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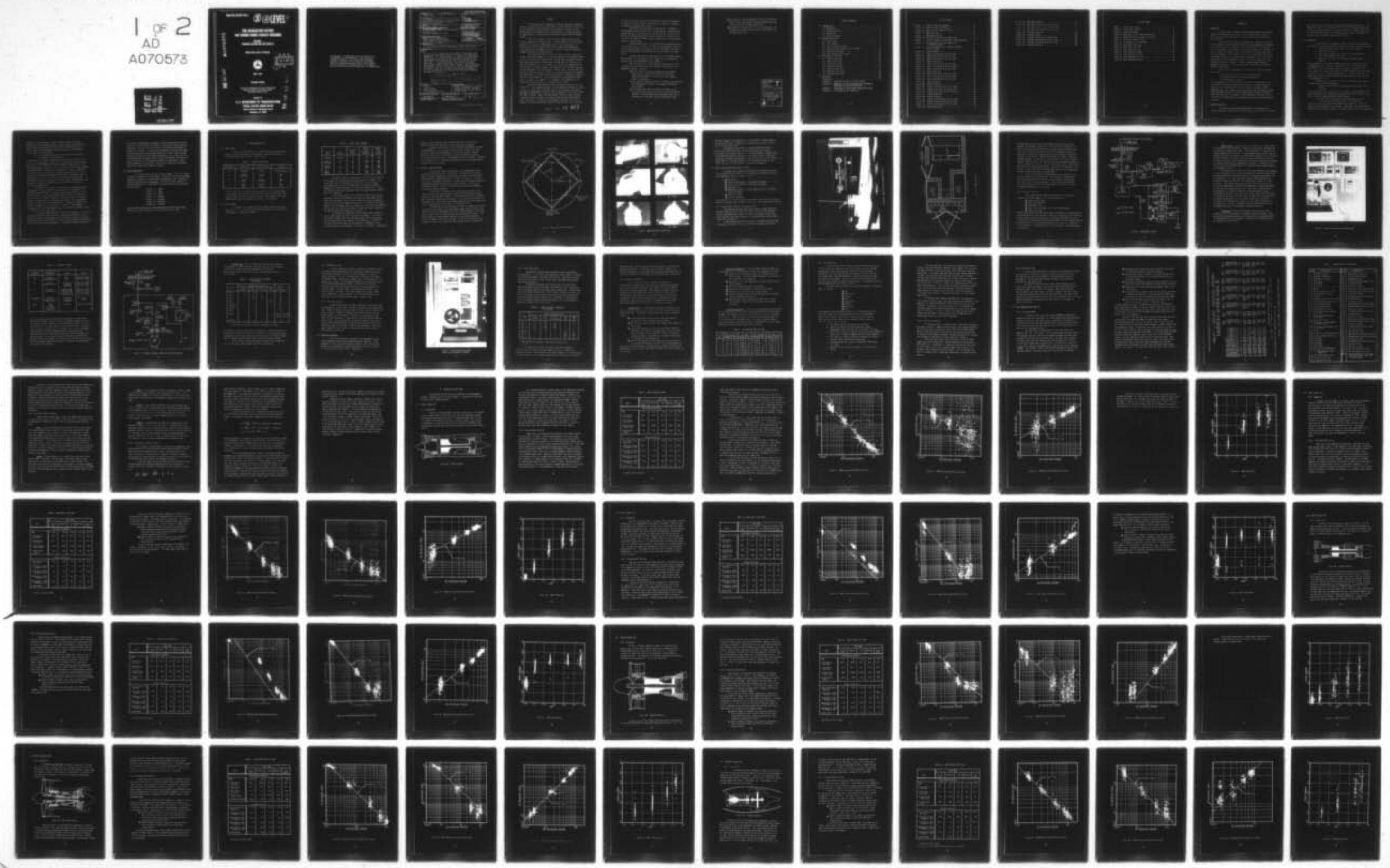

Report No. FAA-RD-78-56, I

LEVEL II

TIME DEGRADATION FACTORS FOR TURBINE ENGINE EXHAUST EMISSIONS

VOLUME I
PROGRAM DESCRIPTION AND RESULTS

Melvin Platt and E. R. Norster

MAY 1978

INTERIM REPORT

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16. Abstract

This is the first volume of an eight-volume interim report which documents the test data obtained in a study of turbine emission degradation. This volume contains an introduction to the program, a description of the test schedule, equipment, procedures, and data processing techniques, as well as a discussion of the test data itself. A total of 519 repetitious emission tests were conducted over a period of 22 months on units of the following engine types: JT8D-9, JT8D-7, JT3D-7, JT3D-3B, JT9D-3A, RB211-22B, and CF700-2D. Emissions of CO_2, CO, HC, NO, NO_x, and smoke were monitored, in addition to various engine operating parameters, over an eight-mode test cycle ranging from cold idle to take-off and back to hot idle.

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PREFACE

The turbine emission degradation study was conducted by Northern Research and Engineering Corporation (NREC) as prime contractor, and United Air Lines (UAL) as primary subcontractor, pursuant to Contract No. DOT FA74NA-1100 with the Federal Aviation Administration. Also participating as subcontractors in the study were Trans World Airlines (TWA) and Federal Express.

This interim report is being issued to document the test data which was obtained in the above study. A final report will be issued upon completion of an extensive degradation analysis of the test data. In addition to statistical analyses which have already been accomplished, Arnold Engineering Development Center will conduct an analysis employing mathematical models of engine operation.

The program was under the over-all direction of Mr. Melvin Platt of NREC, the Program Manager. Mr. Platt had responsibility for NREC efforts as well as coordination of NREC efforts with UAL, TWA, and Federal Express. Other major participants in the program for NREC were E. R. Norster, R. G. Hanson, M. Chandler, and I. P. Krepchin. Dr. Norster was responsible for the design of the sampling probes, the specifications of the test facility, and the development of test procedures. With Mr. Platt, he also guided the analysis of the test data. Mr. Hanson, with the assistance of Mr. Chandler, was responsible for all NREC field testing, while Mr. Krepchin was responsible for all data processing. Also participating in the program for NREC were T. A. Blatt, E. P. Demetri, M. J. Paradise, W. H. Robinson, R. D. Gryzbinski, D. B. Chouinard, C. E. DeLong, and S. D. Ham.

UAL efforts were performed under the over-all direction of L. C. "Tom" Ellis. Other major participants in the program for UAL were D. Center, F. Dilts, J. Gibson, and R. Johnson. Messrs. Dilts, Gibson, and Johnson operated and maintained the emission testing equipment for all tests of the UAL JT8D-7, JT3D-3B, JT3D-7, and JT9D engines, while Mr. Center designed the sampling probe attachments for these engines and was responsible for probe manufacture. In addition, acknowledgment should be given to Mr. R. Raymond, who coordinated special routings of UAL aircraft to San Francisco

for emission testing, and to the SFO mechanics of UAL who operated the aircraft during testing under the supervision of Messrs. P. Giampoli, P. Snowden, R. Sorenson, and R. Horn.

TWA efforts were coordinated by Gary Riedl. In addition, acknowledgment should be given to Mr. C. Doan, who was responsible for special routings of TWA aircraft for emission testing, as well as the MCI SFO maintenance personnel of TWA who operated the aircraft during testing of the JT8D-9 and RB211 engines, respectively, and assisted the program in numerous ways.

Federal Express efforts were coordinated by George Boller with the assistance of E. J. Prestia. In addition, acknowledgment should be given to the schedulers who routed the aircraft to Memphis for emission testing and the mechanics who operated the aircraft during the CF700 tests.

The designated Technical Representative of the Federal Express Administration for this program was Mr. Thomas Rust of the National Aviation Facilities Experimental Center (NAFEC).

NREC would also like to acknowledge the cooperation of other individuals and organizations who contributed to the success of the degradation program. They are:

- Don Seizinger of the Energy Research and Development Administration, Bartlesville Research Center, who coordinated the analysis of all the jet fuel samples taken in the program
- Dick Pfuntner of General Electric, Wilmington, Massachusetts, who provided specifications for the special CF700 fuel flow indicator
- Al Reinhardt, Don Eiler, Art Nelson and others at the Pratt and Whitney Aircraft Division of United Technologies Corporation, who provided engine performance data used in the analysis of the JT8D, JT3D, and JT9D engine types

- Tony Wassell of the Derby Engine Division of Rolls-Royce (1971) Limited, who provided engine performance data used in the analysis of the RB211 engine type
- Gene Martin of General Electric, Lynn, Massachusetts, who provided engine performance data used in the analysis of the CF700 engine type

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1. INTRODUCTION

1.1 BACKGROUND

In recent years, important federal legislation has been directed towards the improvement of air quality in the United States. Aircraft have been one source of pollutant emissions at which such legislation has been directed.

Section 231 of the Clean Air Amendments of 1970 (Ref 1) directed the Environmental Protection Agency (EPA) to establish appropriate standards for the emissions of air pollutants from aircraft engines. At the same time, Section 232 of the amendments directed the Department of Transportation (and, ultimately, the FAA) to prescribe regulations to insure compliance with all standards. Such standards were initially proposed as EPA Part 87 in December 1972 and final standards were promulgated in July 1973 (Ref 2). The availability of a comprehensive draft of "tentative regulations" was announced by the FAA in January, 1973 and a Special Federal Aviation Regulation concerning initial compliance with standards was published in December, 1973 (Ref 3).

Section 87.31, paragraph (e) of the aircraft emission standards states that

> "... each in-use aircraft gas turbine engine shall not exceed the level of emissions applicable to such engine when it was new."

As a consequence, to insure compliance, the FAA must be prepared to take into account the effect of engine operating time on aircraft emissions. Operating time for commercial aircraft can amount to between 2,500 and 3,000 hours per year. However, available emission data for aircraft turbine engines had been limited to a span of approximately 50 hours of operation. This report documents a program which was undertaken by the FAA to obtain information for commercial aircraft operating over a period of approximately one year.

1.2 PROGRAM OBJECTIVE

The objective of the program described in this report was to develop degradation factors for pollutant emissions of each class of aircraft gas-turbine engines over operating times between 2,500 and 3,000 hours. The degradation factors will provide a basis for the FAA to develop regulations which (1) insure compliance with the aircraft emission standards established by the EPA, and (2) provide for reasonable service times of the commercial aircraft fleet with respect to pollutant emissions.

1.3 METHODOLOGY

The development of degradation factors for turbine engine emissions over operating times between 2,500 and 3,000 hours implies several requirements:

1. Information from a large number of engines to provide statistical validity.
2. Heavy engine usage so that the hours may be accumulated in a reasonable amount of time.
3. Repetitious testing so that incremental changes may be observed.

These requirements dictated a methodology based upon the emission testing of installed engines in regularly scheduled service. This meant, among other things, that the EPA specification of conducting such tests on a thrust measuring test stand (see Subpart G of Ref 2) would not be satisfied. In addition, as will be indicated elsewhere in this report, other EPA specifications were not satisfied where they conflicted with the interests of the degradation testing.

Implementation of emission testing on installed aircraft engines involved several areas of development:

1. Sampling probes which could be positioned both quickly and securely.

Due to the movement of an installed engine at power, it was determined that a probe assembly must be used which was directly and simply attached to the engine, yet would remain attached at take-off power.

2. A test facility which would allow the emission tests to be conducted at designated airport run-up locations.

Since emission testing requires high power engine operation, it must be restricted to designated run-up locations. These tend to be rather remote locations near the airport runways. The remote location led to instrumentation, together with bottled gases, housed in mobile trailers which were equipped with their own power supply. Further, due to the proximity of such a significant exposed noise source as an aircraft engine, the trailers had to provide adequate sound attenuation for the protection of test personnel and equipment.

3. A test procedure which would cause minimum interference with normal airline operations.

Since aircraft in regularly scheduled service would be involved in the testing, it was necessary to keep their out-of-service time to a minimum. This led to a test procedure (including equipment specifications) which emphasized automatic acquisition of emission and calibration data, onboard instrumentation for engine operating parameters, minimum but practical engine stabilization periods, and a simplified smoke analysis. On the other hand, the procedure was expanded to allow for the special needs of a degradation study. For instance, fuel handling requirements were established to minimize variations in the fuel supply, and additional test modes were included to provide better definition of the variation of emissions with power level.

The amount of test data to be obtained in the program dictated a methodology for data processing and analysis which relied heavily on large-scale computer usage. A computer program was developed to accept raw test data and to provide calibrated emission levels, corrected for ambient effects. Further, all pertinent data was stored by the computer program into data banks to facilitate later analysis. This allowed many analysis techniques to then be computerized. The need for computerized analysis was amplified by the variation in emission levels between individual units of the same engine type, thus ensuring that analysis had to be done on a unit-by-unit basis.

It was also recognized that the effect of degradation on emissions could only be found if other concurrent effects were eliminated. Those effects which had to be addressed were the variation of ambient conditions (affecting emission levels directly, as well as engine operation conditions), fuel content, and airline maintenance. In the case of ambient conditions, this led to the development of parameters which characterize the nominal variation of emission levels with ambient conditions and engine operating conditions. For fuel, this led to efforts to minimize and document the variations in content. In the case of maintenance, no efforts were made to alter normal airline maintenance procedures. Rather, extensive documentation was kept of all maintenance performed on test engines and tests were cancelled on all engines requiring major maintenance. Major maintenance was defined for this purpose as removal and replacement of major engine components in the gas path, such as fans, compressors, diffusers, combustors, nozzle guide vanes, and turbines.

1.4 REPORT ARRANGEMENT

The interim report consists of eight volumes. This first volume contains an introduction to the program, a description of the test schedule, equipment, procedures, and data processing techniques, and a discussion of the test data obtained in the program. The remaining seven volumes are devoted, respectively, to the detailed test data obtained for each engine type as follows:

Volume II - JT8D-9
Volume III - JT8D-7
Volume IV - JT3D-7
Volume V - JT3D-3B
Volume VI - JT9D-3A
Volume VII - RB211-22B
Volume VIII - CF700-2D

Each volume of engine data includes maintenance and fuel analysis data, as well as the data obtained from the series of emission tests.

2. PROGRAM DESCRIPTION

2.1 ENGINE TYPES

Using two mobile facilities, it was possible to coordinate the testing of seven engine types in the program. These engine types are presented by EPA classification in Table 1 below.

TABLE 1. - ENGINE TYPES TESTED

EPA Class	Engine Type	Aircraft Type	Airline
T1	CF700-2D	Falcon	Federal Express
T2	JT9D-3A	747-100	UAL
	RB211-22B	L1011	TWA
T3	JT3D-3B	DC-8-61	UAL
	JT3D-7	DC-8-62	UAL
T4	JT8D-7	727-100	UAL
	JT8D-9	727-231	TWA

It can be seen that United Air Lines provided units of four engine types to the program, while Trans World Airlines provided two engine types and Federal Express provided a single engine type. No turboprop engine types (EPA Class P2) could be economically included in the program.

2.2 TEST SCHEDULE

An overall test schedule was established for each engine type, appropriate to its utilization, maintenance requirements, and reliability. The schedule is summarized in Table 2.

TABLE 2. - OVERALL TEST SCHEDULE

Engine Type	Test Location	Original Number of Units	Nominal Test Frequency in Hours	Nominal Test Period in Hours
CF700-2D	Memphis	16	400	1600
JT9D-3A	SF	20	600	3000
RB211-22B	SF	20	150	600
JT3D-3B	SF	18	600	3000
JT3D-7	SF	18	600	3000
JT8D-7	SF	20	600	3000
JT8D-9	KC	20	600	3000

One mobile facility accommodated all of the testing scheduled for San Francisco, where UAL maintenance operations is located. The second mobile facility was based in Kansas City, site of the TWA maintenance center, during the JT8D-9 tests and traveled to Memphis, headquarters of Federal Express, for each round of CF700 tests. These tests could be scheduled for weekends, when the Federal Express aircraft were not in operation.

The original number of units tested for each engine type was selected to insure, where possible, that ten units would remain at the end of the test period. Ten units were selected to allow a reasonable statistical basis for the degradation results. In the case of the JT9D, however, this requirement had to be relaxed due to practical considerations. The high attrition rate of this engine, in combination with a 3000 hour test period, required too many units initially.

A test period of 3000 hours had originally been an objective for all engine types, but this also had to be relaxed. In the case of the CF700, a reduced period was specified because the engine undergoes required maintenance of the combustor every 1350 hours. A 1600 hour test period was established to allow evaluation of degradation both with and without this maintenance. In the case of the RB211, a modularized engine, current reliability data indicated that few units could be tested over more than 600 hours without a module being replaced.

Selection of the actual units to be tested was based on a number of considerations. First, the unit could not have a "hard time" limit, such as a turbine disk replacement, during the test period. Second, variation within the unit of combustor nozzle time should be minimal. Third, the number of aircraft in the program should be minimized. (Although, for the RB211, units in the center position could not be selected because they are difficult to reach.)

2.3 EMISSION SAMPLING PROBES

The emission sampling probes used in the program were custom designed for each engine type to be tested. The sampling configuration, based on a design developed by the FAA after extensive testing and optimization analysis at NAFEC (see Ref 4), is shown in Figure 1. It consists of a tube in the shape of a diamond, with each leg of the diamond containing three equally-spaced sampling holes of equal diameter. As such, the configuration does not conform to specifications contained in Reference 2 for emission sampling probes.

In each case, the sampling tube was fabricated from a single length of 0.375 inch outside diameter, Type 321 stainless steel tubing. The ends of the tube were welded into a block manifold which was provided with a straight-through quick-disconnect fitting for ease of connection to the sample line. Twelve 0.04 inch diameter holes were drilled in each tube using a standard process to prevent the formation of burrs.

The sampling tube was secured with straps to a back-up structure consisting of four beams in the same general shape, and positioned on the nozzle rim with four equispaced clevis mounting pads (except for the CF700 where a blast shield limited the design to two wide mounting pads). This design allows for radial thermal expansion of the probe and provides minimal blockage of the nozzle flow area. The entire structure was then secured using four or six tensioning rods between the engine frame and a

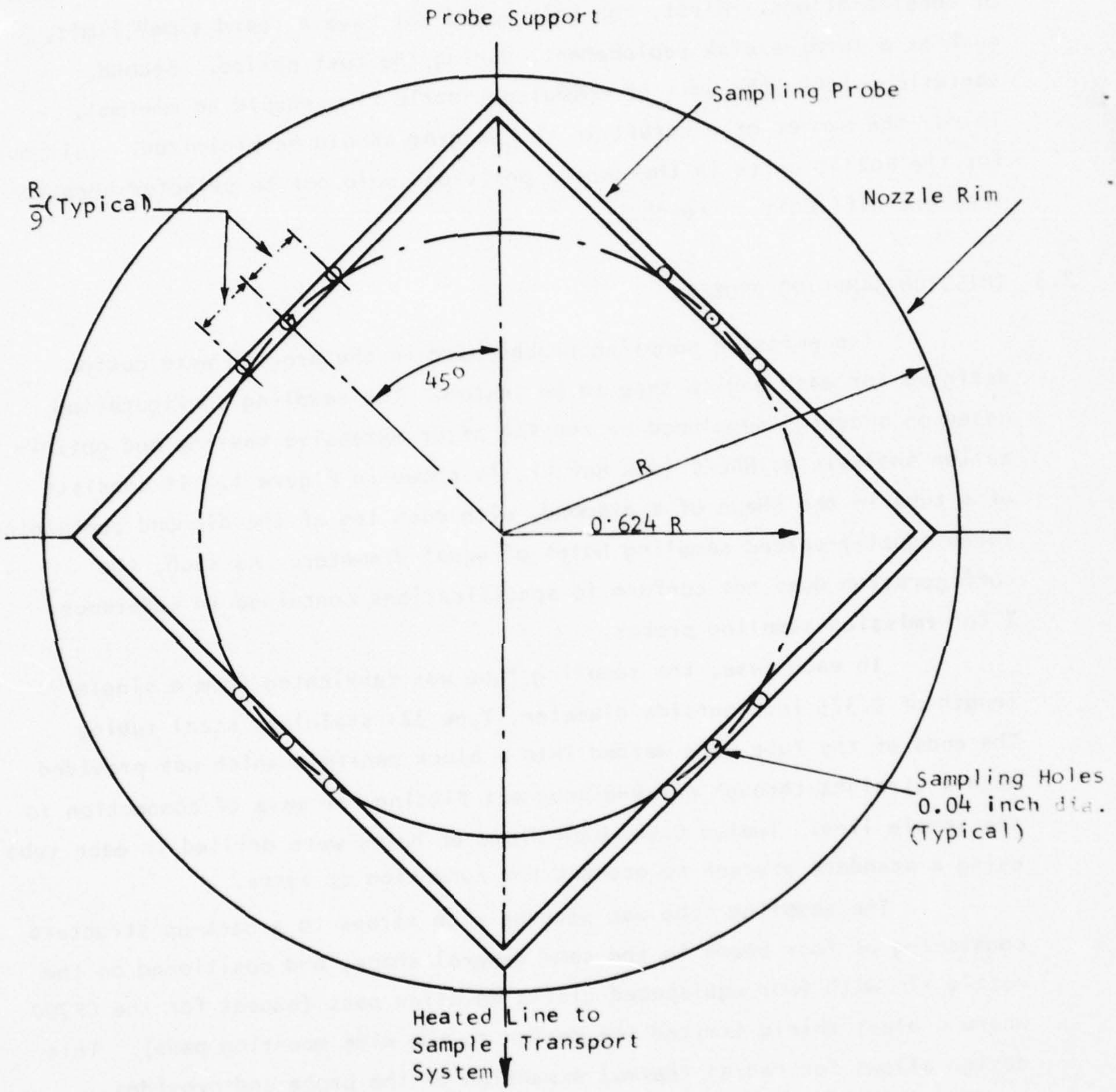
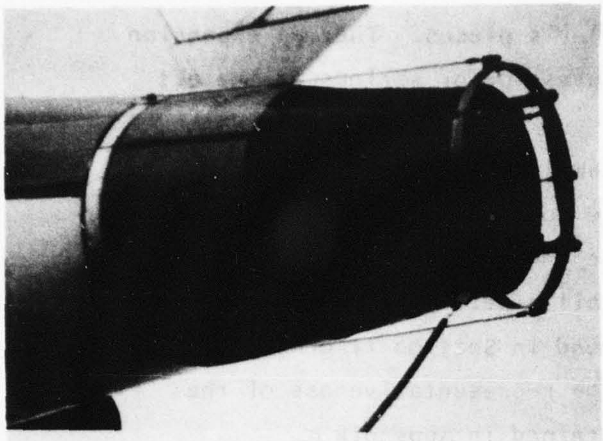
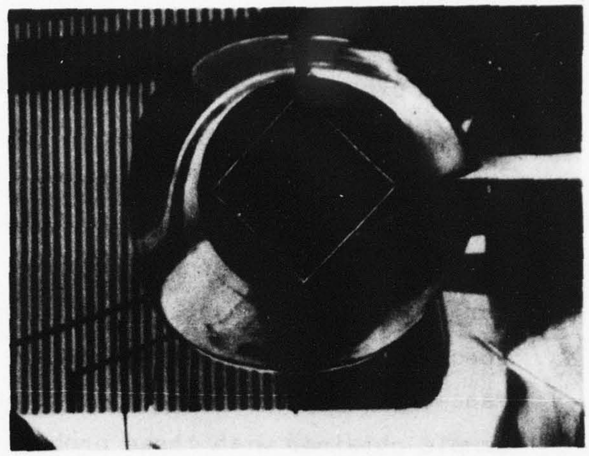


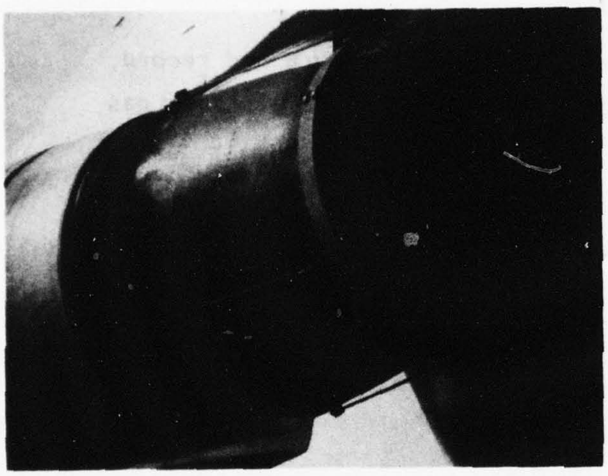
Figure 1. Sampling Probe Configuration



(a) JT8D-7, 9

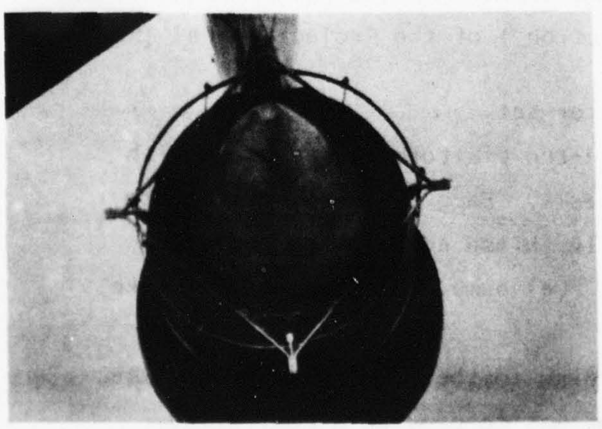


(b) CF700

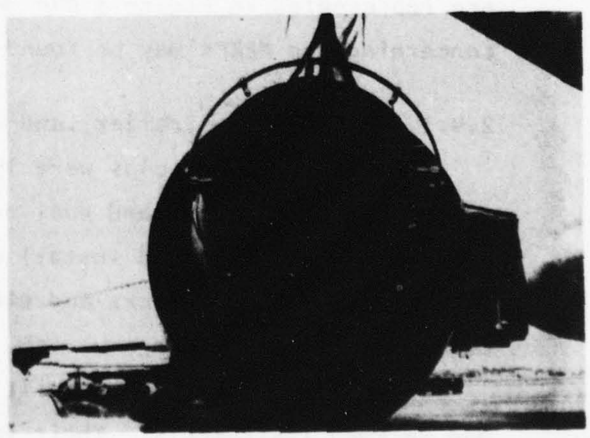


(c) JT3D-3B

(d) JT3D-7



(e) JT9D-3A



(f) RB211

Figure 2. Sampling Probe Installations

torsional support ring attached to the clevis pieces. Thermal expansion of the exhaust nozzle is taken up by compression of springs at the aft end of the tensioning rods.

Photographs of the installed sampling probes are shown in Figure 2 for each engine type. To assure consistent test-to-test orientation of the probes relative to the engine exhausts, a positioning scribe mark was located on each engine tail pipe. Further information concerning the sampling probes may be found in Section II of the Project Manual (Ref 5). Test data relating to the representativeness of the sample obtained with these probes is contained in Appendix A.

2.4 MOBILE EMISSION RESEARCH FACILITY (MERF)

Two MERFs were custom designed and built to measure and record, both accurately and consistently, the emissions of installed aircraft gas turbine engines. The units, consisting of

- Tow vehicle
- Trailer, provided with the following equipment
- Built-in air conditioning and heating systems
- Generator set
- Measurement system, including sampling train, instruments, and bottled gases
- Recording system
- Auxiliary equipment

are represented in Figure 3 and described below. More detailed information concerning the MERFs may be found in Section I of the Project Manual (Ref 6).

2.4.1 Tow Vehicle, Trailer, and Generator Set

The tow vehicles were 1974 one-ton platform stake trucks with auxiliary rear springs and dual rear wheels. Each unit was modified to shorten the platform and install a trailer hitch adjacent to the rear axle, auxiliary fuel tanks and electric fuel pump, and an electric brake control for the trailer.

The trailers were built according to the specifications of NREC and Beckman Instruments. Their function was to provide a controlled,

Figure 3. Mobile Emission Research Facility

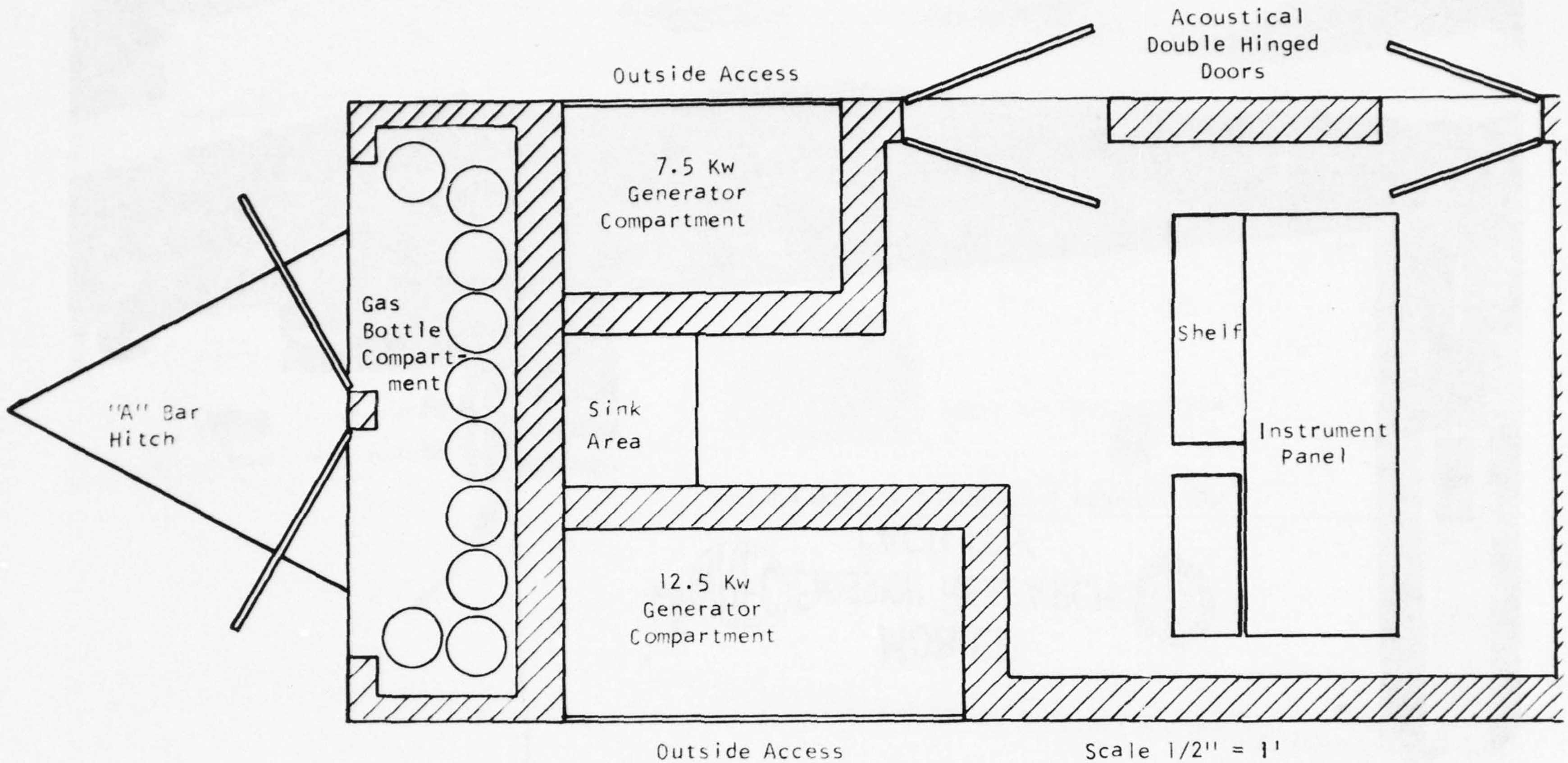


Figure 4. MERF Floor Plan

transportable and self-contained environment for emission measuring equipment and personnel. Each unit, 16 ft long by 8 ft wide by 11 ft high, was constructed specifically as a sound-attenuated enclosure with walls, floor and ceiling containing high- and low-frequency absorbing materials. A two-ton air conditioning unit was mounted on the exterior rear wall of the trailer. Heating was provided by a number of 220 volt baseboard heaters. As can be seen in the trailer floor plan of Figure 4, access to the main area of the trailer was through two double doorways on the left side of the trailer. This main area housed the instrument panel which was shock mounted for protection. Also within the perimeter of the trailer, but not within the sound-attenuated enclosure were compartments for gas cylinders, and each of two generators.

A 7.5 kw vacu-flow air cooled generator was installed in the trailer to power the instrumentation. The heating, air conditioning, and lighting requirements of the trailer were separately powered by a 12.5 kw vacu-flow air cooled generator. These units provide 120/240 volts at 60 hertz with an AC voltage regulation of $\pm$ 3 per cent and an AC frequency regulation of $\pm$ 5 per cent.

2.4.2 Measurement System

The aircraft engine exhaust was analyzed by a system which provided for the measurement of the following emissions:

- Carbon dioxide (CO_2)
- Carbon monoxide (CO)
- Hydrocarbons (HC)
- Both nitric oxide (NO) and nitrogen dioxide (NO_2)
- Smoke number (SN)

CO_2 and CO concentrations were determined by nondispersive infrared analysis, HC was determined by flame ionization detection, NO and NO_2 by the chemiluminescent method, and SN by the indirect filtration method, ARP 1179, and in accordance with paragraphs 87.82 through 87.88 of the EPA standards (Ref 2). The system, which is illustrated schematically by Figure 5, is comprised of three elements-- the sampling train, the instruments, and the associated bottled gases.

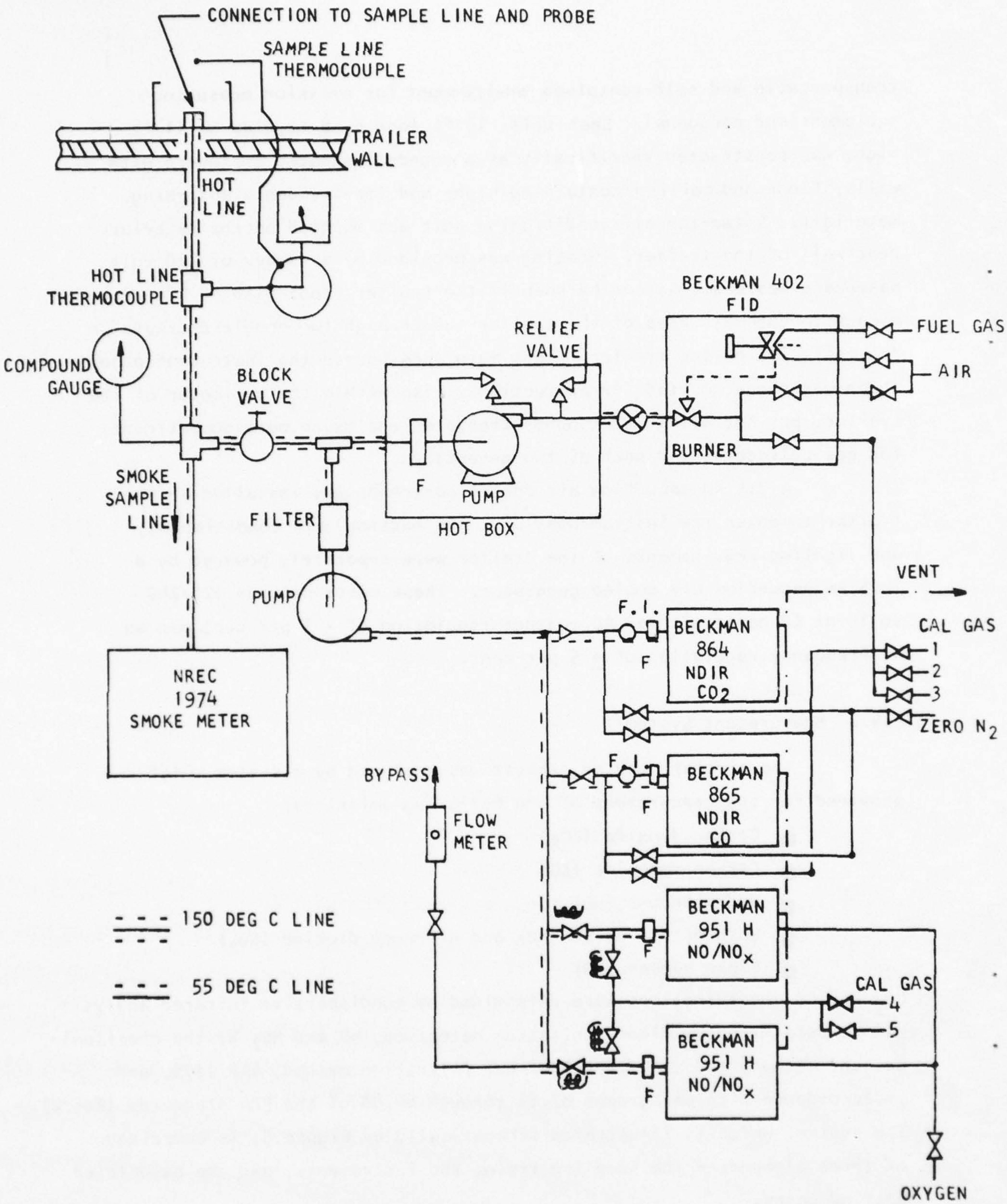


Figure 5. Measurement System

Sampling Train - The sampling train transports the exhaust sample from the probe to the instruments. External to the trailer, the sample was transported in a heated teflon line. The line was 80 ft in length with an internal diameter of 0.18 inches. It was covered by steel braid, a heating element of 60 watts per lineal foot, double-thick insulation, and an abrasion resistant covering. The sample line, which was furnished with a heating controller, a built-in Type J thermocouple, and an over-temperature thermostat, was capable of maintaining a temperature of 150 deg C. Connection of the line to the trailer was again made with a stainless steel straight-through quick-disconnect fitting.

The sampling train inside the trailer was confined to the immediate vicinity of the panel. The system was provided with three main pumps which supplied separately the hydrocarbon analyzer, the remaining analyzers, and the smoke unit. It is seen from Figure 5 that samples taken from the exterior line pass through a hot line maintained at 150 deg C to a tee connection. The flow of exhaust gas could be diverted at this tee so that the flow requirements of either the smoke meter or the gas analyzers or both could be satisfied at any time. The 150 deg C temperature was maintained for the sample flow leading to the hydrocarbon analyzer, necessitating the use of a hot box for its filter, pump, and relief valve. A separate tee upstream of the hot box led to sample line connections for the remaining gas analyzers in the system. These lines, which were maintained at a temperature of 55 deg C, also provided a connection to the bypass line. Finally, the sample line to the smoke meter was also maintained at 55 deg C in accordance with EPA requirements.

Instruments - The five gas analyzers and smoke meter were mounted on the instrument panel in the MERF as shown in Figure 6. Easy access for maintenance, adjustment, and connection to the sampling train was accomplished by the arrangement. A summary of the individual units is presented in Table 3 below.

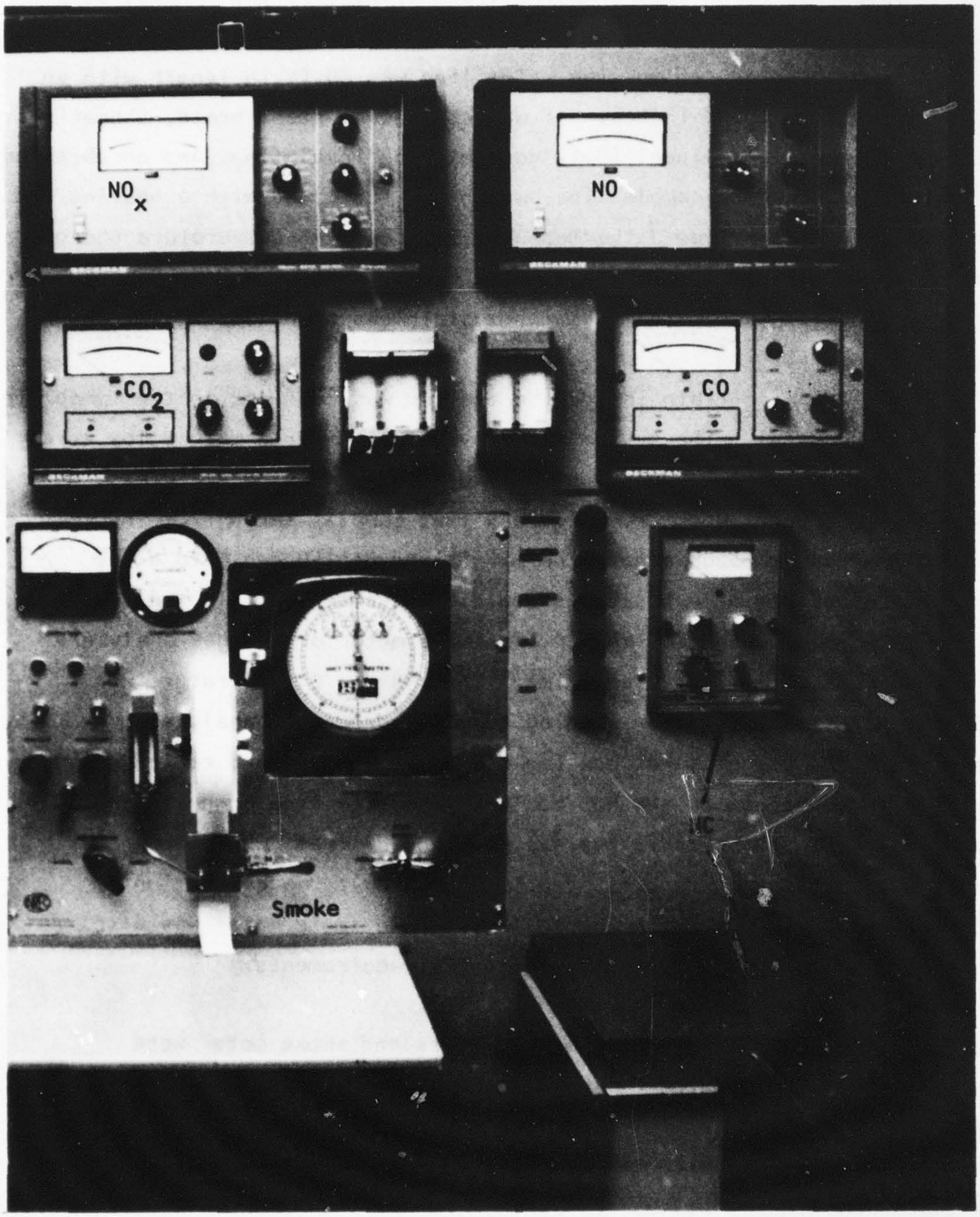


Figure 6. Mounted Gas Analyzers and Smoke Meter

TABLE 3. - INSTRUMENT SUMMARY

Emission Component	Manufacturer/ Instrument	Range	Accuracy
CO_2	Beckman/ NDIR Model 864	0-2% 0-4%	±1% full scale ±1% full scale
CO	Beckman/ NDIR Model 865	0-100 ppm 0-500 ppm 0-2500 ppm	±2% full scale ±1% full scale ±1% full scale
HC	Beckman/ FID Model 402	0-50 ppm C_3H_8 0-100 ppm C_3H_8 0-500 ppm C_3H_8 0-1000 ppm C_3H_8	±2% full scale ±2% full scale ±1% full scale ±1% full scale
NO and NO_x	Beckman/ Chemiluminescent Model 951H	0-100 ppm 0-250 ppm 0-1000 ppm	±1% for all ranges
Smoke	NREC/ Indirect Filtration Model 1974	0-100 SN	±0.5% full scale

Of the instruments summarized above, the smoke meter was specifically designed for the MERF. Figure 7 presents a schematic diagram of the unit to illustrate the main elements of the smoke analysis system. At the instrument panel, the smoke sample may be diverted from the filter paper holder through a three-way valve to a bypass line. Both main and bypass flows were maintained at the required rate by a downstream pump. The sample passed through a flow meter and wet meter before discharging to the system vent. The two-stack valve was included to allow the smoke analysis system to be isolated in conjunction with the gas analysis system, so that the compound gauge could be used to determine the engine exhaust total pressure at the probe.

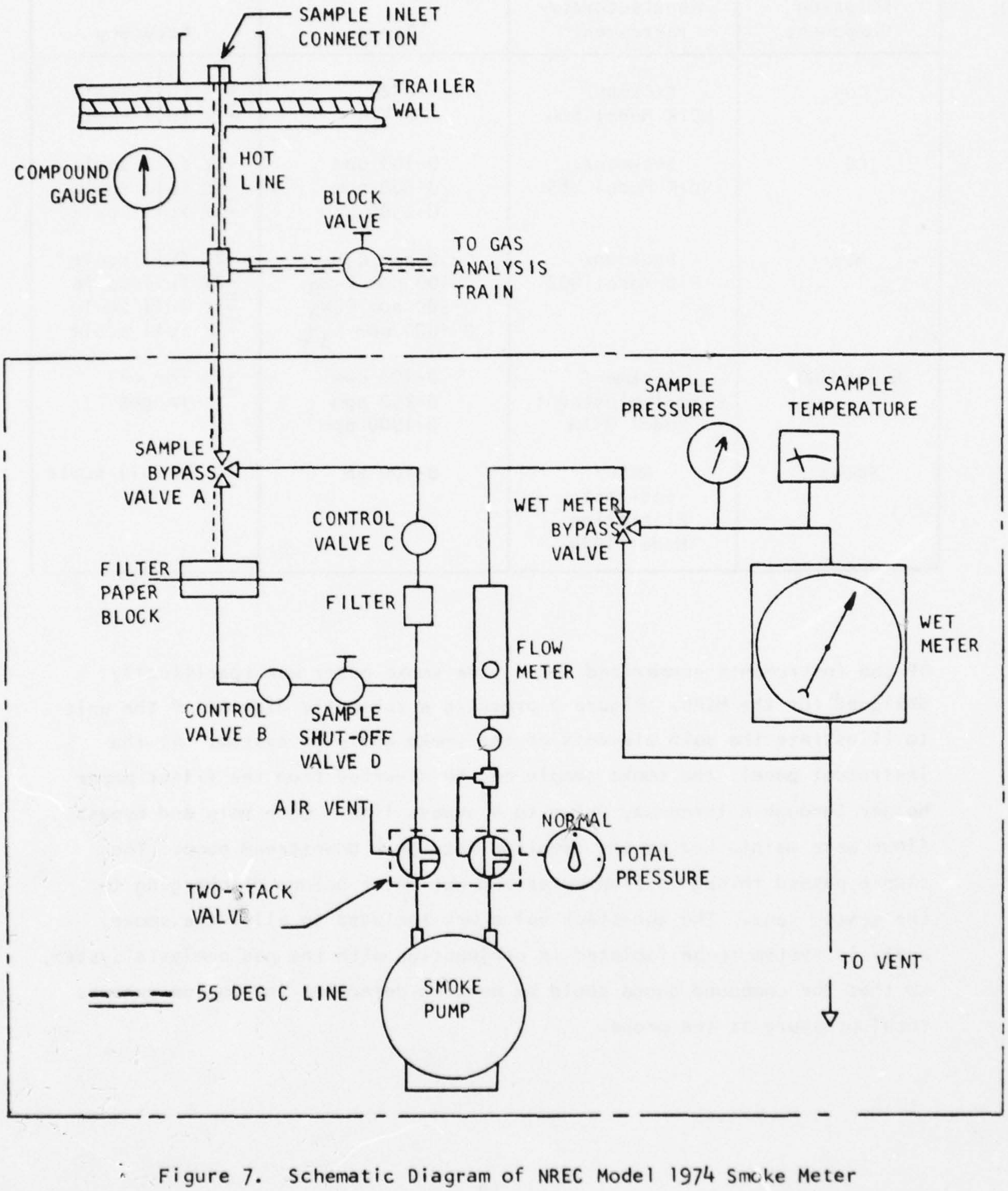


Figure 7. Schematic Diagram of NREC Model 1974 Smoke Meter

Bottled Gases - The instruments were provided with regulated bottled gases for flame ionization, oxidation, zeroing, and calibration. A total of ten bottled gases are accommodated by the trailer. Specifications used for the bottles during the program are given in Table 4 below.

TABLE 4. - SPECIFICATIONS OF PRIMARY GAS BOTTLES

Bottle	Nominal Concentration				Balance of Mixture
	CO_2 per cent	CO ppmv	HC ppm C_3H_8	NO ppmv	
CAL 1	3.6	90	--	--	N_2
CAL 2	1.8	450	50	--	N_2
CAL 3	1.0	1200	500	--	N_2
CAL 4	--	--	--	200	N_2
CAL 5	--	--	--	50	N_2
NITROGEN	--	--	--	--	N_2
ZERO 1	*	*	*	--	Air
ZERO 2	*	*	*	--	Air
FUEL	--	--	--	--	40 per cent H_2 60 per cent He
OXYGEN	--	--	--	--	O_2

* Concentrations conform to industry standard air mixture

The calibration gases, listed as CAL 1 through CAL 5, were used before and after each engine emission test to provide current instrument calibrations. Supplementary calibrations, required on a monthly basis by the EPA standards made use of additional calibration gases not carried onboard the MERF.

Control valves for the bottled gases, as well as the sample gas main control valves, were operated from the instrument panel.

2.4.3 Recording System

A digital recording system was installed on the MERF to provide high speed, accurate data acquisition suitable for computer processing. The system was composed of seven individual components: a scanner, a digital voltmeter, a printer, two paper punch controllers (for manual and automatic data, respectively), a paper punch, and a keyboard for the manual entry of data. Interchangeable thumbwheel and push-button versions of the keyboard were made. As shown in Figure 8, all but the last component were racked mounted and located on the left-hand side of the instrument panel. Directly below, the keyboard was situated on the working shelf of the panel. The system could be used to acquire data either independently or simultaneously on the printer and punch units. The punch unit enters data onto paper tape in the ASCII code.

2.4.4 Auxiliary Equipment

Besides assorted hand tools and miscellaneous supplies the MERF was equipped with several other instruments which were used to obtain test data. These included a sling psychrometer to obtain wet-bulb and dry-bulb values of ambient temperature (ambient pressure was obtained from the airport tower), a reflectometer to determine the reflectance of smoke spots, and radio equipment to communicate with the test aircraft and the airport tower. Also carried aboard the MERF were special fuel flow indicators which replaced cockpit indicators during emission tests of both JT8D engine types and the CF700 to improve their accuracy. In all other cases, standard aircraft cockpit instrumentation was used to monitor engine operating conditions.

2.5 OPERATING PROCEDURES

Since consistency was so important to the degradation study, standard operating procedures were adopted wherever possible. These procedures, covering system maintenance, pre-test, test, and post-test operations, are presented in step-by-step detail in Sections I and III of the Project Manual (Refs 6 and 6, respectively).

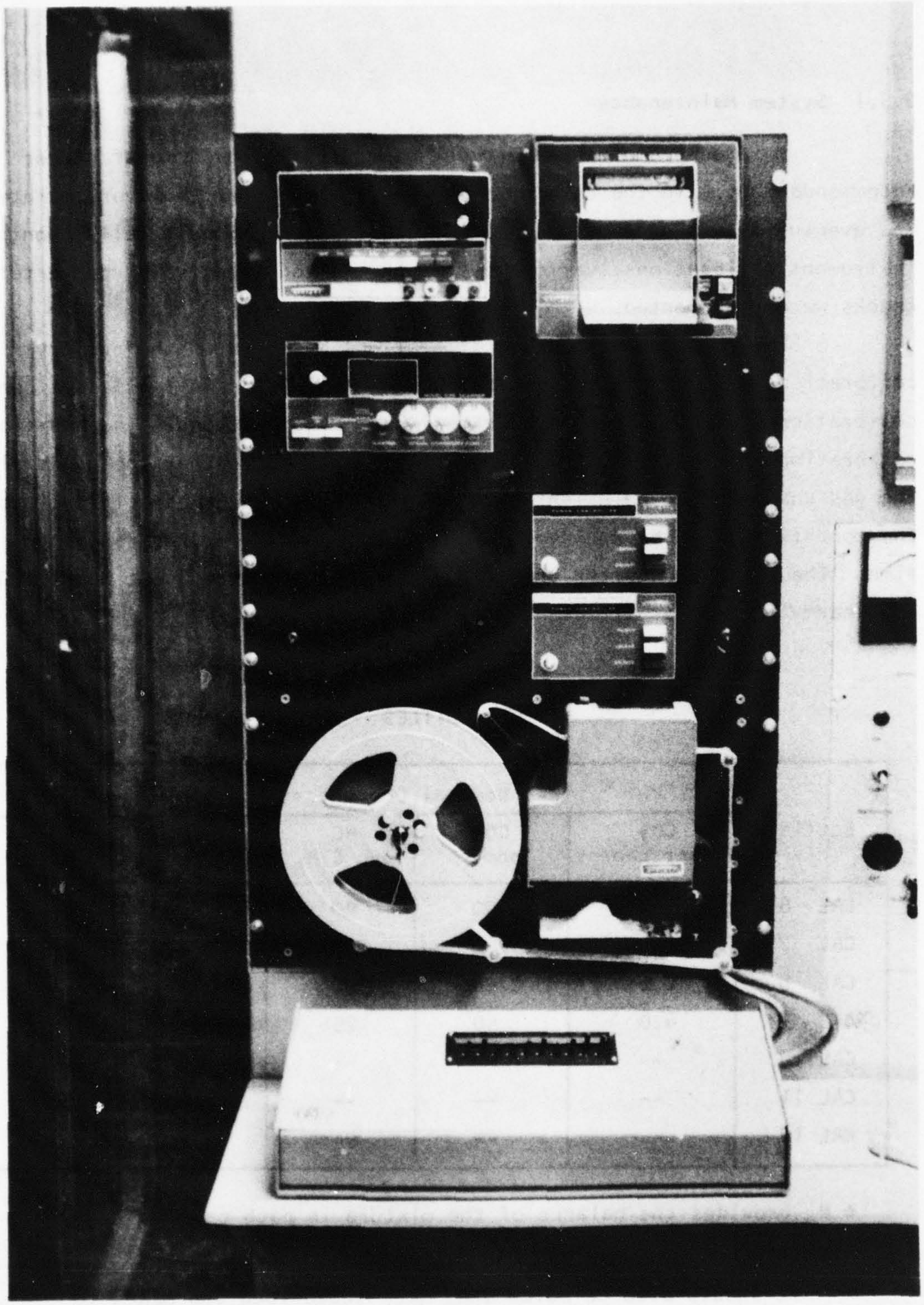


Figure 8. Digital Recording System
(Shown with Thumbwheel Keyboard)

2.5.1 System Maintenance

Maintenance of the equipment generally followed manufacturer recommendations. In the case of the measurement system, however, maintenance was eventually expanded to meet EPA specifications. Specifically, monthly instrument calibrations, various system checks, and weekly NO_x converter checks were implemented.

The monthly instrument calibrations made use of the primary calibration gases carried by the MERF (see Table 4) as well as additional calibration gases stored at the primary base of operations. The additional calibration gases are specified in Table 5 below. Together the gases allow the gas analyzers to be calibrated in accordance with EPA specifications. The monthly system checks involved leaks, contamination, and residence time. The weekly converter check was conducted with the Scott Model 140 NO_x Thermal Converter Efficiency Tester.

TABLE 5. - SPECIFICATIONS OF SECONDARY GAS BOTTLES

Bottle	Nominal Concentrations *				
	CO_2 per cent	CO ppmv	HC ppm C_3H_8	NO ppmv	NO_2 ppmv
CAL 6	2.5	300	90	--	--
CAL 7	1.4	750	250	--	--
CAL 8	0.6	2200	900	--	--
CAL 9	4.0	50	25	--	--
CAL 10	--	--	--	80	15
CAL 11	--	--	--	850	100
CAL 12	--	--	--	450	50

* N_2 provides the balance of the mixture in each case

It should also be noted that NREC subscribed the MERFs to both the Scott CVS (Constant Volume Sampling) and Nitric Oxide Cross-Reference Services. The subscription provided a comparison of the performance of these two facilities in measuring concentrations of CO_2, CO, HC, and NO versus each other, as well as versus various industrial, scientific and government facilities. In addition, late in the test schedule, the relative performance of the two MERFs were evaluated versus each other on the basis of special tests conducted on an FAA 727 aircraft (see Ref 8).

2.5.2 Pre-Test Procedures

Prior to an emission test, a general procedure was followed for all engine types. The aircraft on which the test engines were installed, would be withdrawn from regular service and released to airline maintenance personnel. The maintenance personnel were then responsible for the preparation of the aircraft for testing. This included probe installation (as previously discussed), fuel handling, and movement of the aircraft to the test site. Meanwhile, the test engineer was responsible for movement of the MERF to the test site, warm-up and check-out of the facility, and pre-test calibration.

Fuel Handling -- A fuel handling procedure was adopted in an effort to minimize the impact of variations in fuel content on measured exhaust emissions. In the case of UAL and TWA, the fuel was handled as follows:

- One designated fuel tank on the aircraft was emptied of any remaining fuel by onboard transfer pumps.
- That tank was then filled with the standard fuel supplied to the airport.
- A one quart sample of the fuel was taken and subsequently analyzed for API gravity, hydrogen-carbon ratio, and hydrocarbon characterization as paraffin, olefin, and aromatic (volume per cent). The analysis is included in the volumes of test data for each engine type.
- During the subsequent emission testing, each test engine on the aircraft was supplied with fuel from the designated tank.

In the case of Federal Express, the fuel handling procedure could not be accommodated, necessitating a fuel sample from each tank used to supply the test engines.

Warm-Up and Check-Out -- After the MERF reached the test site, final preparations for testing would be made. The preparations included:

- Connection of the extermal sample line, together with its heating system. (All other heating elements in the sampling train would also be connected.)
- Operation of first the smoke pump, and later the hot box and auxiliary pumps.
- Zeroing and spanning of each gas analyzer.
- Operation of all components of the recording system.
- Reading of air blank and zero nitrogen samples
- Recording ambient conditions (dry bulb and wet bulb temperatures, and barometric pressure).
- Recording test identification data (engine and aircraft serial numbers, engine position and time since overhaul, and date).

Pre-Test Calibration -- All of the gas analyzers were calibrated prior to each engine emission test using the bottled gases carried aboard the MERF. The sequence of events, as given in Section III of the Project Manual (Ref 7), began the acquisition of both printed and punched test data on the automatic recording system. Six sets of analyzer readings were acquired during calibration, normally corresponding to the instrument ranges and calibration gases shown below in Table 6.

TABLE 6. - CALIBRATION SPECIFICATIONS

Set No.	CO_2, per cent		CO, ppm		HC, ppm C_3H_8		NO, NO_x, ppm	
	Range	Gas	Range	Gas	Range	Gas	Range	Gas
1	0-4	3.6	0-100	90	0-500	0	0-1000	200
2	0-4	3.6	0-500	90	0-500	0	0-250	200
3	0-4	1.8	0-500	450	0-50	50	0-250	50
4	0-2	1.8	0-2500	450	0-100	50	0-100	50
5	0-2	1.0	0-2500	1200	0-500	500	0-100	0
6	0-4	1.0	0-2500	1200	0-500	500	0-100	0

2.5.3 Test Operations

Once the aircraft had arrived at the test site and the pre-test calibration had been completed, the external sample line from the MERF was attached to the installed probe. For all but the high bypass flow engines, this was done while the test engine was idling. For the other engine types (the JT9D and RB211), the test engine was shut down for sample line attachment. The test engine was then started with all sampling pumps shutdown to create a back pressure in the sampling train and prevent contamination with liquid jet fuel.

The engine was then tested over a specified sequence of operating modes, as follows:

- Idle
- "Idle Plus"
- Take-Off
- Climb
- Intermediate
- Approach
- "Idle Plus"
- Idle

This sequence follows EPA specifications, but is supplemented by the "Idle Plus" modes in the low power regime and by the Intermediate mode at higher powers. Each volume of test data contains precise definitions of the test modes for the respective engine types, but there are several items in common:

1. Idle was set as the idle stop on the throttle.
2. "Idle Plus" was set as a designated rotor speed, approximately 500 rpm higher than the nominal idle speed.
3. Take-Off was set as the take-off EPR from the engine operating guide (which is ambient-temperature and altitude dependent).
4. Climb was set by EPR at either 85 or 90 percent of rated take-off thrust, according to engine type.
5. Intermediate was set by EPR at 60 percent of rated take-off thrust.
6. Approach was set by EPR at 30 percent of rated take-off thrust.

For each mode above, the aircraft crew would set and record manually the engine operating conditions (rotor speeds, fuel flow, EGT, and EPR), and allow no throttle movement while the emission data was being taken. In the MERF, upon word from the crew, a smoke sample would be taken first and then the gas analyzers would be read. The gas analyzers were scanned automatically and at least one cycle of readings was acquired by the recording system for the mode on both printed and punched tape. In addition, sample train temperatures and pressures were recorded manually. After the emission data was acquired, the aircraft crew would record the engine operating conditions once more, before moving the throttle to the next mode. Step-by-step detail of this general test procedure is provided in Section III of the Project Manual (Ref 7).

At take-off power special procedures had to be employed to limit transient effects, due to the time limitation which applies to such operation. A common procedure was, rather than moving directly from "Idle Plus" to Take-Off, to move the throttle first to the maximum continuous power position and allow the engine to stabilize for approximately five minutes. In other instances, the sampling pumps would be shutdown and the sample line disconnected from the MERF while the throttle was moved from "Idle Plus" to Take-Off.

2.5.4 Post-Test Procedures

At the conclusion of an emission test, a post-test calibration was always conducted. However, when one engine test followed immediately after another (such as consecutive engine tests on the same aircraft), one set of data was used for both post-test and pre-test calibrations. As implied by the preceding statement, the data acquired during the post-test calibration conformed to the specifications in Table 6.

After the last emission test of the day, a final air blank sample would be analyzed and all the data sheets would be collated for each engine test. Subsequently, the manually acquired test data would be either added directly onto the punched paper tape containing the automatic data or entered onto punched cards. The test data was then sent to the NREC offices in Cambridge, Massachusetts for processing and analysis.

2.5.5 Maintenance Data

Aircraft maintenance data, as compiled by the respective airlines, were reviewed for the period of engine testing in an effort to extract all items which pertain to the engines in the test program and their performance. The extracted data has been included in the volumes of test data for each engine type.

In addition, engine life-limit audits were obtained for each engine type, except the JT8D-9, to define the baseline configuration of the units tested. Due to their bulk, however, these audits have not been included in the final report. Also not included in the final report, are engine performance histories which were maintained in the case of the UAL engines. The performance histories of a unit provide deviations of engine operating parameters from manufacturer specifications on the date of every emission test.

2.6 DATA PROCESSING AND ANALYSIS

2.6.1 Program EMISHØN

A computing system, entitled Program EMISHØN was developed to process and store the large amounts of aircraft engine data obtained during degradation testing. The system, which is documented in Reference 9, converts the raw test data into meaningful form, performs certain calculations, and then stores the data and the results of the calculations in a data base for subsequent analysis.

The data requiring processing for a test, arrived at the NREC offices in one of two forms: (a) all data punched onto paper tape, or (b) automatic data plus identifying information punched onto paper tape, and manually acquired data on punched cards. The paper tape, punched in the ASCII code, would then undergo preliminary processing in the form of conversion to BCD code on punched cards. The entire set of data for a test, now in the form of punched cards, comprised the input to Program EMISHØN. This program, written in the Fortran language for use with the CDC 6600 computer, completed processing of the test data as follows:

- Checked pre-test calibrations versus post-test calibrations for significant changes in analyzer response.
- Converted gas analyzer readings, using exact concentrations of the calibration gases, to constituent concentrations in the exhaust sample.
- Calculated corresponding values of emission indexes, emission rates, and over-all EPA parameter for each exhaust constituent.
- Calculated various engine operating parameters based on the cockpit data.
- Calculated emission indexes of CO, HC, NO, and NO_x corrected to standard day conditions, using both empirical equations supplied by the FAA and analytical formulas derived by NREC.
- After sufficient data had been acquired, checked items of data versus typical values for the engine type.

A typical computer printout of processed test data for the second and third items above are shown in Figure 9. Specific equations used in the various calculations are defined by engine type in the respective volumes of test data. Discussion of the approaches to ambient corrections will follow later in this section.

Storage of the data into easily accessible data bases was also accomplished using Program EMISHØN. Two data bases were created and maintained over the course of the program. The original data base was created using the System 2000 software package, a general purpose data base management system. Unfortunately, this data base did not prove to be cost or time efficient, and was displaced for analysis purposes by what has been termed the "System NREC" data base. In the System NREC data base, one 72-item array per mode was used to contain all of the information stored in the data base for an emission test of the engine type. Each array on the tape was identified by the unit number, test series number, and mode number, and all auxiliary computer programs which had been developed to aid the degradation analysis were designed to access data stored in this manner. The items within each array are listed in Table 7.

NORTHERN RESEARCH AND ENGINEERING CORP -- PROGRAM TO DEVELOP TIME DEGRADATION FACTORS FOR TURBINE ENGINE EMISSIONS
****************************RESULTS FOR EMISSION TEST NO 5 OF JT3D-3B UNIT NO 1****************************

AIRLINE- UNITED	TEST SITE- SAN FRAN	DATE OF TEST 06/16/76	TEST NO OF DAY- 1
AIRCRAFT NO 2470	ENGINE POSITION 1	ENGINE SERIAL NO 669229	TSO (HRS)-22919.00

DRY BULB TEMP START (DEG F)=	55.00	DRY BULB TEMP FINISH (DEG F)=	55.00
WET BULB TEMP START (DEG F)=	53.00	WET BULB TEMP FINISH (DEG F)=	53.00
BARO PRESSURE START (IN HG)=	29.82	BARO PRESSURE FINISH (IN HG)=	29.82

	MODE 1 IDLE	MODE 2 IDLE +	MODE 3 TAKE-OFF	MODE 4 CLIMB	MODE 5 INTERMED	MODE 6 APPROACH	MODE 7 IDLE +	MODE 8 IDLE
100 PER CENT N2= 9655 RPM								
ENGINE SPEED N1(PER CENT)----------------	34.00	36.40	102.40	96.80	85.30	67.20	35.00	33.00
ENGINE SPEED N2(PER CENT)----------------	61.00	64.00	101.00	99.00	94.00	86.00	63.00	60.00
MEASURED FUEL FLOW LB/HR-----------------	1280.00	1350.00	9600.00	8000.00	5500.00	2980.00	1260.00	1210.00
GAS GEN AIR FL LB/SEC FROM EMISSION COMP	40.70	43.83	176.14	163.01	135.04	94.01	43.64	40.44
GAS GEN AIR FL LB/SEC FROM MANUF THEORY-	42.19	45.58	195.19	176.51	142.11	98.00	45.77	42.37
EXHAUST SAMPLE PR (PSI)------------------	.90	1.00	12.10	9.70	6.00	2.90	.90	.80
AIRCRAFT PT7 (PSI)-----------------------	.44	.51	12.30	9.52	5.71	2.49	.51	.44
TT7 (DEG F)------------------------------	581.00	581.00	968.00	878.00	761.00	644.00	572.00	572.00
ENGINE PRESSURE RATIO--------------------	1.03	1.03	1.84	1.65	1.39	1.17	1.03	1.03
THRUST (LBS)-----------------------------	1153.86	1153.86	17960.03	15301.14	10836.22	5769.28	1153.86	1153.86
SMOKE NUMBER-----------------------------	18.16	18.16	51.51	51.82	47.58	37.34	19.82	19.01
CO2 CONCENTRATION (PER CENT)------------	1.54	1.54	3.21	2.88	2.38	1.83	1.42	1.44
CO2 EMISSION RATE (LBS/HR)--------------	3404.31	3669.52	30411.63	25339.73	17384.92	9305.49	3364.33	3177.37
CO2 EMISSION INDEX(LB/1000 LB FUEL)----	2660.08	2718.16	3167.88	3167.47	3160.89	3122.65	2670.10	2625.93
CO CONCENTRATION (PPM)-----------------	980.52	920.38	18.76	25.99	69.53	224.18	934.70	968.62
CO EMISSION RATE (LBS/HR)--------------	138.09	139.55	11.32	14.54	32.30	72.70	136.66	135.62
CO EMISSION INDEX(LB/1000 LB FUEL)----	107.88	103.37	1.18	1.82	5.87	24.39	108.46	112.08
HC CONCENTRATION (AS C3H8) (PPM)-----	660.12	550.32	7.44	4.90	4.56	21.37	586.49	678.19
HC EMISSION RATE (LBS/HR)--------------	159.71	143.35	7.72	4.71	3.64	11.90	152.26	163.13
HC EMISSION INDEX(LB/1000 LB FUEL)----	124.77	106.19	.80	.59	.66	3.99	120.79	134.82
NO CONCENTRATION (PPM)----------------	11.29	10.25	93.40	74.07	44.83	25.72	11.66	11.30
NO EMISSION RATE (LBS/HR)-------------	2.61	2.55	92.63	68.08	34.21	13.70	2.89	2.60
NO EMISSION INDEX(LB/1000 LB FUEL)----	2.04	1.89	9.65	8.51	6.22	4.60	2.30	2.15
NOX CONCENTRATION (PPM)---------------	10.12	9.86	87.29	70.20	44.79	25.23	10.51	9.64
NOX EMISSION RATE (LBS/HR)------------	2.34	2.46	86.57	64.52	34.18	13.44	2.61	2.22
NOX EMISSION INDEX(LB/1000 LB FUEL)----	1.83	1.82	9.02	8.07	6.22	4.51	2.07	1.83

EMISSION MASS/EPA CYCLE (LB/1000 LB FUEL THRUST-HR)

CO2- 2032.66 CO- 39.439 HC- 42.835 NO- 3.407 NOX- 3.196

NOTE- TEST PROCEDURES DO NOT FULLY CONFORM TO THOSE SPECIFIED BY EPA

Figure 9. Typical EMISHØN Output of Measured Exhaust Emission Levels

TABLE 7. - STORAGE ARRAY OF SYSTEM NREC

Item	Description
1	Ambient humidity
2	Ambient temperature
3	Barometric pressure
4	N1 speed
5	N2 speed
6	Fuel flow
7	EPR
8	Carbon balance air flow
9	Performance air flow
10	Thrust
11	Carbon balance fuel-air ratio
12	Performance fuel-air ratio
13	Corrected N1 speed
14	Corrected N2 speed
15	Corrected fuel flow
16	Corrected carbon balance air flow
17	Corrected performance air flow
18	Corrected thrust
19	Corrected carbon balance fuel-air ratio
20	Corrected performance fuel-air ratio
21	TSO
22	TSB (time since baseline test)
23	Smoke number, front side
24	CO EPAP
25	HC EPAP
26	NO EPAP
27	NO_x EPAP
28	Exhaust gas temperature
29	Corrected exhaust gas temperature
30	N3 speed (RB211 only)
31	CO_2 concentration
32	CO_2 emission index
33	Smoke number, back side
34	Corrected smoke number
35	TSMM (CF700 only)
36	Corrected N3 speed (RB211 only)
37	CO concentration
38	CO emission index
39	FAA-corrected CO emission index
40	NREC-corrected CO emission index
41	CO emission factor
42	Standardized CO emission factor
43	HC concentration
44	HC emission index
45	FAA-corrected HC emission index
46	NREC-corrected HC emission index
47	HC emission factor
48	Standardized HC emission factor
49	NO concentration
50	NO emission index
51	FAA-corrected NO emission index
52	NREC-corrected NO emission index
53	NO emission factor
54	Standardized NO emission factor
55	NO_x concentration
56	NO_x emission index
57	FAA-corrected NO_x emission index
58	NREC-corrected NO_x emission index
59	NO emission factor
60	Standardized NO_x emission factor
61	Deg API of fuel
62	H/C ratio of fuel
63	Per cent paraffins of fuel
64	Per cent aromatics of fuel
65-72	Same as 49-52 and 55-58, respectively but based on modified calibration gases

In Table 7, it should be noted that Items 33 and 34 were added to the data base after it was discovered that contaminated smoke samples had been obtained in certain instances. Appendix C details the contamination problem and the corrective action which was taken. All smoke data appearing in this report, and results based on that data, have been corrected where possible. In addition, Items 65 through 72 were added to the data base when it was decided that concentrations of two NO calibration gases used on the San Francisco MERF were incorrectly specified. Appendix D provides the information on which the concentrations were modified. All affected NO and NO_x data appearing in this report, and results based on that data, have been corrected accordingly.

2.6.2 Auxiliary Computer Programs

Programs SCAN, CHANGE, RPORT, CALDSP, and INTERP were written during the course of the program to interface with the data base. The programs, which are documented in Reference 10, each filled individual needs as described below.

SCAN -- For each item designated from Table 7 and on a modal basis, this program scanned the test data for an engine type to calculate a mean value and standard deviation, identify outliers, and recalculate the mean value and standard deviation without the outliers. A modification based on the Grubbs Method of Reference 11 was used to statistically detect the outlying observations. In the modification, the sample size was assumed not to exceed 20 although, in fact, it did reach as large a value as 105 for the JT8D-7 data. Concerning the mean values and standard deviations, as mentioned previously, they were subsequently introduced into Program EMISHØN to detect outliers during processing. Such outliers were examined in greater detail to determine their cause.

CHANGE -- Program CHANGE, in its various forms, was used to add, delete, and/or alter data in the data base. New values could be either specified in the input data, or calculated using the data already in the data base and an equation incorporated into the program. The former approach was used to correct erroneous values detected through Programs SCAN or EMISHØN, while the latter approach was used to update various calculated items in the data base.

RPORT -- This program was written to tabulate in various formats, for analysis and report purposes, items designated from Table 7. The computer outputs appearing in Volumes II through VIII of this final report, which contain the test data of the degradation program, were printed using RPORT.

CALDSP -- This program allowed any two items designated from Table 7 to be plotted versus each other using the DISSPLA software package and the CALCOMP plotter. Such plots could be linear, semilog, or log-log in form, with individual units or test series specified by different symbols if required. Many of the plots appearing later in this volume were generated using CALDSP.

INTERP -- Program INTERP was used as an integral part of the degradation analysis. On a unit-by-unit basis, it obtained plots and performed interpolations of emission data versus specified engine operating parameter and time. Further, it performed various statistics on the results for individual units to obtain maximum, minimum, and mean changes of emission levels with time, and to identify standard deviations and outlying values in terms of emission degradation for the engine type.

2.6.3 Correction for Ambient Effects

As indicated in the Methodology, the effect of degradation could be determined only if other concurrent effects were eliminated. In the case of engine maintenance and fuel content, their effects could be taken into account only qualitatively. However, sufficient information was available to allow the effect of ambient variations to be quantitatively eliminated from the test data of the degradation program.

It has been common practice to analyze the test-bed data of gas turbine engines using operating parameters which are "corrected" to standard conditions. According to Reference 12, such corrections assume that

$$\frac{N}{\sqrt{T_a}}, \quad \frac{F}{P_a\sqrt{T_a}}, \quad \frac{A\sqrt{T_a}}{P_a}, \quad \frac{TH}{P_a}, \text{ and } \frac{T}{T_a}$$

remain constant, where P_a is ambient pressure, T_a, is ambient temperature, N is rotor speed, F is fuel flow, A is air flow, TH is thrust, and T is gas temperature. Engine operating parameters, corrected in this manner, have been calculated for the test data of the degradation program and can be found as items 13 through 20, 29, and 36 of the System NREC data base (see Table 7). However, it was recognized that these parameters alone, were insufficient to eliminate the total effect of ambient conditions on pollutant emissions. Rather, correlating parameters, specifically derived to characterize the emissions, were required.

Correlating parameters which characterize the emissions of CO, HC, and NO from aircraft gas turbine engines were developed during the course of the program. As derived in Appendix B they are of the basic form

$$P_b^{0.75}\sqrt{T_b}\ e^{T_b/B_1} \quad \text{for CO (also HC in JT8D case)}$$

$$P_b^{1.8}\sqrt{T_b}\ e^{T_b/B_2} \quad \text{for HC (except in JT8D case)}$$

$$P_b^{0.5}\ e^{(T_b/B_3 - 19H)} \quad \text{for NO}$$

and vary inversely for CO and HC, and directly for NO, with emission index. In the parameters, the subscript b denotes burner inlet conditions, B_1, B_2, and B_3 are constants which depend upon engine type, and H is the specific humidity of the ambient air. The burner inlet conditions, themselves, can be represented in terms of measured operating parameters and ambient conditions.

In the System NREC data base, values of the above correlating parameters are normalized according to engine type and identified as "emission factors" (see items 41, 47, and 53 of Table 7). The emission factors have been used in two ways in the analysis of the test data. First, they have been used simply to present the scatter in the measured values of the respective emission indexes during the entire program. Secondly, as explained in Appendix B, they have been used in connection with "corrected emission factors" (items 42, 48, and 54 of Table 7) to correct the measured emission indexes to values which would have been obtained for the same EPRs at standard day conditions (i.e. 518.7 deg R, 29.92 in HG abs, and 0.0 lbm

H_2O/lbm dry air). The corrected emission indexes are identified as "NREC-corrected emission indexes" in the System NREC data base (items 40, 46, 52, and 58 in Table 7).

Values of emission indexes corrected to standard day conditions were also obtained using empirical factors supplied by the FAA. These factors are based on testing done at NAFEC and documented in Reference 13. The factors, which vary with power setting, correct for variations in ambient temperature and humidity. They were developed individually for the TF30 and J57 engine types. The correction factors for the TF30 (a mixed-flow exhaust engine) were applied to the mixed-flow exhaust types in the degradation program -- JT8D-9, JT8D-7, and CF700-2D -- while the correction factors for the J57 (a non-mixed exhaust engine) were applied to the non-mixed exhaust types -- JT3D-7, JT3D-3B, JT9D-3A, and RB211-22B. In the System NREC data base, values of emission indexes corrected using these factors are identified as "FAA-corrected emission indexes" (see items 39, 45, 51, and 57 of Table 7). Comparison of these FAA-corrected emission indexes with NREC-corrected values, by engine type, are also contained in Appendix B.

3. DISCUSSION OF TEST DATA

The test data obtained during the degradation program appear in Volumes II through VIII of the interim report. A discussion of this data by engine type is presented below.

3.1 JT8D-9 ENGINE TYPE

3.1.1 Background

The Pratt & Whitney JT8D-9, as shown in Figure 10, is a two spool turbofan engine rated at 14,500 lbf thrust which was developed to power short-medium range transport aircraft. An annular by-pass duct runs the full length of the engine with mixing of the gas streams in the tailpipe. The combustor is a cannular type with nine cylindrical flametubes, each downstream of a single Duplex burner and discharging into a single annular nozzle.

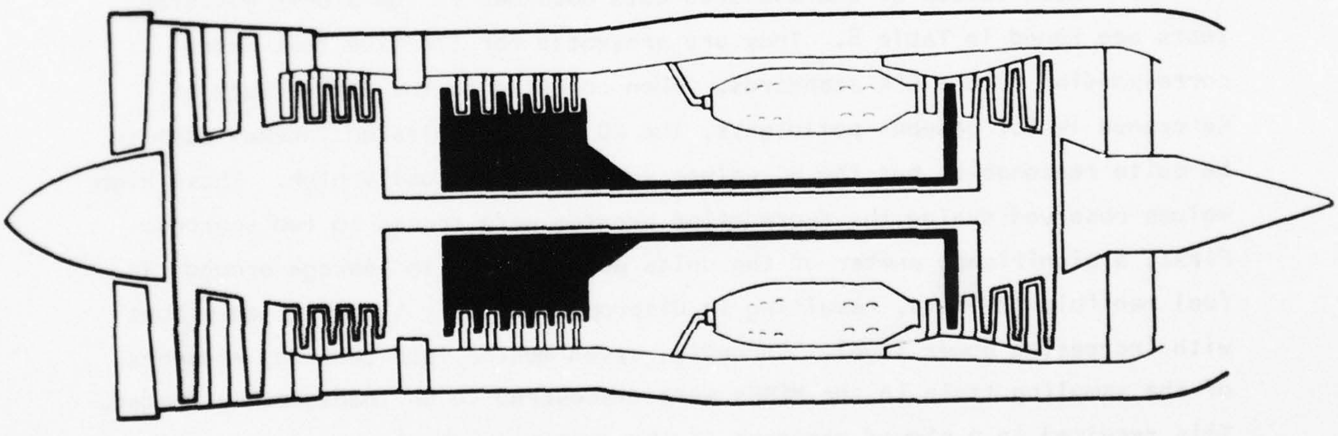


Figure 10. JT8D-9 Schematic

As indicated previously, emission tests of the JT8D-9 were conducted on installed units of the Boeing 727-231 fleet owned and operated by TWA. The tests took place at the TWA Maintenance Base adjacent to Kansas City International Airport. They were conducted during the 11 pm to 7 am shift under the direction of NREC personnel, who operated the MERF. Baseline testing was initiated on February 4, 1975 and the last test occurred on April 23, 1976. Ambient conditions varied between the following extremes: 15 to 82 deg F, 29.62 to 30.49 in Hg abs, and 0.00097 to 0.01649 lb H_2O/lb dry air. Of the twenty (20) units which were baselined, fourteen (14) were tested through at least 2400 hours of elapsed operating time. The maximum elapsed time was 3095 hours, and up to six tests were conducted per unit. Eight (8) of the fourteen surviving units were relatively new, each with less than 1700 hours of operation at baseline. The remaining six (6) engines had baseline TSOs of between 7350 and 15,316 hours. A total of 83 engine tests have been documented in Volume II for the JT8D-9.

3.1.2 Processed Data Overview

Mean values of the measured data obtained in the JT8D-9 emission tests are found in Table 8. They are presented for the five test modes corresponding to the EPA standards. When compared to the JT8D-9 data of Reference 14 for gaseous pollutants, the CO and NO_x emission indexes seem to be quite reasonable, but the HC values seem to be unusually high. These high values observed during the degradation program were traced to two sources. First, a significant number of the units were subject to leakage around the fuel manifold "B" nuts, resulting in disproportionately higher HC emissions with increasing power level. Secondly, seven months into testing, elements of the sampling train in the MERFs were discovered to be inadequately heated. This resulted in a slowed response of the system which was most noticeable at take-off power where test time is strictly limited. The deficiencies were corrected, but too late to prevent a sizeable percentage of the HC data from being affected. In the presentation of test data which continues

TABLE 8. - MEAN JT8D-9 TEST DATA*

Item	Initial Idle	Take-Off	Climb	Approach	Final Idle
	TEST MODE				
Performance Parameters					
EPR	1.06	2.05	1.85	1.23	1.06
Corrected N_1, per cent	34.2	95.2	88.7	61.2	35.1
Corrected N_2, per cent	58.2	94.2	91.3	77.7	58.9
Corrected Fuel Flow, lb/hr	1060	8720	7150	2370	1060
Corrected EGT, deg R	1150	1460	1390	1130	1140
Exhaust Emissions					
CO_2 Concentration, per cent	0.59	1.92	1.60	0.65	0.56
CO Emission Index, lb/1000 lb fuel	38.1	1.5	2.0	13.5	37.2
HC Emission Index, lb/1000 lb fuel	12.4	1.8	1.9	5.4	12.7
NO Emission Index, lb/1000 lb fuel	3.0	13.9	11.5	5.3	2.7
NO_x Emission Index, lb/1000 lb fuel	3.5	14.3	12.1	6.4	3.6
Smoke Number	---	30.7	29.6	9.0	---

* Without outlying values

below, the effect of both sources of misleading HC data can be seen on individual test points.

The scatter of the emission data from unit to unit and test to test for the entire body of JT8D-9 test data are combined in the next group of plots. The data is, however, limited to modes 3 through 8 for the purposes of continuity and clarity. Figures 11, 12, and 13 provide, respectively, values of CO, HC, and NO emission indexes versus their appropriate emission factors (as introduced in Section 2.6.3, and defined for the JT8D-9 in the nomenclature of Volume II). As such, they also serve to indicate visually the validity of the relationship between independent and dependent variables for each pollutant.

In the case of CO, it can be seen that the emission index is highly correlated by the emission factor F_{CO} and that the dependency is accurately described by an inverse relationship (i.e., a line with a slope of -1 on the log-log plots). These observations have been quantified through the calculation of various statistics. For example, based on modes 6 through 8 (i.e. values of F_{CO} less than 0.2) where the CO emissions are most important, EI_{CO} versus F_{CO} data points for the entire set of JT8D-9 tests have a correlation coefficient of 0.91 with the inverse relationship (versus a value of 1.0 for perfect correlation).

The HC emission data for the JT8D-9, as shown in Figure 12, provides graphic evidence of the problems discussed above -- particularly at high power. The statistics bear out the poor quality of the data with correlation coefficient of 0.54 between EI_{HC} versus F_{HC} data points and an inverse relationship. It is obvious that any subsequent analysis of JT8D-9 HC emissions must eliminate the data invalidated by "B" nut leaks and inadequate heating of the sample train.

It can be seen from Figure 13 that the emission index of NO is highly correlated by F_{NO} at high powers, but the correlation deteriorates as idle is approached. Further, the dependency is accurately described by a direct proportionality (i.e., a line with a slope of +1, on the log-log plots). Based on modes 3 through 6 where the NO emissions are most important, EI_{NO} versus F_{NO} data points for the entire set of JT8D-9 tests have a correlation coefficient of 0.91 with direct proportionality.

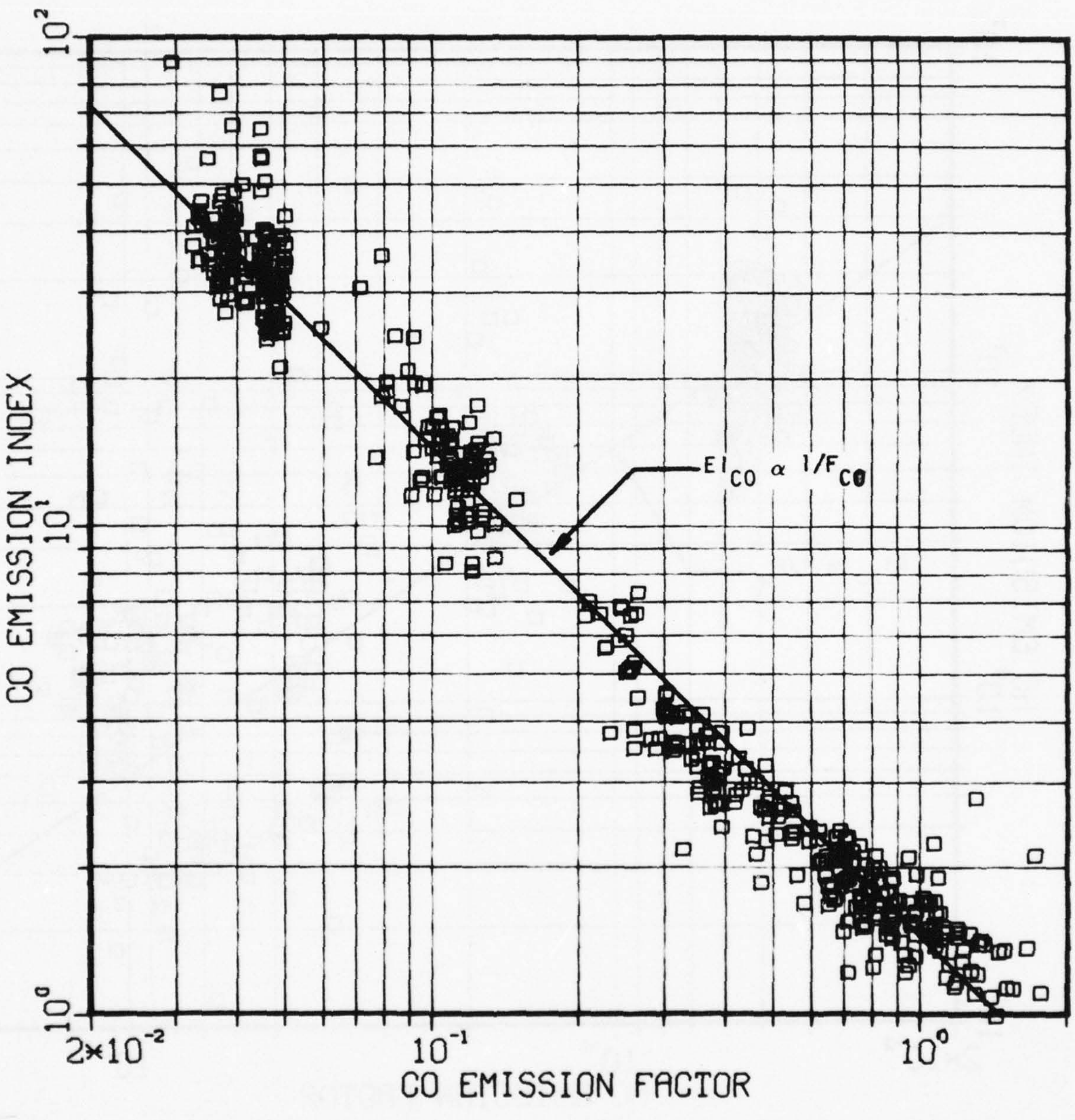


Figure 11. JT8D-9 Uncorrected CO Emission Data

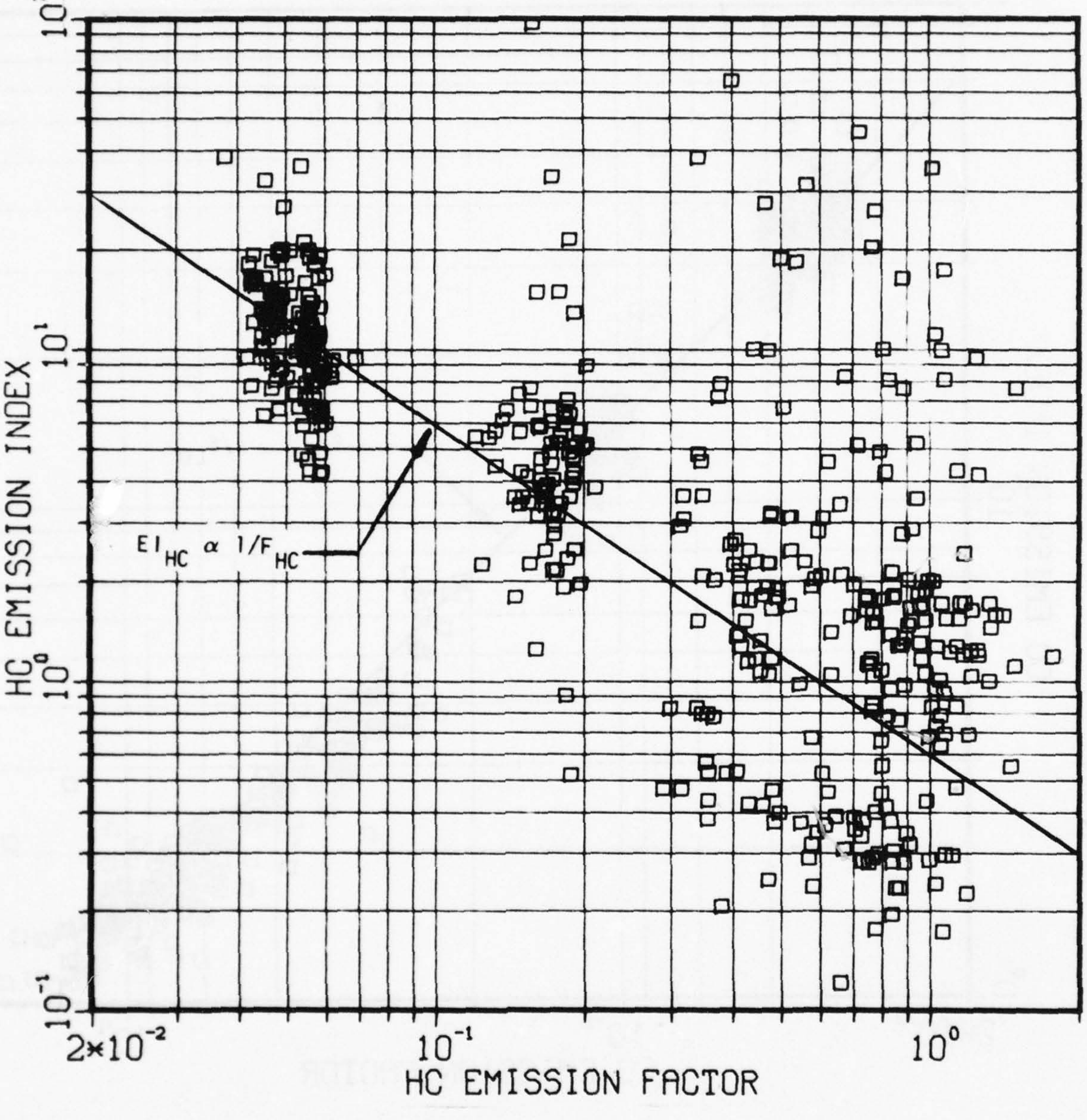


Figure 12. JT8D-9 Uncorrected HC Emission Data

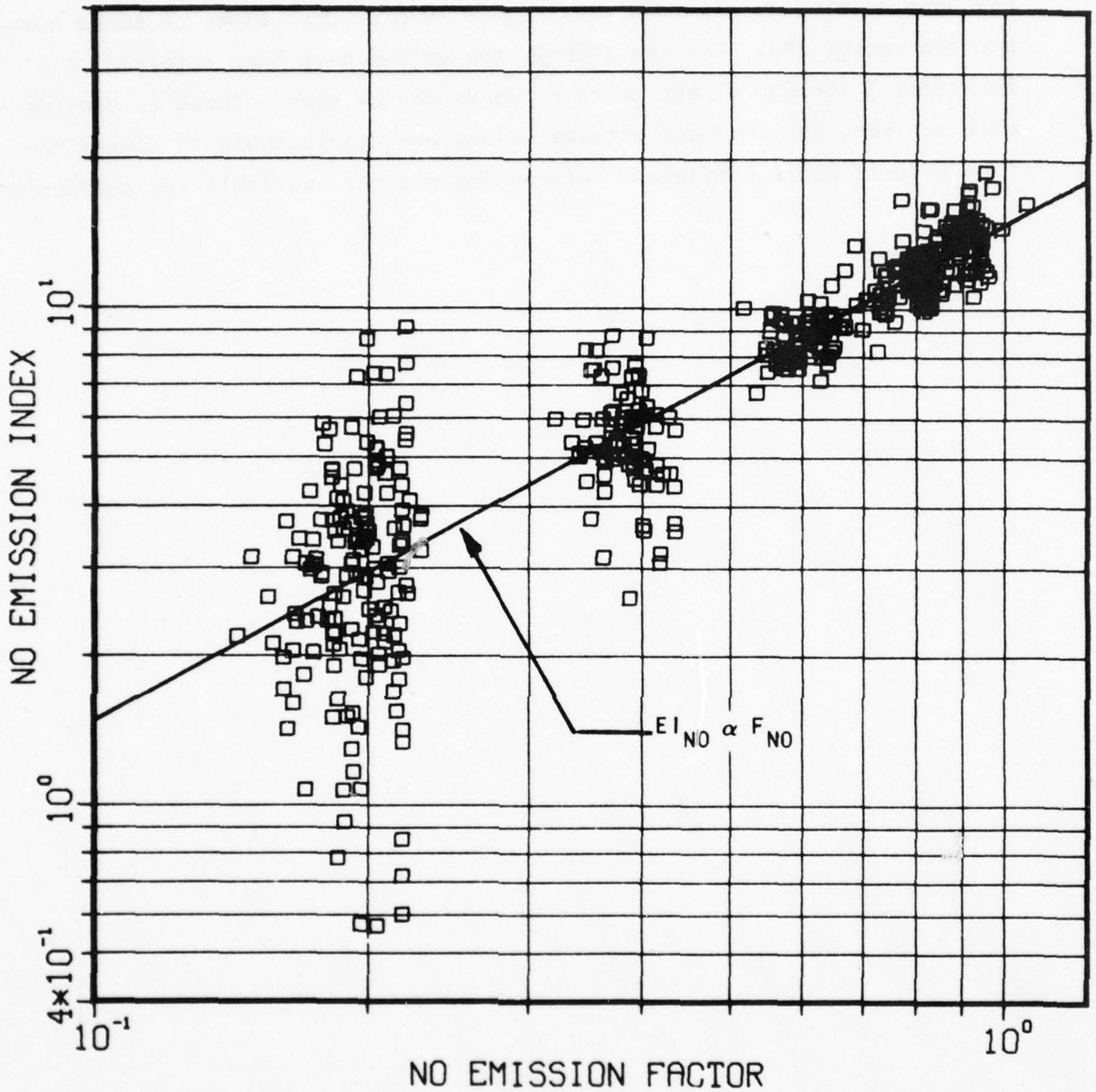


Figure 13. JT8D-9 Uncorrected NO Emission Data

In the case of smoke, no emission factor to correlate the data has been developed. As a result, Figure 14 provides values of smoke number plotted versus EPR. For the JT8D-9, the values have been obtained only for modes 3 through 6, but certain trends can be seen. These is considerable scatter, but the most extreme values are attributable to contamination effects where sufficient information was not available for correction.

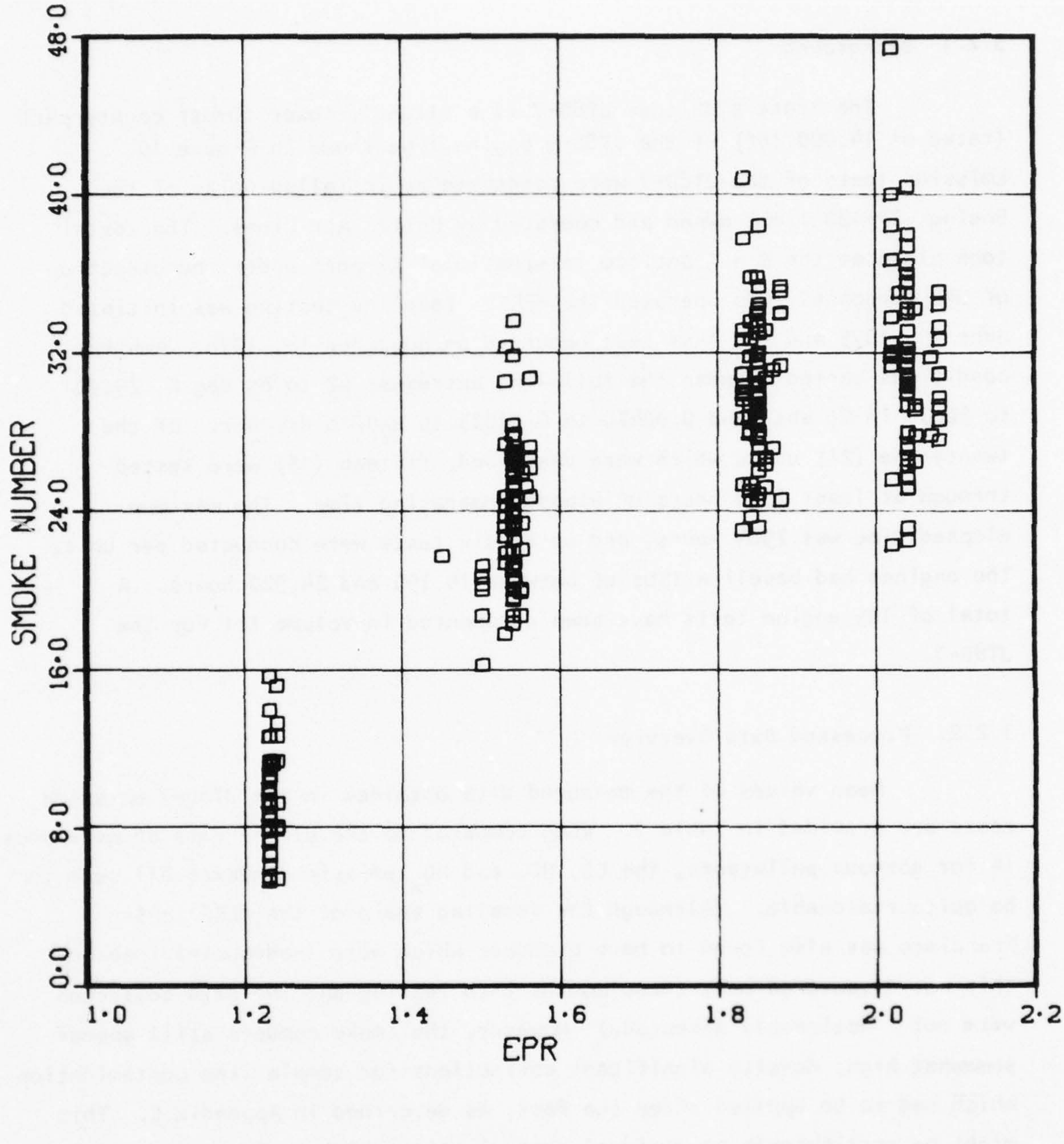


Figure 14. JT8D-9 Smoke Data

3.2 JT8D-7 ENGINE TYPE

3.2.1 Background

The Pratt & Whitney JT8D-7 is a slightly lower thrust counterpart (rated at 14,000 lbf) of the JT8D-9 engine type shown in Figure 10. Emission tests of the JT8D-7 were conducted on installed units of the Boeing 727-100 fleet owned and operated by United Air Lines. The tests took place at the San Francisco International Airport under the direction of UAL personnel, who operated the MERF. Baseline testing was initiated June 19, 1975 and the last test occurred on November 18, 1976. Ambient conditions varied between the following extremes: 42 to 85 deg F, 29.92 to 30.37 in Hg abs, and 0.00426 to 0.01023 lb H_2O/lb dry air. Of the twenty-one (21) units which were baselined, fifteen (15) were tested through at least 2300 hours of elapsed operating time. The maximum elapsed time was 2984 hours, and up to six tests were conducted per unit. The engines had baseline TSOs of between 14,190 and 24,920 hours. A total of 105 engine tests have been documented in Volume III for the JT8D-7.

3.2.2. Processed Data Overview

Mean values of the measured data obtained in the JT8D-7 emission tests are provided in Table 9. When compared to the JT8D-7 data of Reference 14 for gaseous pollutants, the CO, HC, and NO_x emission indexes all seem to be quite reasonable. (Although the sampling train of the MERF in San Francisco was also found to have elements which were inadequately heated, this was discovered only three months into testing and the data collected were not noticeably affected.) However, the smoke numbers still appear somewhat high, despite significant corrections for sample line contamination which had to be applied after the fact, as described in Appendix C. This might be attributable to residual contamination which could not be eliminated, a core-rich sample at high power (see Appendix A), or perhaps a high aromatic content of the fuel.

TABLE 9.- MEAN JT8D-7 TEST DATA*

Item	TEST MODE				
	Initial Idle	Take-Off	Climb	Approach	Final Idle
Performance Parameters					
EPR	1.05	1.98	1.80	1.23	1.05
Corrected N_1, per cent	32.2	93.4	88.1	61.2	33.0
Corrected N_2, per cent	56.1	93.3	91.0	77.4	56.6
Corrected Fuel Flow, lb/hr	1130	8300	6930	2500	1130
Corrected EGT, deg R	1160	1450	1380	1100	1140
Exhaust Emissions					
CO_2 Concentration, per cent	0.63	1.92	1.54	0.51	0.58
CO Emission Index, lb/1000 lb fuel	38.1	1.5	1.9	10.7	36.6
HC Emission Index, lb/1000 lb fuel	10.1	0.3	0.3	1.9	9.2
NO Emission Index, lb/1000 lb fuel	1.6	14.0	12.1	4.9	1.7
NO_x Emission Index, lb/1000 lb fuel	3.7	14.2	12.5	6.9	3.7
Smoke Number	1.5	33.1	31.7	9.5	1.4

* Without outlying values

Figures 15, 16, and 17 provide, respectively, values of CO, HC, and NO emission indexes versus their appropriate emission factors (as defined for the JT8D-7 in the nomenclature of Volume III). It is apparent, in each case, that the values of emission index are highly correlated by the emission factor. Specifically, for the entire set of JT8D-7 tests,

- Based on modes 6 through 8, EI_{CO} versus F_{CO} data points have a correlation coefficient of 0.93 with an inverse relationship, while EI_{HC} versus F_{HC} data points have a correlation coefficient of 0.90.
- Based on modes 3 through 6, EI_{NO} versus F_{NO} data points have a correlation coefficient of 0.96 with direct proportionality.

Figure 18 provides values of smoke number versus EPR for the JT8D-7. The pattern is seen to be similar to that for the JT8D-9, but the values are higher generally. The smoke numbers again tend to level off at high power.

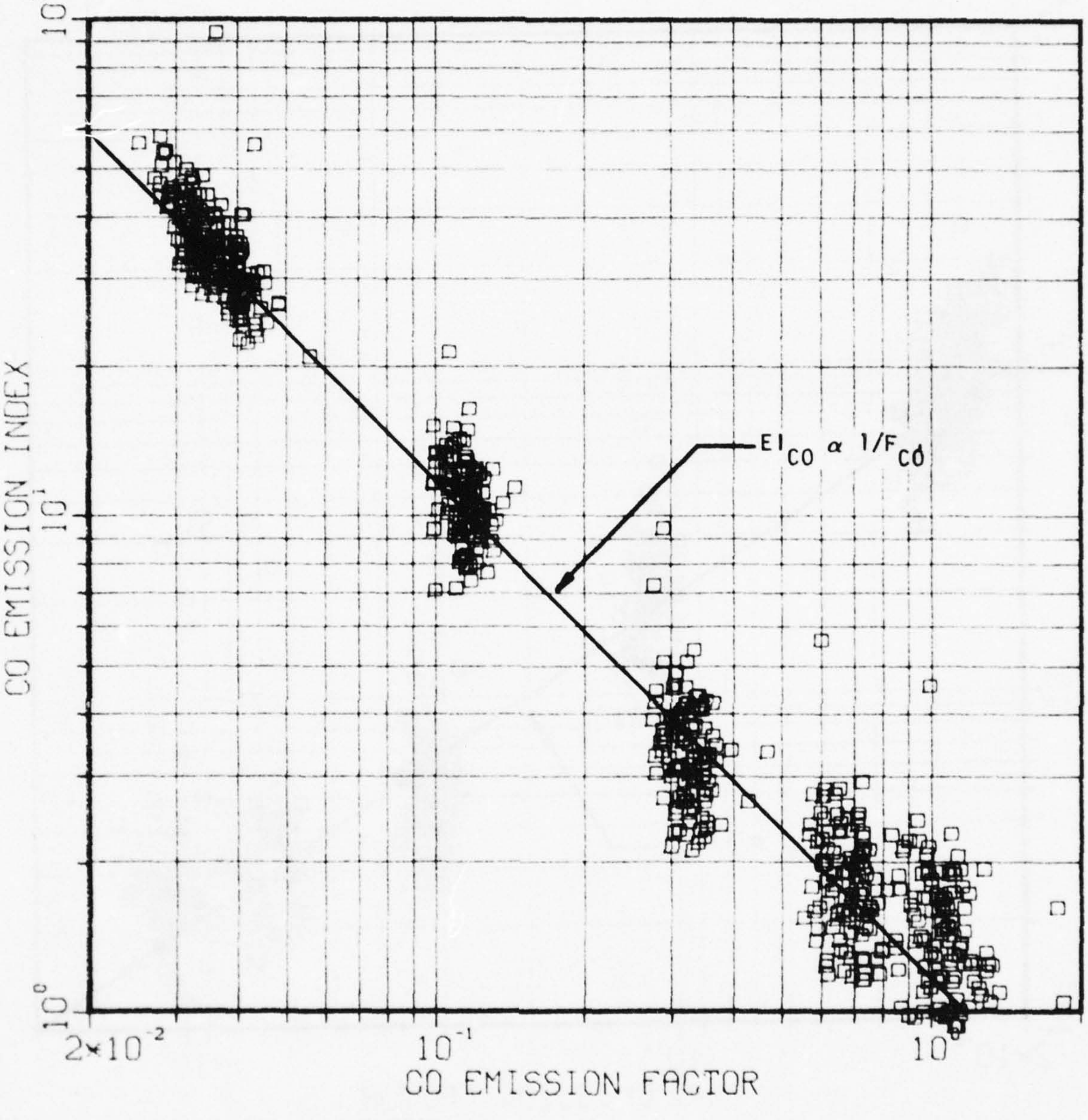


Figure 15. JT8D-7 Uncorrected CO Emission Data

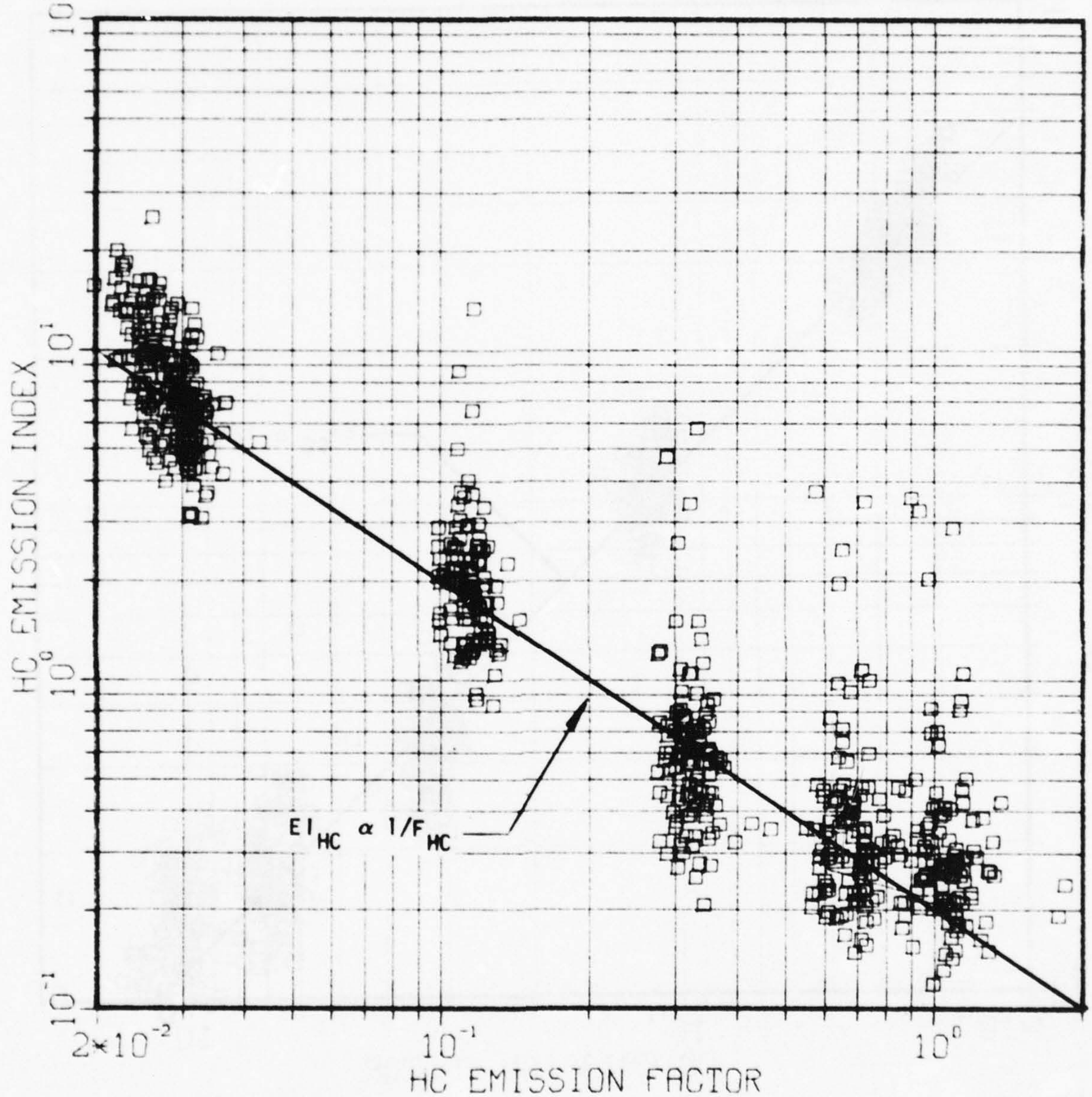


Figure 16. JT8D-7 Uncorrected HC Emission Data

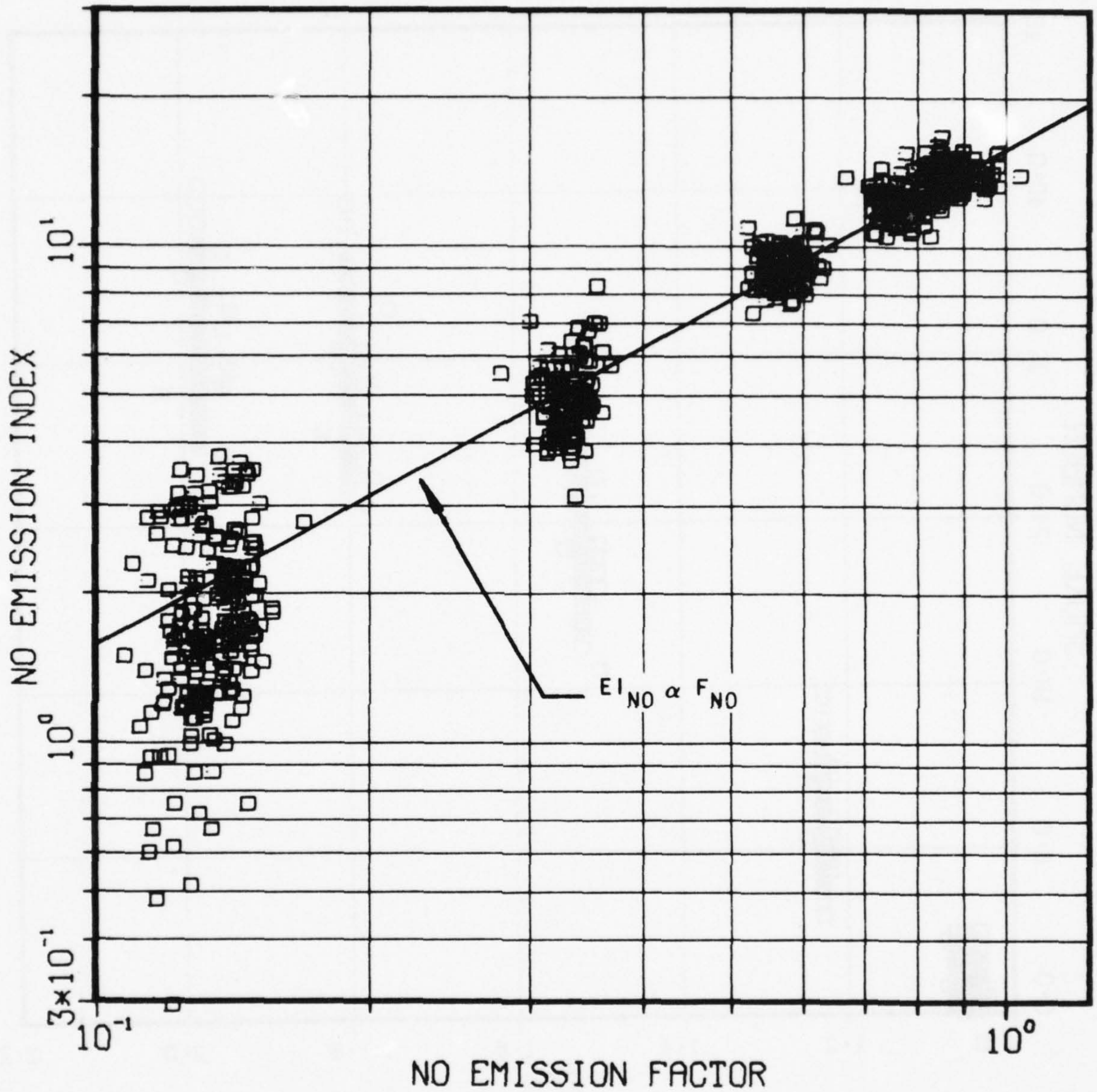


Figure 17. JT8D-7 Uncorrected NO Emission Data

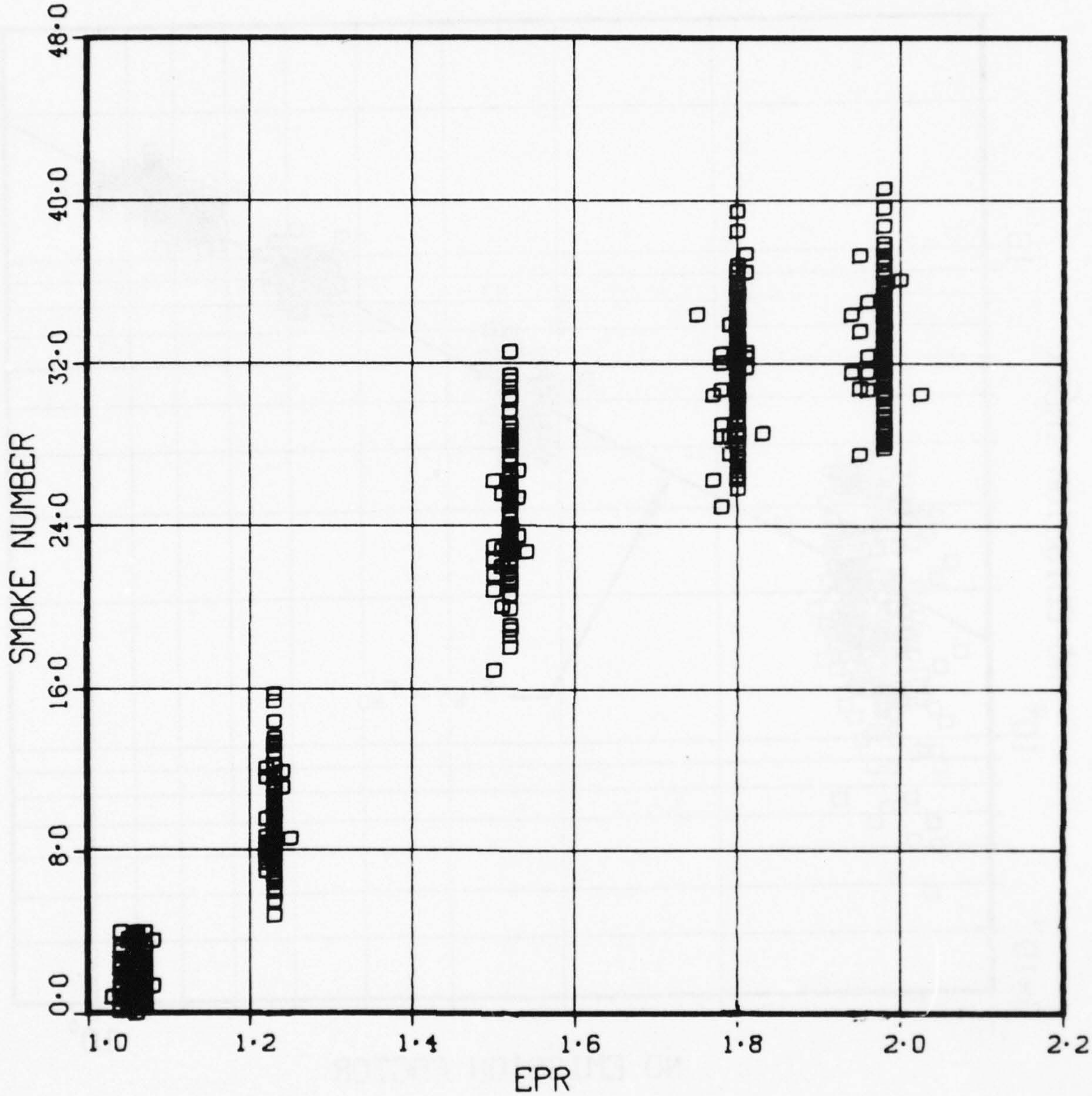


Figure 18. JT8D-7 Smoke Data

3.3 JT3D-7 ENGINE TYPE

3.3.1 Background

The Pratt & Whitney JT3D-7 is a higher thrust counterpart (rated at 19,000 lbf) of the JT3D-3B engine type shown in Figure 23. Emission tests of the JT3D-7 were conducted on installed units of the DC-8-62 fleet owned and operated by United Air Lines. The tests took place at the San Francisco International Airport under the direction of UAL personnel, who operated the MERF. Baseline testing was initiated August 18, 1975 and the last test occurred on November 16, 1976. Ambient conditions varied between the following extremes: 42 to 76 deg F, 29.85 to 30.29 in Hg abs, and 0.00354 to 0.01169 lb H_2O/lb dry air. Of the eighteen (18) units which were baselined, ten (10) were tested through at least 2300 hours of elapsed operating time. The maximum elapsed time was 3012 hours, and up to six tests were conducted per unit. The engines had baseline TSOs of between 15,760 and 25,860 hours. A total of 74 engine tests have been documented in Volume IV for the JT3D-7.

3.3.2 Processed Data Overview

Mean values of the measured data obtained in the JT3D-7 emission tests are found in Table 10. When compared to the JT3D-7 data of Reference 14 for gaseous pollutants, the CO, HC, and NO_x emission indexes all seem to be quite reasonable. For CO and HC, the variation with power level and the low values agree very well, although the peak values in Table 10 tend to be higher. In the case of NO_x, again the low values agree very well, but the peak values in Table 10 are somewhat lower than the comparable values from Reference 14.

Figures 19, 20, and 21 provide, respectively, values of CO, HC, and NO emission indexes versus their appropriate emission factors (as defined for the JT3D-7 in the nomenclature of Volume IV). It is apparent, in each case, that a small group of values are different from the others. These are values obtained from measurements of Unit 13 which was fitted prior to the degradation program with a special low-smoke combustor. Aside from Unit 13, it should be noted that special considerations,

TABLE 10.- MEAN JT3D-7 TEST DATA*

Item	TEST MODE				
	Initial Idle	Take-Off	Climb	Approach	Final Idle
Performance Parameters					
EPR	1.03	1.85	1.66	1.17	1.03
Corrected N_1, per cent	32.8	101.4	96.1	69.2	33.3
Corrected N_2, per cent	60.4	101.7	99.5	87.1	61.0
Corrected Fuel Flow, lb/hr	1240	10,000	8300	3280	1230
Corrected EGT, deg R	1030	1420	1340	1100	1030
Exhaust Emissions					
CO_2 Concentration, per cent	1.50	3.36	2.98	1.96	1.44
CO Emission Index, lb/1000 lb fuel	109	1.2	1.7	17.8	106
HC Emission Index, lb/1000 lb fuel	124	0.7	0.4	2.7	112
NO Emission Index, lb/1000 lb fuel	1.5	9.8	8.9	4.5	1.7
NO_x Emission Index, lb/1000 lb fuel	2.2	9.9	9.1	5.6	2.4
Smoke Number	19.5	50.5	50.6	43.6	18.7

* Without outlying values

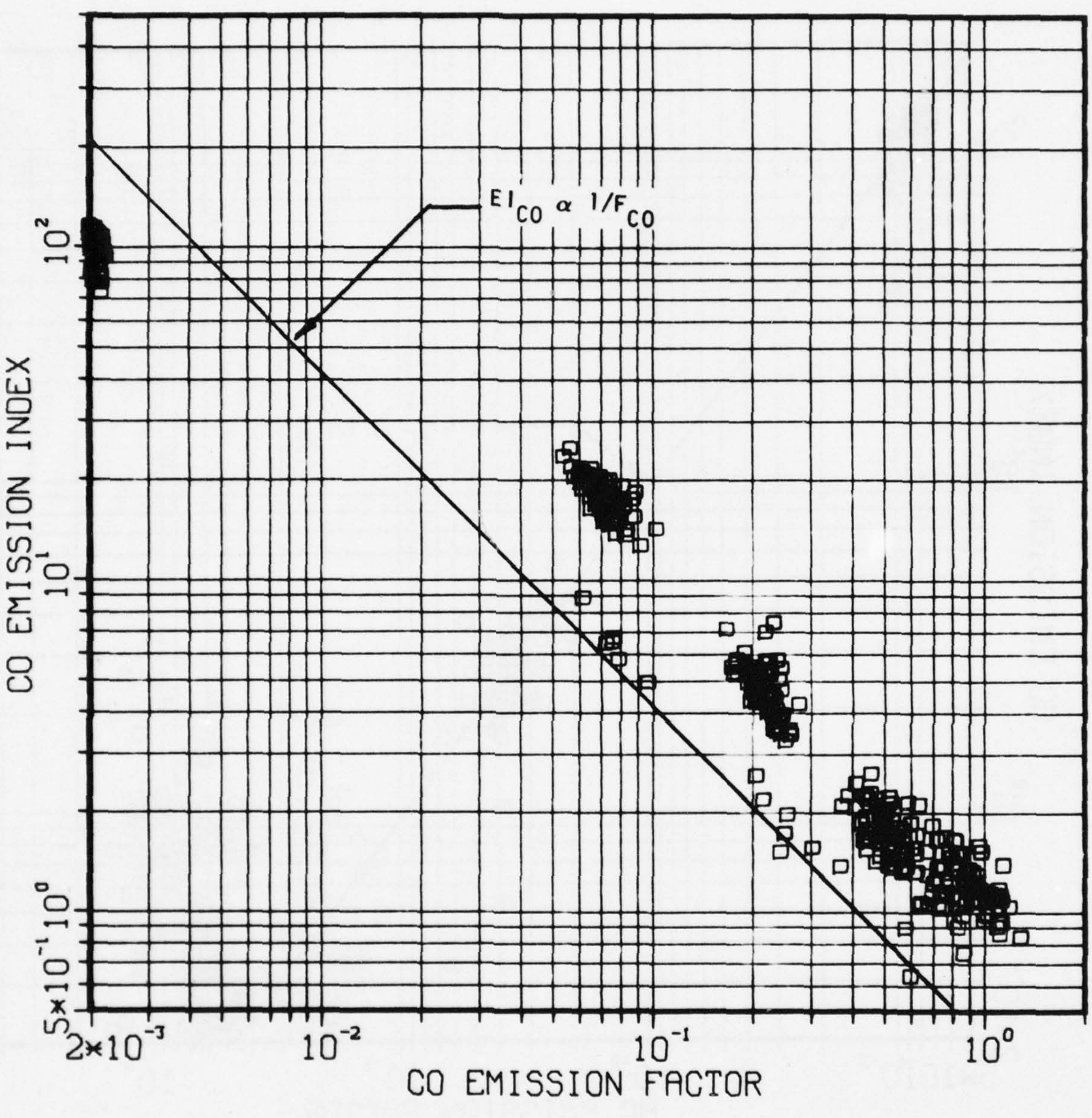


Figure 19. JT3D-7 Uncorrected CO Emission Data

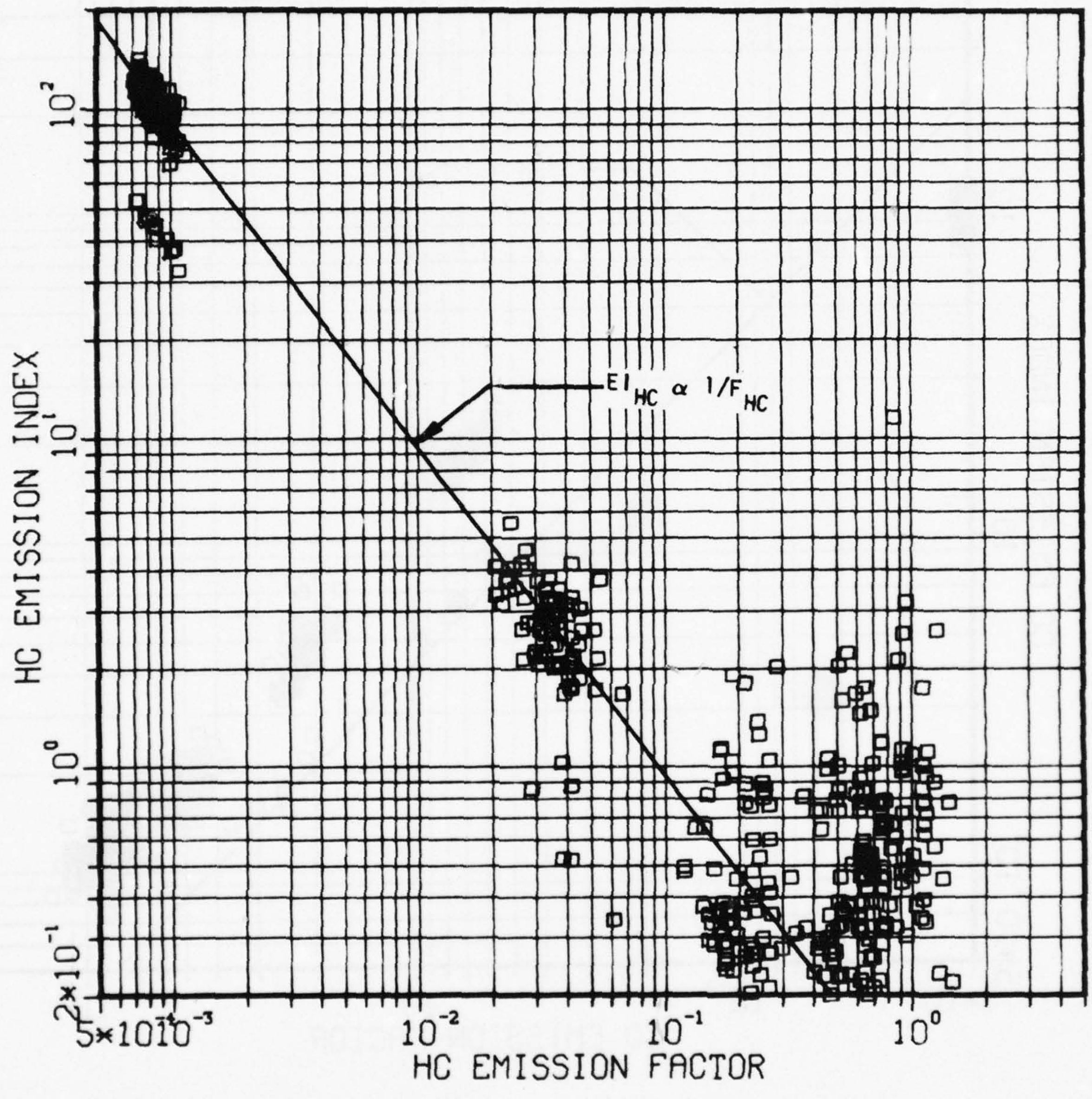


Figure 20. JT3D-7 Uncorrected HC Emission Data

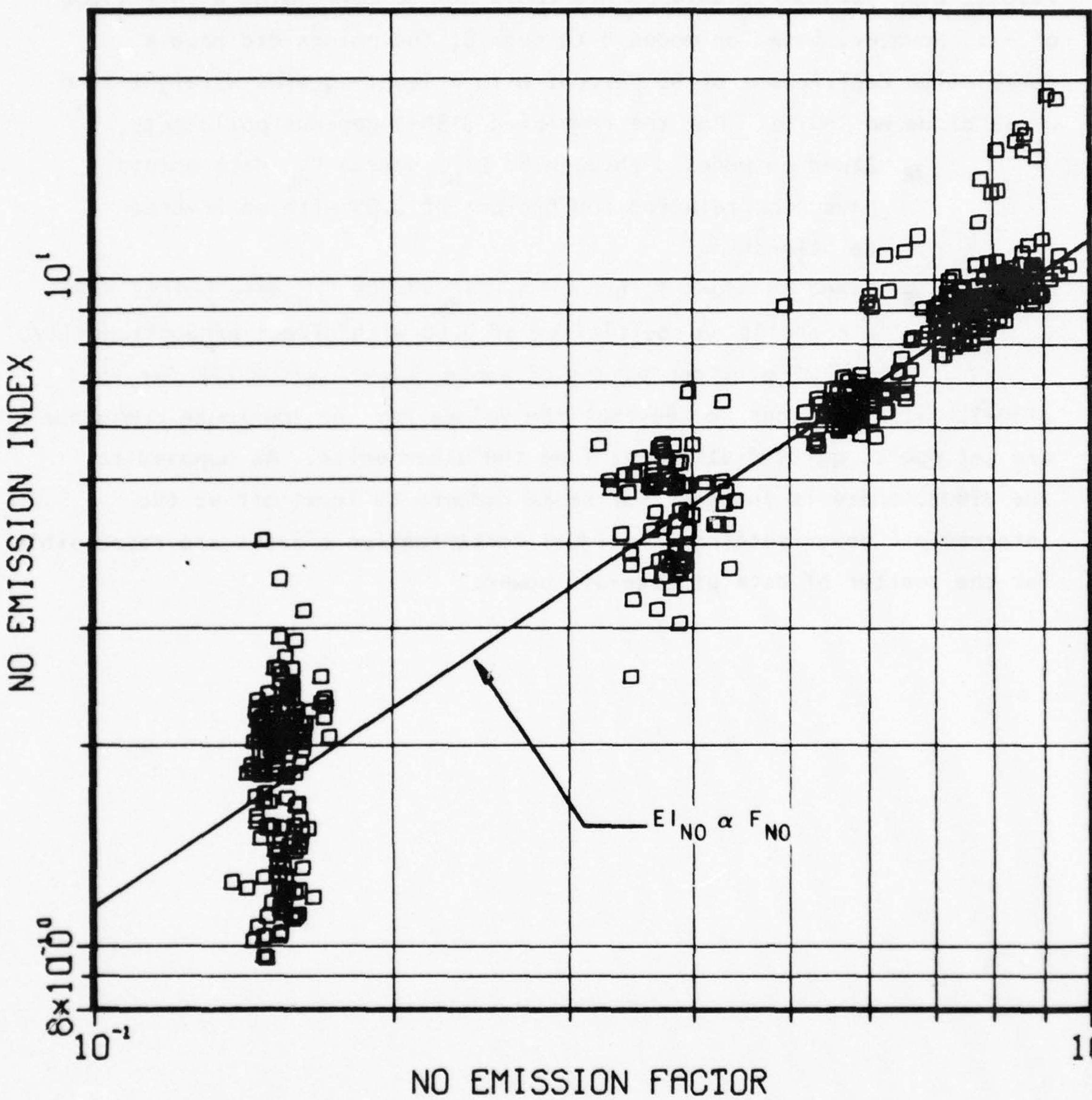


Figure 21. JT3D-7 Uncorrected NO Emission Data

as detailed in Appendix B led to a modified CO emission factor. As a result, EI_{CO} versus F_{CO} data points could not be correlated with a slope of -1. However, based on modes 6 through 8, the points did have a correlation coefficient of 98 percent with a least-squares straight line whose slope was -0.51. For the remaining JT3D-7 gaseous pollutants,

- Based on modes 6 through 8, EI_{HC} versus F_{HC} data points have a correlation coefficient of 0.99 with an inverse relationship.
- Based on modes 3 through 6, EI_{NO} versus F_{NO} data points have a correlation coefficient of 0.90 with direct proportionality.

Figure 22 provides values of smoke number versus EPR for the JT3D-7. It is obvious to see that the values for the low-smoke combustor are set apart, quite distinctly, from the other units. As opposed to the JT8Ds, there is tendency for smoke numbers to level off at the intermediate power setting. Residual contamination effects are responsible for the scatter of data at take-off power.

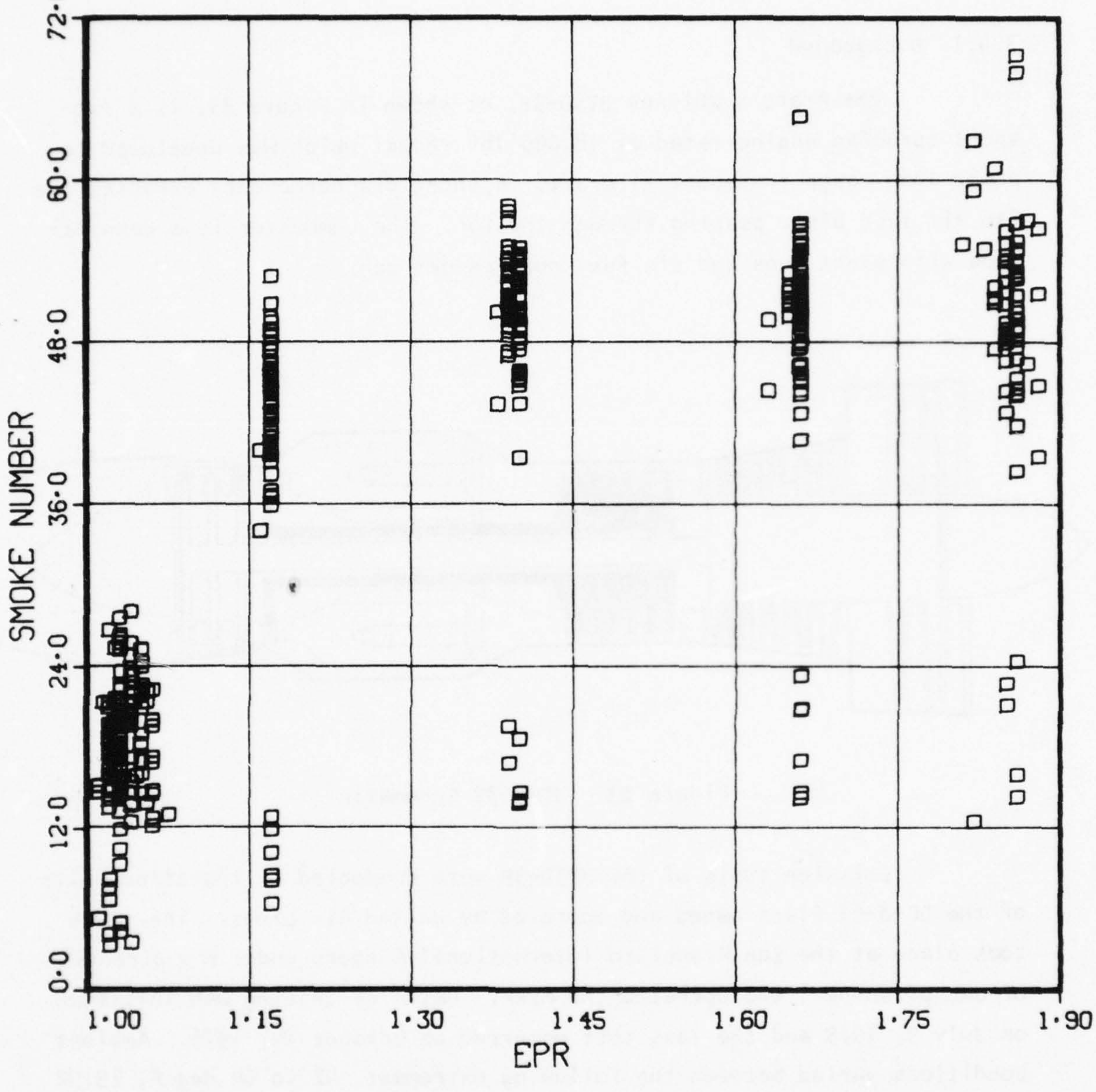


Figure 22. JT3D-7 Smoke Data

3.4 JT3D-3B ENGINE TYPE

3.4.1 Background

The Pratt & Whitney JT3D-3B, as shown in Figure 23, is a two spool turbofan engine rated at 18,000 lbf thrust which was developed to power long range transport aircraft. A short discharge duct exhausts the fan air just after passing through the fan. The combustor is a cannular type with eight cans and six fuel nozzles per can.

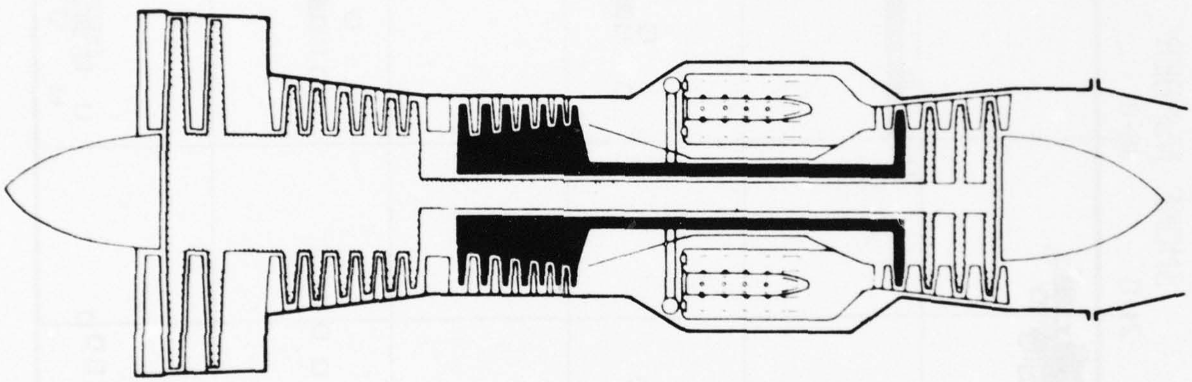


Figure **23**. JT3D-3B Schematic

Emission tests of the JT3D-3B were conducted on installed units of the DC-8-61 fleet owned and operated by United Air Lines. The tests took place at the San Francisco International Airport under the direction of UAL personnel, who operated the MERF. Baseline testing was initiated on July 9, 1975 and the last test occurred on October 14, 1976. Ambient conditions varied between the following extremes: 42 to 64 deg F, 29.92 to 30.32 in Hg abs, and 0.00464 to 0.00998 lb H_2O/lb dry air. Of the eighteen (18) units which were baselined, ten (10) units were tested through at least 2365 hours of elapsed operating time. The maximum elapsed time was 3031 hours, and up to six tests were conducted per unit. The engines had baseline TSOs of between 17,670 and 31,250 hours. A total of 78 engine tests have been documented in Volume V for the JT3D-3B.

3.4.2 Processed Data Overview

Mean values of the measured data obtained in the JT3D-3B emission tests are found in Table 11. When compared to the JT3D-3B data for gaseous pollutants of Reference 14 the CO, HC, and NO_x emission indexes again seem to be quite reasonable. As the JT3D-7, the variation with power level and the low values agree very well for CO and HC, although the peak values of Table 11 tend to be higher. For NO_x, Table 10 generally gives high values at low power and lower values at high power.

Figures 24, 25, and 26 provide, respectively, values of CO, HC and NO emission indexes versus their appropriate emission factors (as defined for the JT3D-3B in the nomenclature of Volume V). As for the JT3D-7, special considerations for the JT3D-3B led to a modified CO emission factor which could not correlate the EI_{CO} versus F_{CO} data points with a slope of -1. However, based on modes 6 through 8, the points did have a correlation coefficient of 99 percent with a least-squares straight line whose slope was -0.47. For the remaining JT3D-3B gaseous pollutants,

- Based on modes 6 through 8, EI_{HC} versus F_{HC} data points have a correlation coefficient of 0.99 with an inverse relationship.
- Based on modes 3 through 6, EI_{NO} versus F_{NO} data points have a correlation coefficient of 0.95 with direct proportionality.

Figure 27 provides values of smoke number versus EPR for the JT3D-3B. The values are seen to be very similar to those for the JT3D-7 at all power levels.

TABLE 11. - MEAN JT3D-3B TEST DATA *

Item	TEST MODE				
	Initial Idle	Take-Off	Climb	Approach	Final Idle
Performance Parameters					
EPR	1.04	1.84	1.65	1.17	1.04
Corrected N_1, per cent	33.5	103.5	97.2	68.4	33.6
Corrected N_2, per cent	60.6	101.3	98.7	86.4	60.7
Corrected Fuel Flow, lb/hr	1280	9590	7860	3060	1260
Corrected EGT, deg R	1020	1400	1310	1090	1020
Exhaust Emissions					
CO_2 Concentration, per cent	1.47	3.31	2.91	1.84	1.42
CO Emission Index, lb/1000 lb fuel	108	1.3	2.0	20.6	109
HC Emission Index, lb/1000 lb fuel	128	0.5	0.4	3.4	132
NO Emission Index, lb/1000 lb fuel	1.6	9.6	8.3	4.5	1.8
NO_x Emission Index, lb/1000 lb fuel	2.2	9.6	8.6	5.2	2.3
Smoke Number	21.9	52.2	52.0	43.3	22.6

* Without outlying values

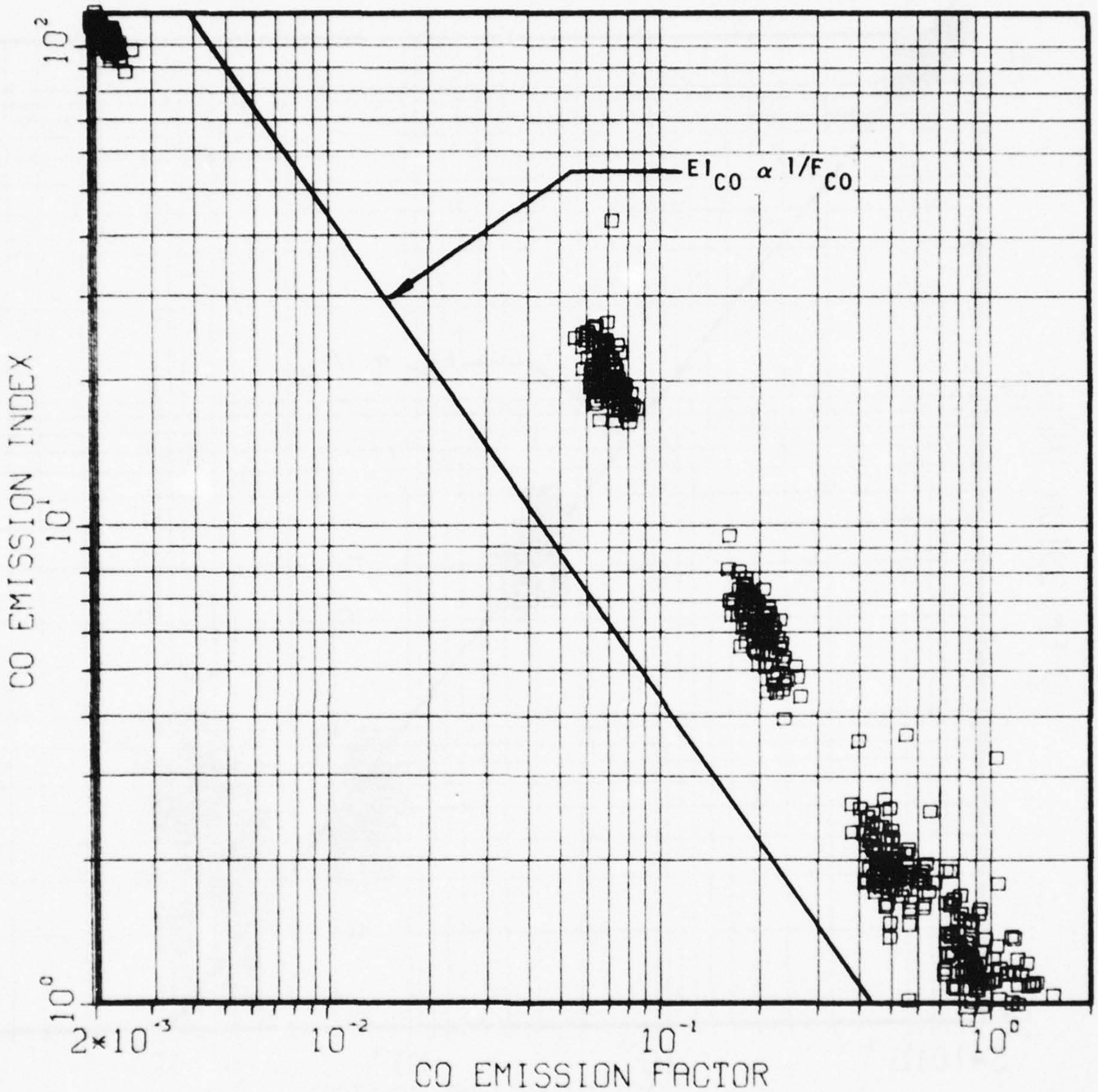


Figure 24. JT3D-3B Uncorrected CO Emission Data

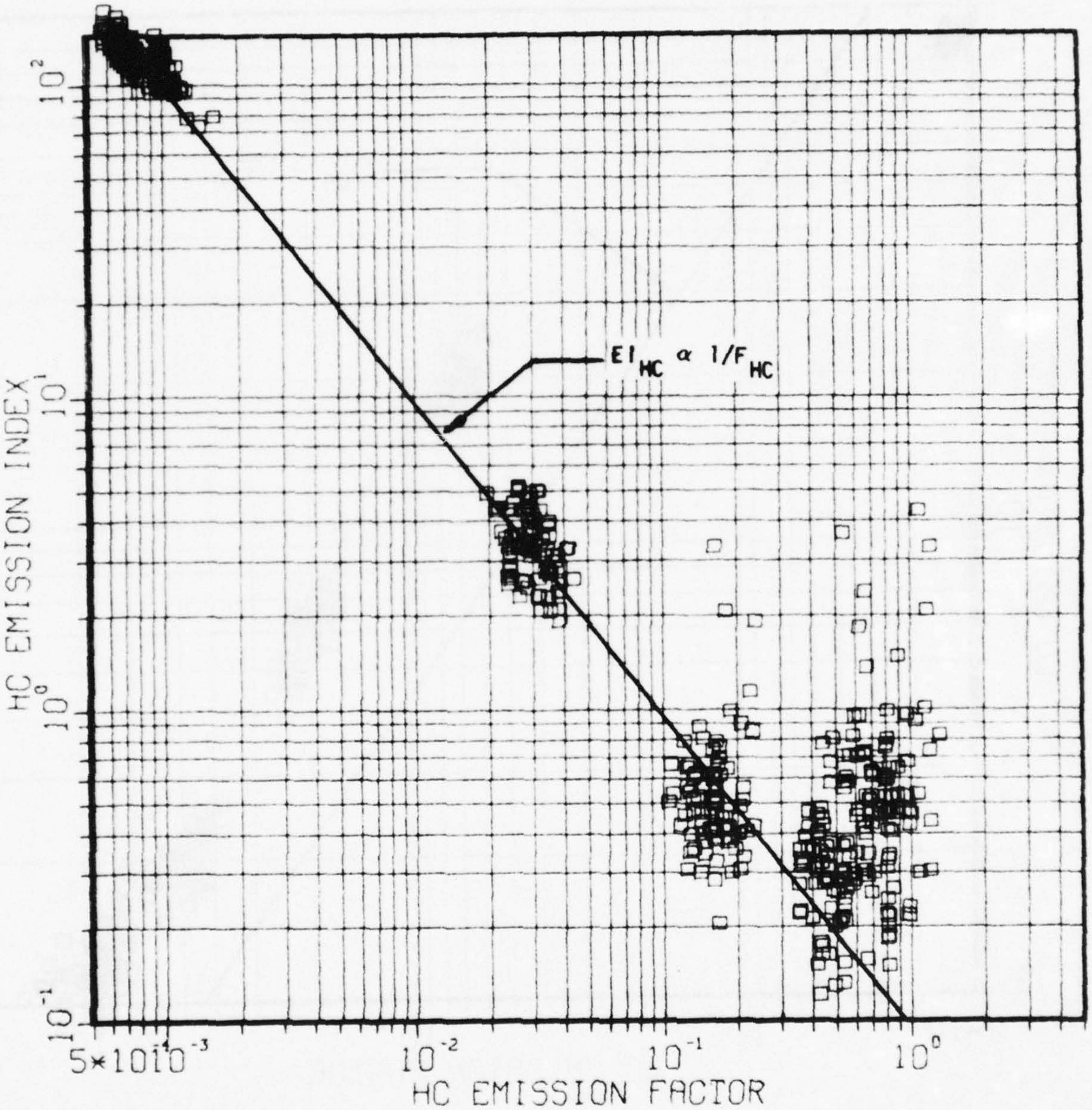


Figure 25. JT3D-3B Uncorrected HC Emission Data

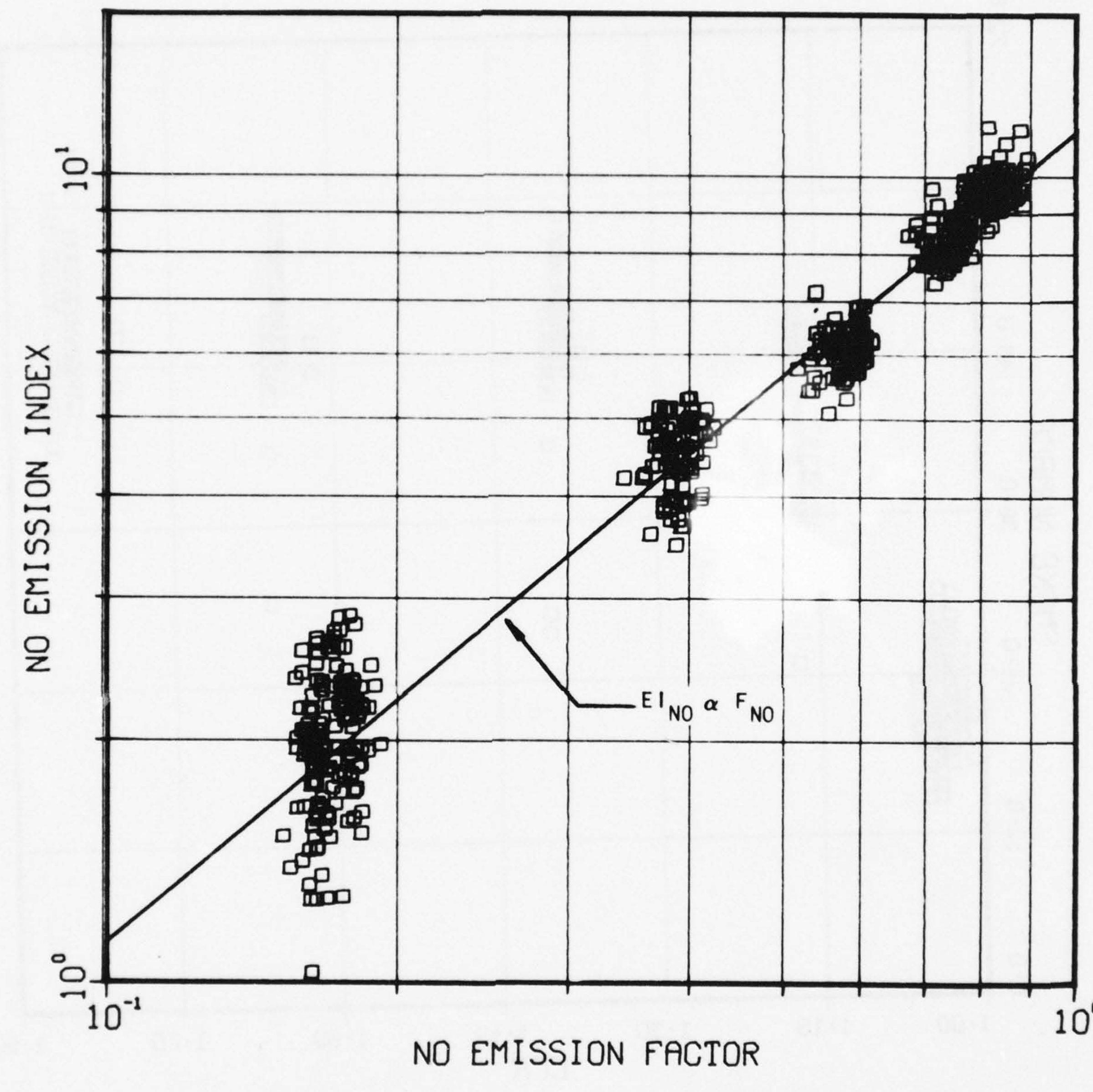


Figure 26. JT3D-3B Uncorrected NO Emission Data

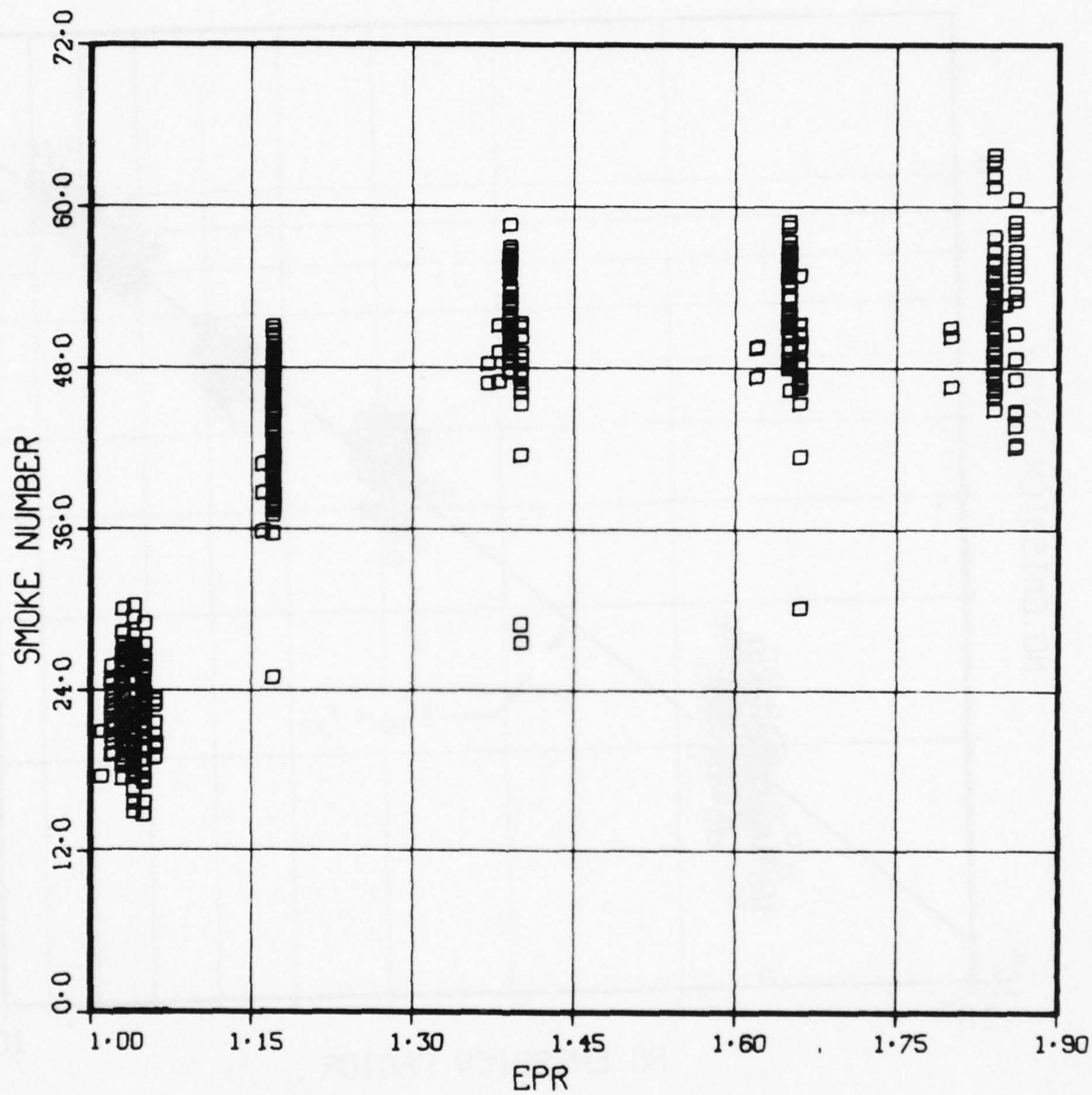


Figure 27. JT3D-3B Smoke Data

3.5 JT9D-3A ENGINE TYPE

3.5.1 Background

The Pratt & Whitney JT9D-3A, as shown in Figure 28 without exhaust plug, is a two spool turbofan engine with a compression ratio of approximately 22 to 1 and a bypass ratio of 5 to 1. The engine is rated dry at 43,500 lbf thrust and was developed to power jumbo jet transport aircraft. The combustor is an annular type design and contains two igniter plugs capable of continuous duty operation.

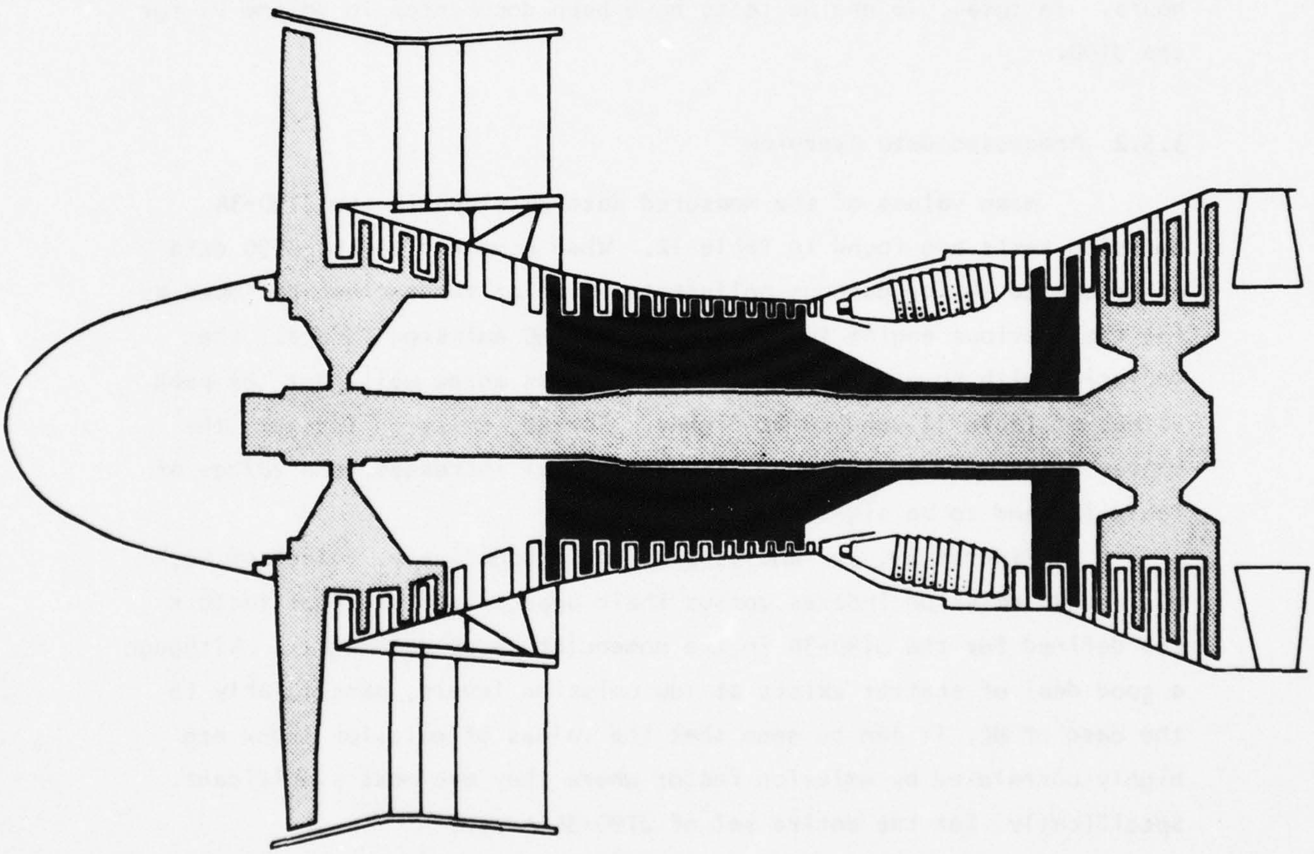


Figure 28. JT9D-3A Schematic

Emission tests of the JT9D-3A were conducted on installed units of the Boeing 747-100 fleet owned and operated by United Air Lines. The tests took place at the San Francisco International Airport under the direction of UAL personnel, who operated the MERF. Baseline testing was initiated on September 4, 1975 and the last test occurred on November 22, 1976. Ambient conditions varied between the following extremes: 42 to 76 deg F, 29.80 to 30.46 in Hg abs, and 0.0046 to 0.0102 lb H_2O/lb dry air. Of the twenty-five (25) units which were baselined, ten (10) units were tested through at least 1490 hours of elapsed operating time. The maximum elapsed time was 2722 hours, and up to seven tests were conducted per unit. The engines had baseline TSOs of between 7,623 and 15,270 hours. In total, 76 engine tests have been documented in Volume VI for the JT9D.

3.5.2 Processed Data Overview

Mean values of the measured data obtained in the JT9D-3A emission tests are found in Table 12. When compared to the JT9D data of Reference 14 for gaseous pollutants, similar tendencies are found as for the previous engine types. For CO and HC emission indexes, the variation with power level and the low values agree well, but the peak values of Table 12 tend to be higher. For NO_x emission indexes, the values agree well at idle but, as power level increases, the values of Table 12 tend to be significantly lower.

Figures 29, 30, and 31 provide, respectively, values of CO, HC, and NO emission indexes versus their appropriate emission factors (as defined for the JT9D-3A in the nomenclature of Volume VI). Although a good deal of scatter exists at low emission levels, particularly in the case of HC, it can be seen that the values of emission index are highly correlated by emission factor where they are most significant. Specifically, for the entire set of JT9D-3A tests,

- Based on modes 6 through 8, EI_{CO} versus F_{CO} data points have a correlation coefficient of 0.98 with an inverse relationship, while EI_{HC} versus F_{HC} data points have a correlation coefficient of 0.96.
- Based on modes 3 through 6, EI_{NO} versus F_{NO} data points have a correlation coefficient of 0.95 with direct proportionality.

TABLE 12. - MEAN JT9D-3A TEST DATA*

Item	TEST MODE				
	Initial Idle	Take-Off	Climb	Approach	Final Idle
Performance Parameters					
EPR	1.02	1.40	1.31	1.08	1.02
Corrected N_1, per cent	28.5	89.8	84.3	56.5	27.5
Corrected N_2, per cent	64.5	94.5	92.7	83.9	65.2
Corrected Fuel Flow, lb/hr	1920	15,800	12,900	5210	1840
Corrected EGT, deg R	1160	1870	1770	1400	1180
Exhaust Emissions					
CO_2 Concentration, per cent	1.72	3.92	3.48	2.35	1.71
CO Emission Index, lb/1000 lb fuel	81.3	0.6	0.7	7.1	82.0
HC Emission Index, lb/1000 lb fuel	35.4	1.0	0.7	0.9	32.7
NO Emission Index, lb/1000 lb fuel	2.2	24.9	18.6	6.3	1.8
NO_x Emission Index, lb/1000 lb fuel	3.3	25.6	19.1	7.6	3.2
Smoke Number	1.5	11.9	9.7	2.7	1.3

* Without outlying values

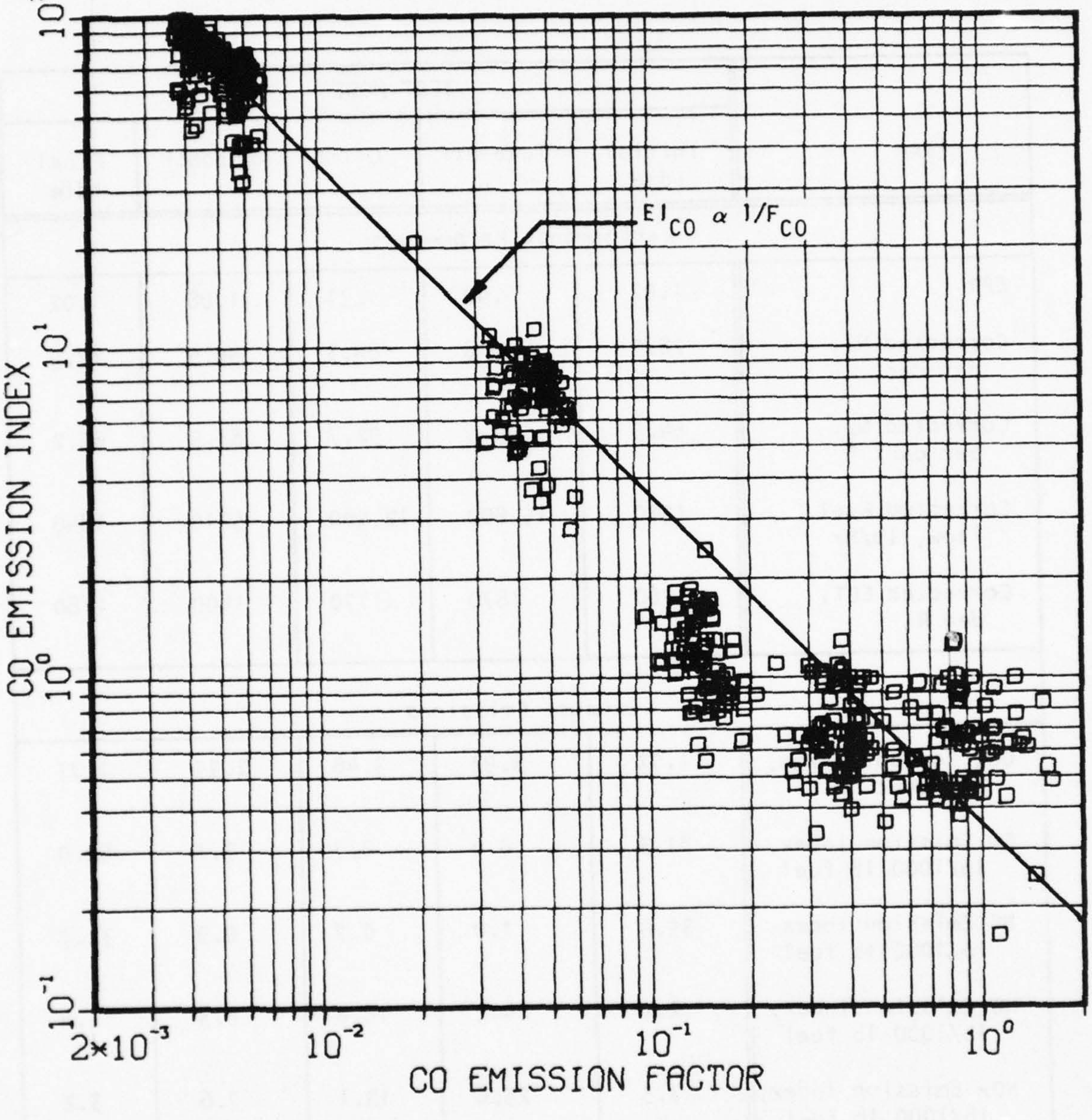


Figure 29. JT9D-3A Uncorrected CO Emission Data

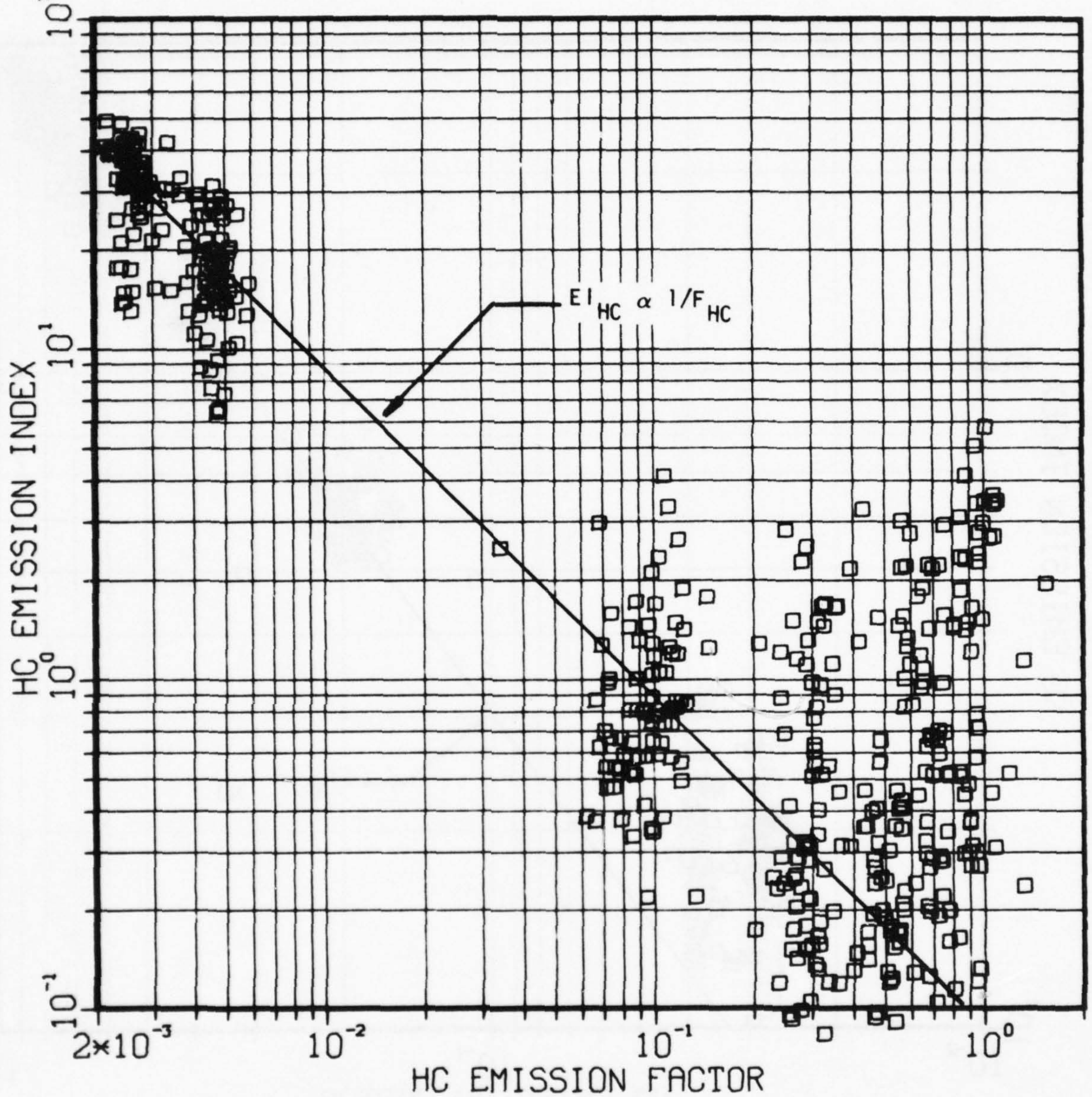


Figure 30. JT9D-3A Uncorrected HC Emission Data

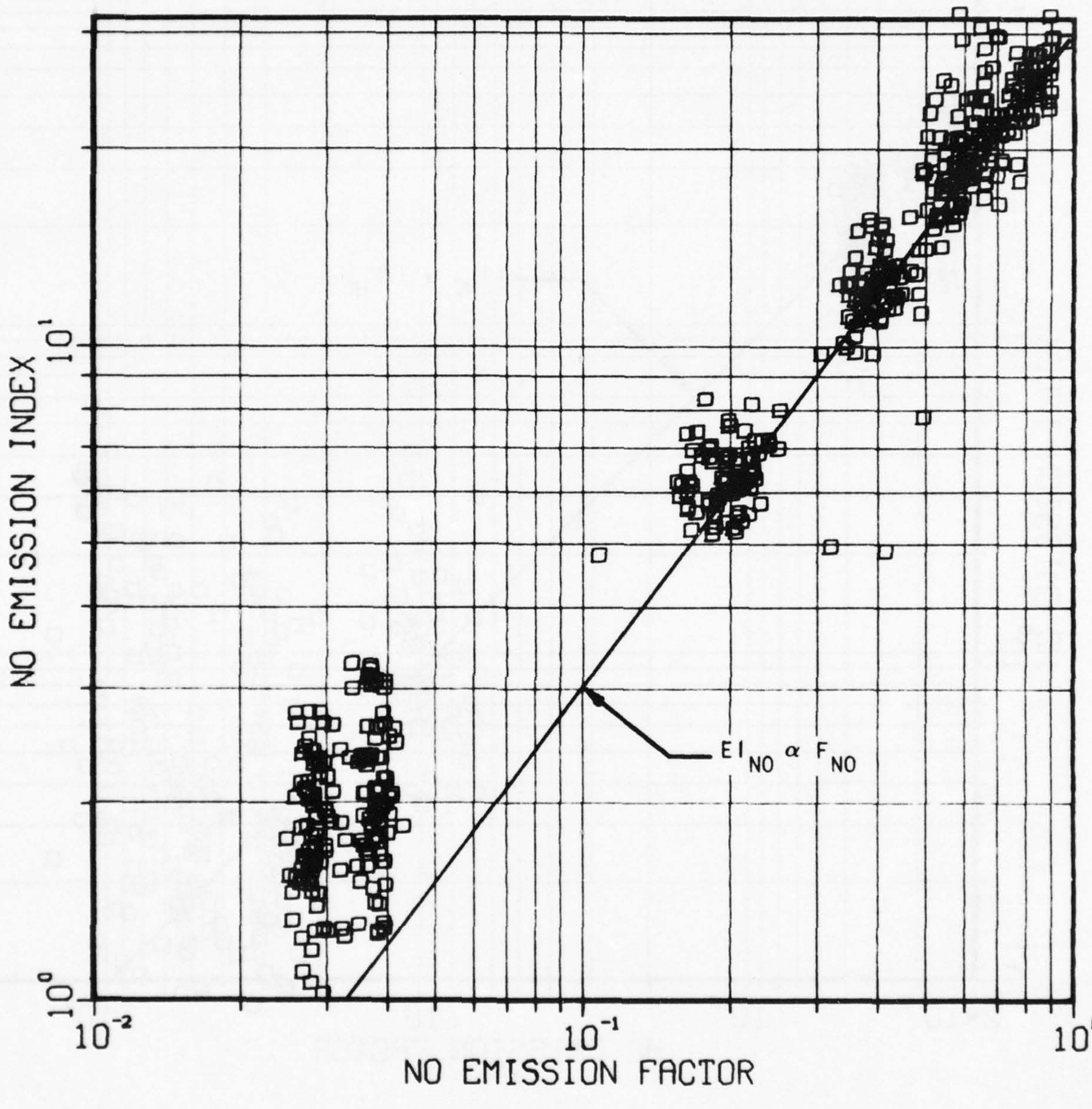


Figure 31. JT9D-3A Uncorrected NO Emission Data

Figure 32 provides values of smoke number versus EPR for the JT9D-3A. A great deal of scatter can be seen in the values which increase steadily with power level.

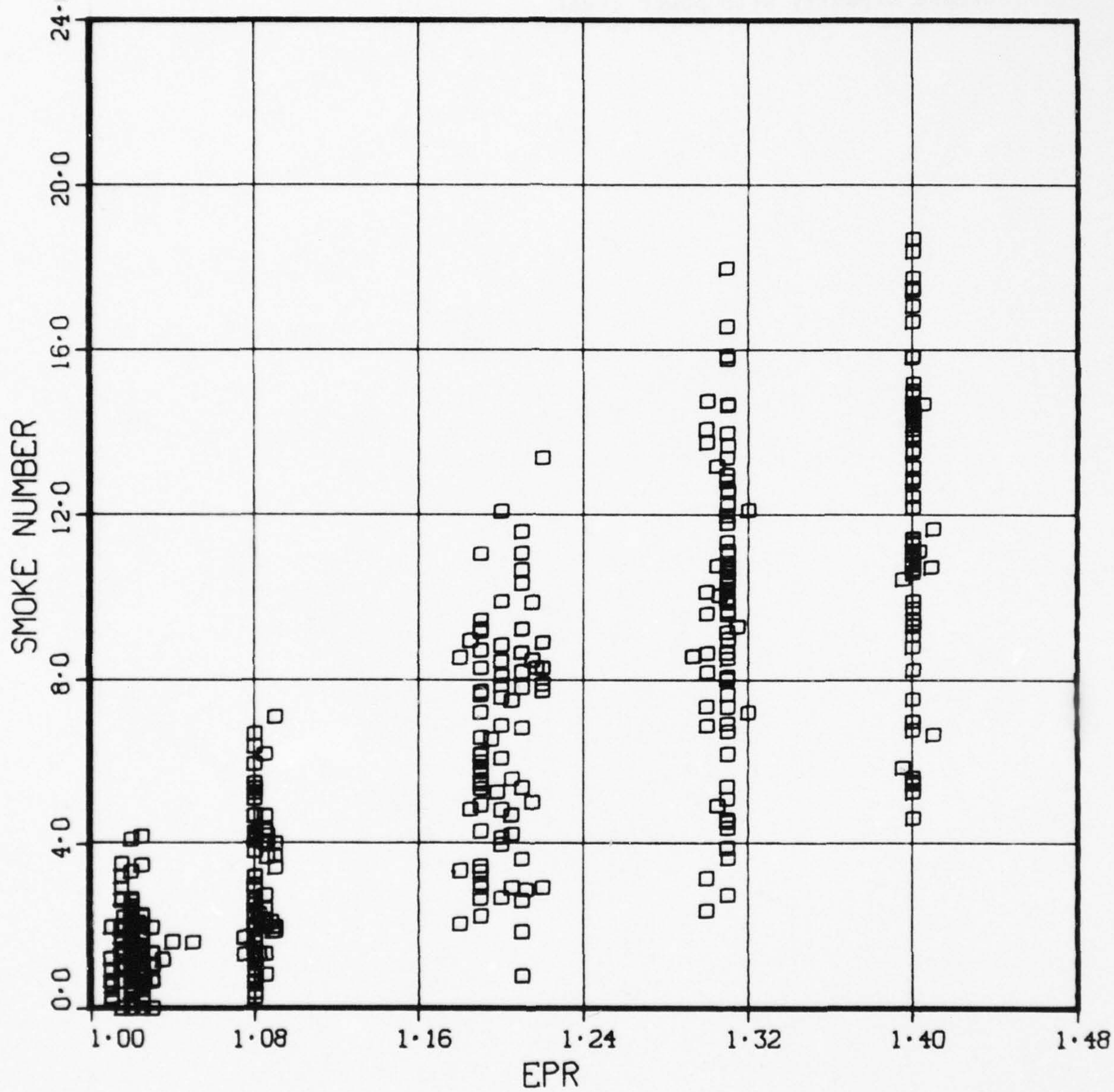


Figure 32. JT9D-3A Smoke Data

3.6 RB211-22B ENGINE TYPE

3.6.1 Background

The Rolls-Royce RB211-22B, as shown in Figure 33, is a three spool, high bypass turbofan engine with a compression ratio of 27 to 1. The engine is rated at 40,600 lbf thrust and was developed to power jumbo jet transport aircraft. The combustor is annular and is fitted with 18 fuel spray nozzle assemblies, two of which incorporate high energy igniter plugs.

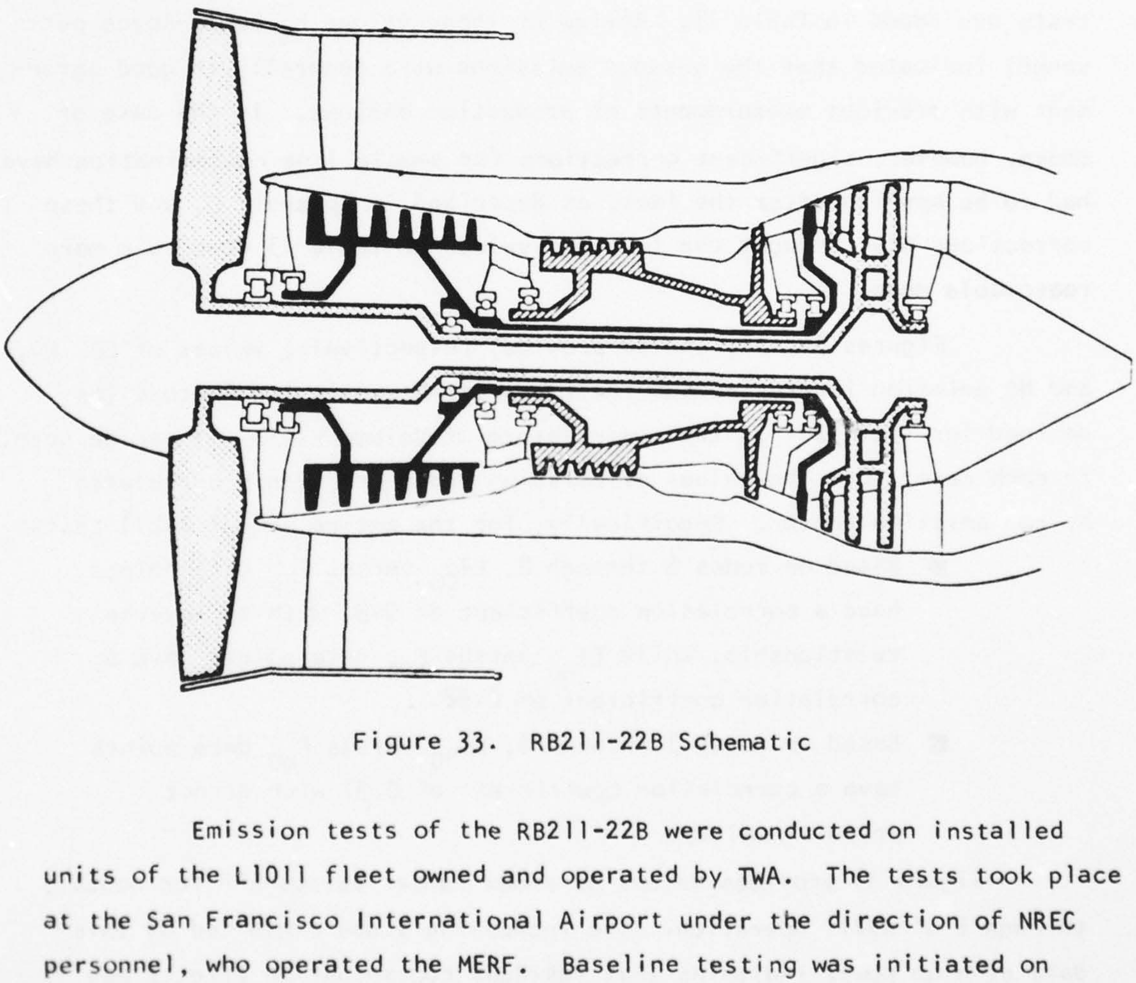


Figure 33. RB211-22B Schematic

Emission tests of the RB211-22B were conducted on installed units of the L1011 fleet owned and operated by TWA. The tests took place at the San Francisco International Airport under the direction of NREC personnel, who operated the MERF. Baseline testing was initiated on June 1, 1976 and the last test occurred on October 8, 1976. Ambient conditions varied between the following extremes: 59 to 84 deg F, 29.80

to 30.10 in Hg abs, and 0.00618 to 0.01162 lb H_2O/lb dry air. Of the nineteen (19) units which were baselined, ten (10) units were tested through at least 500 hours of elapsed operating time. The maximum elapsed time was 819 hours, and up to six tests were conducted per unit. The engines had baseline TSOs of between 859 and 6,295 hours. A total of 55 engine tests have been documented in Volume VII for the RB211.

3.6.2 Processed Data Overview

Mean values of the measured data obtained in the RB211 emission tests are found in Table 13. Review of these values by Rolls-Royce personnel indicated that the gaseous emissions were generally in good agreement with previous measurements of production engines. In the case of smoke, however, significant corrections for sample line contamination have had to be applied after the fact, as described in Appendix C, and these corrections have brought the take-off values of Table 13 down to a more reasonable mean.

Figures 34, 35, and 36 provide, respectively, values of CO, HC, and NO emission *indexes versus their appropriate emission factors* (as defined for the RB211 in the nomenclature of Volume VII). It can be seen, in each case, that the values of emission index are highly correlated by the emission factor. Specifically, for the entire set of RB211 tests,

- Based on modes 6 through 8, EI_{CO} versus F_{CO} data points have a correlation coefficient of 0.97 with an inverse relationship, while EI_{HC} versus F_{HC} data points have a correlation coefficient of 0.98.
- Based on modes 3 through 6, EI_{NO} versus F_{NO} data points have a correlation coefficient of 0.97 with direct proportionality.

Figure 37 provides values of smoke number versus EPR for modes 3 through 6 of RB211 operation. The increasing slope exhibited by this data at high power indicates that residual contamination effects may still be present.

TABLE 13. - MEAN RB211-22B TEST DATA*

Item	TEST MODE				
	Initial Idle	Take-Off	Climb	Approach	Final Idle
Performance Parameters					
EPR	1.02	1.53	1.45	1.13	1.02
Corrected N_1, per cent	23.4	92.8	87.2	54.1	23.2
Corrected N_2, per cent	44.6	96.8	93.8	76.8	44.1
Corrected N_3, per cent	62.1	91.7	89.6	77.5	62.2
Corrected Fuel Flow, lb/hr	1560	15,700	13,000	4230	1510
Corrected EGT, deg R	1040	1710	1610	1210	1030
Exhaust Emissions					
CO_2 Concentration, per cent	1.54	3.88	3.45	1.98	1.46
CO Emission Index, lb/1000 lb fuel	96.3	1.3	2.0	22.2	108
HC Emission Index, lb/1000 lb fuel	93.4	0.5	0.3	6.7	99.8
NO Emission Index, lb/1000 lb fuel	1.2	34.3	26.2	6.4	1.1
NO_x Emission Index, lb/1000 lb fuel	2.1	34.9	26.9	8.4	2.4
Smoke Number	---	24.2	17.8	6.6	---

* Without outlying values

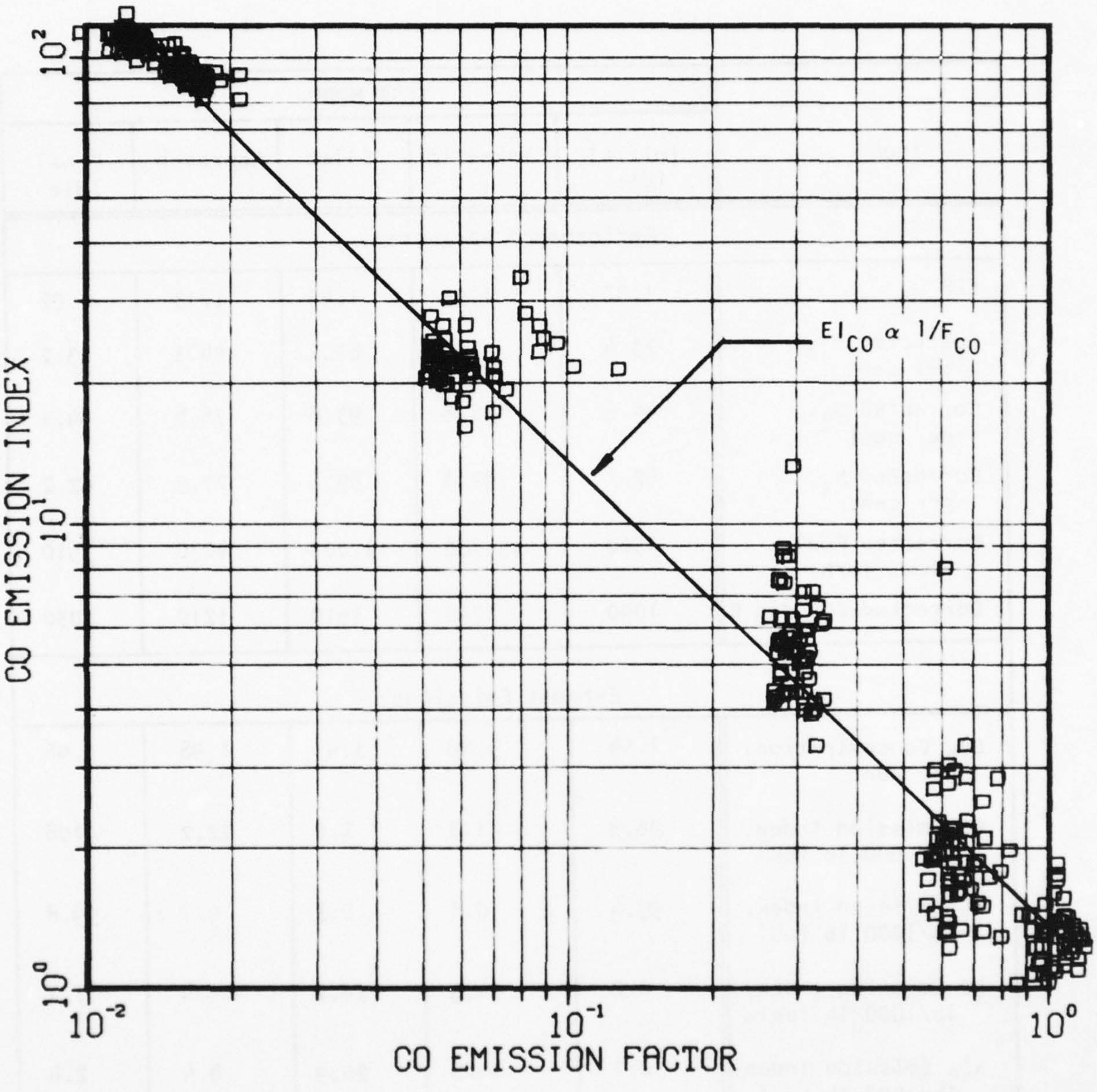


Figure 34. RB211-22B Uncorrected CO Emission Data

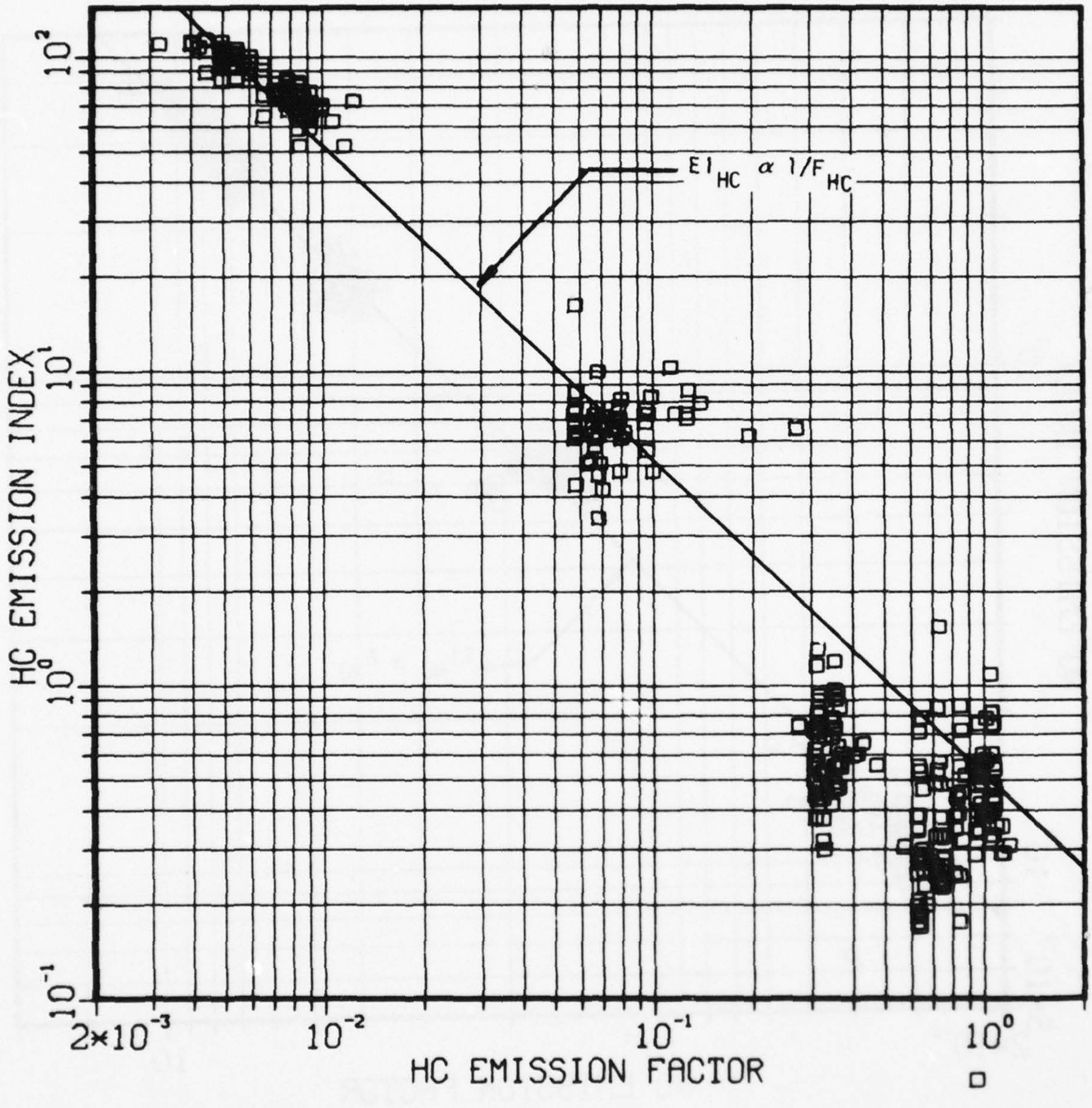


Figure 35. RB211-22B Uncorrected HC Emission Data

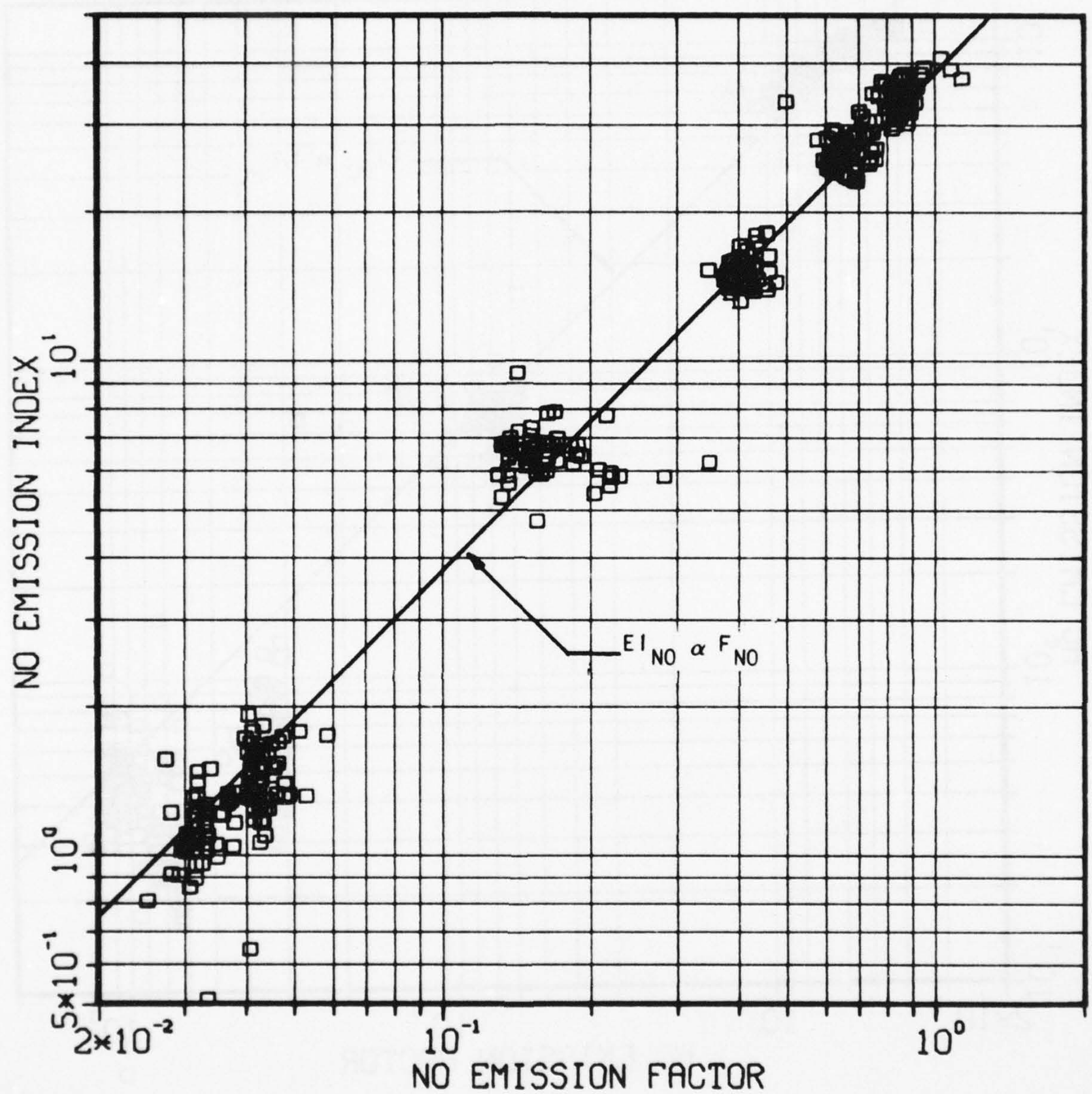


Figure 36. RB211-22B Uncorrected NO Emission Data

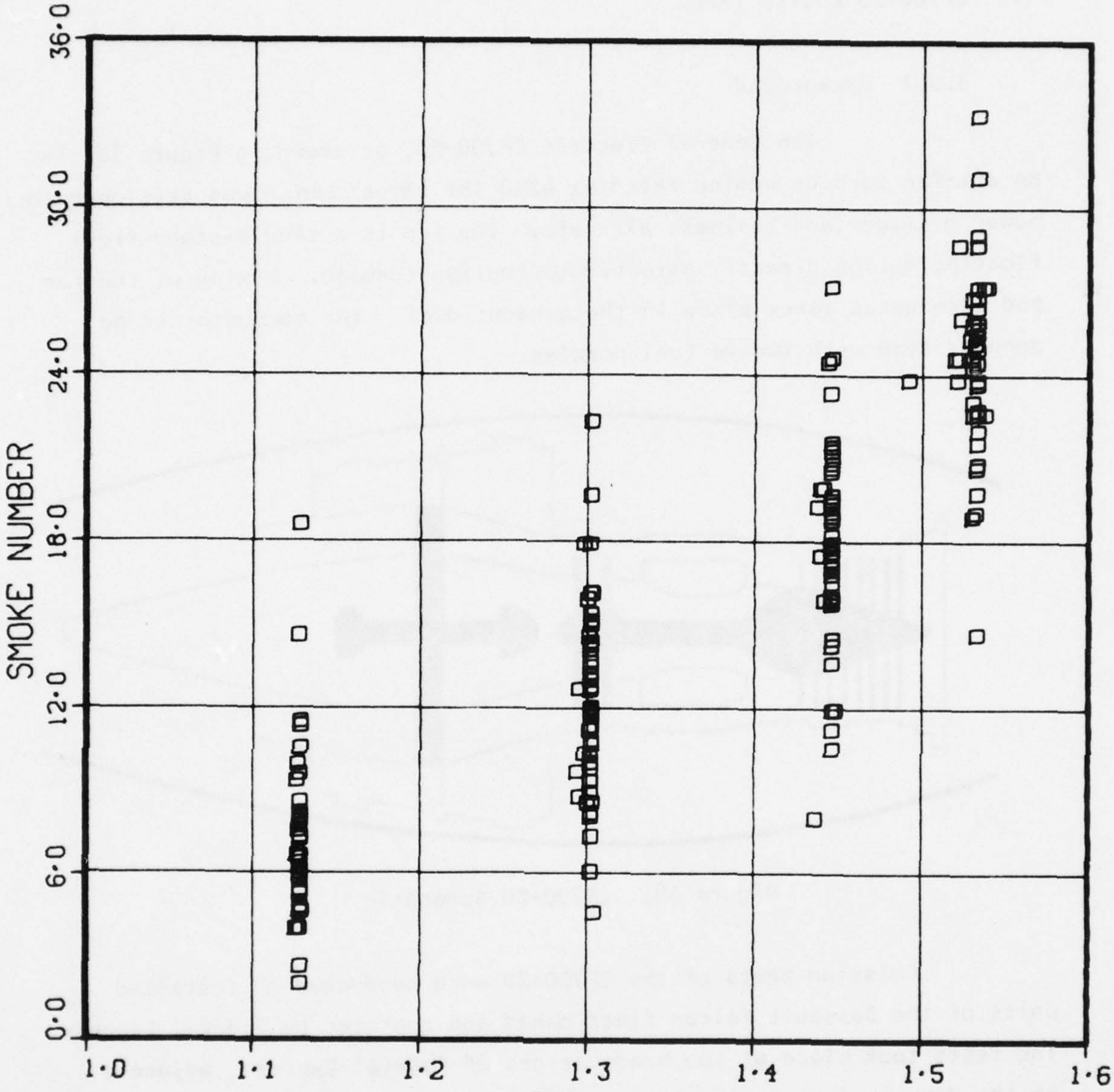


Figure 37. RB211-22B Smoke Data

3.7 CF700-2D ENGINE TYPE

3.7.1 Background

The General Electric CF700-2D, as shown in Figure 38, is an aft-fan turbine engine rated at 4250 lbf thrust which was developed to power military and business aircraft. The fan is a single-stage free-floating design directly attached to the fan turbine. Mixing of the fan and core gases takes place in the exhaust duct. The combustor is an annular type with twelve fuel nozzles.

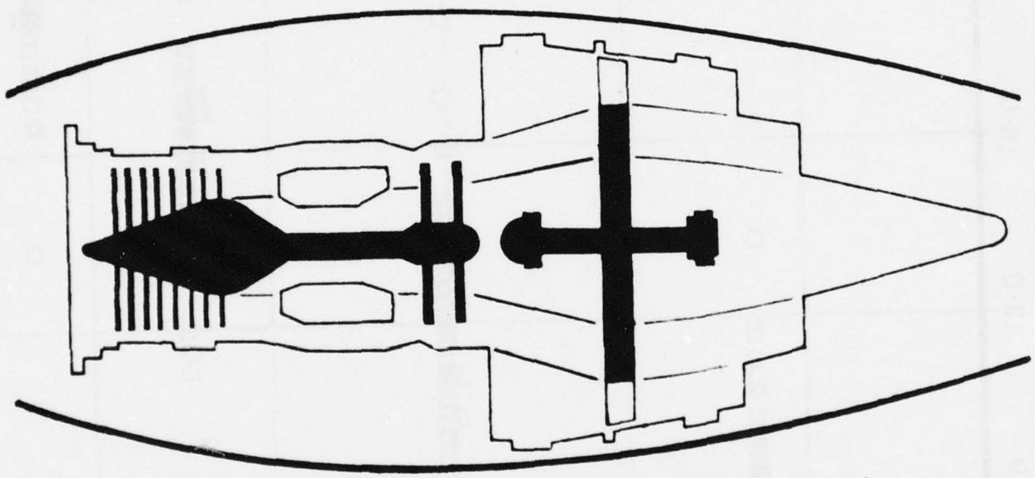


Figure 38. CF700-2D Schematic

Emission tests of the CF700-2D were conducted on installed units of the Dassault Falcon fleet owned and operated by Federal Express. The tests took place at the headquarters of Federal Express, adjacent to the Memphis International Airport. They were conducted under the direction of NREC personnel, who operated the MERF. Baseline testing was initiated on December 6, 1975 and the last tests occurred on July 17, 1976. Ambient conditions varied between the following extremes: 40 to 83 deg F, 29.75 to 30.43 in Hg abs, and 0.00097 to 0.01504 lb H_2O/lb dry air. Of the sixteen (16) units which were baselined, eleven

(11) were tested through at least 898 hours of elapsed operating time. The maximum elapsed time was 1205 hours, and up to four tests were conducted per unit. The engines had baseline TSOs of between 297 and 3054 hours (TSO, in this case, is assumed to be "time since extended maintenance"). With a final series of tests precluded, a total of 48 engine tests have been documented in Volume VIII for the CF700.

3.7.2 Processed Data Overview

Mean values of the measured data obtained in the CF700-2D emission tests are found in Table 14. A published source of comparative emission data has not been found but, based on personal communication with GE personnel, it appears that the tabulated emission data is reasonable.

Figures 39, 40, and 41 provide, respectively, values of CO, HC, and NO emission indexes versus their appropriate emission factors (as defined for the CF700-2D in the nomenclature of Volume VIII). It is apparent, in each case, that the values of emission index are correlated by the emission factor, although considerable scatter exists for NO at low power. Specifically, for the entire set of CF700 tests,

- *Based on modes 6 through 8,* EI_{CO} *versus* F_{CO} data points have a correlation coefficient of 0.97 with an inverse relationship, while EI_{HC} versus F_{HC} data points have a correlation coefficient of 0.94.
- Based on modes 3 through 6, EI_{NO} versus F_{NO} data points have a correlation coefficient of 0.89 with direct proportionality.

Figure 42 provides values of smoke number versus EPR for the CF700. These values, which were only obtained for modes 3 through 6, again show considerable scatter and an increasing trend to higher values as take-off power is approached.

TABLE 14. - MEAN CF700-2D TEST DATA*

Item	TEST MODE				
	Initial Idle	Take-Off	Climb	Approach	Final Idle
Performance Parameters					
EPR	1.05	1.53	1.47	1.13	1.05
Corrected N_1, ** per cent	28.6	99.2	95.9	56.2	29.2
Corrected N_2, ** per cent	47.1	97.0	94.5	74.4	47.3
Corrected Fuel Flow, lb/hr	536	2740	2410	992	531
Corrected EGT, deg R	1450	1720	1640	1330	1430
Exhaust Emissions					
CO_2 Concentration, per cent	0.88	1.57	1.40	0.90	0.85
CO Emission Index, lb/1000 lb fuel	166	28.5	32.2	88.5	169
HC Emission Index, lb/1000 lb fuel	22.4	1.2	1.1	5.3	22.5
NO Emission Index, lb/1000 lb fuel	1.6	3.4	3.2	1.6	1.4
NO_x Emission Index, lb/1000 lb fuel	1.8	3.7	3.6	2.3	1.8
Smoke Number	---	15.4	13.6	3.7	---

* Without outlying values

** N_1 refers to fan speed while N_2 refers to core speed

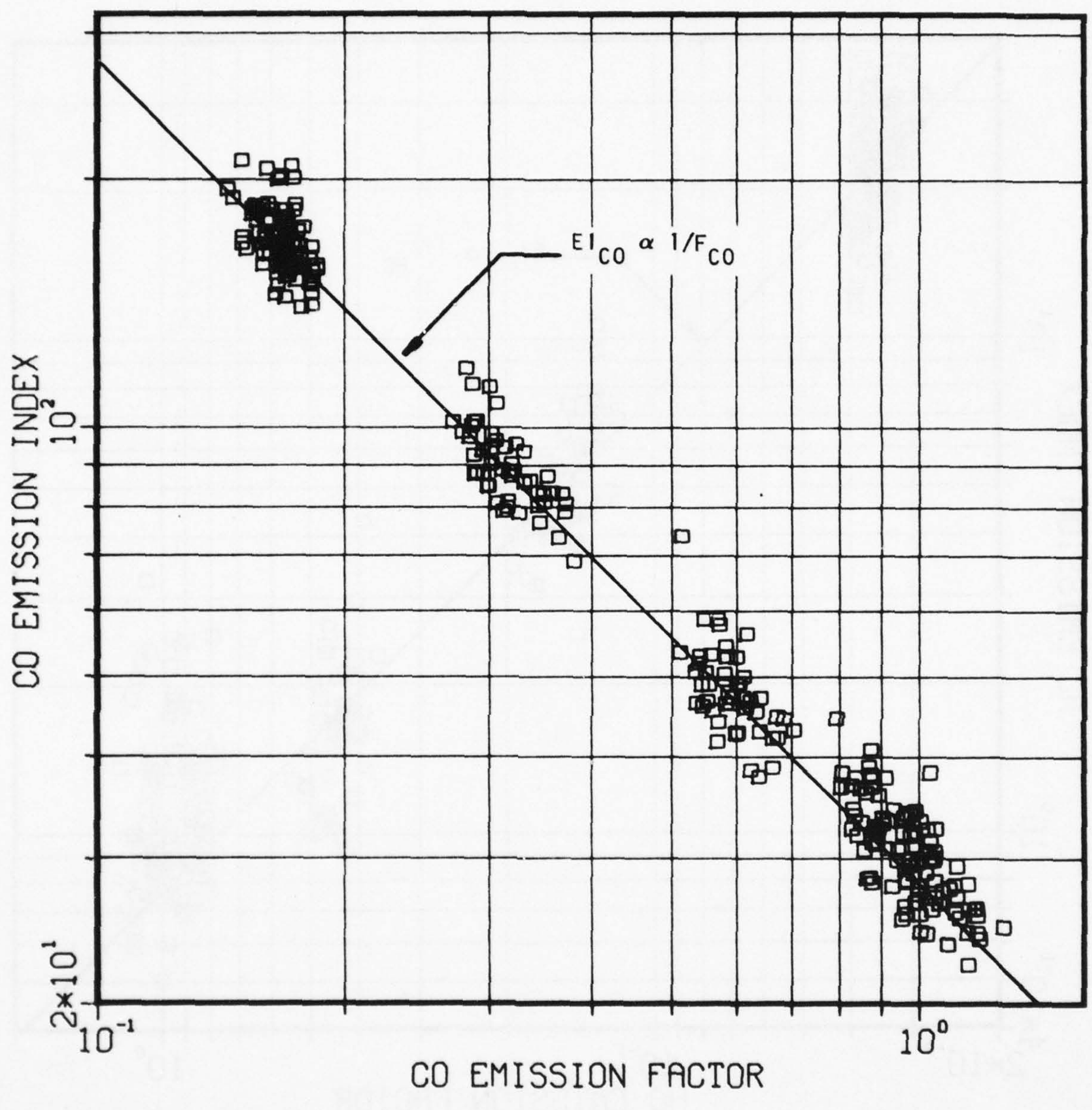


Figure 39. CF700-2D Uncorrected CO Emission Data

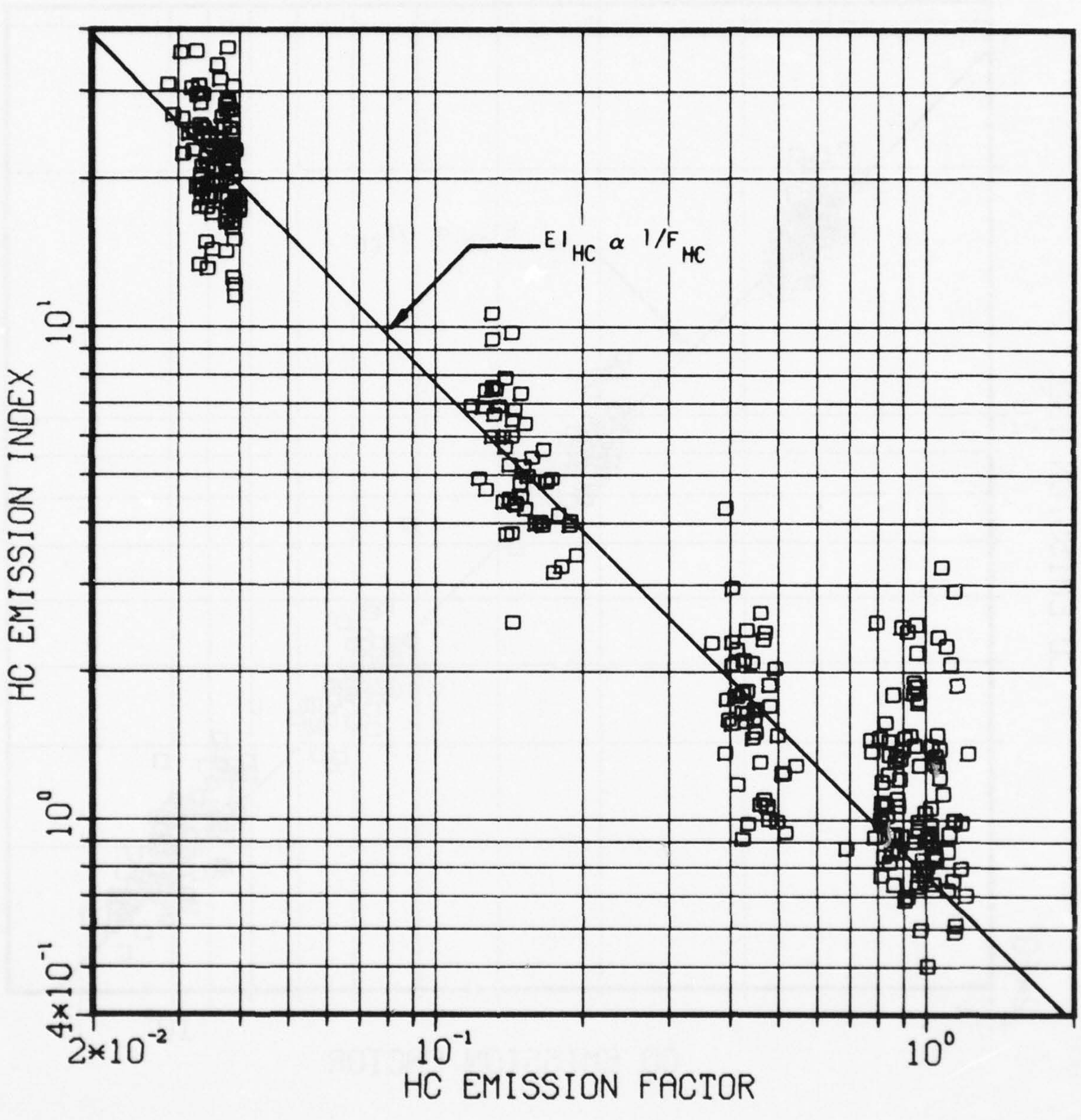


Figure 40. CF700-2D Uncorrected HC Emission Data

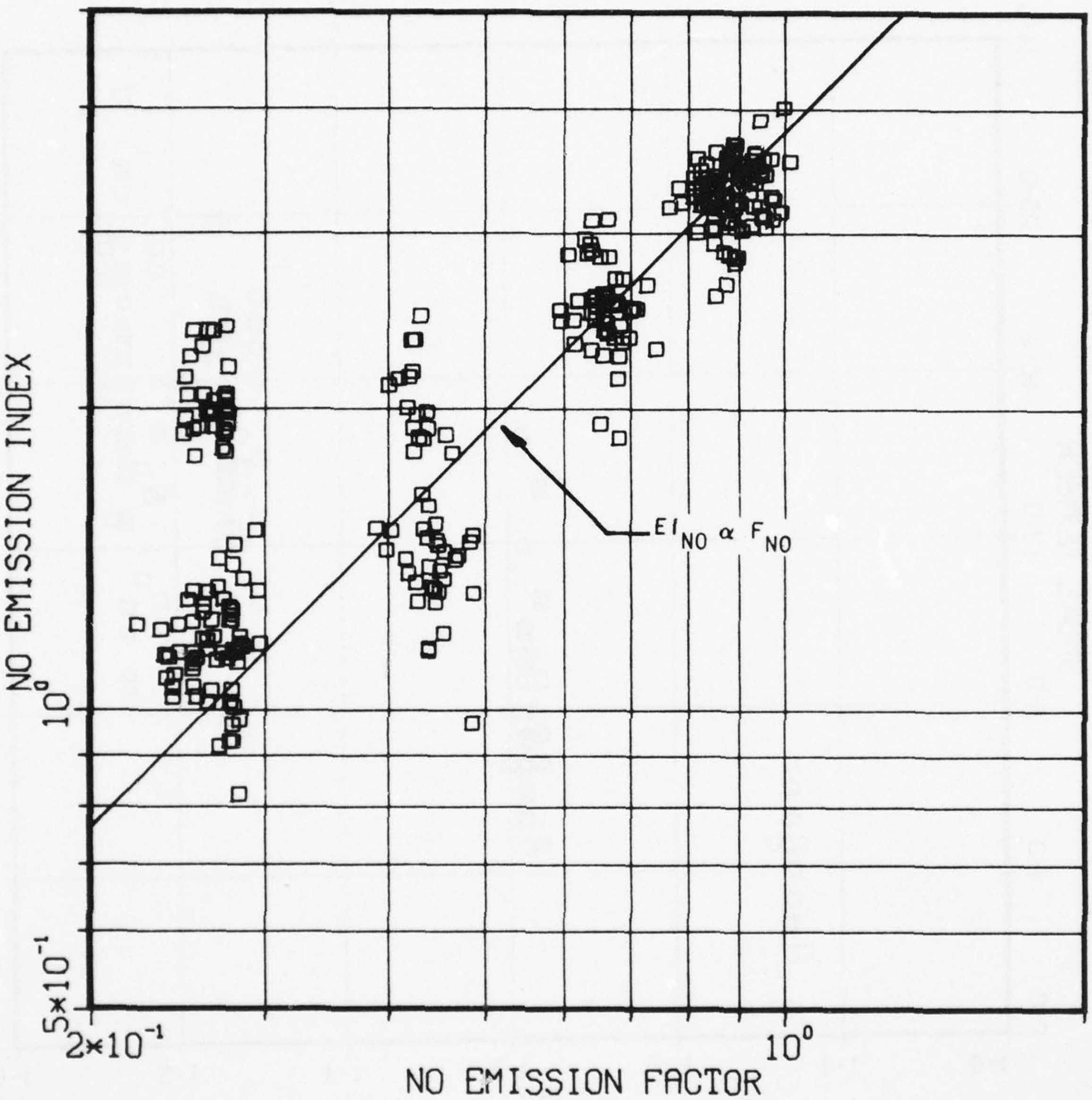


Figure 41. CF700-2D Uncorrected NO Emission Data

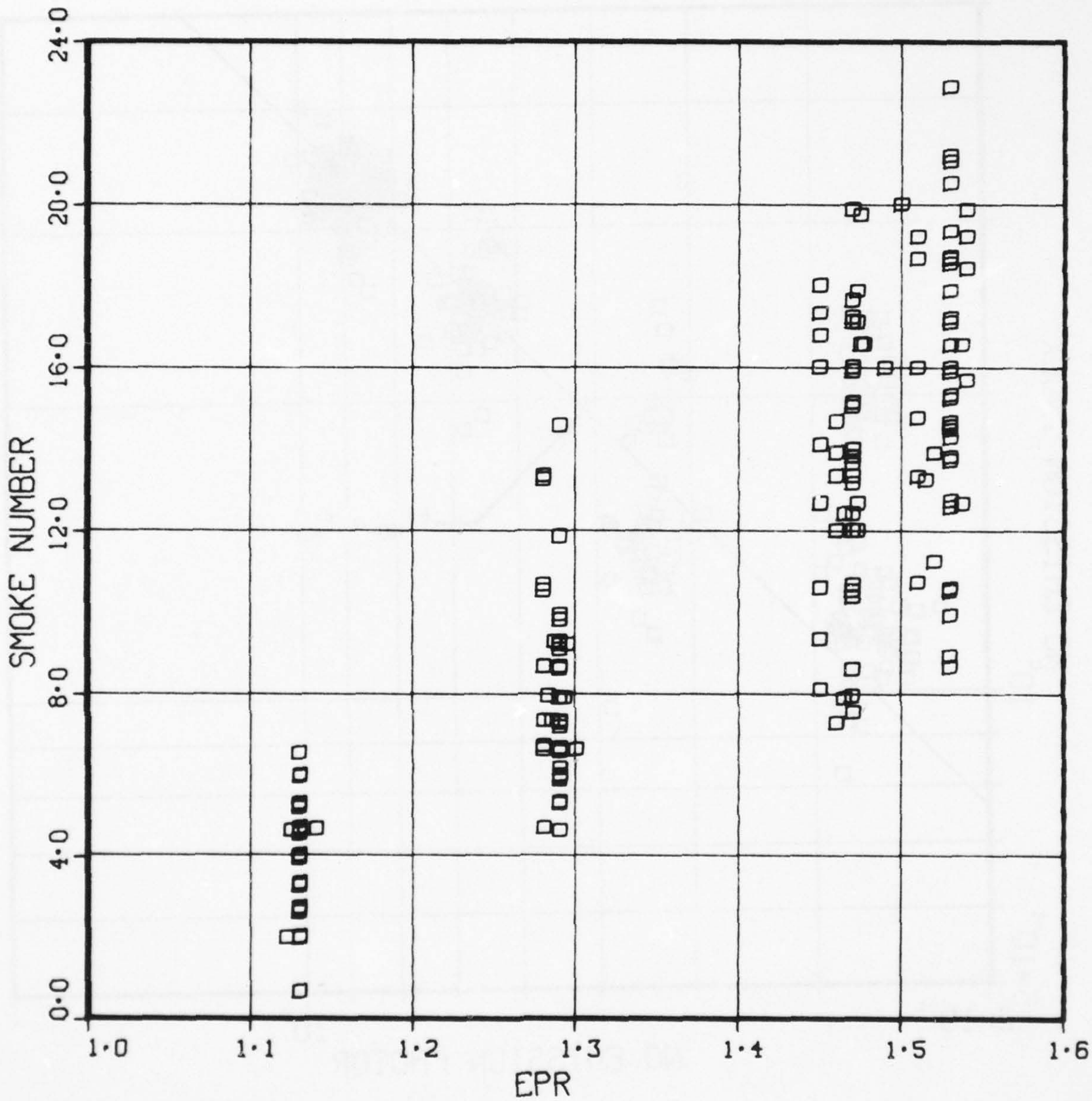


Figure 42. CF700-2D Smoke Data

AD-A070 573   NORTHERN RESEARCH AND ENGINEERING CORP CAMBRIDGE MASS   F/G 13/2
TIME DEGRADATION FACTORS FOR TURBINE ENGINE EXHAUST EMISSIONS. --ETC(U)
MAY 78 M PLATT, E R NORSTER   DOT-FA74NA-1100
UNCLASSIFIED   NREC-1238-6   FAA-RD-78-56-1   NL

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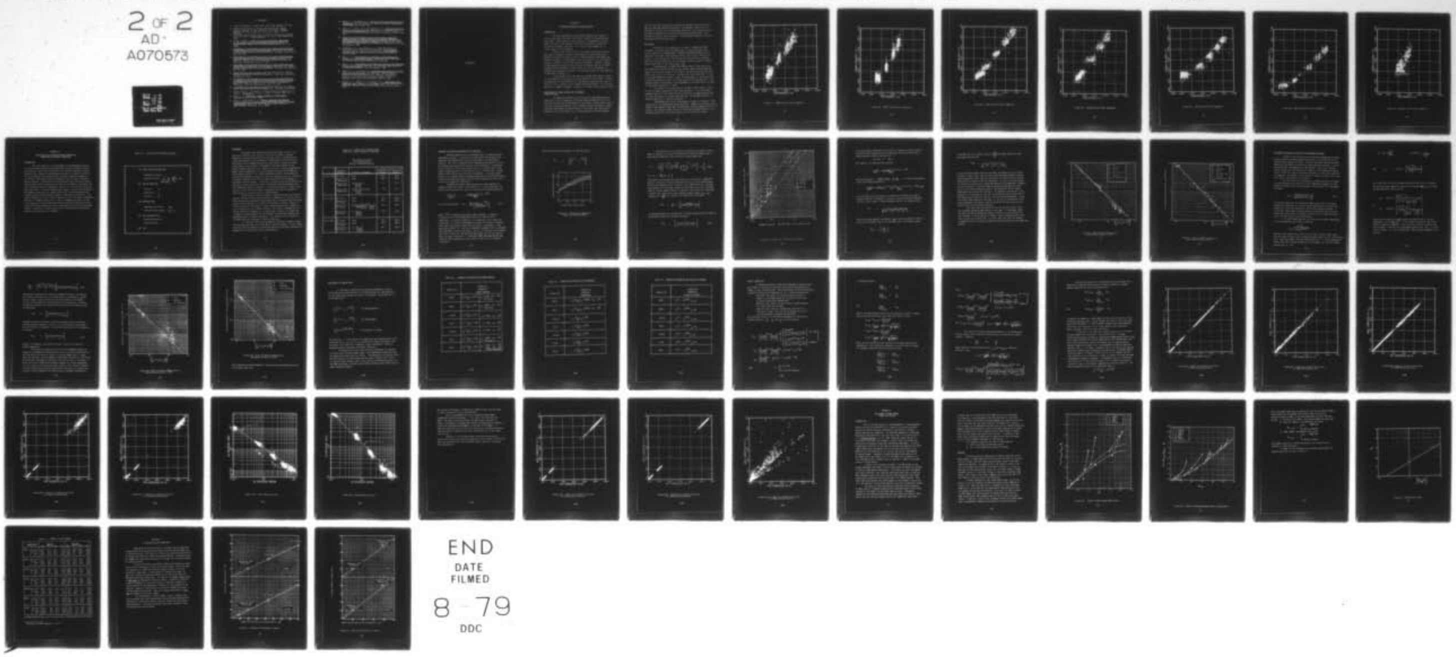

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4. REFERENCES

1. Clean Air Amendments of 1970, Public Law 91-604, December 31, 1970.
2. "Control of Air Pollution from Aircraft and Aircraft Engines, Emission Standards and Test Procedures for Aircraft", Federal Register, vol. 38, no. 136, Part II, July 17, 1973.
3. "Compliance with Aircraft Emission Standards Issued by Environmental Protection Agency", Federal Register, vol. 38, no. 248, December 28, 1973.
4. Slusher, Gerald R., Analytical Study of Mixed-Flow JT8D Exhaust Emissions Measurements for Fixed-Probe Requirements (Report No. FAA-RD-76-140), Federal Aviation Administration, Washington, D.C. 20590.
5. Development of Time Degradation Factors for Turbine Engine Emissions, Project Manual Section II - Sampling Probes (NREC Report No. 1238-2), Northern Research and Engineering Corporation, Cambridge, Massachusetts, April 22, 1975.
6. Development of Time Degradation Factors for Turbine Engine Emissions, Project Manual Section I - Mobile Emission Research Facility (NREC Report No. 1238-1), Northern Research and Engineering Corporation, Cambridge, Massachusetts, April 10, 1975.
7. Development of Time Degradation Factors for Turbine Engine Emissions, Project Manual Section III - Test Procedures (NREC Report No. 1238-3), Northern Research and Engineering Corporation, Cambridge, Massachusetts, April 9, 1975.
8. Special Emission Tests of FAA A/C 727 (NREC Memorandum No. 1238-M4), Northern Research and Engineering Corporation, Cambridge, Massachusetts, September 16, 1976.
9. Development of Time Degradation Factors for Turbine Engine Emissions - A Computing System for the Analysis and Storage of Aircraft Emission Data (NREC Report No. 1238-5), Northern Research and Engineering Corporation, Cambridge, Massachusetts, April 14, 1975.
10. System NREC Auxiliary Computer Programs (NREC Memorandum No. 1238-M5), Northern Research and Engineering Corporation, Cambridge, Massachusetts.
11. Grubbs, Frank E., " Procedures for Detecting Outlying Observations in Samples", Technometrics, volume 11, number 1, February 1969, pp. 1-21.
12. Adams, H. T., Elements of Internal Combustion Turbine Theory, Cambridge University Press, 1949.
13. Allen, L., and Slusher, G. R., Ambient Temperature and Humidity Correction Factors for Exhaust Emissions from Two Classes of Aircraft Turbine Engines (Report No. FAA-RD-76-149), Federal Aviation Administration, Washington, D. C., 20590.

14. Bogdan, L., and McAdams, H. T., Analysis of Aircraft Exhaust Emission Measurements (CAL No. NA-5007-K-1), Cornell Aeronautical Laboratory, Buffalo, New York, October 1971.

15. Sarli, V. J., Eiler, D. C., and Marshall, R. L., Effects of Operating Variables on Gaseous Emissions, APCA Specialty Conference on Air Pollution Measurement Accuracy, New Orleans, Louisiana, October 26-28, 1975.

16. The Design and Performance Analysis of Gas-Turbine Combustion Chambers, Volume I - Theory and Practice of Design, and Volume II - Design Methods and Development Techniques (NREC Reports Nos. 1082-1 and 1082-2), Northern Research and Engineering Corporation, Cambridge, Massachusetts, 1964.

17. Greenhough, V. W., and Lefebvre, A. H., "Some Applications of Combustion Theory to Gas Turbine Development," Sixth Symposium (International) on Combustion, Reinhold Publishing Corporation, New York, 1956.

18. Dryer, F. L., High Temperature Oxidation of Carbon Monoxide and Methane in a Turbulent-Flow Reactor (AFOSR Report No. TR-72-1109), Air Force Office of Scientific Research, March 1972.

19. Haasis, J. M., Development of the Combustion System for the AiResearch TPE331 Turboprop Engine (ASME Paper No. 67-9T-25), American Society of Mechanical Engineers, New York, December, 1966.

20. Demetri, E. P., and Murad, R. J., Low NOx Emission Combustor for Automobile Gas Turbine Engines (NREC Report No. 1169-4), Northern Research and Engineering Corporation, Cambridge, Massachusetts, prepared for the Environmental Protection Agency, Rockville, Maryland, under Contract No. 68-04-0017, March 10, 1972.

21. Gleason, C. C., Rogers, D. W., and Bahr, D. W., Experimental Clean Combustor Program, Phase II - Final Report (Report No. NASA CR-134971, R76AEG422), National Aeronautics and Space Administration, August 1976.

APPENDICES

APPENDIX A

REPRESENTATIVENESS OF EMISSION SAMPLE

INTRODUCTION

For some considerable time two major problems with respect to emission measurement have been identified by industrial and governmental study teams. These problems involve acquiring a representative emission sample from gas turbine exhausts and correction of emission levels for the effect of ambient conditions. The first of these problems is of primary concern in this appendix.

Stratification of emissions in the exhaust from gas turbines has been shown in numerous instances through detailed traverse probing and analysis of profile and contour plots of carbon monoxide, hydrocarbons and oxides of nitrogen. It would appear that the variability in stratification presents a problem for fixed probe sampling techniques. However, studies of data acquired by extensive sampling over the exhaust section of a JT8D-11 turbofan engine, Reference 4, indicate that the use of fixed probes for representative sampling is feasible. The optimized probe, for such sampling, is described in Section 2.3.

In the absence of similar data for the additional engines studied in this program the same design rules were applied for all probes. It should be emphasized that considerations of consistency of sampling, over long intervals of time, outweigh those of sample representativeness. It is the purpose of this appendix, however, to examine this factor for all engines tested.

COMPARISONS OF CARBON BALANCE AND PERFORMANCE FUEL-AIR RATIOS

An important technique which indicates the representativeness of sampling is a direct comparison of measured carbon balance fuel-air ratio with that derived from the performance of the engine. Carbon balance fuel-air ratios are calculated directly from the measured exhaust emissions-- carbon monoxide, hydrocarbons and carbon dioxide. Since only fuel flow could be measured on the test engines, the air flow pertaining to the performance fuel-air ratio and the operating condition was predicted from performance data and measurable operating parameters-- N_2 and EPR. Attention should be drawn to the fact that all performance data used in the prediction of air flow had no allowance for installation and probe blockage effects. Comparisons of fuel-air ratios are shown in the following figures for all test data acquired on each engine type.

DISCUSSION

The fuel-air ratio comparisons for both the JT8D-9 and JT8D-7 are shown in Figures A-1 and A-2 respectively. Both engine types show similar trends with ascending power, changing from good agreement at idle conditions to a higher carbon balance fuel-air ratio bias at take-off conditions. It can be seen that considerable data spread exists, presumably due to unit-to-unit variation, and the maximum deviations amount to approximately 25 per cent at the highest power level.

The comparison for JT3D-7 and JT3D-3B, shown in Figures A-3 and A-4 respectively, exhibit similar but less severe trends than the JT8D type engine. Unit-to-unit spread is significantly improved and the maximum deviation varies from 10 to 15 percent. Although the trends exhibited in Figure A-5 for the JT9D-3A are similar to those discussed above, it can be seen that a high carbon balance fuel-air ratio bias exists at the idle condition. With ascending power an improvement in correspondence is indicated and at the take-off condition the deviation is small.

The fuel-air ratio comparison for the RB211 engine shown in Figure A-6 has the same characteristic trend seen previously. In this case good agreement exists at idle conditions and a distinctly low carbon balance fuel-air ratio bias exists for higher power settings. The average deviation at take-off conditions is close to 15 percent.

Considerable unit-to-unit data spread is shown in the fuel-air ratio comparison for the CF700 engine (see Figure A-7). Generally the carbon balance fuel-air ratio appears higher than the performance value by amounts from 5 to 15 percent. The unmixed co-axial nature of the fan-core streams presents a considerable problem for fixed probe sampling in this particular engine.

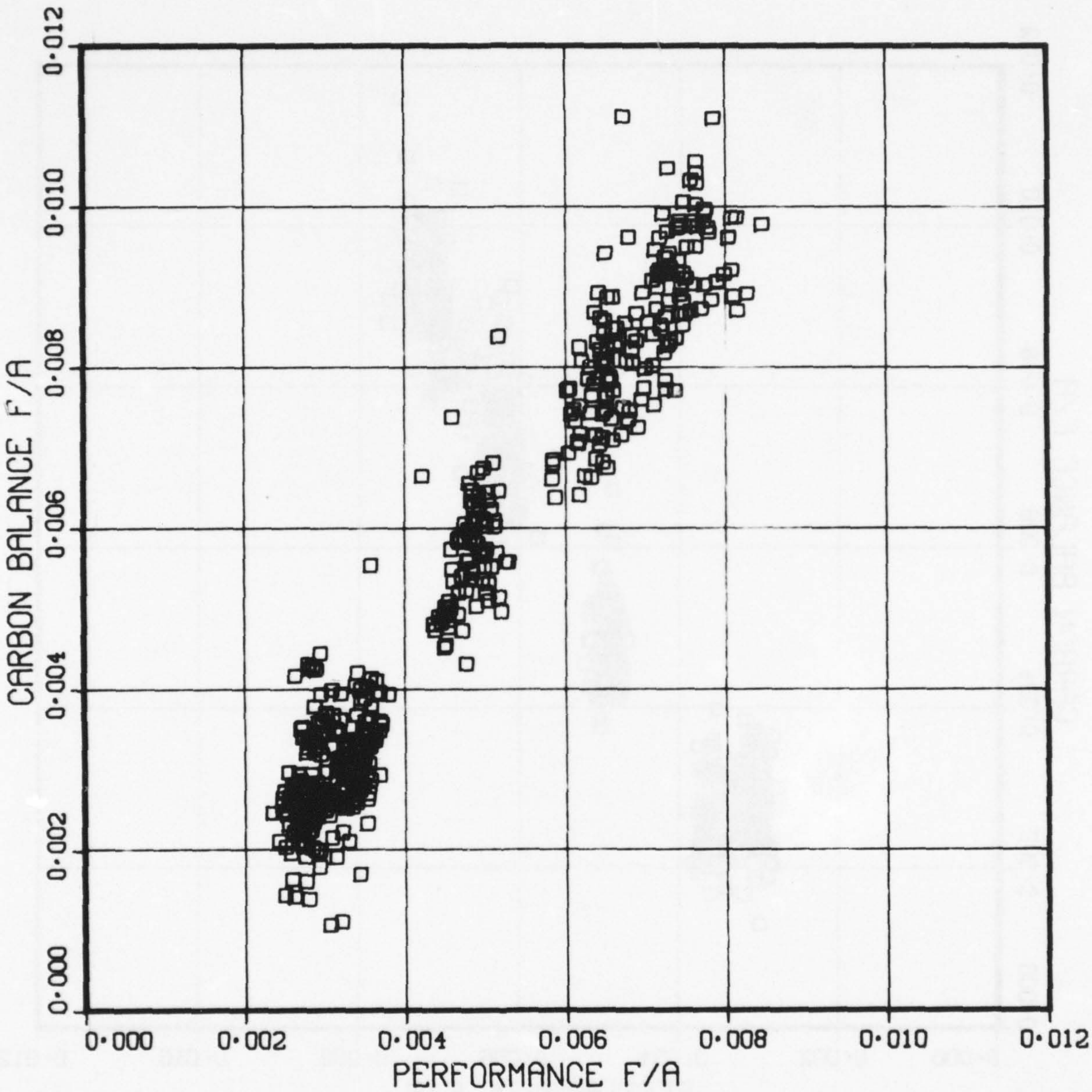

Figure A-1. JT8D-9 Fuel-Air Ratio Comparison

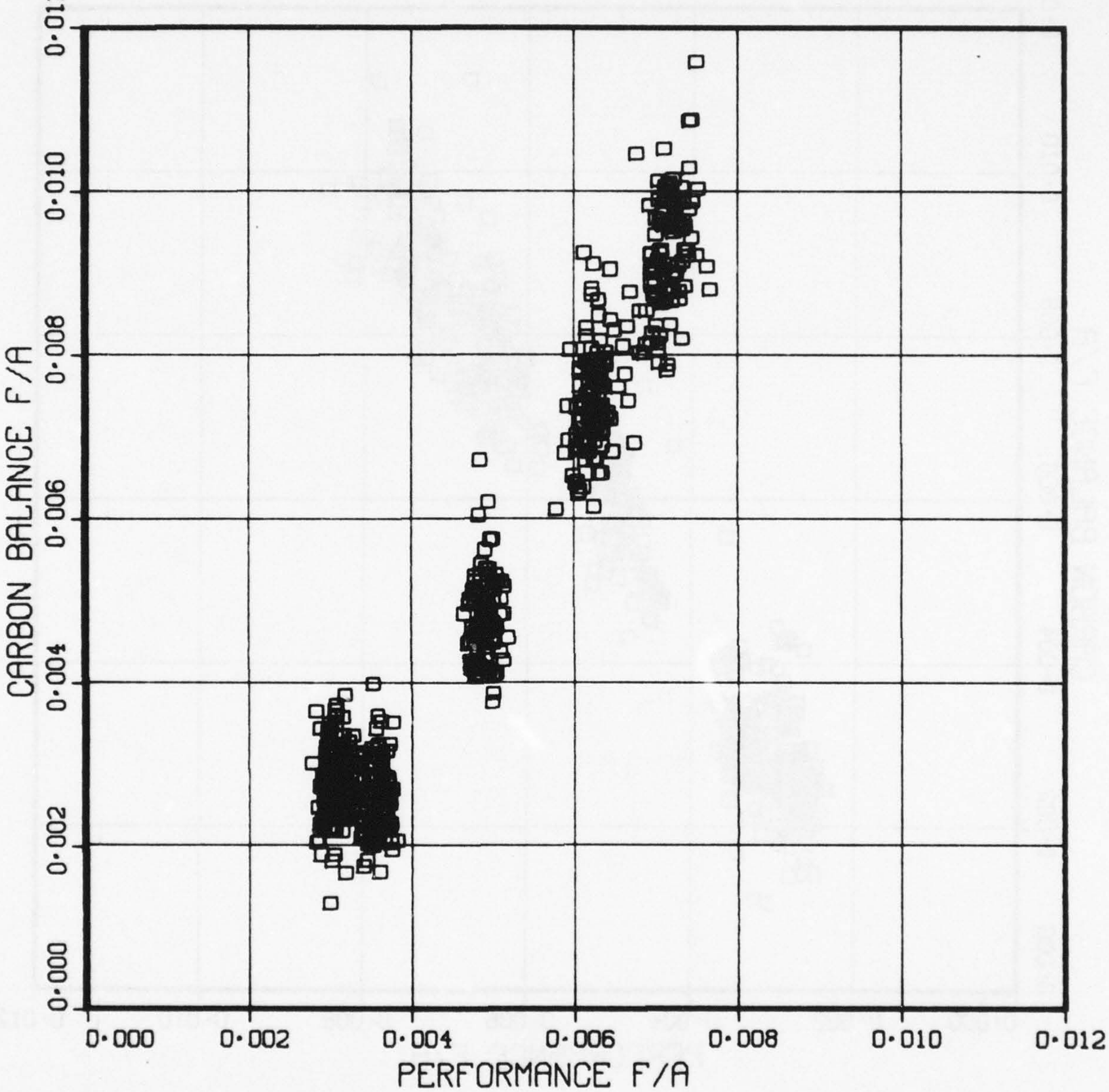

Figure A-2. JT8D-7 Fuel-Air Ratio Comparison

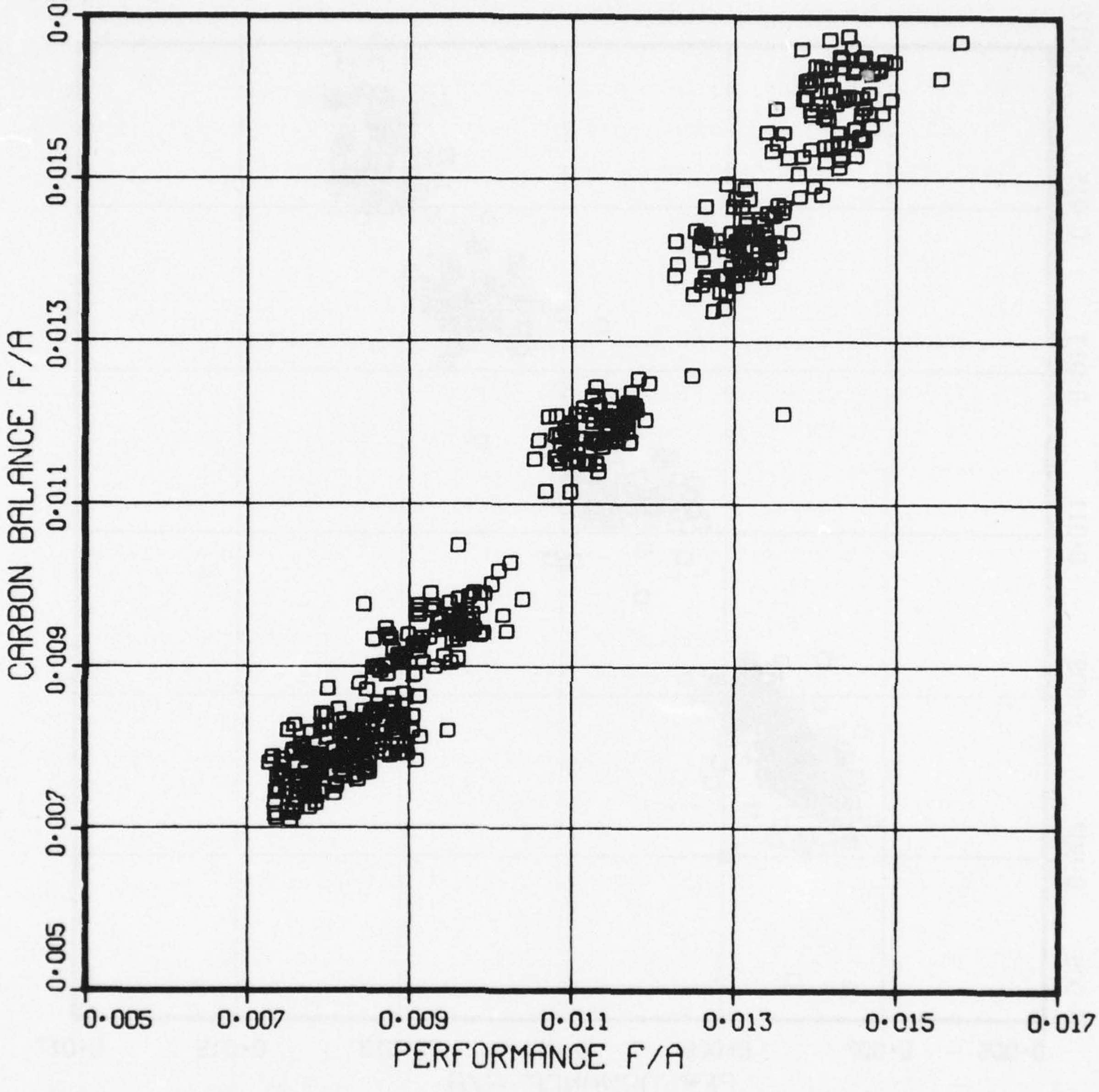

Figure A-3. JT3D-7 Fuel-Air Ratio Comparison

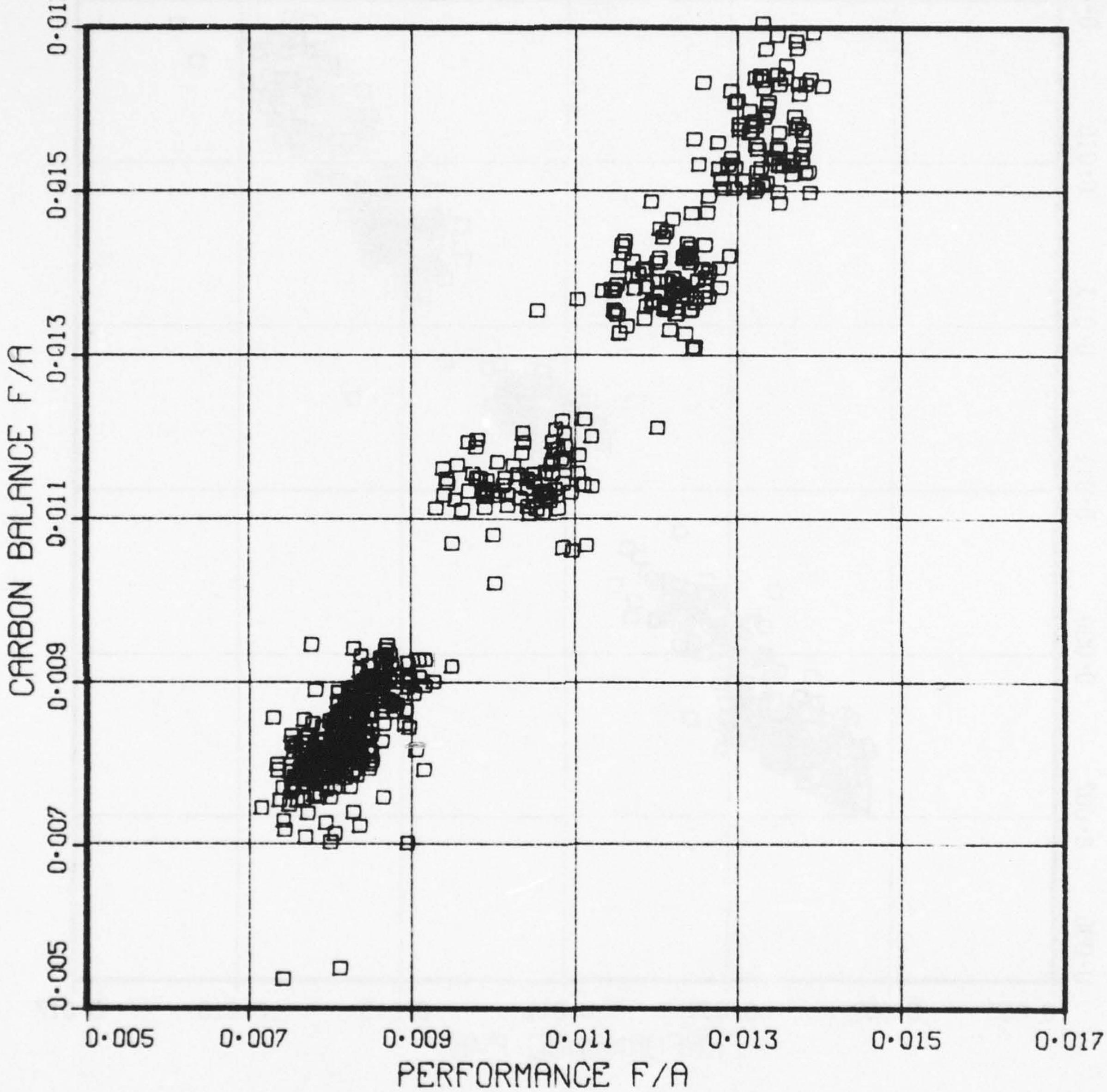

Figure A-4. JT3D-3B Fuel-Air Ratio Comparison

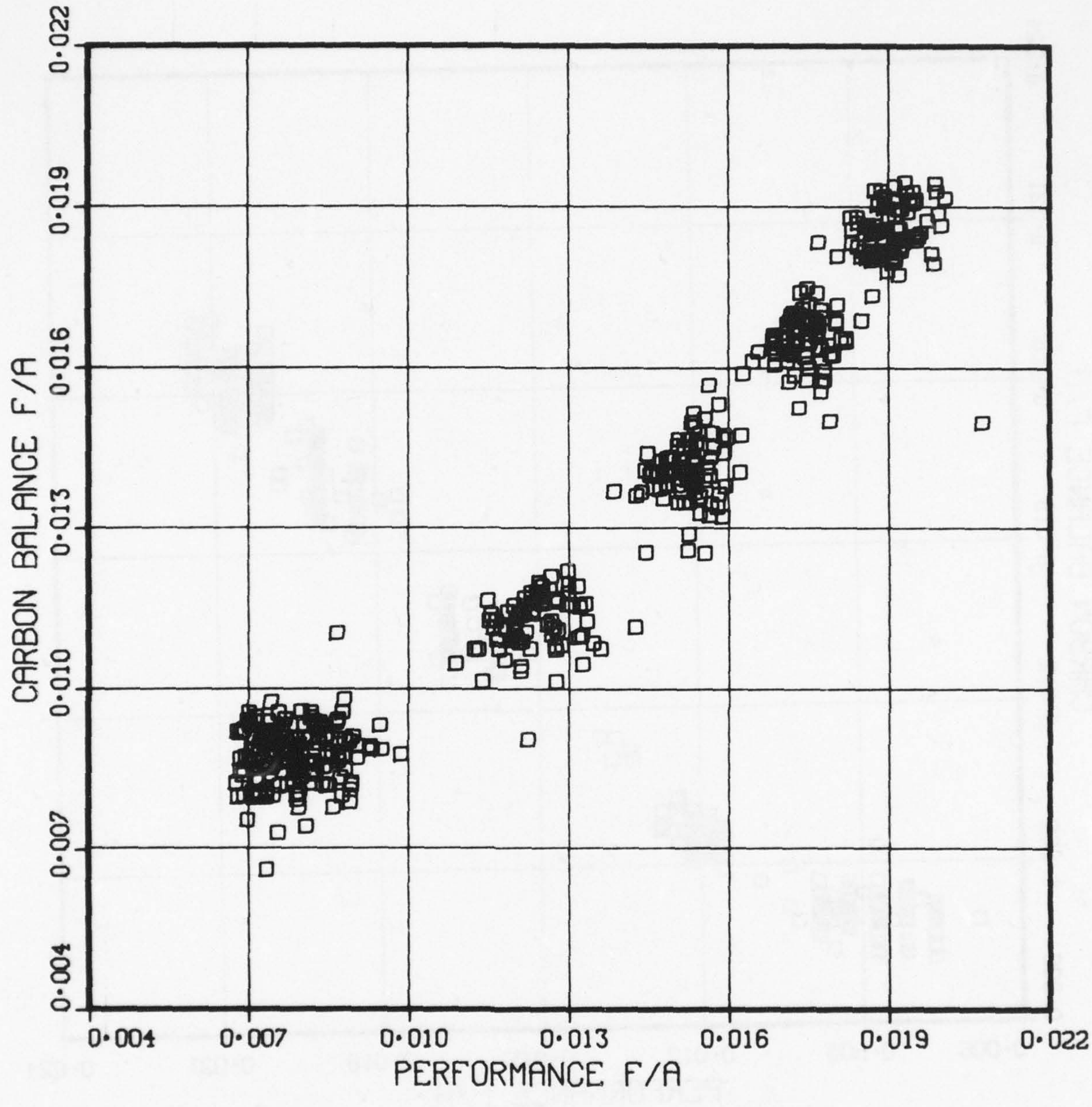

Figure A-5. JT9D-3A Fuel-Air Ratio Comparison

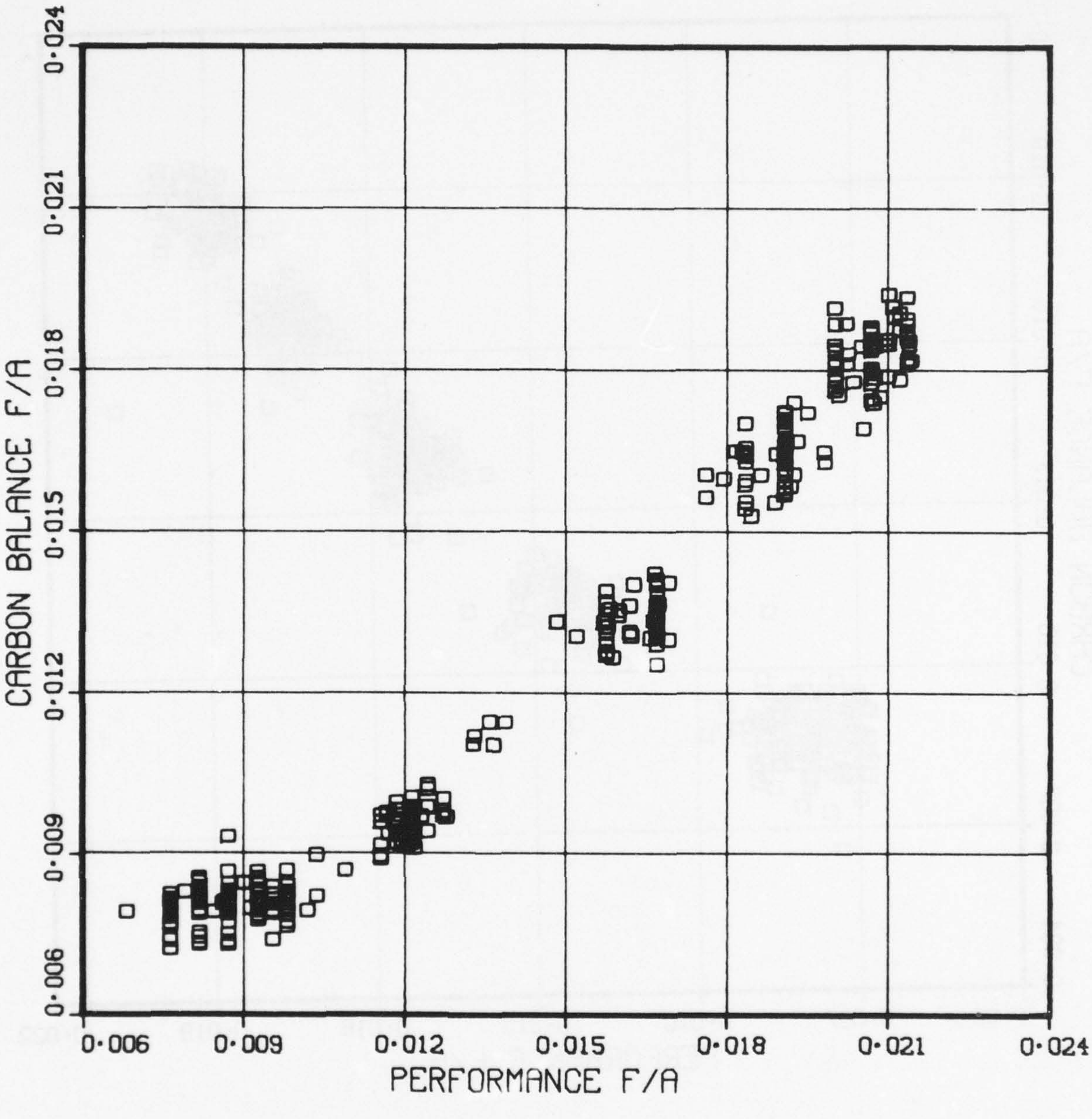

Figure A-6. RB211-22B Fuel-Air Ratio Comparison

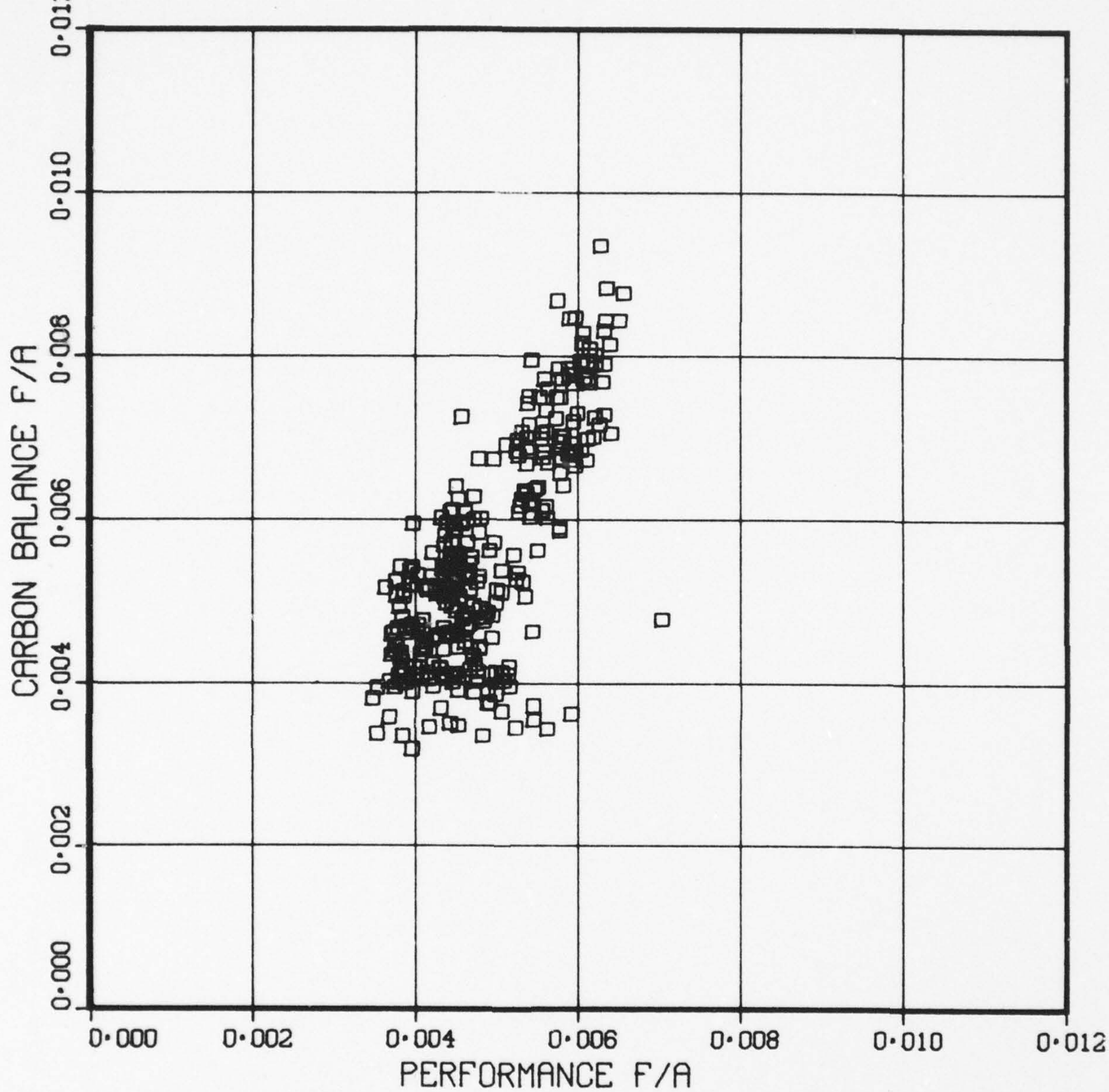

Figure A-7. CF700-2D Fuel-Air Ratio Comparison

APPENDIX B

DERIVATION OF GAS TURBINE EMISSION CORRELATING PARAMETERS AND AMBIENT CORRECTIONS

INTRODUCTION

The test program for the development of Time Degradation Factors for Turbine Engine Emissions was conducted on in-service engines to ensure that realistic results were obtained over the required intervals of engine operating time. Because of unavoidable variations in a number of factors in this field program, particularly ambient and engine operating conditions, the effect of time must be carefully separated from all other variables affecting emissions. Examination of the many factors which effect gas turbine emissions shows that the operating condition of the combustor, defined by the inlet variables pressures, temperature, humidity, air flow and fuel flow, are most significant. It should be appreciated, however, that for a given engine the combustor conditions are related specifically to engine operating conditions and the prevailing ambient pressure, temperature and humidity. From the more complete listing of factors together with their variables illustrated in Table B-1, it appears obvious that in order to separate the effect of time it is necessary to develop quantitative expressions which allow emission correlations for engine operating conditions and ambient corrections to be established. The analysis of these factors aimed at developing the required expressions is presented in this appendix.

TABLE B-1. - FACTORS EFFECTING ENGINE EMISSIONS

- ENGINE OPERATING CONDITIONS

  Independent Variable - F

  Dependent Variable - $\frac{N_1}{\sqrt{T_a}}, \frac{N_2}{\sqrt{T_a}}, \frac{M\sqrt{T_a}}{A\ P_a}$, EPR

- AMBIENT CONDITIONS

  Pressure - P_a

  Temperature - T_a

  Humidity - H_a

- OPERATING LINE

  Compressor Efficiency - η_{CP}

  Compressor-Turbine Match - A_{NZ}, T_4

- FUEL CHARACTERISTICS

  Carbon-Hydrogen Ratio

  Aromatic Content

- TIME

BACKGROUND

The problem area affecting emission measurements, which is of particular importance here, involves the effect of changes in ambient temperature, pressure and humidity, on emission levels. The FAA has conducted investigations on this problem at the National Aviation Facilities Experimental Center (NAFEC) Atlantic City, New Jersey in order to quantify these effects for two engines, the TF30-P1 mixed flow turbofan and the J57-43 turbojet engine (Ref 13). Whereas the results of these investigations appear directly applicable to the data acquired from testing the JT8D and JT3D turbofan engines in the current degradation program, the mathematical expressions developed to describe the emissions characteristics as a function of ambient temperature and humidity cannot be applied with any degree of confidence to other engines. In addition, the results provide no quantitative expressions relating emission levels to the engine operating variable which will undoubtedly change in practice. It should be pointed out, however, that the data in covering a wide range of temperature and humidity presents an ideal source for the verification of emission models.

The derivation of emission models for NO_x and CO based on a kinetic analysis by Pratt & Whitney workers appears in Reference 15. The validity of these techniques was assessed through comparisons of corrected and uncorrected emission data spread and by the ability of the model to predict changes in emission levels with variations in burner operating conditions. Comparisons of the corrections, due to ambient effects, with those of the NAFEC work indicated substantial agreement in the case of NO_x. However, the comparisons in respect to carbon monoxide and hydrocarbons indicated poor agreement and anomalous effects of ambient temperature. An indication of the accuracy of the P&WA correction techniques is given in Table B-2.

As a result of these findings NREC has directed its efforts towards improved emission models for carbon monoxide and hydrocarbons. In this respect the early work associated with correlating combustion efficiency, Reference 16, appeared to be a particularly useful starting point.

TABLE B-2. - COMPARISON OF EMISSION INDEX SPREAD WITH VARIOUS CORRECTION TECHNIQUES

JT9D Production Engines
19 Engine Pilot Lot
Based on Interpolated Values

	Independent Variable	Correction Procedure	Standard Deviation 2S percent	Total Emission Index Spread percent
NO_x at Climb	Net Thrust	None	48.0	± 25.5
	Burner Inlet Temperature	None	30.4	± 23.2
	Burner Inlet Temperature	$NO_x \left[\frac{P_{ref}}{P_{obs}}\right]^{1/2}$	17.5	± 17.8
	Burner Inlet Temperature	$NO_x \left[\frac{P_{ref}}{P_{obs}}\right]^{1/2} \cdot e^{19 \Delta H}$	9.8	± 7.5
CO at Idle	Net Thrust	None	56.4	± 40.9
	Burner Fuel Air Ratio	None	48.4	± 39.8
	Burner Fuel Air Ratio	$2016 \left[\frac{CO}{2016}\right] \left[\frac{P_{ref}}{P_{obs}}\right]^{.75} \left[\frac{T_{ref}}{T_{obs}}\right]$	35.0	± 27.0
	Burner Fuel Air Ratio	$CO \cdot \left[\frac{P_{obs}}{P_{ref}}\right]$	19.6	± 16.0
HC at Idle	Net Thrust	None	93.0	± 92.6
	Burner Fuel Air Ratio	None	64.6	± 62.9
	Burner Fuel Air Ratio	$HC \cdot \left[\frac{P_{obs}}{P_{ref}}\right]$	28.1	± 30.2

INFLUENCE OF OPERATING VARIABLES ON CO EMISSIONS

Although combustion of a hydrocarbon fuel is a complex process considerable progress in quantifying its description may be made on the assumption that combustion can be fully described by a single global reaction. This view is supported by the suggestion that there is a limiting reaction which governs the over-all rate of combustion. Examination of the chemistry of the process shows that this is unlikely over a wide range of conditions and its justification lies in the fact that it allows greater simplification under limited circumstances. In the gas turbine combustor the circumstances which appear opportune for such simplifications are the normal operating conditions where carbon monoxide is a major contribution to combustion inefficiency.

Following the second order reaction rate theory approach of Longwell, Herbert and others, see Reference 16, it can be shown that the rate of fuel burned per unit volume is given by the following expression:

$$\frac{M \cdot F/A \cdot \eta}{V} = K\,[F]\,[O_2]\left(\frac{P}{RT}\right)^2 T^{0.5}\, e^{-E/RT}$$

or the fraction burned $\quad \eta \;\alpha\; \frac{VP^2}{M}\left\{\frac{[F]\,[O_2]\, e^{-E/RT}}{F/A \;\; T^{1.5}}\right\} \qquad$ (B-1)

where M/VP^2 is known as the reaction zone "loading". A weakness of Equation (B-1) is the complicated function of reaction zone temperature. In practical combustors this expression is not easily described and it is clearly advantageous to relate this factor to combustor entry conditions which are known more accurately. Fortunately, it has been found (see Ref 17), that this temperature dependent term is reasonably well described by the term $\exp(T_b/B)$, where T_b is the burner inlet temperature and B varies with the effective equivalence ratio of the reaction zone, as shown in Figure B-1. It should be added that experimental data indicates closer agreement with this overall model for a 1.75 exponent of pressure.

Hence a modified form of Equation B-1 may be written:

$$\eta \quad \alpha \quad \left[\frac{VP^{1.75}}{M} \cdot e^{T_b/B} \right]$$

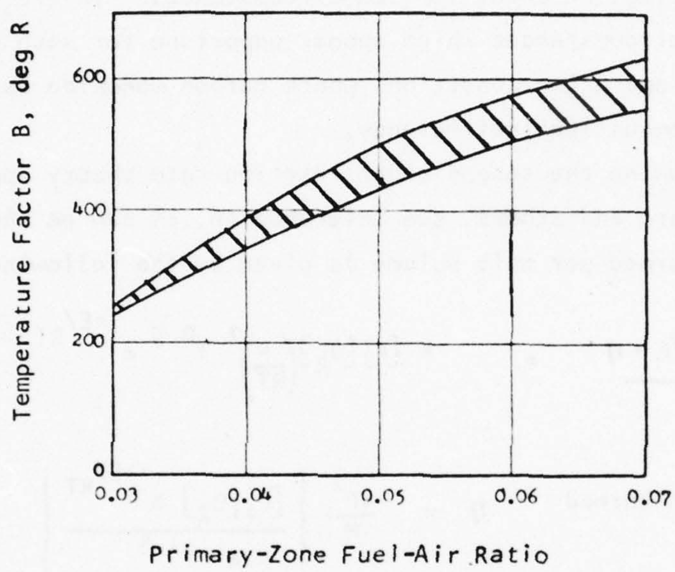

Figure B-1. Variation of Temperature Factor with Fuel-Air Ratio

The application of the theory of Greenhough and Lefebvre, Reference 17, results in a similar relationship which has been widely used in the design of combustors and correlation of experimental data.

$$\eta = f\left\{\left[\frac{P_b^{1.75}\, A_{ref}\, D_{ref}^{0.75}}{M}\cdot\left(\frac{\Delta P}{q_{ref}}\right)^{0.4}\cdot e^{T_b/B}\right],\ \varphi\right\} \qquad \text{(B-2)}$$

or $\eta = f\left(\theta,\ \varphi\right)$

where again the reaction zone temperature term is replaced by $\exp(T_b/B)$ in which B varies with effective equivalence ratio φ of the reaction zone. The over-all parameter given in Equation B-2, symbolized by θ, has been used extensively to correlate combustion efficiency and in most instances shows an inverse proportionality to combustion inefficiency as illustrated in Figure B-2. Hence for a given combustor geometry where A_{ref}, D_{ref}, $\Delta P/q_{ref}$ and $\frac{M\sqrt{T}}{P}$ are constants the combustion inefficiency:

$$\Delta\eta \quad \alpha \quad \frac{1}{\theta} = \left[\frac{\text{Constant}}{P_b^{0.75}\, T_b^{0.5}\, e^{T_b/B}}\right]$$

It follows therefore that correlations of carbon monoxide emission index may be achieved through the following expression:

$$EI_{CO} \quad \alpha \quad \left[\frac{1}{P_b^{0.75}\, T_b^{0.5}\, e^{T_b/B}}\right] \qquad \text{(B-3)}$$

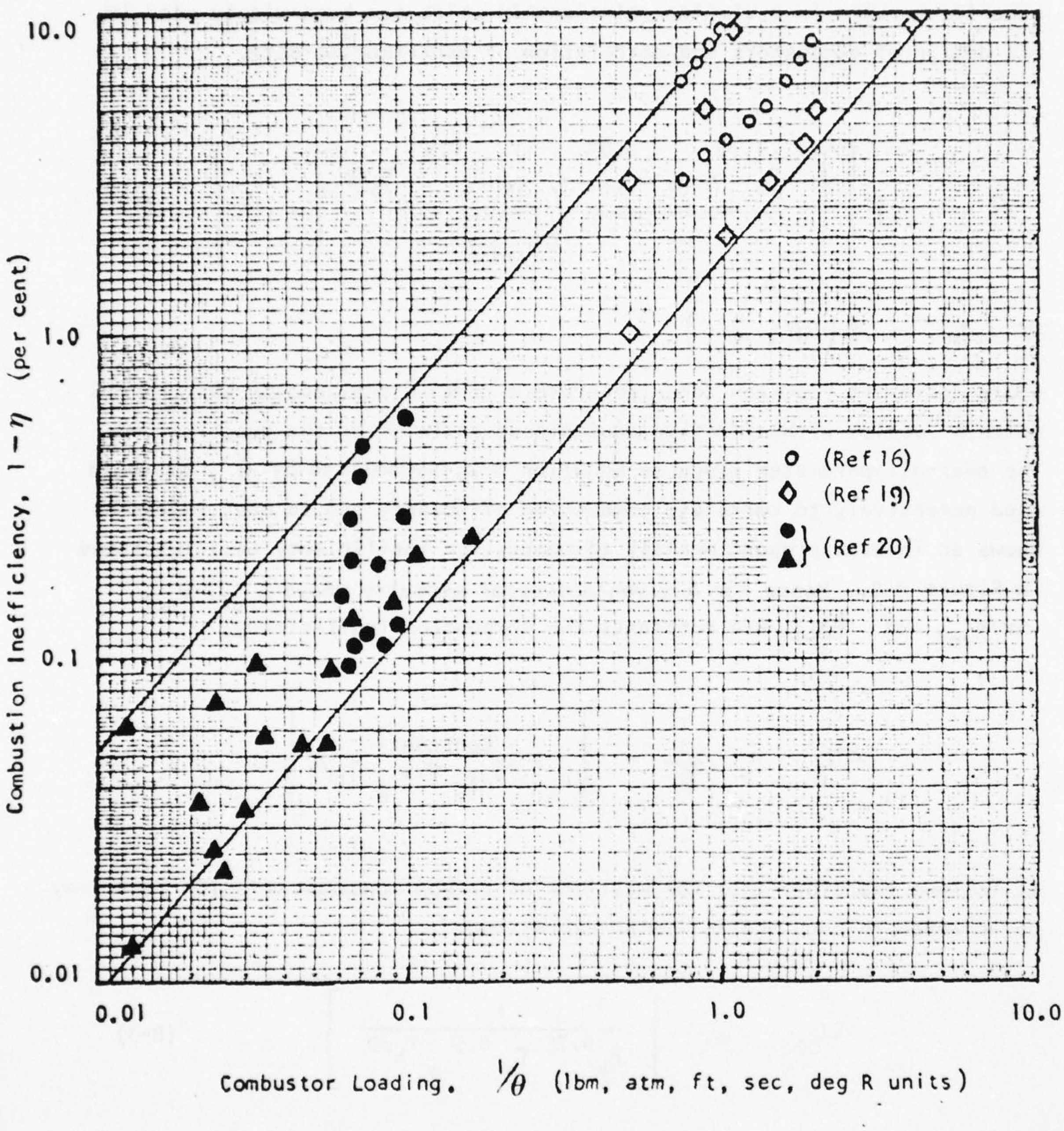

Figure B-2. Combustion Inefficiency Correlation

It is particularly significant at this point to compare the above relationships with those developed for the established rate controlling step for carbon monoxide oxidation, Reference 18.

$$CO + OH \rightleftarrows CO_2 + H$$

This leads to the following rate equation:

$$-\frac{d\,[CO]}{dt} = K\,[CO]\,[OH]\left(\frac{P}{RT}\right)^2 T^{0.5} e^{-E/RT}$$

For the equilibrium $2\,[OH] \rightleftarrows [H_2O] + \frac{1}{2}\,[O_2]$, the above rate equation yields the following expression,

$$-\frac{d\,[CO]}{dt} = K\,[CO]\,[H_2O]^{0.5}\,[O_2]^{0.25}\left(\frac{P}{RT}\right)^{1.75} T^{0.5} e^{-E/RT} \qquad \text{(B-4)}$$

It can be seen that this expression satisfactorily explains the experimentally observed 1.75 exponent of pressure. Equation B-4 also indicates that for a given change in carbon monoxide fraction, the oxidation time

$$t_{ox} \quad \alpha \quad \frac{1}{\left[[H_2O]^{0.5}[O_2]^{0.25} P_b^{1.75}\, e^{T_b/B}\right]}$$

Since the carbon monoxide inefficiency $\Delta\eta_{CO}$ may be expressed in terms of the ratio of oxidation time to the residence time in the reaction zone,

$$\eta_{CO} \quad \alpha \quad \left[\frac{t_{ox}}{t_{res}}\right]$$

it follows that for a constant value of $\frac{M\sqrt{T_b}}{P_b}$ and small effects of water and oxygen concentrations:

$$EI_{CO} \quad \alpha \quad \frac{1}{\left[P_b^{\ 0.75} \cdot T_b^{\ 0.5} \cdot e^{T_b/B}\right]}$$

It would therefore appear comparing the above relationship with that found previously, Equation B-3, that from both carbon monoxide oxidation kinetics and semi-empirical global reaction rate theory the carbon monoxide emission index may be correlated using this expression. In order to further examine the validity of Equation B-3, a detailed analysis of the NAFEC work, Reference 13, was undertaken. Figure B-3 shows the carbon monoxide emission correlation over the operating power range of the TF30 engine and for ambient temperature varying from 18 to 90 deg F. The degree of correlation is very good and it is also apparent that over the prevailing ambient conditions investigated these effects are intrinsic to the correlating parameter. Since, for a given engine operating condition, T_b and P_b are related only to ambient temperature and pressure, ambient correction factors may be derived directly from the correlating parameter.

The carbon monoxide correlation for the J57 engine data, Figure B-4, although indicating some scatter is also good. At high power levels the effect of ambient temperature appears intrinsic to the correlation as with the TF30. At idle conditions, however, ambient temperature had little, if any, effect on the emissions. It will be seen later that this anomaly introduced an error in the derived ambient correction factor for both JT3D type engines.

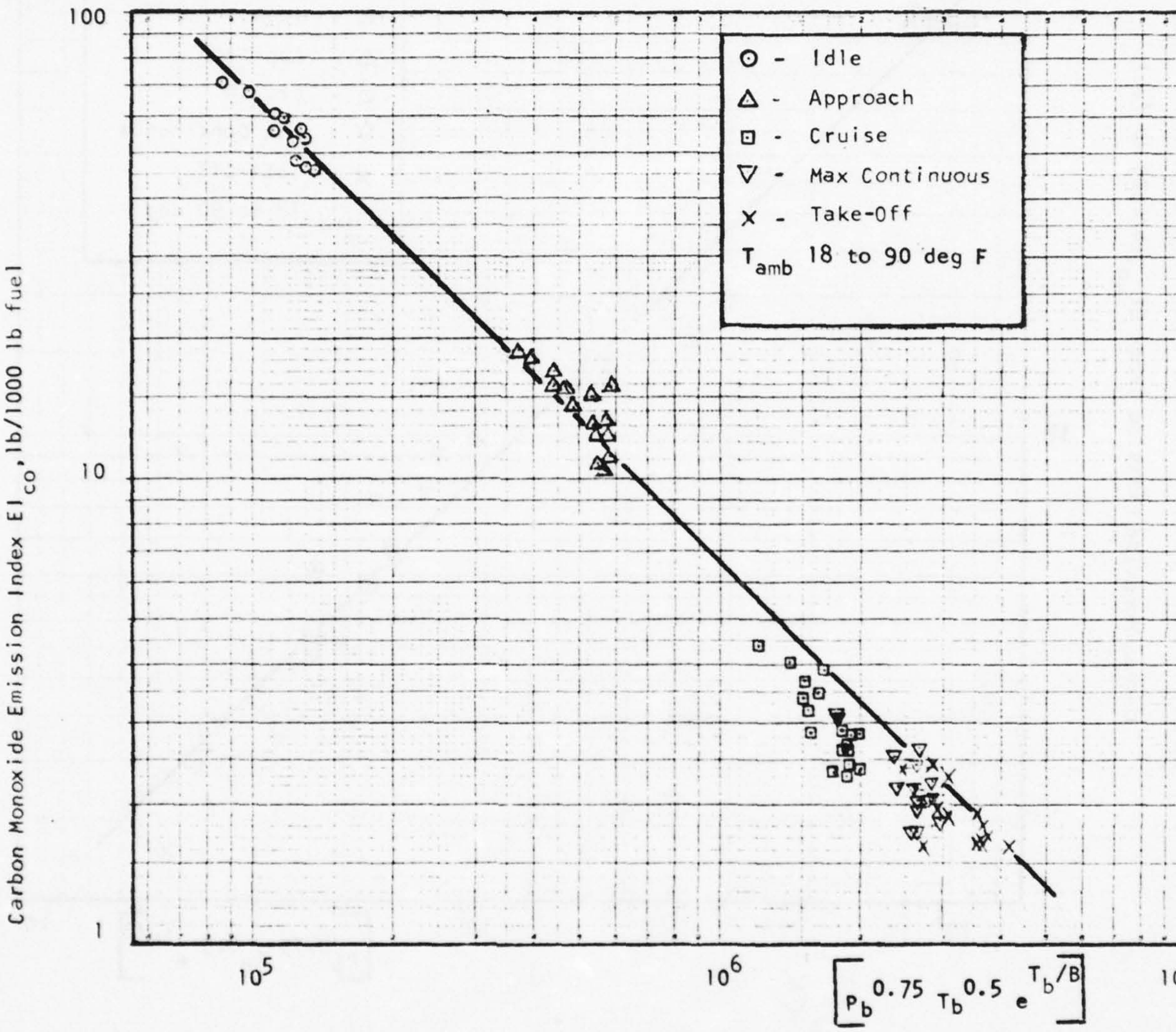

Figure B-3. Effect of Ambient Temperature on Carbon Monoxide Emissions for TF30

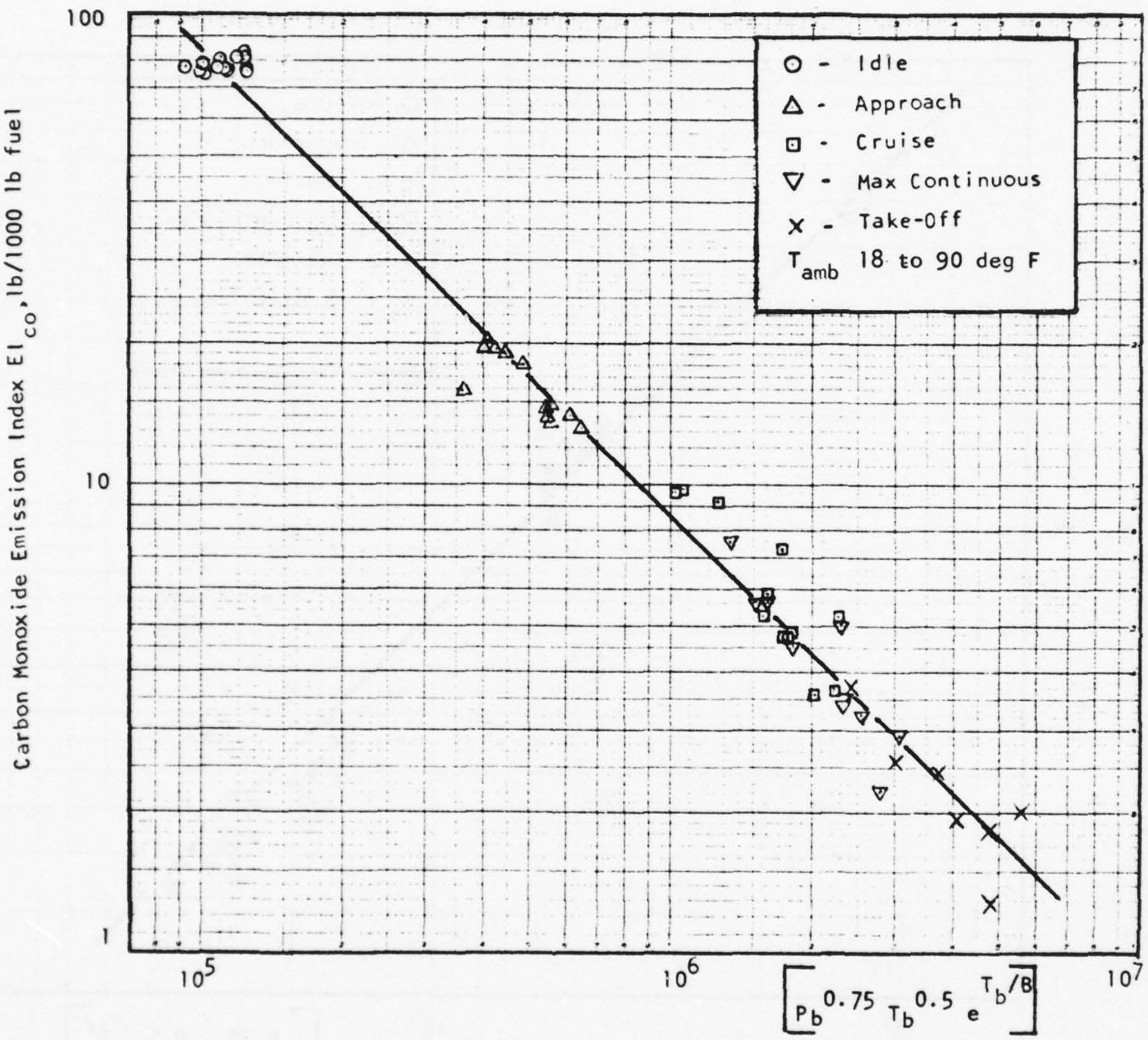

Figure B-4. Effect of Ambient Temperature on Carbon Monoxide Emissions for J57

INFLUENCE OF OPERATING VARIABLES ON HYDROCARBON EMISSIONS

As seen in the previous section simplified homogeneous gas phase reaction kinetics provided adequate expressions for correlating and correcting carbon monoxide emissions. Since the gas phase reaction of hydrocarbons are much faster than that for carbon monoxide oxidation, it may be postulated that the appearance of hydrocarbons in the exhaust from gas turbine combustors is due primarily to vapor or liquid phase-limiting processes. Under such conditions droplet evaporation in the cooler regions of the combustor, for example in film cooling or quenching layers close to the liner walls, is particularly significant.

The fraction of fuel injected which remains unburned will depend to a great extent on the over-all time for evaporation compared with the effective residence time in the combustor. On this basis it is reasonable to assume:

$$EI_{HC} \,\alpha\, \frac{\text{Evaporation Time} - t_{ev}}{\text{Residence Time} - t_{res}} \qquad \text{(B-5)}$$

It should be noted that this expression appears more valid at low power conditions of operation of the engine where temperatures are low and fuel droplets are relatively large due to the low fuel injector pressure. It is precisely these conditions where accurate correlations and correction factors are required due to the major contribution of low power emissions to the over-all emission cycle calculations.

It is well established that the lifetime of a droplet evaporating in a high temperature gas stream is given by:

$$t_{ev} = \frac{\rho_f \, d_o^{\,2}}{2.12\, \mu_g \, B^{0.6} Re^{0.5}}$$

where ρ_f is the density of the fuel, B is the fuel transfer number, μ_g is the gas stream viscosity, R_e is the Reynolds number and d_o is the initial droplet size. Since the droplet size and relative velocity, U , may be expressed in terms of the fuel injector characteristic flow number, FN , and the volume flow of fuel, Q , as:

$$d_o = 300 \cdot \frac{FN^{0.8}}{Q^{0.55}} \quad , \quad U = \text{Constant} \cdot \frac{Q}{FN\, \rho_f^{0.5}}$$

then

$$t_{ev} = \text{Constant} \cdot \left[\frac{\rho_f^{1.25}\, FN^{1.7}}{\mu_g^{0.5}\, \rho_g^{0.5}\, Q^{1.325}} \right]$$

The volume flow of fuel may be expressed alternatively as $Q = (M \cdot F/A)/\rho_f$ and since for normal operating condition of an engine $M\sqrt{T_b}/P_b$ is constant, the above expression may be written

$$t_{ev} = \text{Constant} \left[\frac{\rho_f^{1.25}\, FN^{1.7}}{\mu_g^{0.5}\, \rho_g^{0.5} \left(\frac{P_b \cdot F/A}{T_b^{0.5}\, \rho_f} \right)^{1.325}} \right]$$

or

$$t_{ev} = \text{Constant} \left[\frac{\rho_f^{2.575}\, FN^{1.7}}{P_b^{1.825} \left(\frac{F/A}{T_b^{0.5}} \right)^{1.325} \left(\frac{\mu_g}{T_g} \right)^{0.5}} \right]$$

Since the gas viscosity is proportional to the square root of the gas temperature, the term $\left(\mu_g/T_g\right)^{0.5}$ is approximately constant for the normal operating range of a combustor. Also, since the effective residence time of the droplet is related to the percentage pressure drop, $\Delta P/_{P_b}$, a characteristic length, L_E , and the temperature, the following expression may be derived:

$$\frac{t_{ev}}{t_{res}} = \left[\frac{\rho_f^{2.575} FN^{1.7} \Delta P/P_b}{L_E}\right]\left[\frac{1}{P_b^{1.825}\, T_b^{0.5}\, f(F/_A, T_b)}\right] \qquad \text{(B-6)}$$

Examination of Equation B-6 indicates the powerful effect of fuel density and injector flow number and to a lesser extent, the influence of characteristic length. Also from both Equations B-5 and B-6 it can be seen that for a given combustor, fuel injector and fuel properties, the effect of operating conditions on hydrocarbon emissions may be correlated through the expression:

$$EI_{HC} \quad \alpha \quad \left[\frac{1}{P_b^{1.825}\, T_b^{0.5}\, f(F/_A, T_b)}\right]$$

Although the precise functional relationship between the gas temperature effecting droplet evaporation, fuel-air ratio and combustor inlet temperature is difficult to establish, a convenient expression may be incorporated as follows:

$$EI_{HC} \quad \alpha \quad \left[\frac{1}{P_b^{1.8}\, T_b^{0.5}\, e^{T_b/B}}\right] \qquad \text{(B-7)}$$

where B will depend on the effective fuel-air ratio in the region of droplet evaporation.

The validity of Equation B-7 was initially examined through the analysis of the NAFEC work, Reference 13, and the resulting correlations for the TF30 and J57 are shown in Figures B-5 and B-6 respectively. In both cases the low power, idle and approach, hydrocarbon emissions are illustrated. As can be seen the degree of correlation for the J57 engine is noticeably better than for the TF30 and would appear adequate for further development. It is of interest to note that although a search of the literature produced no help in establishing the above relationship, Equation B-7, a recent publication of work conducted by the General Electric Company, Reference 21,

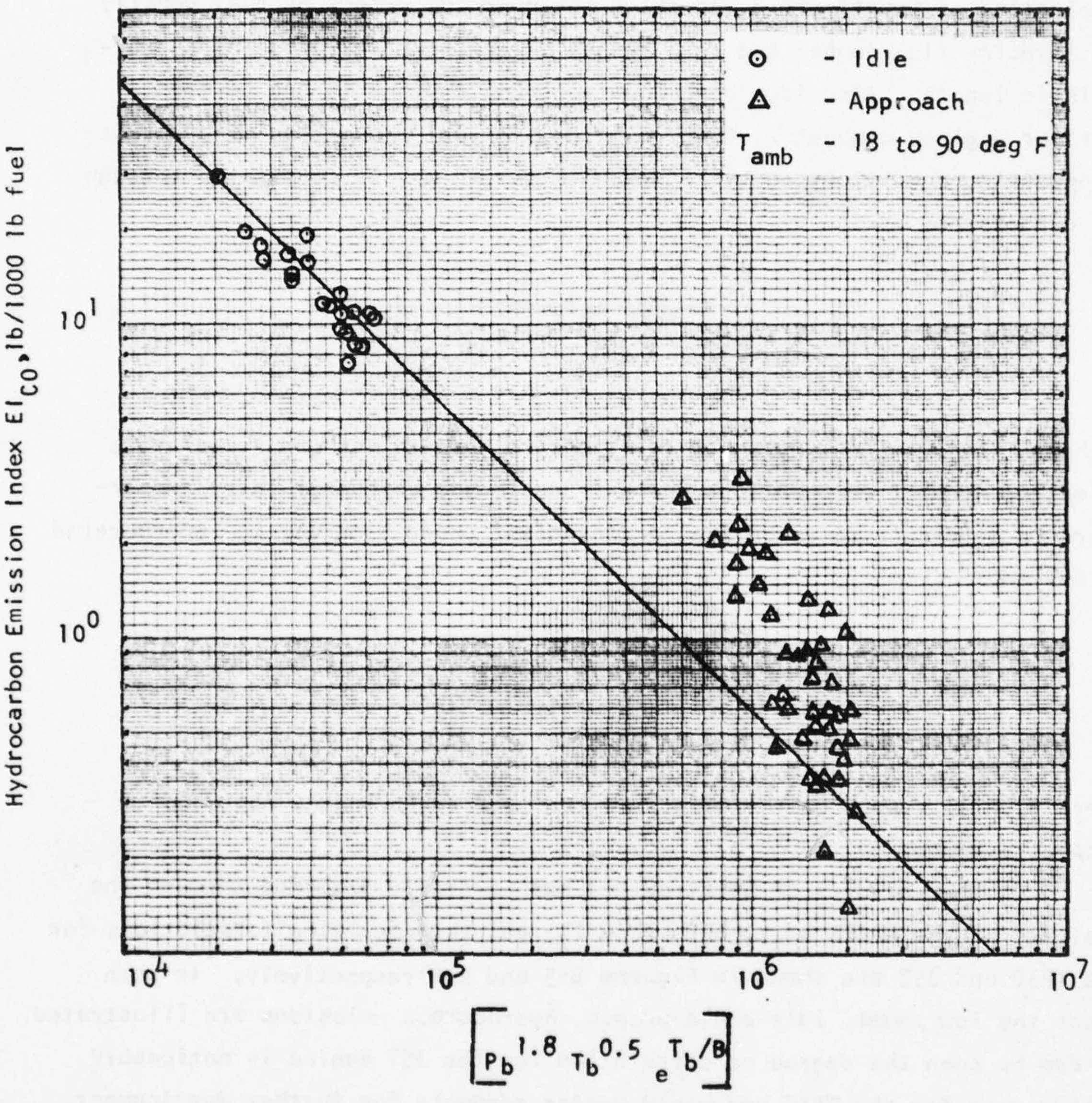

Figure B-5. Effect of Ambient Temperature on Hydrocarbon Emissions for TF30

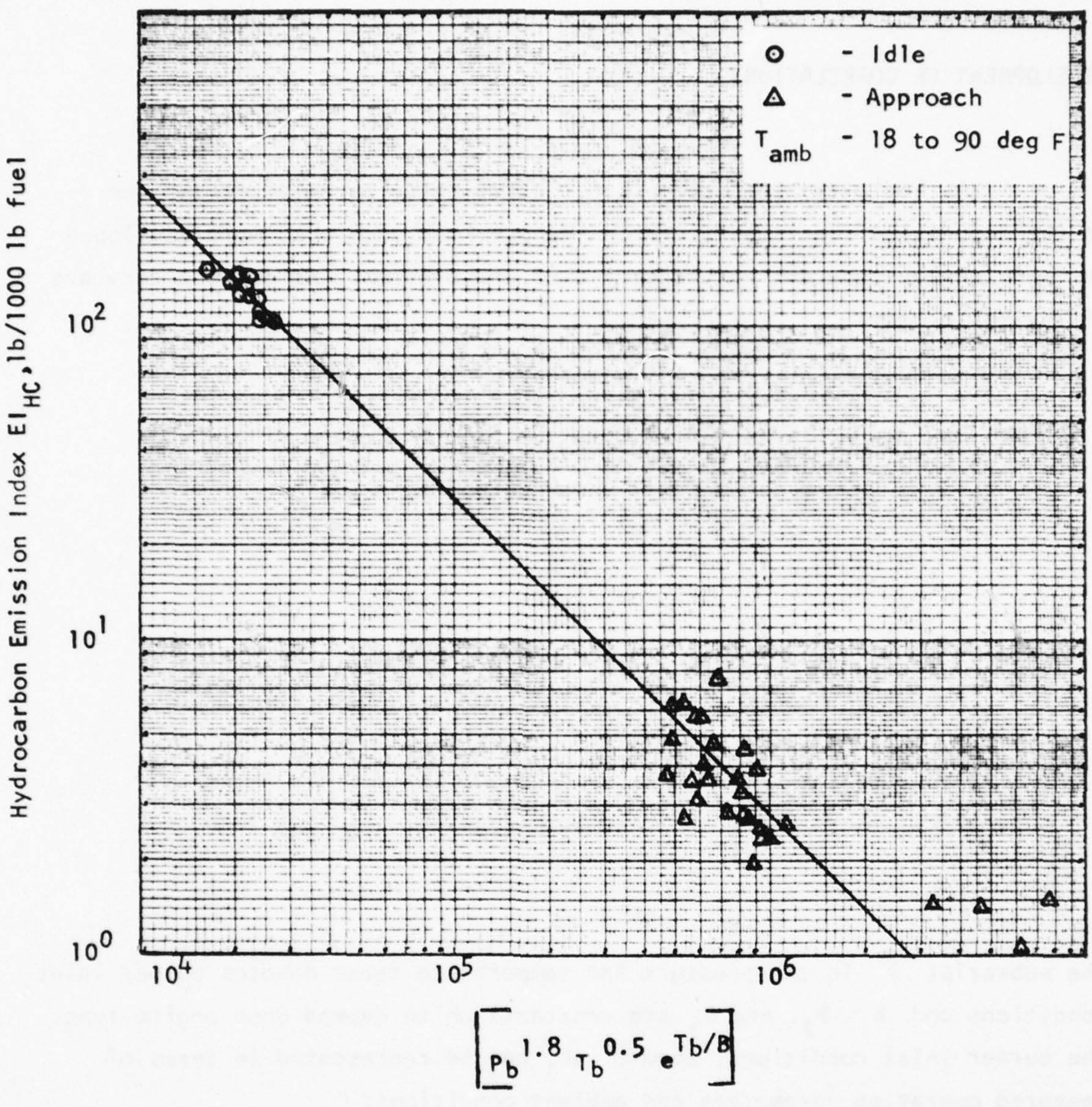

Figure B-6. Effect of Ambient Temperature on Hydrocarbon Emissions for J57

also indicates a pressure exponent of 1.8 controlling hydrocarbon emissions at low power conditions.

DEVELOPMENT OF CORRELATIONS

As indicated in Section 2.6.3 correlating parameters, derived on the theoretical basis outlined in the previous sections, were developed for each engine type during the course of the program. As derived they are of the basic form:

$$\left[P_b^{0.75} \cdot T_b \cdot e^{T_b/B_1}\right] \quad \text{- for carbon monoxide}$$

$$\left[P_b^{1.8} \cdot T_b \cdot e^{T_b/B_2}\right] \quad \text{- for hydrocarbons}$$

$$\left[P_b^{0.5}\, e^{(T_b/B_3 - 19H)}\right] \quad \text{- for oxides of nitrogen}$$

The subscript b in the pressure and temperature terms denotes burner inlet conditions and B_1, B_2, and B_3 are constants which depend upon engine type. The burner inlet conditions, themselves, can be represented in terms of measured operating parameters and ambient conditions.

In addition to the basic data provided in Reference 13, analysis of results from individual engine types in the degradation program provided the appropriate values of B_1, B_2, and B_3. The appropriate correlating parameter and constants for each engine type are given in Tables B-3, 4 and 5. It should be noted, however, that in the case of hydrocarbon emissions from the JT8D type engines, a significantly better correlation was found using the carbon monoxide parameter.

TABLE B-3. - CORRELATION PARAMETER FOR CARBON MONOXIDE

ENGINE TYPE	CORRELATING PARAMETERS CARBON MONOXIDE	
JT8D-9	$P_b^{0.75}\sqrt{T_b}\; e^{T_b/B_1}$	$B_1 = \begin{cases} (400 - F/A \cdot 10^4) \\ 315 \text{ Idle} \end{cases}$
JT8D-7	$P_b^{0.75}\sqrt{T_b}\; e^{T_b/B_1}$	$B_1 = \begin{cases} (400 - F/A \cdot 10^4) \\ 330 \text{ Idle} \end{cases}$
JT3D-3B	$P_b^{0.75}\sqrt{T_b}\; e^{T_b/B_1}$	$B_1 = (400 - F/A \cdot 10^4)$
JT3D-7	$P_b^{0.75}\sqrt{T_b}\; e^{T_b/B_1}$	$B_1 = (400 - F/A \cdot 10^4)$
JT9D-3A	$P_b^{0.75}\sqrt{T_b}\; e^{T_b/B_1}$	$B_1 = (400 - F/A \cdot 10^4)$
CF700	$P_b^{0.75}\sqrt{T_b}\; e^{T_b/B_1}$	$B_1 = \begin{cases} (600 - F/A \cdot 10^4) \\ 500 \text{ Idle} \end{cases}$
RB211	$P_b^{0.75}\sqrt{T_b}\; e^{T_b/B_1}$	$B_1 = \begin{cases} (525 - F/A \cdot 10^4) \\ (600 - F/A \cdot 10^4) \text{ Idle and Approach} \end{cases}$

TABLE B-4. - CORRELATION PARAMETER FOR HYDROCARBONS

ENGINE TYPE	CORRELATING PARAMETERS HYDROCARBONS
JT8D-9	$P_b^{0.75} \sqrt{T_b}\ e^{T_b/(500 - F/_A \cdot 10^4)}$
JT8D-7	$P_b^{0.75} \sqrt{T_b}\ e^{T_b/(400 - F/_A \cdot 10^4)}$
JT3D-3B	$P_b^{1.8} \sqrt{T_b}\ e^{T_b/140}$
JT3D-7	$P_b^{1.8} \sqrt{T_b}\ e^{T_b/140}$
JT9D-3A	$P_b^{1.8} \sqrt{T_b}\ e^{T_b/240}$
CF700	$P_b^{1.8} \sqrt{T_b}\ e^{T_b/475}$
RB211	$P_b^{1.8} \sqrt{T_b}\ e^{T_b/450}$

TABLE B-5. - CORRELATION PARAMETER FOR OXIDES OF NITROGEN

ENGINE TYPE	CORRELATING PARAMETERS OXIDES OF NITROGEN
JT8D-9	$P_b^{0.5} \cdot e^{T_b/725} / e^{19H}$
JT8D-7	$P_b^{0.5} \cdot e^{T_b/500} / e^{19H}$
JT3D-3B	$P_b^{0.5} \cdot e^{T_b/675} / e^{19H}$
JT3D-7	$P_b^{0.5} \cdot e^{T_b/600} / e^{19H}$
JT9D-3A	$P_b^{0.5} \cdot e^{T_b/225} / e^{19H}$
CF700	$P_b^{0.5} \cdot e^{T_b/600} / e^{19H}$
RB211	$P_b^{0.5} \cdot e^{T_b/275} / e^{19H}$

AMBIENT CORRECTIONS

A convenient method of establishing "Reference" values of emission indexes is provided by normalizing the correlating parameter with respect to some reference value. These correlations are given below using a notation consistent with Reference 15, but it should be noted that--

Subscript "ref" refers to reference values, arbitrarily chosen as the average values for the baseline tests (and at take-off power where appropriate)

Subscript "obs" refers to actual values or values observed for a particular test and mode

Subscript "std" refers to standard day conditions (i.e., 518.7 deg R, 29.92 in Hg, and 0.0 lbm H_2O/lbm dry air), or a value corrected to standard day conditions.

The normalized values of the correlating parameter are identified as "Emission Factors" - F_{CO}, F_{HC} and F_{NO} - and are defined:

$$F_{CO} = \left[\frac{P_{b,obs}}{P_{b,ref}}\right]^{0.75}\left[\frac{T_{b,obs}}{T_{b,ref}}\right]^{0.5}\left\{\begin{array}{ll}\left[\dfrac{e^{T_{b,obs}/B'_1}}{e^{T_{b,ref}/(B'_1-F/A_{ref}\cdot 10^4)}}\right] & \text{for idle}\\ \left[\dfrac{e^{T_{b,obs}/(B'_1-F/A_{obs}\cdot 10^4)}}{e^{T_{b,ref},/(B'_1-F/A_{ref}\cdot 10^4)}}\right] & \text{elsewhere}\end{array}\right\}$$

$$F_{HC} = \left[\frac{P_{b,obs}}{P_{b,ref}}\right]^{1.8}\left[\frac{T_{b,obs}}{T_{b,ref}}\right]^{0.5}\cdot e^{(T_{b,obs} - T_{b.ref})/B_2}$$

$$F_{NO} = \left[\frac{P_{b,obs}}{P_{b,ref}}\right]^{0.5}\cdot e^{\{(T_{b.obs} - T_{b.ref})/B_3 - 19H\}}$$

where

$$B' = \begin{cases} B_1 & \text{for idle}\\ B_1 + F/A.10^4 & \text{elsewhere}\end{cases}$$

It follows therefore,

$$\frac{EI_{CO}}{(EI_{CO})_{ref}} = \frac{1}{F_{CO}}$$

$$\frac{EI_{HC}}{(EI_{HC})_{ref}} = \frac{1}{F_{HC}}$$

and

$$\frac{EI_{NO}}{(EI_{NO})_{ref}} = F_{NO}$$

Each of the above Emission Factors may be evaluated in terms of cockpit data by defining the burner inlet conditions P_b and T_b from:

$$P_{b,ref} = P_{a,ref} \cdot \left(\frac{T_{b,ref}}{T_{a,ref}}\right)^{\alpha}$$

$$T_{b,ref} = \frac{T_{a,ref}}{518.7} \cdot f\left(N_{2,ref} / \sqrt{\frac{T_{a,ref}}{518.7}}\right)$$

$$P_{b,obs} = P_{a,obs} \cdot \left(\frac{T_{b,obs}}{T_{a,obs}}\right)^{\alpha}$$

$$T_{b,obs} = \frac{T_{a,obs}}{518.7} \cdot f\left(N_{2,obs} / \sqrt{\frac{T_{a,obs}}{518.7}}\right)$$

where the functions f and α are obtained for an engine type from the manufacturer. The relationship necessary to correct emission indexes to "standard" conditions may be similarly derived:

$$\frac{(EI_{CO})_{std}}{(EI_{CO})_{ref}} = \frac{1}{(F_{CO})_{std}}$$

$$\frac{(EI_{HC})_{std}}{(EI_{HC})_{ref}} = \frac{1}{(F_{HC})_{std}}$$

$$\frac{(EI_{NO})_{std}}{(EI_{NO})_{ref}} = (F_{NO})_{std}$$

where

$$(F_{CO})_{std} = \left[\frac{P_{b,std}}{P_{b,ref}}\right]^{0.75} \left[\frac{T_{b,std}}{T_{b,ref}}\right]^{0.5} \left\{ \begin{array}{ll} \dfrac{e^{T_{b,std}/B_1'}}{e^{(T_{b,ref}/B_1' - F/A_{ref} \cdot 10^4)}} & \text{for idle} \\[2ex] \dfrac{e^{(T_{b,std}/B_1' - F/A_{std} \cdot 10^4)}}{e^{(T_{b,ref}/B_1' - F/A_{ref} \cdot 10^4}} & \text{elsewhere} \end{array} \right\}$$

$$(F_{HC})_{std} = \left[\frac{P_{b,std}}{P_{b,ref}}\right]^{1.8} \left[\frac{T_{b,std}}{T_{b,ref}}\right]^{0.5} \cdot e^{(T_{b,std} - T_{b,ref})/B_2}$$

$$(F_{NO})_{std} = \left[\frac{P_{b,std}}{P_{b,ref}}\right]^{0.5} \cdot e^{(T_{b,std} - T_{b,ref})/B_3}$$

and $P_{b,std} = P_{a,std}\left(\dfrac{T_{b,std}}{T_{a,std}}\right)^{\alpha}$, $T_{b,std} = \dfrac{T_{a,std}}{518.7} \cdot f\left(N_{2,std}\Big/\sqrt{\dfrac{T_{a,std}}{518.7}}\right)$

The values of the engine operating parameters in the standardized emission factors may be obtained by assuming that corrected thrust remains constant. Therefore,

$$\frac{F/A}{T_a} \quad \text{and} \quad \frac{N_2}{T_a}$$

remain constant, and the equations for $T_{b,std}$ and $(F_{CO})_{std}$ should be modified to read

$$T_{b,std} = \cancel{\frac{T_{a,std}}{518.7}}^{\,1} \cdot f\left(N_{2,obs}\Big/\sqrt{\frac{T_{a,obs}}{518.7}}\right)$$

$$(F_{CO})_{std} = \left[\frac{P_{b,std}}{P_{b,ref}}\right]^{0.75} \left[\frac{T_{b,std}}{T_{b,ref}}\right]^{0.5} \left\{ \begin{array}{ll} \left[\dfrac{e^{T_{b,std}/B_1'}}{e^{(T_{b,ref}/B_1 - F/A_{ref} \cdot 10^4)}}\right] & \text{for idle} \\[2ex] \left[\dfrac{e^{\{T_{b,std}/B_1 - T_{a,std}(F/A_{obs}/T_{a,obs}) \cdot 10^4\}}}{e^{(T_{b,ref}/B_1 - F/A_{ref} \cdot 10^4)}}\right] & \text{otherwise} \end{array} \right\}$$

Dividing the equations for standardized emission indexes by the equations for observed values, emission indexes corrected to standard ambient conditions can then be calculated from

$$(EI_{CO})_{std} = \frac{F_{CO}}{(F_{CO})_{std}} \cdot EI_{CO}$$

$$(EI_{HC})_{std} = \frac{F_{HC}}{(F_{HC})_{std}} \cdot EI_{HC}$$

and

$$(EI_{NO})_{std} = \frac{(F_{NO})_{std}}{F_{NO}} \cdot EI_{NO}$$

In general the comparisons between NREC and FAA corrected data for CO, HC, and NO are extremely good. Typical examples are shown in Figure B-7, B-8, and B-9 for the JT8D-7. In some instances, however, deviations appeared, particularly at idle conditions for carbon monoxide and hydrocarbons, which indicated a need for further examination.

In the case of the JT3D-7 and JT3D-3B variability in the carbon monoxide comparisons are evident-- Figure B-10 and B-11. Although the actual correlations of data for these engines appeared particularly good from Figures B-12 and B-13, closer examination of the original data from which these correlations were derived showed that the carbon monoxide emission index at idle had little if any dependence on ambient conditions (see Fig. B-4). It is evident, therefore, that in this particular case the deviations indicated are introduced by the application of the NREC ambient correction factor. Although a simple solution to this anomaly could be the elimination of any correction, in order to preserve the above rationale a mathematical approach is adopted. The approach consists of increasing the constant, B, in the correlating factor so as to make the correction relatively insensitive to ambient temperature at the idle condition. The modified expression used for this particular case is:

$$P_b^{\,0.75} \sqrt{T_b} \; e^{T_b / 2\times10^3}$$

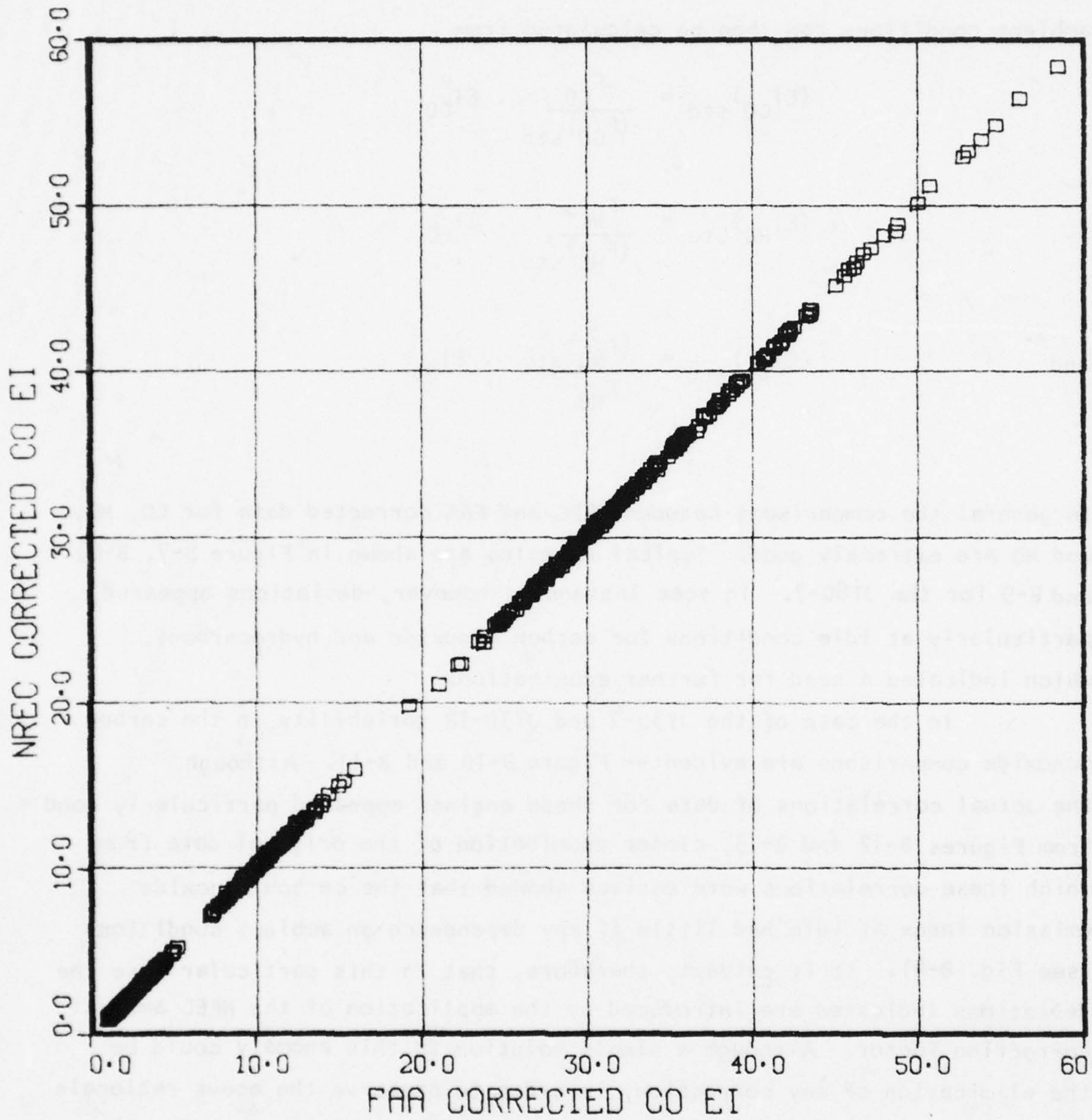

Figure B-7. Comparison of Ambient Corrections for JT8D-7 CO Emissions Data

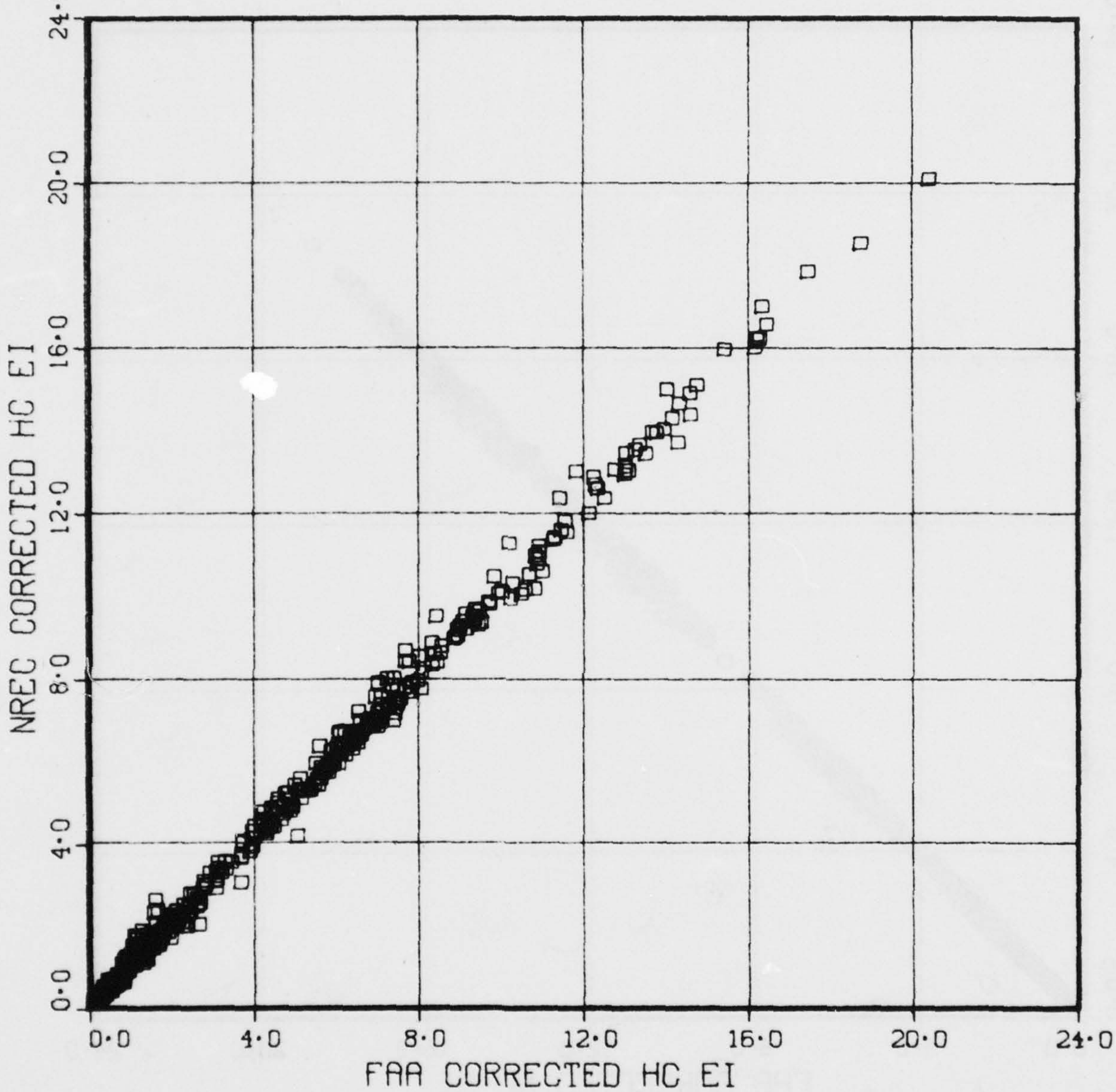

Figure B-8. Comparison of Ambient Corrections for JT8D-7 HC Emissions Data

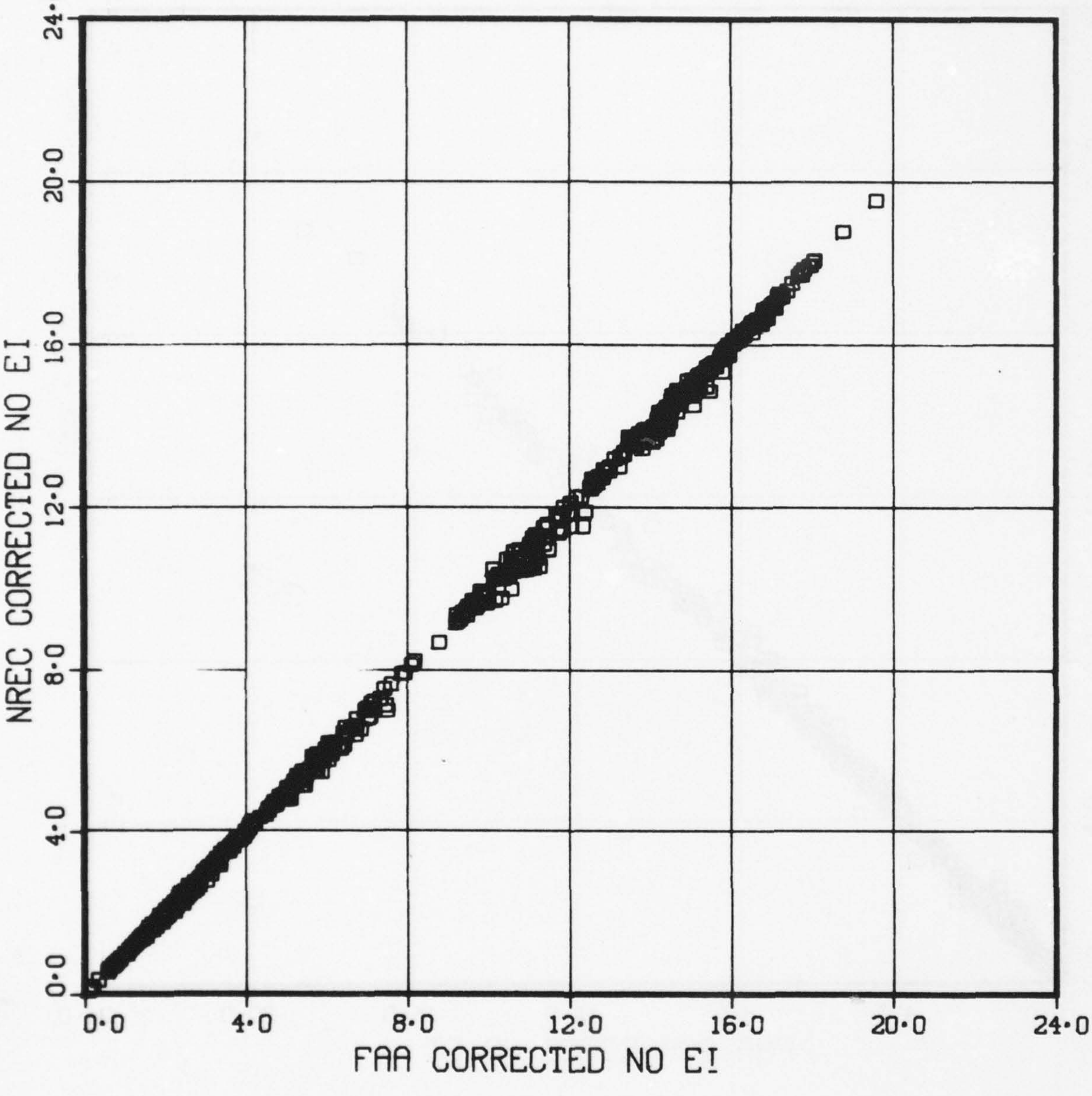

Figure B-9. Comparison of Ambient Corrections
for JT8D-7 NO Emissions Data

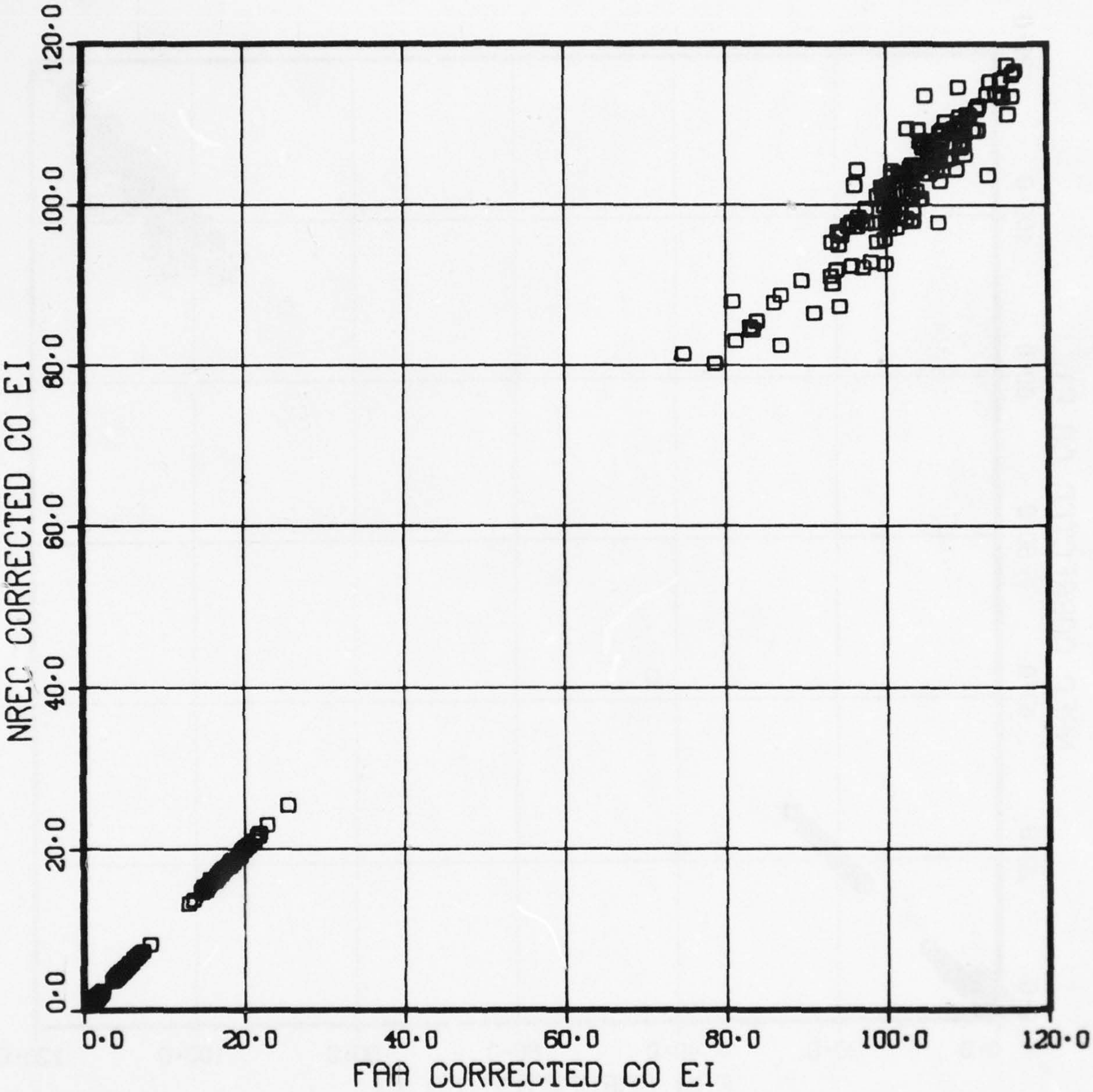

Figure B-10. Comparison of Ambient Corrections for JT3D-7 CO Emission Data

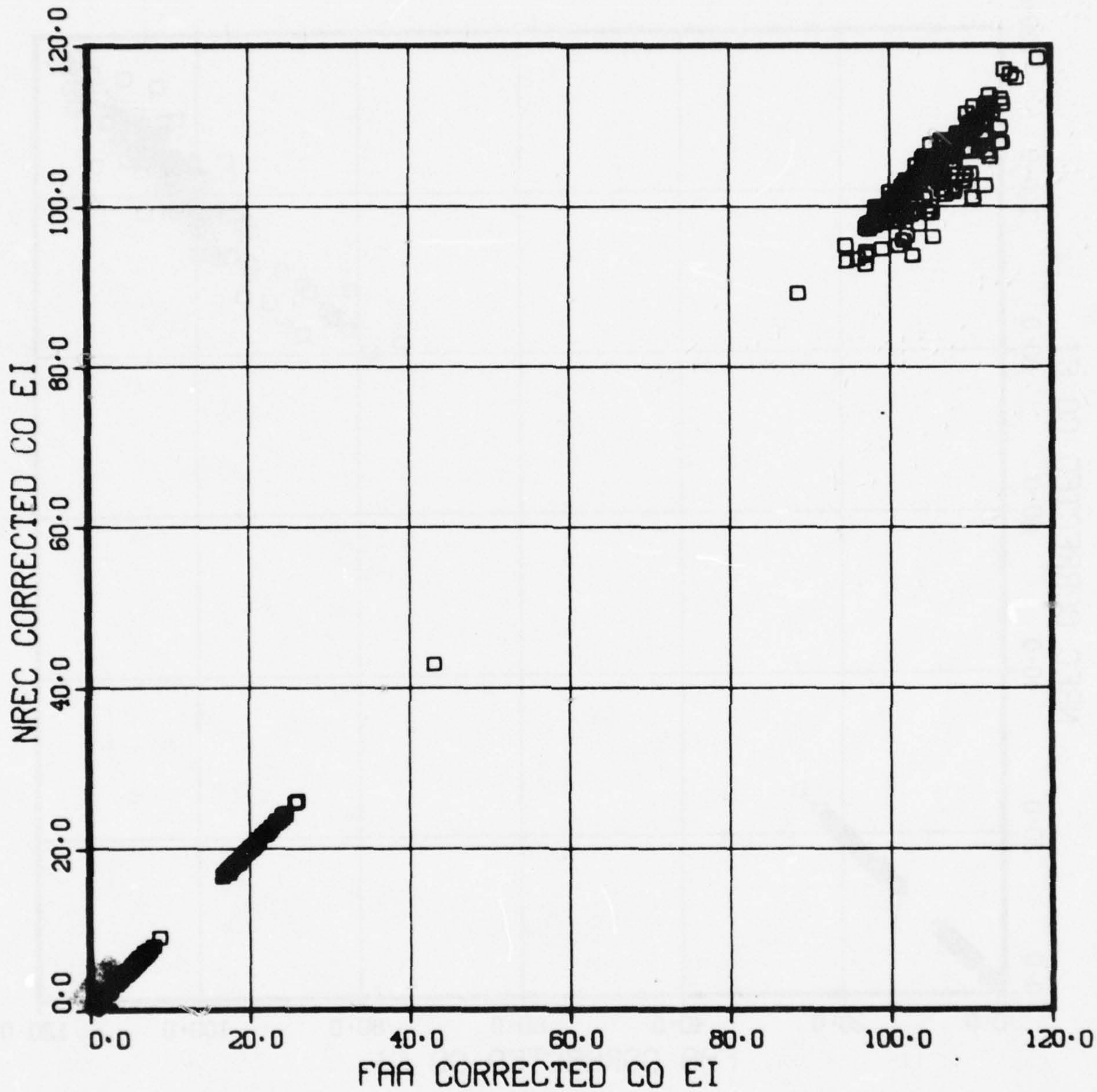

Figure B-11. Comparison of Ambient Corrections for JT3D-3B CO Emission Data

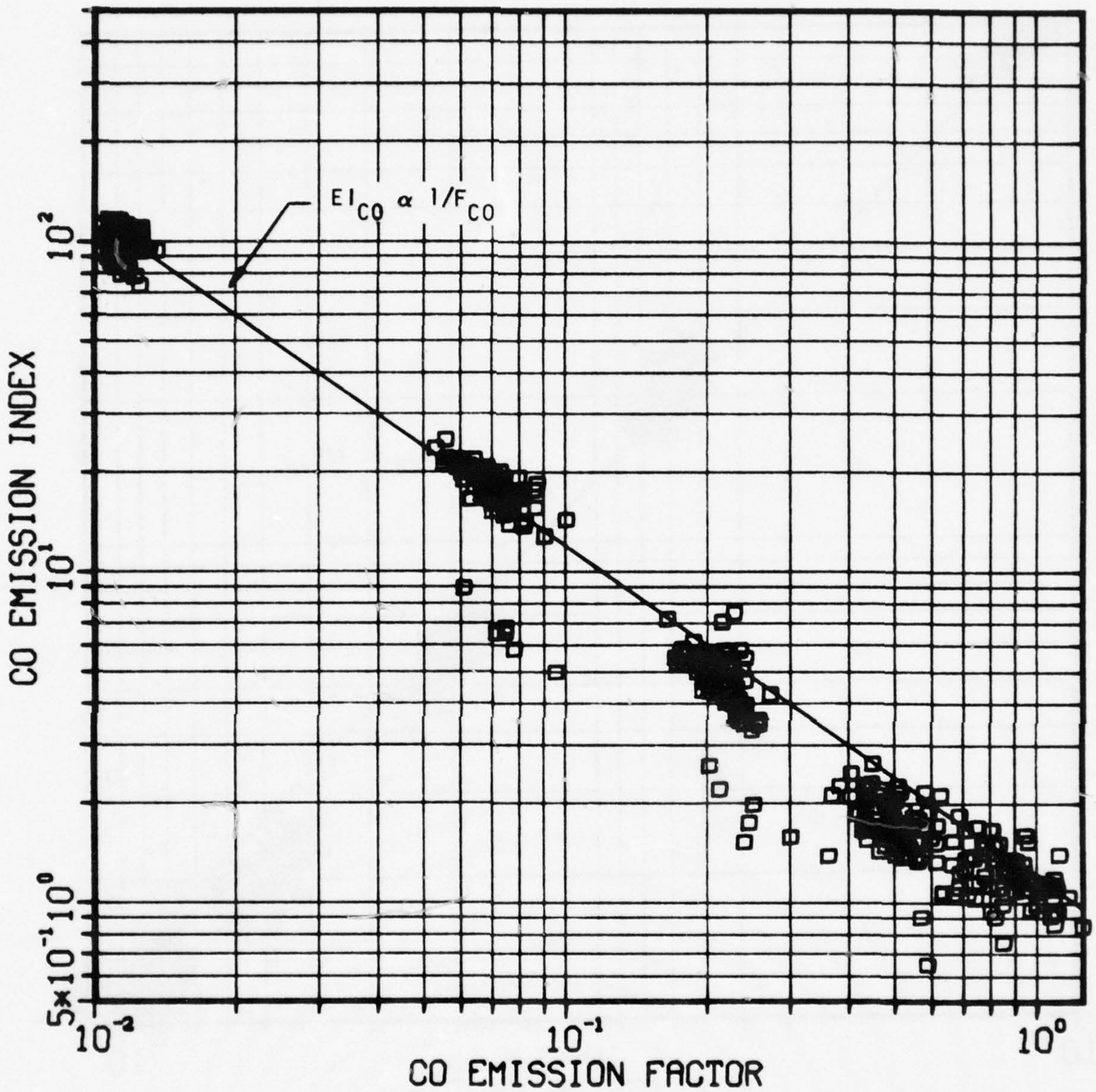

Figure B-12. JT3D-7 CO Emission Data

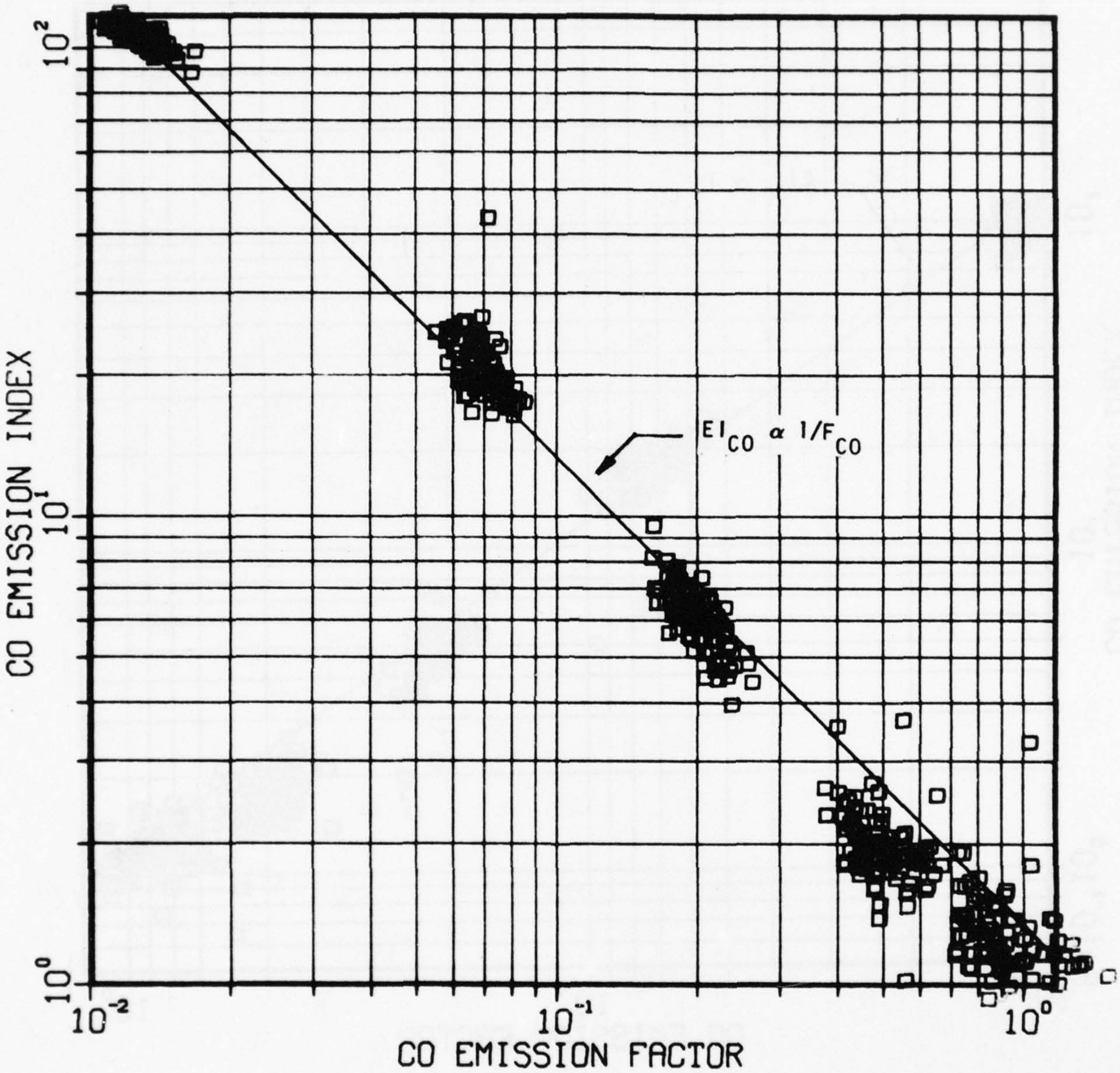

Figure B-13. JT3D-3B CO Emission Data

The resultant improvement in comparisons of NREC and FAA corrected index is clearly indicated in Figure B-14 and B-15.

Due to considerable difficulty in applying the standard hydrocarbon correlating parameter, in the case of the JT8D-9 and the JT8D-7, the carbon monoxide parameter was applied more successfully. However, the comparisons between NREC and FAA corrected emission indexes in Figure B-16 indicates poor agreement in the case of the JT8D-9. It should be noted that for this particular engine type considerable problems were encountered in measuring consistent hydrocarbons due to fuel leaks from "B" nuts.

Generally it can be stated that correlation and correction factors were found to be successfully applied on most engines. Difficulties were only encountered with the hydrocarbon factors applied to the mixed flow type engines.

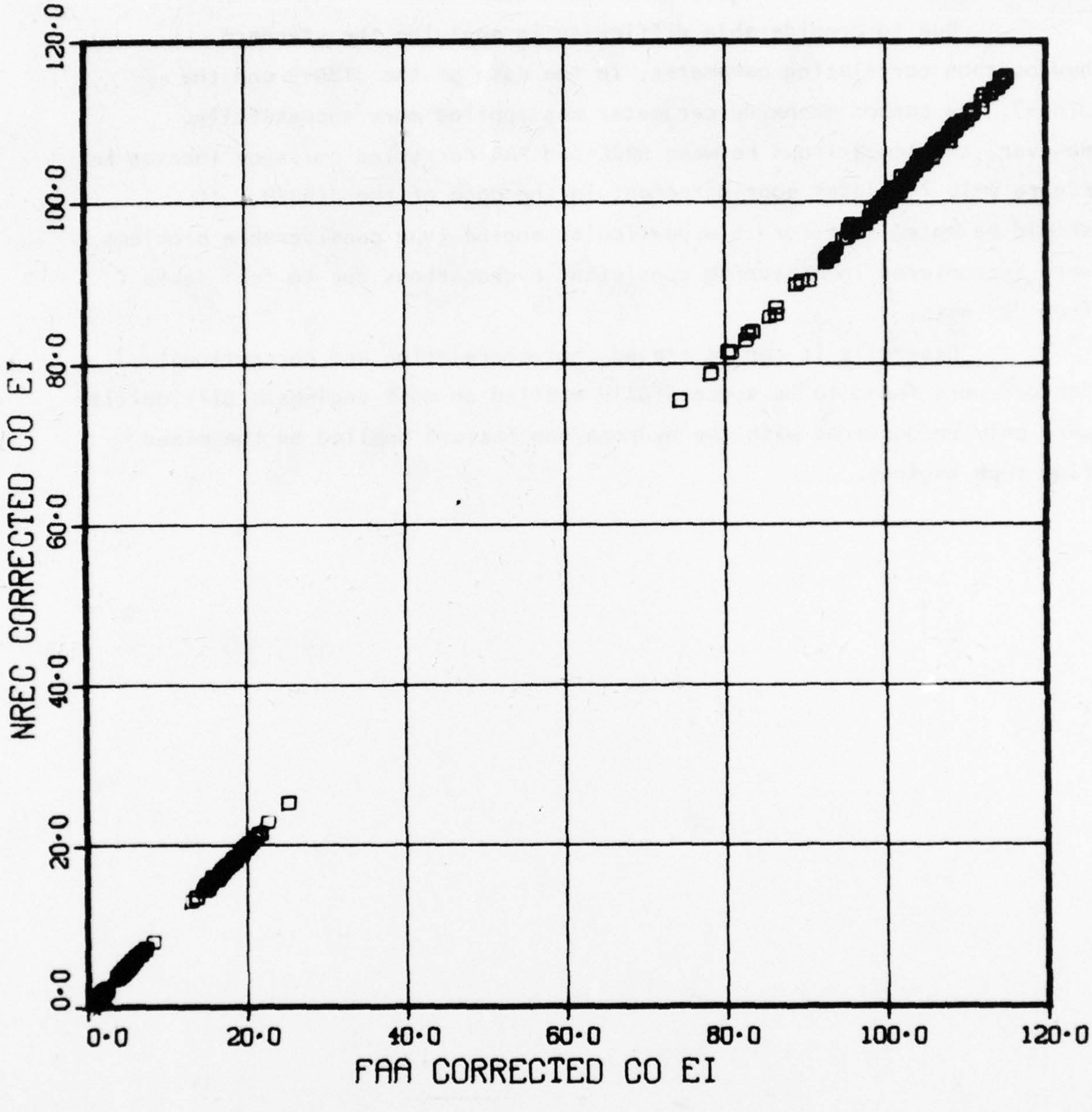

Figure B-14. Comparison of Ambient Corrections for JT3D-7 CO Emission Data

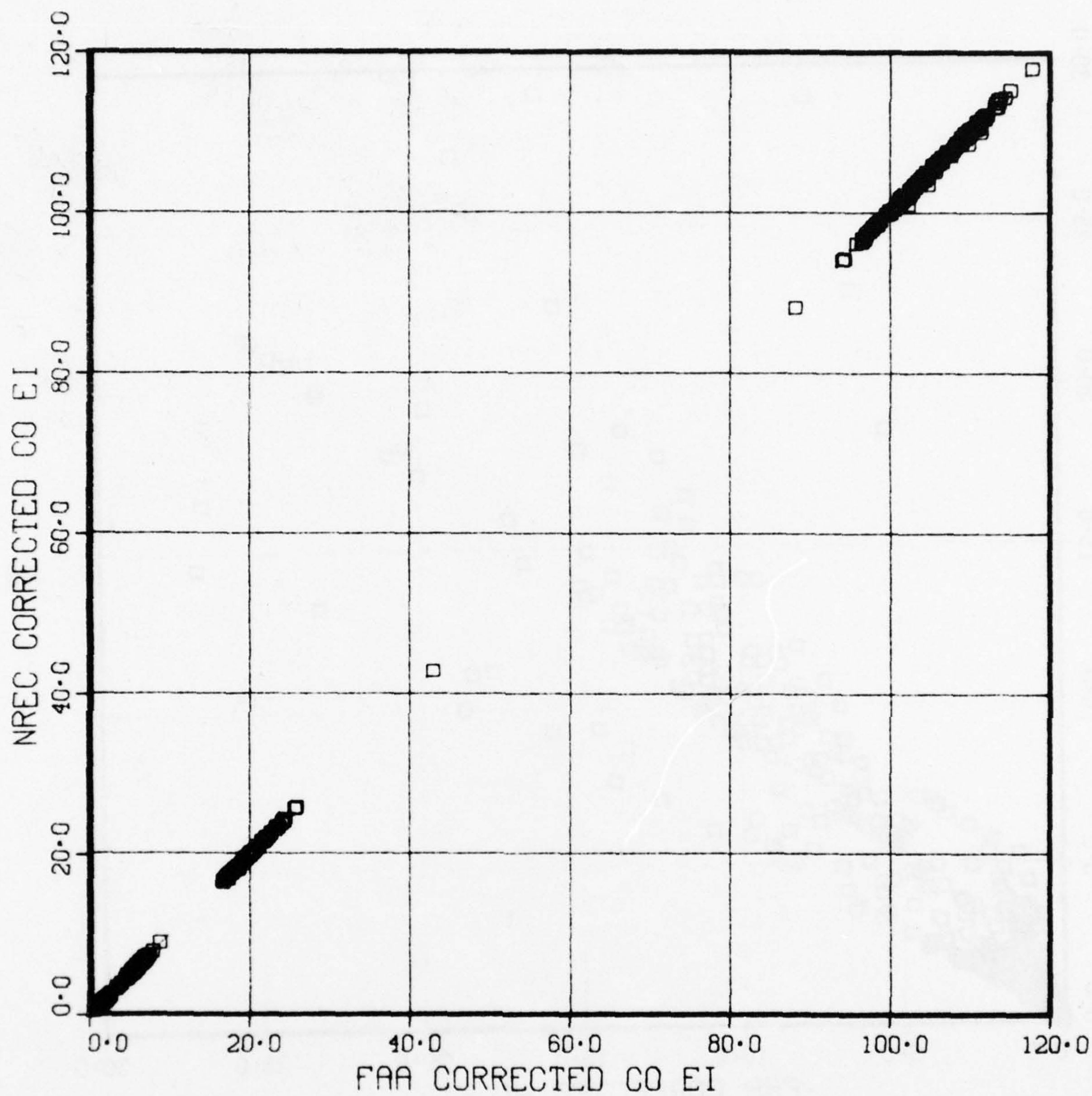

Figure B-15. Comparison of Ambient Corrections for JT3D-3B CO Emission Data

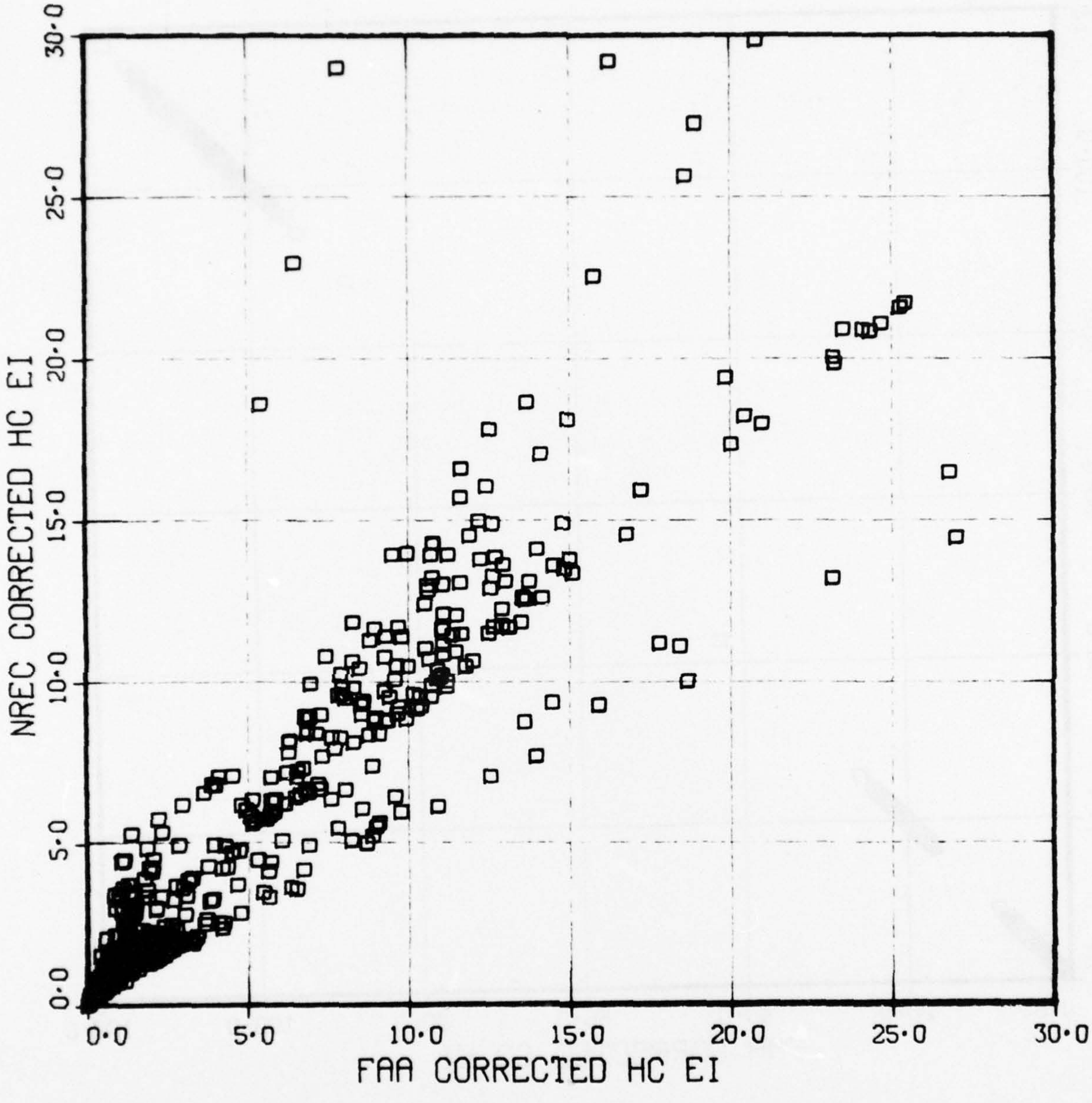

Figure B-16. Comparison of Ambient Corrections for JT8D-9 HC Emission Data

APPENDIX C

DEVELOPMENT OF SMOKE NUMBER CORRECTION FACTORS

INTRODUCTION

During the test program for the development of Time Degradation Factors for Turbine Engine Emissions in addition to monitoring gaseous emissions of carbon monoxide, hydrocarbons, and oxides of nitrogen, exhaust smoke was also measured. The technique employed for these smoke measurements was essentially that outlined by EPA, for aircraft engines in the Federal Register, July 17, 1973, Volume 38, Number 136 Part II. The method is basically one of paper filtration under controlled flow conditions and subsequent smoke spot reflectance measurement. Although a smoke meter conforming to the required standards was employed for smoke number determination procedural difficulties were encountered in the execution of the method due to the limited time engines could operate at take-off power. Consequently smoke measurements were made at only one sample weight per square inch of filter paper and corresponding to the interpolated value, 0.0230 lb/sq ins required in reporting the smoke number by the EPA method.

In addition to the above limitation it became evident as the program proceeded that sample line and smoke system contamination resulted in spurious smoke number measurements. The effects were most noticeable with tests conducted in San Francisco where smoke data from the JT9D and RB211 appeared higher than normal and also some unexplicably high smoke numbers were encountered from time-to-time on the JT8D-9 engines. From the evidence accumulated the problem appears to be related to soot build-up in the sampling line and smoke sampling train and is reasoned as follows.

The testing of JT3D type engines, which are copious producers of smoke results in gradual accumulation of smoke particles on the inside surfaces of the sample line and smoke sampling train. Subsequent operation of the system at high pressures, particularly at take-off EPR, scours the soot from the surfaces resulting in apparently high levels of smoke due to this additional soot deposition on the filter paper. This reasoning is substantiated by the fact that most of the erratic levels of smoke are recorded for engines operating at take-off conditions. Also it has been seen that after cooling of the sample line, purging with nitrogen, at the appropriate pressure and flow for take-off conditions, deposits considerable amounts of soot on the smoke sampling filter paper. Detailed examination of the contaminating soot shows flakes of various sizes all much larger than normal soot particles. In addition it was found from chronological examination of smoke results that high smoke results usually appeared subsequent to JT3D testing.

This appendix summarizes the finds of work aimed at:

1. Identifying smoke contaminated results
2. Est·blishing appropriate correction factors.

APPROACH

Following carefully examination of numerous smoke spot filter paper samples it became apparent that significant variations in the ratio of front to back side smoke number occurred when unusually high smoke numbers were detected. An appreciation of the change in value of this ratio can be made from the data illustrated in Figure C-1. It can be seen that at high operating EPR values, for the JT8D-9, JT8D-7, JT9D-3A and RB211 engines, a significant increase in the ratio symbolized by **k** occurs. The unusually high values of **k** were found to be the result of soot flakes on the front side of the smoke spot.

Further examination of many smoke sample spots, for all the engines in the test program, provided the average values of **k** shown in Figure III-2. Here the smoke ratio is compared with front side smoke number and it can be seen for low smoke engines large deviations from the average relationship are exhibited. As a result of these findings it would appear that identification of contaminated results may be made through higher than average values of front to back side smoke number. In addition, since in most instances the back side smoke numbers were not appreciably changed by contamination a corrected value of

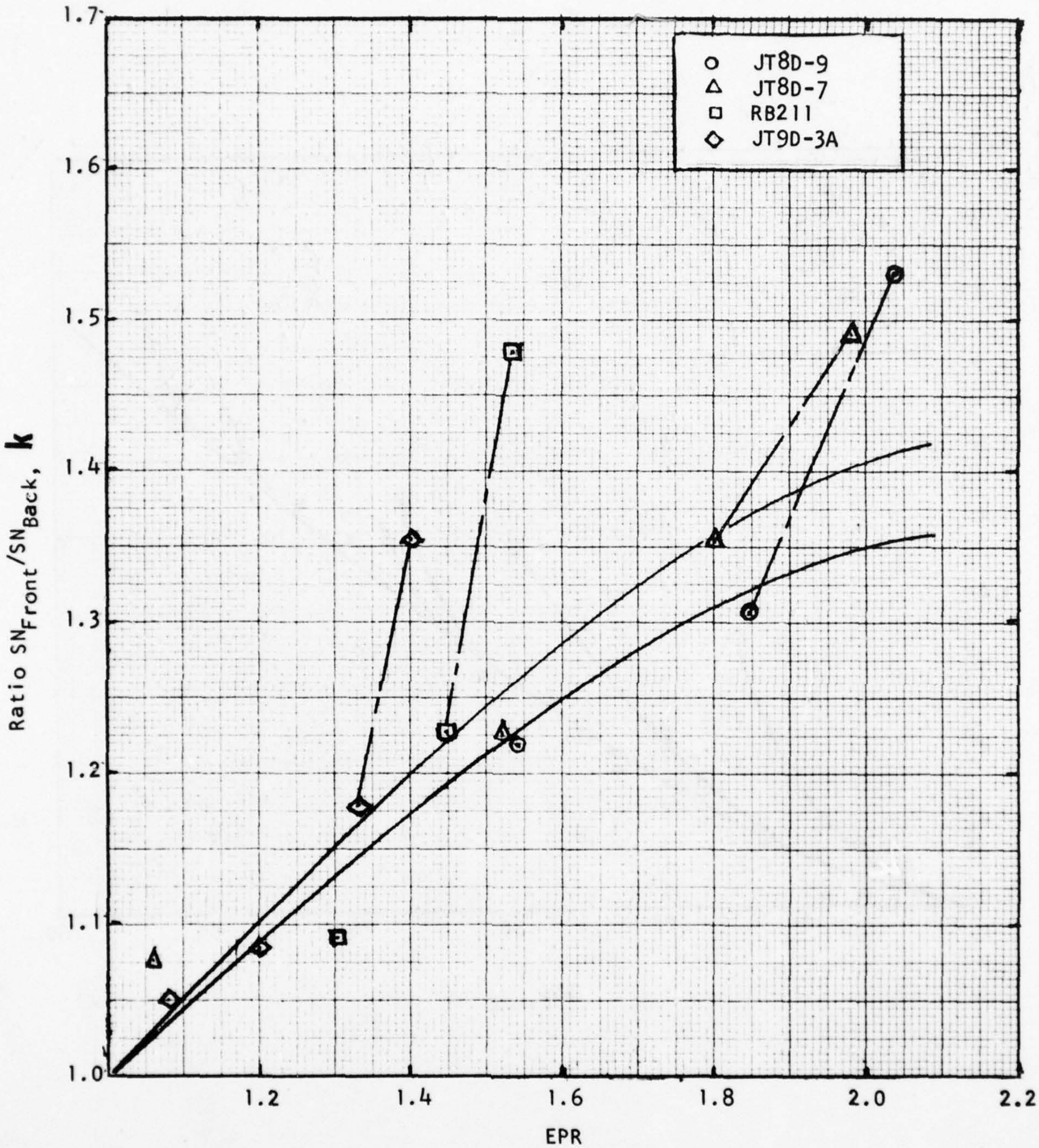

Figure C-1. Effect of EPR on Smoke Number Ratio

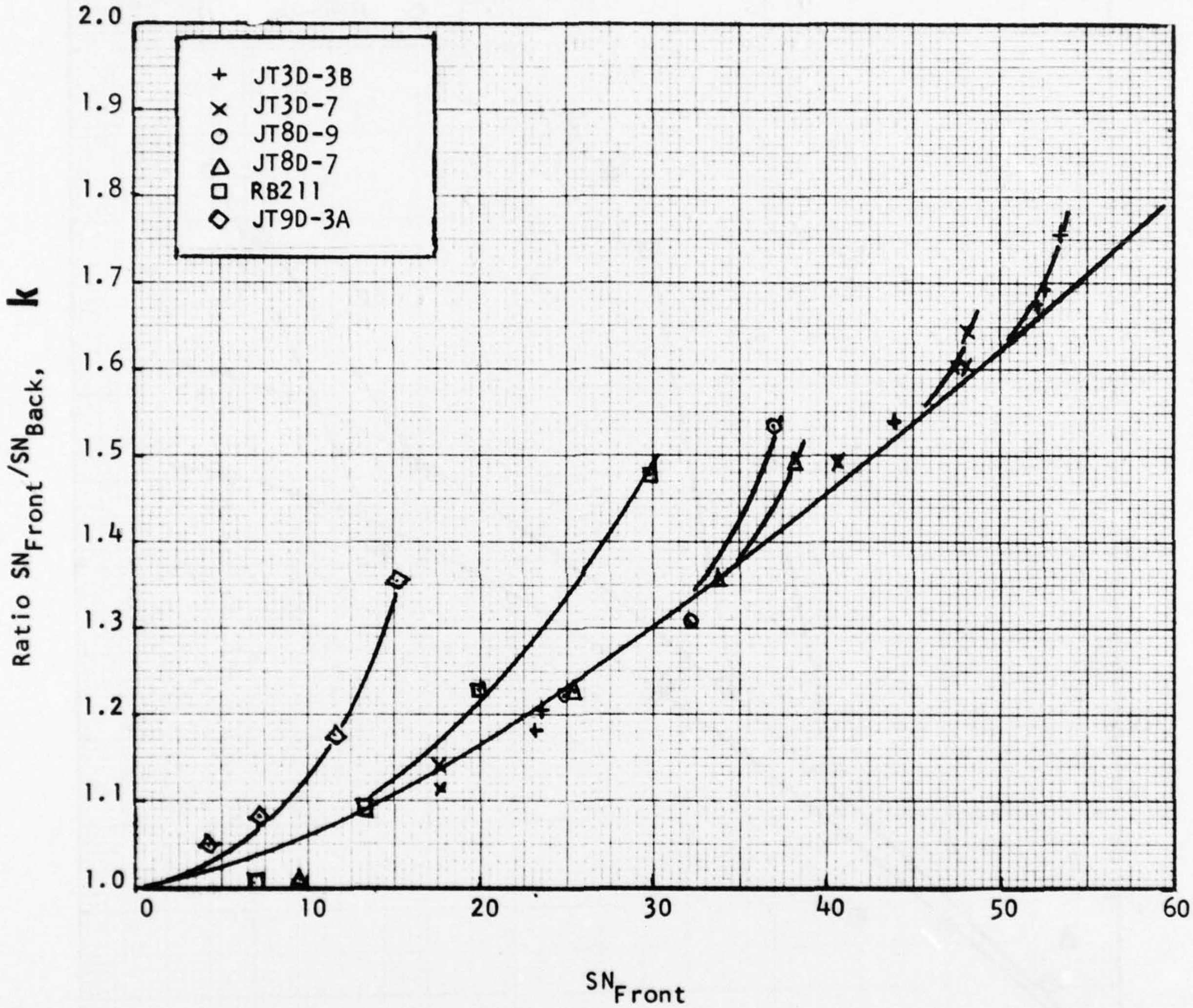

Figure C-2. Effect of Front-Side Smoke Number on Smoke Ratio front side smoke number may be predicted for all but the JT3D and JT8D-7 engine types from the average relationship shown in Figure C-3. Corrections were not made to the smoke number data for both JT3D type engines. In the case of the JT8D-7, the following equations were used:

a) Baseline, 600-hour, and 1200-hour test series

$$SN_{F,\ corr} = \begin{cases} SN_F & \text{if } k \leq 1.38 \\ 1.38\ SN_B & \text{otherwise} \end{cases}$$

b) 1800-, 2400-, and 3000-hour test series

$$SN_{F,corr} = \begin{cases} SN_F & \text{if } k \leq 1.28 \\ 1.28\ SN_B & \text{otherwise} \end{cases}$$

(The JT8D-7 corrections differed according to test series due to a variation in flow conditions.)

A summary of the corrected and uncorrected smoke numbers at take-off and climb is given in Table C-1.

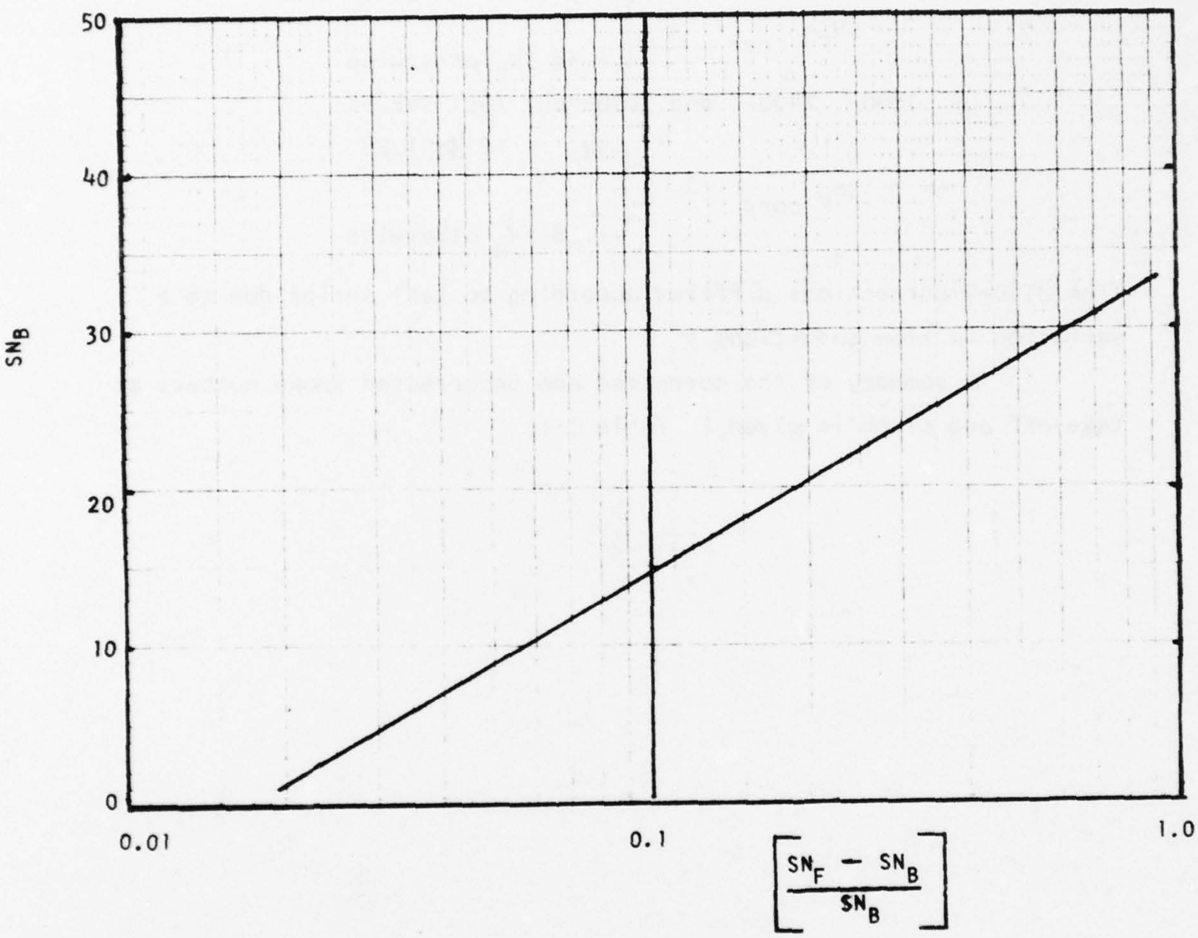

Figure C-3. Smoke Correction Chart

TABLE C-1. SUMMARY OF SMOKE NUMBERS

ENGINE TYPE		TAKE-OFF				MAX CONT			
		Max	Min	Mean	Std	Max	Min	Mean	Std
JT8D-9	w/o uncor	44.0	21.2	31.2	4.47	37.7	22.3	30.0	3.53
	w/o cor	40.4	21.2	30.7	4.16	35.8	22.3	29.6	3.42
	w uncor	55.0	21.2	32.3	5.94	40.8	21.1	30.0	3.99
	w cor	50.3	21.2	31.3	5.23	40.8	21.1	29.7	3.90
JT8D-7	w/o uncor	51.7	27.5	35.5	4.77	41.2	24.9	32.7	3.82
	w/o cor	40.6	27.5	33.1	2.73	39.4	24.9	31.7	3.03
	w uncor	85.3	00.0	36.0	9.19	53.7	24.9	33.0	4.40
	w cor	40.6	00.0	32.1	6.15	39.4	24.9	31.4	4.21
JT3D-3B	w/o uncor	63.8	42.1	52.2	4.69	58.8	45.3	52.0	3.61
	w/o cor	63.8	42.1	52.2	4.69	58.8	45.3	52.0	3.61
	w uncor	75.9	42.1	52.8	5.95	58.8	30.1	51.6	4.50
	w cor	75.9	42.1	52.8	5.95	58.8	30.1	51.6	4.50
JT3D-7*	w/o uncor	60.9	39.5	50.7	4.38	56.8	42.7	50.5	3.41
	w/o cor	60.9	39.5	50.7	4.38	56.8	42.7	50.5	3.41
	w uncor	69.2	38.4	51.0	5.86	64.6	40.7	50.6	3.98
	w cor	69.2	38.4	51.0	5.86	64.6	40.7	50.6	3.98
JT9D-3A	w/o uncor	25.3	4.64	15.2	5.19	18.3	2.8	11.1	4.05
	w/o cor	18.7	4.64	11.9	3.61	16.5	2.4	9.7	3.37
	w uncor	35.8	00.0	15.1	6.1	21.1	00.0	10.9	4.50
	w cor	18.7	00.0	11.6	4.04	18.0	00.0	9.5	3.78
RB211	w/o uncor	36.4	21.3	29.8	3.23	26.7	11.4	19.4	3.54
	w/o cor	29.1	18.9	24.2	2.42	24.6	11.2	17.8	2.93
	w uncor	48.0	14.7	29.7	4.66	30.2	8.0	19.4	4.37
	w cor	33.3	14.7	24.3	3.10	27.2	8.0	17.7	3.53
CF700	w/o uncor	21.2	9.9	15.9	3.18	19.9	7.3	13.6	3.23
	w/o cor	21.2	8.7	15.4	3.37	19.9	7.3	13.6	3.27
	w uncor	22.9	8.7	15.9	3.44	19.9	7.3	13.6	3.23
	w cor	22.9	8.7	15.6	3.51	19.9	7.3	13.6	3.27

w/o denotes data without outlying values while w denotes data with such values

* excluding low smoke combustor - Unit 13

APPENDIX D

NO CALIBRATION GAS CORRECTIONS

Examination of daily calibrations indicated that the specified concentrations of two NO gas bottles used on the San Francisco MERF were in substantial error. One, Bottle No. 52671 with a specified concentration of 192 ppm, was installed 11/18/75 and removed 4/22/76. The second, Bottle No. 72902 with a specified concentration of 50 ppm, was installed 10/10/75 and removed 6/14/76.

Monthly calibrations performed on 2/25/76 and 4/22/76 confirmed the errors and were used to correct the concentrations. Figure D-1 shows the responses to a number of calibration gases on Range 1 of the NO analyzer on those dates. A least-squres fit through the origin, for each case, yielded calculated concentrations for Bottle No. 52671 of 208 ppm and 207 ppm, respectively. As a result, an average concentration of 207.5 ppm was adopted for Bottle No. 52671. In addition, Figure D-2 shows the responses of the two gas bottles in question on Range 2 of the NO analyzer for the same dates. Assuming a linear response of the analyzer, respective concentrations for Bottle No. 72902 of 53.9 ppm and 53.6 ppm were calculated. Again, an average concentration of 53.7 ppm was adopted for Bottle No. 72902.

All affected data, including JT8D-7, JT3D-7, JT3D-3B, JT9D, and a few RB211 tests were reprocessed using the adopted concentrations. New emission levels were stored as Items 65 through 72 of the System NREC data array. The original emission levels were retained as Items 49 through 52 and 55 through 58.

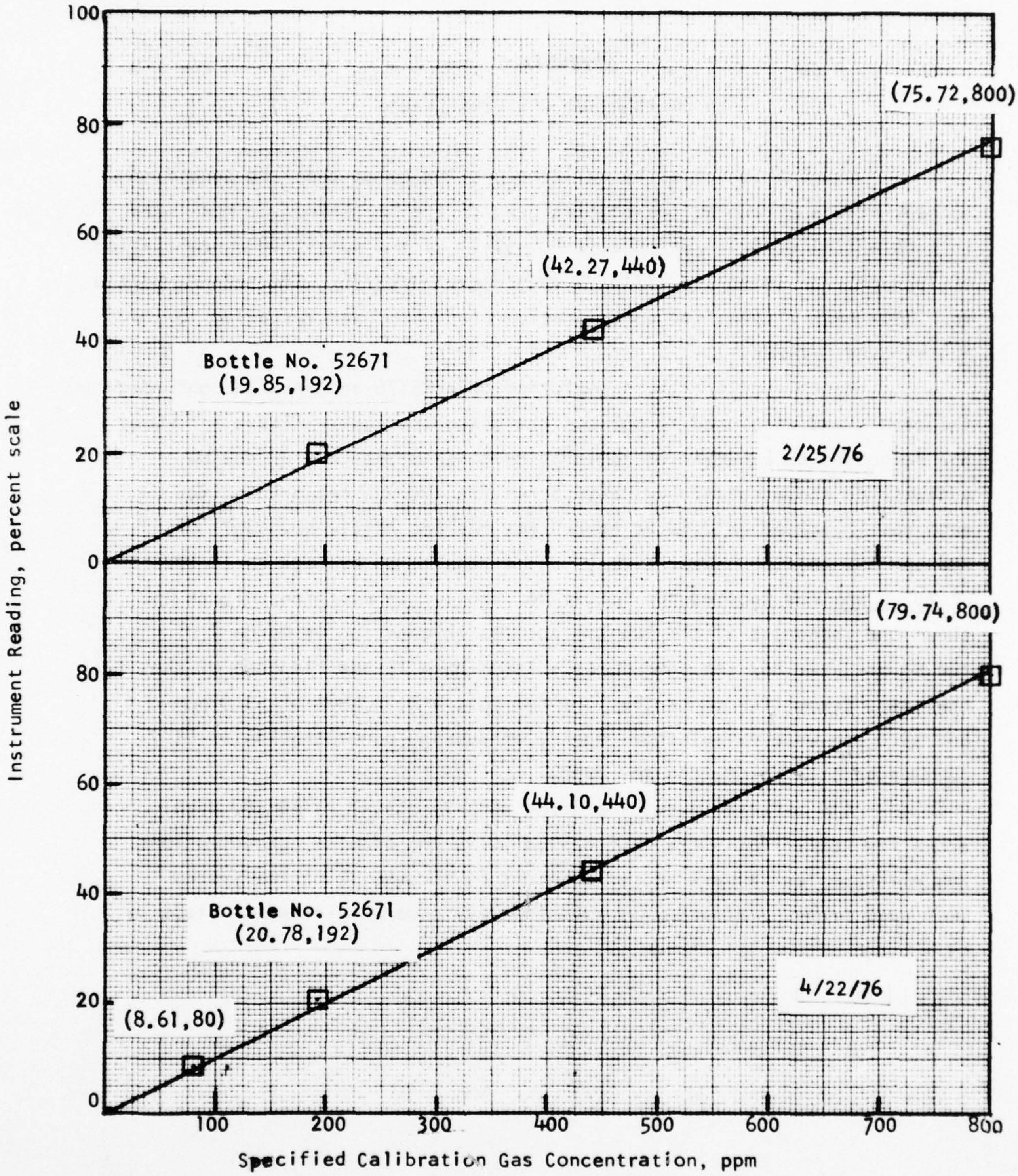

Figure D-1. Monthly NO Calibrations - Range 1

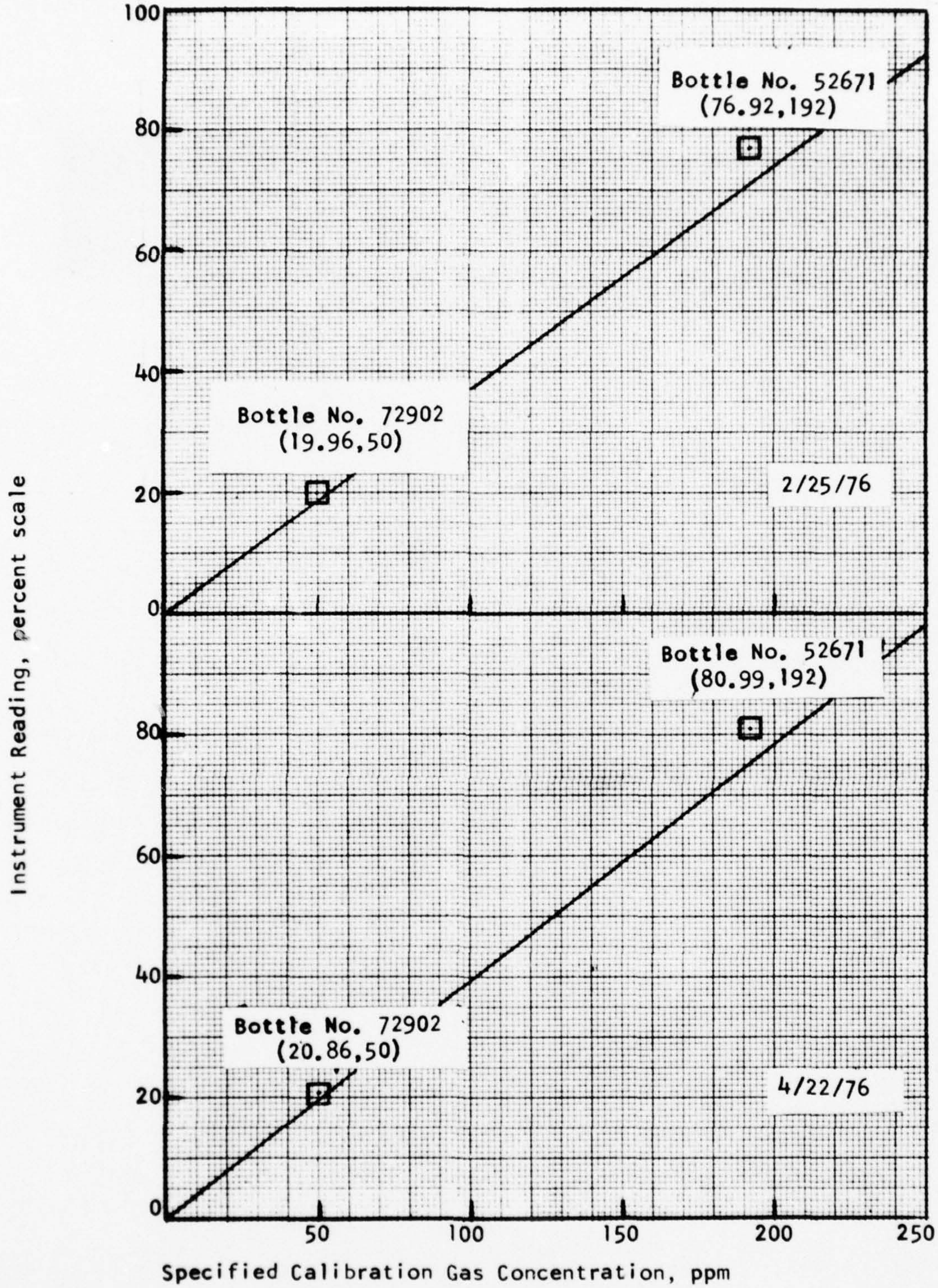

Figure D-2. Monthly NO Calibration - Range 2