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STUDY OF ALTITUDE AND MACH NUMBER EFFECTS ON EXHAUST GAS EMISSIONS OF AN AFTERBURNING TURBOFAN ENGINE

Aeronautical Turbine Department
NAVAL AIR PROPULSION TEST CENTER
Trenton, N.J. 08628

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Prepared by:

J. Lawrence Palcza

J. LAWRENCE PALCZA

Approved by:

G. R. Simpson

G. R. SIMPSON

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16. Abstract

A TF30-P-412 augmented turbofan engine was tested at simulated altitudes and Mach numbers to determine the effects of these parameters (altitude and Mach number) on exhaust pollution emissions. Emission measurements were made over a range of engine power settings from idle to full augmentation at altitudes from sea level to 70,000 feet and a Mach number range of 0 to 1.8.

There was no apparent effect on emission levels due to altitude or Mach number.

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INTRODUCTION

This report describes a program conducted by the Naval Air Propulsion Test Center (NAPTC) for the Federal Aviation Agency (FAA), Department of Transportation, authorized by Inter-Agency Agreement No. DOT-FA71WAI-207 (reference 1). The purpose of the program was to analyze the possible effects of altitude and Mach number on exhaust emissions of an afterburning jet engine. To this end, engine exhaust data was sampled and evaluated for various chemical emissions and particulate data between idle and maximum afterburning power level positions and between sea level and 70,000 feet altitude.

BACKGROUND

World operation of a large fleet of Supersonic Transport (SST) aircraft has posed a potential problem on overall climatology effects. Numerous reports have appeared calling attention to the possible threat to the meteorological environment. Emission data from aircraft powerplants operating in stratospheric regions is unknown. Consequently, the FAA has awarded NAPTC at Trenton, New Jersey this project for determining powerplant exhaust gas emission of an afterburning engine at various altitudes and flight speeds. Scott Research Laboratories, Inc. of Plumsteadville, Pennsylvania assisted NAPTC in measuring the exhaust gas emission. The following types of emission were measured: carbon monoxide, unburned hydrocarbons, oxides of nitrogen, water vapor, and solid particulates. Measurements were made over a range of altitude from sea level to 70,000 feet and a Mach number range of 0 to 1.8.

SUMMARY

A TF30-P-412 augmented turbofan engine was tested at NAPTC to determine possible effects of altitude and Mach number on exhaust emissions. Emission measurements were made between idle and maximum afterburning, sea level and 70,000 feet, and over a Mach range from 0 to 1.8. Test results indicated that, within areas of efficient engine component operation, altitude and Mach number effects on emission levels were negligible.

Particulate samples collected revealed close agreement of particle size to data collected during previous ground tests.

METHOD OF TEST

Emission measurements were made while the engine was operated at various simulated altitudes, Mach numbers and power settings. The pollutants sampled were carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), unburned hydrocarbons (HC), and water vapor (H_2O). In addition, information was gathered on the size, distribution and amount of particulate matter emitted.

The analytical instrument system was located on the engine deck of the test cell. Two NAPTC-designed and fabricated water-cooled sampling probes were utilized. Figure 1 presents a photograph of the probe as installed downstream of the test cell ejector. One probe was installed three inches aft of the engine exhaust nozzle, while the other was installed approximately 27 feet downstream of the engine exhaust nozzle. The data presented and evaluated in this report are all samples from the downstream probe due to operational difficulties with the other.

Approximately 30 feet of one-half inch diameter stainless steel tubing carried the sample from the probe to the gas sampling instrumentation. In order to prevent condensation of the exhaust gases, the line was heated by four 400-watt strip heaters, and insulated with asbestos tape. A selector valve, located outside the test chamber, allowed the instrument systems operator to sample from either the nozzle probe or the

downstream probe. After the selector valve, the sample line divided into three streams: one to the particulate sampler, another to the water vapor meter, and another to the gas sampling system. Sample flow through each stream was driven by two Thomas Model 726CA39 Teflon diaphragm pumps operating in series.

Particulate samples were collected on membrane filters housed in a stainless steel filter holder located upstream of the pumps. The flow through the filter was measured by a wet test meter on the pump exhaust, while sample gas was continuously flowing in a by-pass line parallel to the filter, to ensure a representative sample. When sampling, valves were operated to switch the filter into the line in place of the by-pass.

Water vapor was measured by a dew-point hygrometer, and a pressure gauge was used to measure the total pressure. The hygrometer measured the temperature of dew formation on a thermoelectrically cooled or heated mirror. A 7-cm glass filter was used to remove the particulates at the inlet to the sub-system, and the pumps were located downstream of the meter.

The stream, to be analyzed for the other gaseous components, was passed through a set of pumps and then through various instruments.

In addition to the analytical instrument systems measurements, flask samples for NO and NO_2 were analyzed in the Scott Laboratory using the Saltzman procedures.

Nitrogen filled flasks were used to collect samples of ten cubic centimeters. The nitrogen served to stop the conversion of NO to NO_2 allowing a true assessment of their relative concentrations.

Hydrocarbons were measured utilizing a flame ionization detector and an electrometer in conjunction with a thermally-controlled sample train to permit accurate measurement of low levels of the relatively high molecular weight hydrocarbons found in JP-5 fuel.

Due to the low levels of carbon monoxide emitted at some engine operating conditions, special gas samples were collected for laboratory analysis. Five-liter Tedlar bags were filled with gas samples and these were analyzed for CO and CO_2 by gas chromatography. The CO_2 analysis was used as a test for the integrity of the sample by comparing the chromatographic analyses of the bag sample in the laboratory and the continuous infrared analyses in the field.

The bag samples, flask samples and particulate samples taken in the field were analyzed at the Scott Laboratory. The bag samples were analyzed for carbon monoxide and carbon dioxide by gas chromatography. The flask samples were analyzed for nitric oxide and nitrogen dioxide by the modified Saltzman method. The particulate samples were sent to the Franklin Institute in Philadelphia, Pennsylvania to have scanning electron micrographs taken of them. These micrographs were then analyzed by Scott to determine particle size distribution and particle count.

Figure 2 presents an instrumentation and installation diagram of the XTF30-P-412 engine, as utilized during this test program. The instrumentation shown was used primarily for a previous engine performance evaluation.

The types of instrumentation utilized for the exhaust gas emission analysis is as follows:

Instrument	Particle Measured
Gelman GA-8 Membrane Filters	Particulate sample measurement
Gelman Model 2220 Filter Holder	Particulate sample measurement
Beckman NDIR	Monitor carbon monoxide and carbon dioxide
MSA Model 300	Monitor carbon monoxide and carbon dioxide
Beckman NDIR	Nitric oxide measurement
Beckman Ultraviolet Unit	Nitrogen dioxide
Whittaker Electrochemical NO_x Unit	Nitric Oxides
Scott Model 115 Heated Total Hydrocarbon Analyser	Measures C_2 through C_{18} Hydrocarbons

ENGINE DESCRIPTION

The TF30-P-412 turbofan engine is a twin-spool, continuous axial-flow, gas turbine engine with a common-flow afterburner. The major components include a sixteen-stage split compressor; a can-annular type combustion chamber; a four-stage, split, reaction turbine; an accessory gearbox oil tank assembly driven by the high pressure rotor; a common flow afterburning thrust augmentation system; and a variable-area iris convergent-divergent primary nozzle.

The combustion section consists of an annular diffuser and eight removable combustion liners evenly spaced in an annular chamber. Fuel is supplied to each liner by four, dual-orifice fuel nozzles through a multi-segment fuel manifold external to the combustion section. An engine-driven fuel pump delivers the fuel to a hydromechanical fuel control which schedules the fuel flow as a function of the high rotor speed, low compressor inlet temperature and pressure, main burner pressure, Mach number and power lever angle.

The five-zone, variable-augmentation afterburner consists of an afterburner diffuser assembly, afterburner combustion chamber and a variable-area iris convergent-divergent nozzle. The afterburner diffuser contains a vee-gutter flameholder, multi-segment spray rings, and a splitter duct. The afterburner diffuser accepts both cold, fan-exhaust air and hot, engine-exhaust air. These exhausts are segregated by a splitter for a short-length prior to discharge of the hot and cold streams into a common afterburner combustion chamber. The afterburner combustion chamber consists of an outer duct and a concentric inner liner. The duct assembly receives the total common exhaust of the engine (fan stream and engine stream) which then passes through the variable-area nozzle. The outer duct is mounted in tandem behind the afterburner diffuser. The liner provides a conduit for fan air for cooling the outer duct and liner and provides acoustic damping. The variable-area nozzle consists of eighteen convergent-divergent panels. The panels are hinged at the front to a unison ring. The unison ring is moved axially by four hydraulic fuel pressure actuators.

Afterburning operation can be modulated through the five zones. Zones I and IV burning takes place in the engine airstream, and Zones II, III and V burning in the fan stream. The zones light in numerical sequence. Afterburner ignition is of the hot-streak type. Afterburner augmentation is regulated by injecting varying amounts of fuel through spray rings into both the turbine and fan discharge air. Combustion is stabilized by means of a multi-ring, vee-gutter flameholder.

The afterburner fuel is delivered to the combined afterburner fuel and exhaust nozzle control by engine driven fuel pumps. The control portion, which is hydro-mechanical, schedules the fuel as a function of the main burner pressure, power lever angle and compressor inlet temperature. The afterburner nozzle area is programmed by the exhaust nozzle control section of the afterburner fuel control. The nozzle is scheduled in such a manner that the proper engine match is maintained during all regimes of afterburning. Nozzle area varies from a fully-closed area of 3.53 square feet to a fully-opened area of 7.50 square feet.

DISCUSSION OF RESULTS

Appendix A presents the emission data sampled during the test program. The emission levels of CO, HC and NO_x were converted to a standard emission index (EI) parameter. This is required since the overabundance of air in a gas turbine's exhaust can give a misleading low pollutant level compared to other heat engines if only a volumetric unit is used. The EI is essentially a measure of the pounds of pollutants emitted per pound of fuel burned. It is calculated by using the concentration of pollutant and the fuel-air ratio of the engine. The equations used for the conversions are included in Appendix B. A list of symbols is included as Appendix C.

1. Unburned Hydrocarbon Emissions

Unburned hydrocarbons represent unburned and wasted fuel. Under the action of sunlight, and in conjunction with other air pollutants, the unburned hydrocarbons react to form compounds which are considered to be a major contributor to smog.

For this test program, the unburned hydrocarbons were measured as parts per million carbon (ppmC). Consequently, the form of the unburned hydrocarbons was assumed to be CH_2. This assumption was necessary to convert ppmC to the EI (gHC/Kg Fuel).

Figure 3 presents the values of the unburned hydrocarbons. The shape of the curve is substantiated by engine performance data when acknowledging the different levels of engine operation. Idle power and low levels of afterburning (Zones 1-3) result in comparatively low levels of combustion efficiency; whereas, intermediate and high levels of afterburner operation (Zones 4-5) indicate excellent combustion efficiency. It is interesting to note that approximately 10 grams of unburned hydrocarbon per kilogram of fuel burned would result in a combustion inefficiency of 1% (reference 2).

Analysis of the data indicates that the levels of unburned hydrocarbon emissions are not affected by either altitude and/or Mach number.

2. Nitric Oxide Emissions

These compounds are formed by the combination of nitrogen and oxygen in the combustion air reacting at combustion temperatures. The available nitrogen from the combustion air begins disassociation at approximately 3000°F. With the addition of sunlight, nitrogen oxides and hydrocarbons react to form photochemical oxidants. These oxidants, along with liquid and solid particles in the air, make up what is commonly known as smog.

The measured values of nitrogen oxides (NO_x) emission concentrations are presented in Figure 4. Analysis of the data indicates that the engine gas generator determines the overall NO_x level. This is in agreement with data collected by the National Aeronautics and Space Administration (NASA) during a TF30-P-3 gaseous emission investigation (reference 2).

Review of the data indicates that the level of nitrogen emissions are not affected by either altitude or Mach number.

Theoretical studies show that of all the exhaust pollutants, oxides of nitrogen (NO_x) present the most formidable problem. Some research has been accomplished to understand the phenomena of formation of this exhaust emission. However, a firm technology for its reduction in actual engine combustion systems does not exist as yet.

3. Carbon Monoxide Emissions

This compound is a colorless, odorless, poisonous gas that is produced by the incomplete combustion of carbon in the fuel. Combustion is completed when carbon monoxide burns to form carbon dioxide.

The carbon monoxides measured during this test program are presented in Figure 5. Review of the curve indicates that the levels of CO emission are not affected by either altitude and/or Mach number.

4. Visible Emissions

For the past five years, the aircraft engine industry has enacted a major effort towards the elimination of visible emissions. Analysis of the visible smoke has revealed that it consists primarily of dry, solid, sub-micron particles of sooty carbon.

The visibility of the plume is directly related to the very small size of the smoke particles, thus, resulting in a maximum amount of light scattering. Consequently, small quantities of aircraft gas turbine smoke are dark and highly visible, whereas, other sources such as the automotive internal combustion engine which emit much greater quantities of larger size smoke particles have effectively invisible plumes.

Fortunately, the mechanics of producing visible emissions in gas turbine engines was determined to be the result of locally fuel-rich regions in the primary burning zone. Consequently, visible smoke emissions of present gas turbine engines can be virtually eliminated by either:

a. Increasing primary airflow.

b. Increasing primary mixing rates.

c. Improving fuel nozzle atomization.

d. Lowering the fuel's aromatic content.

5. Total Particulate Matter

Particulate matter is defined as any material except uncombined water that exists in a finely divided form as a liquid or solid at standard atmospheric conditions.

By weight, more than 50% of the total particulate matter emitted from gas turbine engines is due to unburned and partially oxidized fuel. Approximately 90% of the non-hydrocarbon material present is elemental carbon while the remainder is material eroded from the engine, fuel contaminants and dust ingested by the engine.

During the test program, particulate samples were taken of the exhaust stream and analyzed for particle size through a Scanning Electron Microscope.

Analysis of the reduced data indicated little difference between particulate samples taken at different altitudes or Mach number. However, the least particulate matter was observed during maximum afterburner (Zone 5) operation. This observation agrees favorably with the very low hydrocarbon emissions previously noted during Zone 5 operation (Figure 3).

A typical particulate size and distribution curve is presented in Figure 6. The "band" plotted reveals the variation in particle size obtained at some of the other conditions tested. Investigation of these other conditions indicate that the variation in particle size can be attributed to data scatter rather than change in test conditions. The complete particulate data acquired during the test program can be found in reference 3, volume II.

6. Sample Validity

The measured values of CO and CO_2 were used to check the sample validity by computing an emission-based fuel-to-total-air ratio (F/A) and comparing it with the known F/A ratio. The rationale of calculating an emission-based F/A is that if the quantity of solid carbon particles is assumed to be negligible then closure is obtained on the carbon atom system through the measured quantities of CO, CO_2 and unburned hydrocarbons. The results of these computations are shown on Figure 7. Of the 84 samples taken throughout the test program, 14 were considered invalid due to poor F/A comparisons; however, the remaining 70 samples agreed within $\pm$ 6%.

These results indicate that the downstream probe location utilized was as ideal a location as one could expect in a test cell. Location of the sampler probe closer to the engine exhaust nozzle would require a probe in the fan and gas generator streams for integration of the results. This would undoubtedly increase both complexity and error.

Figure 8 presents estimated wake diagrams of the flow through the test cell ejector at SLS conditions for idle, intermediate and maximum engine power settings. The profiles were obtained from Pratt and Whitney Aircraft estimates (reference 4) and theoretically modified for test cell ejector effects.

Analysis of the diagram reveals that the sampler probe was located in a highly mixed, subsonic flow region. Dwell-time of the mixture ranged between approximately 0.02 and 0.2 seconds.

EMISSION DATA

Power Setting	Altitude (1000 Ft)	Mach No.	Engine Airflow (Lb/Sec)	Test Cell Airflow (Lb/Sec)	Airflow Dilution (%)	F/A Actual	F/A Emission Based	CO (g/Kg Fuel)	HC (g/Kg Fuel)	NO_x (g/Kg Fuel)
Idle	SL	0	91	16.7	118	.00264	.00278	52.5	29.7	132.2
Idle	SL	0	91	0	100	.003123	.00272	44.5	16.9	NA
Military	SL	0	242	0	100	.00878	.00903	0.93	1.6	27.2
Military	SL	0	242	0	100	.00878	.00831	1.16	2.9	21.2
Military	SL	0	242	0	100	.00877	.00844	1.15	0.5	20.8
Military	SL	0	243	0	100	.00899	.00843	0.95	0.11	24.7
Military	SL	0	242	0	100	.0089	.00828	1.18	NA	17.4
Zone 1	SL	0	NA	0	100	NA	.01317	61.0	40.9	11.3
Zone 3	SL	0	239	0	100	NA	.0275	7.2	3.3	2.0
Zone 3	SL	0	239	0	100	.00246	.00241	139.0	8.0	7.4
Zone 3	SL	0	NA	0	100	NA	.0335	1.5	NA	3.9
Zone 3	SL	0	240	0	100	.0237	.0218	145.0	NA	7.8
Zone 5	SL	0	236	0	100	.0611	.0509	4.8	NA	4.9
Military	20	0.8	176	0	100	.00969	.00903	1.2	0.5	28.4
Military	20	0.8	230	0	100	.00912	.00904	1.1	1.6	27.2
Zone 1	20	0.8	174	0	100	.01336	.01166	6.7	65.4	10.7
Zone 3	20	0.8	174	0	100	.0259	.0271	8.6	4.2	7.5
Zone 5	20	0.8	175	0	100	.0505	.0552	4.6	0.3	4.8

EMISSION DATA (CONTINUED)

Power Setting	Altitude (1000 Ft)	Mach No.	Engine Airflow (Lb/Sec)	Test Cell Airflow (Lb/Sec)	Airflow Dilution (%)	F/A Actual	F/A Emission Based	CO (g/Kg Fuel)	HC (g/Kg Fuel)	NO_x (g/Kg Fuel)
Military	35	1.0	115	1.02	101	.0091	.00927	3.15	NA	NA
Military	35	1.0	116	4.71	104	.00895	.0083	1.2	0.52	33.0
Zone 1	35	1.0	113	1.26	101	.0160	.0154	55.2	52.0	10.8
Zone 1	35	1.0	114	4.8	104	.0142	.0134	51.1	63.4	9.1
Zone 2	35	1.0	114	4.8	104	.0203	.0201	53.7	69.4	14.
Zone 3	35	1.0	113	1.02	101	.0359	.0375	39.3	4.2	2.6
Zone 3	35	1.0	114	4.8	104	.0259	.0268	133.0	26.6	5.2
Zone 4	35	1.0	113	4.8	104	.0432	.0468	17.3	20.3	4.6
Military	35	1.2	139	4.7	103	.0088	.0083	1.17	0.7	34.8
Military	35	1.2	140	1.03	100.7	.0091	.0093	2.1	0.9	15.2
Military	35	1.2	140	5.2	104	.0089	.0093	1.6	1.4	7.2
Zone 1	35	1.2	140	5.3	104	.0162	.0161	36.6	36.9	9.6
Zone 1	35	1.2	138	1.03	100.7	.0154	.0153	46.4	48.0	8.0
Zone 1	35	1.2	139	0.8	100.6	.0142	.0131	72.2	28.7	9.6
Zone 2	35	1.2	138	4.7	103	.0194	.018	59.8	45.9	5.8
Zone 2	35	1.2	137	1.03	100.7	.0242	.0245	84.1	65.9	4.0
Zone 3	35	1.2	140	5.22	104	.0262	.0267	110 ?	13.6	8.8
Zone 3	35	1.2	NA	0	--	--	.0179	--	--	--

EMISSION DATA (CONTINUED)

Power Setting	Altitude (1000 Ft)	Mach No.	Engine Airflow (Lb/Sec)	Test Cell Airflow (Lb/Sec)	Dilution (%)	F/A Actual	F/A Emission Based	CO (g/Kg Fuel)	HC (g/Kg Fuel)	NO_x (g/Kg Fuel)
Zone 3	35	1.2	138	1.03	100.7	.027	.0275	73.2	4.9	6.4
Zone 3	35	1.2	139	4.64	103.3	.0255	.0269	129.6	28.5	6.0
Zone 4	35	1.2	137	5.24	103.8	.0450	.0520	4.9	1.2	2.3
Zone 4	35	1.2	137	1.03	101	.0363	.0387	22.2	2.0	5.1
Zone 5	35	1.2	140	5.16	104	.0598	.0648	27.2	0.8	5.0
Zone 5	35	1.2	137	0.73	100.5	.0598	.0658	22.3	1.0	2.8
Military	35	1.4	169	4.8	103	.0088	.0093	1.05	0.5	20.7
Zone 1	35	1.4	170	4.9	103	.0145	.0151	53.4	34.9	21.4
Zone 2	35	1.4	170	5.0	103	.0201	.0217	47.6	1.02	9.7
Zone 3	35	1.4	169	4.9	103	.0272	.0304	36.0	0.7	6.4
Zone 4	35	1.4	169	4.9	103	.0466	.0476	5.2	0.9	7.7
Zone 5	35	1.4	169	4.9	103	.0633	.0742	37.8	0.6	5.0
Military	35	1.6	202	NA	NA	NA	.0087	0.22	0.42	29.8
Zone 1	35	1.6	203	NA	NA	NA	.014	48.9	31.5	NA
Zone 5	35	1.6	203	NA	NA	NA	.0729	34.2	0.64	NA
Military	35	1.8	239	7.2	103	.0765	.078	1.74	0.41	32.9
Military	35	1.8	246	3.6	101.5	.0816	NA	NA	0.71	35.8
Zone 1	35	1.8	239	7.1	103	.0130	.0134	47.4	27.4	18.5

EMISSION DATA (CONTINUED)

Power Setting	Altitude (1000 Ft)	Mach No.	Engine Airflow (Lb/Sec)	Test Cell Airflow (Lb/Sec)	Dilution (%)	F/A Actual	F/A Emission Based	CO (g/Kg Fuel)	HC (g/Kg Fuel)	NO_x (g/Kg Fuel)
Zone 1	35	1.8	255	8.8	103.5	.0127	.0124	51.2	28.4	19.1
Zone 2	35	1.8	NA	7.1	NA	NA	.0191	48.8	50.1	11.7
Zone 3	35	1.8	249	8.8	103.5	.0271	.0299	6.64	0.25	10.5
Zone 3	35	1.8	237	10.2	104.3	.0256	.0291	17.1	1.28	13.5
Zone 5	35	1.8	251	5.9	102.3	.0629	.0704	28.65	0.8	9.0
Zone 5	35	1.8	235	7.2	103	.0668	.0725	25.3	0.5	9.5
Military	55	1.6	79.9	1.3	101.7	.00852	.00806	1.21	3.3	18.5
Zone 1	55	1.6	78.2	1.3	101.7	.0204	.0197	75.0	75.6	6.4
Zone 2	55	1.6	78.4	1.4	101.8	.0219	.0216	86.9	52.6	4.9
Zone 3	55	1.6	77.2	1.4	101.8	.0361	.0389	9.0	4.1	6.1
Zone 4	55	1.6	77.8	1.4	101.8	.0381	.0449	7.9	3.0	5.7
Zone 2	70	1.8	48.1	1.4	103	.0223	.0256	45.3	9.9	5.03

APPENDIX B

EQUATIONS USED FOR DATA REDUCTION

1. $$W_{CO}\ (LB/HR) = \frac{2\ \frac{CO}{10^4}\ F}{\frac{CO}{10^4} + CO_2 + \frac{C}{10^4}}$$

2. $$W_{HC}\ (LB/HR) = \frac{\frac{C}{10^4}\ F}{\frac{CO}{10^4} + CO_2 + \frac{C}{10^4}}$$

3. $$W_{NO}\ (LB/HR) = \frac{3.29\ \frac{NO}{10^4}\ F}{\frac{CO}{10^4} + CO_2 + \frac{C}{10^4}}$$

4. $$F/A_{Measured} = \frac{\frac{CO}{10^4} + CO_2 + \frac{C}{10^4}}{207 - 2\frac{CO}{10^4} - CO_2}$$

5. $$F/A_{Actual} = \frac{\text{Fuel Flow}}{\text{Engine Air Flow} + B_{Rig}\ \text{Flow}}$$

6. $$\%\ \text{Dilution} = \frac{\dot{M}_{Engine} + \dot{M}_{B_{Rig}}}{\dot{M}_{Engine}}$$

APPENDIX C

LIST OF SYMBOLS

Symbol	Definition	Unit
B_{Rig}	Test Cell Cooling Air	LB/SEC
C	Concentration of Hydrocarbon (HC) in Exhaust	ppm
CO	Concentration of CO (Carbon Monoxide)	ppm
CO_2	Concentration of CO_2 (Carbon Dioxide)	%
EI	Emission Index	g(X)/Kg Fuel
F	Mass Rate of Fuel Usage	LB/HR
F/A	Fuel to Total Air Ratio	--
HC	Concentration of Unburned Hydrocarbons	ppm
H_2O	Water Vapor	%
$\dot{M}$	Mass Rate of Airflow	LB/SEC
$\dot{M}_{Total}$	Engine Airflow Plus Test Cell Cooling Air	LB/SEC
NO	Concentration of Nitric Oxide	ppm
NO_2	Concentration of Nitrogen Dioxide	ppm
NO_x	Concentration of Nitrogen Oxide	ppm
SLS	Sea Level Static	--
W_X	Mass Emission Rate of Component X	LB/HR

FIGURE 1: PHOTOGRAPH OF SAMPLING PROBE

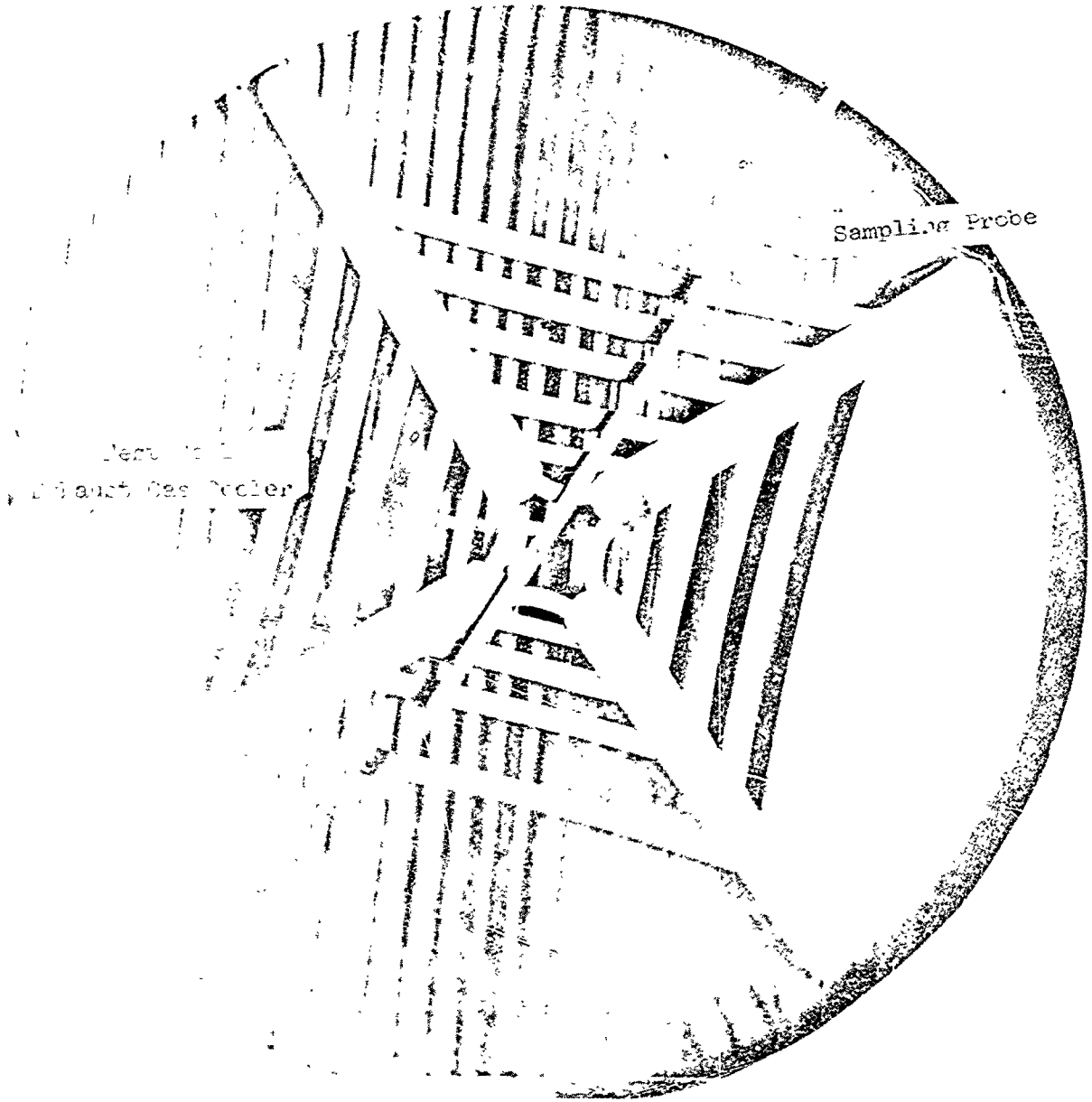
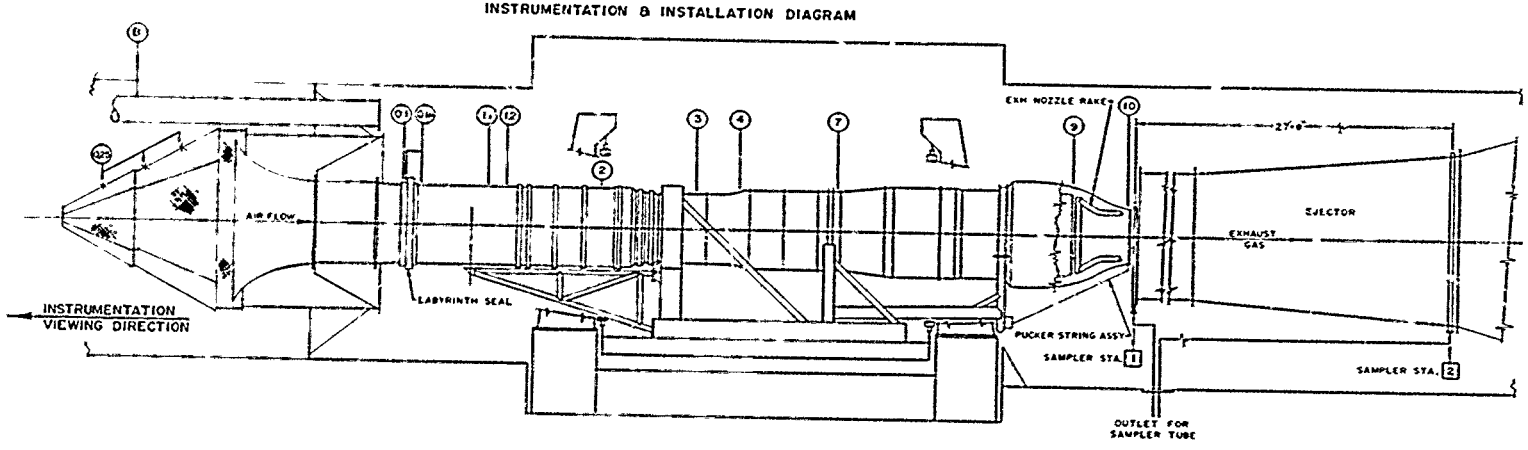
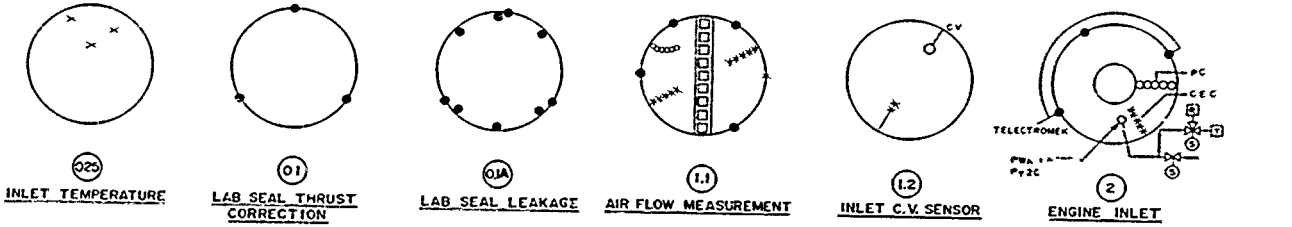
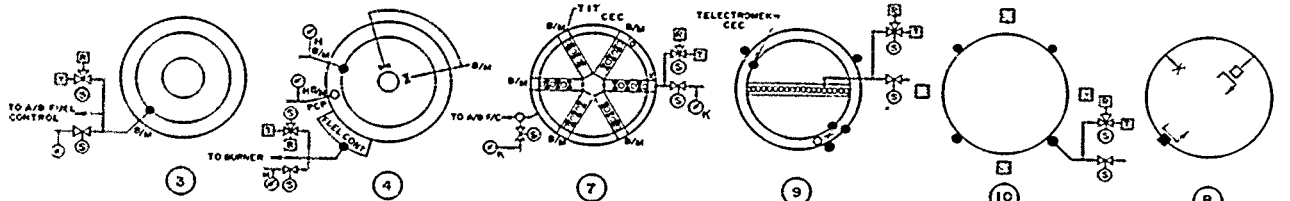


FIGURE 2: XTF30-P-412 ENGINE EXHAUST GAS EMISSION ANALYSIS TEST
INSTRUMENTATION & INSTALLATION DIAGRAM





(025) INLET TEMPERATURE
(01) LAB SEAL THRUST CORRECTION
(01A) LAB SEAL LEAKAGE
(1.1) AIR FLOW MEASUREMENT
(1.2) INLET C.V. SENSOR
(2) ENGINE INLET



(3) LOW COMPRESSOR DISCHARGE
(4) HIGH COMPRESSOR DISCHARGE
(7) TURBINE DISCHARGE
(9) EXHAUST NOZZLE ENTER
(10) EXHAUST NOZZLE EXIT
(B) "B" RIG COOLING AIR

SYMBOLS

- STATIC PRESSURE, INDIVIDUAL FINGER TYPE
- STATIC PRESSURE, WALL
- STATIC PRESSURE, LIP
- STATIC PRESSURE, STEAM HEATED
- R REFERENCE PRESSURE INPUT
- T TRANSDUCER
- HEISE GAGE
- TOTAL PRESSURE, INDIVIDUAL FINGER TYPE
- TOTAL PRESSURE, INTEGRATING TYPE
- TOTAL PRESSURE, STEAM HEATED
- TOTAL TEMPERATURE, I/C
- TOTAL TEMPERATURE, C/A
- TOTAL TEMPERATURE, CU/CN
- BASKET STATIC
- KOLLSMAN GAGE
- ROSEMOUNT TEMPERATURE
- 2-WAY SOLENOID VALVE
- 3-WAY SOLENOID VALVE
- B/M ENGINE COMPONENT

FIGURE 3: UNBURNED HYDROCARBON EMISSIONS

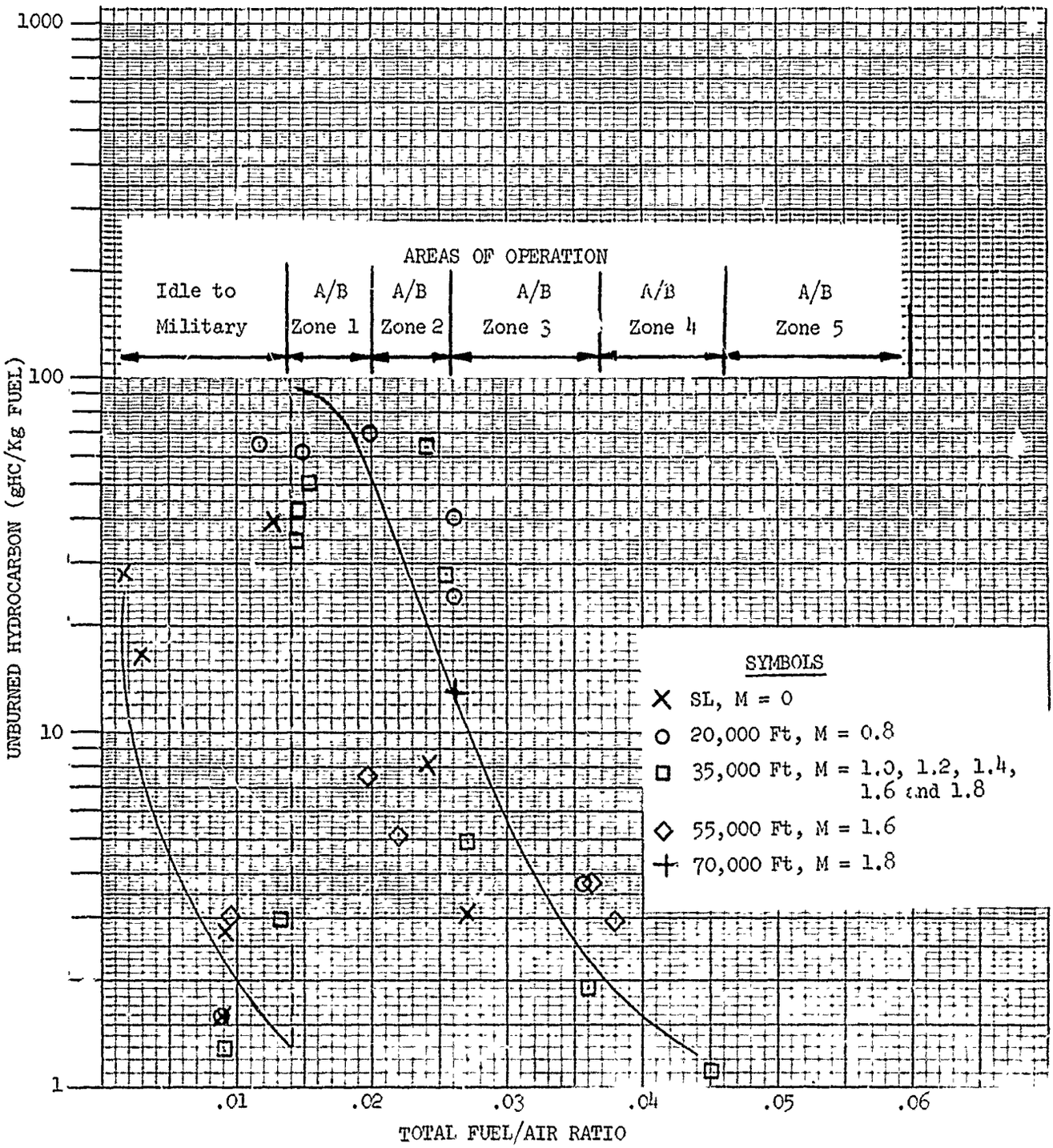


FIGURE 4: NITROGEN OXIDE EMISSIONS

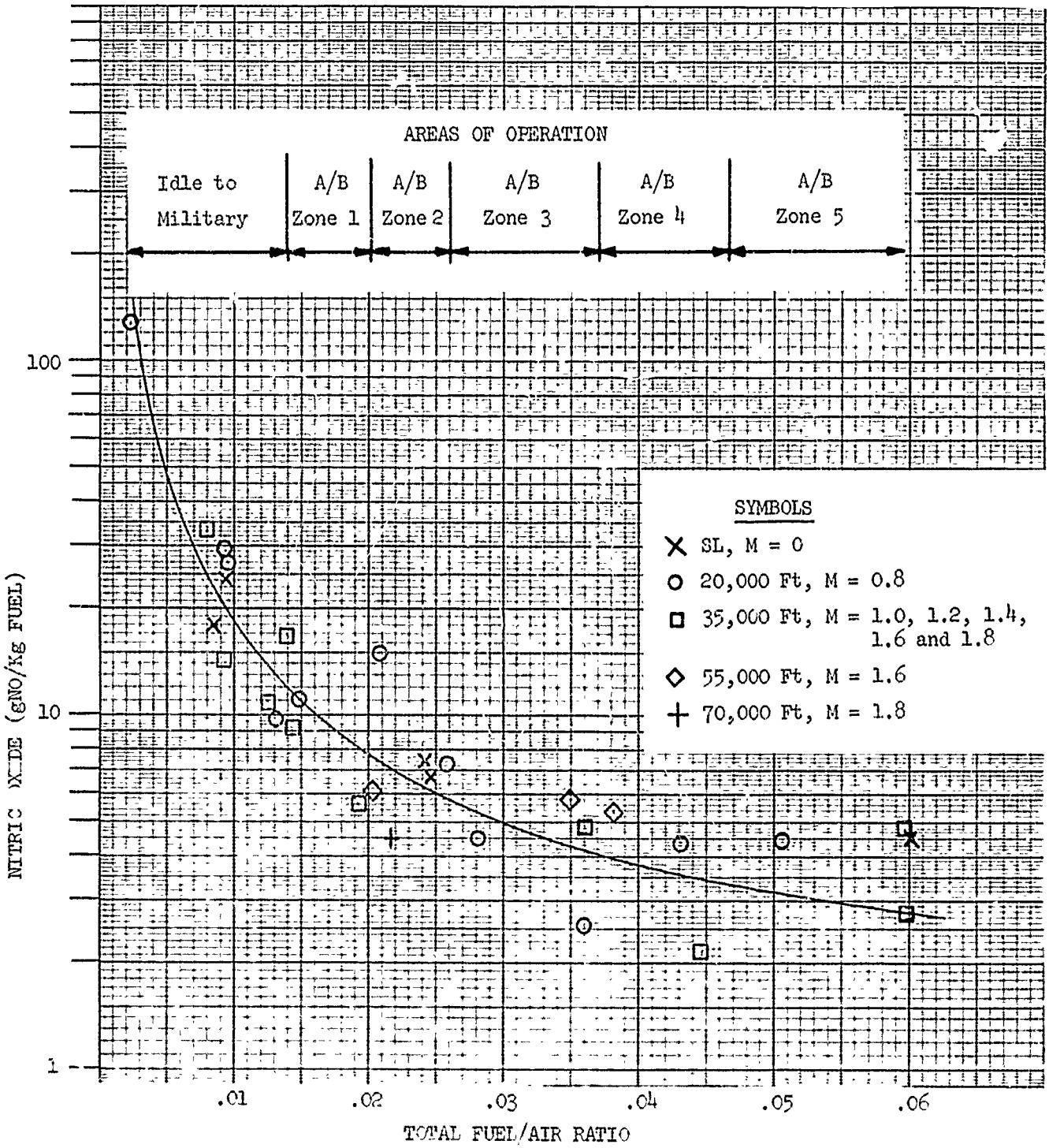


FIGURE 5: CARBON MONOXIDE EMISSIONS

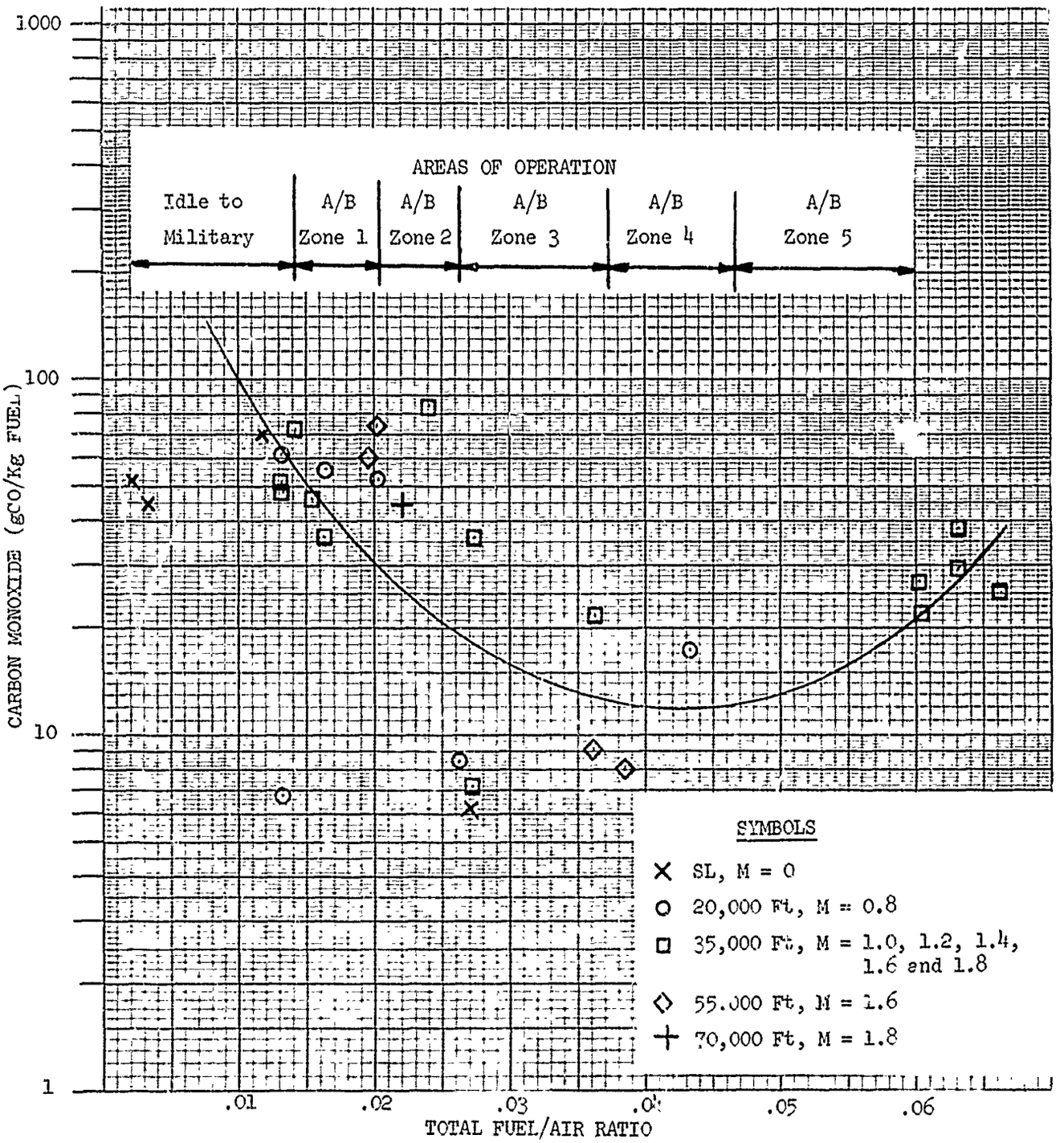


FIGURE 6: TYPICAL PARTICULATE SIZE OF JET ENGINE EXHAUST

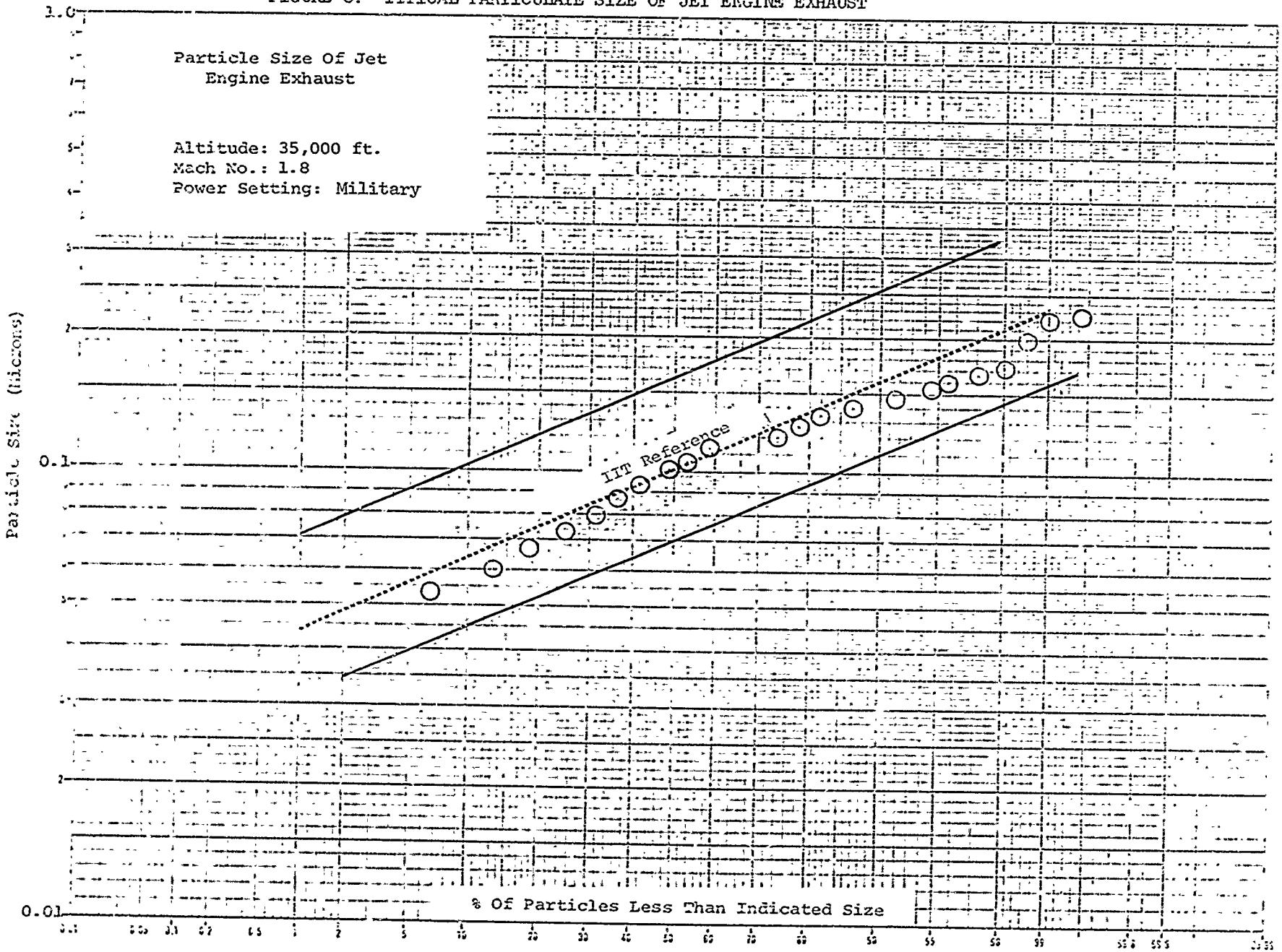


FIGURE 7: SAMPLE VALIDITY (COMPARISON OF MEASURED AND ACTUAL FUEL/AIR RATIOS)

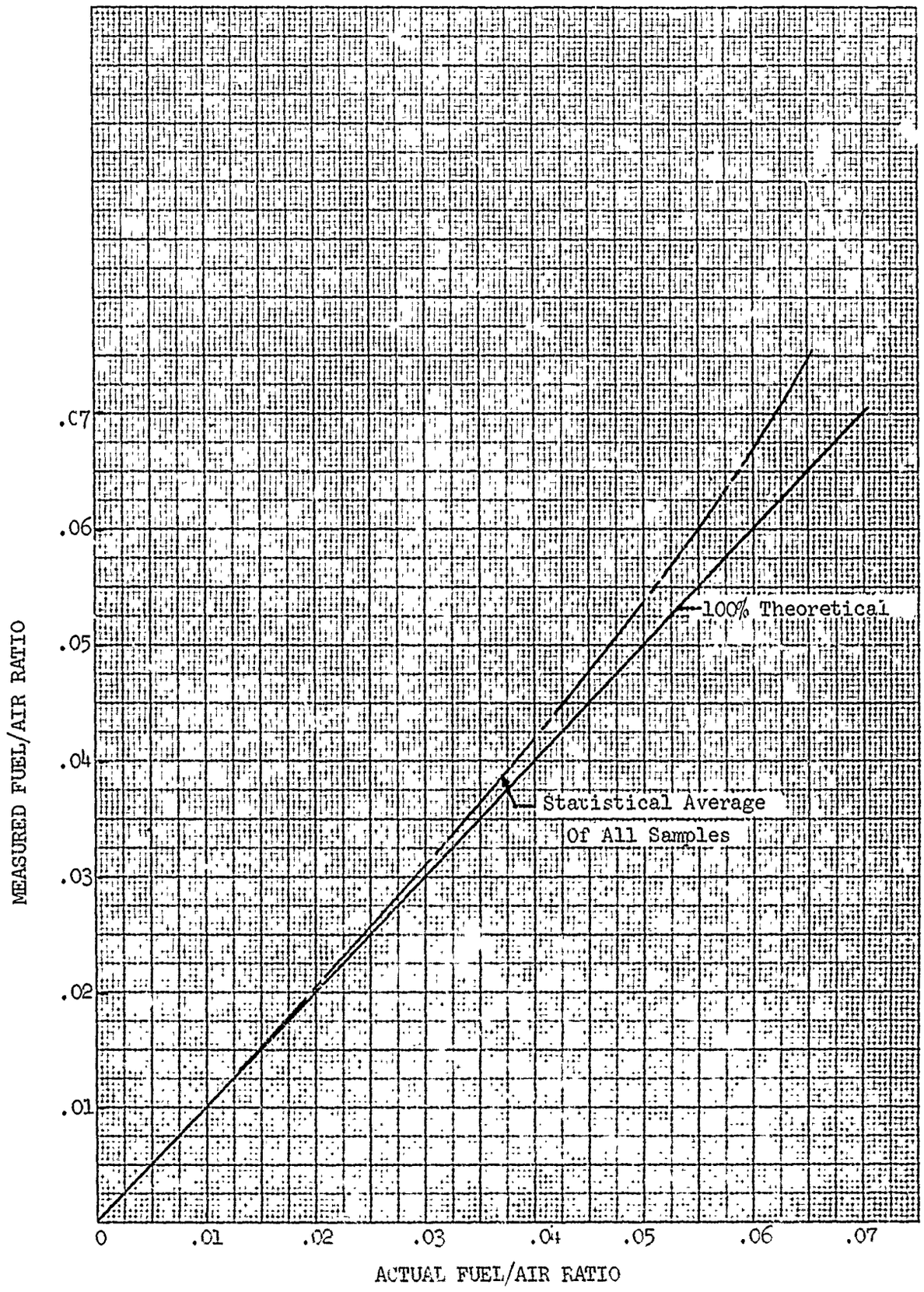
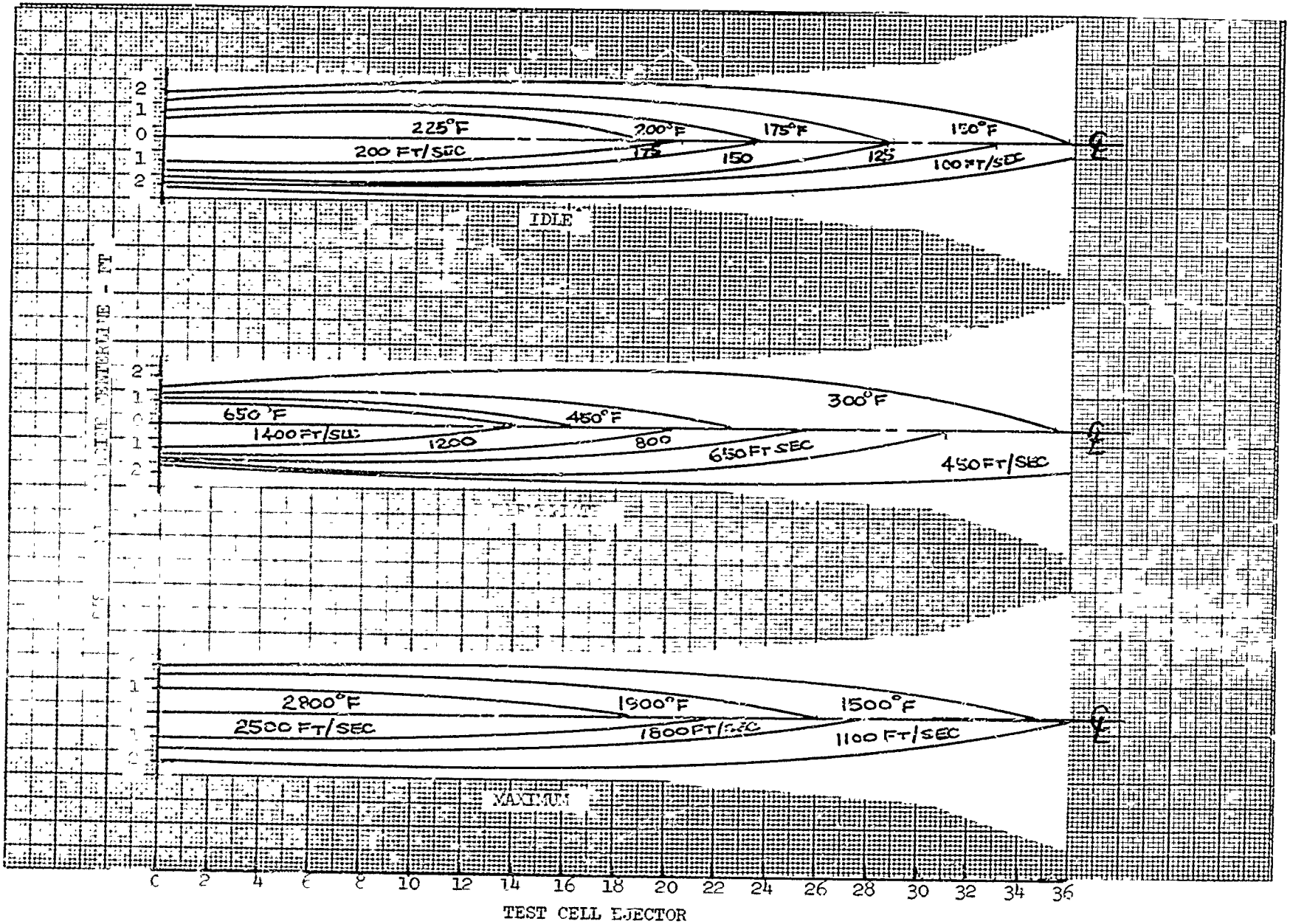


FIGURE 8: ESTIMATED JET WAKE DIAGRAM



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