AESO REPORT NO 110-06-83
JULY 1983

AIRCRAFT ENVIRONMENTAL SUPPORT OFFICE
NAVAL AIR SYSTEMS COMMAND
NAVAL AIR REWORK FACILITY
NORTH ISLAND, CALIFORNIA 92135

GAS TURBINE ENGINE
SMOKE MEASUREMENT CROSS CORRELATION

NEPSS
Naval
Environmental
Protection
Support
Service

AESO REPORT NO 110-06-83
JULY 1983

GAS TURBINE ENGINE
SMOKE MEASUREMENT CROSS CORRELATION

AIRCRAFT ENVIRONMENTAL SUPPORT OFFICE
NAVAL AIR REWORK FACILITY, NORTH ISLAND
SAN DIEGO, CALIFORNIA 92135

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

An extensive air sampling program was undertaken to measure the particulate emissions from various gas turbine (jet) engines used in military aircraft. This joint Navy, Air Force project was directed and accomplished by the Navy Aircraft Environmental Support Office (AESO) at NAVAIREWORKFAC North Island. The project was accomplished per MIPR S-80-21.

The objectives of the study were: First, measure smoke mass emissions at the engine exhaust plane and correlate the results with measured smoke numbers. Second, compare the smoke mass emissions measured simultaneously by two different direct mass measurement procedures. A third objective was to measure the particle size distribution of the jet engine exhaust aerosol. Descriptions of the sampling methods used in this project are given in the next section.

The aim of the project was to correlate the results obtained using several different particulate emission sampling methods on various military jet engines and determine if other indirect measurement methods can be used to adequately determine particulate emissions. A variety of engine types were tested including: J79-GE-8C/D, J79-GE-10B, F404-GE-400, TF30-P-414, and J52-P-6B engines. The bulk of the testing and analysis was centered around three engine types: J79-GE-8C/D, J79-GE-10B, and F404-GE-400, due to their availability and widespread use by the Navy.

2.0 SAMPLING METHODS

Extensive tests were conducted to determine air emission rates from several types of gas turbine (jet) engines. Direct emission measurements were conducted in jet engine test cells both immediately behind the engine nozzles and at the top of the test cell stacks. Indirect emission measurements were also performed using techniques given in this section.

Particulate emission measurements at the top of the stack were made using sampling equipment which conformed to U.S. Environmental Protection Agency Method 5 specifications.(40 CFR Part 60) The sampling technique involved collecting a representative, isokinetic particulate sample from a stationary source using a heated probe, filter, and cooled condenser array. Particulate matter was collected on the probe, nozzle, and filter. Condensible particulate matter was collected in the condenser array. A schematic drawing of a typical Method 5 sampling train is given in Figure 2.1. As a modification to Method 5, the samples for this project were collected at the top of the test cell exhaust stacks. The stack designs and construction did not allow for the entry of probes through the walls to obtain air samples in a representative fashion. Therefore, a matrix of sampling points was used immediately above the top of each test cell stack during Method 5 sampling.

Measurements of particulate emissions directly behind the engine were made using a modified prototype exhaust plane analyzer system. The exhaust plane analyzer incorporated a nozzle and probe assembly designed to collect air samples directly behind the engine exhaust nozzle. The probe could be remotely manipulated to sample a matrix of points within the engine exhaust plane. The exhaust gases passed from the probe to a high flowrate (greater than 1 cfm possible) gas sampling system similar to the Method 5 train. During this phase of testing, the exhaust plane analyzer was only operated during idle engine modes. The exhaust plane analyzer's relatively high sampling rate allowed for much shorter sampling times, saving fuel and manhour expenses.

Several of the aircraft engine types tested smoke heavily under normal operating conditions. These engines, including the J79-GE-8C/D and J52-P-6B, produce highly opaque smoke plumes in test cell operations and in flight. A ferrocene-based fuel additive was used with these engines to help reduce the visible smoke plume during many of the sampling runs at military power. These runs with ferrocene were analyzed seperately from military power runs without ferrocene.

For data presentation and discussion purposes, the terms "Exhaust Plane analyzer" and "Method 5 analyzer" will be used in this report.

Simultaneous measurements of gaseous emissions were made using continuous-reading electronic instrumentation appropriate for the specific gaseous component. Although not discussed in this report, those measurements were included in the original, referenced reports.

In addition to these direct emission measurements, data were collected using several indirect measurement methods. Smoke Numbers were obtained using a ROSECO Model 473A engine smoke emission sampler designed according to Society of Automotive Engineers (SAE) specifications contained in Aerospace Recommended Practice ARP 1179. A Smoke Number is a dimensionless number quantifying smoke density continuously from 0 to 100. The smoke density is determined by measuring the optical reflectance of a filter which has been exposed to a sample of the smoke stream. The Smoke Number is then calculated from this reflectance measurement. The smoke emission sampler probe was positioned at the end of the test cell augmenter. This allowed the smoke to mix with the augmentation air prior to sampling.

Visible emission measurements, based on visible smoke plume opacities determined by an observer certified by the State of California, Air Resources Board, were made simultaneously with most of the smoke number runs. Plume opacities were measured and recorded based on the Ringelmann Scale, the accepted standard of the State of California for black and grey colored smoke plumes.

Finally, several test runs were made to determine the mass distribution of the jet engine exhaust aerosol. Data were obtained at the top of the test cell stack using industrial particle-sizing equipment. This equipment included an in-stack cascade impactor and a screen-type, in-stack diffusion classifier.

Testing locations included NAVAIREWORKFAC North Island, NAS Miramar, and NAS Lemoore. Testing at NAVAIREWORKFAC North Island was conducted in an engine test facility, Test Cell 19 (Figure 2.2). Testing at NAS Miramar was conducted in Test Cell A, Figure 2.3. NAS Lemoore testing was conducted on an open-air jet engine test stand. The specific engines tested at each of these facilities are given in the next section.

3.0 RESULTS AND DISCUSSION

Method 5 source testing took place at NAVAIREWORKFAC North Island and NAS Miramar. Average particulate concentration results are presented in Tables 3.1 through 3.3 and again in Figures 3.1 through 3.6. Because emission regulations presently contain particulate concentrations corrected to 12% CO2, results are given in terms of particulate concentration at both stack conditions and at CO2 concentrations adjusted to 12%. For each condition, two concentrations are given: Front and Total. "Front" indicates the concentration based on just the particulate mass collected from the Method 5 probe nozzle to the sample filter. "Total" includes in the calculation of concentration the mass of condensible particulate material collected in the impingers. Each of these four concentrations were averaged for each engine type and power mode.

Table 3.1 gives the average particulate concentrations for J79-GE-8C/D and J79-GE-10B engines tested at NAVAIREWORKFAC North Island in Test Cell 19. (Ref. 5) Particulate concentrations average about 0.019 gr/dscf for the J79-GE-8C/D engines and 0.012 gr/dscf for the J79-GE-10B engines at stack CO2 concentrations. Figures 3.1 and 3.2 show the data in bar-graph form for particulate concentrations at stack CO2 and 12% CO2 concentrations, respectively. F404-GE-400 engine results are given in Table 3.2.(Ref. 4) Engine testing results from NAS Miramar are given in Table 3.3 for J79-GE-8D, TF30-P-414, and J52-P-6B engines.(Ref. 6). These data are plotted in Figures 3.3 through 3.6. The data indicates that total particulate concentration at stack CO2 remains fairly constant for each engine and is probably not a function of power mode. Since the CO2 concentration does vary with power mode, the adjusted (12%) particulate concentrations appear to vary with power mode. At Military power, the use of the ferrocene additive does not produce a significant concentration decrease.

Exhaust Plane analyzer tests were run on three different engine types: J79-GE-8D, J79-GE-10B, and F404-GE-400, all in the idle power mode. The J79 engines were tested at NAVAIREWORKFAC North Island in Test Cell 19. However, only the front half particulate mass was collected for these tests. The impingers were not analyzed for condensible particulate. For comparison purposes, an estimate of the total concentration was calculated by examining the relationship between the front half and total mass values for the Method 5 runs. Table 3.4 lists the average mass ratios obtained from each of the Method 5 sample runs for the J79-GE-8D, J79-GE-10B, and F404-GE-400 engines, along with their standard deviations as indications of spread. The idle ratios were used to calculate expected total concentrations for the J79-GE-8C/D and J79-GE-10B engines in Table 3.5.

The F404-GE-400 engines were tested at NAS Lemoore on a jet engine test stand.(Ref. 2) At this location, a Method 5 sampling train was used with the sampling nozzle placed in the engine exhaust plane. Front half and back half data were collected and used in the results. The particulate concentration data are presented in Table 3.6. All of the actual concentration values were measured quantities using particulate matter collected on the front half and back half portions of the sampling train.

Smoke Numbers and opacity (Ringelmann) measurements were made simultaneously with Method 5 particulate mass measurements for 52 runs which included seven different engines. A summary of the data collected is given in Table 3.7, including: engine information, Smoke Number, Ringelmann number, and particulate concentration. For comparison purposes, the Ringelmann numbers and Smoke Numbers were averaged by engine type and power mode. Table 3.8 lists the averages including two additional engine types which were not tested for particulate emissions. The averages indicate that Smoke Number and opacity generally increase as expected with increasing engine power. The actual magnitudes, however, vary greatly for different engine types for a given power mode. The individual variation within an engine type is relatively much smaller, based on the standard deviations. The use of ferrocene as a smoke abatement fuel additive does result in lower average Smoke Numbers and lower opacities.

To determine if a correlation exists between Smoke Number and Method 5 particulate concentration, the data in Table 3.7 were examined using least-squares regression analysis. Paired data consisting of Smoke Number and either actual or adjusted Method 5 particulate concentration were tabulated and plotted in Figures 3.7 and 3.8, respectively. A computer-assisted analysis was made using linear, geometric, and exponential regression subroutines. Table 3.9 gives the results of the regression analysis. There appears to be no correlation between Smoke Number and particulate concentration based on the low correlation coefficients. As a matter of fact, Figure 3.7 indicates that the actual particulate concentration is fairly constant, regardless of smoke number. There is still some variation in particulate concentration, especially when adjusted to a 12% CO_2 concentration. But the variability does not seem to reflect a correlation between Smoke Number and particulate concentration. Stated another way, Smoke Number is not a reasonable indication of Method 5 particulate concentration.

Possible correlations between Smoke Number and Exhaust Plane particulate concentration were examined. Since the Exhaust Plane analyzer was only used during idle mode, direct comparisons were impossible. However, since the Method 5 concentration has been shown to not correlate with Smoke Number, then the relationship between Method 5 concentration and Exhaust Plane concentration would be useful.

Ordered pairs of Method 5 and Exhaust Plane concentrations were not available to conduct regression analysis. However, a statistical analysis using the comparison of sample means was possible. To accomplish this, all valid sample runs at idle were averaged, and the average, standard deviation, and number of sample runs were recorded. Table 3.10 lists the data for particulate concentrations at measured CO2. Table 3.11 list the data with particulate concentrations adjusted to 12% CO2. Table 3.12 again lists all of the data in the appropriate pairs for analysis. Each pair of averages was analyzed using the following method: Using the "F-test", a statistical analysis of variances, the standard deviations of each pair were compared for statistically significant differences. If there were significant differences, then further analysis was impossible. If, however, the standard deviations were not significantly different, then the "Student T-test", a statistical analysis of means, was used. This analysis tests for significant differences between a pair of means.

The results of these analyses are given in Table 3-13. There were no significant differences between Method 5 and Exhaust Plane averages in the J79-GE-8C/D and J79-GE-10B engines at measured CO2. The concentrations were significantly different after adjustment to 12% CO2 in the J79-GE-10B but not the J79-GE-8C/D engines. The F404-GE-400 data showed significant differences in standard deviations in most cases and could not be further analyzed. The one situation analyzed showed no significant difference between the means.

These results indicate that there is little difference between the Exhaust Plane analyzer and the Method 5 analyzer. A more exact relationship between the two analyzers is impossible to describe due to the small number of samples. A larger number of samples were not obtained because the engines tested were under tight production schedules. Since the Exhaust Plane analyzer and the Method 5 analyzer give similar results, there should be little correlation expected between the Exhaust Plane particulate concentration and Smoke Number.

These results imply that the Exhaust Plane analyzer, a relatively faster, and cheaper method of emission analysis than the Method 5 analyzer, may be useful in future determinations of particulate concentration. Considerable savings in fuel and manhours can be had if the Exhaust Plane analyzer is adopted for routine use. Further testing, using side-by-side simultaneous analysis is necessary to determine with greater confidence that the two analyzers give equivalent results.

As stated previously, Method 5 analysis for particulates is expensive and requires a large commitment of manpower and equipment each time a sample is taken. A simpler, quicker method of obtaining particulate concentration would be desirable. One method already suggested is the use of the Exhaust Plane analyzer. The time and money requirement here is not as large, but still considerable. Another analysis method is based on the observation that there is an apparent correlation between CO2 and particulate concentration. This correlation was observed in a multivariate statistical analysis using a wide variety of parameters.(Ref 1) The results indicated, in part, that there was some correlation between CO2 concentration and particulate concentration for particular engines types, especially in the idle mode. A summary of the data is presented in Table 3.14. Analysis for CO2 is simple and quick, so this would be an excellent way to obtain a rapid measurement of particulate concentration for a particular engine. The relationship between CO2 and particulate concentration has not yet been fully described. This correlation requires further refinement and examination. The statistical analysis used above considered just linear relationships. Higher order correlations may exist which are not yet known.

The size distribution of the exhaust aerosol from a J79-GE-8D engine was determined using an in-stack impactor and a diffusion battery.(Ref. 3) An average distribution was computed from the test runs and is presented in Table 3.15. The table gives both a listing of normalized concentrations and a cumulative log probability (% mass greater than...) listing. The normalized concentration distribution lists, by particle size interval, the particulate concentration, normalized for size interval width. Figure 3.9 is a distribution histogram of the concentration data. Normalizing the concentrations is useful because the ratio of area under a segment of the histogram to the total area is then equal to the fraction of mass in that particular size interval. Note that two peaks or "modes" are present in the distribution, making this a bimodal distribution. The smaller mode (at about 0.02 um) is probably due to combustion aerosols. The other mode (at about 0.2 um) is probably due to aerosols produced from degradation of engine parts, large fuel particles, lubrication oils, etc.

The cumulative log probability distribution in Table 3.15 is plotted in Figure 3.10. A line of best fit shows a slight "S" shape, also an indication of a bimodal distribution. This plot is useful to determine the percentage of mass smaller (or larger) than any given particle size. Note that 50% of the mass is less than .01 um diameter and 88% of the mass is less than 1.0 um diameter.

This distribution is an average for J79-GE-8D data, but it is probably a good estimate of the size distribution for other jet engines, since the mechanisms of aerosol generation are so similar. However, it is recommended that additional particle size information be collected. This information would be particularly useful in determining mechanisms for smoke abatement using the various fuel additives under investigation.

4.0 SUMMARY AND CONCLUSIONS

An extensive air sampling program was undertaken to measure the particulate emissions from various gas turbine (jet) engines used in military aircraft. The aim of the project was to correlate the results obtained using several different particulate emission sampling methods on various gas turbine (jet) engines and determine if other indirect measurement methods can be used to adequately determine particulate emissions. Direct measurements of particulate emissions were accomplished in stationary engine test facilities using two different analytical methods. These two methods were: particulate sampling with an EPA Method 5 analyzer, and particulate sampling with an Exhaust Plane analyzer. Also, several methods of indirect measurement were used. Indirect measurements were made for: Smoke Number, and Ringelmann Number.

The following conclusions were drawn from the study. First, there was little or no correlation between Smoke Number and particulate concentration measured with the Method 5 analyzer. This observation was extended to conclude that there was little or no correlation between Smoke Number and particulate concentration measured with the Exhaust Plane analyzer. Second, there was good agreement between results from the Method 5 analyzer and the Exhaust Plane analyzer, indicating that they may be equivalent samplers. Third, CO_2 concentration was found to be a possible indirect indicator of particulate concentration. It was recommended that further examination of this method of indirect measurement be undertaken. Finally, the exhaust aerosol exhibited a bimodal mass distribution with 50% of the mass less than 0.1 um diameter and 88% of the mass less than 1.0 um diameter.

REFERENCES

1. "Draft Report on Statistical Analysis of Jet Engine Test Cell Emission Data", Draft Report to Aircraft Environmental Support Office, York Research Consultants, Denver, Colorado, undated.

2. "Gaseous and Particulate Emissions Test Program Naval Air Station Lemoore F404-GE-400 Test Stand Lemoore, California", Prepared for Aircraft Environmental Support Office, YRC Report No. 1-7135-06, York Research Consultants, Denver, Colorado, December 6, 1982.

3. Lundgren, D. A., "Measurement of Jet Engine Particle Size Distribution Using an In-stack Diffusion Classifier", AESO Report No. 110-02-81, Aircraft Environmental Support Office, San Diego, California, November 1981.

4. "Particulate Emissions Test Program F404-GE-400 Jet Engine Test Cell # 19 Building 397 Naval Air Rework Facility North Island San Diego, California", AESO Report No. 110-02-82, Aircraft Environmental Support Office, San Diego, California, April 1982.

5. "Particulate Emissions Test Program Jet Engine Test Cell 19 Building 397 Naval Air Rework Facility North Island San Diego, California", Volume 1, AESO Report No. 110-01-81, Aircraft Environmental Support Office, San Diego, California, October, 1981.

6. "Particulate Emissions Test Program Turbofan Jet Engine Test Cell Facility Cell A, Building 545 Naval Air Station Miramar San Diego, California", Volume 1, AESO Report No. 110-01-82, Aircraft Environmental Support Office, San Diego, California, March 1982.

Table 3.1

Summary of Method 5 Test Results
NAVAIREWORKFAC North Island Test Cell 19
J79-GE-8C/D and J79-GE-10B Engines

Engine	Mode	# of Tests	Particulate Concentration (gr/DSCF) Front(1)	at 12%(3)	Total(2)	at 12%
J79-GE-8C/D	Military	10 (4)	0.016	0.170	0.019	0.250
"	Mil.(w/Ferr.)	12	0.013	0.170	0.024	0.304
"	30% Thrust	10 (5)	0.012	0.307	0.016	0.354
"	Idle	7 (6)	0.010	0.229	0.017	0.385
J79-GE-10B	Military	5	0.006	0.070	0.010	0.116
"	30% Thrust	7	0.006	0.144	0.010	0.234
"	Idle	6	0.008	0.170	0.015	0.336

(1)- Mass collected on "front half" of sampling train only. That is, no particulate mass was measured beyond the filter (such as condensibles).

(2)- Total mass collected in entire sampling train including condensibles.

(3)- Particulate mass concentration when CO_2 is adjusted from the actual measured concentration to a concentration of 12%.

(4)- Test #2 omitted from averages.

(5)- Tests #9 and 10 omitted from averages.

(6)- CO_2 value for Test #27 omitted.

Table 3.2

Summary of Method 5 Test Results
NAVAIREWORKFAC North Island Test Cell 19
F404-GE-400 Engine

Mode	# of Tests	Particulate Concentration (gr/DSCF) Front	at 12%	Total	at 12%
Flight Idle	5	0.004	0.121	0.007	0.199
86% RPM-N2 (1)	2	0.002	0.032	0.006	0.094
IRP	4	0.004	0.053	0.005	0.070

(1)- Core speed based on 4000' altitude chart for IRP.

Table 3.3

Summary of Method 5 Test Results
Miramar Test Cell A
J79-GE-8D, TF30-P-414, and J52-P-6B Engines

Engine	Mode	# of Tests	Particulate Concentration (gr/DSCF) Front	at 12%	Total	at 12%
J79-GE-8D S/N 401117	Military	6 (1)	0.013	0.148	0.023	0.250
"	Mil.(w/Ferr.)	2 (2)	0.008	0.096	0.012	0.132
TF30-P-414 S/N 679457	Military	4	0.003	0.050	0.006	0.086
"	85% RPM	5	0.004	0.115	0.008	0.217
"	Idle	5	0.004	0.135	0.008	0.262
TF30-P-414 S/N 695016	Military	1	0.004	0.061	0.005	0.078
"	85% RPM	1	0.006	0.146	0.006	0.163
"	Idle	1	0.002	0.059	0.004	0.122
J52-P-6B S/N 649859	Military	3	0.008	0.124	0.013	0.207
"	Mil.(w/Ferr.)	3	0.006	0.094	0.010	0.163
"	85% RPM	4	0.009	0.226	0.013	0.335
"	Idle	5	0.009	0.327	0.014	0.498

(1)- Particulate data from Test 1 omitted from averages.
(2)- Test 23 omitted from average.

Table 3.4

Mass Ratios From
Method 5 Source Test Results
Mass Collected On Front Half / Total Mass Collected

Engine	Mode	Ratio Front Half / Total		# of Tests	Standard Deviation
J79-GE-8C/D	Idle	0.608	(1)	7	0.138
J79-GE-8C/D	30%	0.769	(1)	10	0.108
J79-GE-8C/D	Military	0.613	(1)	10	0.215
J79-GE-8C/D	Mil.(w/ Ferrocene)	0.582	(1)	12	0.147
J79-GE-10B	Idle	0.497	(1)	6	0.102
J79-GE-10B	30%	0.574	(1)	7	0.153
J79-GE-10B	Military	0.607	(1)	5	0.062
F404-GE-400	Flight Idle	0.653	(2)	5	0.090
F404-GE-400	86%	0.375	(2)	2	0.172
F404-GE-400	IRP	0.689	(2)	4	0.137

(1)- Based on NAVAIREWORKFAC North Island Test Cell 19 data (Ref. 5)

(2)- Based on NAVAIREWORKFAC North Island Test Cell 19 data (Ref. 4)

Table 3.5

Exhaust Plane Analyzer Data
NAVAIREWORKFAC North Island, Test Cell 19
All Measurements in Idle Mode

Engine	Serial No.	Particulate Concentration (gr/DSCF) Front	at 12%	Total(1)	at 12%
J79-GE-8D	401270	0.012	0.082	0.019	0.135
J79-GE-8D	401851	0.026	0.186	0.043	0.306
J79-GE-8D	421761	0.011	0.079	0.018	0.130
J79-GE-10B	448017	0.008	0.059	0.017	0.118
J79-GE-10B	433656	0.008	0.054	0.015	0.109
J79-GE-10B	433305	0.005	0.036	0.010	0.073
BLANK	------	0.001	0.004	-------	-------
BLANK	------	0.000	0.000	-------	-------
J79-GE-10B	448194	0.005	0.035	0.010	0.071
J79-GE-10B	433708	0.005	0.037	0.010	0.073
J79-GE-10B	433674	0.003	0.020	0.006	0.040

(1)- Total mass estimated by multiplying front half mass by a correction factor. This factor was calculated based on the ratio of front half mass to total mass ratios calculated in Table 3.4.

Table 3.6

Exhaust Plane Analyzer Data Summary
F404-GE-400, NAS Lemoore
Ground Idle Power Mode

Engine S/N	Front or Total?	Particulate Concentration (gr/DSCF) Actual CO2 (1)	1% CO2	12% CO2
310031	Front	0.027	0.017	0.206
"	Total	0.053	0.034	0.404
310043	Front	0.018	0.012	0.141
"	Total	0.042	0.028	0.339
310091	Front	0.015	0.009	0.109
"	Total	0.029	0.018	0.217
310049	Front	0.013	0.008	0.096
"	Total	0.027	0.017	0.207

(1)- Actual CO_2 value is average of three runs.

Table 3.7

Summary of Test Data
Smoke Number, Ringelmann Number, and
Method 5 Particulate Concentration

Engine	Mode	Smoke Number	Ringelmann Number	Particulate Concentration (gr/DSCF) Stack CO2	12% CO2
J79-GE-8D	Military	76.9	2 1/2	0.029	0.335
S/N 421841	Military	77.0	----	0.061	1.082
"	Mil.(w/Ferr.)	53.6	1 1/4	0.055	0.771
"	Mil.(w/Ferr.)	53.7	1 1/4	0.034	0.457
"	Mil.(w/Ferr.)	53.3	1 1/4	0.045	0.526
"	30% Thrust	67.7	2 1/4	0.016	0.435
"	30% Thrust	66.0	2 1/4	0.023	0.624
"	30% Thrust	62.9	2	0.015	0.385
"	Idle	40.4	----	0.031	1.057
"	Idle	41.5	3/4	0.040	1.037
"	Idle	42.4	3/4	0.011	0.241
"	Idle	41.8	1/2	0.015	0.311
J79-GE-8C	Military	68.0	2 3/4	0.024	0.291
S/N 401123	Military	67.9	2 3/4	0.009	0.113
"	Mil.(w/Ferr.)	40.9	1	0.010	0.110
"	Mil.(W/Ferr.)	43.6	1	0.005	0.062
"	Idle	37.2	1/2	0.024	0.558
"	Idle	37.3	1/2	0.014	0.322
J79-GE-8D	Military	76.3	2 3/4	0.025	0.283
S/N 401607	Military	77.6	2 1/2	0.029	0.342
"	Mil.(w/Ferr.)	54.3	1	0.028	0.375
"	Mil.(w/Ferr.)	54.6	1 1/4	0.020	0.254
"	Mil.(w/Ferr.)	54.1	1 1/4	0.019	0.236
"	30% Thrust	63.9	2 1/4	0.016	0.345
"	30% Thrust	62.3	2 1/4	0.023	0.477
"	30% Thrust	63.2	2 1/4	0.014	0.293
"	30% Thrust	64.2	2 1/4	0.012	0.260
"	Idle	34.9	1/4	0.028	0.614
"	Idle	34.7	1/4	0.018	0.401
J79-GE-8D	Military	76.5	2 3/4	0.017	0.187
S/N 421252	Military	77.2	3	0.026	0.274
"	Mil.(w/Ferr.)	52.3	1	0.015	0.158
"	Mil.(w/Ferr.)	50.9	1	0.016	0.209
"	Mil.(w/Ferr.)	51.7	1 1/4	0.020	0.213
"	Idle	35.4	3/4	0.012	0.250

Table 3.7 (continued)

Summary of Test Data
Smoke Number, Ringelmann Number, and
Method 5 Particulate Concentration

Engine	Mode	Smoke Number	Ringelmann Number	Particulate Concentration (gr/DSCF) Stack CO2	12% CO2
J79-GE-10B	Military	32.5	1/2	0.012	0.117
S/N 433959	Military	32.0	1/2	0.012	0.172
"	30% Thrust	8.2	0	0.014	0.342
"	30% Thrust	6.5	----	0.010	0.227
"	30% Thrust	5.0	----	0.007	0.149
"	30% Thrust	4.5	----	0.020	0.472
"	Idle	15.6	0	0.011	0.245
"	Idle	11.7	----	0.017	0.396
J79-GE-10B	Military	33.1	1/2	0.007	0.078
S/N 448297	Military	35.6	1/2	0.010	0.115
"	30% Thrust	4.1	0	0.005	0.115
"	30% Thrust	4.6	0	0.005	0.122
"	Idle	19.5	0	0.016	0.321
"	Idle	21.7	0	0.016	0.390
J70-GE-10B	Military	34.5	1/2	0.009	0.098
S/N 433780	Idle	16.2	0	0.017	0.320
"	Idle	15.2	0	0.016	0.344

Table 3.8

Smoke Number Data Summary
Average Smoke Numbers Obtained from
SAE Design Smoke Sampler

Engine	Mode	Ringelmann Number	# of Samples	Smoke Number Average	Smoke Number Standard Deviation
J79-GE-8C/D	Idle	1/2	9	38.4	3.14
J79-GE-8C/D	30% Thrust	2 1/4	9	62.8	3.39
J79-GE-8C/D	Military	2 3/4	9	76.1	3.09
J79-GE-8C/D	Mil.(w/Ferr.)	1	11	51.2	4.60
J79-GE-10B	Idle	0	6	16.7	3.51
J79-GE-10B	30% Thrust	0	6	5.5	1.57
J79-GE-10B	Military	1/2	5	33.5	1.48
F404-GE-400	Flight Idle	0	2	2.3	0.00
F404-GE-400	86% RPM	0	1	2.0	----
F404-GE-400	IRP	0	2	10.1	0.28
J52-P-6B	Idle	0	2	25.4	2.90
J52-P-6B	Military	2	2	56.1	0.28
J52-P-6B	Mil.(w/Ferr.)	1/4	2	30.3	2.40
TF30-P-414	Idle	---	3	7.8	1.25
TF30-P-414	85%	---	3	36.3	1.29
TF30-P-414	Military	---	2	34.4	1.63

Table 3.9

Determination of Correlation Between
Smoke Number Measurements and
Particulate Concentration Obtained From
Method 5 Analysis (1)

Engine	Actual or 12% CO2	Regression Analysis Method	Correlation Coefficient
All	Actual	Linear	0.44
All	Actual	Geometric	0.50
All	Actual	Exponential	0.50
All	12%	Linear	0.19
All	12%	Geometric	0.20
All	12%	Exponential	0.21
J79-GE-8C/D	Actual	Linear	-0.14
J79-GE-8C/D	Actual	Geometric	0.09
J79-GE-8C/D	Actual	Exponential	0.19
J79-GE-8C/D	12%	Linear	0.08
J79-GE-8C/D	12%	Geometric	0.04
J79-GE-8C/D	12%	Exponential	0.02
J79-GE-10B	Actual	Linear	-0.34
J79-GE-10B	Actual	Geometric	0.10
J79-GE-10B	Actual	Exponential	0.30
J79-GE-10B	12%	Linear	-0.42
J79-GE-10B	12%	Geometric	0.26
J79-GE-10B	12%	Exponential	0.45
F404-GE-400	Actual (1)	Linear	0.42

(1)- Correlation determined by least-squares fit using linear, geometric, and exponential regression equations.

(2)- Statistical analysis of 56 F404-GE-400 engine runs (Ref. 1).

Table 3.10

Particulate Concentration
Averages and Standard Deviations
In Grains/DSCF at Measured CO2 -Idle Mode

For: Method 5 Train (M-5)
Exhaust Plane Analyzer (E-P)

Engine	Sampler	# of Samples	Particulate Concentration (gr/DSCF) Average	Standard Deviation
J79-GE-8C/D	M-5 (front)	7	0.010	0.0042
J79-GE-8C/D	M-5 (total)	7	0.017	0.0066
J79-GE-8C/D	E-P (front)	3	0.016	0.0085
J79-GE-8C/D	E-P (total)	3	0.027	0.0140
J79-GE-10B	M-5 (front)	6	0.008	0.0023
J79-GE-10B	M-5 (total)	6	0.016	0.0023
J79-GE-10B	E-P (front)	6	0.006	0.0018
J79-GE-10B	E-P (total)	6	0.011	0.0040
F404-GE-400	M-5 (front)	5	0.005	0.0009
F404-GE-400	M-5 (total)	5	0.007	0.0019
F404-GE-400	E-P (front)	4	0.018	0.0063
F404-GE-400	E-P (total)	4	0.038	0.0120

Table 3.11

Particulate Concentration
Averages and Standard Deviations
In Grains/DSCF at 12% CO_2 -Idle Mode

For: Method 5 Train (M-5)
Exhaust Plane Analyzer (E-P)

Engine	Sampler	# of Samples	Particulate Concentration (gr/DSCF) Average	Standard Deviation
J79-GE-8C/D	M-5 (front)	7	0.230	0.1045
J79-GE-8C/D	M-5 (total)	7	0.385	0.1478
J79-GE-8C/D	E-P (front)	3	0.116	0.0609
J79-GE-8C/D	E-P (total)	3	0.190	0.1002
J79-GE-10B	M-5 (front)	6	0.170	0.0622
J79-GE-10B	M-5 (total)	6	0.336	0.0554
J79-GE-10B	E-P (front)	6	0.040	0.0129
J79-GE-10B	E-P (total)	6	0.081	0.0284
F404-GE-400	M-5 (front)	5	0.121	0.0235
F404-GE-400	M-5 (total)	5	0.199	0.0241
F404-GE-400	E-P (front)	4	0.138	0.0489
F404-GE-400	E-P (total)	4	0.292	0.0961

Table 3.12

Particulate Concentration Data Summary
Exhaust Plane and Method 5 Analyzers

J79-8 = J79-GE-8C/D Engines
J79-10 = J79-GE-10B Engines
F404 = F404-GE-400 Engines

Engine	Sampler	# of Samples	Particulate Concentration (gr/DSCF) Average	Standard Deviation	Measured or 12% CO2
J79-8 (front)	E-P	3	0.016	0.0085	Measured
	M-5	7	0.010	0.0042	
J79-8 (total)	E-P	3	0.027	0.0140	Measured
	M-5	7	0.017	0.0066	
J79-8 (front)	E-P	3	0.116	0.0609	12%
	M-5	7	0.230	0.1045	
J79-8 (total)	E-P	3	0.190	0.1002	12%
	M-5	7	0.385	0.1478	
J79-10 (front)	E-P	6	0.006	0.0018	Measured
	M-5	6	0.008	0.0023	
J79-10 (total)	E-P	6	0.011	0.0040	Measured
	M-5	6	0.016	0.0023	
J79-10 (front)	E-P	6	0.040	0.0129	12%
	M-5	6	0.170	0.0622	
J79-10 (total)	E-P	6	0.081	0.0284	12%
	M-5	6	0.336	0.0554	
F404 (front)	E-P	4	0.018	0.0063	Measured
	M-5	5	0.005	0.0009	
F404 (total)	E-P	4	0.038	0.0120	Measured
	M-5	5	0.007	0.0019	
F404 (front)	E-P	4	0.138	0.0489	12%
	M-5	5	0.121	0.0235	
F404 (total)	E-P	4	0.292	0.0961	12%
	M-5	5	0.199	0.0241	

Table 3.13

Comparison of Averages
Exhaust Plane vs. Method 5 Analyzers
Using Analysis of Sample Means

Engine	Front Half or Total?	Measured CO2 or 12% ?	Insignificant Statistical Difference.	Averages Are Statistically Different.
J79-GE-8C/D	Front	Measured	YES	---
J79-GE-8C/D	Total	Measured	YES	---
J79-GE-8C/D	Front	12%	YES	---
J79-GE-8C/D	Total	12%	YES	---
J79-GE-10B	Front	Measured	YES	---
J79-GE-10B	Total	Measured	YES	---
J79-GE-10B	Front	12%	---	YES
J79-GE-10B	Total	12%	---	YES
F404-GE-400	Front	Measured	---	(1)
F404-GE-400	Total	Measured	---	(1)
F404-GE-400	Front	12%	YES	---
F404-GE-400	Total	12%	---	(1)

(1)- These sample variances are significantly different, cannot do comparison of sample means.

Table 3.14

Correlation of CO2 Concentration and
Actual Particulate Concentration
Using Linear Regression Analysis

Engine	Mode	# of Samples	Correlation Coefficient
J79-GE-8C/D	Idle	7	-0.62
J79-GE-8C/D	85% RPM	8	-0.10
J79-GE-8C/D	Military	15	-0.68
J79-GE-8C/D	Mil. (w/Ferro.)	12	-0.54
TF30-P-414	Idle	5	-0.84
TF30-P-414	85% RPM	6	-0.83
TF30-P-414	Military	6	0.56
J52-P-6B	Idle	5	-0.94
J52-P-6B	85% RPM	4	-0.07
J52-P-6B	Military	6	0.37
F404-GE-400	Idle	5	0.88
F404-GE-400	85% RPM	2	1.0
F404-GE-400	Military	4	0.68

Table 3.15

Particle Size Distribution
Results of an Average Distribution for
Gas Turbine Engine Exhaust

Particle Size Interval (micrometers)	Normalized Concentration dWT/V dLogD_p(mg/m^3)	% Mass Greater Than D_p
31 - 100	0.39	1.4
14 - 31	0.49	2.6
5.2 - 14	0.67	4.7
2.6 - 5.2	1.06	7.0
1.5 - 2.6	1.55	9.7
0.74 - 1.5	2.25	14.7
0.38 - 0.74	4.66	24.5
0.14 - 0.38	6.50	44.9
0.07 - 0.14	4.42	54.5
0.04 - 0.07	5.88	64.8
0.01 - 0.04	8.07	(100.0)

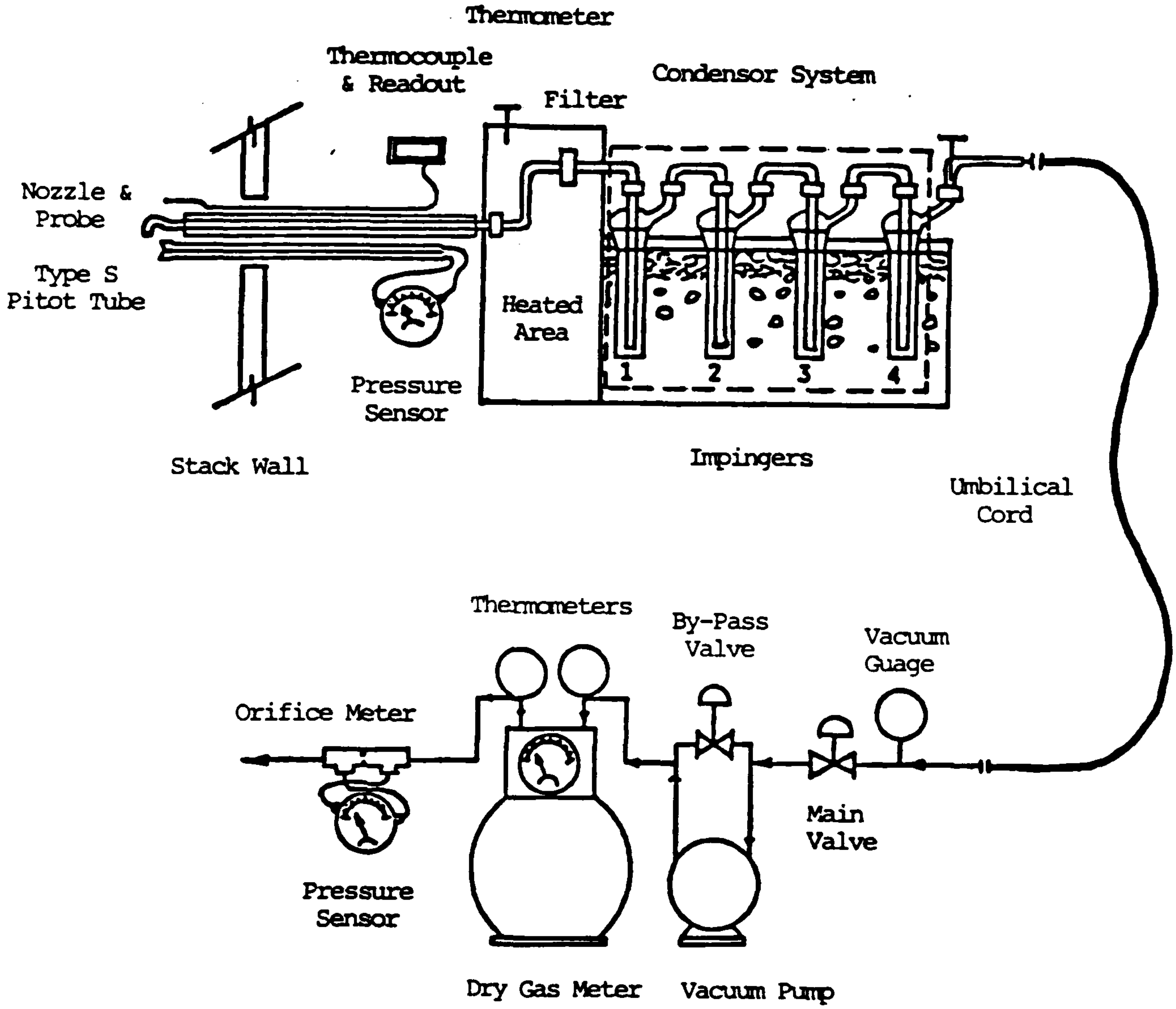

Figure 2.1 Schematic of Method 5 Sampling Train.

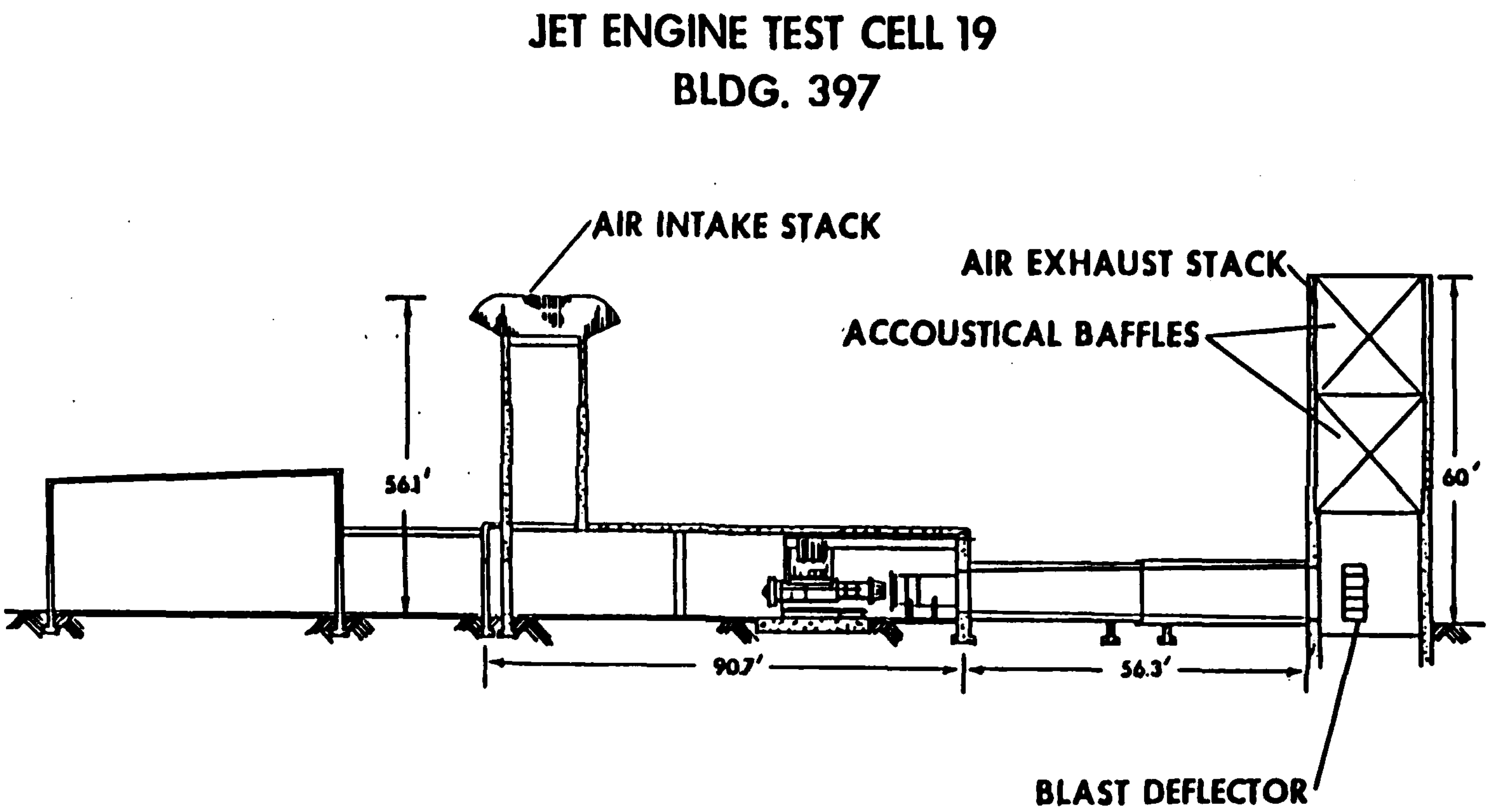

Figure 2.2 NAVAIREWORKFAC North Island Test Cell 19.

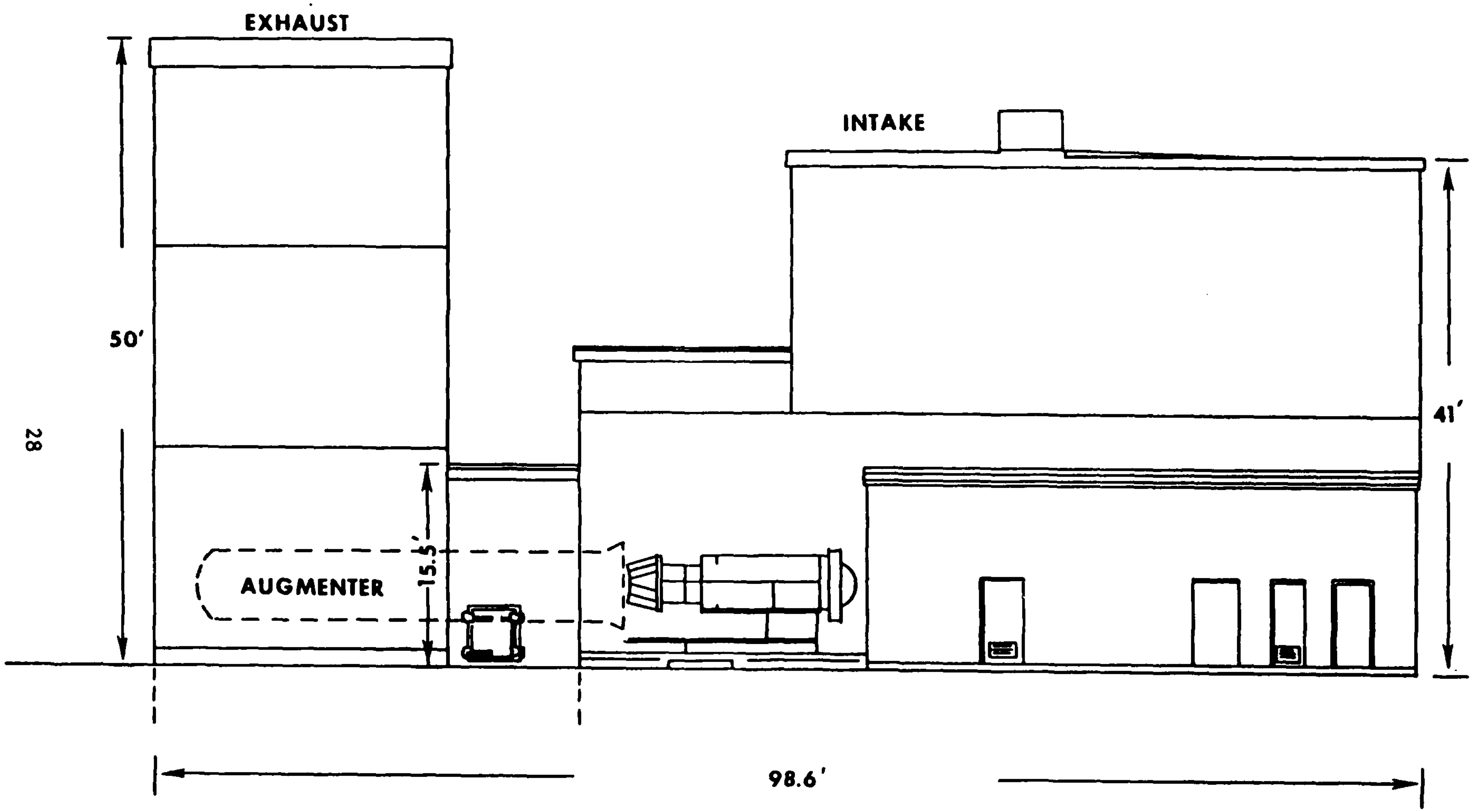

Figure 2.3 NAS Miramar A-Cell.

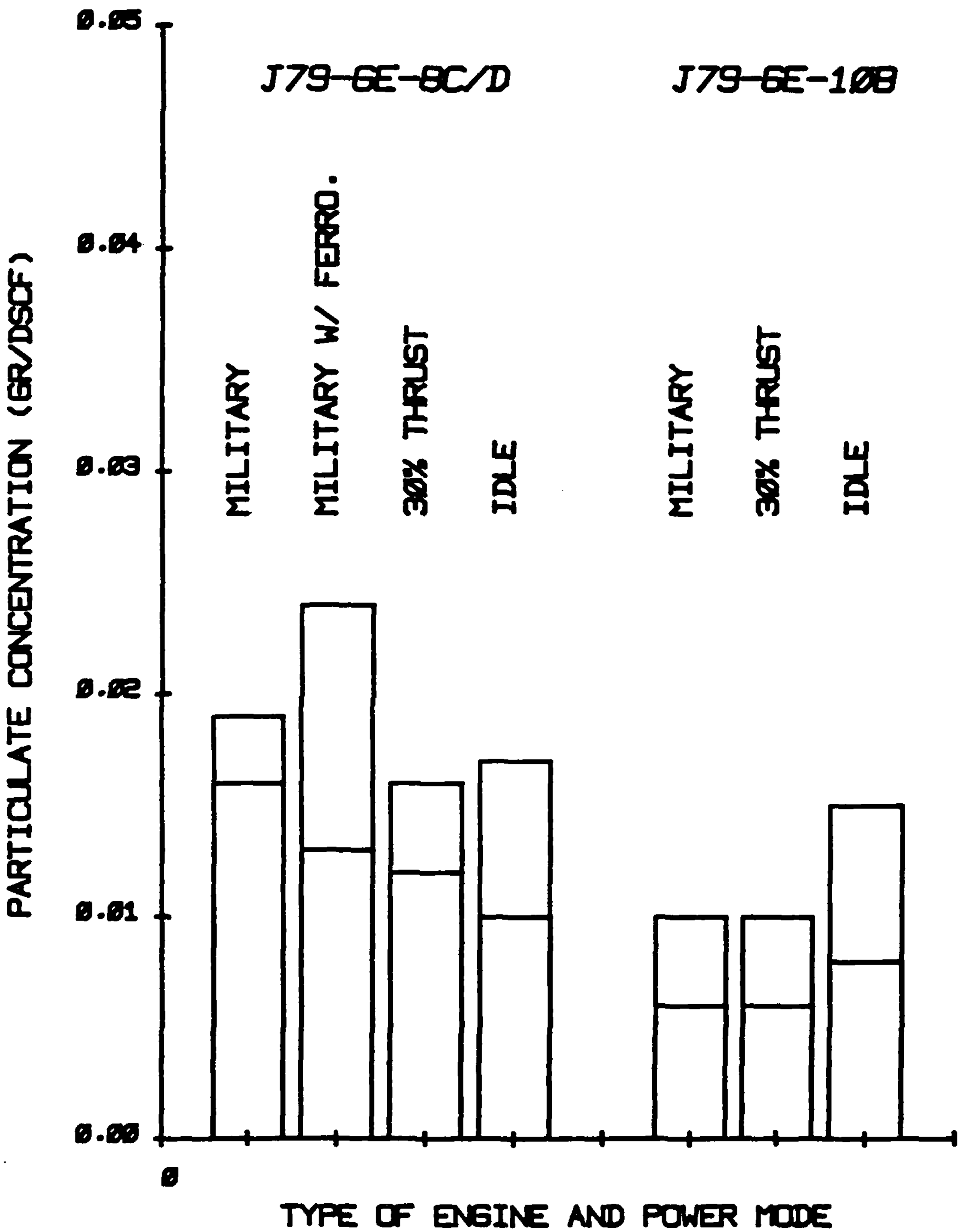

Figure 3.1 Particulate Concentrations for J79-GE-8C/D and J79-GE-10B Engines at NAVAIREWORKFAC North Island- at Measured CO2 Concentration.
(Lower segment of bar indicates front half concentration.)

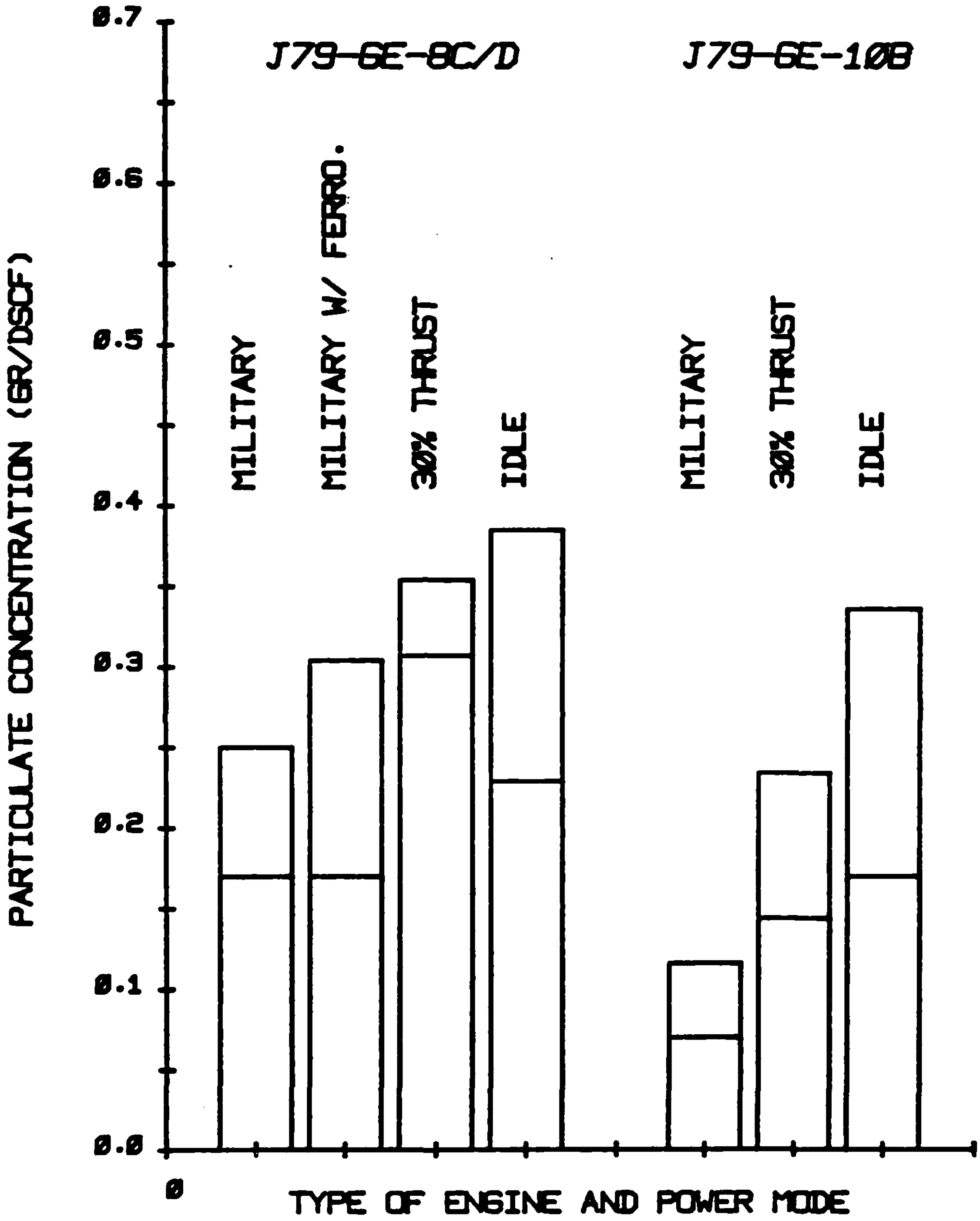

Figure 3.2 Particulate Concentrations for J79-GE-8C/D and J79-GE-10B Engines at NAVAIREWORKFAC North Island- at 12% CO_2 Concentration.
(Lower segment of bar indicates front half concentration.)

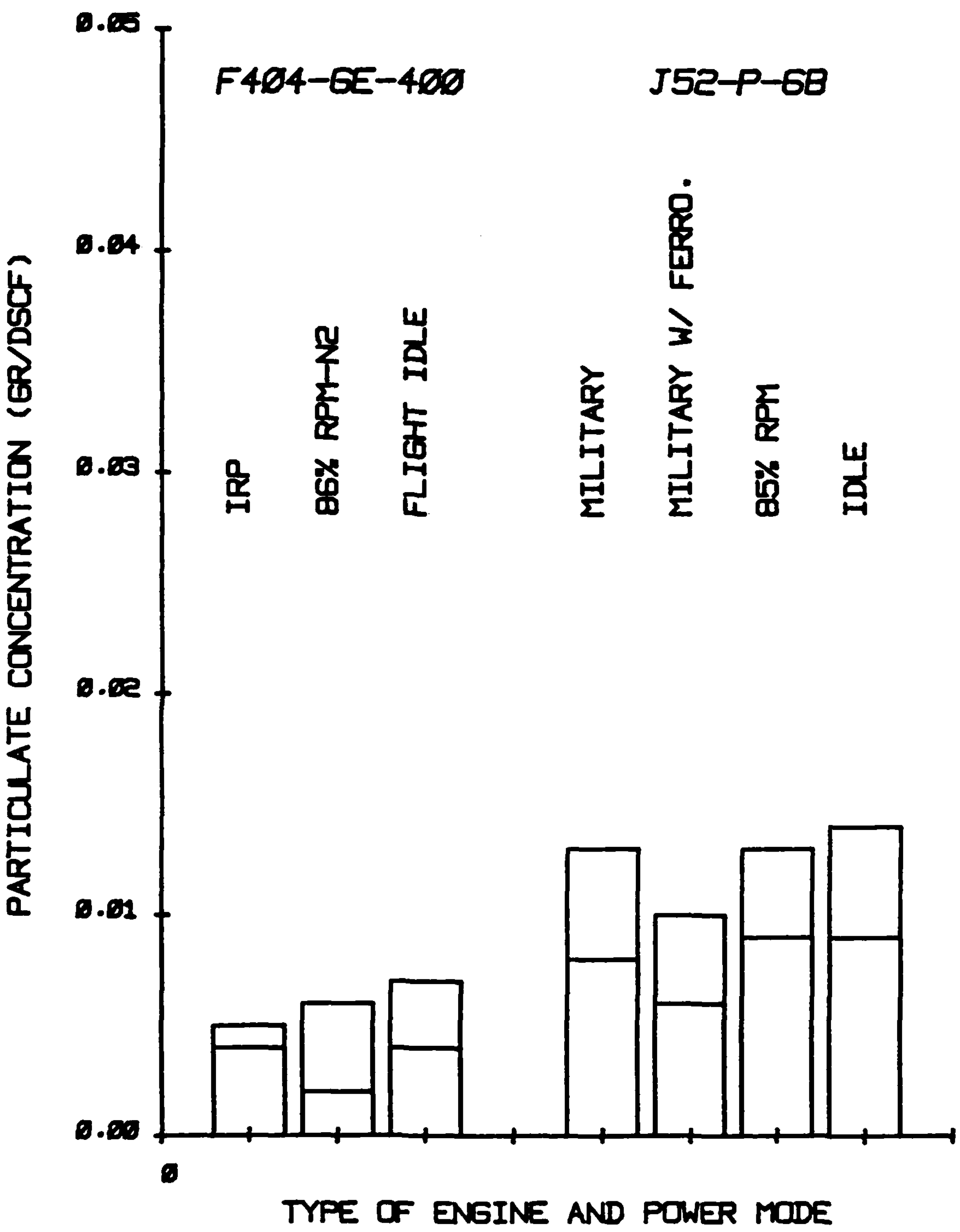

Figure 3.3 Particulate Concentrations for F404-GE-400 Engines at NAVAIREWORKFAC North Island and J52-P-6B Engines at NAS Miramar- at Measured CO2 Concentration. (Lower segment of bar indicates front half concentration.)

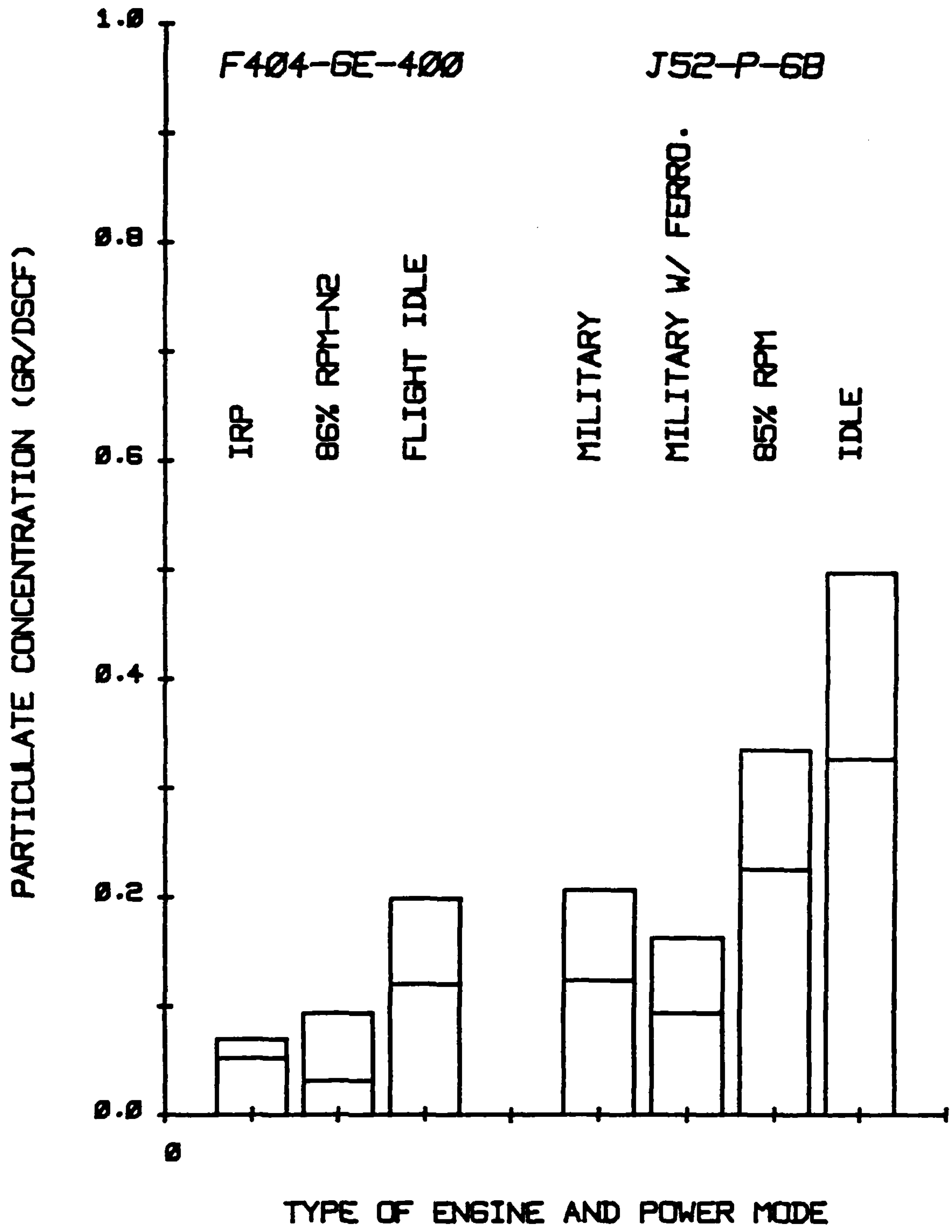

Figure 3.4 Particulate Concentrations for F404-GE-400 Engines at NAVAIREWORKFAC North Island and J52-P-6B Engines at NAS Miramar- at 12% CO_2 Concentration. (Lower segment of bar indicates front half concentration.)

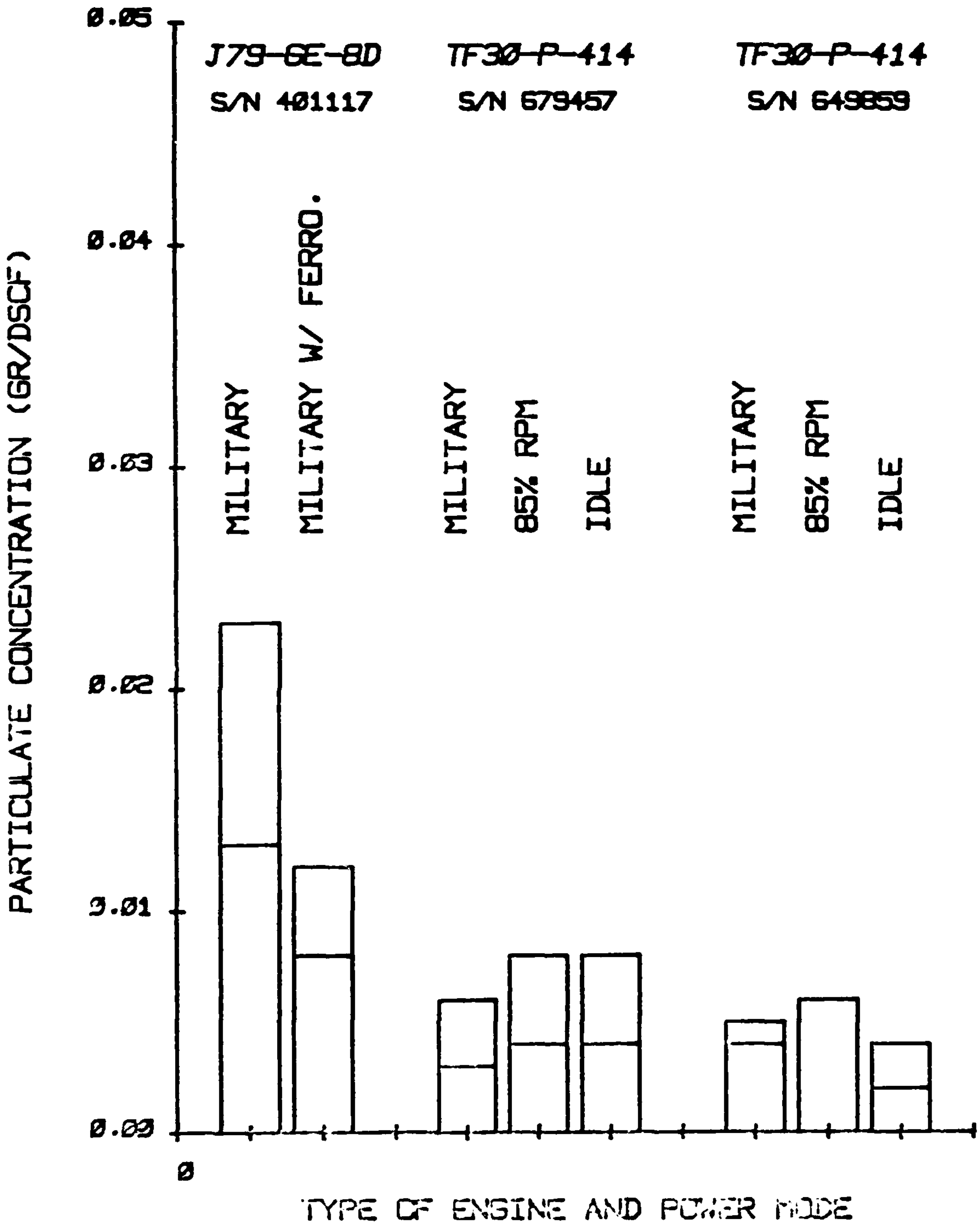

Figure 3.5 Particulate Concentrations for J79-GE-8D and TF30-P-414 Engines at NAS Miramar- at Measured CO2 Concentration. (Lower segment of bar indicates front half concentration.)

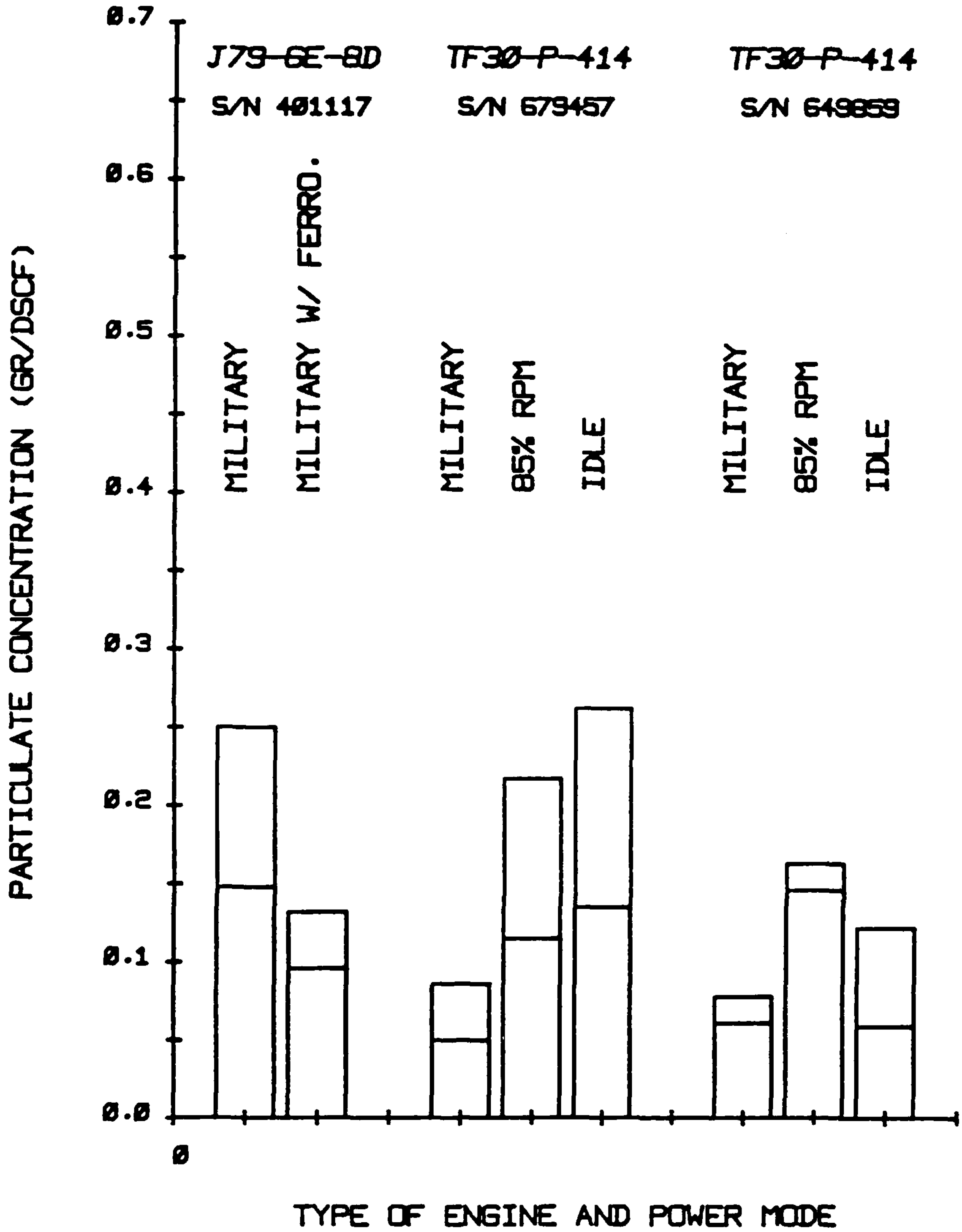

Figure 3.6 Particulate Concentrations for J79-GE-8D and TF30-P-414 Engines at NAS Miramar- at 12% CO2 Concentration. (Lower segment of bar indicates front half concentration.)

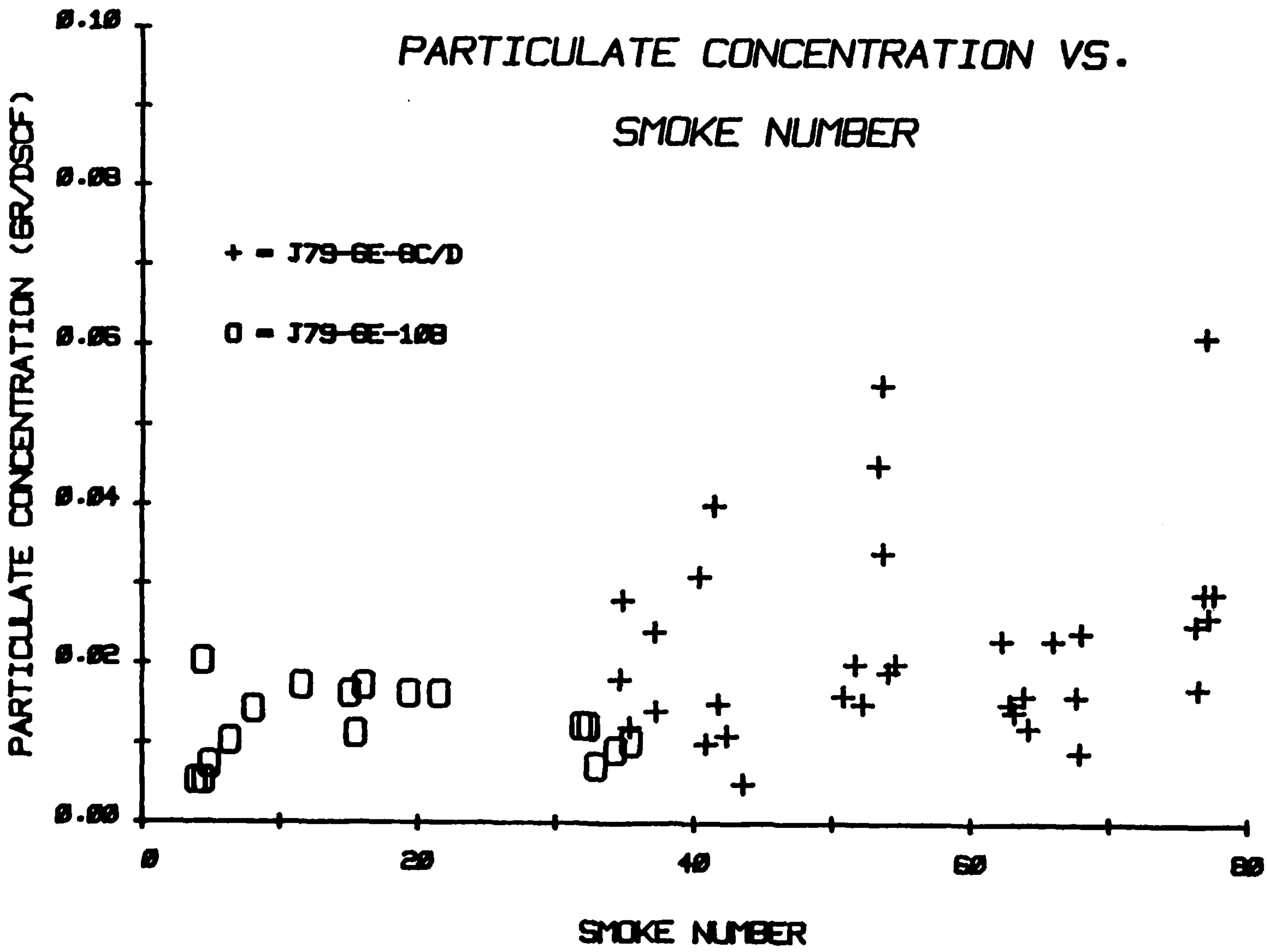

Figure 3.7 Particulate Concentration vs. Smoke Number for J79-GE-8C/D and J79-GE-10B Engines with Concentrations at Measured CO2 Concentration.

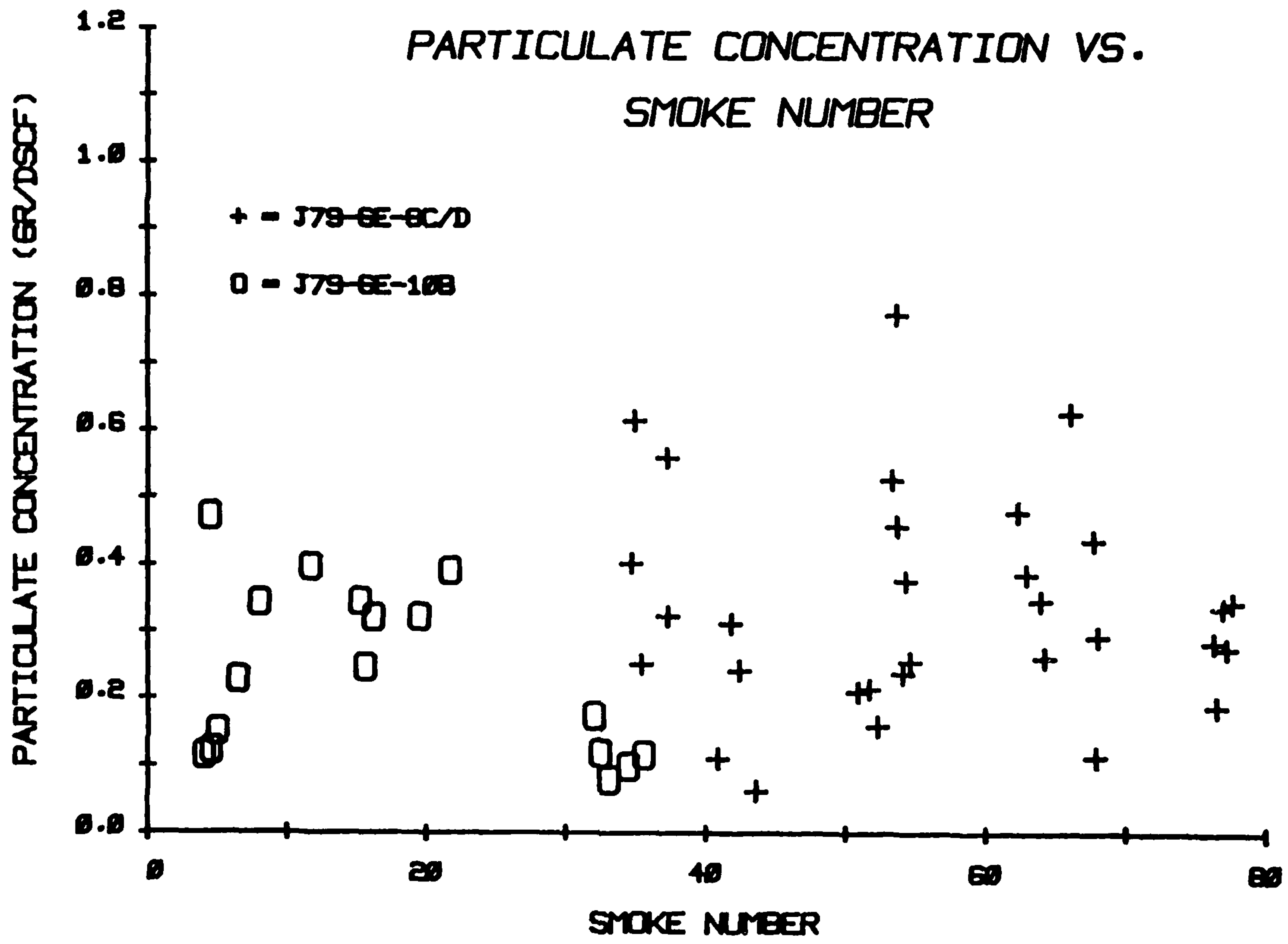

Figure 3.8 Particulate Concentration vs. Smoke Number for J79-GE-8C/D and J79-GE-10B Engines with Concentrations at 12% CO2 Concentration.

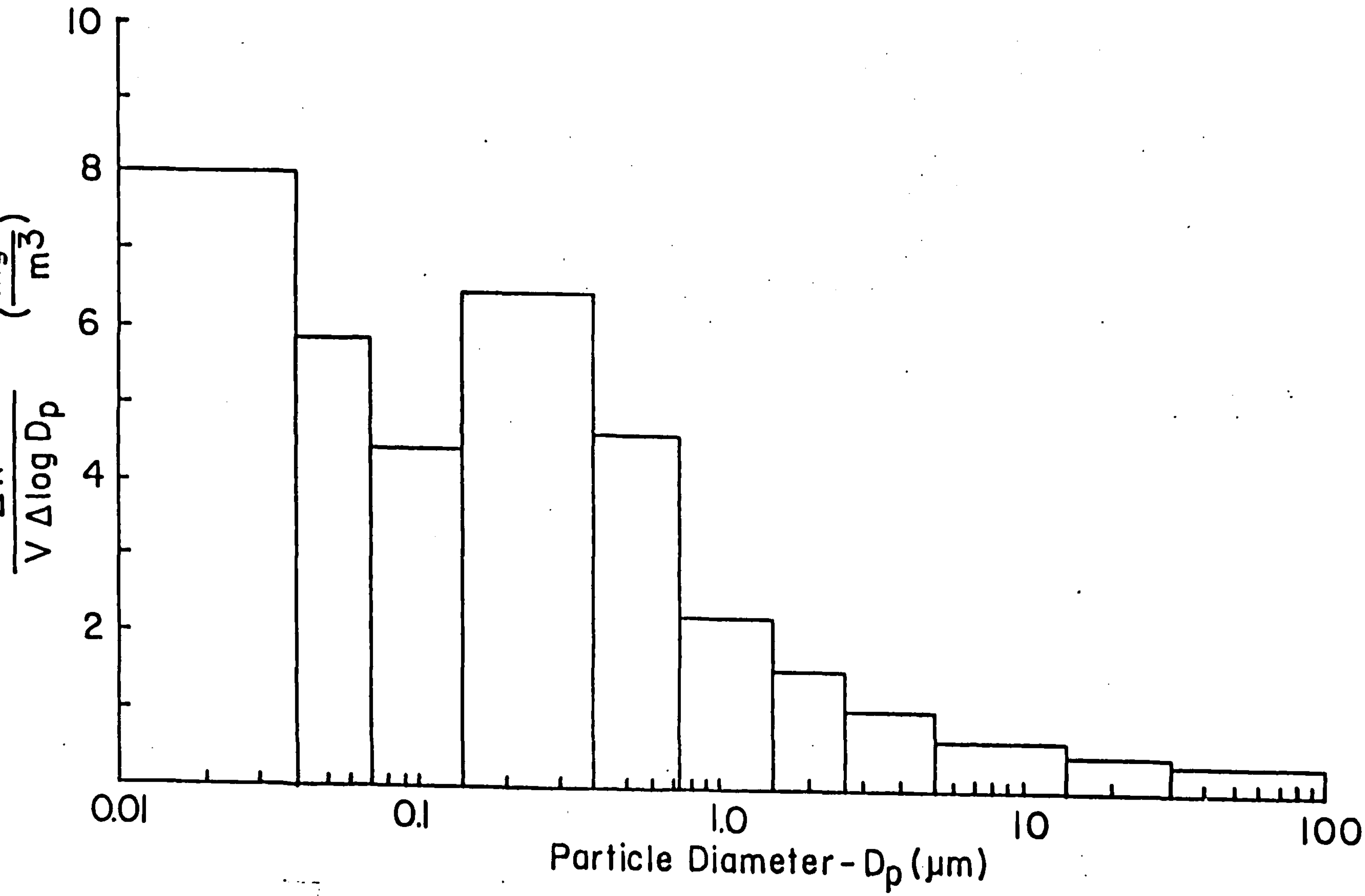

Figure 3.9 Normalized Histogram for the Average Particle Size Distribution. (Ref. 3)

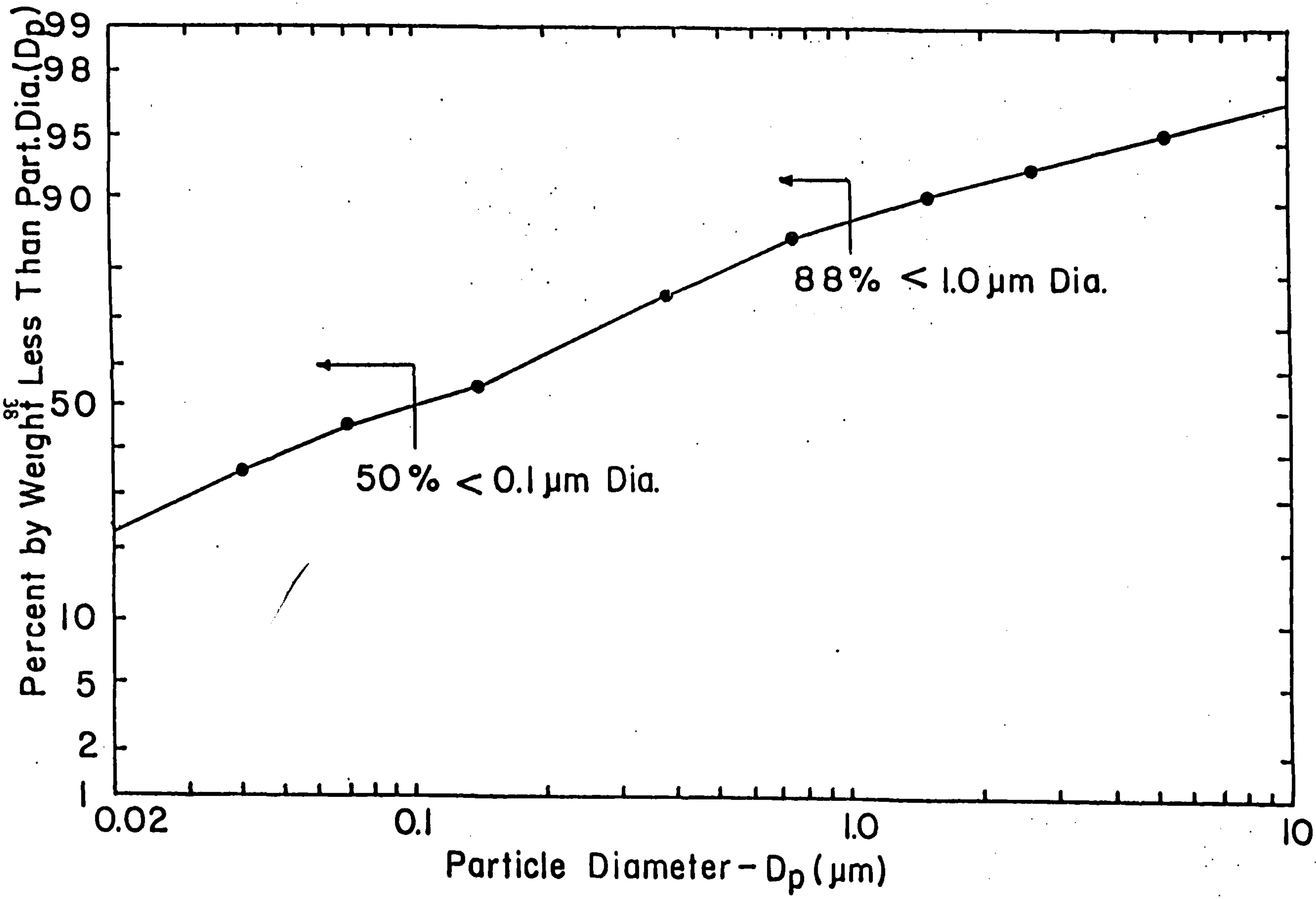

Figure 3.10 Cumulative Log Probability Plot for the Average Particle Size Distribution Data. (Ref. 3)