EXHAUST EMISSIONS FROM WILLIAMS RESEARCH CORPORATION GAS TURBINE ENGINES

Williams Research Corporation
Walled Lake, Michigan

18 June 1970

Report No. WR-ER8

INTERIM REPORT

EXHAUST EMISSIONS FROM WILLIAMS RESEARCH CORPORATION GAS TURBINE ENGINES

TO

NATIONAL AIR POLLUTION CONTROL ADMINISTRATION
CONSUMER PROTECTION AND ENVIRONMENTAL HEALTH SERVICE
PUBLIC HEALTH SERVICE
UNITED STATES DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE

FROM

WILLIAMS RESEARCH CORPORATION
2280 West Maple Road
Walled Lake, Michigan 48088

CONTRACT NO. CPA 22-69-84

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FROM: 18 June 1969

TO: 18 April 1970

PROJECT ENGINEER H. B. Moore

CHIEF PROJECT ENGINEER J. A. Royer

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FOREWORD

This report, No. WR-ER8, entitled "Exhaust Emissions from Williams Research Corporation Gas Turbine Engines," is submitted as an interim report under Contract No. CPA 22-69-84, Gas Turbine Engine Emissions, and covers the work between 18 June 1969 and 18 April 1970. The work is continuing and the results reported herein are tentative.

The work upon which this publication is based was performed pursuant to Contract No. CPA 22-69-84 with the National Air Pollution Control Administration, Environmental Health Service, Public Health Service, Department of Health, Education, and Welfare.

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ABSTRACT

The exhaust emissions of several different models of gas turbine engines under development or in production at Williams Research Corporation were measured under contract with the National Air Pollution Control Administration.

The emissions measured were carbon dioxide, carbon monoxide, unburned hydrocarbons, and the oxides of nitrogen. The results are presented in a generalized form relating emissions to fuel air ratio and engine power or thrust.

Techniques were developed to convey exhaust samples from engines in test cells to analysis equipment located elsewhere. Measurements were also made of the emissions from a gas turbine engine installed in a vehicle.

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INTRODUCTION

Williams Research Corporation over the past fifteen years has developed a family of gas turbine engines ranging from a 121 lb thrust turbojet to a 440 hp industrial engine. The exhaust emissions of all of these engines were measured during the program using sampling equipment developed by Williams Research and analysis equipment furnished by the Division of Motor Vehicle Pollution Control of the National Air Pollution Control Administration, Ypsilanti, Michigan.

Most of the measurements were made with the engines running in test cells at Williams Research. The 131Q vehicular engine was also measured for emissions while installed in a vehicle. These tests were run on a chassis dynamometer at Ypsilanti.

The exhaust gases were pumped through a specially constructed line from a probe installed in the engine exhaust system to a console containing the analysis equipment. Constituents measured were carbon dioxide, carbon monoxide, unburned hydrocarbons, and oxides of nitrogen. An attempt was made to measure particulates present in the exhaust but concentrations were too low for the method used.

Infrared analyzers were used for the CO_2 and CO analysis. The hydrocarbons were detected with a flame ionization detector and a modified Saltzmann technique was employed to measure the oxides of nitrogen. Particulates were collected on a filter.

Continuous recordings were made of the CO_2, CO, and hydrocarbons and some transient data was taken during engine starting and shutdown. The equipment and its operation are shown in Figs. 12 and 13.

DESCRIPTION OF ENGINES

General characteristics of the Williams Research Corporation engines tested in this program are given in this section. The engines are shown in Figs. 1 through 4.

WR24-6 Turbojet

The WR24-6 is a small turbojet engine used in drone aircraft applications. It has a single stage centrifugal compressor driven by a single stage axial turbine and employs an annular combustor.

Rated sea level static thrust is 121 lbs at 60,000 rpm. Airflow is 2.2 lbm/sec and exhaust temperature is 760^{o} C (1400^{o}F) The engine uses MIL-J-5624 grade JP-4 or JP-5 fuel at a rated specific fuel consumption of 1.2 lbm/hr-lbf.

Over 700 units have been produced in the past two years. The WR2-6 turbojet is basically the same engine with a different exhaust nozzle and electric generator. It is also in production.

WR9-7 Auxiliary Power Unit

The WR9-7 is an auxiliary power unit for turbine engine aircraft providing a combination of pneumatic, hydraulic, and electric power. The engine has a single shaft with a single stage centrifugal compressor and two axial turbine stages driving a gearbox. The annular combustor is similar to that in the WR24-6.

The engine provides a rated .55 lbm/sec of bleed air from its compressor for pneumatic starting of the aircraft main engines. Hydraulic power up to 7 1/2 hp, or electric power up to 15 kw are also available.

At a maximum total load of 65 hp, the turbines pass 1.7 lbm/sec of air. Exhaust gas temperature is 593° C (1100° F). The engine normally runs on JP-4 fuel.

The WR9-7 is installed on the Buffalo DHC-5 turbo-prop produced by DeHavilland Aircraft of Canada, Ltd.

WR19 Turbofan

The WR19 is a twin spool turbofan with a bypass ratio of 1.0 and a rated thrust of 430 lbs. The total airflow is 11.1 lbm/sec and the SFC is 0.7 lbm/hr-lbf. Mixed exhaust temperature is 304° C (580° F).

The engine was developed as the power plant for the Bell Aerospace Flying Jet Belt.

131L Industrial Engine

The 131 L engine features a single stage centrifugal compressor driven by a single stage, axial turbine and has an annular combustor. Power is produced by a single stage axial turbine on a separate shaft which drives the load through an integral gearbox.

With a rating of 440 hp and an airflow of 6.1 lbm/sec, the exhaust gas temperature is 593^{o} C (1100^{o} F) and the SFC is 0.86 lbm/hr-hp. The engine will run on a wide range of fuels including natural gas and diesel No. 2.

<u>131Q Vehicular Engine</u>

This engine is in development both on the test stand and in a test bed vehicle. It has a regenerator which recovers turbine exhaust heat to improve its fuel economy.

An experimental version of this engine without regenerator, designated 131QNR in this report, is also being run at Williams Research as a component development tool. Data were also taken on this engine in an attempt to assess the effect of the regenerator on emissions.

SAMPLING EQUIPMENT

Sampling Line Development

Tests on gas turbine engines at Williams Research are generally conducted in test cells for safety and convenience with the engine mounted on a test stand in the cell and the operator stationed at a control console outside. With the exhaust analysis equipment also outside the test cell, it was necessary to provide a suitable line from the exhaust system of the engine to the analyzer, a distance of 15 to 25 feet. To prevent condensation of the exhaust constituents in the line, especially the unburned hydrocarbons of gas turbine engine fuels, it was necessary to keep the line at a temperature between 150 and 200° C (302 to 392° F). The analyzer pumped gas from the line at 3 to 4 liters/minute.

To maintain the line at temperature, an oil jacketed construction was used. In the early part of the program, this consisted of sections of 3/8 in. stainless tubing brazed inside lengths of 1 in. cast iron pipe capped at each end. The sections were joined with short pieces of aircraft type teflon hose. The cast iron pipe sections, covered with steam pipe insulation, were connected in series with a heated oil supply. This line worked satisfactorily but was cumbersome to set up.

A coaxial flexible line was built consisting of .313 in. I.D. teflon hose (AMS 3380-6) inside a .875 in. I.D. hose (AMS 3380-16Z) with flared swivel fittings on each end. The inner fittings were inserted into drilled plugs installed in the outer fittings and then welded in place so that the outer hose became a sealed jacket over the inner hose. Oil connections were made through tubes mounted radially in the outer fittings. The outside was insulated with asbestos and fiberglass tape. The line was 25 feet long and is shown schematically in Figure 5.

A bypass pump was used to improve the response of the system by increasing the sample gas velocity in the line to 12 liters/minute. Thermocouples monitored the sample gas temperature entering and leaving the line.

The oil system for heating the lines is shown schematically in Figure 5 and depicted in Figure 11. It consists of a pump, two 1500 watt electric heaters, a reservoir, valves, and flexible connecting lines. For ease of set up in the various engine test cells, the system was built on a dolly. Temperature of the oil at each end of the sample line was monitored with thermocouples and was held between 160 and 190° C (320 and 374° F) by thermostats in the heating units. The system could be brought up to temperature in two hours.

Sampling Probes

For each engine tested in the program, sampling probes were fabricated to fit each exhaust system. These are all shown schematically in Figures 6, 7, and 8. Refer also to Figures 9 and 10.

The general approach was to provide a total pressure probe aimed directly into the exhaust stream in a region of relatively smooth flow so that the possibility of recirculation and dilution by outside air was minimized. This was no problem with the jet engines where the gas velocity was high but special care was necessary with the 131Q NR engine.

Different probe locations in the same exhaust plane were investigated only with the 131Q NR engine, but need further study, especially with the jet engines, where there is known to be considerable non-uniformity in the exhaust stream temperature at the sampling station. Any large sampling error showed up in the reduced data as a large CO_2 error, as defined in the next section.

RESULTS

CO_2 Summary

Throughout the program, a summary sheet was maintained on which was plotted measured CO_2 concentration in the exhaust and a calculated CO_2 concentration for each data point. These values ranged from 0.7 to 4.2 per cent and are shown in Figure 14.

The calculated value was based on complete combustion of the fuel to water and CO_2 using the measured engine fuel flow, airflow, and a handbook value for hydrogen to carbon ratio of the fuel. Since measured values for carbon containing pollutants, namely CO and unburned hydrocarbons, rarely exceeded 500 ppm, the error incurred in not subtracting the carbon present in these constituents from the calculated CO_2 value was small compared with the overall accuracy of the measurements.

Accuracy of Data

The comparison of measured and calculated CO_2 concentration was taken as a measure of the validity of the data. The difference between the two values, called CO_2 error, could be due to any combination of the following:

a. Non-representative sampling - probe and line failing to pick up an average sample of the exhaust gas.

b. Failure to detect large concentrations of other carbon containing constituents in the exhaust.

c. Excessive oil system leakage into the engine gas stream.

d. Errors in CO_2 measurement.

    1. Detector error

    2. Calibration gas error

e. Errors in calculated CO_2 value.

    1. Engine airflow measurement

    2. Engine fuel flow measurement

    3. Assumed hydrogen to carbon ratio of fuel

The distribution of CO_2 error taken over all engines and operating conditions was examined for randomness. If it could be shown that the combined influence of the presumed sources of error listed above affected the data in a purely random way, then predictions on the accuracy of all the data could be made. Data known to be bad due to discovered line leakage or sample pump failure was discounted. Some data, notably the APU data of October 16, 1969 and the early 131Q NR data, showed a systematic error of opposite polarity to that of all of the rest of the data in that the measured values of CO_2 concentration were considerably lower than the calculated values. These points were also suspect. The data points underlined with a dashed line at the bottom of Figure 14 were shown to be consistent with a normal population. This analysis is shown in Appendix D. These points are the only ones used in presenting the results on the pollutant measurements.

The mean value of the CO_2 error for the sample underlined in Figure 14, consisting of 83 points, is 0.14 per cent CO_2 and the standard deviation is 0.16 per cent. Since the expected value of the mean of CO_2 errors is zero, the 0.14 per cent represents some form of systematic error of unknown origin. Arbitrarily adding to this quantity one standard deviation of the normal distribution, the estimated magnitude of error in the CO_2 measurements becomes 0.30 per cent. As a per cent of average CO_2 reading, this works out to be 22 per cent for the 131Q engine and 11 per cent for the other engines. These figures are taken as a measure of the overall accuracy of the CO_2 determination.

The measurements of the concentration of other constituents in the exhaust do not have a common basis for comparison nor were a large enough number of samples taken under the same engine operating conditions to perform a statistical analysis on each point. The factors contributing to errors in these measurements and the quantities derived from them are the same as for the CO_2 measurements except that the detection equipment is different for each constituent. The accuracy of the determinations of CO, unburned hydrocarbons, and NO_2 is assumed to be no better than the per cent accuracies for each engine quoted above for CO_2.

If these accuracy limits are applied to the assumed curves of emission variables plotted in Figures 15 through 33, the resulting bands will cover most of the points.

It is expected that refinements in exhaust sampling techniques and fuel and airflow measurement will reduce or eliminate the apparent systematic error in CO_2 determination found in this data and reduce the standard deviation of the distribution of CO_2 error.

Steady State Results

Emissions measurements results have been plotted in Figures 15 through 33 in three formats. General parameters were chosen for plotting so that data for different engines and different fuels could easily be compared.

The first format is pollutant concentration in the exhaust in parts per million vs. equivalence ratio, which is fuel air ratio normalized to stoichiometric. These plots show the range of pollutant concentrations for each engine and its dependence on fuel air ratio.

The second format, Figures 20 through 27, shows emission index, or mass of pollutant emitted per unit mass of fuel burned, vs. specific fuel economy, or engine energy output per unit mass of fuel burned. For the jet engines, thrust was used in place of energy output. The abscissa variable is reciprocally related to the specific fuel consumption which is shown on a separate scale. Alternatively, these plots can be considered as mass of pollutant vs. engine output.

Finally, Figures 28 through 33 give specific emission, defined as mass of pollutant per unit of engine output, vs. power or thrust. The semi-log plot allows large and small engines to be shown on one graph.

The plots within each format are further divided between the three pollutants measured in the program; carbon monoxide, hydrocarbons, and nitrogen dioxide. Data on the WR19 engine was taken too late to be incorporated in this report.

a. Concentration vs. equivalence ratio. Figure 15 shows a steep dependency of CO emission on fuel air ratio for the 131Q engine. The regenerative engine appears to have a critical fuel air ratio of 0.09 of stoichiometric with diesel No. 2 fuel, 0.07 with lighter fuels, for CO emission. The non-regenerative engine, with twice the fuel consumption, appears to have twice the CO emission and a critical fuel air ratio of 0.19 stoichiometric. In Figure 17, a similar result is obtained for the 131Q hydrocarbon emissions except that non-regenerative concentrations are comparable to the regenerative.

Figures 16 and 18 show a less critical dependency of emission concentration on fuel air ratio for the WR9-7 APU and 131L industrial engine. The APU data shows a tendency to go through a minimum in Figure 16, but further measurements are needed to verify this. There is considerable scatter in the APU hydrocarbon data in Figure 18, but the 131L data shows some tendency toward lower concentrations at higher equivalence ratios. With the limited data available, Figure 19 shows the opposite tendency for nitrogen dioxide vs. equivalence ratio, the concentration increasing with fuel air ratio.

These results are in general agreement with those of Sawyer and Starkman[1] on several gas turbine engines and point up the difficulty of the nitrogen oxide problem.

b. Emission index vs. specific fuel economy. These plots clearly show that the more efficiently the engine is operated, the lower the emissions of CO and hydrocarbons as a per cent of fuel burned. All the shaft engines appear to approach the same minimum of 5 mg/g of CO and 0.3 mg/g of hydrocarbons. The exception is the 131Q NR which does not go below 10 mg/g of CO at its lowest SFC.

The range of emission index for CO in Figures 20 through 22 is from 5 to 110 mg/g and the range for hydrocarbons in Figures 23 through 25 is 0.3 to 4 mg/g. These reflect the variation in combustion or burner efficiency. It should be noted that these variations can account for only about 4 per cent of the variation in SFC, the rest arising from efficiency variations in other engine components.

Figure 26 shows a moderate rising trend of NO_2 emission index with specific fuel economy.

c. Specific emission vs. engine output. Figure 28 shows the CO emission per unit of output for all the shaft engines tested. The 131Q and 131L engines both reach down to 2 g/hphr of CO at their highest power output. The 131Q NR shows significantly higher specific emission of CO than the regenerative engine.

The APU reaches only 5 g/hphr at its heavy load points (both air and shaft horsepower included). The upper points on the APU curve reflect low loading on the engine rather than high emissions. The shape of the curve between low and high loading is unknown.

The hydrocarbon results in Figure 29 indicate that all the shaft engines reach approximately 0.2 g/hphr at high loading. Note that the 131Q NR results on this plot are indistinguishable from those of the regenerative engine.

Limited data was available on the specific emission of NO_2. There is an indication, however, in Figure 30, that NO_2 per unit of engine output continues to diminish slightly up to the maximum power output, although the quantity of NO_2 emitted markedly increases.

Vehicle Tests

Although considerable data was taken on the 131Q engine in test cell running, the emission performance of the engine in a vehicle was considered important for comparison with other vehicle power plants. In particular, the measurement of performance over the standard California driving cycle was a major objective of the program.

The 131Q engine burner was developed to run on commercial diesel No. 2 fuel. It operates well with JP-4 jet fuel but some instability was experienced attempting to run with commercial white gasoline. Stable operation was obtained with a 50-50 mixture of white gasoline and JP-4. It was decided to conduct the vehicle tests with the normally used diesel No. 2 fuel, recognizing that the bag sampling equipment using unheated lines, might fail to pick up the heavy hydrocarbons in the exhaust.

Engine serial no. 5 was first run on the test stand at Williams to establish baseline performance. It was then installed in the test vehicle and the vehicle was driven to NAPCA, Ypsilanti, a distance of 25 miles, where it was installed on a chassis dynamometer in Building 2042. The heated sample line and analysis cart used in the Williams tests were also used as shown in Figure 34.

A portable instrument console was placed near the vehicle to monitor shaft speeds, temperatures, and pressures in the engine. First and second stage shaft speeds were also continuously recorded on a strip chart.

The NAPCA bag sampler equipment was connected into the sample line at the analysis cart. This permitted simultaneous bag and continuous sampling. All samples were analyzed on the same equipment, continuous samples during the test, bag samples after the test. Fuel in all vehicle tests was diesel No. 2.

Table I is a summary of the chassis dynamometer test results. Details of the calculations are given in Appendix B. The steady state data, engine data points 58 and 63-66, were also put through the 131Q data reduction program and appear favorably on the CO_2 error summary, Figure 14, thus validating the sampling arrangement. Also, continuous and bag readings on CO_2 for the same run, where presented in Table I, compare favorably.

Continuous and bag results on CO for the steady state points are also consistent. The unburned hydrocarbons, however, are lower by a factor of at least 2 for the bag samples. This is believed to be due to the failure to maintain the sample gas above 150° C (302° F) during the bag sampling procedure.

Due to the weighting procedure (Appendix B) used in preparing the continuous sample results for runs 3 and 4, the pollutant concentrations and grams per mile figures for bag and continuous samples cannot be expected to agree. The continuous sample figures in grams per mile, however, are consistent with current federal procedure for measuring pollutant emissions from vehicles.

TABLE I

SUMMARY OF CHASSIS DYNAMOMETER TEST RESULTS

Run	Eng. Data Pt.	Type of Run	Sample Line*	Sample	CO_2 pct	CO ppm	CO g/mi.	CH_x as C_3H_8 ppm	CH_x as $CH_{1.85}$ g/mile	NO_x as NO_2 ppm	NO_x as NO_2 g/mile
1	--	9 cycles hot start	A	bag	1.37	90	--	1.8	--	--	--
2	58	steady state, N_1 = 45 krpm	A	continuous	1.45	70	--	1.6	--	--	--
				bag	1.45	70	--	0.2	--	--	--
3	--	9 cycles cold start	A	bag	1.53	160	8.0	11.5	0.85	41	3.4
				continuous**	--	86	4.3	11.5	0.86	--	--
4	--	9 cycles hot start	B	bag	1.48	125	6.2	2.2	0.16	56	4.5
				continuous**	--	118	5.9	3.9	0.29	--	--
5	63	steady state, N_1 = 40 krpm	B	continuous	1.37	75	--	1.4	--	--	--
				bag	1.32	80	--	0.7	--	40	--
6	64	steady state, N_1 = 45 krpm	B	continuous	1.48	60	--	0.5	--	--	--
				bag	1.42	60	--	0.2	--	42	--
7	65	steady state, N_1 = 50 krpm	B	continuous	1.58	52	--	0.2	--	--	--
				bag	1.56	55	--	0.1	--	69	--
8	66	steady state, N_1 = 55 krpm	B	continuous	1.78	45	--	0.2	--	--	--
				bag	1.76	50	--	0.1	--	73	--

*A 25 foot heated line to analyzer - 15 foot unheated line to bag sampler

B 6 foot heated line to analyzer - 15 foot unheated line to bag sampler

** All figures calculated on basis of standard weighting applied to profiles of 6 out of 9 cycles; see Appendix B .

N_1 = gas generator speed

Transient Measurements

With continuous recording equipment available for CO_2, CO, and hydrocarbons, some transient data was taken on these constituents. On a cold engine start, it was necessary to reduce the sensitivity of the hydrocarbon detector to a nominal 2000 ppm full scale to remain on the chart whereas during steady state running a 20 ppm scale was employed. Cold start measurements were generally avoided because the line and detector became so loaded that subsequent measurements were impossible until the system had been thoroughly purged. Hot engine starts presented the same problem to a lesser degree.

Engine accelerations caused little disturbance in the emissions traces beyond that of adjustment to the new operating level. Decelerations and shutdowns caused large temporary increases in CO and hydrocarbons.

A typical recording of emissions transients is presented in Figure 35. Chassis dynamometer results during the California cycle are given in Appendix B.

CONCLUSIONS

1. Gas turbine engines are inherently low polluters in carbon monoxide and unburned hydrocarbons compared to other types of engines of the same power output.
2. Transient engine operation produces many times the CO and hydrocarbon emission that steady state operation produces.
3. Part load engine operation produces more CO and hydrocarbon emission than full load. The opposite is true of the oxides of nitrogen.
4. The oxides of nitrogen are the most serious emission problem of gas turbine engines with respect to proposed emission controls.
5. Satisfactory methods have been developed in this program for sampling exhaust pollutants from a variety of gas turbine engines.
6. A heated sampling system is necessary to prevent deterioration of the unburned hydrocarbon sample between engine and analyzer.

RECOMMENDATIONS

1. Refine sampling techniques with heated probes and faster sample handling.
2. Develop techniques for better measurement of emissions during engine transients and study the effect of engine hardware changes on transient emissions.
3. Employ continuous detector for more complete data on oxides of nitrogen.
4. Continue emissions measurements on all WRC gas turbine engines to provide solid basis for comparison with other power plants and for evaluating developmental changes in the engines with regards to emissions.
5. Continue measurement on the 131Q vehicle both on the chassis dynamometer and on the road.
6. Conduct gas turbine engine burner and regenerator development programs using both rigs and engines to reduce pollutant emissions without substantially reducing component performance.

Most of the recommendations resulting from the work on this program are discussed in Williams Research Corporation Proposal No. 729, Gas Turbine Engine Exhaust Emission Analysis, Supplementary Program, 5 March 1970.

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Gas Turbine Engine Exhaust Emission Analysis
March 1969

8 Monthly Progress Reports 1 through 9
Gas Turbine Engine Exhaust Emission Analysis
2 August 1969 through 2 April 1970

Fig. 1 WR24-6 Turbojet

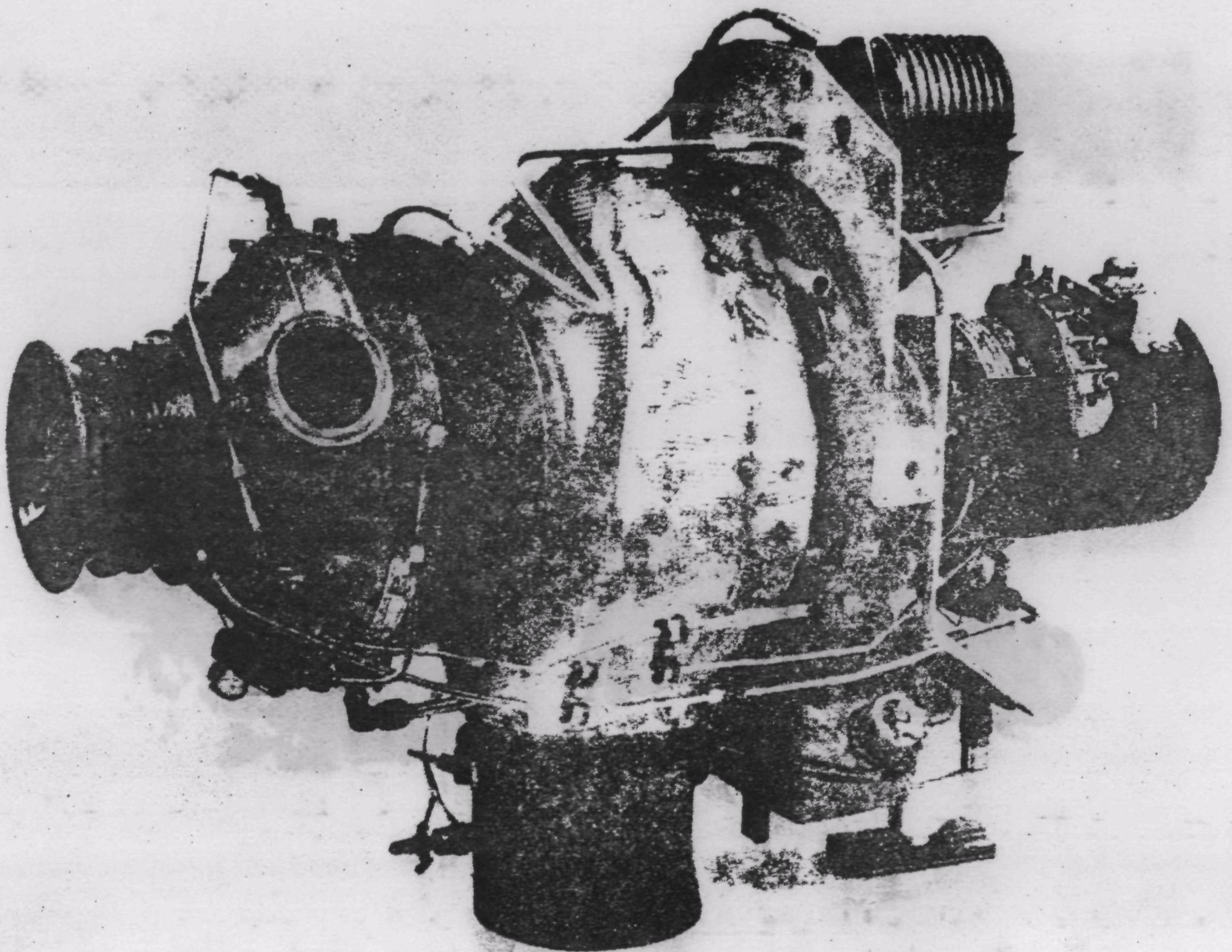

Fig. 2 WR9-7 Auxiliary Power Unit

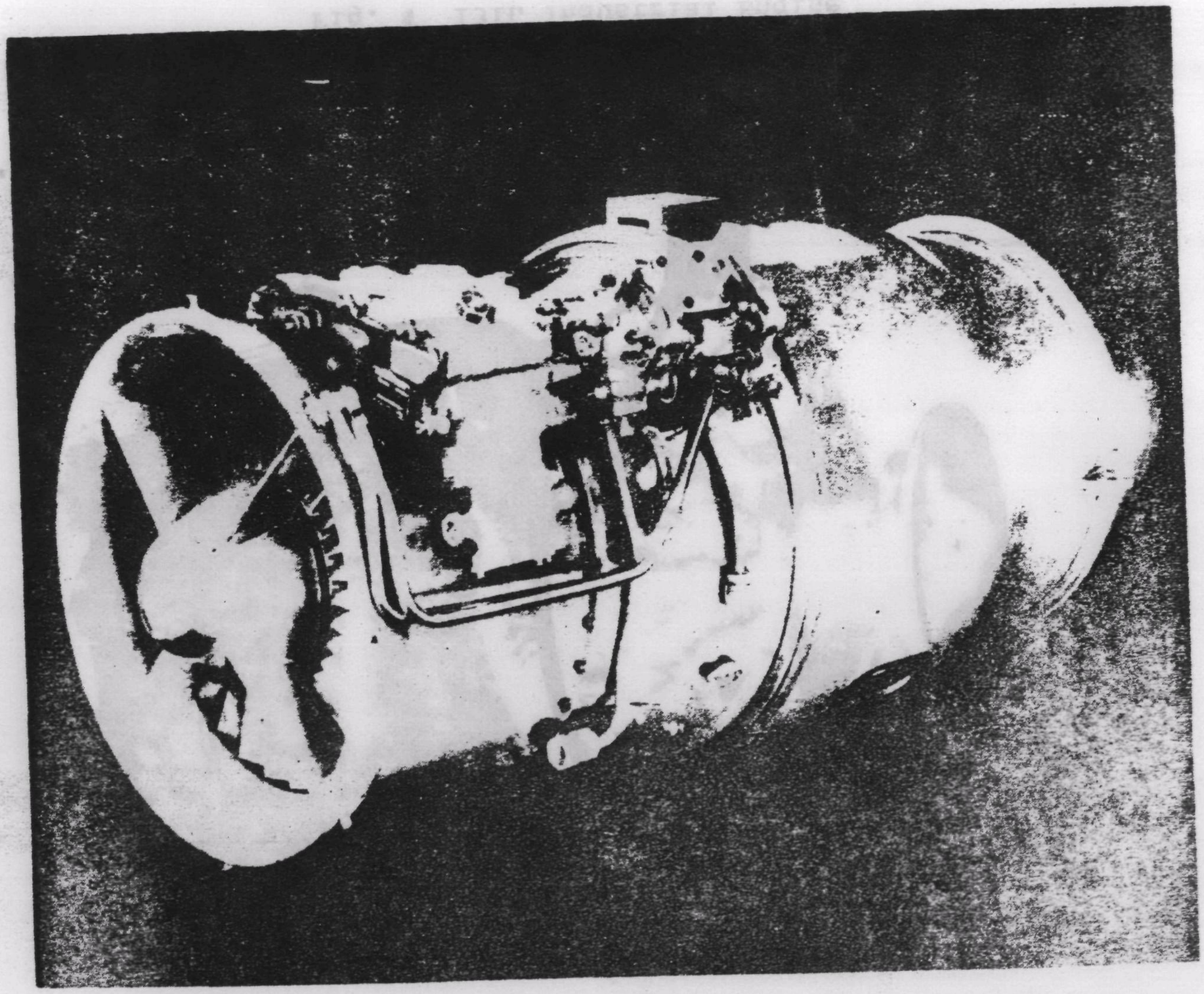

Fig. 3 WR19 Turbofan

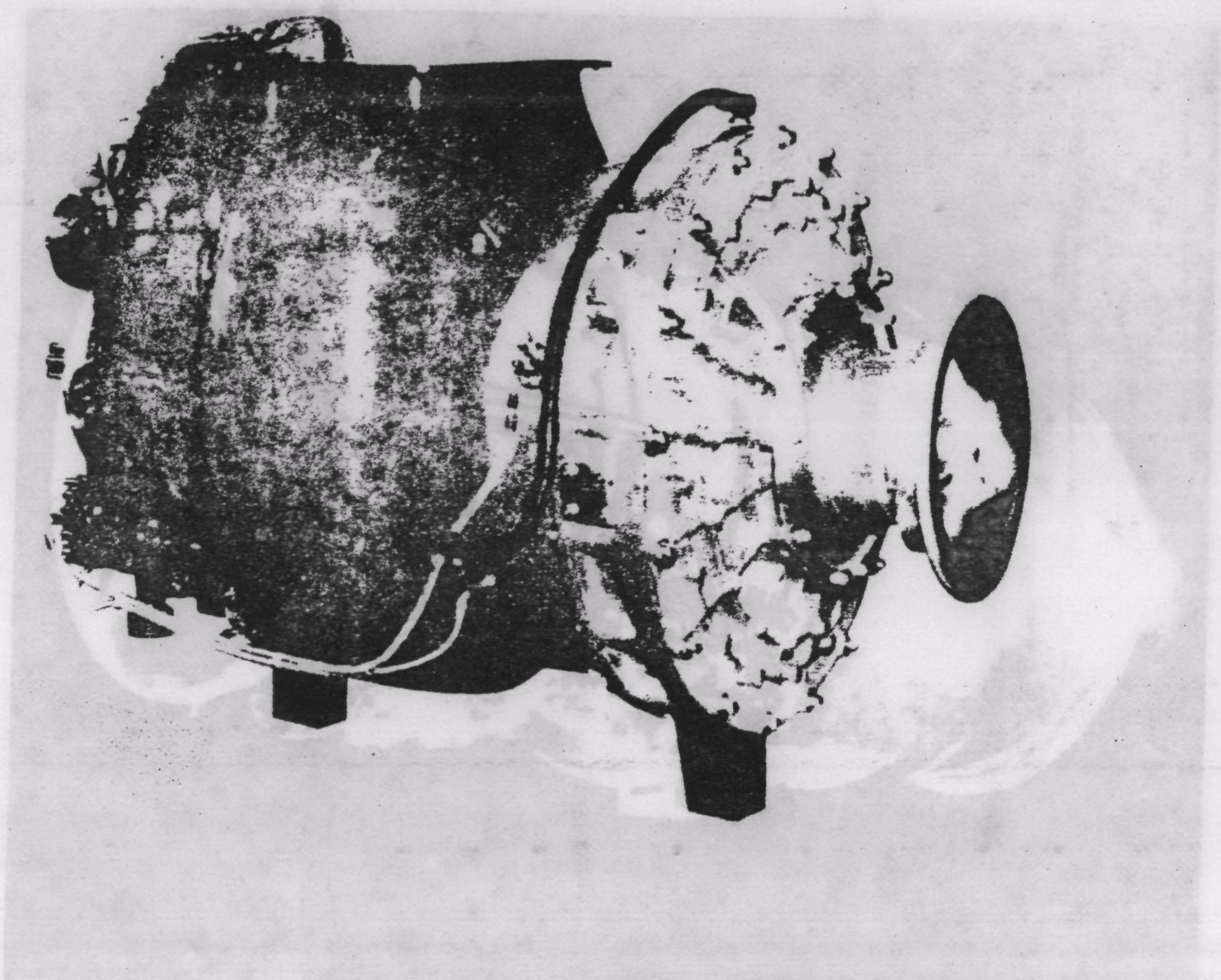

Fig. 4 131L Industrial Engine

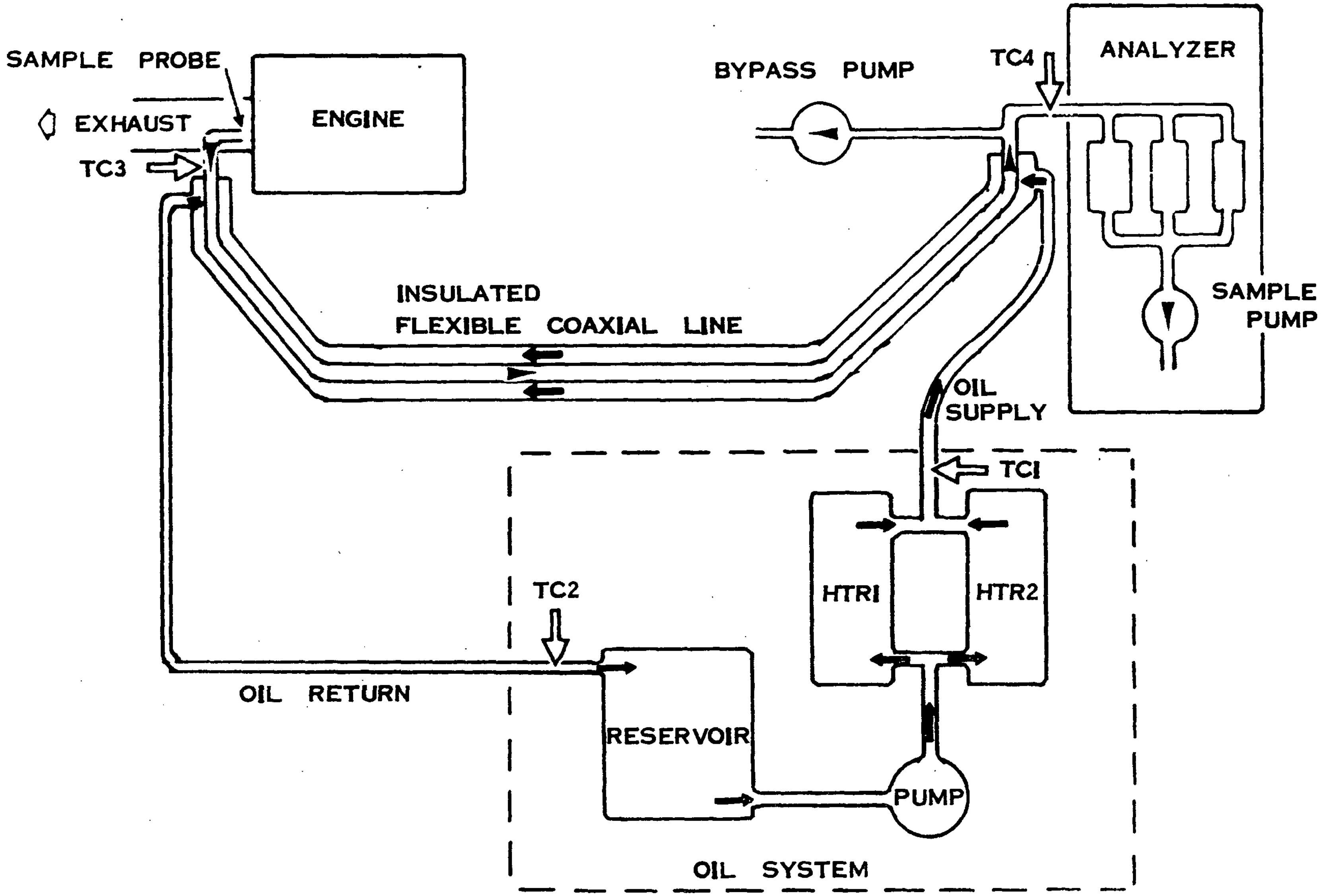

Fig. 5 Exhaust Sampling System Schematic

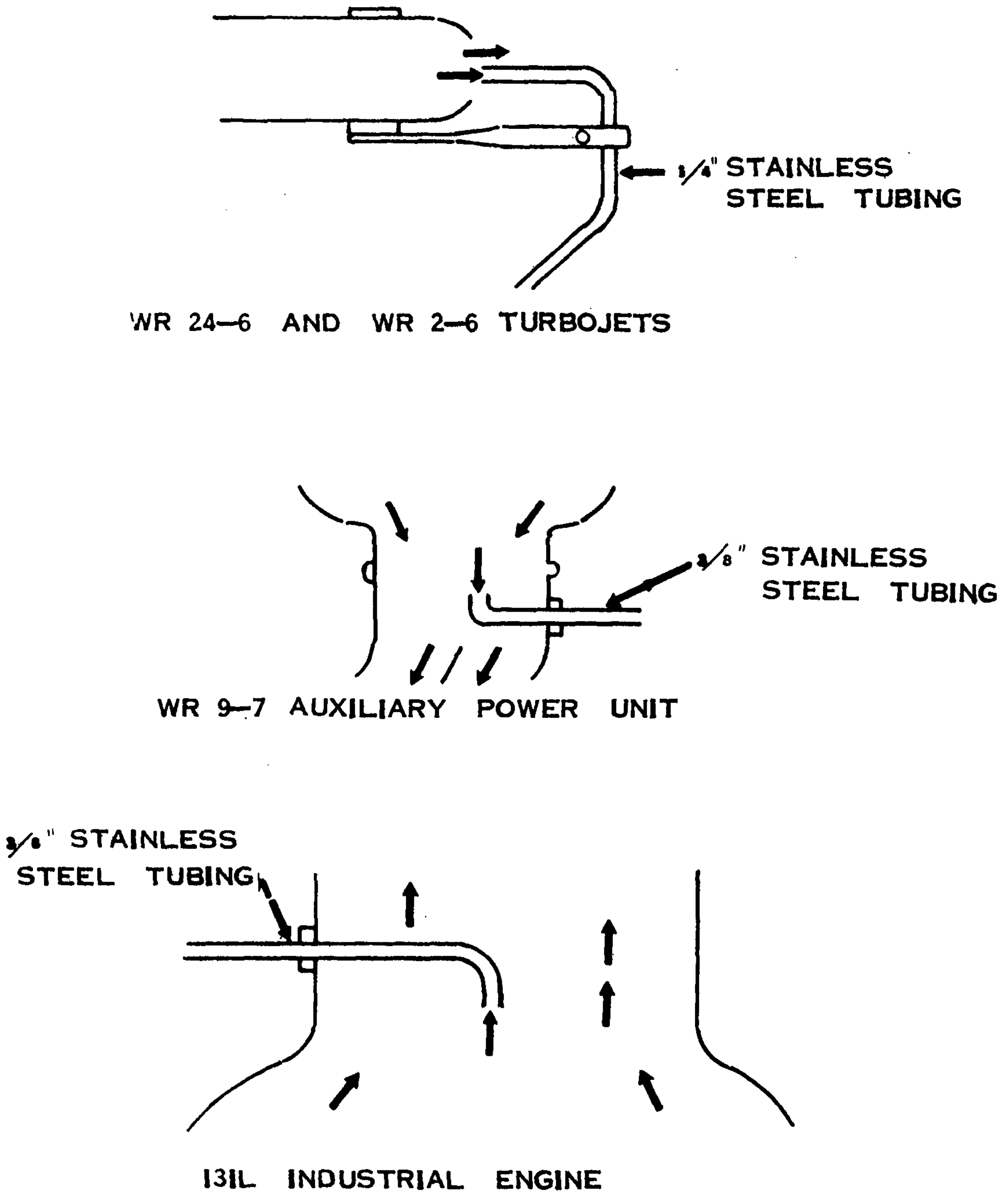

Fig. 6 Sampling Probes

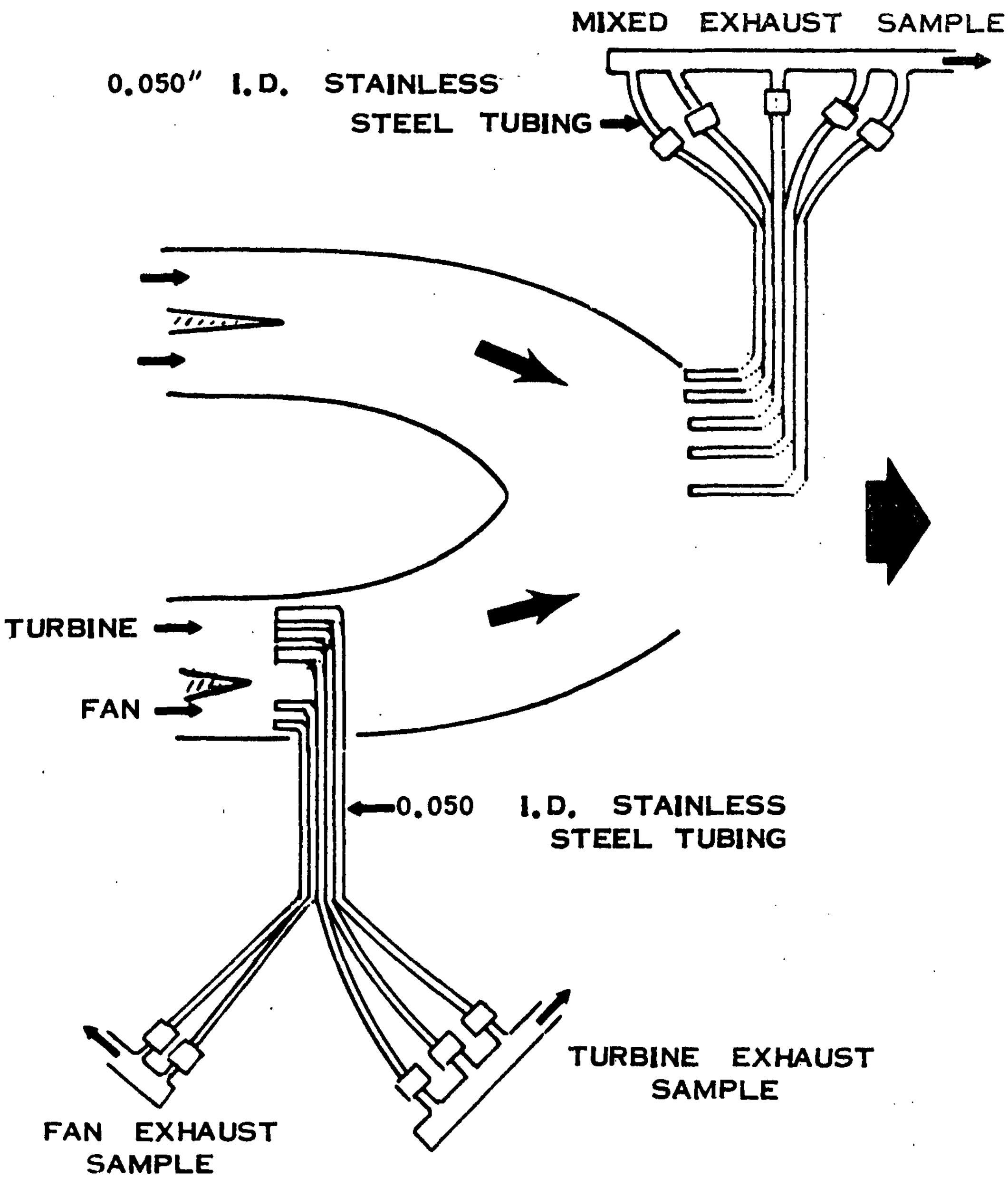

Fig. 7 WR19 Sampling Probe System

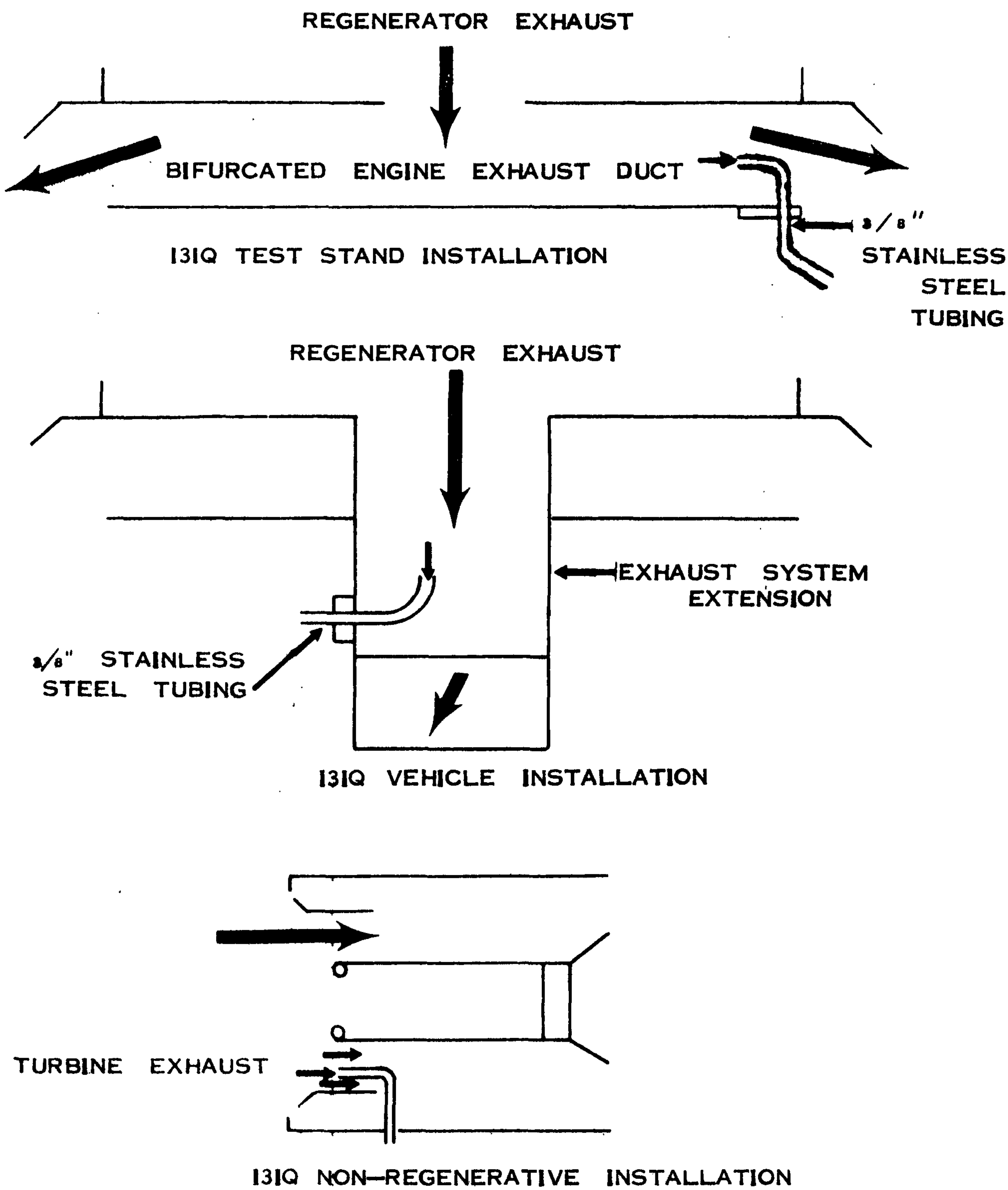

Fig. 8 131Q Sampling Probe Installations

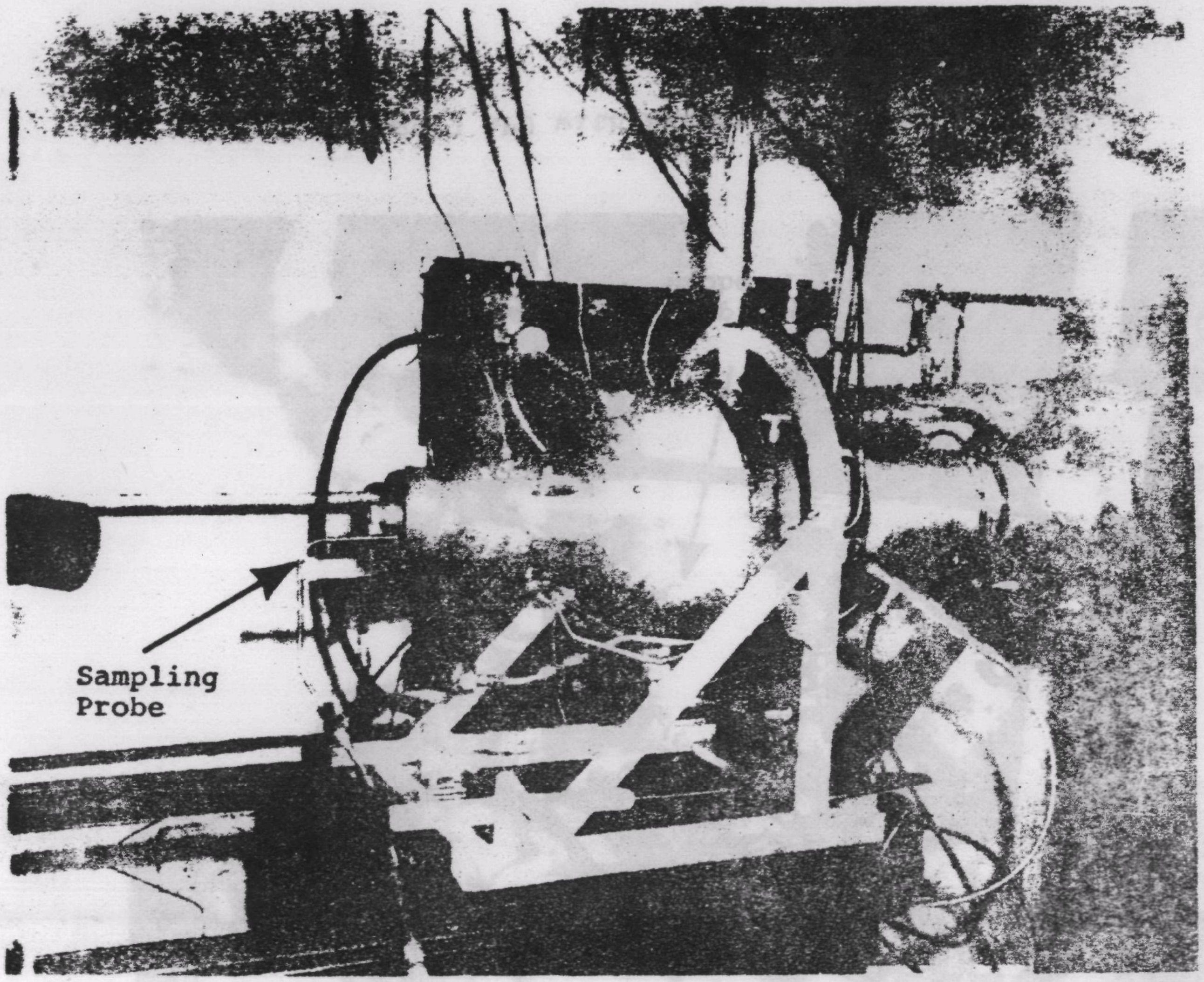

Fig. 9 WR2-6 Turbojet with Exhaust Sampling Probe

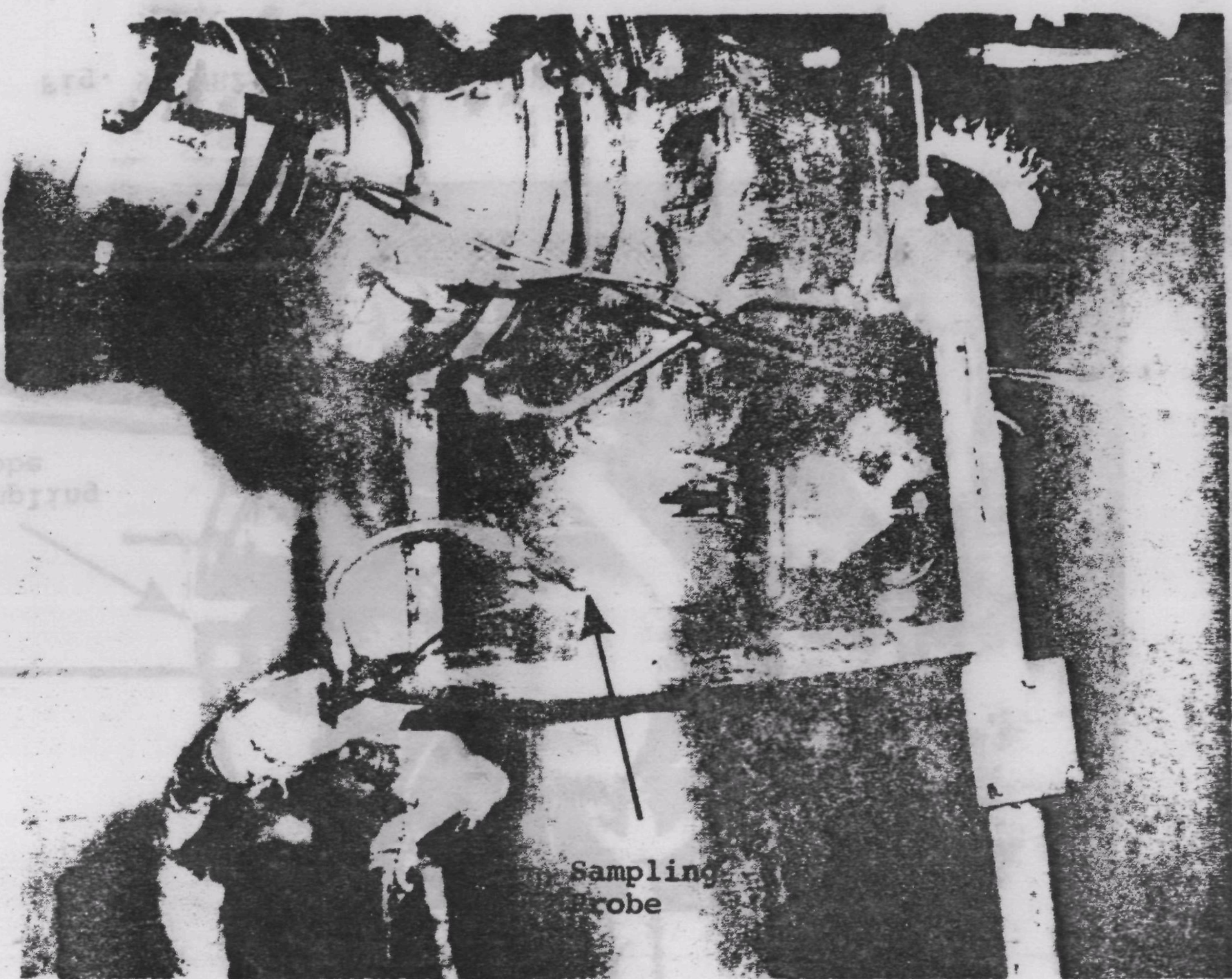

Fig. 10 WR9-7 APU with Exhaust Sampling Probe

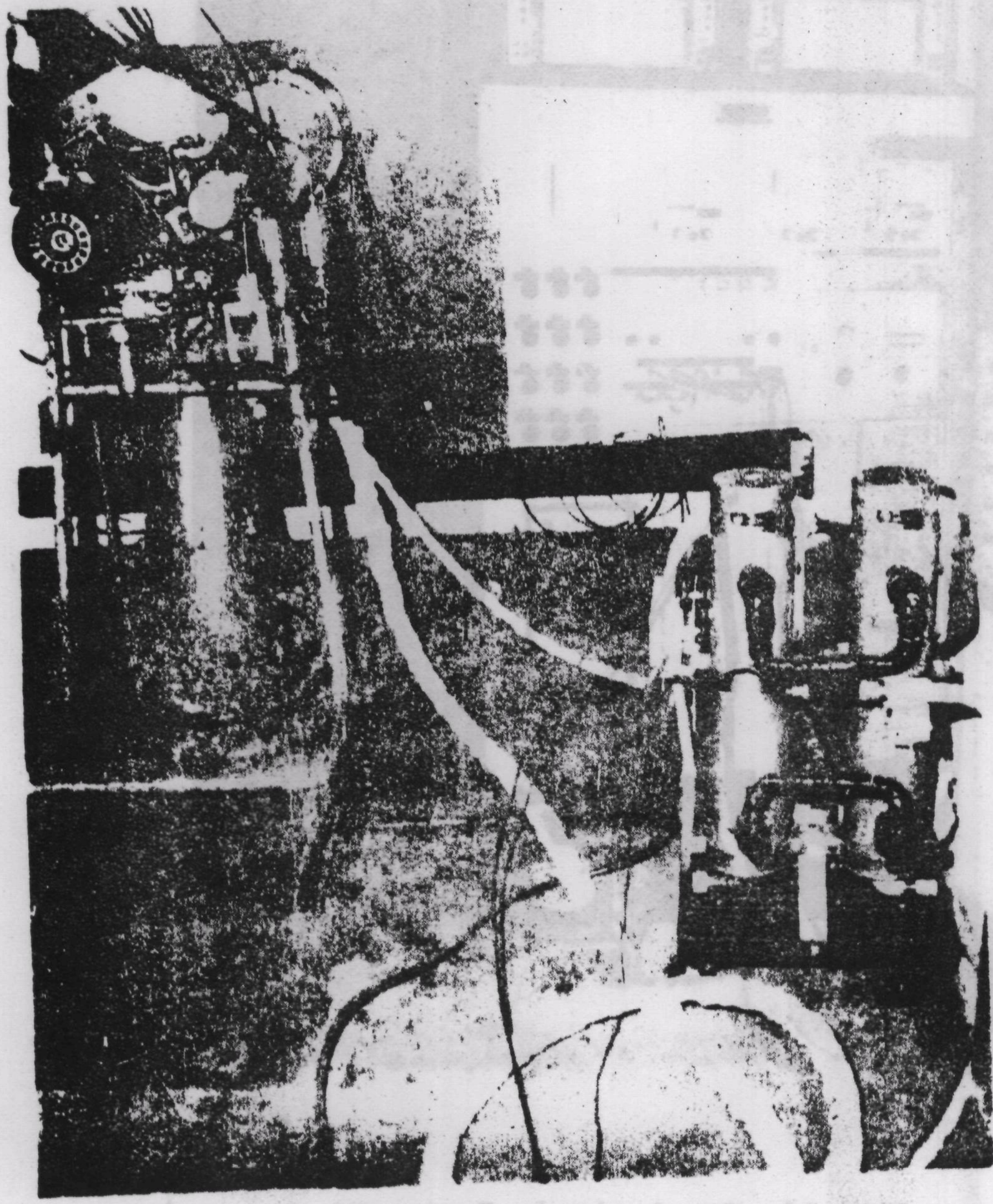

Fig. 11 Heated Sampling Line with
Oil System Installed on WR9-7 APU

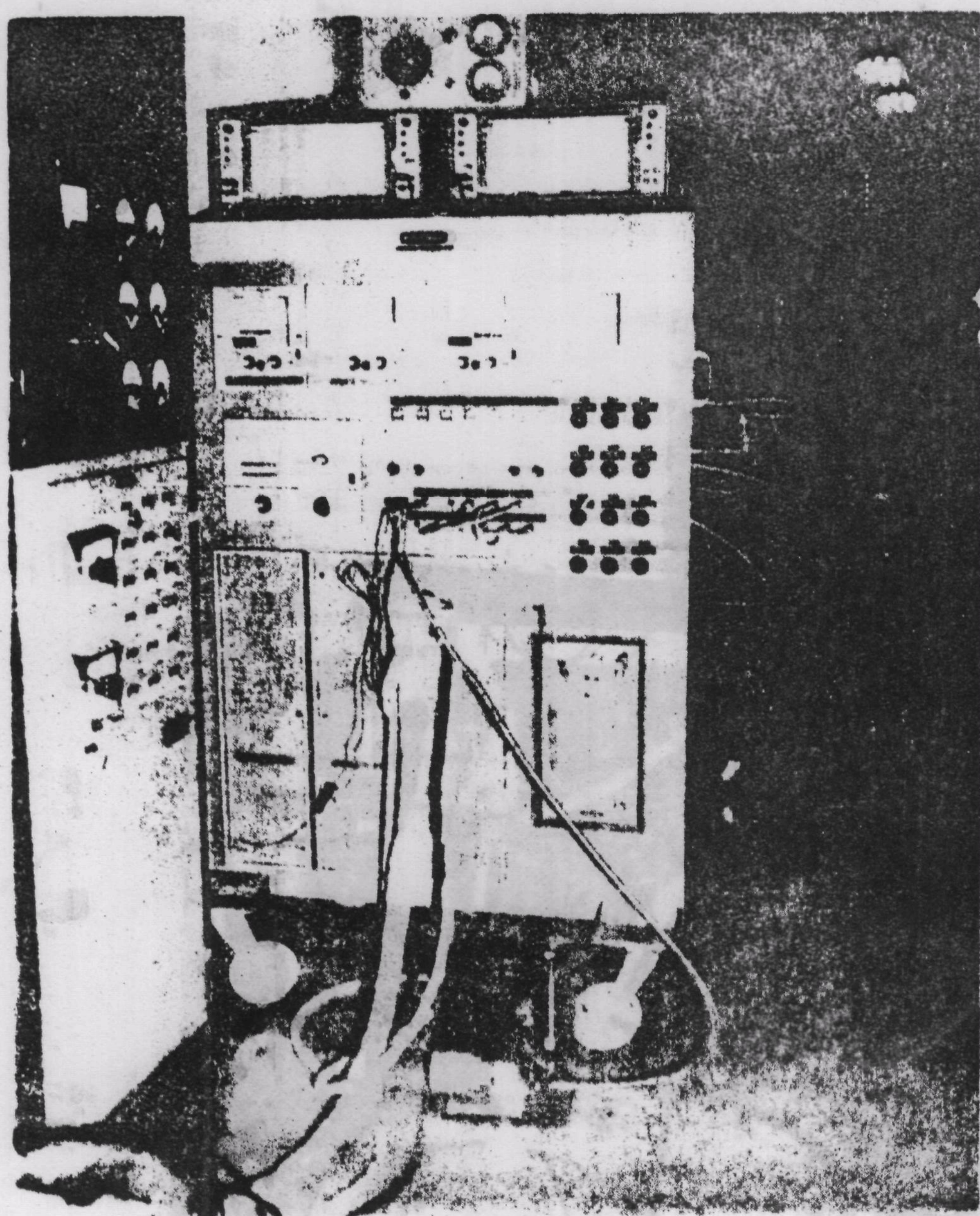

Fig. 12 Gas Analysis Equipment

Fig. 13 Emissions Measurement During Engine Operation in Test Cell

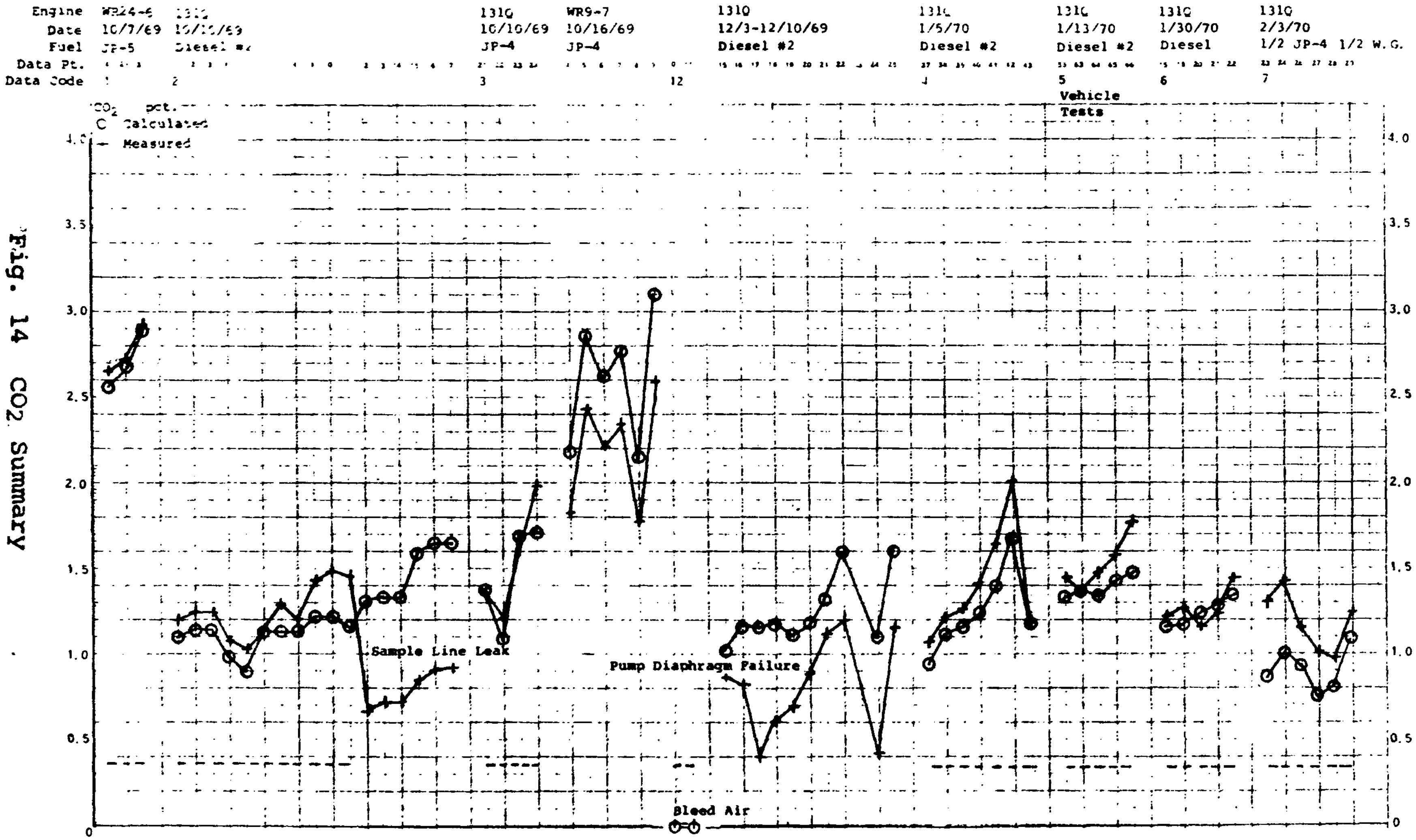

Fig. 14 CO2 Summary

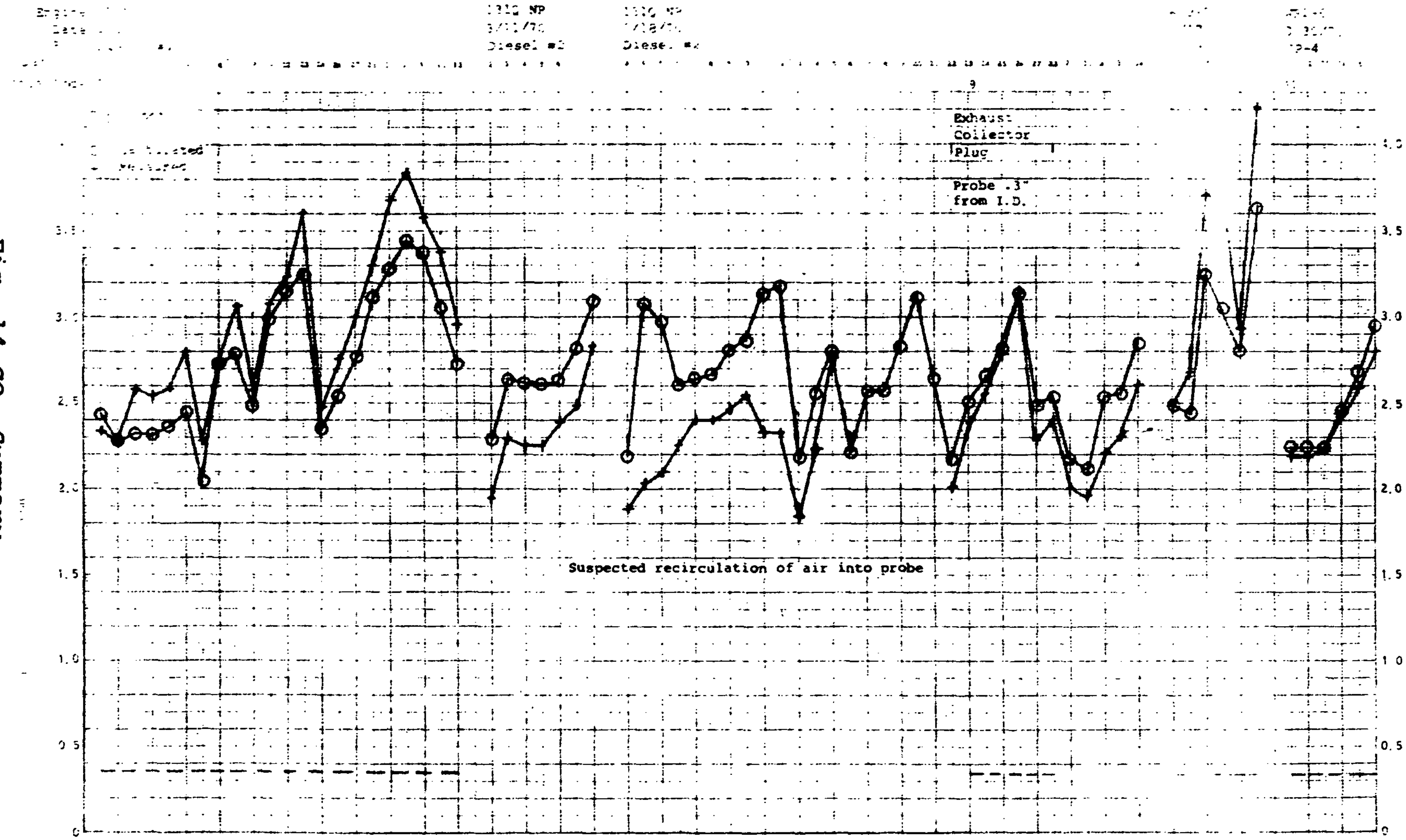

Fig. 14 CO_2 Summary (continued)

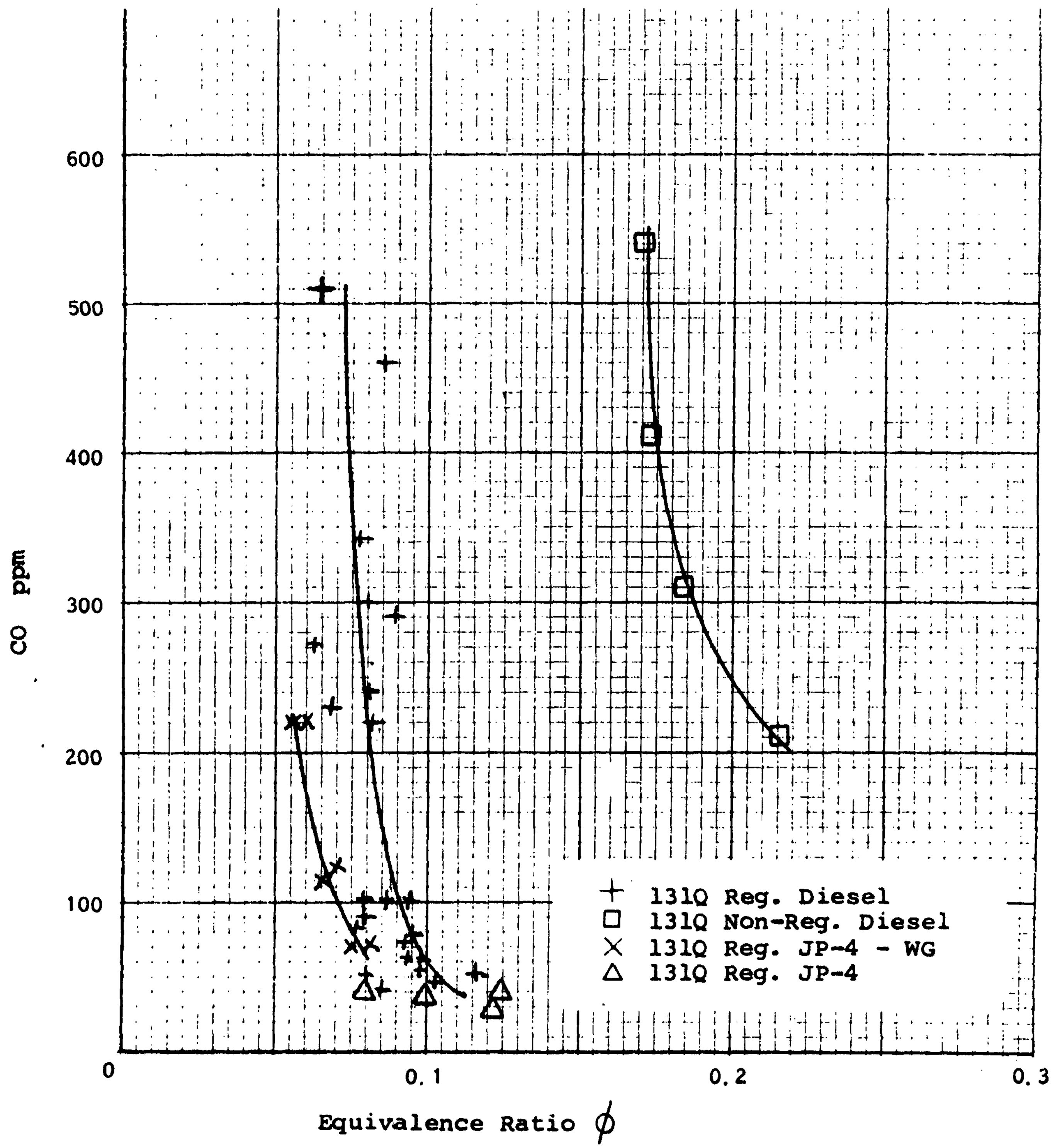

Fig. 15 CO Concentration vs. Equivalence Ratio 131Q Engine

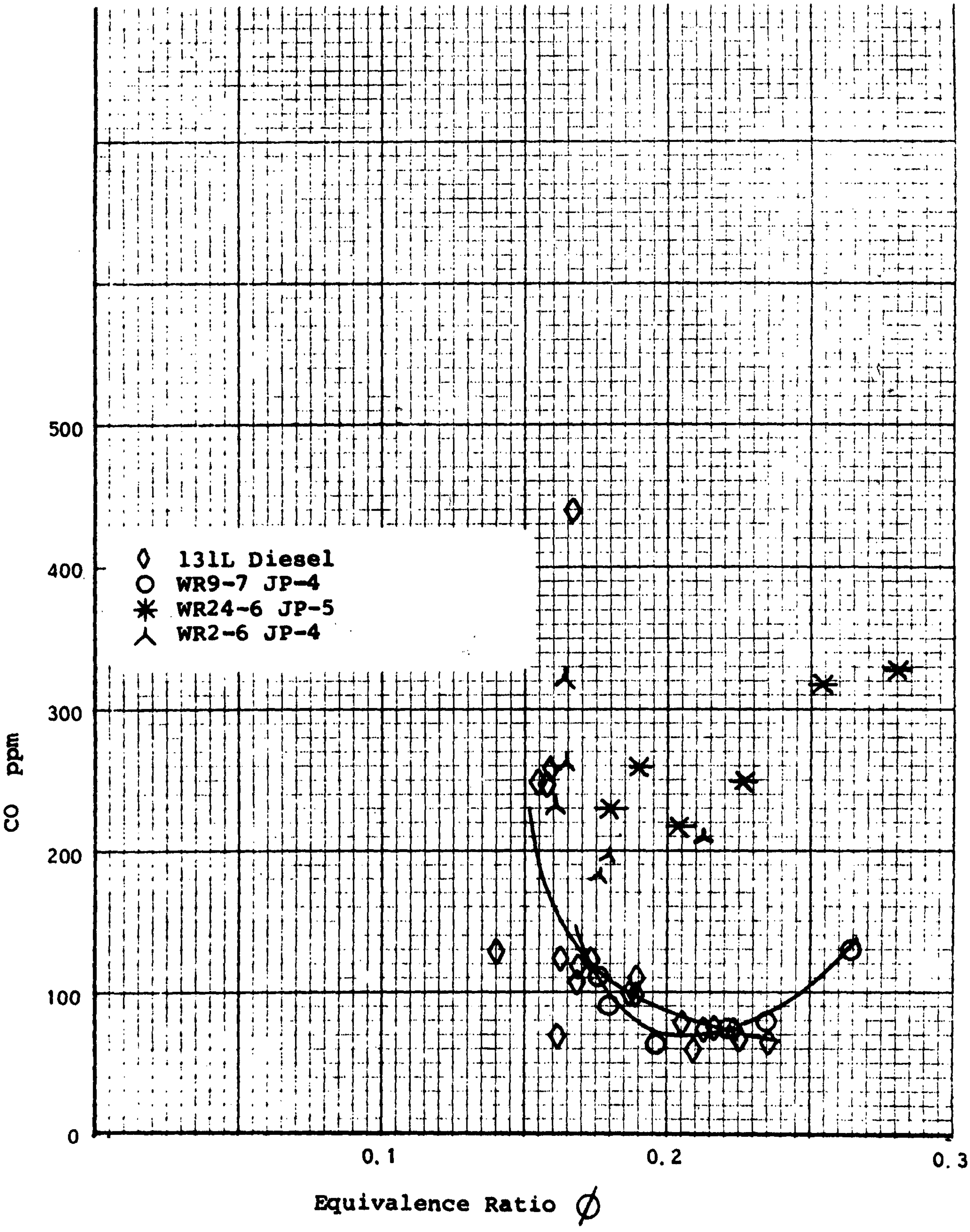

Fig. 16 CO Concentration vs. Equivalence Ratio 131L, WR24-6, WR2-6, WR9-7 Engines

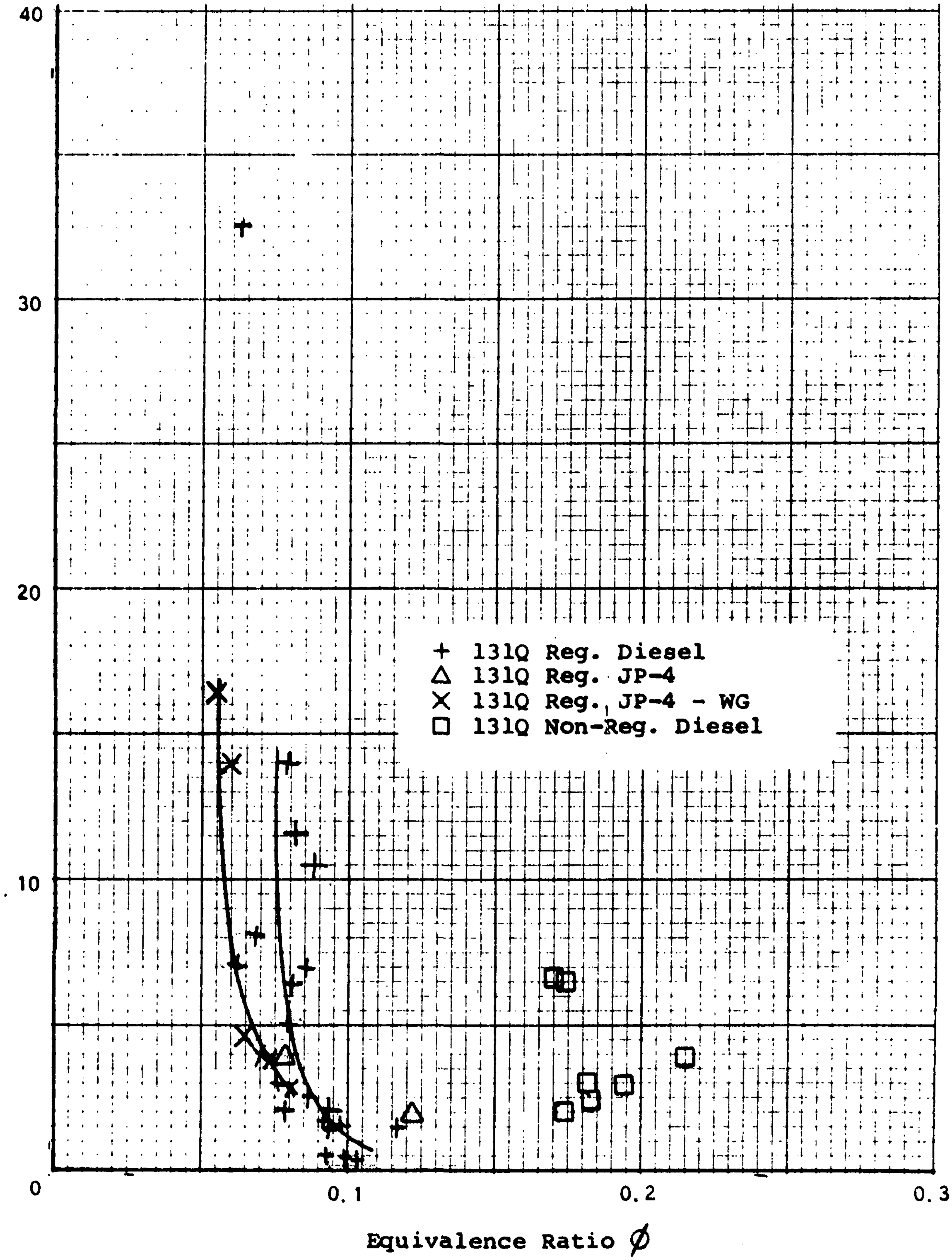

Fig. 17 CH_x Concentration vs. Equivalence Ratio 131Q Engine

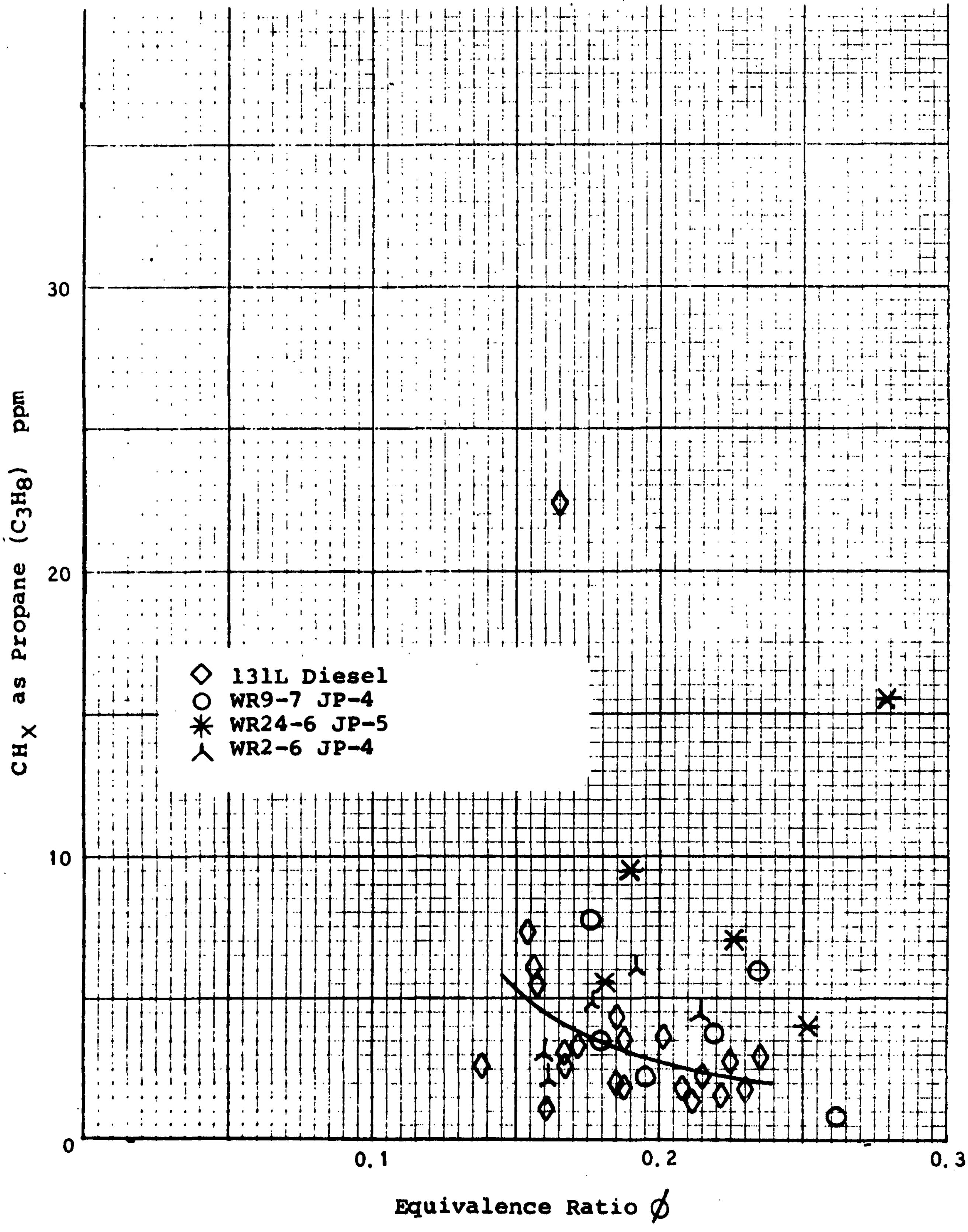

Fig. 18 CH_x Concentration vs. Equivalence Ratio
131L, WR24-6, WR2-6, WR9-7 Engines

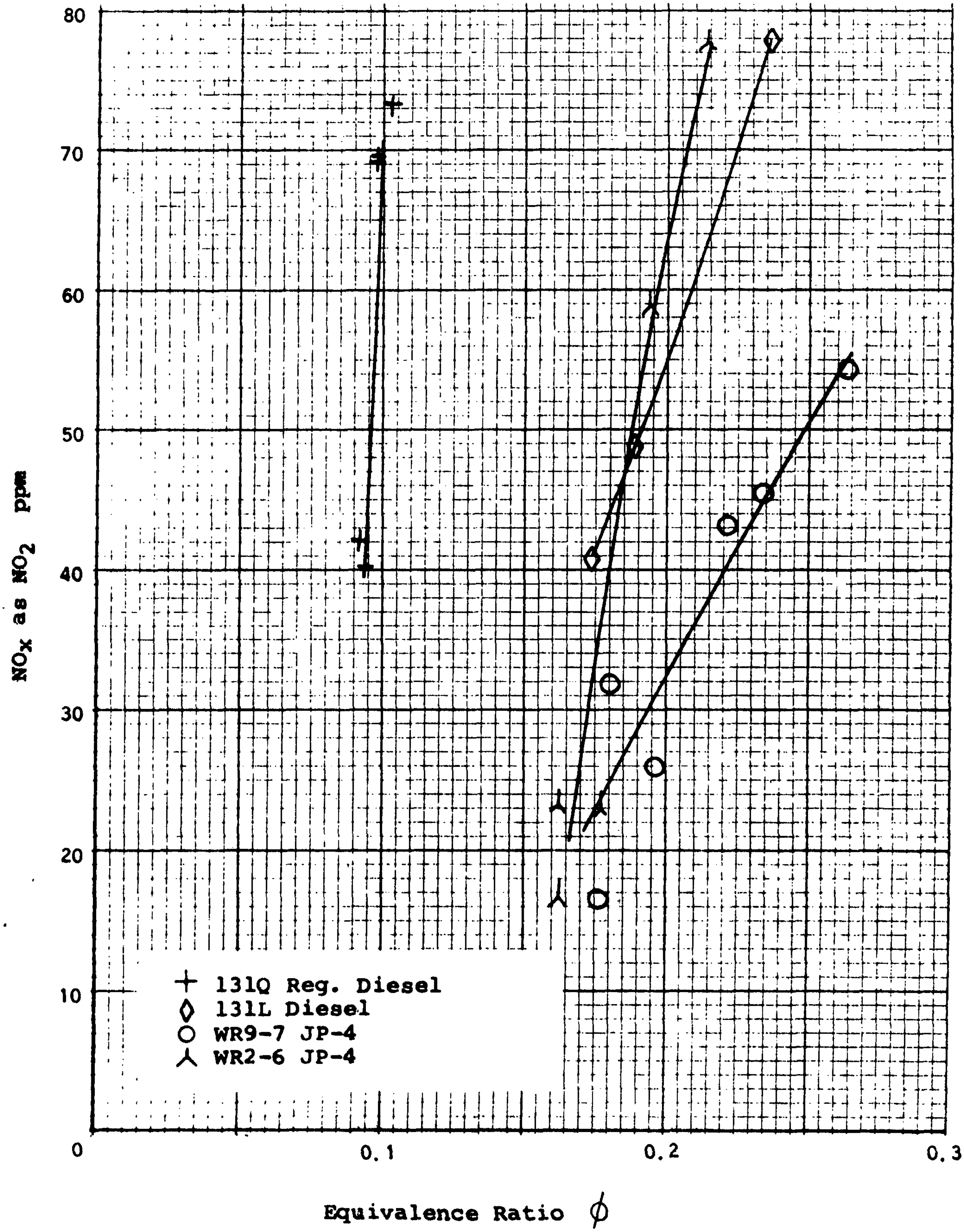

Fig. 19 NO_x Concentration vs. Equivalence Ratio
131Q, 131L, WR9-7, WR2-6 Engines

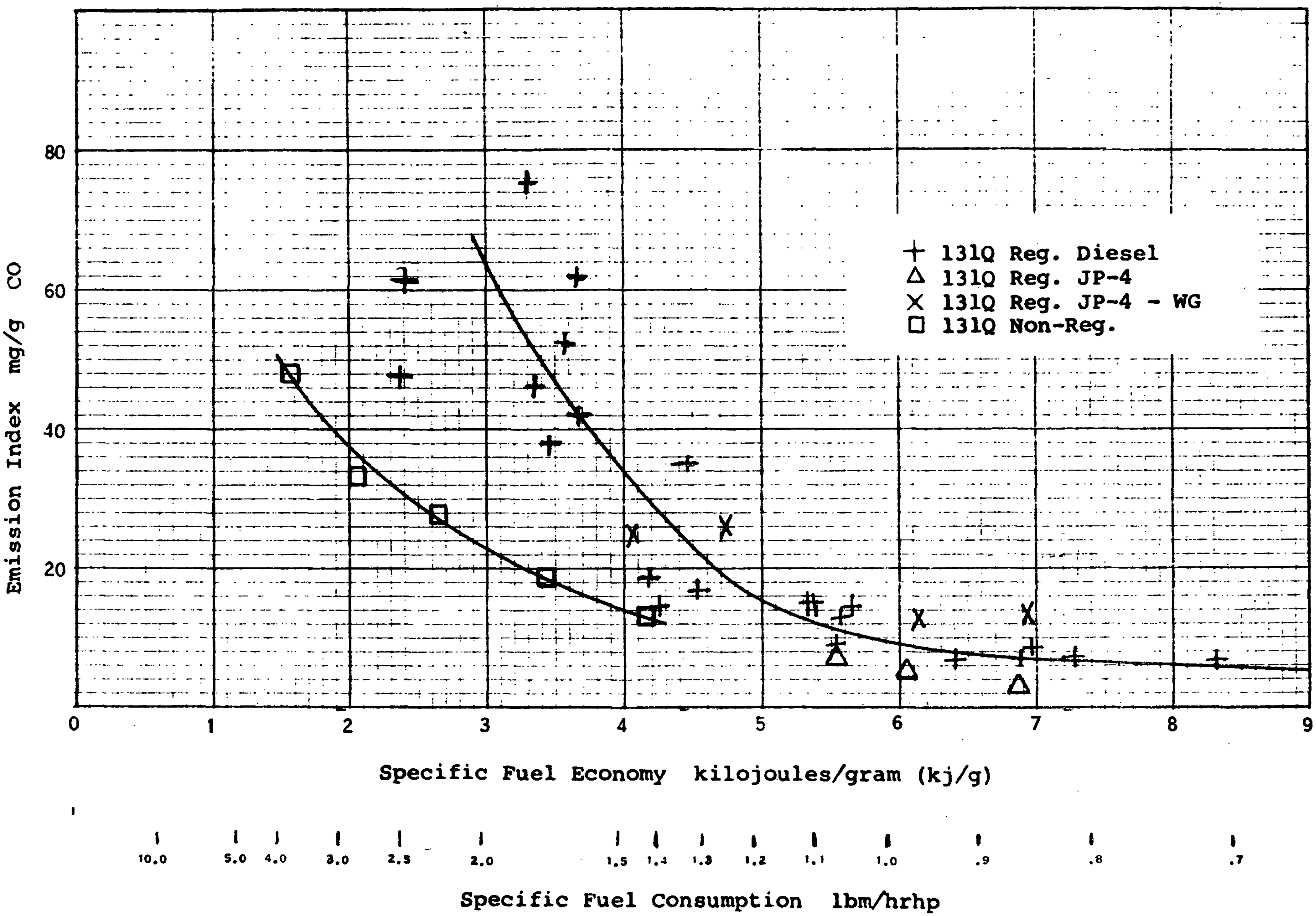

Fig. 20 Emission Index vs. Specific Fuel Economy 131Q Engine

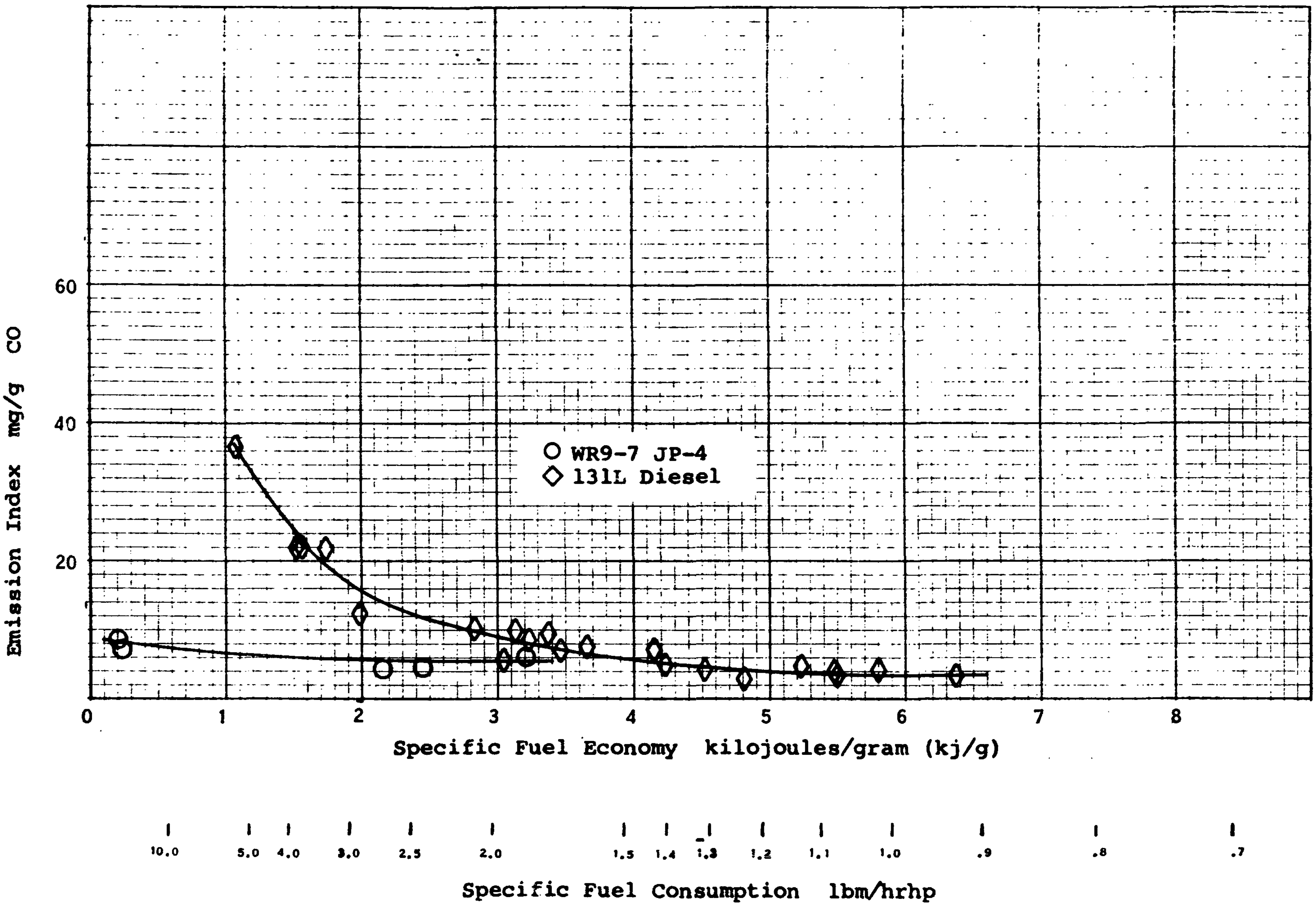

Fig. 21 CO Emission Index vs. Specific Fuel Ecomony 131L, WR9-7 Engines

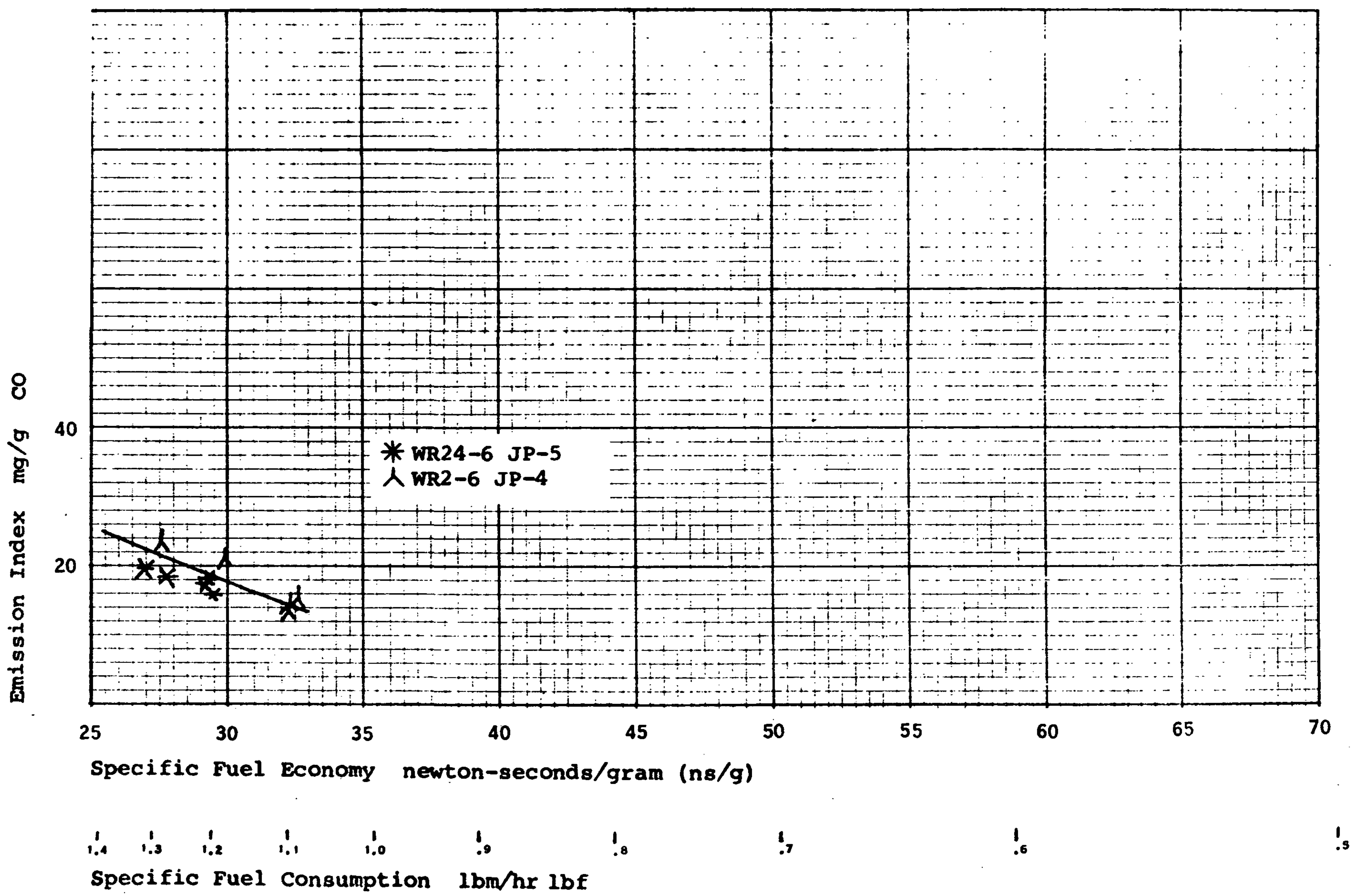

Fig. 22 CO Emission Index vs Specific Fuel Economy WR24-6, WR2-6 Engines

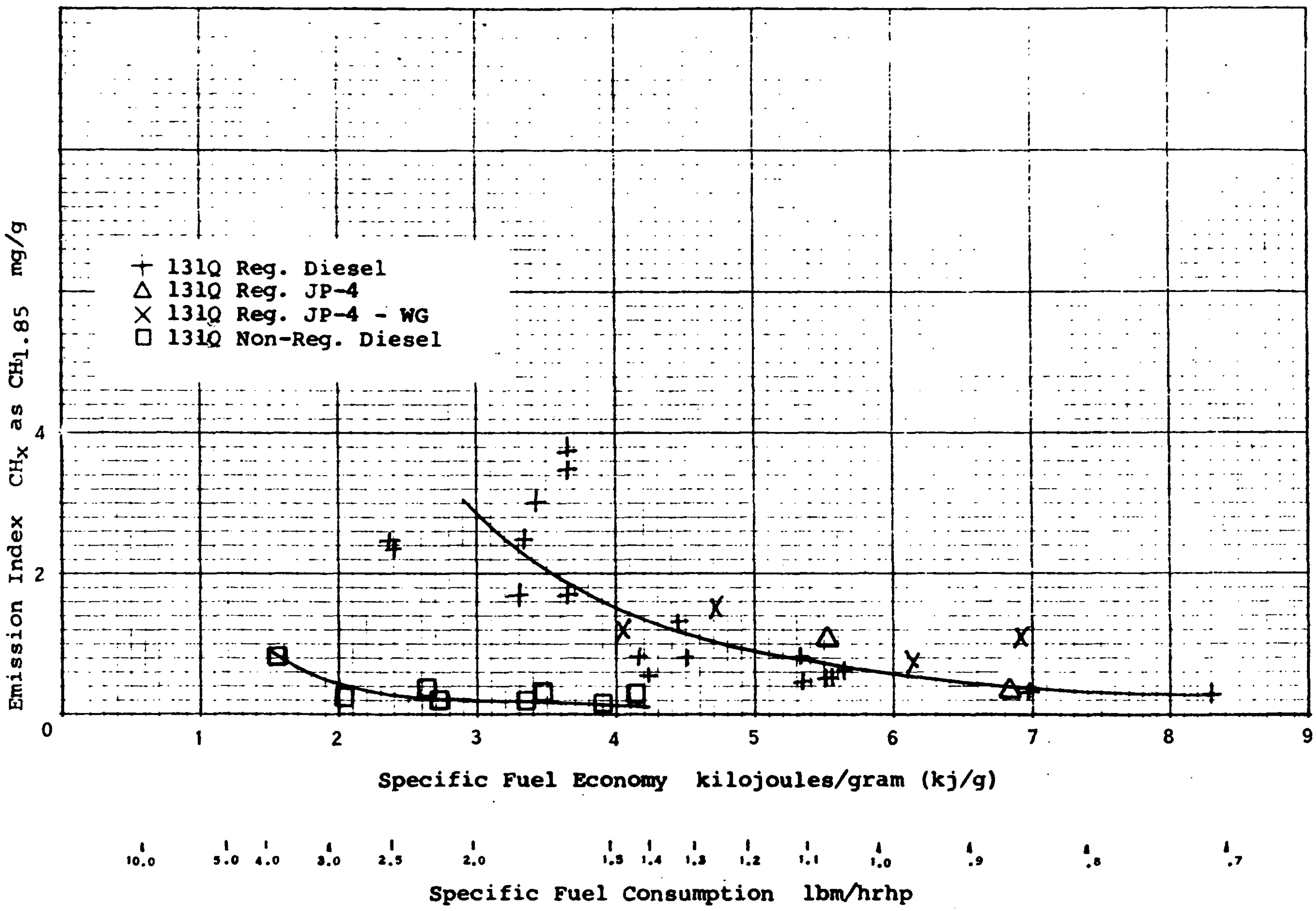

Fig. 23 CH_x Emission Index vs. Specific Fuel Economy 131Q Engine

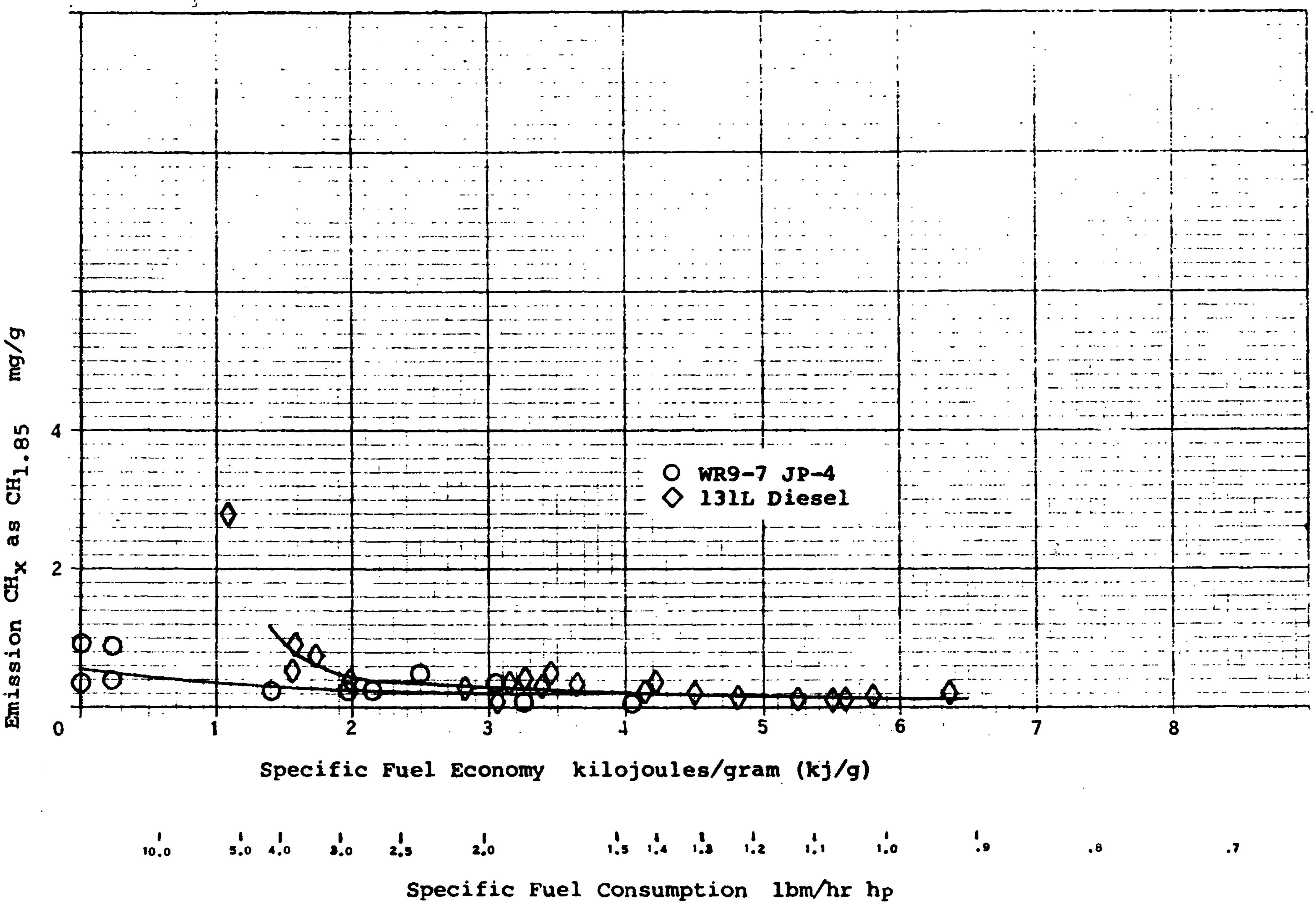

Fig. 24 CH_x Emission Index vs. Specific Fuel Ecomony 131L, WR9-7 Engines

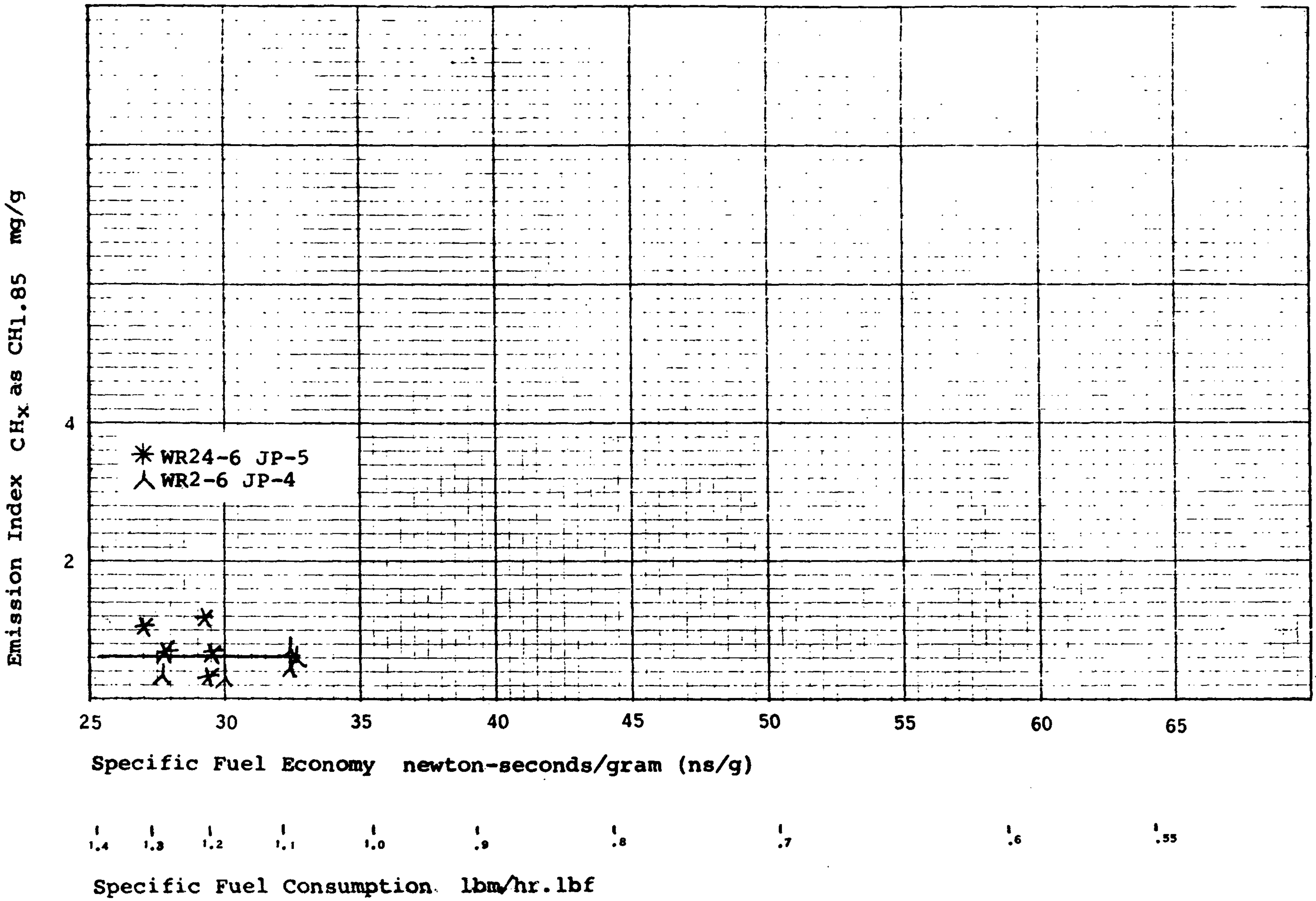

Fig. 25 CH_x Emission Index vs. Specific Fuel Economy WR24-6, WR2-6 Engines

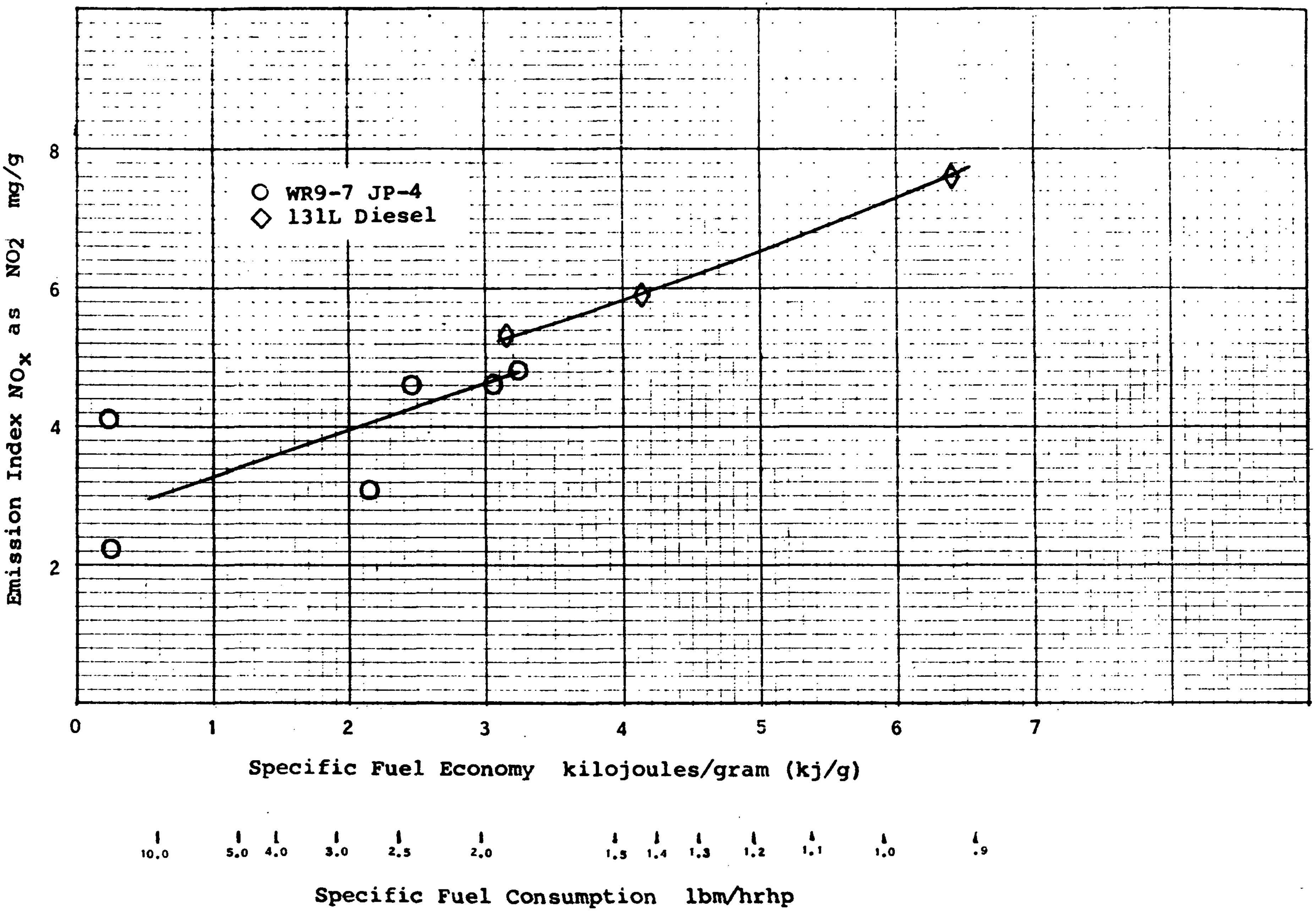

Fig. 26 NO_x Emission Index vs. Specific Fuel Economy 131L, WR9-7 Engines

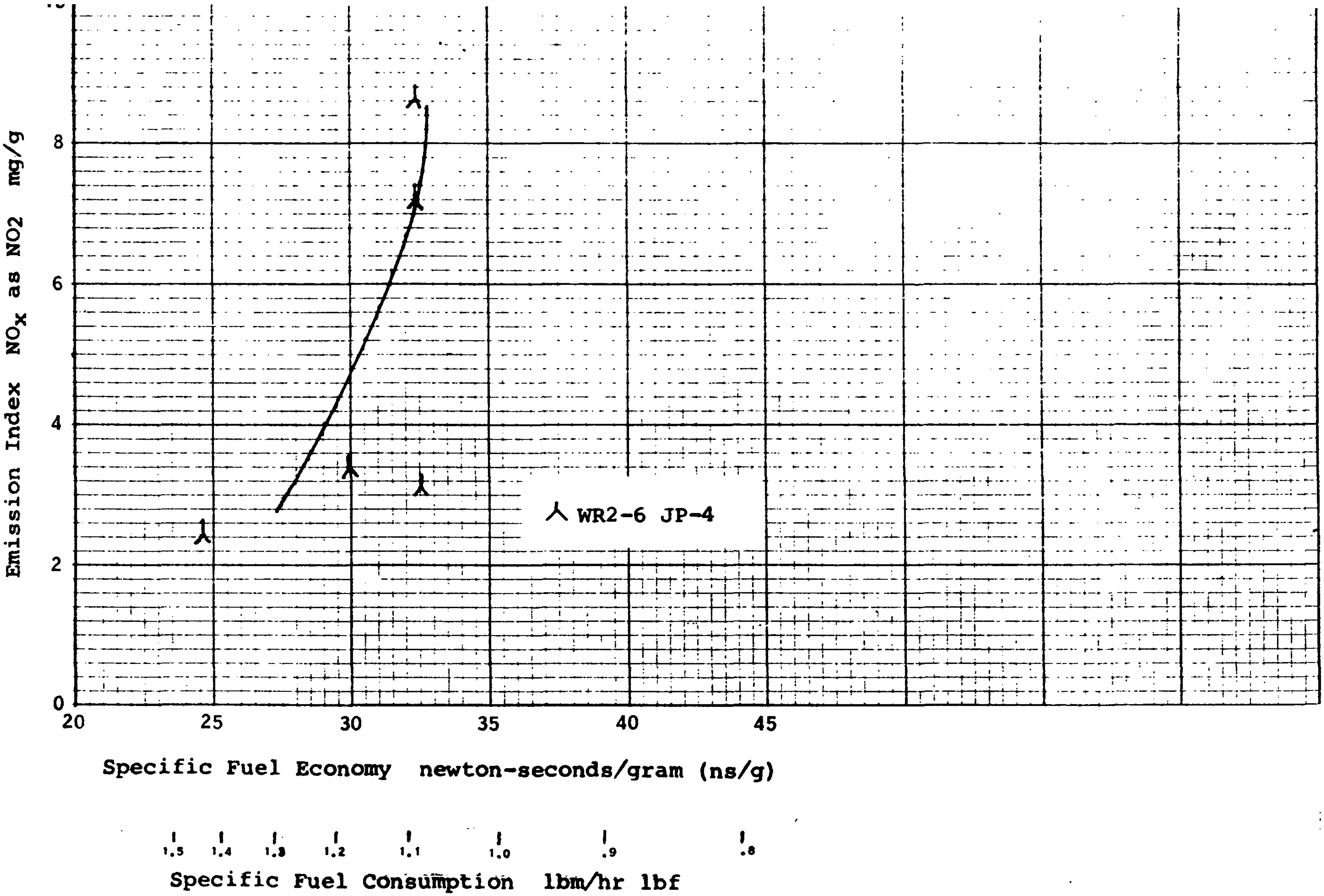

Fig. 27 NO_x Emission Index vs. Specific Fuel Economy WR24-6 Engine

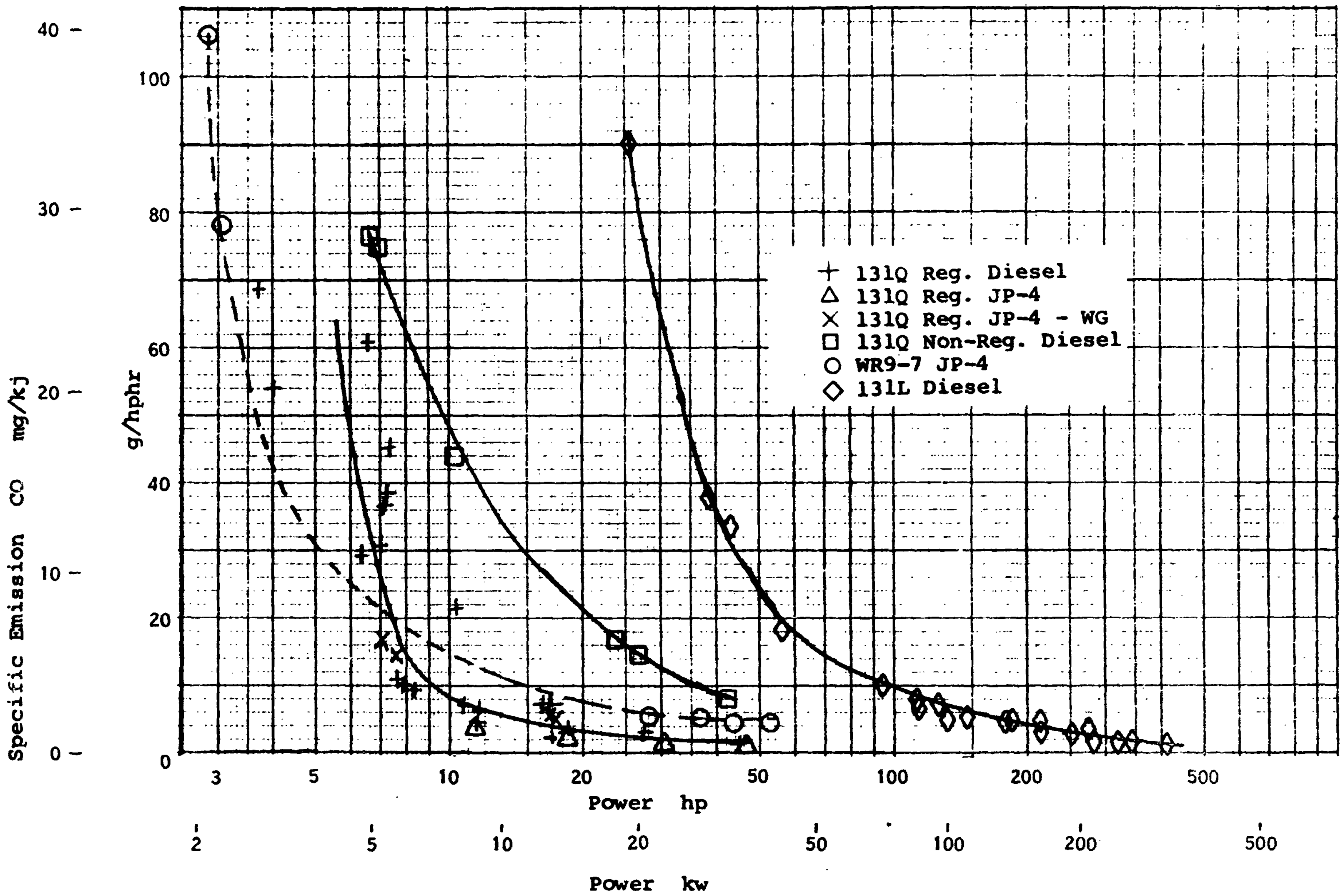

Fig. 28 CO Specific Emission vs. Power Output

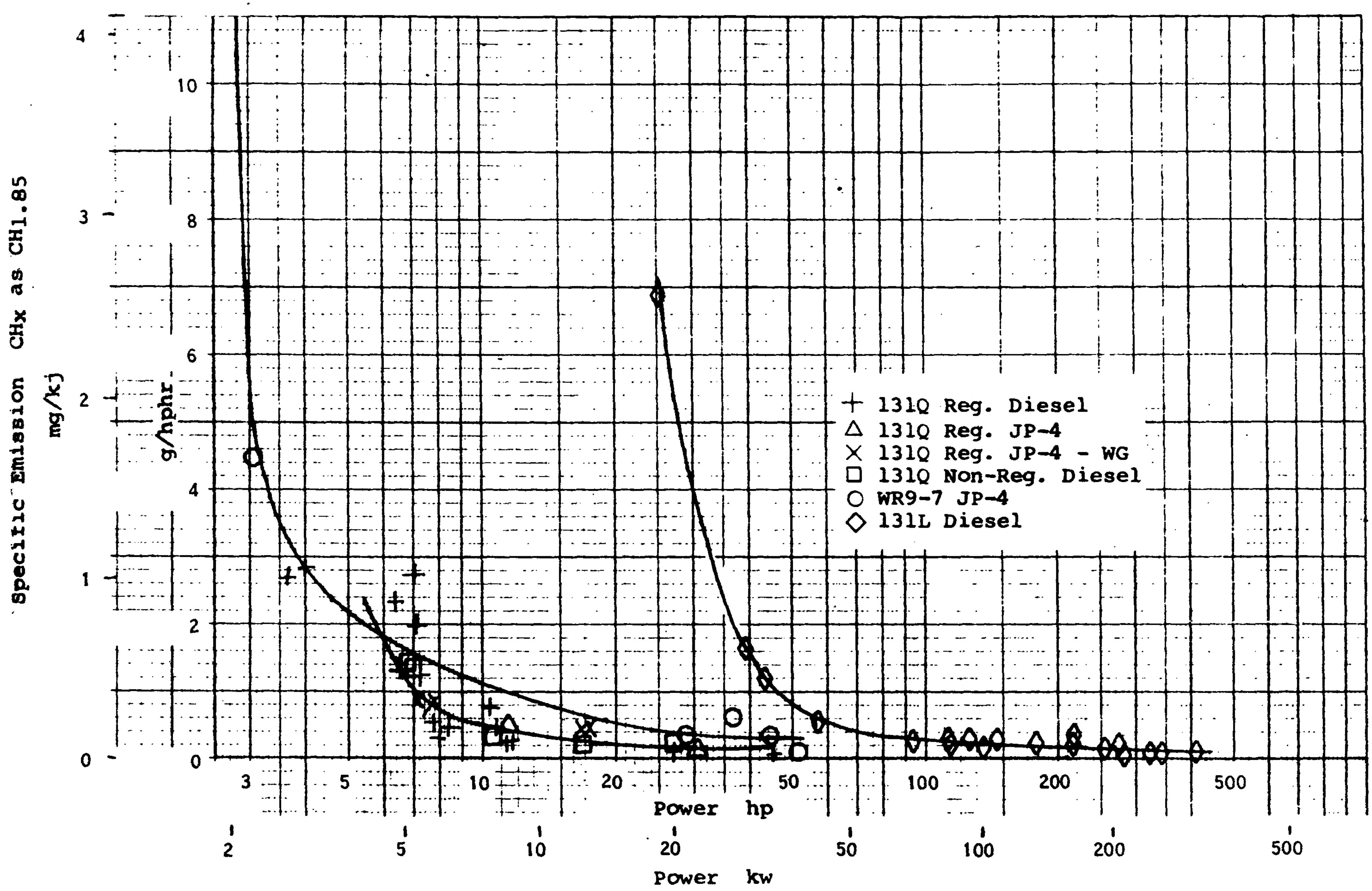

Fig. 29 CH_x Specific Emission vs. Power

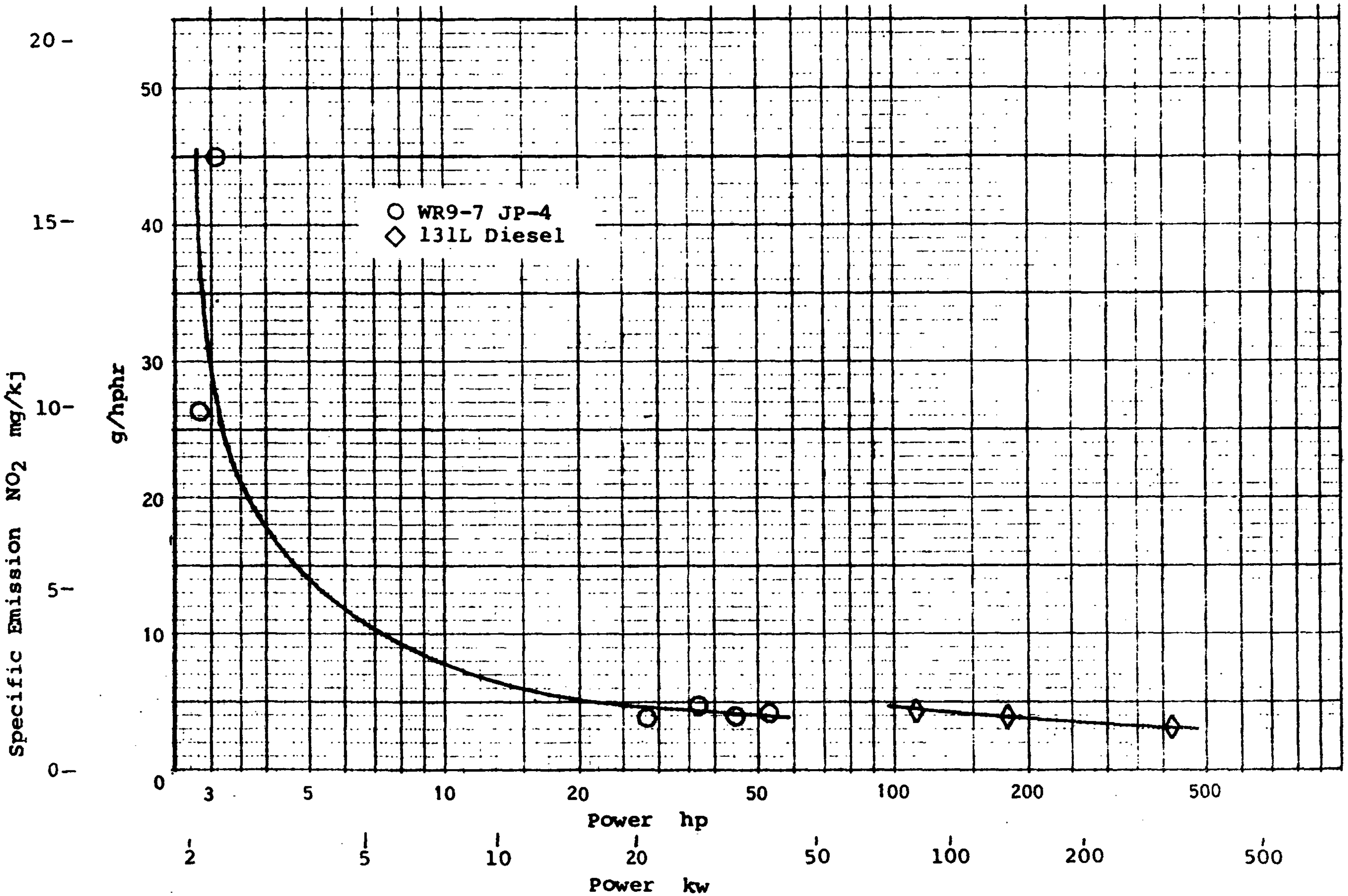

Fig. 30 NO_x Specific Emission vs. Power

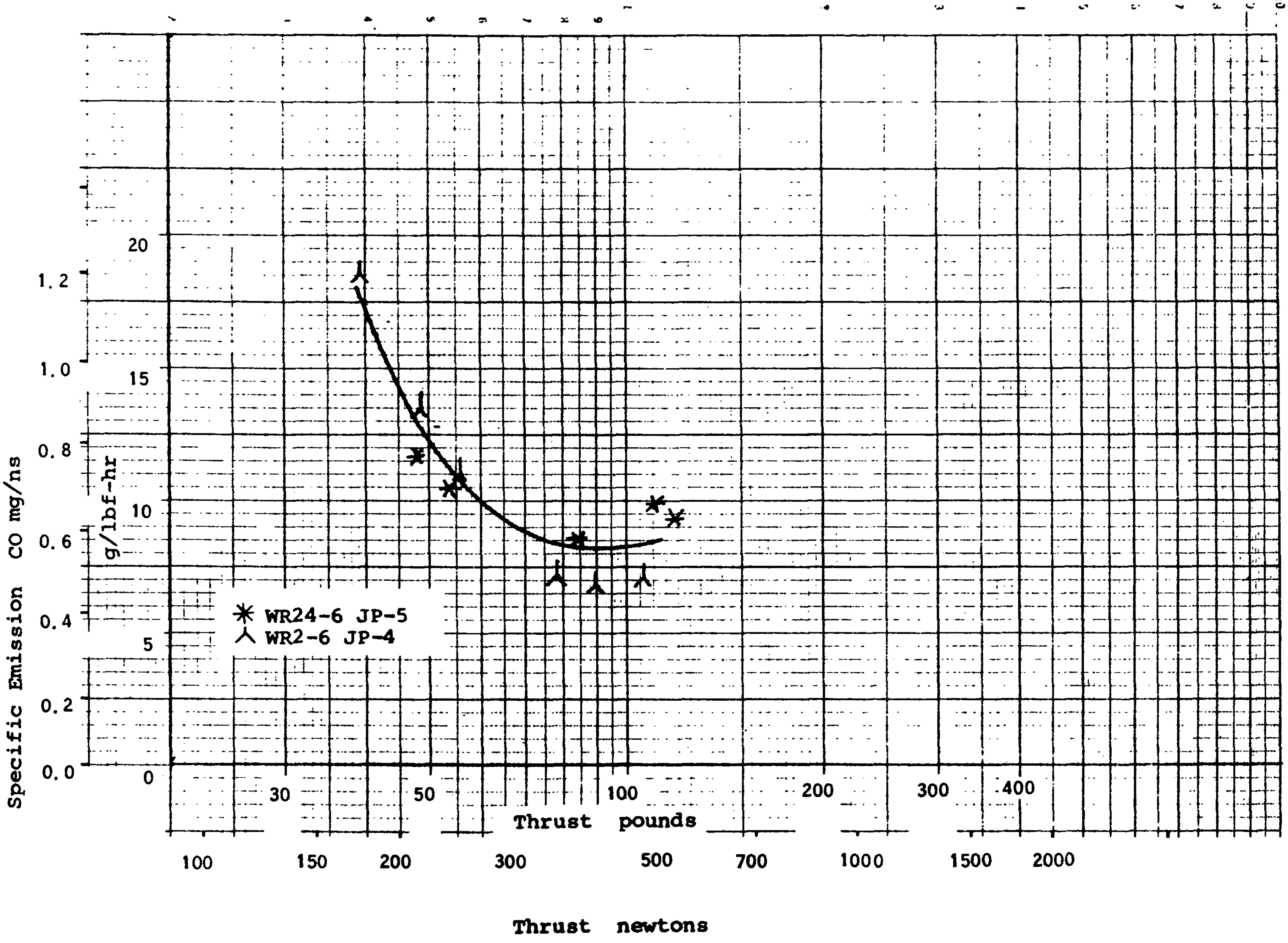

Fig. 31 CO Specific Emission vs. Thrust

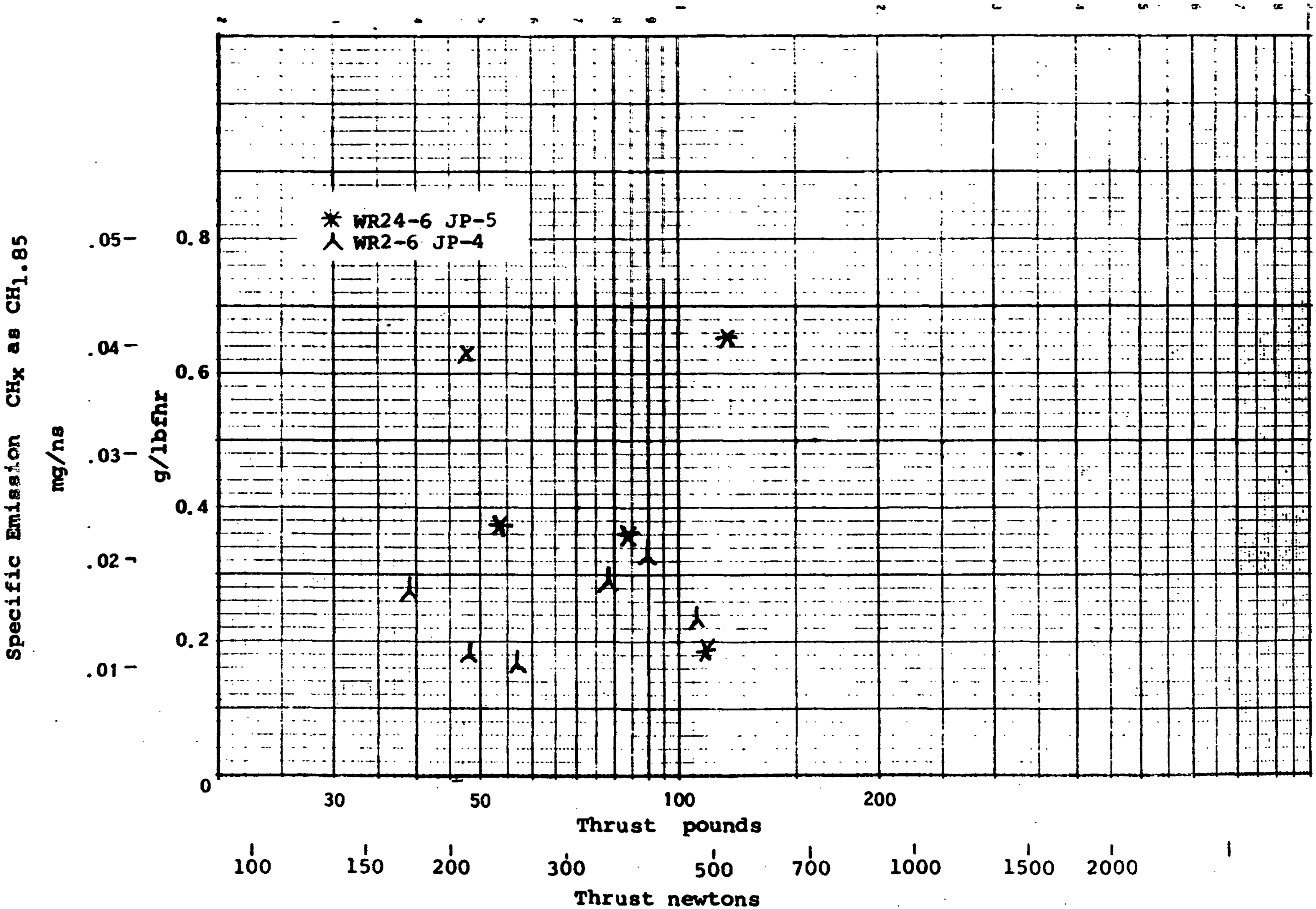

Fig. 32 CH_x Specific Emission vs. Thrust

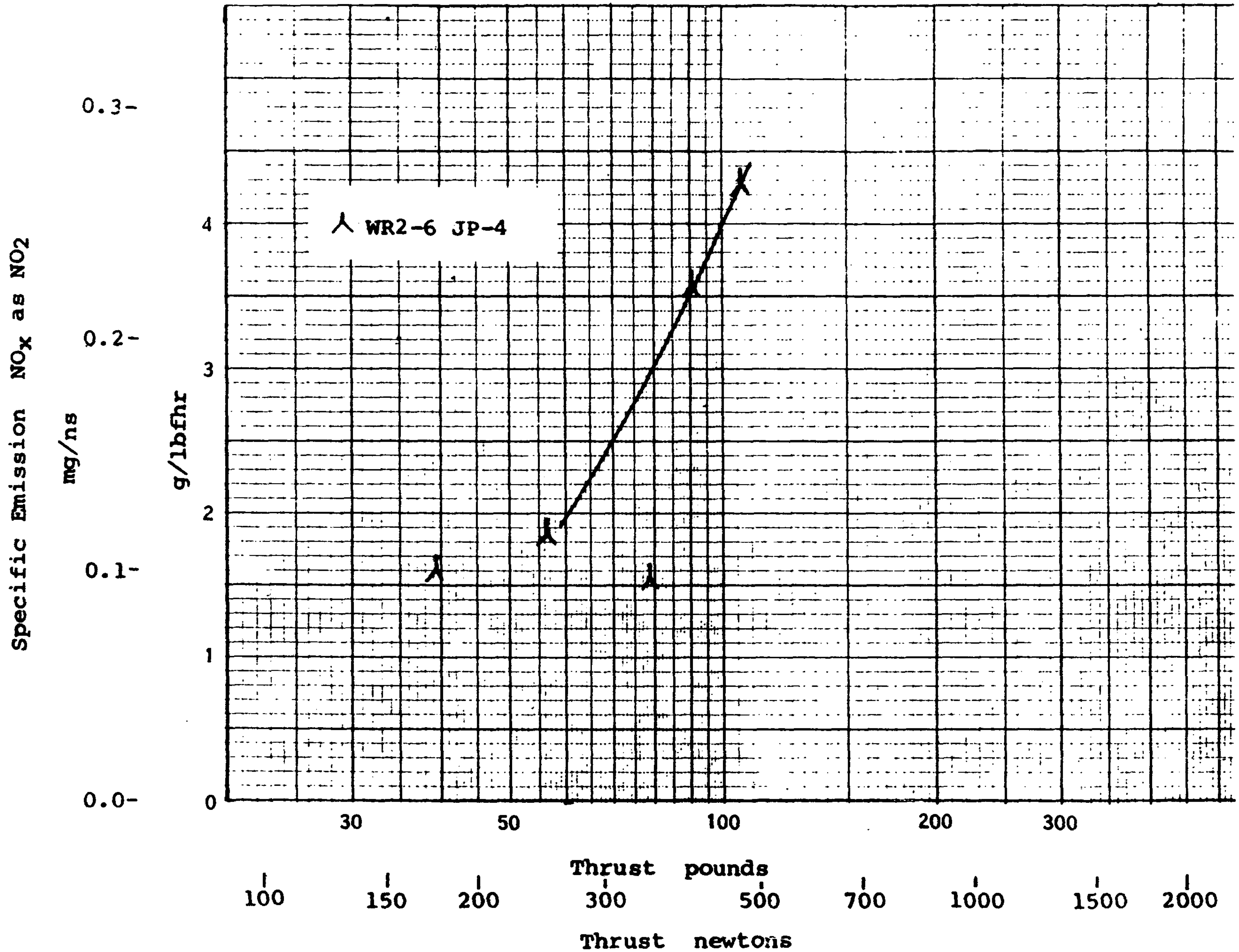

Fig. 33 NO_x Specific Emission vs. Thrust

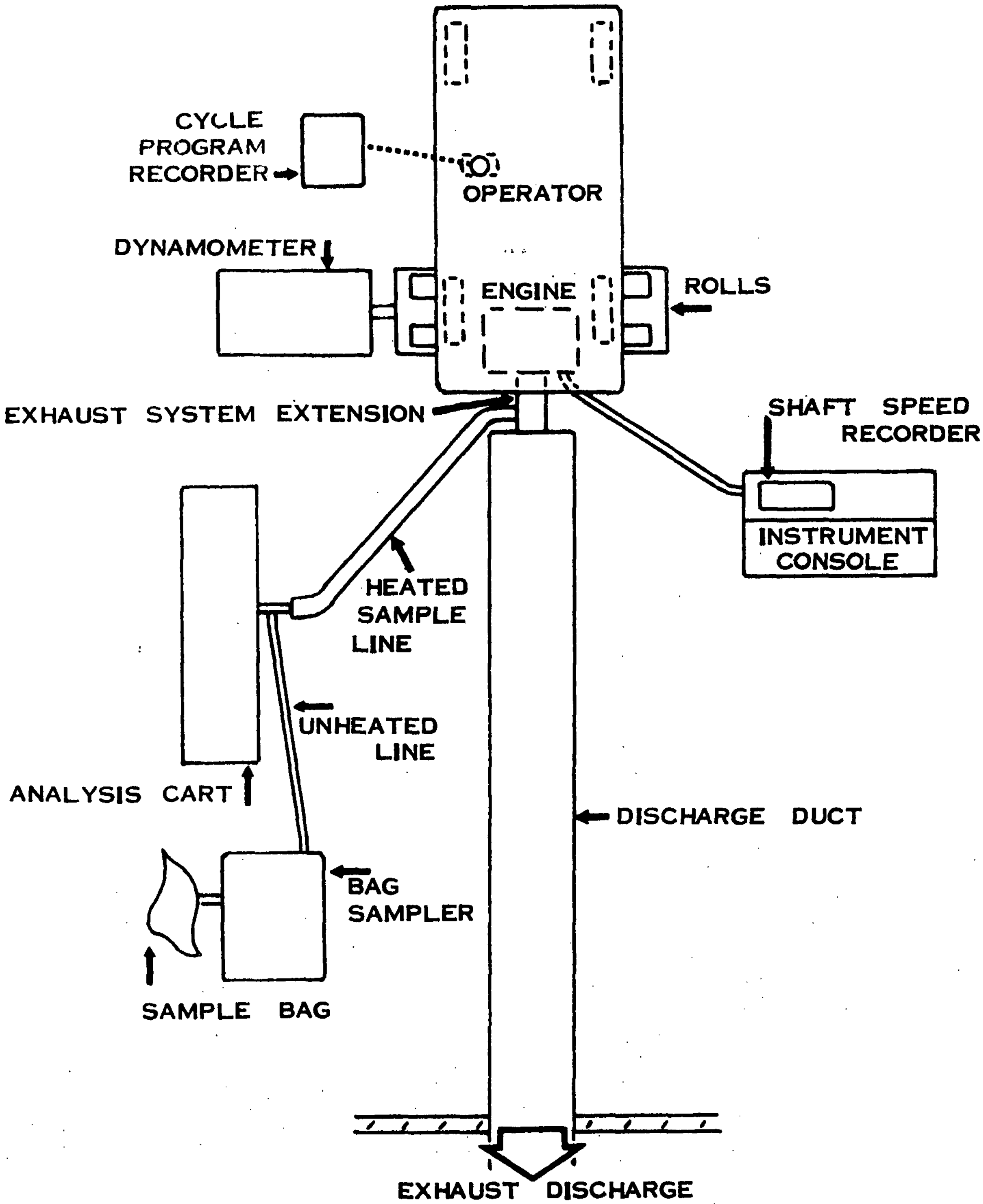

Fig. 34 Schematic Plan View of Vehicle Test

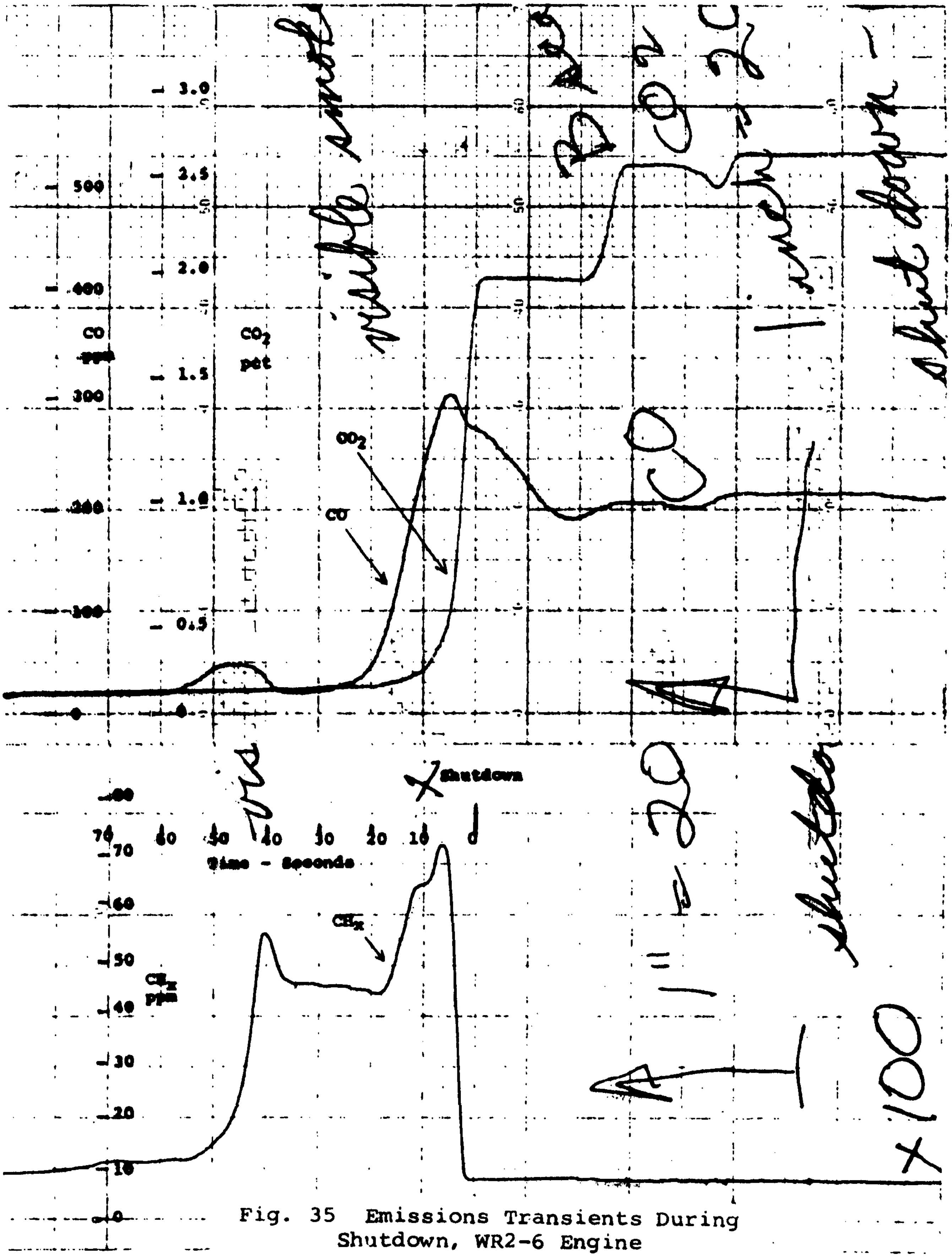

Fig. 35 Emissions Transients During
Shutdown, WR2-6 Engine

APPENDIX A

STEADY STATE DATA REDUCTION

Data Reduction

The large volume of data taken during the program demanded orderly processing. Two general classes of data were manually recorded for each steady state running condition, engine operational data, and emissions data.

All engine developmental and production programs at Williams Research routinely employ data reduction programs to calculate and print out engine operating parameters such as speeds, temperatures, pressures, and fuel consumption normalized or "corrected" to standard ambient conditions. These programs are written in Fortran and are run on the G.E. 405 System at Williams. The raw data is manually recorded.

In the early part of this program, the emissions data was reduced on a Wang desk calculator with a tape programmer using the results of the engine reduced data printout from the 405. This method was useful in developing proper emission parameters to relate to engine performance but was unsatisfactory for the large volume of data developed.

Consequently, four duplicate Fortran programs were prepared for engine data reduction to which were added the emissions data calculations. The format of the printout was merely to add an extra page of emission results to the engine test results. Thus, the data reduction programs with and without emissions data could be used almost interchangeably, depending on whether or not emissions data was taken.

The following variables and parameters were developed for reduction of the emissions data and some of these appear as graphs in the results section of the report.

TABLE A-1

COMPUTER PROGRAM VARIABLES

Variable	Name	Explanation
	Input Constants	
dry bulb temp.	TDBZ	ambient
wet bulb temp.	TWBZ	ambient
hydrogen to carbon ratio of fuel	HCRZ	handbook or measured value for fuel used
stoichiometric fuel air ratio	FARSZ	calculated for fuel used
	Input Data	
measured CO_2 percent	CO2RZ	measured volume percent CO_2 in exhaust
measured CO ppm	CORZ	measured volume percent CO in exhaust
measured unburned hydrocarbons	UHRZ	measured volume ppm hydrocarbons as propane (C_3H_8)
measured oxides of nitrogen	ONRZ	measured volume ppm oxides of nitrogen as NO_2

Variable	Name	Explanation
	Output Data	
shaft speed	RPMZ	one or more engine shaft speeds (actual) in rpm
fuel flow	WFZ	engine fuel consumption in grams/sec. Main program has corrected fuel flow in lbs/hr.
air flow	W1Z	engine air flow in kilograms/second. Main program has corrected air flow in lbs/second.
fuel/air ratio	FARZ	actual fuel air ratio
equivalence ratio	EQRZ	fuel air ratio divided by stoichiometric fuel air ratio
exhaust flow	WEZ	sum of air and fuel flow in kg/s
	VEMZ	exhaust flow in standard cubic meters per second treating all exhaust as air at 15°C (59°F)
	VEFZ	same as above in standard cu. ft. per min.
power	HPZ	total horsepower output (shaft engines)
thrust	FZ	thrust in pounds (jet engines)
specific fuel consumption	SFCZ	fuel consumption divided by engine output

Variable	Name	Explanation
calculated CO_2 percent	CO2CZ	calculated CO_2 concentration in exhaust
mass flow (all emissions)	WCO2Z WCOZ WHCZ WONZ	CO_2 in grams/second, all others in mg/s, computed from measured concentration and exhaust flow
emission index (all pollutants)	EICO EIHC EION	pollutant emission per unit weight of fuel consumed, mg/g
specific emission	SEICO SEIHC SEINO	pollutant emission per unit of engine output, grams per horsepower or grams per pound of thrust

The equations used for calculating the above output quantities are given as follows:

<u>Actual fuel air ratio</u> = $\frac{\text{mass flow of fuel in g/s}}{\text{mass flow of air in kg/s x 1000}}$

FARZ = WFZ/(W1Z * 1000)

<u>Equivalence ratio</u> = actual fuel air ratio/stoichiometric fuel air ratio

EQRZ = FARZ/FARSZ

<u>Exhaust mass flow (kg/s)</u> = (fuel mass flow in g/s)/1000 + air mass flow in kg/s

WEZ = WFZ/1000 + W1Z

<u>Exhaust volume flow (standard cubic meters per second)</u>

(at 59°F) = Exhaust mass flow (kg/s)/standard density (kg/m^3)

$$\text{density} = \frac{MP}{RT} = \frac{(28.98)(1.01325 \times 10^5)}{(8315)(288.16)} \frac{\text{kg n (kg mole) °K}}{\text{(kg mole) m}^2 \text{ j °K}}$$

VEMZ = WEZ * .81598

<u>Exhaust volume flow (standard cubic feet per minute)</u> =

exhaust volume flow (SCMS) x 60/(.3048)^3

VEFZ = VEMZ * 2118.6

<u>Calculated CO_2 concentration (volume percent)</u>

hydrogen/carbon weight ratio of fuel = HCR

$$W_F = W_C + W_H = W_C + \frac{W_H}{W_C} W_C = W_C(1 + HCR)$$

$$W_C = \frac{W_F}{1 + HCR}$$

$$CO_2\% = \frac{W_F}{(HCR+1)} \frac{M_A}{M_C} \frac{(100)}{W_E(1000)}$$

$$CO_2\% = \frac{W_F}{(HCR+1)} \frac{(28.98)}{(12.01)} \frac{(100)}{WEZ(1000)}$$

CO2CZ = (WFZ * .2413)/([HCRZ+1]*WEZ)

<u>Measured mass flow CO_2 (g/s)</u> = (measured volume percent) x

$$\frac{M_{CO_2}}{M_A} \times W_E \times \frac{1000}{100} = \% \times W_E \times \frac{44.01}{28.98} \times 10$$

WCO2Z = CO2RP * WEZ * 15.186

Measured mass flow CO (mg/s) = (measured volume parts per million) $\times \frac{M_{CO}}{M_A} \times W_E \frac{10^6}{10^6} = \text{ppm} \times W_E \times \frac{28.01}{28.98}$

WCOZ = CORP * WEZ * .96653

Measured mass flow hydrocarbons as $CH_{1.85}$ in mg/s measured as volume ppm propane (C_3H_8) = (measured volume ppm propane) x

$$\frac{3\ M_{CH_{1.85}}}{M_A} \times W_E \times \frac{10^6}{10^6} = \text{ppm} \times$$

$$\frac{3[12.01 + 1.85(1.008)]}{(28.98)} \times W_E$$

WHC1Z = UHR1 * WEZ * 1.4363

Measured mass flow nitrogen oxides as NO_2 in mg/s when measured as volume ppm NO_2 = (measured volume ppm NO_2) x

$$\frac{M_{NO_2}}{M_A} \times W_E \times \frac{10^6}{10^6} = \text{ppm} \times \frac{46.007}{28.98} \times W_E$$

WON1Z = ONR1 * WEZ * 1.5875

Emission index (mg/g) = (mg/s of pollutant)/(g/s of fuel)

EICO = WCOZ/WFZ

Specific emission index (g/hphr or g/lbhr) = (mg/s of pollutant) $\times \frac{3600}{1000}$ / (horsepower or lbs thrust)

SEINO1 = WON1Z * 3.6/HPZ

Hydrogen to carbon ratios of the fuels used in the calculations were taken from the references in Table A-2.

TABLE A-2

FUEL COMPOSITION SUMMARY

Fuel	Hydrogen to Carbon Weight Ratio	Stroichiometric Fuel Air Ratio	Reference
JP-4	0.168	0.067626	NACA RME55627a (p. 1) 1965
JP-5	0.158	0.0687	NACA TN3276 (p. 70) 1956
Diesel No. 2	0.142	0.0699	Kent Handbook (p. 2-49)
White Gasoline	0.176	0.0671	Kent Handbook (p. 2-58)

A sample computer output sheet is shown in Fig. A-1.

WILLIAMS RESEARCH CORPORATION
PRODUCTION JET DATA REDUCTION PROGRAM W.E.

H.E.W. TEST 03/31/70

**** EMISSION INPUT CONSTANTS ****

TDBZ-DRY BULB TEMP	39.500	TWBZ-WET BULB TEMP	32.500
HCRZ- H/C RATIO	0.16800000	FARSZ-STOIC F/A RA	0.06762600

**** INPUT ****

DATA POINT NUMBER	70	71	72	73	74	75	76
CO2RZ-MEAS CO2 PCT	0.00000	2.19000	2.19000	2.23000	2.42000	2.58000	2.80000
CORZ-MEAS CO PPM	0.00000	320.00000	260.00000	230.00000	180.00000	180.00000	210.00000
UHR1Z-ME CHX PPM 1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
UHR2Z-ME CHX PPM 2	0.00000	3.10000	2.30000	2.30000	4.80000	6.00000	4.50000
ONR1Z-ME NOX PPM 1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
ONR2Z-ME NOX PPM 2	0.00000	16.70000	0.00000	23.00000	23.00000	58.80000	77.80000

**** OUTPUT DATA ****

RPM1Z - RPM1	45010.00	45030.00	48010.00	50080.00	55090.00	57060.00	59700.00
WFZ-FUEL FLO G/S	7.15428	7.08066	7.83708	8.40383	10.78835	12.42618	14.68635
W1Z-AIR FLO KG/S	0.65410	0.64543	0.71584	0.77185	0.89980	0.95052	1.01717
FARZ-FUEL/AIR RATIO	0.010938	0.010971	0.010948	0.010888	0.011990	0.013073	0.014438
EQRZ-EQUIVALENCE R	0.161737	0.162223	0.161891	0.161002	0.177294	0.193314	0.213504
WEZ-EXH FLO KG/S	0.66125	0.65251	0.72368	0.78025	0.91059	0.96295	1.03186
VEMZ-EXH FLO SCMS	0.53957	0.53243	0.59051	0.63667	0.74302	0.78574	0.84198
VEFZ-EXH FLO SCFM	1143.130	1128.011	1251.054	1348.853	1574.168	1664.677	1783.809
FZ - THRUST LBF	40.000	39.200	48.700	56.500	79.000	90.300	107.000
CO2CZ-CALC CO2 PCT	2.23518	2.24183	2.23729	2.22513	2.44764	2.66594	2.94041
SFCZ-SFC LBM/HR LBF	1.41950	1.43356	1.27719	1.18048	1.08382	1.09214	1.08933
WCO2Z-M FLO CO2 G/S	0.00000	21.70064	24.06772	26.42313	33.46427	37.72807	43.87541
WCOZ- M FLO CO MG/S	0.000	201.814	181.860	173.452	158.420	167.529	209.437
WHC1Z-M F CHX 1 MG/S	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WHC2Z-M F CHX 2 MG/S	0.000	2.905	2.391	2.578	6.278	8.298	6.669
WON1Z-M F NOX 1 MG/S	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WON2Z-M F NOX 2 MG/S	0.000	17.299	0.000	28.489	33.248	89.886	127.442
EICO-EM IND CO MG/G	0.00000	28.50208	23.20501	20.63963	14.68437	13.48192	14.26069
EIHC1-E I CHX 1 MG/G	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
EIHC2-E I CHX 2 MG/G	0.00000	0.41032	0.30505	0.30671	0.58191	0.66782	0.45411
EION1-E I NOX 1 MG/G	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
EION2-E I NOX 2 MG/G	0.00000	2.44310	0.00000	3.39000	3.08183	7.23361	8.67759
SEICO-SPEI CO G/LBHR	0.00000	18.53390	13.44342	11.05181	7.21915	6.67889	7.04650
SEIHC1- CHX 1 G/LBHR	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SEIHC2- CHX 2 G/LBHR	0.00000	0.26681	0.17672	0.16423	0.28608	0.33084	0.22439
SEINO1- NOX 1 G/LBHR	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SEINO2- NOX 2 G/LBHR	0.00000	1.58866	0.00000	1.81523	1.51509	3.58350	4.28777

TEST NO, 264- 1- 01 701 76
TEST DATE 3-30-1970
TEST CELL NO 3
ENG SN= 264 BLD= 1

Fig. A-1 Sample Emission Data Reduction

APPENDIX B

VEHICLE TEST DATA REDUCTION

Air Flow Calculations

Since no engine airflow measurements were made with the engine installed in the vehicle, it was necessary to calculate airflow from gas generator speed.

Previous measurements taken on this engine in the test cell indicated that corrected airflow is relatively independent of power turbine speed and is reasonably linear with corrected gas generator speed in the range of idle to maximum speed.

An empirical equation for the graph of corrected airflow vs. corrected speed is:

$$\left(\frac{W_a\sqrt{\theta}}{\delta}\right) = \left(\frac{W_a\sqrt{\theta}}{\delta}\right)_{idle} + 2.64 \times 10^{-5}\left(\frac{N_1 - N_{idle}}{\sqrt{\theta}}\right) \quad (1)$$

$$W_a = \frac{\delta}{\sqrt{\theta}}\left(\frac{W_a\sqrt{\theta}}{\delta}\right)_{idle} + 2.64 \times 10^{-5}\,\frac{\delta}{\theta}\left(N_1 - N_{idle}\right)$$

$$\left(\frac{W_a\sqrt{\theta}}{\delta}\right)_{idle} = f\left(\frac{N_{idle}}{\sqrt{\theta}}\right)$$

W_a in lbm/s

N in rpm

$\theta = \dfrac{\text{inlet temperature in °R}}{519}$

$\delta = \dfrac{\text{barometer in "Hg}}{29.92}$

Steady state airflows were computed from values of $\left(\frac{W_a \sqrt{\theta}}{\delta}\right)$ read directly from the graph of equation (1).

Cumulative airflows for each cycle of the nine cycle tests were determined from the area under the recording of N_1 vs. time. A sample of shaft speed recording is shown in Fig. B-1. Each square inch represents $5 \times 10^4 \ \frac{\text{rev. sec.}}{\text{min.}}$

Cumulative airflow is:

$$M_a = \int_{1\ \text{cycle}} W_a dt$$

$$M_a = \frac{\delta}{\sqrt{\theta}} \left(\frac{W_a \sqrt{\theta}}{\delta}\right)_{\text{idle}} t_{\text{cycle}} + 2.64 \times 10^{-5} \times \frac{\delta}{\theta} \int_{\text{cycle}} \left(N_1 - N_{\text{idle}}\right) dt$$

$$\int_{\text{cycle}} \left(N_1 - N_{\text{idle}}\right) dt = 5 \times 10^4 \times (\text{area over idle speed})$$

$$M_a = \frac{\delta}{\sqrt{\theta}} \left(\frac{W_a \sqrt{\theta}}{\delta}\right)_{\text{idle}} t_{\text{cycle}} + 1.320 \frac{\delta}{\theta} \times (\text{area over idle speed}) \qquad (2)$$

A sample calculation of cumulative airflow for cycle no. 3, run no. 4 is given below:

Barometer "Hg	29.58	
δ	.9886	
Inlet temperature °F	72	
θ	1.0250	
$\sqrt{\theta}$	1.0124	
N_1 actual (krpm)	36.7	
N_1 corrected (krpm)	36.3	
W_a idle corrected (lbm/s)	.567	from graph of equation (1)
t_{cycle} (seconds)	137	
$\frac{\delta}{\sqrt{\theta}} \left(\frac{W_a \sqrt{\theta}}{\delta}\right)_{idle} t_{cycle}$ (lbm)	75.90	
Area over idle (in^2)	13.87	
$1.320 \frac{\delta}{\theta}$ x area (lbm)	17.66	
M_a (equation 2)	93.56 lbm = 42.44 kg	

The results of the graphic solution of equation (2) over all graphs for runs 3 and 4 of Table I, page 17, are given in Table B-1.

Fuel flow was not recorded during the nine cycle tests. An average fuel air ratio of 0.006 was assumed to determine exhaust flow from airflow:

WEZ = 1.006 W1Z

where the symbols are defined in Appendix A.

Bag Sample Calculations

Table B-1 gives the results of bag sample measurements using the equations of Appendix A. Total vehicle distance over nine cycles is 7.575 miles.

Continuous Sample Calculations

Tables B-2 and B-3 are samples of continuously recorded emissions of CO, CO_2, and CH_x during one cycle of a nine cycle run. Concentrations were read at seven established points in six of the nine cycles according to standard procedure(6). These values were multiplied by weighting factors and summed for each cycle. A sample of this calculation is shown in Table B-2.

The resulting ppm for each constituent, cycle, and run are shown in Table B-3. Using the equations of Appendix A, the mass contribution of each cycle is computed and these are added for each run. The vehicle distance for six out of nine cycles is 5.050 miles and this figure is used to determine the grams/mile figure reported in Table 1, page 17.

TABLE B-1

MASS EMISSIONS FROM BAG ANALYSIS

Run No.	Type of Run	M_a kg	M_e kg	CO ppm	CH_x as C_3H_8 ppm	NO_x as NO_2 ppm	CO g	CH_x as $CH_{1.85}$ g	NO_x as NO_2 g	CO g/mile	CH_x g/mile	NO_x g/mile
3	9 cycles cold start	389	392	160	11.5	41	60.6	6.5	25.5	8.0	0.85	3.4
4	9 cycles hot start	386	389	125	2.2	56	47.0	1.2	34.6	6.2	0.16	4.5

TABLE B-2

EMISSION CONCENTRATIONS, CONTINUOUS ANALYSIS, CYCLE NO. 3, RUN NO. 4

Reference 6		Recorded			Weighted	
Mode	Weighting Factor	CO_2 pct	CO ppm	CH_x ppm	CO ppm	CH_x ppm
Idle	.042	1.33	110	3.6	4.6	.151
0-25 mph	.244	1.57	100	3.1	24.4	.756
30 mph	.118	1.45	70	3.2	8.2	.378
30-15 mph	.062	1.32	110	5.9	6.8	.366
15 mph	.050	1.35	100	3.1	5.0	.155
15-30 mph	.455	1.71	90	3.0	41.0	1.365
50-20 mph	.029	1.39	120	10.5	3.5	.305
Total	1.000				93.5	3.476

TABLE B-3

MASS EMISSIONS FROM CONTINUOUS ANALYSIS

Run	Cycle	Ma (kg)	CO ppm	CH_x ppm	M_{co} g	M_{chx} g
3	1	48.04	132.10	23.85	6.170	1.655
	2	42.54	80.02	12.005	3.310	.738
	3	42.37	73.03	9.751	3.008	.597
	4	42.43	70.32	8.639	2.901	.530
	6	42.99	75.37	6.853	3.151	.426
	7	42.16	79.82	6.348	3.272	.387
Total					21.812	4.333
4	1	47.69	234.2	4.756	10.860	.328
	2	43.68	124.3	4.050	5.279	.256
	3	42.44	93.5	3.476	3.858	.213
	4	42.53	85.3	3.772	3.527	.232
	6	42.24	71.6	2.990	2.941	.183
	7	41.30	86.3	4.129	3.466	.246
Total					29.931	1.458

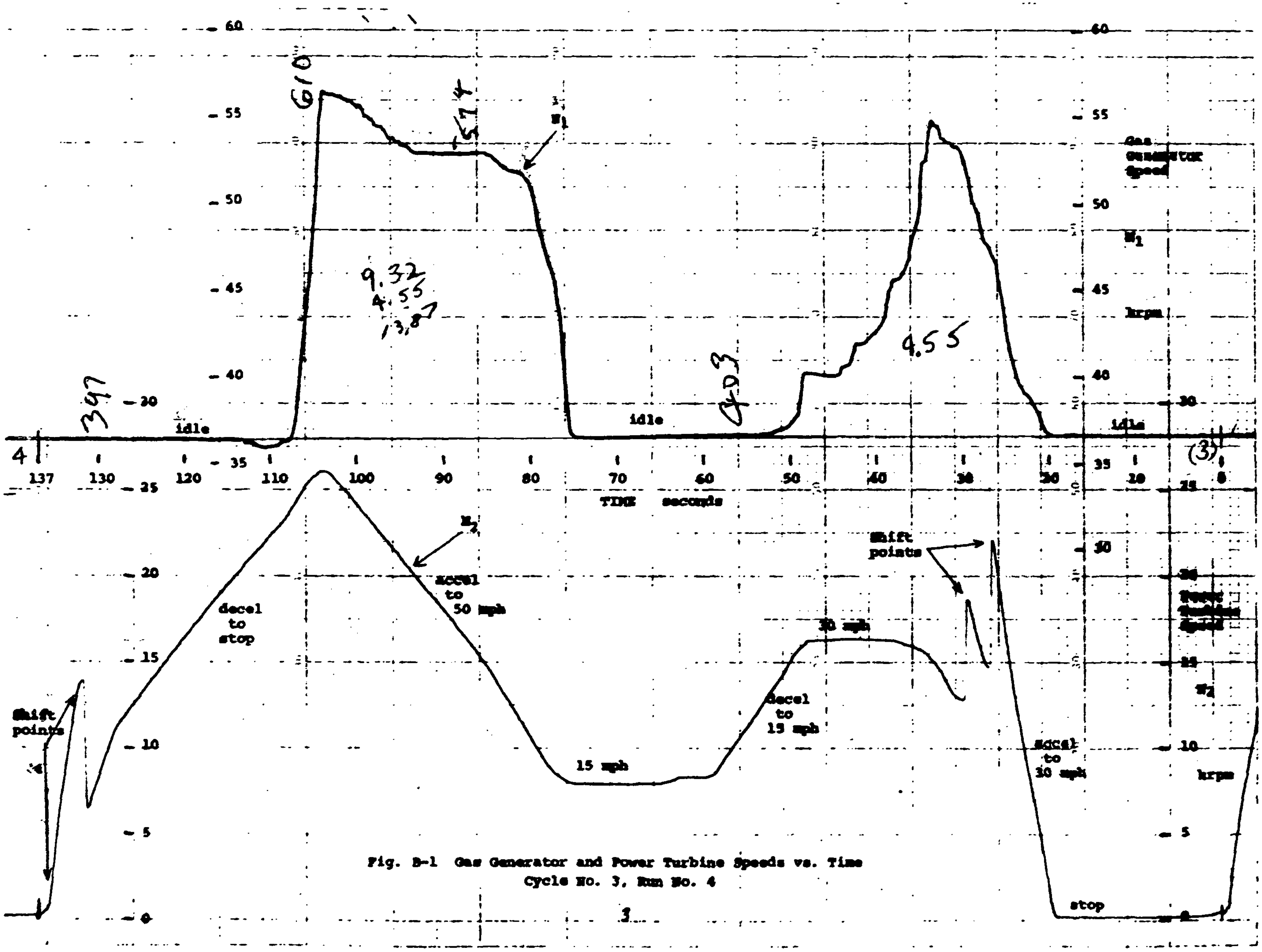

Fig. B-1 Gas Generator and Power Turbine Speeds vs. Time
Cycle No. 3, Run No. 4

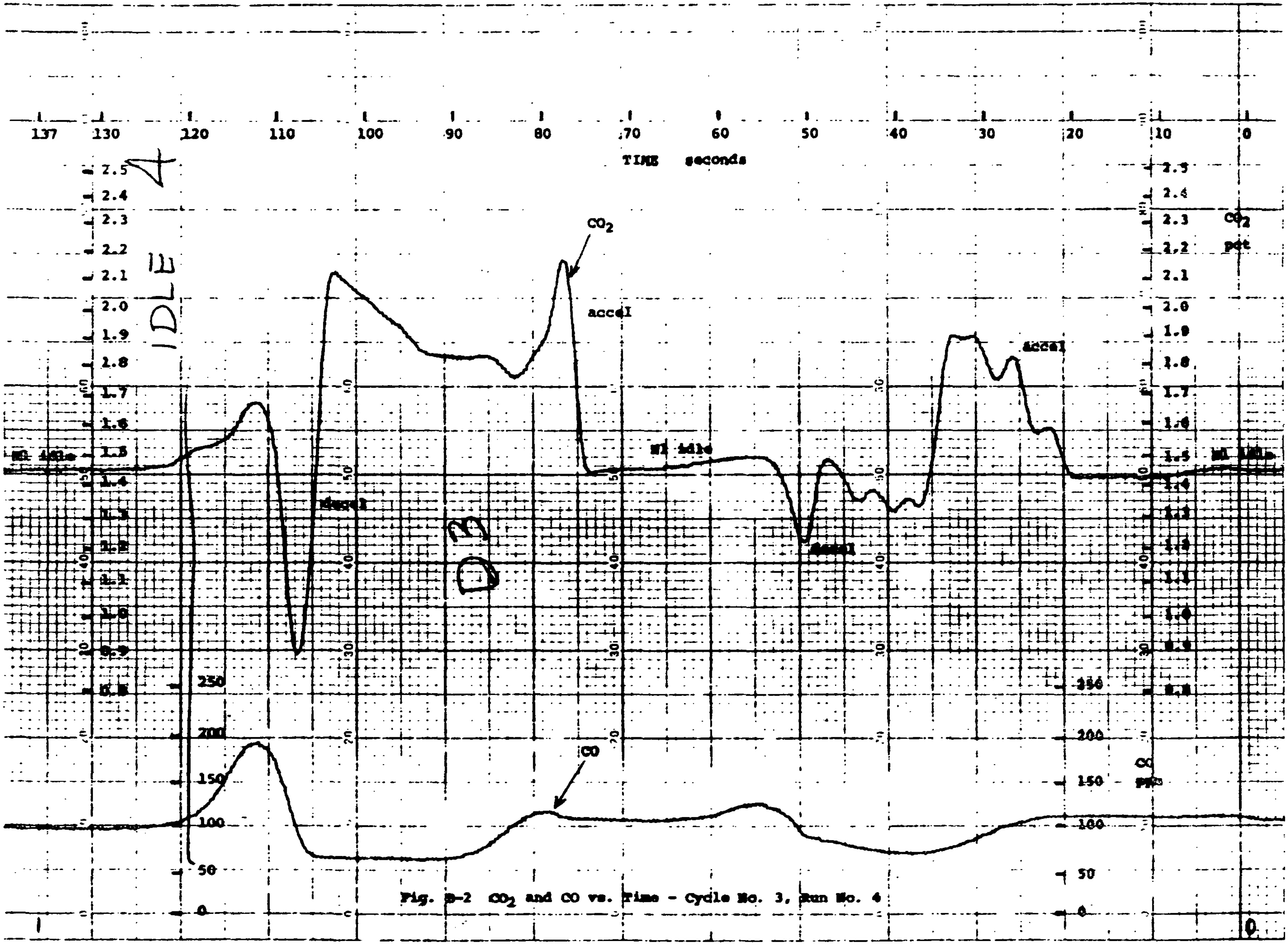

Fig. B-2 CO_2 and CO vs. Time - Cycle No. 3, Run No. 4

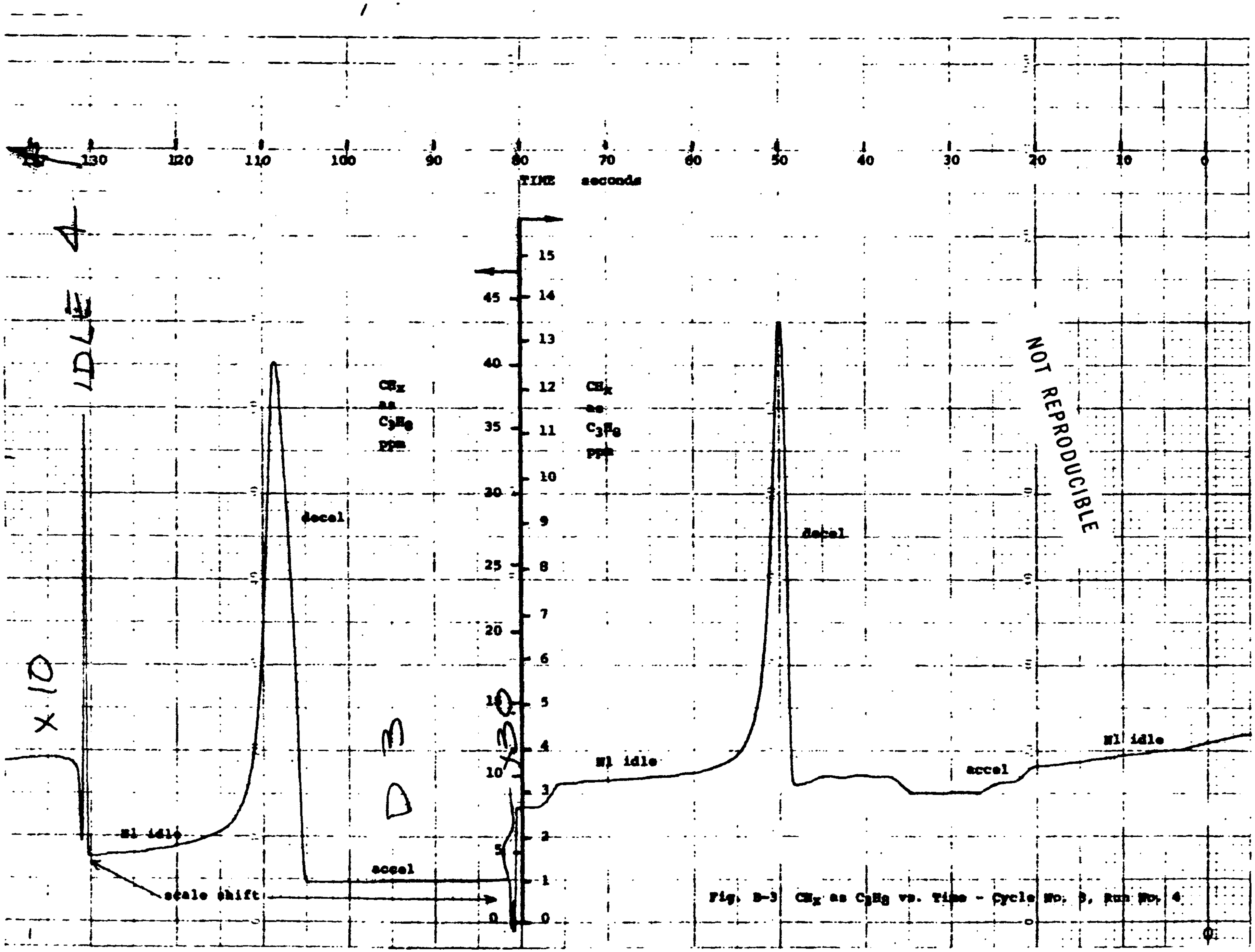

Fig. B-3 CH_x as C_3H_8 vs. Time - Cycle No. 3, Run No. 4

APPENDIX C

LIST OF EQUIPMENT

<u>Analysis Equipment Cart</u>

Beckman Infrared Analyzer Model 1R315

Beckman Hydrocarbon Analyzer Model 108A

Honeywell Electronik 194 Recorder

Brooks E/C Flowmeter 500 cc/min

Neptune Dyna-Pump Model 4K

<u>Oil Heating System</u>

Chromalox NWHO-215 Heaters

Procon Pump

<u>Portable Engine Console</u>

Hewlett Packard Frequency Meter Model 500B

Honeywell Electronik 194 Recorder

Anadex Counter-Timer Model CF-203R

Leeds and Northrup Speedomax H Thermocouple Indicator

Wallace and Tiernan Pressure Gauge Model FA 145

APPENDIX D

STATISTICAL ANALYSIS OF CO_2 ERROR

The statistical analysis of CO_2 error was performed using the Cypherstat computer program of the Cyphernetics Corporation, Ann Arbor, Michigan on a time sharing computer terminal at Williams Research Corporation.

The measured and calculated CO_2 concentrations and the difference, CO_2 error, are listed in Table D-1 for the data points underlined in Fig. 14 (refer to Accuracy of Data, page 8).

A summary of the statistical properties of CO_2 error is given in Table D-2 and a histogram in Table D-3. The chi square test for goodness of fit to a normal distribution is summarized in Table D-4. The Yates corrected chi square value of 5.105 implies that this data represents a sample of a normal population which does not deviate more (have a larger chi square value) than 82 percent of all samples from such a normal population are expected to do.

TABLE D-1

CO_2 CONCENTRATIONS

	Data Code	Data Pt.	Meas. CO_2	Calc. CO_2	CO_2 Error	
00100	1	4	2.650	2.550	0.100	12.000
00101	1	28	2.720	2.680	0.040	10.800
00102	1	29	2.920	2.890	0.030	10.600
00200	2	1	1.200	1.100	0.100	12.000
00201	2	2	1.250	1.140	0.110	12.200
00203	2	3	1.250	1.140	0.110	12.200
00204	2	4	1.070	0.990	0.080	11.600
00205	2	5	1.030	0.900	0.130	12.600
00206	2	6	1.140	1.130	0.010	10.200
00207	2	7	1.290	1.130	0.160	13.200
00208	2	8	1.200	1.140	0.060	11.200
00209	2	9	1.430	1.220	0.210	14.200
00210	2	10	1.480	1.220	0.260	15.200
00211	2	11	1.460	1.160	0.300	16.000
00301	3	21	1.370	1.380	-0.010	9.800
00302	3	22	1.210	1.090	0.120	12.400
00303	3	23	1.640	1.690	-0.050	9.000
00304	3	24	1.980	1.710	0.270	15.400
00401	4	37	1.070	0.950	0.120	12.400
00402	4	38	1.220	1.120	0.100	12.000
00403	4	39	1.270	1.160	0.110	12.200
00404	4	40	1.420	1.250	0.170	13.400
00405	4	41	1.650	1.400	0.250	15.000
00406	4	42	2.020	1.680	0.340	16.800
00407	4	43	1.190	1.170	0.020	10.400
00501	5	58	1.450	1.340	0.110	12.200
00502	5	63	1.370	1.370	0.0	10.000
00503	5	64	1.480	1.350	0.130	12.600
00504	5	65	1.580	1.430	0.150	13.000
00505	5	66	1.780	1.480	0.300	16.000
00601	6	15	1.230	1.170	0.060	11.200
00602	6	18	1.280	1.190	0.090	11.800
00603	6	20	1.170	1.250	-0.080	8.400
00604	6	21	1.250	1.290	-0.040	9.200
00605	6	22	1.450	1.360	0.090	11.800
00701	7	23	1.310	0.880	0.430	18.600
00702	7	24	1.430	1.020	0.410	18.200
00703	7	26	1.160	0.940	0.220	14.400
00704	7	27	1.020	0.760	0.260	15.200
00705	7	28	0.980	0.800	0.180	13.600
00706	7	29	1.250	1.100	0.150	13.000

TABLE D-1

	Data Code	Data Pt.	Meas. CO_2	Calc. CO_2	CO_2 Error	
00800	8	9	2.330	2.430	-0.100	8.000
00801	8	10	2.270	2.270	0.0	10.000
00802	8	11	2.580	2.320	0.260	15.200
00803	8	12	2.540	2.310	0.230	14.600
00804	8	13	2.580	2.360	0.220	14.400
00805	8	14	2.800	2.450	0.350	17.000
00806	8	15	2.270	2.040	0.230	14.600
00807	8	16	2.740	2.720	0.020	10.400
00808	8	17	3.070	2.760	0.310	16.200
00809	8	18	2.570	2.470	0.100	12.000
00810	8	19	3.070	2.980	0.090	11.800
00811	8	22	3.230	3.160	0.070	11.400
00812	8	23	3.600	3.240	0.360	17.200
00813	8	24	2.470	2.350	0.120	12.400
00814	8	26	2.750	2.530	0.220	14.400
00815	8	27	3.000	2.770	0.230	14.600
00816	8	28	3.290	3.110	0.180	13.600
00817	8	29	3.670	3.280	0.390	17.800
00818	8	30	3.830	3.440	0.390	17.800
00819	8	31	3.570	3.360	0.210	14.200
00820	8	32	3.370	3.050	0.320	16.400
00821	8	33	2.950	2.720	0.230	14.600
00901	9	23	2.380	2.510	-0.130	7.400
00902	9	24	2.550	2.650	-0.100	8.000
00903	9	25	2.780	2.810	-0.030	9.400
00904	9	26	3.150	3.130	0.020	10.400
00905	9	27	2.280	2.480	-0.200	6.000
00906	9	28	2.400	2.520	-0.120	7.600
01001	10	3	2.480	2.480	0.0	10.000
01002	10	14	2.680	2.440	0.240	14.800
01003	10	15	3.700	3.230	0.470	19.400
01004	10	16	3.630	3.050	0.580	21.600
01005	10	17	2.930	2.700	0.230	14.600
01006	10	18	4.200	3.610	0.590	21.800
01101	11	71	2.190	2.240	-0.050	9.000
01102	11	72	2.190	2.240	-0.050	9.000
01103	11	73	2.230	2.230	0.0	10.000
01104	11	74	2.420	2.450	-0.030	9.400
01105	11	75	2.580	2.670	-0.090	8.200
01106	11	76	2.800	2.940	-0.140	7.200
01201	12	10	0.016	0.0	0.016	10.320
01202	12	11	0.025	0.0	0.025	10.500

TABLE D-2

STATISTICAL SUMMARY OF CO_2 ERROR

```
TALLY ØF: CØ2ERR

 ADJ N=        83
 MEAN =         0.13567
 SUM  =        11.26100
 SUMSQ=    0.37161D+01
 MIN  =        -0.20000
 MAX  =         0.59000

 USING (ADJ N)             USING (ADJ N)-1

  VAR =    0.26364E-01     0.26686E-01
  SDEV=    0.16237E+00     0.16336E+00

VARIABLE(S)--
```

TABLE D-4

CHI SQUARE TEST OF CO_2 ERROR

CHIFIT ØF: CØ2ERR
AGAINST A NØRMAL CURVE WITH
MEAN= 0.1357
VAR = 0.0267
N = 83.0000

CHISQ= 7.2206 (UNCØRRECTED)
CHISQ= 5.1052 (WITH YATES CØRRECTIØN)
DF = 9

CRITICAL CHISQ VALUES AT:
95% CØNFIDENCE = 3.3251
90% CØNFIDENCE = 4.1682

NØ	INTERVAL LØW	ENDPØINTS HIGH	ACTUAL CØUNT	EXPECTED CØUNT	CØNTRIBUTIØN USING YATES
1	-.2000E+36	-.1910E+00	1.0	1.8841	0.0783
2	-.1910E+00	-.1094E+00	3.0	3.6603	0.0070
3	-.1094E+00	-.2768E-01	10.0	7.6277	0.4596
4	-.2768E-01	0.5400E-01	13.0	12.4334	0.0004
5	0.5400E-01	0.1357E+00	20.0	15.8945	0.8179
6	0.1357E+00	0.2174E+00	8.0	15.8945	3.4401
7	0.2174E+00	0.2990E+00	14.0	12.4334	0.0915
8	0.2990E+00	0.3807E+00	7.0	7.6277	0.0021
9	0.3807E+00	0.4624E+00	4.0	3.6603	0.0070
10	0.4624E+00	0.2000E+36	3.0	1.8841	0.2013

VARIABLE(S)--

TABLE D-3

HISTOGRAM OF CO_2 ERROR

```
TABI ØF: CØ2ERG

 N(IN HISTØGRAM)    =    83    MEAN=  12.3735     SDEV=   3.1995
 N(MISSING DATA)    =     0    MØDE=  12
 N(ØUTSIDE (0-99))=       0
 N TØTAL            =    83     ØNE * =     0.50 ØBSERVATIØNS

    N     PCT   VAL 0        5.00       10.00      15.00      20.00
                    +---------+---------+---------+---------+
    1    1.20 ( 6) -**
    3    3.61 ( 7) -******
    4    4.82 ( 8) -********
    7    8.43 ( 9) -**************
   12   14.46 (10) -************************
    7    8.43 (11) -**************
   13   15.66 (12) -**************************
    6    7.23 (13) -************
   11   13.25 (14) -**********************
    5    6.02 (15) -**********
    5    6.02 (16) -**********
    4    4.82 (17) -********
    2    2.41 (18) -****
    1    1.20 (19) -**
    0    0.0  (20) -
    2    2.41 (21) -****

VARIABLE(S)--
```

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16. Abstracts

The exhaust emissions of several different models of gas turbine engines under development or in production were measured. The emissions measured were carbon dioxide, carbon monoxide, unburned hydrocarbons, and the oxides of nitrogen. The results are presented in a generalized form relating emissions to fuel air ratio and engine power or thrust. Techniques were developed to convey exhaust samples from engines in test cells to analysis equipment located elsewhere. Measurements were also made of the emissions from a gas turbine engine installed in a vehicle. ~~The conclusions follow.~~ Gas turbine engines are inherently low polluters in carbon monoxide and unburned hydrocarbons compared to other types of engines of the same power output. Transient engine operation produces many times the CO and hydrocarbon emission that steady state operation produces. Part load engine operation produces more CO and hydrocarbon emission than full load. The opposite is true of the oxides of nitrogen. The oxides of nitrogen are the most serious emission problem of gas turbine engines with respect to proposed emission controls. Satisfactory methods have been developed in this program for sampling exhaust pollutants from a variety of gas turbine engines. A heated sampling system is necessary to prevent deterioration of the unburned hydrocarbon sample between engine and analyzer.

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

Air pollution		
Gas turbine engines		
Exhaust emissions	Thrust	Auxiliary power plants
Carbon dioxide	Gas sampling	
Carbon monoxide	Motor vehicle engines	
Hydrocarbons	Surges	
Nitrogen oxides	Loads (forces)	
Fuel consumption	Heat transfer	
Air flow	Turbojet engines	
Power	Turbofan engines	

17b. Identifiers/Open-Ended Terms

WR 24-6	Turbojet engines
WR 9-7	Auxiliary Power Unit
WR 19	Turbofan engines
131L	Industrial engines
131Q	Motor vehicle engines

17c. COSATI Field/Group 13/02, 21/05

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