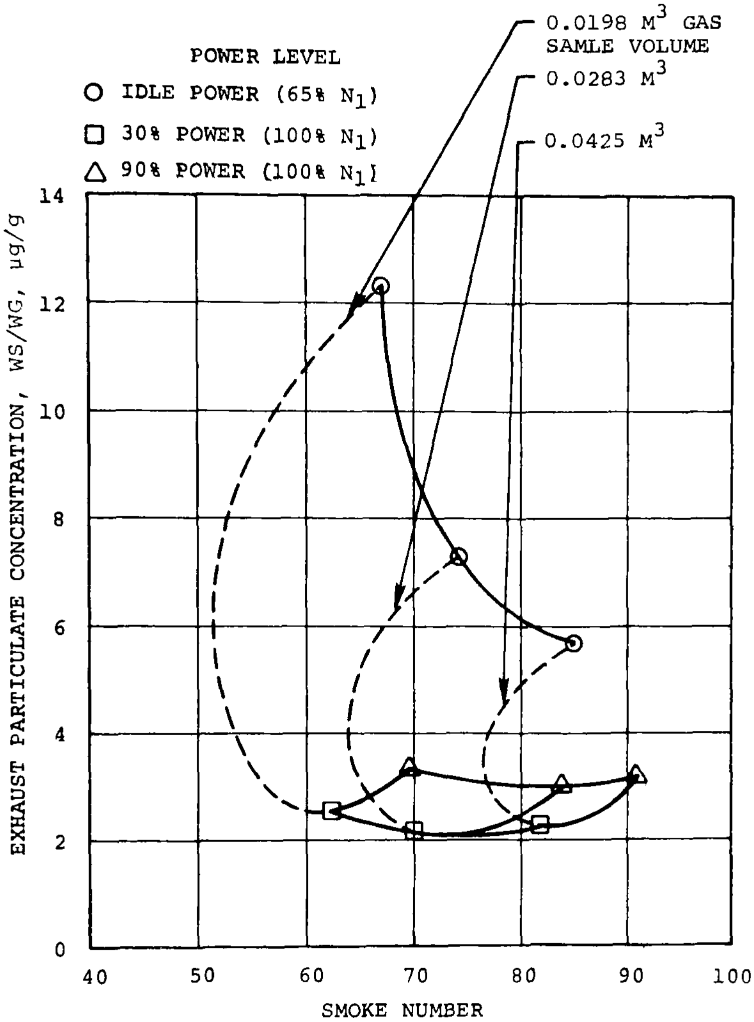
In summary, the following observations and conclusions were derived from this statistical analysis.

(a) The exhaust gas sample volume should be 0.0283 m^3 or larger to obtain minimum variation of particulate concentration due to size of gas sample.

(b) For the TPE331 Engine and within the range of values tested, probe-flow rate and filter-flow rate do not significantly affect smoke number or particulate concentration at the above recommended sample volume.

(c) Additional data obtained at several other engine power conditions (including taxi/idle at 100-percent speed) could provide a more complete correlation between particulate concentration and smoke number.

(d) The conventional exhaust gas smoke number correlates very well with the volume of the gas sample.



NOTE: OPERATING CONDITIONS
PHOENIX ALTITUDE (335 m)
STATIC OPERATION, T_{INLET} = 15°C

Figure 20. TPE331-5-x21 exhaust gas particulate concentration versus smoke number.

PARAMETRIC SAMPLING

The reference engine was tested using two sample transfer line lengths of 4.57 meters and 9.14 meters. Stainless steel tubing with a diameter of 0.9525 centimeters with an 0.0508 centimeter wall was used. The engine was operated at taxi/idle, 30-percent, and 90-percent rated power. The resulting exhaust gas particulate concentrations and smoke numbers are given in Figure 21. There does not appear to be a significant trend with a change in transfer line length. Although the particulate concentration measured in the taxi/idle operation with the 9.14 meter line was lower than with the 4.57 meter line, small increases were observed at the 30-percent and 90-percent power operations.

Deposits of carbon in the probe and transfer lines decreased through the program of testing on the various engines due chiefly to the employment of a larger insulated transfer line of 0.9525 cm O.D. as compared to the initial uninsulated transfer line of 0.635 cm O.D. at the rated flow of 0.85 m^3/hr. The final average probe and line deposition rates of carbon amounted typically to less than 5 percent of the material collected by the filters.

Another parameter of significance in the overall accuracy of the results concerns the amount of particulates passing through a single DM 450 Metricel filter at normal gas flow rate of 0.85 m^3/hr. The data presented in Figure 22 includes the results of testing conducted at the four power conditions. The material measured on the second of two filters (also DM 450 Metricel) positioned in series is shown to increase significantly as the engine power is increased. This may be due smaller size of particulate material generated at the higher power.

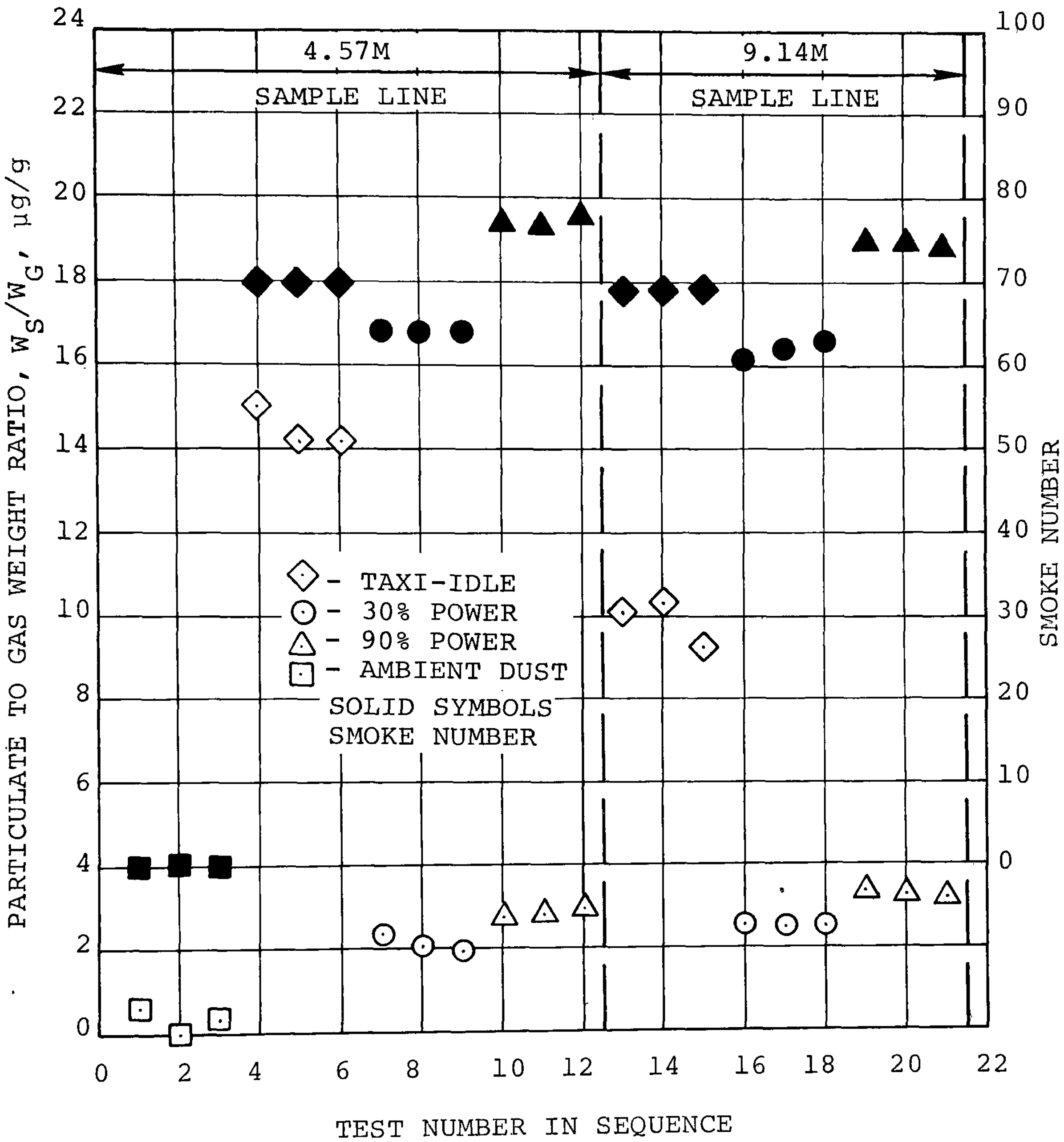


Figure 21. Variable sample transfer line length with reference TPE331 Engine.

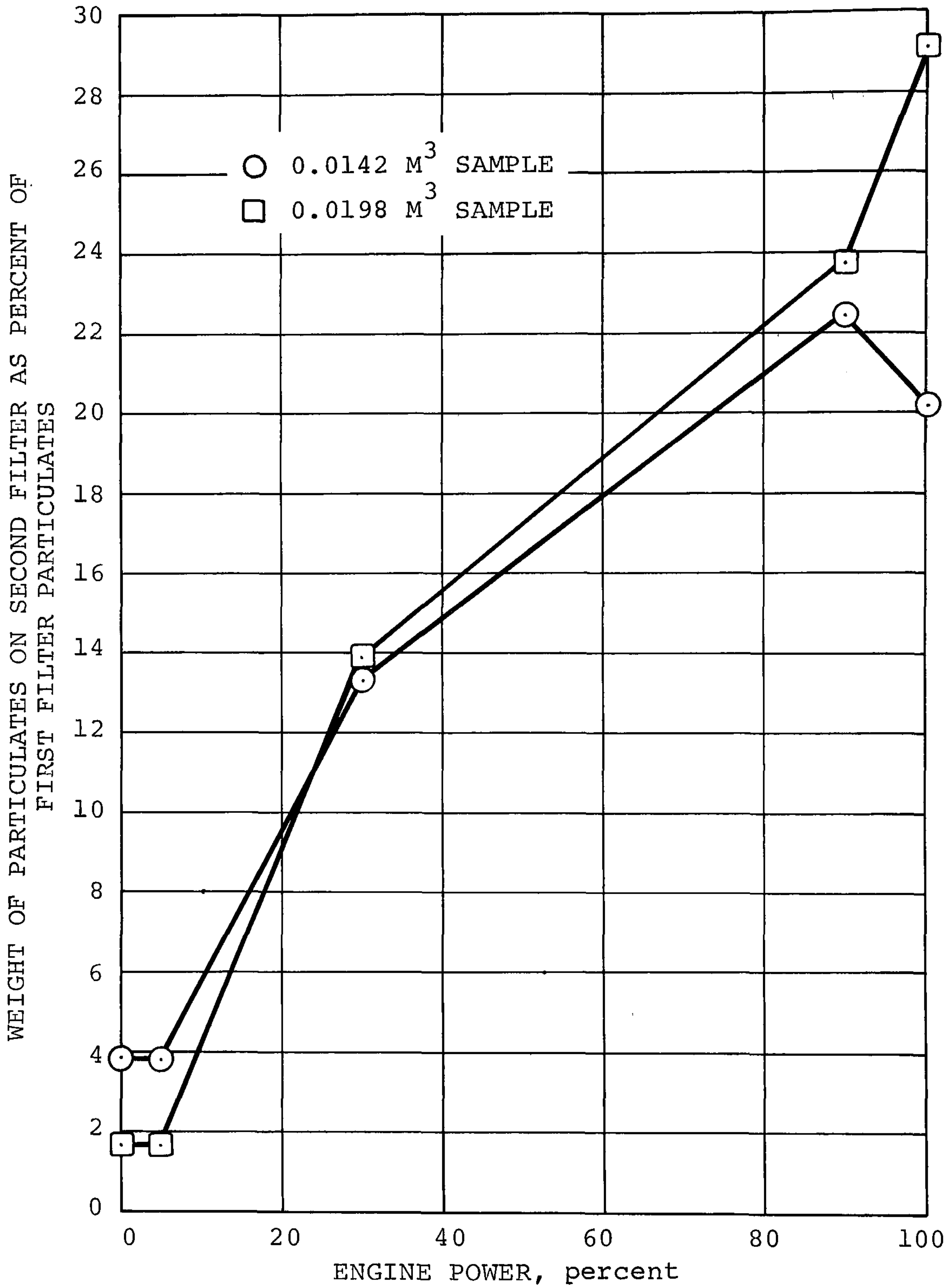


Figure 22. Particulates passing through a DM450 Metricel filter.

The particulate-to-gas concentrations, as compared to the Champagne correlation (shown previously in Figure 13, if corrected for the material passing through the filter shown in Figure 22, would result in the concentrations for the reference engine tests listed in Table 9.

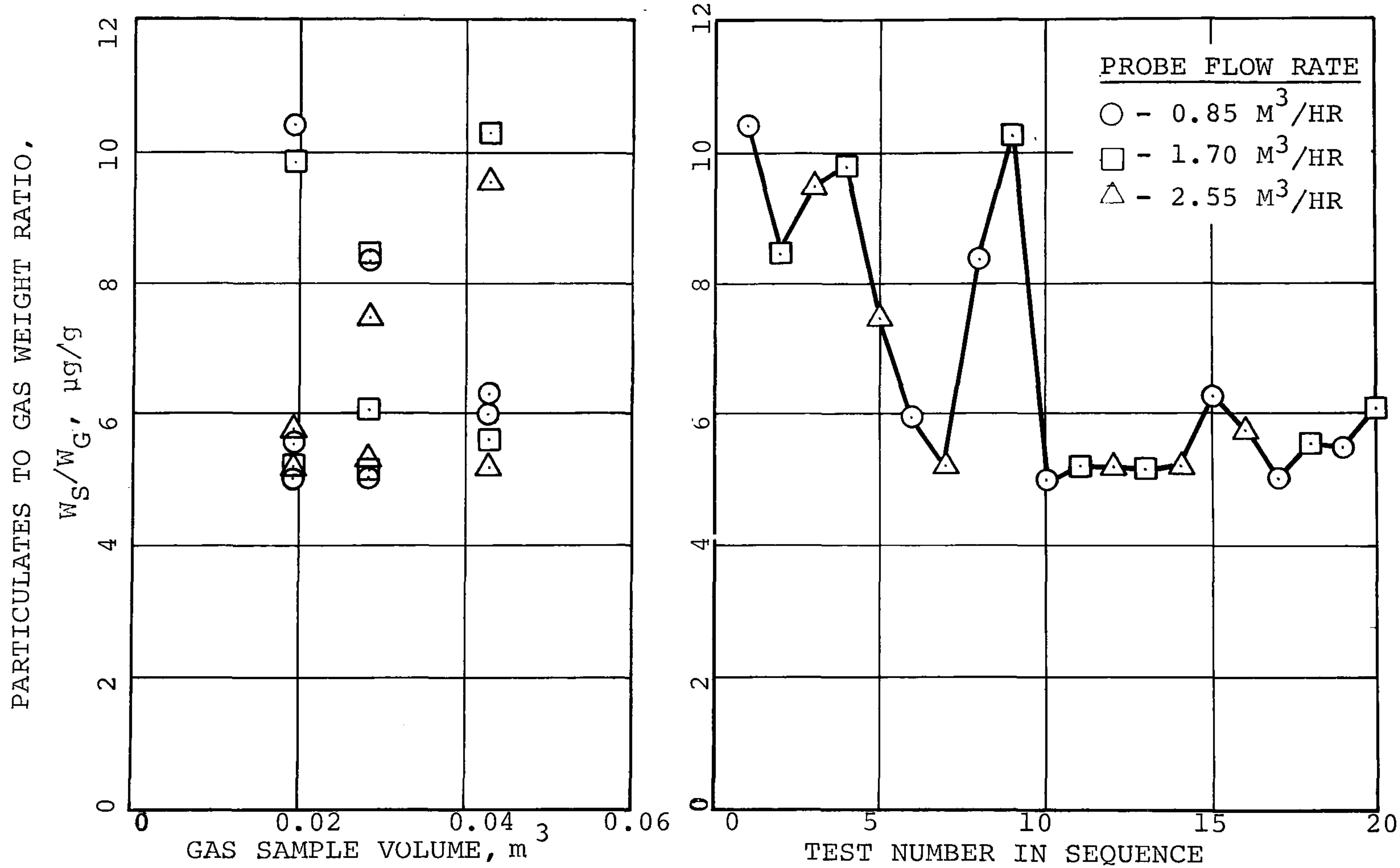
TABLE 9. PARTICULATE CONCENTRATIONS FOR REFERENCE ENGINE.

Engine power setting TPE331-5-251-S/N21	Particulate concentration, micrograms/gram	
	Two filters	One filter
Taxi/Idle	5.81	5.64
30%	5.63	4.96
90%	4.87	3.95
100%	4.68	3.75

TFE731-2 Engine Tests

A test was conducted with, a TFE731-2 Engine to measure particulate concentrations at various probe flow rates and gas sample volumes in order to assess the effects of non-isokinetic sampling. The TFE731 is a turbofan engine and thus has an exhaust gas velocity of approximately twice that of the TPE331. For these tests, the filter flow rate and engine power were held constant at 0.85 m^3/hr and 90 percent of rated thrust, respectively. Combinations of the two variables were tested in a random sequence for a total of twenty individual tests.

The resultant data (Figure 23) did not indicate an optimum gas sample volume or probe flow rate. Thus



NOTES: 1. TFE731 TURBOFAN ENGINE
2. 0.85 M^3/HR FILTER FLOW
3. 90% POWER
4. 12-POINT AVERAGING PROBE

Figure 23. Statistical experiment, particulates variable probe and sample flow.

apparently obviating the requirement for isokinetic sampling. A plot of the particulate concentration based on the test sequence is also presented in Figure 23. This plot indicates that the engine particulate output fluctuated significantly during the initial portion (approximately 30 minutes) of the test and then stabilized at a relatively constant lower value. As previously discussed, this characteristic has also been evidenced by the TPE331 Reference Engine in earlier tests. The particulate concentration of the TFE731 at 90-percent power appears to be about twice that of the TPE331 at the same percentage of rated power.

JT8D-9 Engine Tests

A series of tests were conducted with a JT8D-9 Turbofan Engine at Aviation Power Supply in Burbank, California, to determine possible particulate inhomogeneities in the exhaust flow of an engine having a can-annular combustion system. For these tests, particulate samples were obtained with a 12-point averaging probe located 7.6 cm downstream of the engine exhaust nozzle as shown in Figure 24. Data was obtained at 30- and 85-percent engine power conditions with both DM 450 Metricel and Whatman No. 4 filters. The probe was placed at six different circumferential positions as depicted in Figure 25. The positions of the probe orifices relative to the engine exhaust nozzle and the nine combustor cans are also shown. A photograph of the installation was presented previously in Figure 6.

The probe orifices were located at the center of the equal annular areas in the same manner as the 12-point averaging probes used in the tests performed with the TFE731 and TPE331. However, the probes used in the TFE731 and

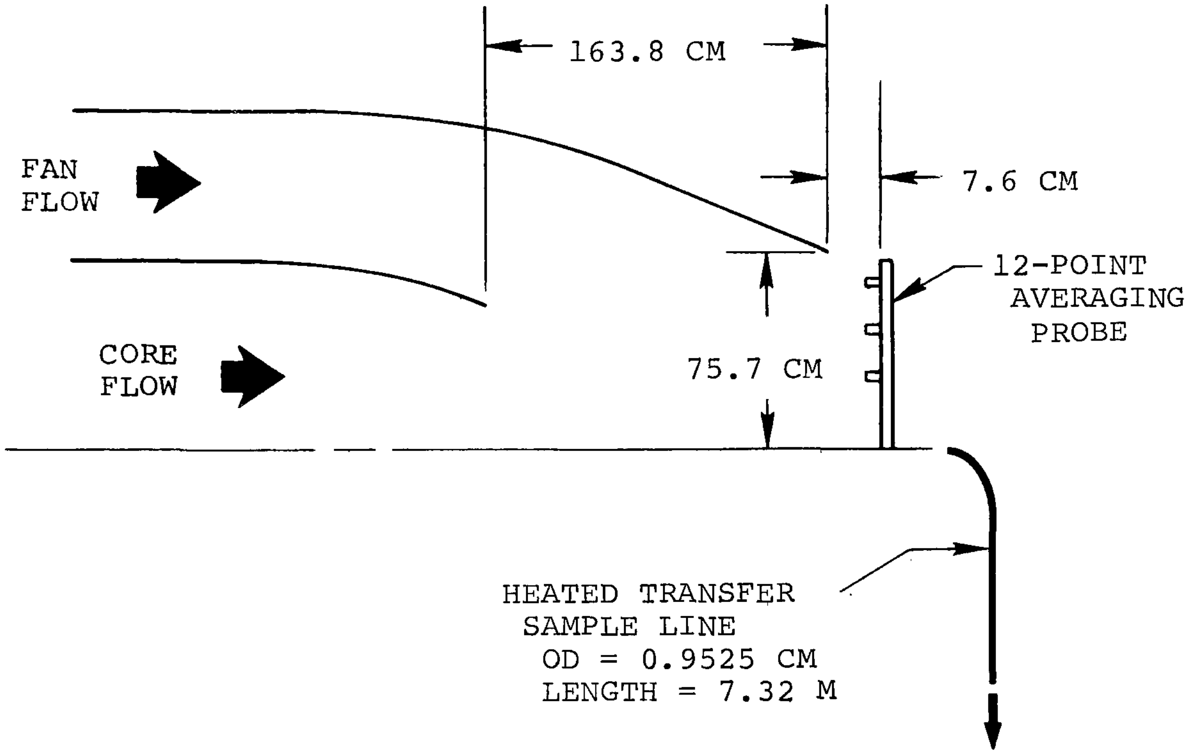


Figure 24. JT8D-9 test setup.

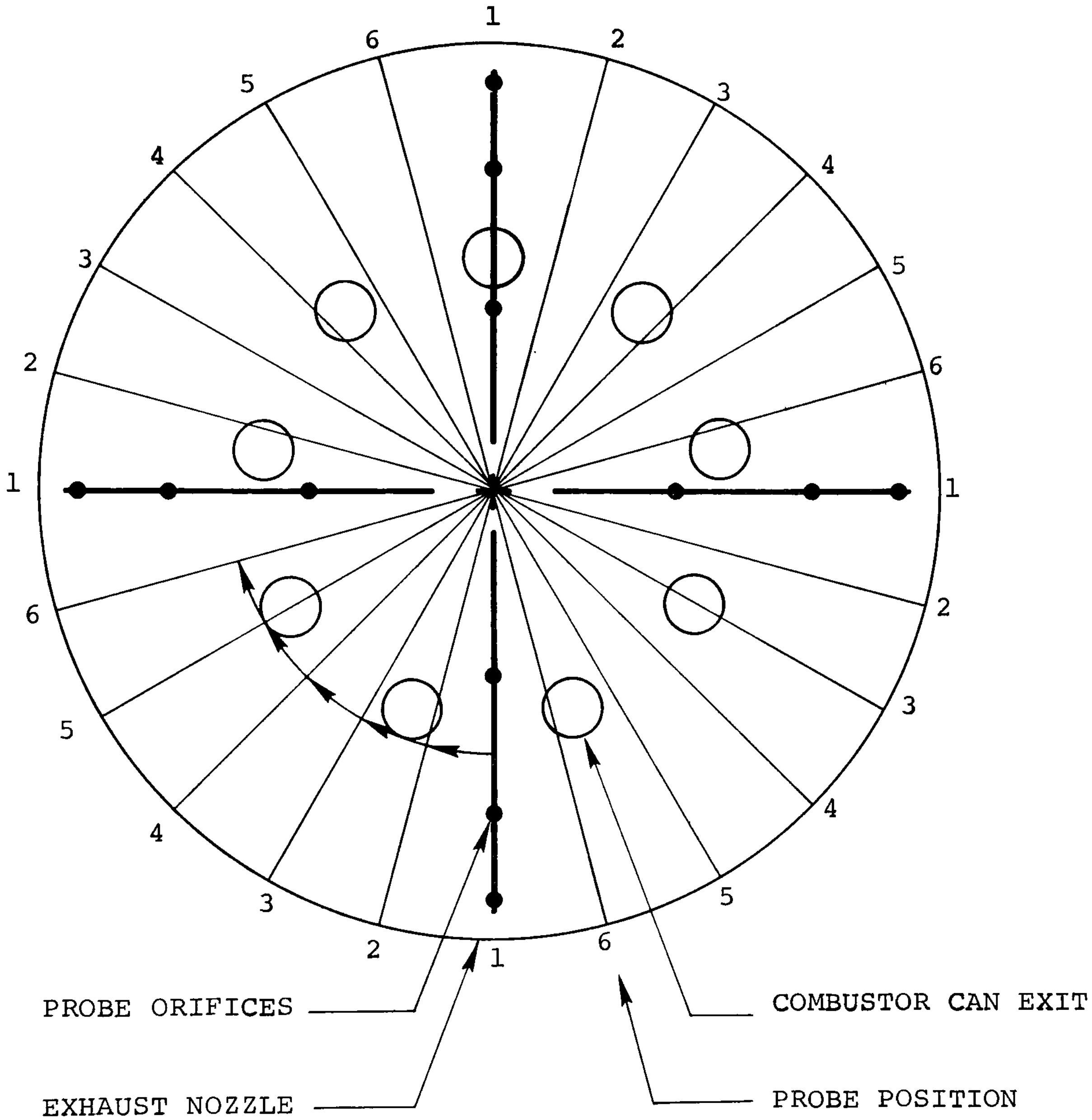


Figure 25. JT8D-9 combustor can/probe relationship.

while the probe for the JT8D-9 Engine was exposed to both fan and core flow. The probes at the smallest radius tended to be immersed in the core engine exhaust, while the probes at the largest radius were exposed to the fan exhaust. The probes at the intermediate radial position were exposed to mixed flow. DM450 Metricel filters were used to collect the particulates at a probe flow rate of 0.85 m^3/hr. Nearly all testing was done with a gas sample volume of 0.0141 m^3 which was necessary because of the very large quantity of particulate material observed in initial tests (probe position No. 1). Subsequent tests at other probe positions produced much lower particulate deposits. After obtaining samples at the six rake positions, testing was repeated at the initial probe rake position (No. 1). Ambient dust was measured twice during the test series.

Test results are given in Figure 26. The average particulate concentration at 30-percent power is $1.75 \pm 1.43 \times 10^{-6}$ grams/gram and the average particulate concentration at 85 percent power is $15.61 \pm 27.5 \times 10^{-6}$ grams/gram. The particulate weight obtained at 85-percent power in position No. 1 was unusually high with considerable scatter. The test results at the other rake positions also evidenced some scatter and variation with position. The particulate concentration at 30-percent power was very low, particularly in certain probe rake positions, and may be due to the fact that the probe samples both fan and engine exhaust flows.

Smoke numbers measured from the DM450 Metricel filters used in the test are presented in Figure 27. Two important facts evident from the data are:

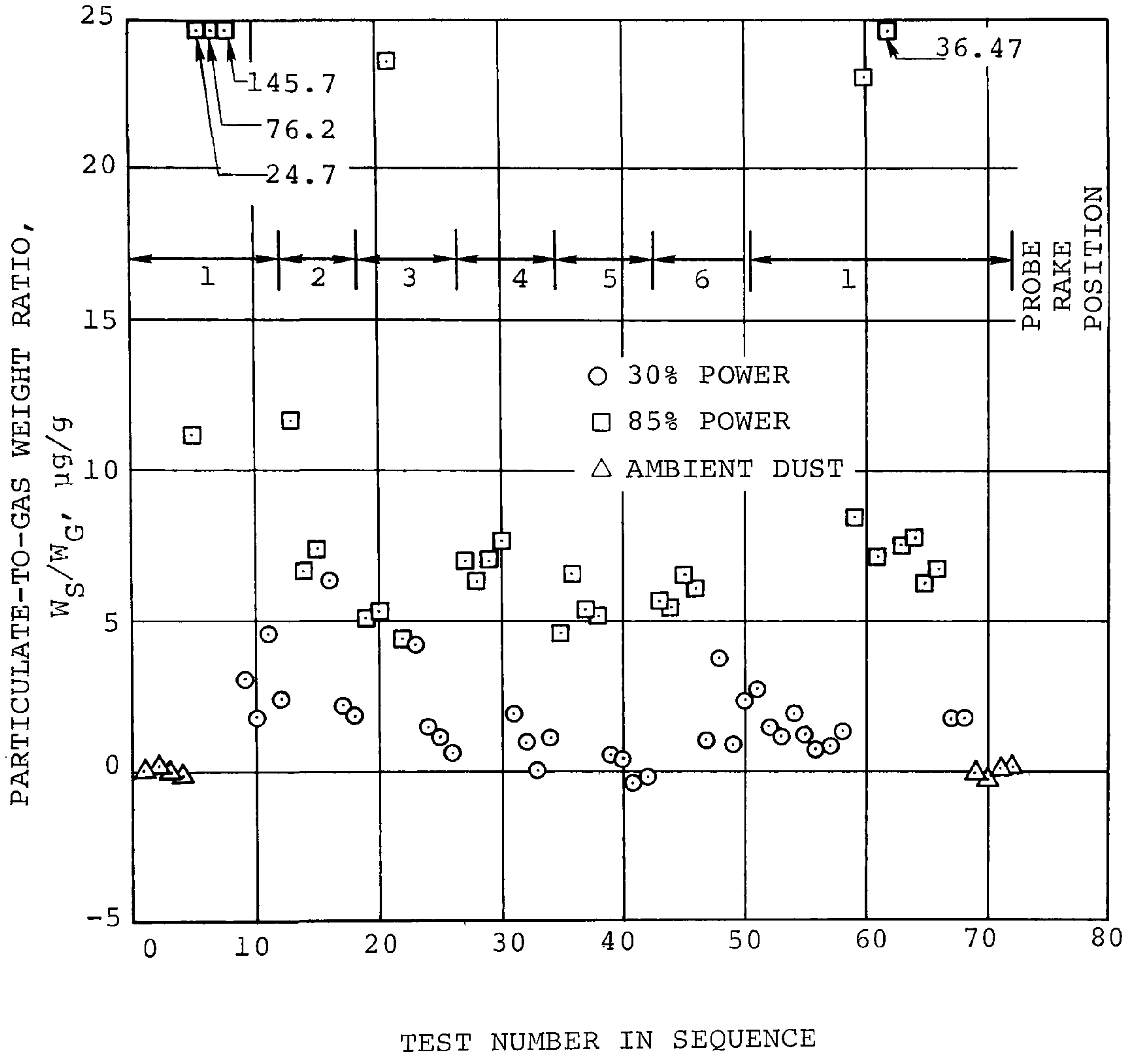


Figure 26. JT8D-9 discharge flow particulate concentration.

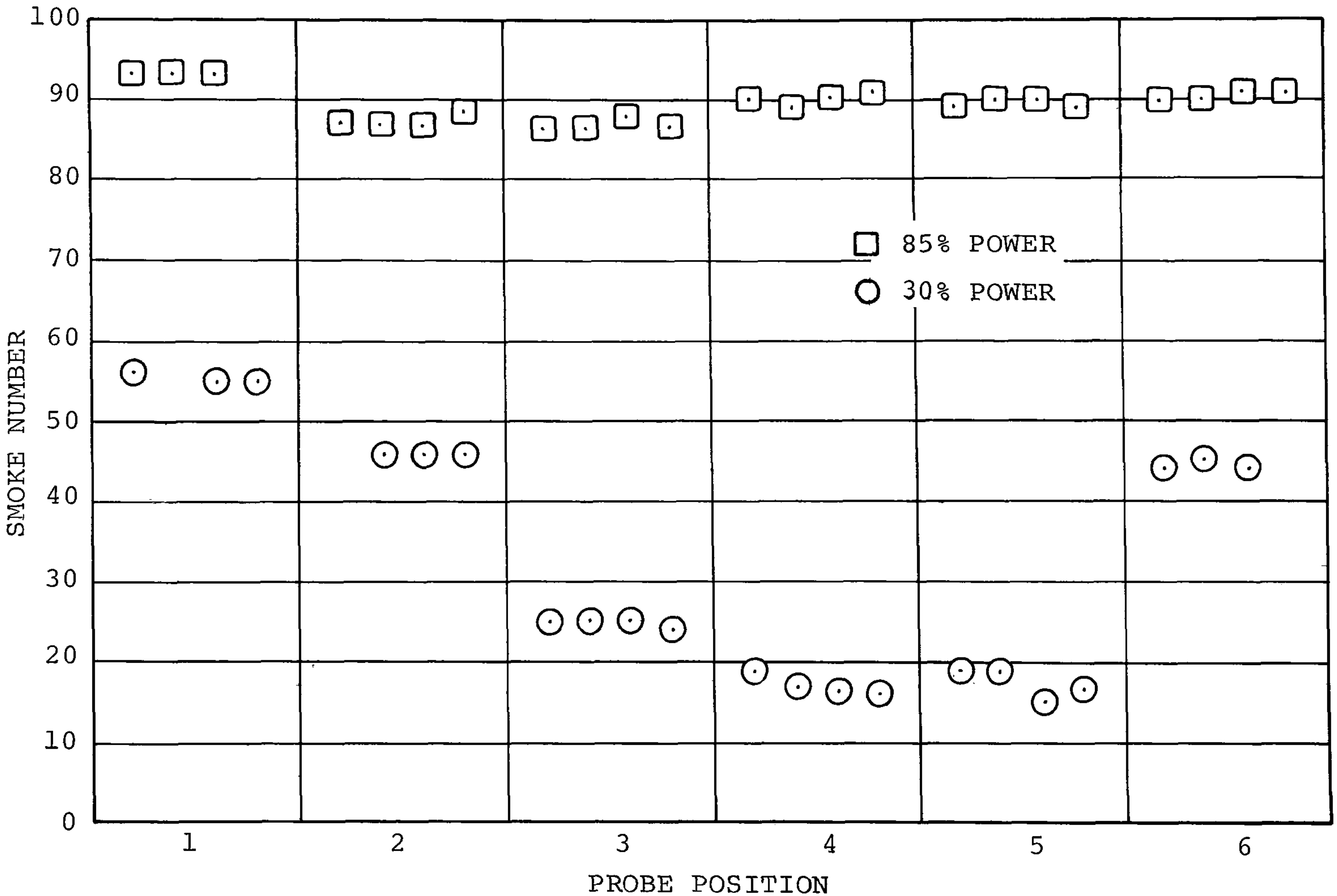


Figure 27. Smoke number (Reflectance) data from JT8D-9 Engine with DM450 Metricel filters.

(1) As with the previous engine tests, the particulate concentration data exhibited a large amount of scatter where as the smoke number data was relatively uniform.

(2) The smoke number data is affected by the probe position (particularly at 30-percent power) thus indicating nonhomogenieties in the engine exhaust.

Conventional smoke numbers (using Whatman No. 4 filters) were obtained. This data is compared to Pratt and Whitney data in Figure 28. The current measurements are somewhat higher than the overall correlation given in PWA-4339, but one sigma equals 3.9, which includes most of the results. The Von Brand Soiling Index using Whatman No. 4 filter paper should give essentially the same results as those shown in Figure 28.

After the JT8D-9 engine test, the probe and lines were flushed. Although negligible amount of carbon was found, the probe contained an unusually large deposit of small metal particles (approximately 20 mg). It was postulated that since the engine had recently been overhauled, there may have been a seal or blade-tip rub that produced the metal particulates. This would also explain some of the exceptionally high data scatter noted previously in Figure 26.

Particulate Sampling with Exhaust Gas Dilution

An exhaust sample dilution apparatus developed by Environmental Research Corporation under contract to EPA

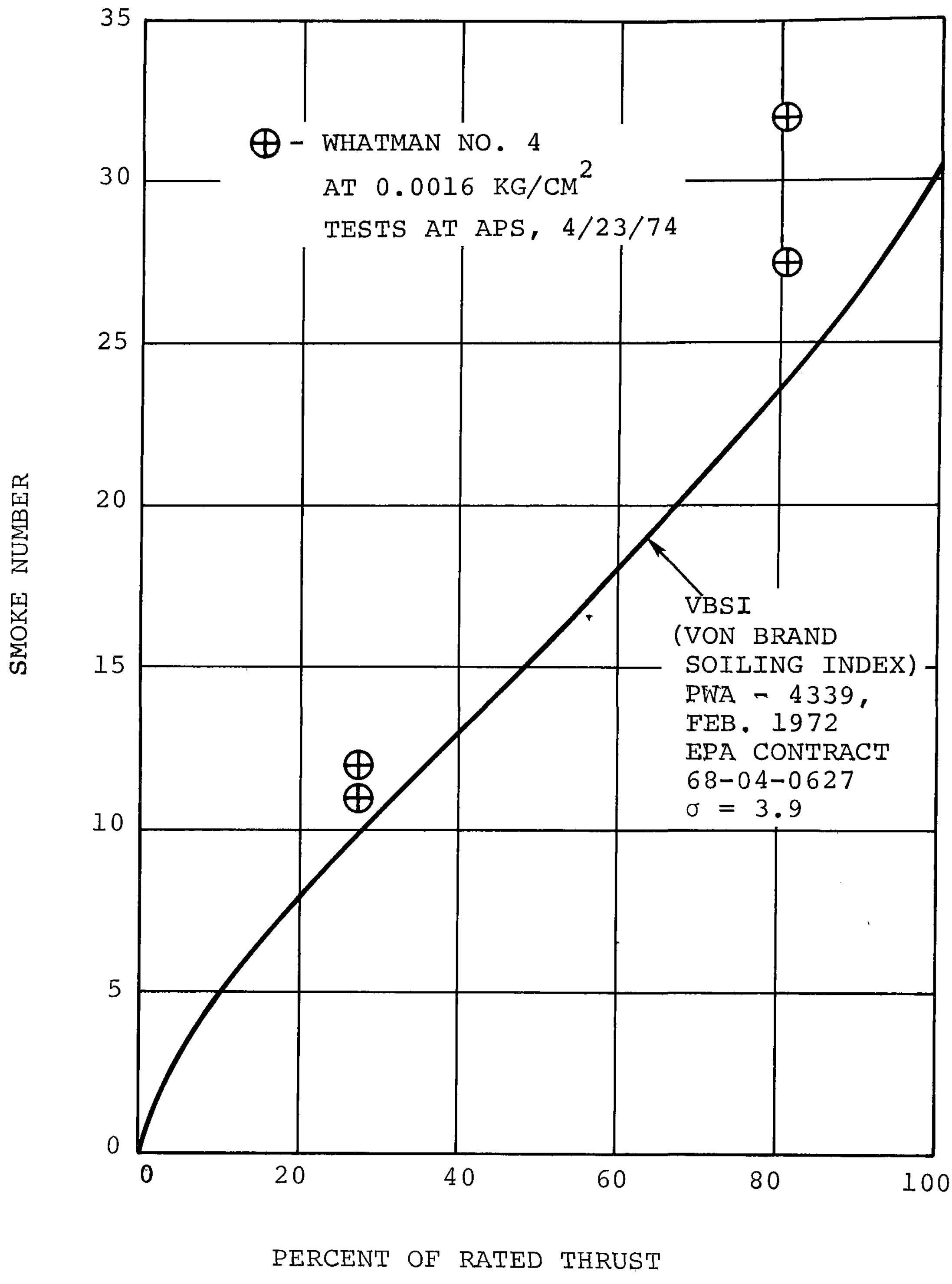


Figure 28. JT8D-9 smoke number by probe rake-position no. 1.

was provided by EPA for use in this program. The construction, and method of operation of the dilution device is given in Reference 5. In theory the diluter provides a means to rapidly cool the engine exhaust gas sample to ambient temperature and thereby condense the unburned hydrocarbons. The diluted exhaust gas sample would therefore contain only solid particulates. Also, since the sample flow rate was the same as had been used in the previous tests (0.85 m^3/hr), the sampling time would be increased proportional to the dilution rate thus providing a very accurate average of the engine particulate emission rate.

A flow diagram of the test arrangement is illustrated in Figure 29. A single point probe was used in lieu of the 12-point averaging probe to match the pressure drop capabilities of the diluter. An insulated line (1.2 meters long with 1.27 cm diameter) was used for a transition line between the probe and sample inlet on the diluter. The temperature of the diluted sample was slightly above the ambient temperature because of radiation and convection cooling together with the direct dilution.

The TPE331 reference engine was tested at two power conditions (30- and 90-percent power) over a range of dilution ratios. The diluted sample flow rate was 0.85 m^3/hr and a gas volume of 0.0283 m^3 was passed through a DM450 Metricel filter. The test results in terms of the exhaust particulate are presented in Figure 30. The mean particulate concentration and standard deviation of data obtained previously (Table 4) with the TPE331 at 30- and 90-percent power is also shown on Figure 30. Except for

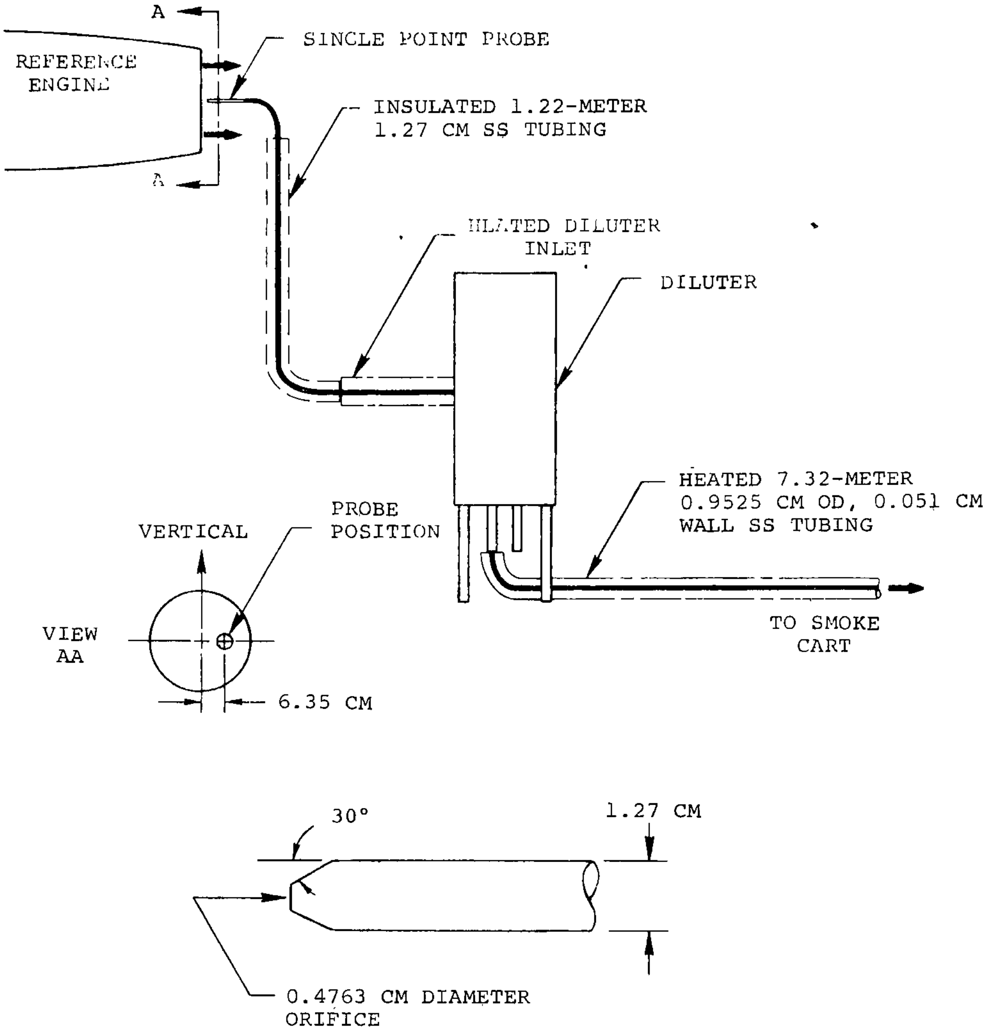


Figure 29. Dilution test setup.

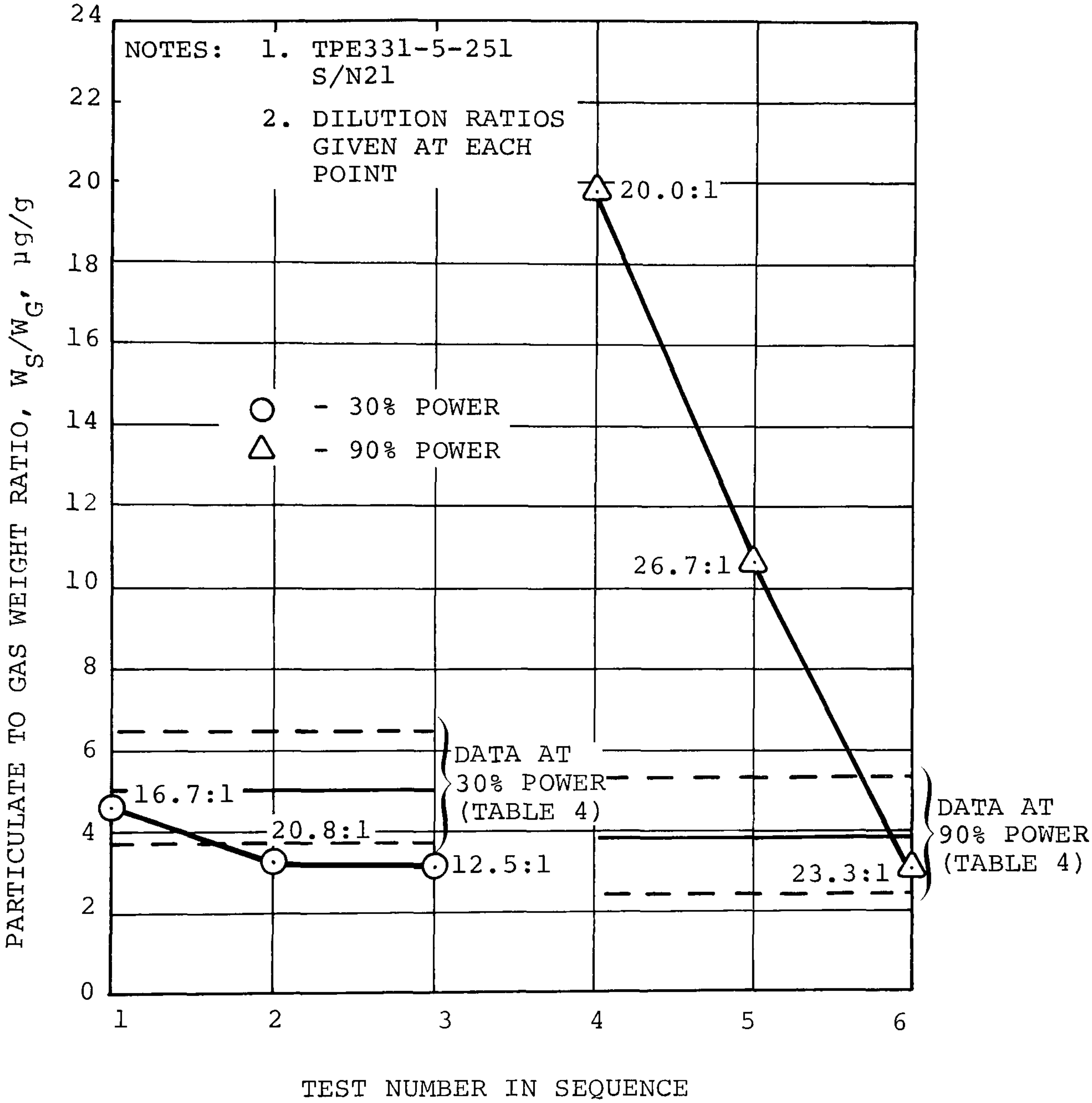


Figure 30. TPE331 exhaust gas particulate sampling with dilution device.

two data points at 90-percent power, particulate concentration in the diluted sample is somewhat lower than the concentration measured previously without dilution. This suggests that some of the deposit on the filters tested without dilution is unburned hydrocarbons. The large discrepancies in the two samples at 90-percent power could not be determined.

There are other major limitations associated with the use of the dilution device:

(1) The diluter itself was received in a somewhat damaged mechanical condition and leakages during its operation in the tests make very questionable the overall accuracy of the results. Also, it is possible that some deposits may have accumulated in the interior walls of the diluter.

(2) A single-point probe must be used because of the low pumping capacity of the device. Thus, the resulting data may not be representative if the particulate concentration in the engine exhaust is stratified (nonhomogenous).

(3) Particulate sampling with the dilution device was very time consuming since the operating time to obtain the same filter flow rate varied directly with the dilution ratio. Thus, a dilution ratio of 20:1 required engine operation for 20 times the duration of the direct sampling for the same filter particulate weight gain.

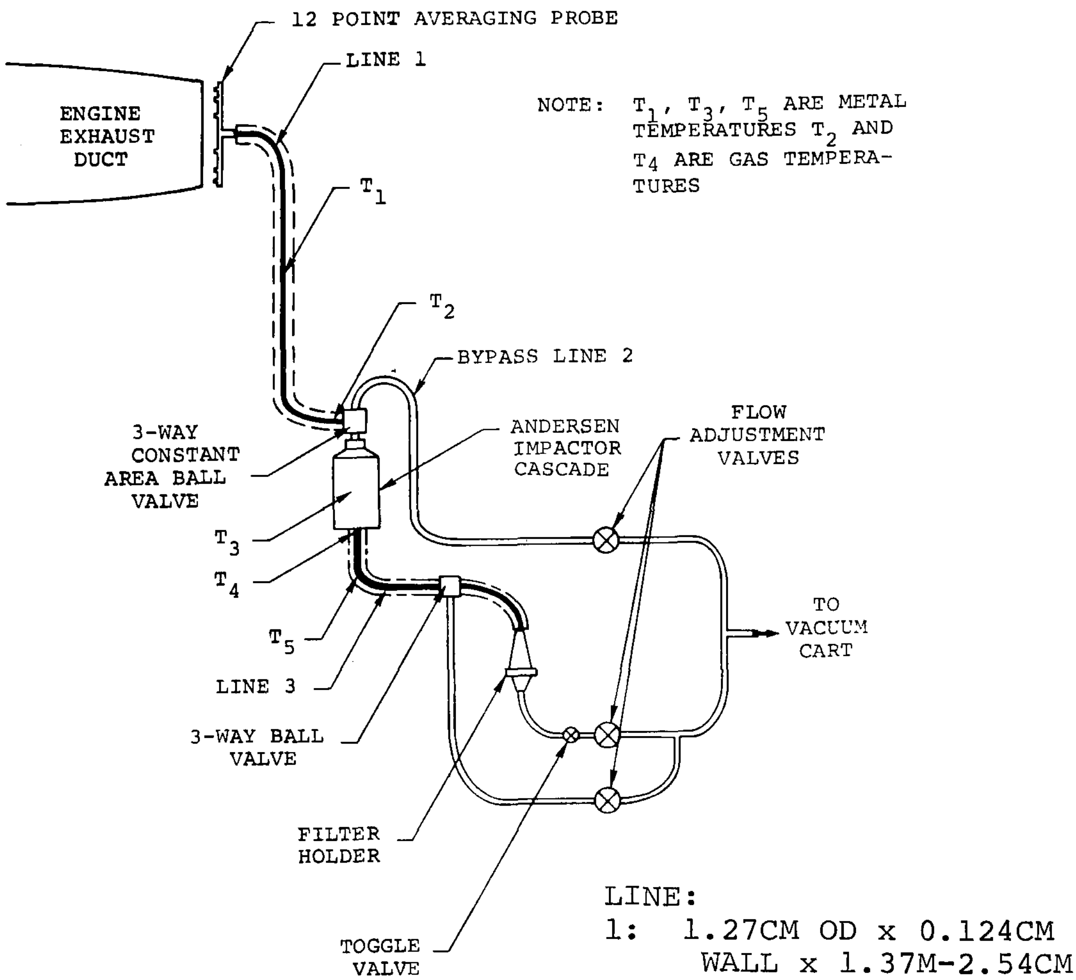
(4) Probe and line deposits were significantly lower in the above tests - apparently due to the larger transfer line size.

Cascade Impactor Tests for Particulate Size

A test was conducted with the TPE331 Engine, the 12-point averaging probe, and a 7 stage Anderson cascade impactor (a dry impingement device) to determine the size and distribution of particles emitted from the engine. The theory of operation for the cascade impactor is as follows: An exhaust gas sample is drawn through a series of jets on each impaction stage. Since the jet diameters progressively decrease from stage to stage, the velocity imparted to a particle continually increases. Thus at each stage, successively smaller particles are separated from the gas stream and deposited on the impaction plates. A filter located downstream of the impactor collects all particles with diameter smaller than the last stage cut-off limit.

A schematic of the test setup is shown in Figure 31. Type A Glass fiber filters (80 mm diameter) were used on each stage. The impactor was wrapped with insulation to reduce convective heat loss. The temperature of gas at the impactor inlet was typically 120°C and at the discharge was typically 38°C during the tests. Condensation was not visually apparent on any of the filter plates. Also, microscopic and gravimetric analysis of the filtrate obtained from the probe and line flushings did not reveal any carbon.

The test conditions are presented in Table 10. The data is presented in Table 11. It is noteworthy that the



LINE:
1: 1.27CM OD x 0.124CM WALL x 1.37M-2.54CM DIA LDS MOLDABLE

2: 0.9525CM FLEXIBLE LINE TEFLON CORE 4.57M LONG

3: 0.9525CM x 0.051CM WALL SS, 3.66M LONG ELECTRICALLY HEATED

Figure 31. Cascade impactor test schematic.

Table 10. CASCADE IMPACTOR TEST SEQUENCE

Test number	Engine power, percent	Sample time, minutes
1	Idle	20
2	Idle	20
3	Idle	45
4	30	20
5	30	30
6	30	45
7	90	20
8	90	30
9	90	20
10	100	20
11	100	30

Table 11. PARTICULATE TO GAS WEIGHT RATIO COLLECTED BY ANDERSEN CASCADE IMPACTOR STAGES - FINAL SERIES.

Impactor stage number	Taxi-idle test minutes			30% Power test minutes			90% Power test minutes			100% Power test minutes	
	20	30	45	20	30	45	20	30	45	20	30
	W_S/W_G µg/g			W_S/W_G µg/g			W_S/W_G µg/g			W_S/W_G µg/g	
1	1.70	1.41	1.18	0.17	0.07	0.21	0.48	0.46	0.36	0.76	1.08
2	1.66	1.52	1.13	0.26	0.22	0.14	0.20	0.18	0.09	0.29	0.30
3	1.57	1.51	1.08	0.28	0.16	0.17	0.35	0.29	0.26	0.34	0.37
4	1.60	2.31	0.99	0.65	0.67	0.52	0.37	0.30	0.31	0.46	0.42
5	1.67	1.63	1.23	0.28	0.27	0.24	0.49	0.38	0.34	0.57	0.53
6	1.74	1.67	1.25	0.30	0.25	0.24	0.45	0.30	0.28	0.55	0.39
7	1.88	1.82	1.39	0.41	0.27	0.26	0.53	0.41	0.15	0.50	0.36
Subtotal	11.82	11.87	8.25	2.35	1.91	1.78	2.88	2.32	1.79	3.47	3.45
Impactor exhaust flow	5.89	4.85	6.05	1.42	1.64	2.23	2.14	1.60	2.23	1.45	2.08
Total	17.71	16.72	14.30	3.77	3.55	4.01	5.02	3.92	4.02	4.92	5.53

NOTES:

(1) Type A glass fiber plates used on impactor stages

(2) DM450 Metricel used to filter exhaust flow from impactor

(3) TPE331 Reference engine

(4) Test setup - Figure 31

particulate concentrations measured on each stage were of the same order of magnitude for each test indicating a wider range and more uniform distribution of particles than has been anticipated.

Assuming that the 50-percent effective stage cutoff diameter (D50) as given for Anderson Cascade Impactor at 1.7 m^3/hr[6] to be equivalent to the mass median diameter, the results of Table 11 were converted into the particle size distribution data of Table 12.

Reference 6 gives the following D_{50} values for the different stages of the Andersen cascade impactor:

D_{50} (microns)	Stage
9.2	1
5.8	2
3.3	3
1.8	4
0.86	5
0.54	6
0.30	7

Additional analysis of the data in Table 11 (30-minute test) was conducted to determine and illustrate the cumulative mass distribution of particulate emission as a function of particulate size and engine power level. As shown in Figure 32, approximately half (50- to 60-percent) of the particulate mass is below D_{50} (MMD) of 1 micron. Also, at 30-percent power there is no significant emission of particles having an MMD greater than 10 micron while at 100-percent power, approximately 20 percent of the particulate mass emission is contained in particulates larger than 10 microns.

Table 12. PARTICULATE SIZE VERSUS WEIGHT PERCENTAGE EMITTED AT VARIOUS POWER LEVELS BY THE TPE331 REFERENCE ENGINE.

Particulate size (D_{50}), microns	Particulate Weight Percentage			
	Taxi-idle	30% Power	90% Power	100% Power
9.2 +	8.80	3.97	10.03	17.61
5.8	8.84	5.84	3.65	5.65
3.3	8.54	5.38	6.95	6.79
1.8	10.06	16.24	7.57	8.42
0.86	9.30	6.97	9.35	10.53
0.54	9.56	6.97	7.96	9.00
0.30	10.45	8.30	8.42	8.23
Less than 0.30	34.46	46.69	46.06	33.78

NOTE: As derived from Andersen cascade impactor.

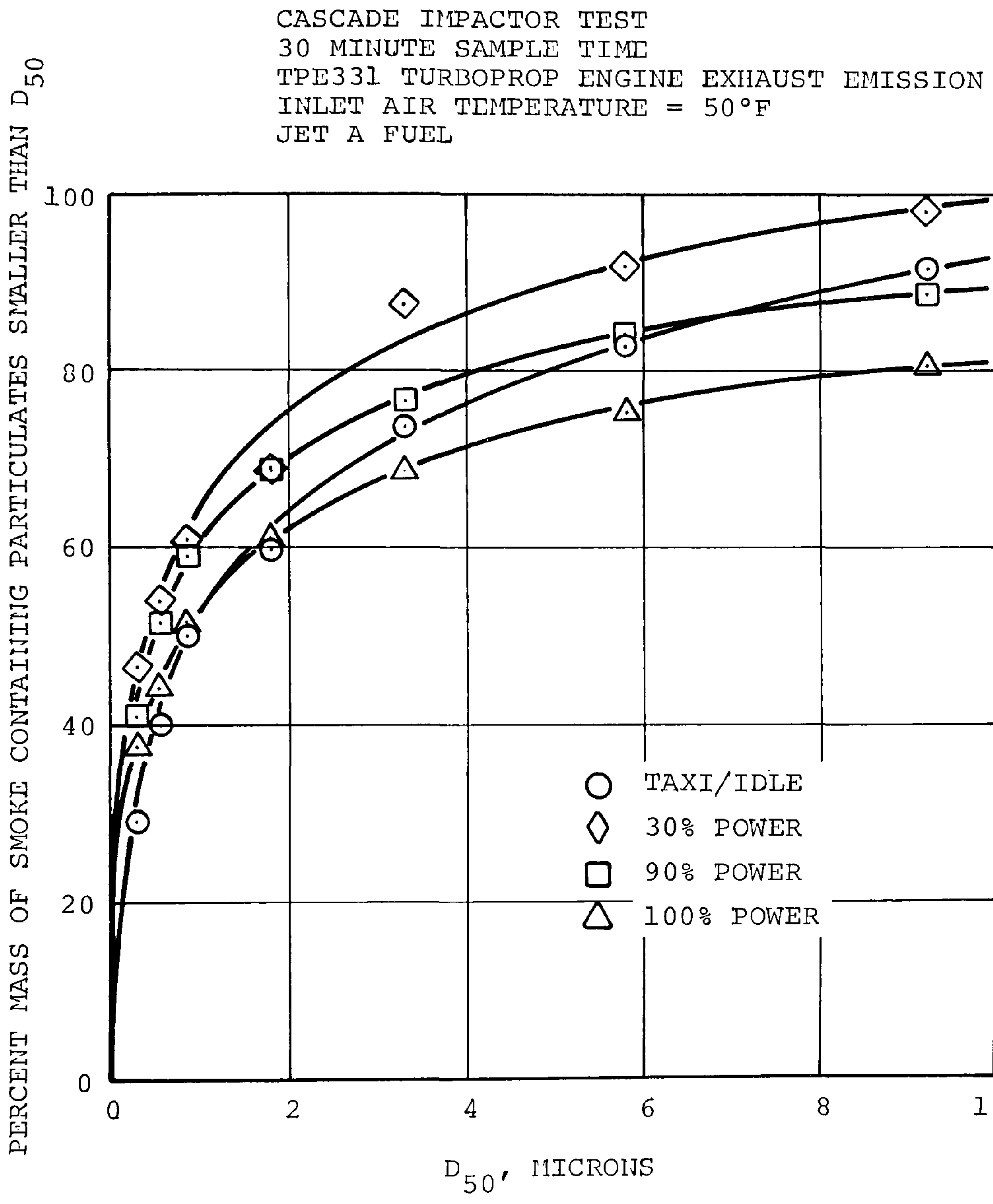


Figure 32. Cumulative mass distribution of particulates as a function of particulate size.

Previous information on smoke particulate size from the J-57 Engine [7] indicated such particles were very small--a geometric median diameter of 0.53 microns with a standard deviation of 1.63. Much larger particulates are indicated by the data from the test with a much larger range of sizes.

VII. DISCUSSION OF RESULTS

The test results obtained in this program varied substantially from some theoretical estimates and preliminary assumptions as to gas turbine smoke generation. Particulate stratification in the exhaust gas flow and variation of particulate concentration with time was obtained in testing on all engines. The conventional smoke number varied only slightly with changes in particulate concentration being chiefly dependent on the smaller, more physicologically damaging particulate material not removed in the atmosphere by gravity. Particulate concentration in gas turbine exhaust flow as obtained in this study is of the order of 5 micrograms per gram as compared to 0.05 to 0.20 micrograms per gram typical of urban areas in the U.S.

It appears that the particulates produced by gas turbine engines are generated in at least two major paths - small particles of smoke directly from fuel rich combustion and from combustor carbon deposits released intermittently to be shattered into grossly larger particulate by the turbine blades. This would appear to explain the variation in particulate concentration with test duration, the more uniform results with increased sample volume, and the wide range in particulate size obtained on a cascade impactor.

The experimental technique as developed in this study cannot compare test results to any true absolute measurements. Hence, the statistical approach necessarily required considerable point by point evaluation of the techniques employed. Accurate weighings of filter particulates in the microgram range was achieved by using reference filters subjected to the same humidity and temperature changes as the test filters to correct for the weight change of the test filters (due to water absorption or desorption) and by following a precise weighing procedure. A specific 12 point averaging probe design as used with a larger insulated transfer line and heated connecting line was found to generate little or no carbon deposits. Variation of the probe flow rates and sample flow rate showed suprisingly small effect on the particulate concentration measurement. Using the procedures detailed in this report it now appears possible to obtain consistent test results for the measurement of particulates.

The particulate generation of a gas turbine can change significantly and vary between engines of even the same type. This is basically believed due to the sensitivity of the combustion process to all the combustion factors; fuel, fuel nozzle, airflow, pressure, temperature, combustor geometry, thermal changes, etc. The probe pickup efficiency was also thought to be affected significantly by the flow capture area ratio which depended on the degree of isokinetic sampling but this appeared in test results to have little significance. The exhaust gas mass flow variation across the exit nozzle is appreciable but as this varies from engine to engine, the 12 point averaging probe was designed only with a constant exhaust gas flow area per probe.

Due to the stratification of the particulates in the exhaust gas, it is apparently necessary to examine the flow with several different positions of even the 12 point averaging probe to obtain a good measurement. For any specific engine, measurements would also have to be made at several power levels and over a time duration to determine intermitten emissions. Thus, the amount of tests to reasonably specify the particulate emissions of a new engine could easily involve 40 hours of engine test time and 480 filter samples. Considering the labor involved in the weighing procedure, it becomes obvious that cost for measuring the mass of gas turbine exhaust particulates is substantial. Also, due to the sensitivity of the combustion process on carbon generation, changes in particulate output with engine time, changes in fuel and operating conditions may be significant. Hence, it does not appear possible to achieve the original objective of an economical method for "determining the mass of insoluble particulates contained in samples of aircraft gas turbine exhausts, and to relate that quantity to the level of particulates emitted to the free atmosphere." Nevertheless, the equipment as developed can and should be used for obtaining better and more accurate engine smoke numbers using both Whatman No. 4 and DM450 Metricel filters on a routine basis, and for particulate sampling on an occasional check basis.

SECTION VIII

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BIBLIOGRAPHIC DATA SHEET	1. Report No. EPA-650/2-75-055	2.	3. Recipient's Accession No.
4. Title and Subtitle DETERMINATION OF AIRCRAFT TURBINE ENGINE PARTICULATES			5. Report Date May 1975
			6.
7. Author(s) KEITH M. JOHANSEN, EMERSON L. KUMM			8. Performing Organization Rept. No. 73-210332(12)
9. Performing Organization Name and Address AIRESEARCH MANUFACTURING COMPANY OF ARIZONA 402 SOUTH 36th STREET Phoenix, AZ 85034			10. Project/Task/Work Unit No. 26ACV-31/1AA010
			11. Contract/Grant No. 68-02-1236
12. Sponsoring Organization Name and Address NATIONAL ENVIRONMENTAL RESEARCH CENTER RESEARCH TRIANGLE PARK NORTH CAROLINA 27711			13. Type of Report & Period Covered Final,
			14.

15. Supplementary Notes

16. Abstracts

SAME AS REPORT

17. Key Words and Document Analysis. 17a. Descriptors

GAS TURBINE ENGINES
EMISSIONS MEASUREMENT
SMOKE
PARTICULATE MEASUREMENT

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
AVAILABLE TO THE PUBLIC RELEASE UNLIMITED	UNCLASSIFIED	89
	20. Security Class (This Page) UNCLASSIFIED	22. Price

FORM NTIS-35 (10-70) USCOMM-DC 40329-P71