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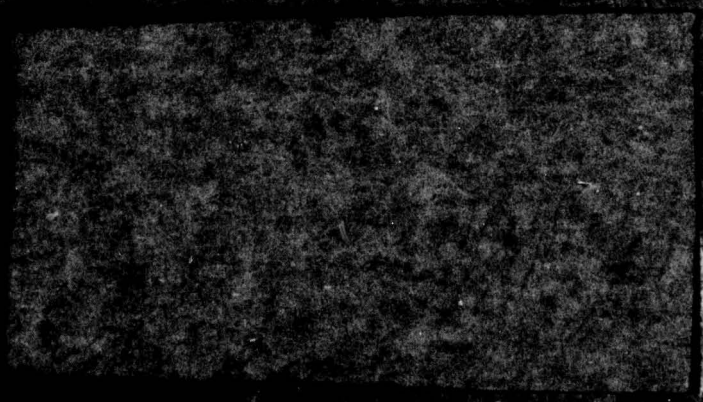
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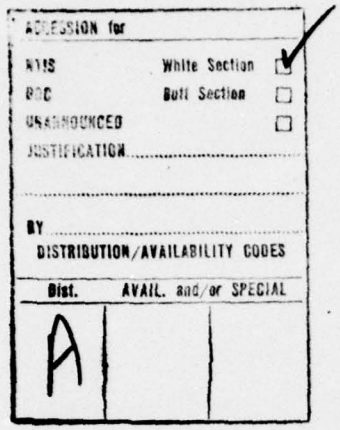
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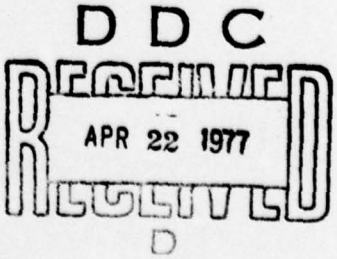


FEASIBILITY OF ELECTROSTATIC PROBES AS AN ION AND POLLUTION SENSOR IN A JET EXHAUST

THESIS

GEP/PH/71-19 Robert A. Vopalensky
Capt USAF

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Alan
by
(10) Robert A. Vopalensky B.S.
Captain USAF

Graduate Engineering Physics

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Preface

This thesis was sponsored by the Control Elements Branch (FGL) of the United States Air Force Flight Dynamics Laboratory. The subject of this thesis is a continuation in the design investigation and background knowledge which may ultimately provide the Air Force with an "instantaneous" and continuous monitor of all aircraft engines. The instantaneous feedback to an aircraft pilot may indicate (1) the efficiency of each engine in converting its fuel energy into thrust, (2) the pollution or contamination by different toxic gases each engine is generating, and (3) possible internal engine failure, hours prior to present aircraft engine control instrumentation.

The purpose of this thesis was to obtain additional data in support of prior investigation results recorded by mounting an electrostatic probe (Langmuir Probe) in the exhaust gases of a Pratt and Whitney J-57 engine. The new data is to be used in further validation of a proposed theory for the collection of charged particles by means of a metal probe placed perpendicular to the exhaust gas flow. In addition, this data is to be correlated with the amount of contamination of toxic gases expelled in the engine exhaust gases at the exit plane.

The effort discussed in this report was performed during Sept-Nov 1970. This effort was part of a continuing project and as a result of the data obtained, numerous follow-on investigations of electrostatic probe characteristics - as related to the aircraft engine exhaust environment - have been

initiated and completed. Applicable results of these later investigations, which parallel the effort documented in this report, are mentioned and referenced in this report.

In appreciation of the support which was received during the experimental phase of this effort, I wish to thank my faculty advisor, Colonel E. L. Battle, and Flight Dynamics Laboratory (FDL) advisor, Major R. P. Couch, who permitted me to undertake the investigation and then provided their help and direction. I am most grateful and deeply indebted to Capt D. Rossbach of FDL for his unending assistance and advice as technical advisor and his untiring help with the theory and data reduction. Also appreciated was the assistance provided by other FDL personnel, especially that of Mr. V. McGirr, in obtaining for me the necessary supplies and equipment and most of all for keeping the test equipment in working order. I wish to express deep gratitude to Mr. J. B. Gisclard of the Atmosphere Control Laboratory (FDFE) of the Air Force Flight Dynamics Laboratory, who provided guidance and practical approaches in the evaluation of jet exhaust gas analysis through volumetric chemical techniques. Mr. Gisclard with his multitude of gas analysis ideas, interest and timely encouragement, made this phase of the thesis a rewarding and maturing experience and I am most grateful for his leadership.

Thanks is also extended to (AFAPL) which provided the J-57 engines and facility for this evaluation. I would like to express my appreciation to Mr. J. B. Schrand and Mr. F. P. Kiger who provided valuable assistance in acquiring the data.

Finally, I would like to thank my wife and children for the sacrifices they have made during my entire course of study.

Dayton, Ohio
December 1976

Robert A. Vopalensky

CONTENTS

	Page
Preface	ii
List of Figures	vi
List of Tables	vi
Abstract	vii
I. Introduction	1
Background	2
Scope	3
Approach	3
II. Theoretical Considerations	6
Jet Exhaust Ionization	6
Probe Theory	7
Jet Exhaust Emissions	8
III. Experimental Apparatus and Instrumentation	14
Description of the J-57 Engine Facilities	14
Probe Assembly	14
Gas Sampling Assembly	18
Gas Collection System	18
Probe Trace Assembly	20
IV. Experimental Procedure	22
Electrostatic Probe Circuit System	22
J-57 I/V Characteristics	23
J-57 Operation Cycle	25
Gas Sampling	26
Gas Collection	26
V. Results and Discussion	28
VI. Recommendations	45
Bibliography	46
Appendix A: Laboratory Procedures for NO_2 Analysis	47
Appendix B: Test Equipment Listing	60

List of Figures

Figure		Page
1	J-57 Probe Assembly	16
2	Electrostatic Probe	17
3	Initial Exhaust Gas Sampling System	19
4	Probe Trace Electronics	21
5	Electro-Optical Isolator	24
6	J-57 Exhaust Sampling System (Rear View)	27
7	J-57 I/V Trace	31
8	Number Density vs Mixture Ratio	33
9	NO_2 Concentrations vs V_f	34
10	NO_2 Concentrations vs Thrust	35
11	Anomalous D.C. Shifts	36
12	I-V Traces with Spikes	38
13	V_f vs Thrust	41
14	Positive Plasma 37 Micron Nickel	42

List of Tables

Table		Page
I	Engine Run Schedule	25

Abstract

The purpose of this thesis was to experimentally investigate the feasibility of electrostatic probes in determining the ionic number density correlation with pollution concentration in the subsonic J-57 jet engine exhaust gases. A cylindrical electrostatic probe inserted normal to the gas flow was used for this experiment. The ionic number density provides an indication of a jet engines over-all efficiency and specifically the efficiency in the combustion chamber region. The pollution concentration is also indicative of an engine's over-all efficiency.

A major contributor to atmospheric contamination or pollution was measured by an off-line grab sampling technique and the application of basic chemical methods. The primary exhaust gas pollutant evaluated was oxide of nitrogen (NO_2), which was shown to correlate with thrust (expected) and, under certain conditions, D.C. potential.

Two new methods of predicting jet engine failure seem possible as a result of the coincidental failure of two engines which were being monitored. The first, counting current "spikes", has been investigated by other authors. The second, observing D.C. shifts, has been overlooked until now, and is reported as a new potential tool.

I. INTRODUCTION

The purpose of this experimental investigation was to examine the electrical characteristics of a jet exhaust with an electrostatic probe (Langmuir Probes). The current-voltage characteristics of the probe are then compared to an exhaust gas property in order to determine the feasibility of using electrostatic probes as contaminant monitoring devices within jet exhausts. This investigation consisted of obtaining current-voltage (I-V) characteristics at various thrust and fuel mixtures and at the same time sampling the exhaust gases. An additional goal was to examine in more detail the previously established correlation of ion number density with mixture ratio.

The contaminants from aircraft engine exhausts are one contributing factor to the problem of air pollution. As filtering devices and possible new fuels are developed to counter this problem, there will be a need for monitoring instrumentation to insure that the exhaust remains free of pollutants. Electrostatic probes offer one possibility as a detector which could be used to monitor exhaust pollution on a continuous basis. The probes, which function as electron and ion sensors, could be placed within the jet exhausts and used to detect pollutants when they are present. The final goal is an instrument which could be used on all Air Force operational jet aircraft.

While attempting this primary objective of pollution monitoring, it was discovered that the electrostatic signature of jet engines changed significantly prior to two failures. Thus, one of the major conclusions is that electrostatic probes can be useful in monitoring engine health.

Background

An electrostatic probe is a small metallic electrode which is used in plasma diagnostics. Through appropriate circuitry the probe is made positive or negative with respect to some fixed potential. As the probe voltage is varied, the current collected by the probe varies in some manner and the resulting I-V curve is called the probe characteristic.

The phenomena governing the behavior of and the techniques of using electrostatic or Langmuir probes immersed in a plasma have been examined and expanded for many decades. Many reasonable and accurate theories of interpreting the probe characteristic in different plasma regions have been developed. Even though probes have been used since the eighteen-nineties, many aspects of their use are still not completely understood.

The majority of the theories and experimental efforts have centered around a collisionless plasma. Work with probes in collision dominated plasmas has only occurred within the last two decades. Extensions into the realm of continum flow of weakly ionized gases have only been investigated in the last decade (Ref. 1, 2, 3).

Recently, Langmuir-type probes have been used to give information about jet engine performance. Research conducted by Fowler (Ref. 4) indicates that optimum engine efficiency can be measured directly with an electrostatic probe. With a fixed negative potential (probe collecting primarily positive ions) the probe current was monitored as a function of engine thrust. The data show a minimum in the probe current at a thrust where the Specific Fuel Consumption (SFC) is a maximum. In addition, the results show that the floating potential of the probe (i.e., the voltage at which the probe collects zero current) also varies with engine power. This phenomenom is not yet understood, but it is suggested that this result occurs because the probe is being struck by charged carbon soot particles, heavy nitrous oxide ions and/or, large long chain hydrocarbon molecules which are present in the exhaust in varying amounts at the different thrust values.

Scope

This project involved the use of a J-57 turbojet engine (without afterburner) exhaust source for analysis.

The theory used in the evaluation of the probe data was developed in Fowler's work (Ref. 4). This same theory is used in this study.

Approach

The possible approaches which could lead to practical methods of contamination sensing via electrostatic probes are:

(a) to study the correlation of current at various fixed potentials as a function of engine thrust and fuel mixtures while monitoring particulate, hydrocarbon, NO and CO levels in the exhaust, (b) to study the correlation of floating potential as a function of engine thrust and fuel mixtures while monitoring particulate, hydrocarbon, NO and CO levels, (c) to study ionization characteristics for highly negative and positive probes (of the order of a thousand volts) as a function of engine thrust and fuel mixtures while monitoring particulate, hydrocarbon, NO and CO levels, (d) to determine if electrical noise in the probe characteristic is related to the presence of particulates and/or hydrocarbons, and (e) to study the time-varying probe work function and probe characteristic hysteresis to determine if such hysteresis can be used as a quantitative measure of contaminants.

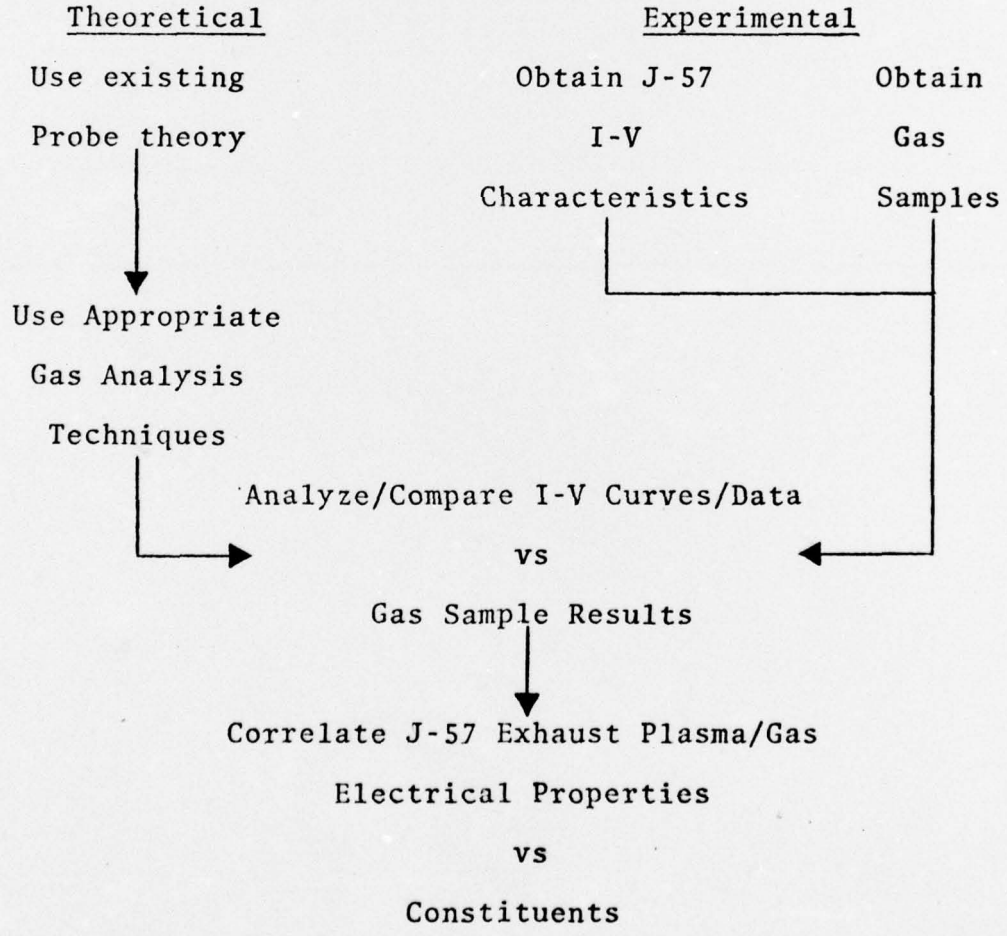
Although all of these are useful efforts, the primary goals for this effort were limited by practical considerations and were: (a) to obtain experimental electrostatic probe characteristic data under a variety of engine operating conditions and/or gas dynamic conditions, and (b) to obtain data samples of specific exhaust gas constituents at various power settings.

Based upon this data, a correlation of the electrical properties of the exhaust with the amounts of nitric oxide (NO) and nitrogen dioxide (NO_2) would then indicate if a feasible method of sensing contamination by means of an electrostatic probe existed.

Experimental probe characteristic (i.e., I-V traces) data and gas samples were obtained for various engine operating conditions in the exhaust of a J-57 Pratt and Whitney jet engine. The probe response data were then analyzed and compared to exhaust gas composition at the various power settings.

The experimental data were collected in a J-57 engine test cell with the exhaust gases being grab sampled and then analyzed using standard chemical methods.

The selected approach is shown schematically below.



II. THEORETICAL CONSIDERATIONS

The major development of the probe theory utilized in this report to interpret the measured current - voltage characteristics of a subsonic jet exhaust is detailed in Fowler's thesis (Ref. 4). His main philosophy was to rely as much as possible on existing probe theories and to extend them only as required to meet the special conditions of a jet exhaust.

The results of his probe theory are applicable to this investigation and were used in the analysis of probe response data.

This section provides a brief review of the predominant ions in the jet exhaust gases and the probe theory, along with a background summary of the expected principal combustion by-products in the jet exhaust gases.

Jet Exhaust Ionization

As mentioned by Fowler (Ref. 4), the main production of ions in hydrocarbon flames is by non-thermal processes and this has been extensively discussed in recent years. The non-thermal origin is indicated by the abundance of these ions in the reaction zone, which is approximately one million times the concentration deduced from the Saha equation. This phenomena is therefore ascribed to chemi-ionization - i.e., non equilibrium ionization which occurs because of the absence of chemical equilibrium in the reaction zone.

When radicals are present in amounts several orders of magnitude above equilibrium, then excess ionization occurs, and stable products are formed. As a result of this, Fowler (Ref. 4) indicates that the dominant ion species occurring in the hydrocarbon flame of an aircraft's combustion chamber, are H_3O^+ (Oxonium) as the predominant positive ion and OH^- as the predominant negative ion. The recombination rate constant is sufficiently low to explain persistence of H_3O^+ some distance after the reaction zone. The concentration of electrons is negligible compared to the ion concentration.

Probe Theory

The Fowler formulation (Ref. 4) is based upon Lam's theory (Ref. 1) which is a combination of the continuity, flux, and Poisson's equations. Lam examined the case when $R\alpha^2 << 1$ in a steady flow of weakly ionized incompressible continuum gas about an arbitrary solid body with absorbing surfaces. Fowler uses $R\alpha^2 >> 1$, as is the situation in jet exhaust gases, and then proceeds to develop his theory. The above parameters are:

Electric Reynolds Number $R = \dfrac{u_\infty r_p}{D_+}$

$$\alpha^2 = \left(\frac{\lambda_d}{r_p}\right)^2$$

$$\lambda_d = \left(\frac{K T_e}{4\pi n_{e\infty} e^2}\right)^{1/2}$$

Free Stream Velocity u_∞

Probe Radius r_p

Ion Diffusion Coefficient	$D+$
Debye-Length	λ_d
Boltzmann's Constant	k
Electron Temperature	T_e
Free Stream Electron Number Density	Ne_∞
Electron Charge	e

Based upon Fowler's postulated probe theory model for flux or ions impacting the probe,

$$n = \frac{I/V}{\mu_+ \pi L e}$$

the following condition is required for the theory to be valid,

$$\frac{\mu_+ E}{u_\infty} << 1$$

Ion Number Density	n
Measured Current	I
Probe Voltage	V
Positive Ion Mobility	μ_+
Electron Charge	e
Electric Field (Around Probe)	E
Free Stream Velocity	u_∞

Jet Exhaust Emissions

The primary pollutants emitted from jet turbine engine exhaust gases are NO, CO, unburned hydrocarbons and particulates.

For comparison (Ref. 5), the pollutants of interest for the aircraft piston engine and the automobile are comparable in total amounts of pollutants emitted. However, the exhaust concentration of all combustion products are correspondingly less in the turbine engine than the piston type engines. This is based upon the fact that a turbine engine operates at different air-fuel ratios and also because of differences in fuels and combustion chamber operations. The piston engine operates at approximately the stoichiometrically correct mixture ratio, while the turbojet uses large quantities of excess air.

Due to the comparatively rich air-fuel ratios in aircraft piston engines, the exhaust gases contain comparatively high concentrations of CO, hydrocarbons, and low concentrations of NO and particulates. For the turbine engine the concentrations of CO and hydrocarbon are very low during all flight operations and higher by factors of 50 to 100 during ground operations (idle). On the other hand, concentrations of NO and particulates are greater during flight operations than during ground operations. In a turbine engine, the particulate consist mainly of carbon (soot). A detailed composition of hydrocarbons from turbine engines is not known.

Other emissions, but only of secondary concern due to small quantities emitted or other characteristics, will now be mentioned and the reason(s) for their unimportance in this discussion. The emission of SO_2 by aircraft is a secondary concern because the sulfur content in aviation fuel (JP-4)

is low. Carbon dioxide (CO_2) is not regarded as a pollutant from the view point of local air quality, since it produces adverse physiological effects only at relatively high concentrations and because biological and geochemical processes are known to provide a natural disposal system. CO_2 is a colorless, odorless gas and is a normal constituent of exhaust gases from all combustion systems which burn carbonaceous or hydrocarbon fuels. The actual smoke and odor emission contained in aircraft engines exhaust produce adverse sensory effects and are regarded as having an esthetic impact but are not regarded as hazardous to health. Aldehydes (i.e., formaldehyde) are also emitted which, at small concentrations, have an effect on humans in that they are extremely irritating to the eyes and to mucous membranes.

Carbon monoxide (CO) is of interest as an air contaminant mainly because of its toxic properties. It is a colorless, odorless gas which is chemically stable and is oxidized to CO_2 in the atmosphere, but at very slow rates.

Hydrocarbons describe substances consisting mainly of carbon and hydrogen with small amounts of oxygen and nitrogen. The majority of hydrocarbon materials are not directly harmful at low concentrations, but are converted to harmful materials through photochemical reactions. The primary reaction responsible for this phenomena is HC + NO + sunlight equals smog.

As mentioned above, the emissions of CO and hydrocarbons are particularly high during idle and taxi operations, while NO and particulate emissions are usually greatest during

takeoff and landing. It is commonly believed (Ref. 6) that the formation of particulates occurs in the rich primary combustion zone of the combustor while NO is formed in near-equilibrium proportions in the combustion chamber but does not reconvert to N_2 and O_2 in the subsequent expansion through the turbine. The excessive CO and hydrocarbons during idle are not a result of a rich over-all mixture, as is encountered in the automotive engine, but occur with low over-all equivalence ratios of about 0.1 due to non-equilibrium processes. Equivalence ratio is defined as follows:

$$\text{Equivalence Ratio} = \phi = \frac{(\text{Fuel/Air})\ \text{actual}}{(\text{Fuel/Air})\ \text{stoichiometric}}$$

$\phi = 1$ Represents Stoichiometric burning

$\phi < 1$ Represents Air Rich Mixtures

Although additional research remains to be done in theoretically and experimental understanding the combustion process in the primary and secondary zone of a turbine engine combustor, considerable information exists in the literature. As noted in reference 7, experimental studies of exhaust compositions and theoretical considerations of combustor conditions have led to the conclusion that the level of NO is fixed by kinetic processes occurring in the combustion chamber. It is hypothesized that no change in concentration occurs in the turbine or nozzle expansion processes of gas turbines. Chemical kinetic considerations showed concentration to be a strong (exponential) function of the maximum combustor gas temperature. Because of the fact that the NO level can be assumed constant upon exit from the combustor

area, it is postulated that a correlation could be established between an electrostatic probe response and the amount of oxides of nitrogen (NO_x) in the exhaust because both depend on flame temperature. The amount of NO_x (ppm) should therefore, correlate with number density which has already (Ref. 4) been shown to correlate with equivalence ratio. The equivalence ratio could then be used in a kinetic model which predicts nitric oxide behavior in the combustion zone and from this a determination of the mass fraction of nitric oxide could be obtained (Ref. 6). Also a determination of the combustor temperature could be made. It is noted that the characteristic formation time is a strong function of temperature, but a weak function of equivalence ratio. Also, several investigators and engine manufacturers have measured nitric oxide concentrations in jet engine exhausts. The measured exhaust nitric oxide concentrations were about 0.1 times the equilibrium values corresponding to combustion of a stoichiometric mixture of compressor air and fuel which approximates conditions in the primary zone. The measured concentrations may be greater or less than the NO equilibrium concentration at combustor exit, depending on the details of the combustor. The measured concentrations did not correlate satisfactorily with over-all engine equivalence ratio, though for a given engine increasing the power level (and hence equivalence ratio) from idle to takeoff did increase the exhaust nitric oxide level. However, using a preliminary model (Ref. 6) and conditions appropriate for a jet engine

combustor, the calculated exhaust NO mass fraction was 1.2×10^{-4} and the measured value was $.9 \times 10^{-4}$.

The model mentioned above assumes simple flow patterns for the primary and secondary zones to show which parts of the combustor are most important in the nitric oxide formation process; however, before realistic kinetic calculations for a complete combustor can be carried out, a detailed thermodynamic and fluid dynamic model of the primary zone must be developed (Ref. 6).

III. EXPERIMENTAL APPARATUS AND INSTRUMENTATION

The description of the experimental phase of this project is divided into two major sections. Section III will provide a general view of the experimental apparatus used and the testing environment encountered during the data acquisition phase. Section IV will describe the experimental procedure used to obtain the required data.

Description of the J-57 Engine Facilities

The J-57 conventional turbojet engines studied in the experiments were located in test cell "C" of Building 71 in area "B" of Wright-Patterson Air Force Base. These engines are used for oil qualification tests conducted by the Air Force Aero-Propulsion Laboratory. Each engine was scheduled to operate for 100 hours (5 hours per day) before scheduled disassembly for inspection.

Three main data acquistion devices were required in order to accomplish the thesis objectives. The devices were probes and their associated probe mount, a collection device to sample the exhaust gases and a high voltage probe trace system.

Probe Assembly

To position the thermocouples, pressure probes, gas collection probe and electrostatic probes in the exhaust of the J-57, it was necessary to construct a probe mount. This

mount allowed 360 degree coverage of the exhaust plane and variation of the distance from the exit plane for each of the different measurements made on the exhaust gases. A typical rear view is shown in Figure 1.

Standard Air Force J-57 engine chromel-alumel thermocouples were used. They were connected to a Honeywell (Type K) thermocouple meter in the main control room, through a Type K and T junction box, with chromel-alumel wires.

The pitot tubes (total and static) were connected to 60" Hg manometers located in the test room.

The electrostatic probes were 1/4 inch diameter stainless steel rods mounted in alumina tubing. The alumina tubing was also insulated with 1/4 inch thick teflon rings placed inside the mounting clamps. The probes were electrically connected to a selectable, six input relay box attached to the probe mount. The relay box contained a low leakage 6PST 26 VDC relay providing a capability for six inputs. The relay box was electrically connected to the main control panel in the control room by a shielded Belden triaxial cable. This cable was used to avoid extraneous noise and leakage. The design of the first probe is shown in Fowler's thesis (Ref. 4). A second electrostatic probe was built to provide a greater degree of experimental flexibility in varying the length of the probe exposed to the exhaust gas flow (Fig. 2).

All wires and lines from the engine to the main control panel had to be approximately 40 feet in length due to a limited number of access ports in the 12 inch thick cement

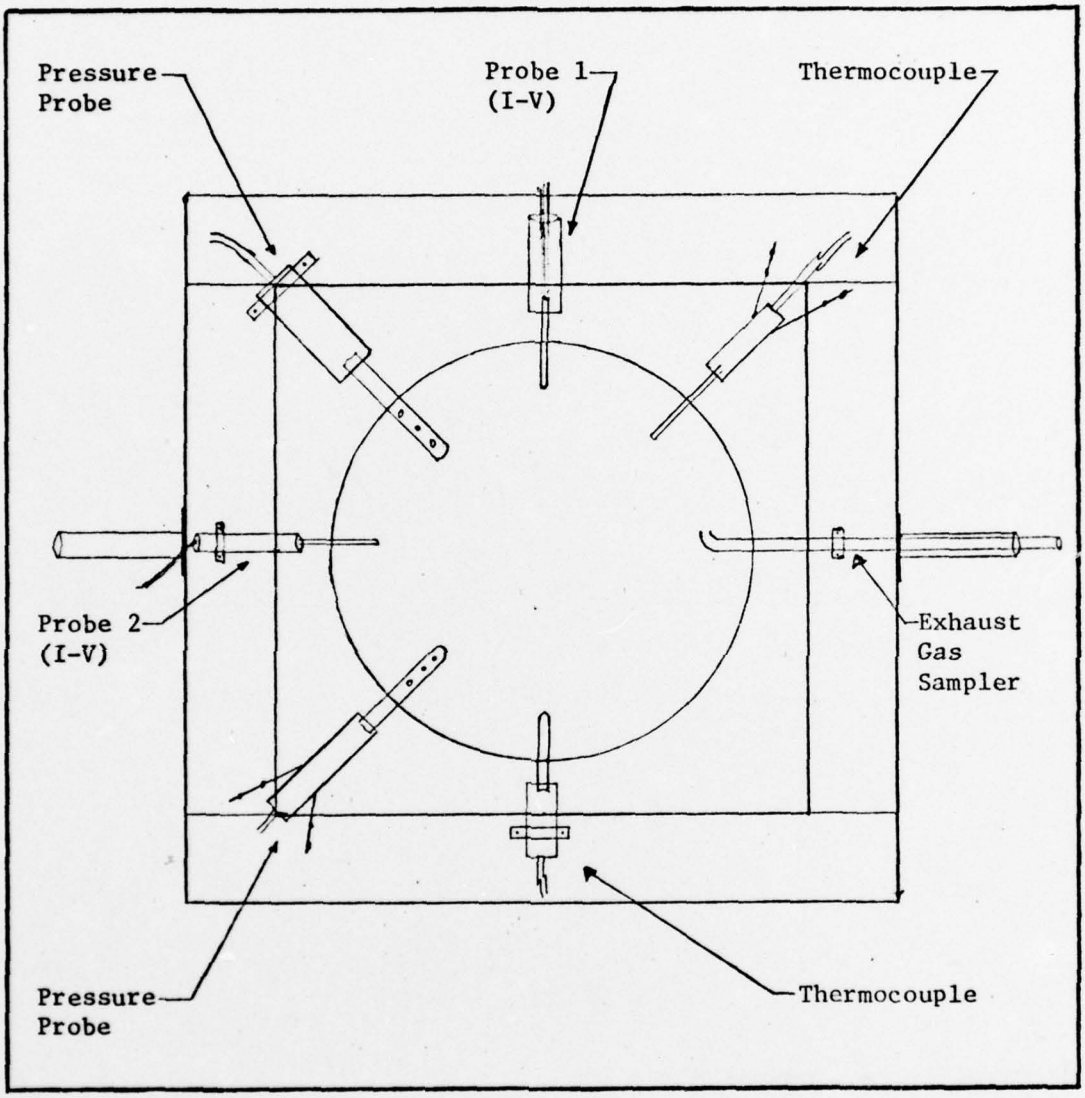


Figure 1. J-57 Probe Assembly

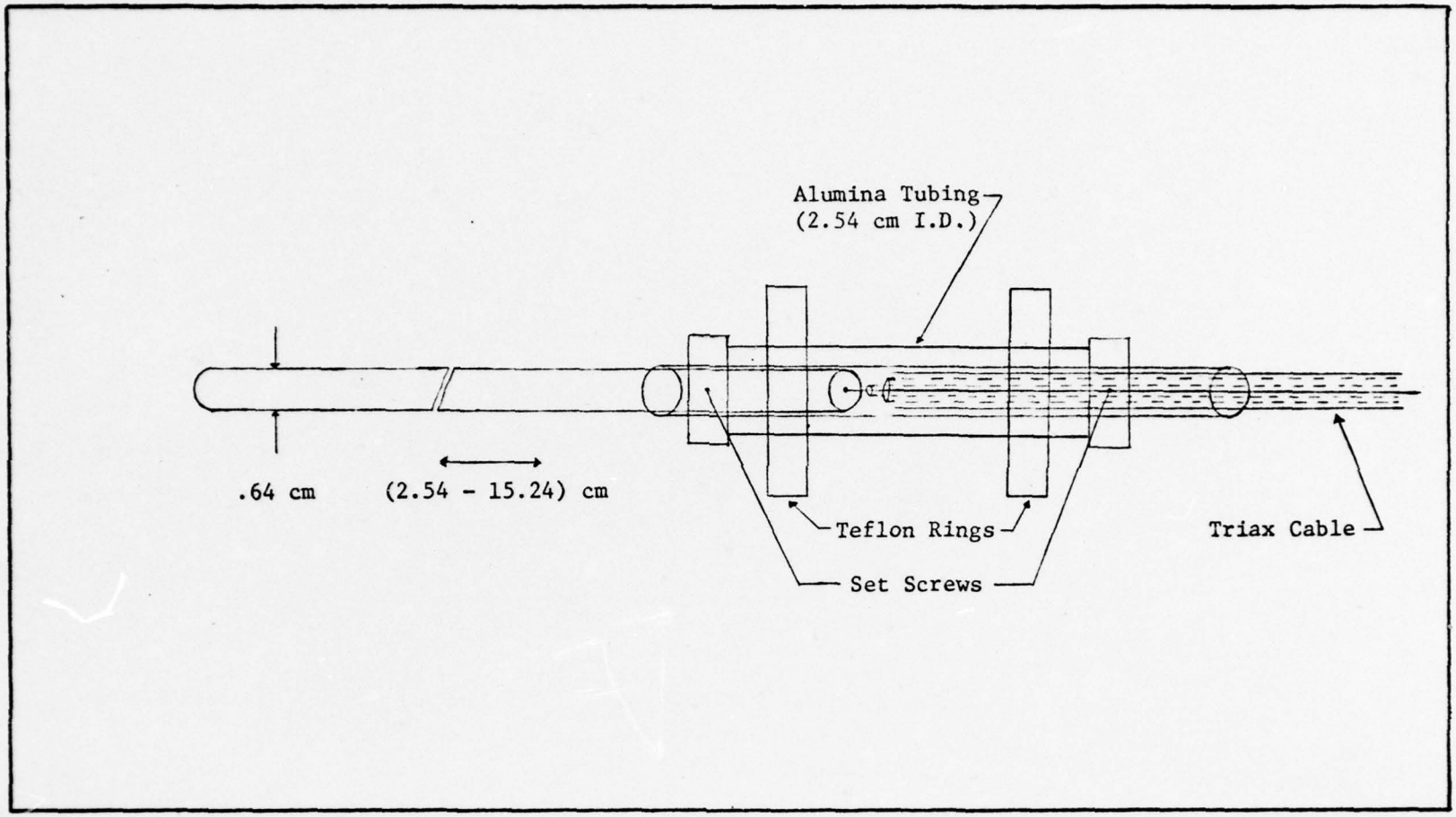


Figure 2. Electrostatic Probe

wall separating the control room and engine. All wires except the thermocouple wires were placed in a 1-inch expandable braid-shield which was used as a common ground between the engine and the main control room.

Gas Sampling Assembly

The initial attempt at exhaust gas sampling used a 1/2 inch stainless steel tube located approximately 3 feet from the exit plane with 1/16 inch holes every 2 inches. The gases were ducted with stainless steel tubing to a sampling manifold located approximately 20 feet from the exhaust area as shown in Figure 3. Due to the exposed cross-sectional area of the tube and the force and heat of the exhaust gases at maximum thrust, a bow developed in the tube which prevented a uniform cross-sectional sampling of the entire exit plane. The 1/2 inch tube was replaced by a 1/4 inch tube with the same result. A reinforcement bar was added behind the tube, but this again failed to withstand the tremendous heat and pressure. Finally, sampling tubes similar to a simple pitot probe were inserted into the exhaust and secured directly to the probe mount. This proved to be the most successful and controllable method for gas sampling.

Gas Collection System

The gas collection hardware for the jet engine exhaust was fabricated from off-the-shelf items and consisted of the following: 50cc sterile plastic disposable syringes, stain-

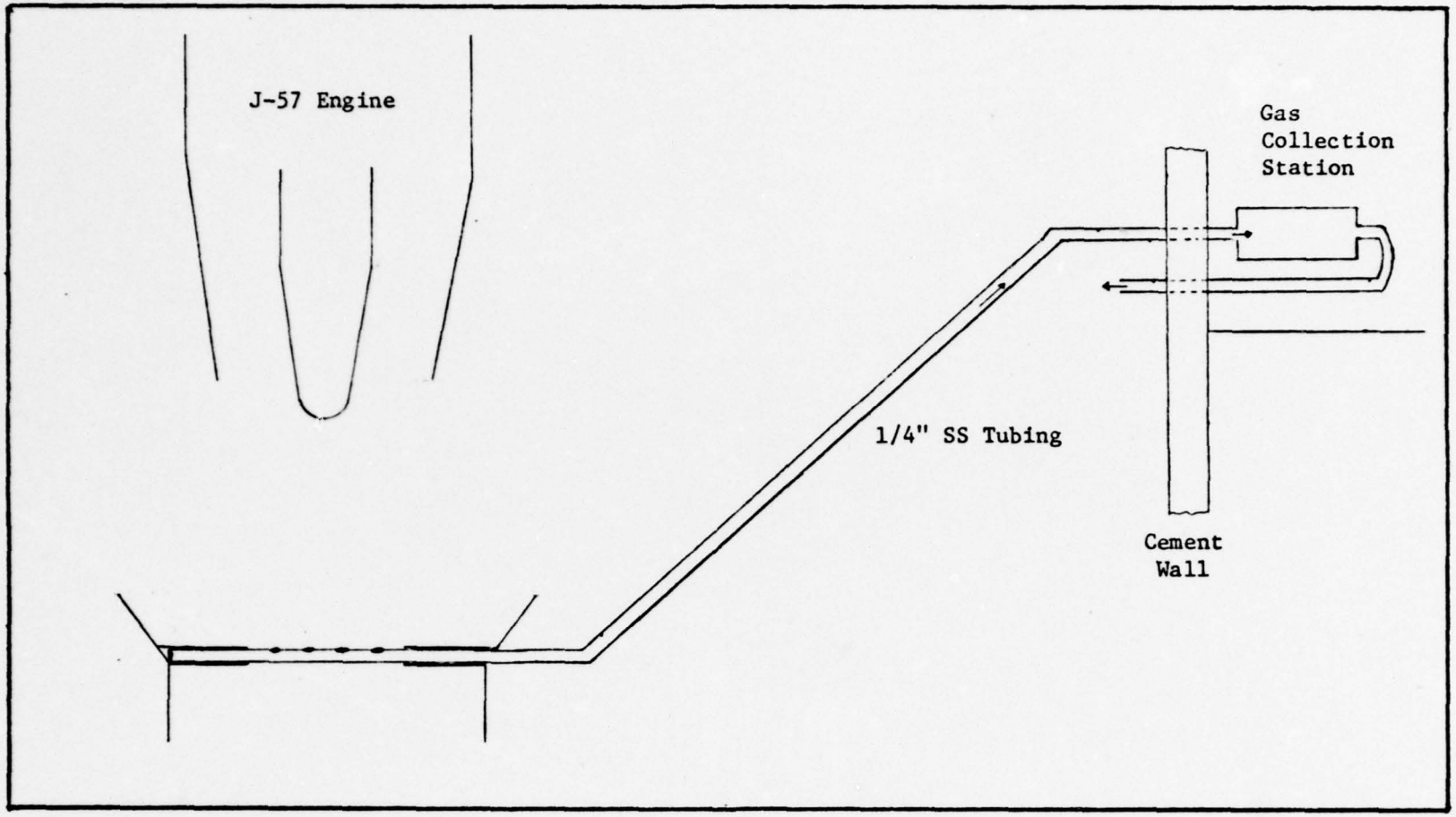


Figure 3. Initial Exhaust Gas Sampling System

less steel needles, 20 ml beaker, glass sample collection bottles, reagents, assorted tubing, pitot tubes and valves. The syringes were the primary collection device used in the grab sampling of the exhaust gases. The technique used is described in the next section.

Probe Trace Assembly

The current-voltage (I-V) electronic probe trace circuitry is shown in Figure 4. The probe current was measured with a Keithley 600 A electrometer whose output was coupled to the Y-axis of an X-Y recorder. The sweep voltage rate was controlled by the horizontal sweep output of an oscilloscope, and was monitored by a digital voltmeter and recorded on the X-axis of the X-Y recorder.

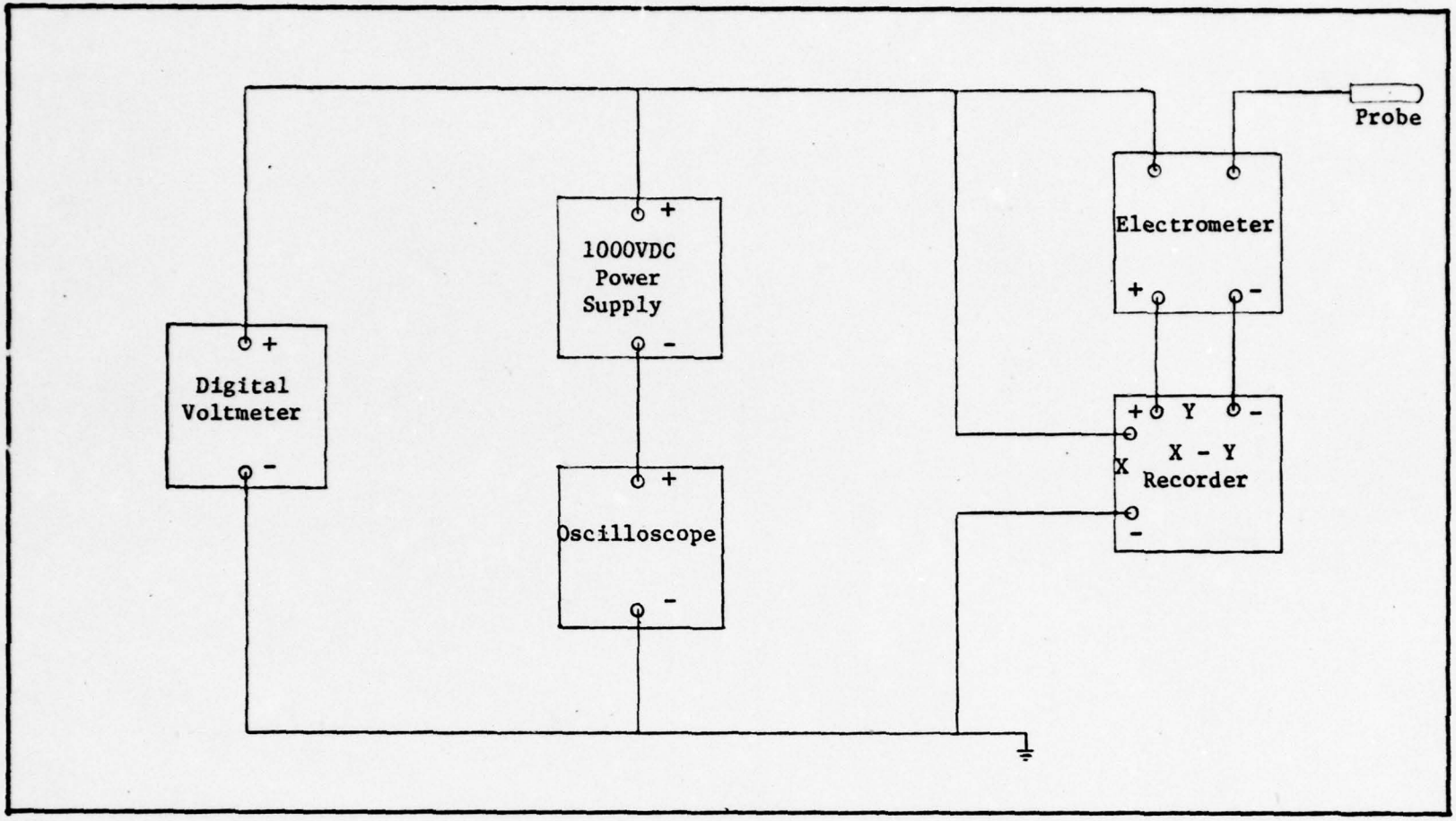


Figure 4. Probe Trace Electronics

IV. EXPERIMENTAL PROCEDURE

The experimental phase of this project had three objectives. The first objective was to design a probe circuit system capable of applying to the probe large and small voltage variations about floating potential. The system would provide additional data points in regions close to zero ($\pm$ 5 volts, $\pm$ 50 volts) to verify a slight deviation from linearity observed in the probe traces taken by Fowler (Ref. 4), and at the extremes of the voltage range ($\pm$ 1000 volts) to examine possible breakdown phenomena and/or current saturation.

The second objective was to obtain experimental current-voltage (I-V) probe characteristics using a cylindrical Langmuir probe in a J-57 engine exhaust. Reduction of the current-voltage data was then to be accomplished using the theory discussed in Section II.

The third objective was to determine the amount of contaminants or pollutants in the engine exhaust gases by an off-line grab sampling technique.

Electrostatic Probe Circuit System

To achieve the first objective a probe circuit was designed which provided an automatic, controllable and variable-voltage sweep circuit that would bias the probe over a wide voltage range of $\pm$ 1000 volts. The initial probe circuit shown in figure 4 was used for voltages up to about 200 volts. However, when going above 200 volts, unusual traces occurred due to internal leakage effects from the recorder

output. To eliminate the effects of the low common mode rejection, an optical isolator was constructed using a photo-diode photon coupled to a light emitting diode as the "line". This procedure allowed the X-Y recorder to be slaved to the Keithley electrometer at potentials of a thousand volts or more, provided suitable insulation for the operator and some shielding were installed. Since the output of the light emitting diode was approximately linear with current (as opposed to voltage) a driving amplifier shown in figure 5 was designed. It was battery powered and provided the linear light output versus electrometer reading required. The light emitting diode was a Monsanto MV10B3 and the photo diode was a Hewlett Packard type 4204. Because the isolated system also worked in the low voltage regions, the original configuration of not using the isolator was abandoned entirely. The voltage to the probe was provided by a Kepco OPS-2000 operational power supply driven by an integrator which was connected to a variable reference potential. The selected voltage "span" then could be swept linearly in time intervals of 10 seconds to 10 minutes.

J-57 I/V Characteristics

Acquiring data from the J-57 involved recording the probe (I/V) curve on an X-Y recorder, recording the changes in engine parameters at the different thrust settings and obtaining gas samples of the exhaust at different thrust settings.

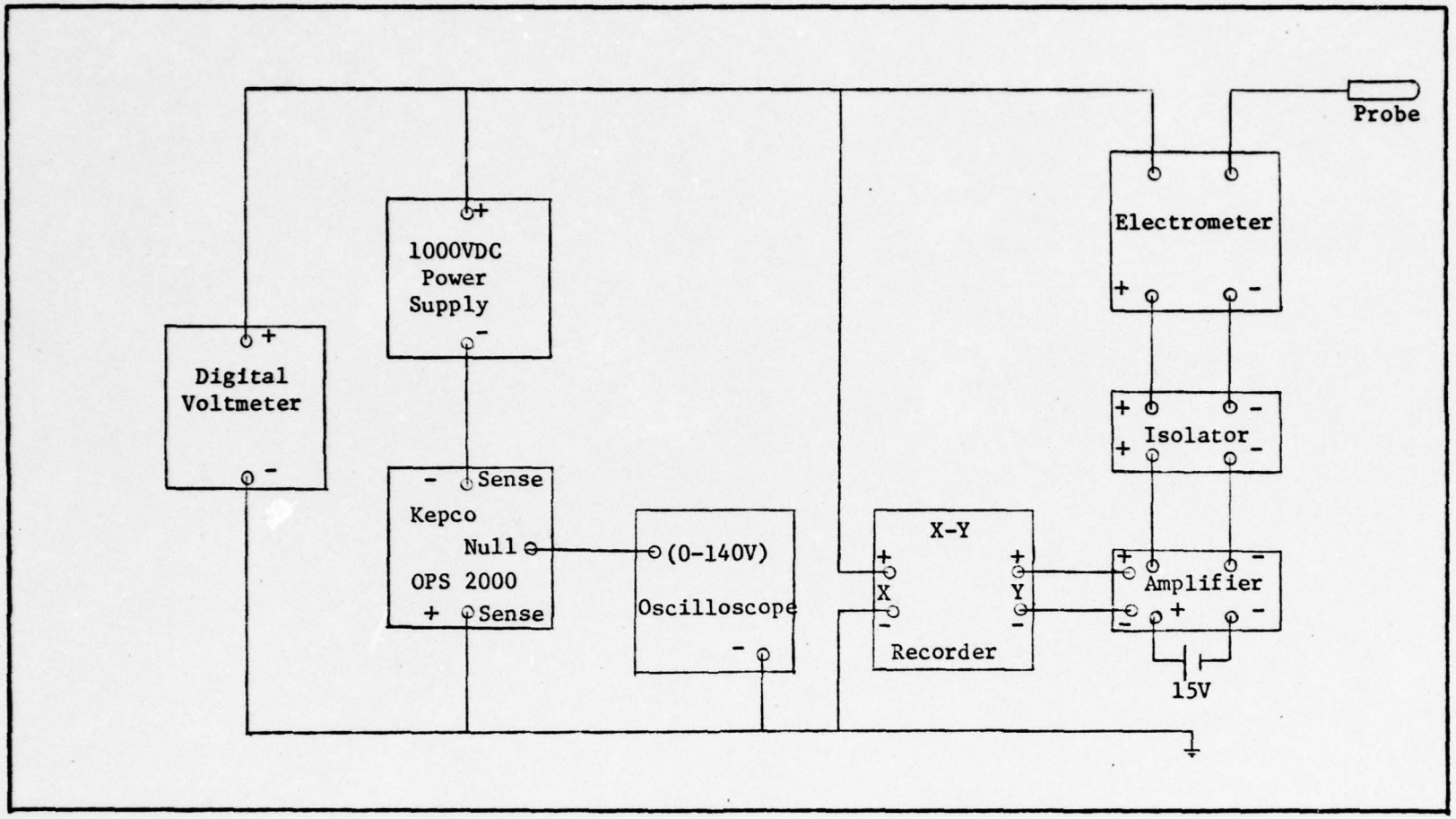


Figure 5. Electro-Optical Isolator

J-57 Operation Cycle

Due to the fact the engine was in an oil test program, normal operation of the engine was 25 minutes at nominal rated power, 5 minutes at the idle power setting and then the 25-5 minute sequence was repeated for each hour of a 100 hour continuous program at 5 hour cycles per day - some minimum intermediate thrust settings were required. A maximum of only 3 hours was obtained from AFAPL out of the 100 hour schedule

The minimum run schedule used is shown in Table I. This intermediate thrust settings schedule allowed for steady state conditions (five minutes minimum) in order to take data measurements while still allowing the maximum number of power settings in a one hour period. This schedule provided the flexibility of inserting the 3 hours of data measurements at any phase of the 100 hour cycle with minimum disruption.

Table I

Engine Run Schedule

Power Setting (%)	Run Duration (Minutes)
Idle	5
20	10
40	10
60	10
80	10
Maximum	10
Idle	5
	1 hour

Gas Sampling

A method for grab sampling was developed and used to sample the NO_2 exhaust gas constituent emitted from the J-57 jet engine. The method of grab sampling is accurate and highly reliable if correct techniques are established and adhered to during the sampling process.

Fortunately, it was possible to install a permanently mounted sampling probe at the exhaust exit plane of the J-57 engine which allowed sampling at any time during engine runs. Stainless steel tubing (1/4" or 3/8" I.D.) was used throughout for sampling lines. Whenever feasible, the tubing length was held to a minimum. The sampling system is shown in Figure 6.

Gas Collection

A 50cc syringe needle was inserted into the sampling line approximately 20 feet from the exhaust source. The syringe was first purged with the exhaust gas and then a 50cc sample was drawn. The 50cc syringe was then moved to a beaker of NO_2 reagent where 5-10cc's was drawn in with the 50cc sample. The syringe was then shaken several times and the needle replaced by a rubber stopper.

The time when each sample was taken was recorded and then at the end of the day's experiments the samples were taken to the Flight Dynamics Atmospheric and Environmental Lab for analysis. The laboratory procedure for NO_2 is explained in Appendix A.

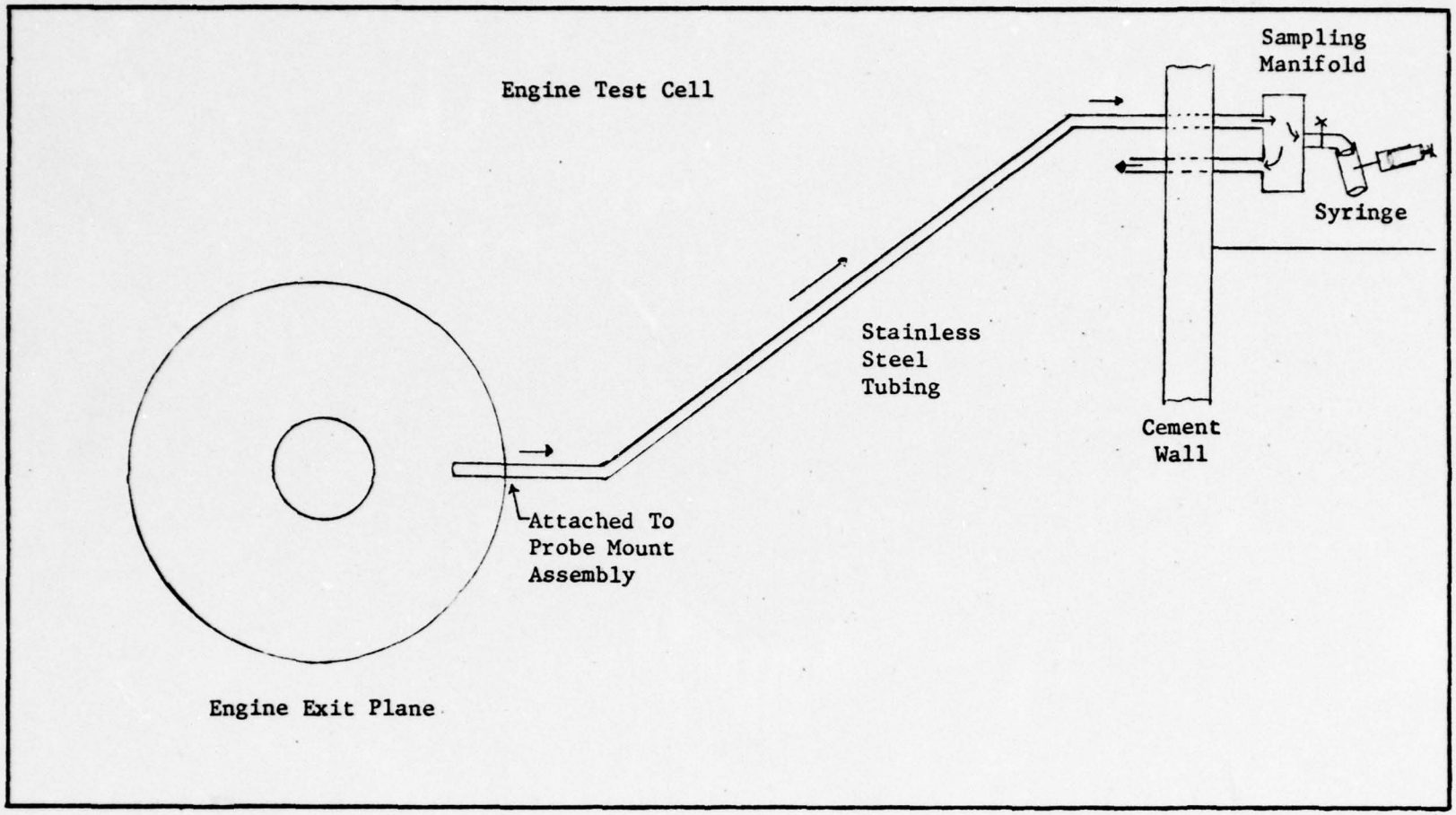


Figure 6. J-57 Exhaust Sampling System (Rear View)

V. RESULTS AND DISCUSSION

The results presented and discussed in this section are based upon probe response data and NO_2 gas samples taken at the exhaust exit plane of two different J-57-29 jet engines located in a test cell. First, some background will be given as to why a considerably smaller measurement data sample size was available versus the original approach and also why only NO_2 was measured when previous discussion mentioned other exhaust pollutants. Next will be a presentation of the data along with a discussion as to possible correlations, trends, and significance.

To satisfy one of the objectives of this experimental effort, the approach was to obtain a substantial amount of probe response data from a number of J-57 engines. Although three engines were available and set up by AFAPL for scheduled 100 hour oil qualification tests during Oct, Nov, and Dec 1970, each test had to be terminated due to internal engine malfunctions. Using the first, some initial data was obtained before the engine oil test was stopped due to metal filings in the oil. Although the second engine was only in operation for 4 days, at which time a turbine bucket disintegrated, it was the main source of data for this effort. The third engine developed problems immediately after oil-tests began and therefore no probe data acquisition was possible.

In attempting to satisfy the second objective of obtaining exhaust gas samples for evaluation of particulates,

hydrocarbons, CO and NO, it was determined that measurements for particulates and unburnt hydrocarbons would be extremely time consuming. The recommended method of analyzing the total exhaust hydrocarbons was continuous monitoring by using a Flame Ionization Detector (FID). Due to non-availability of a FID and other logistical difficulties, this measurement was not made. The recommended approach for acceptable particulate results is isokinetic sampling, however, due to the high velocities encountered at the exhaust of the J-57 and the necessary safety considerations, no practical and logistically feasible technique was found and therefore measurements of exhaust particulates were not accomplished. Planned measurements of carbon monoxide (CO) by a non-dispersive infared (NDIR) photometer were dropped due to non-availability and logistical difficulties. Carbon dioxide (CO_2) measurements were to be accomplished by grab sampling with a 50cc syringe, then adding the exhaust gas to an evacuated bottle containing LiOH and $BaCl_2$, followed by determining the amount of CO_2 in the sample by a volumetric quantitative analysis technique using phenolphthalein and titrating with oxalic acid. These measurements were to be made during the last half of the scheduled run time for the second engine, however, its malfunction prevented any evaluation of CO_2 content in the engine's exhaust. For the oxides of nitrogen, nitrogen dioxide (NO_2) was selected over nitric oxide (NO) due to available gas sampling hardware. The analytical procedure used for determination of NO_2 in the exhaust gas was the Saltzman method which is intended for the

manual determination of NO_2 in the atmosphere in the range of a few parts per billion to about 5 ppm (Ref. 8). This method was appropriate because it allows grab sampling when concentrations are between 5 ppm and 100 ppm and it allows only slight interfering effects from other gases.

Current voltage traces were taken in the J-57 jet engine exhaust and the floating potential, slope and charging current were studied as a function of various engine and exhaust parameters. An example of a typical current-voltage trace is shown in Figure 7. However, there are minor exceptions, the current-voltage traces are straight lines with a slope, M, determined by the ion density according to the relationship (Ref. 9)

$$M = \frac{dI}{dV} \approx n\mu e\pi L$$

where
- n - ion concentration, cm^{-3}
- μ - ion mobility, $cm^2/(Volt\text{-}sec)$
- e - electron charge, coulombs
- π - 3.14
- L - probe length, cm
- I - collected current, amperes
- V - probe voltage, volts

Two additional points of interest are the floating potential (V_f), which is the voltage where the current goes to zero, and the charging current, I_o, which is the current "pumped" onto the probe by the excess charge in the exhaust gases. These

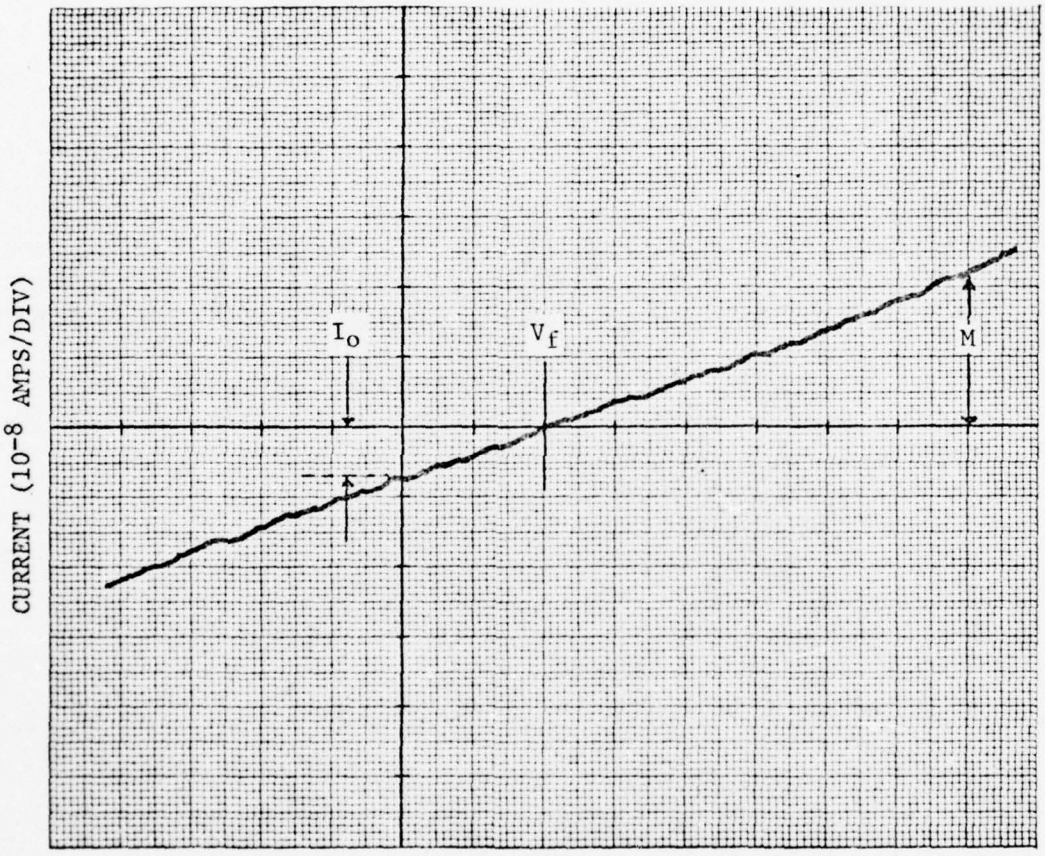


Figure 7. J-57 I/V Trace

three are related by the following equation:

$$I_o = V_f M$$

so that there are only two independent parameters (as there should be for a straight line). The slopes have been studied previously and found to correlate with mixture ratio. Figure 8 shows a plot of the number density as a function of the mixture ratio for data taken in this effort along with plotted data of other authors (Ref. 10). This consistency of slopes lends credence to the major effort of this work which was aimed at studying the factors which govern V_f and I_o. It was postulated that V_f and I_o might be related to pollutants such as NO_2, unburnt hydrocarbons and particulate matter. To substantiate this, NO_2 gas samples were taken simultaneously with I-V data and the gas was analyzed for NO_2. Figure 9 shows a reasonable correlation of NO_2 concentration as a function of V_f. .The correlation is certainly less than hoped for but does show NO_2 is a factor in determining V_f. A correlation of NO_2 concentration versus thrust is shown in figure 10. The increase of NO_2 pollutant with thrust is expected due to higher temperatures in the combustion region. More importantly, however, is the drastic change in V_f as shown in figure 11 which had been consistently positive on 12 Nov 70 and then considerably less positive on the last run at 105% power. Then, on the 16th and 17th of November we see that the major shift towards zero continued and even to $V_f < 0$ on the 17th of November. This engine subsequently failed on 18 Nov 70 due to a fatiguing turbine blade which resulted

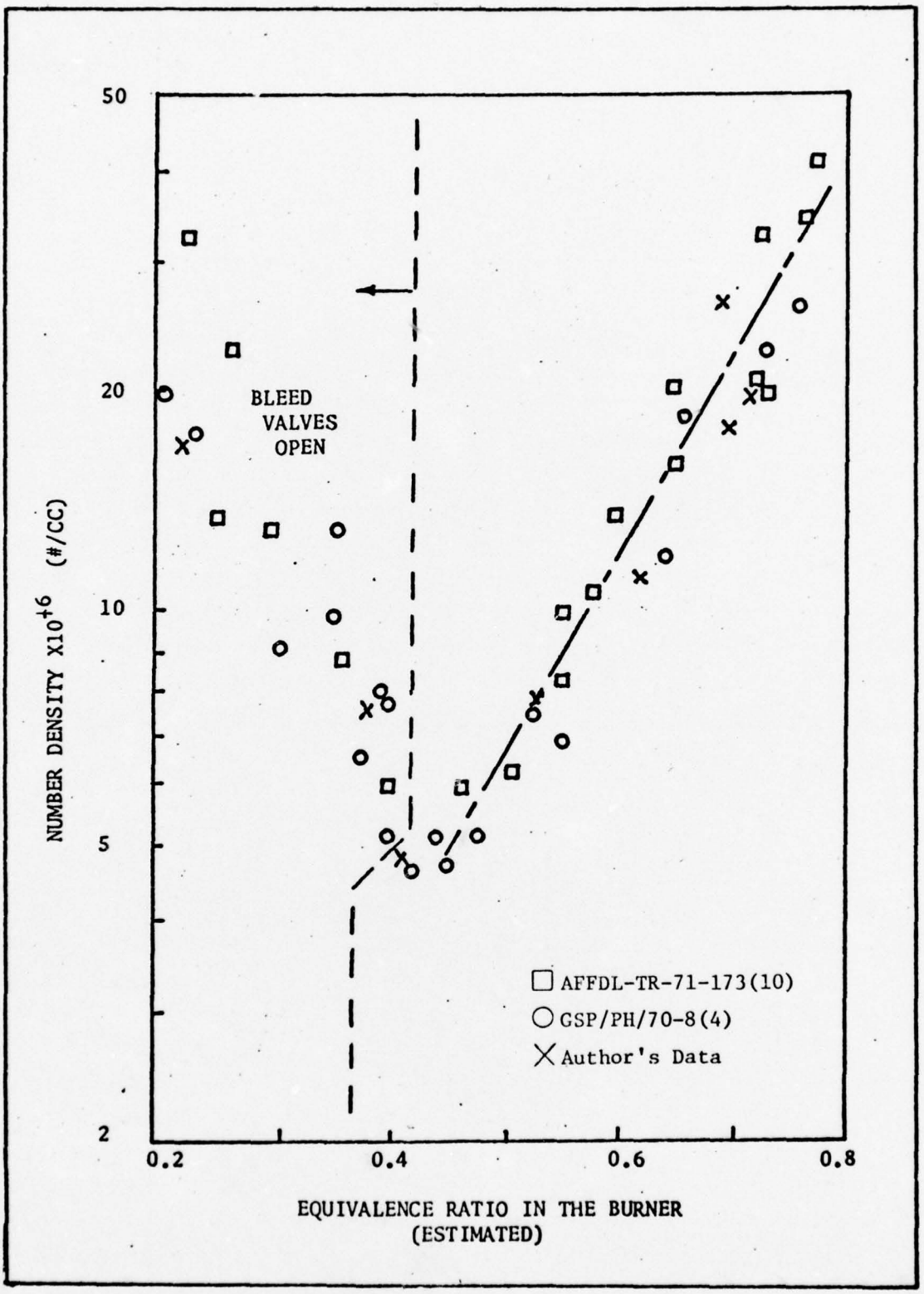


Figure 8. Number Density vs Mixture Ratio

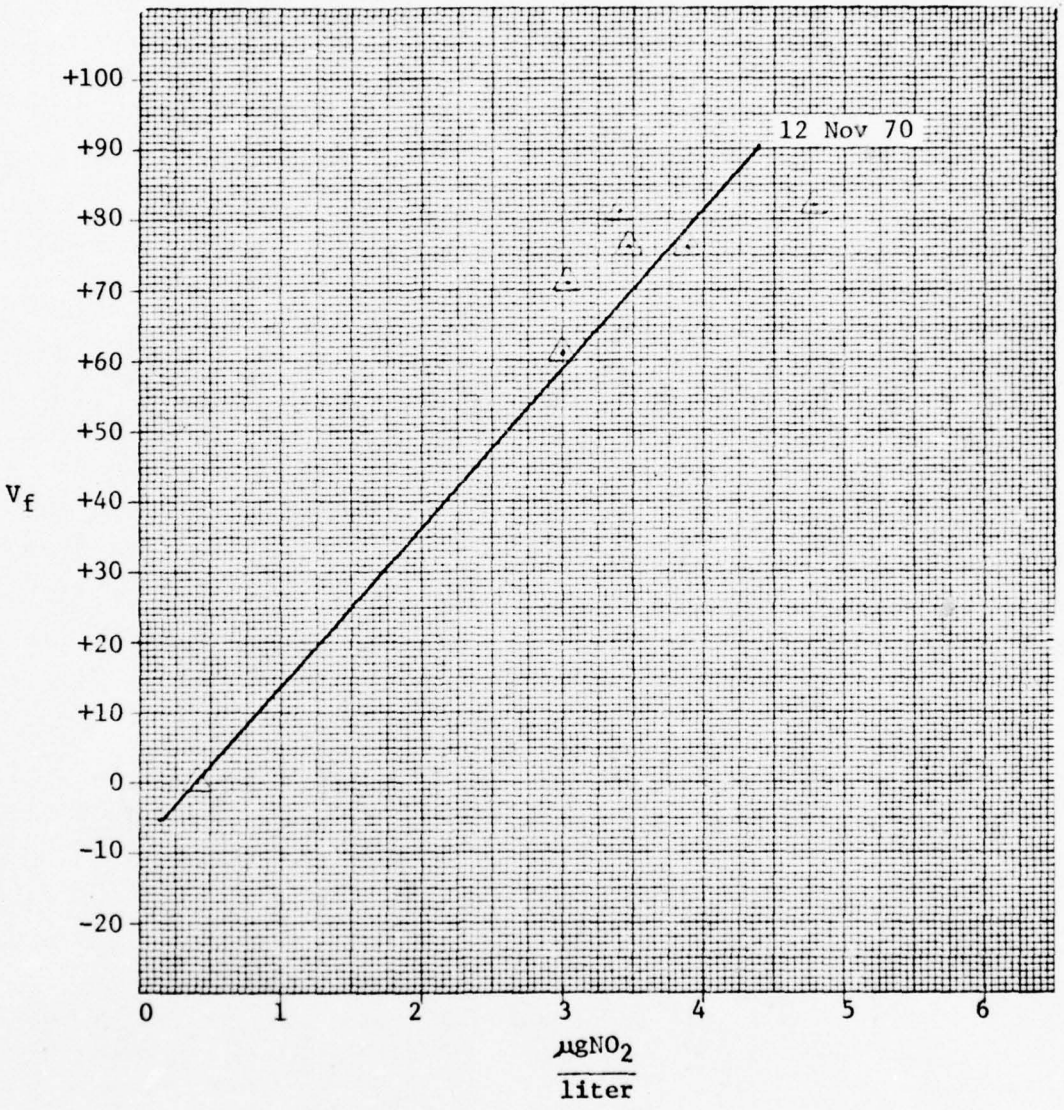


Figure 9. NO_2 Concentrations vs V_f

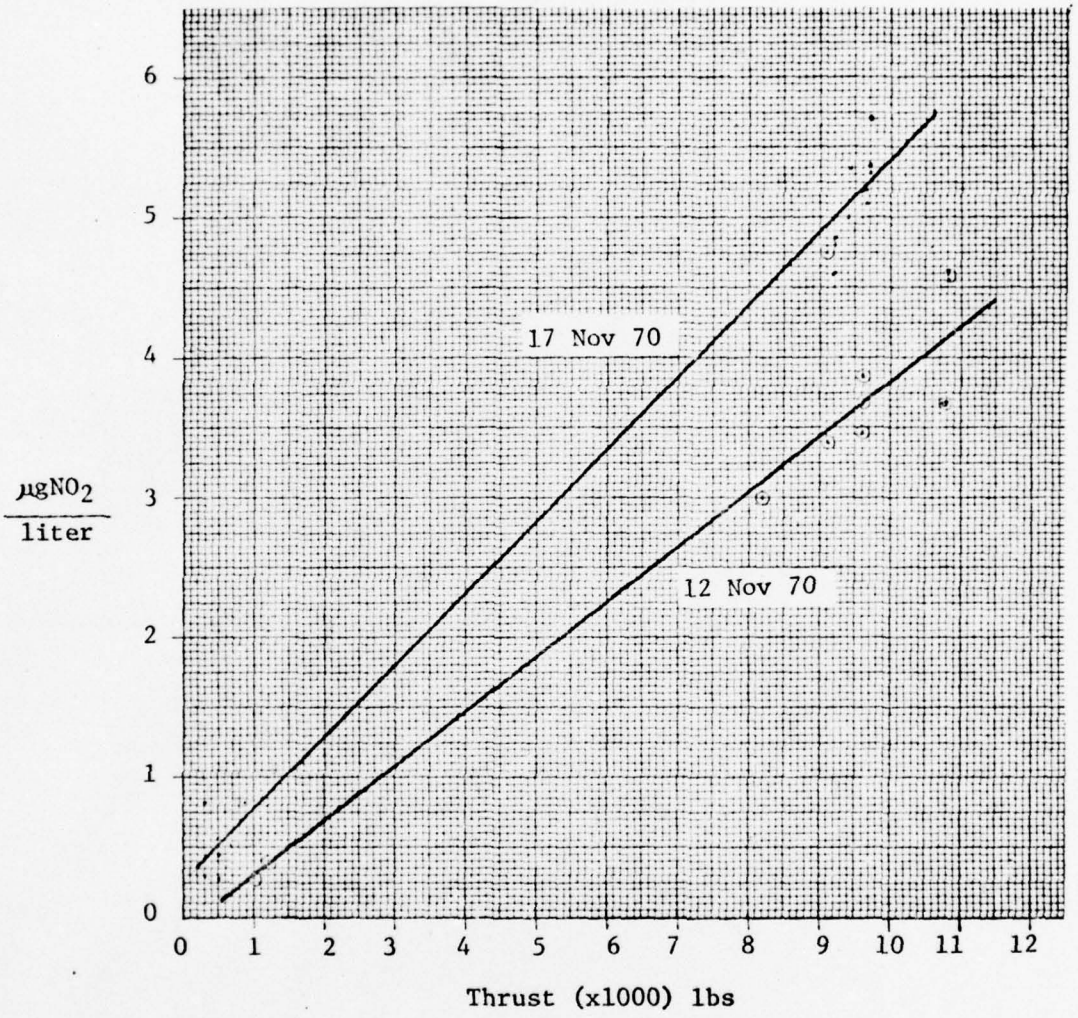


Figure 10. NO_2 Concentrations vs Thrust

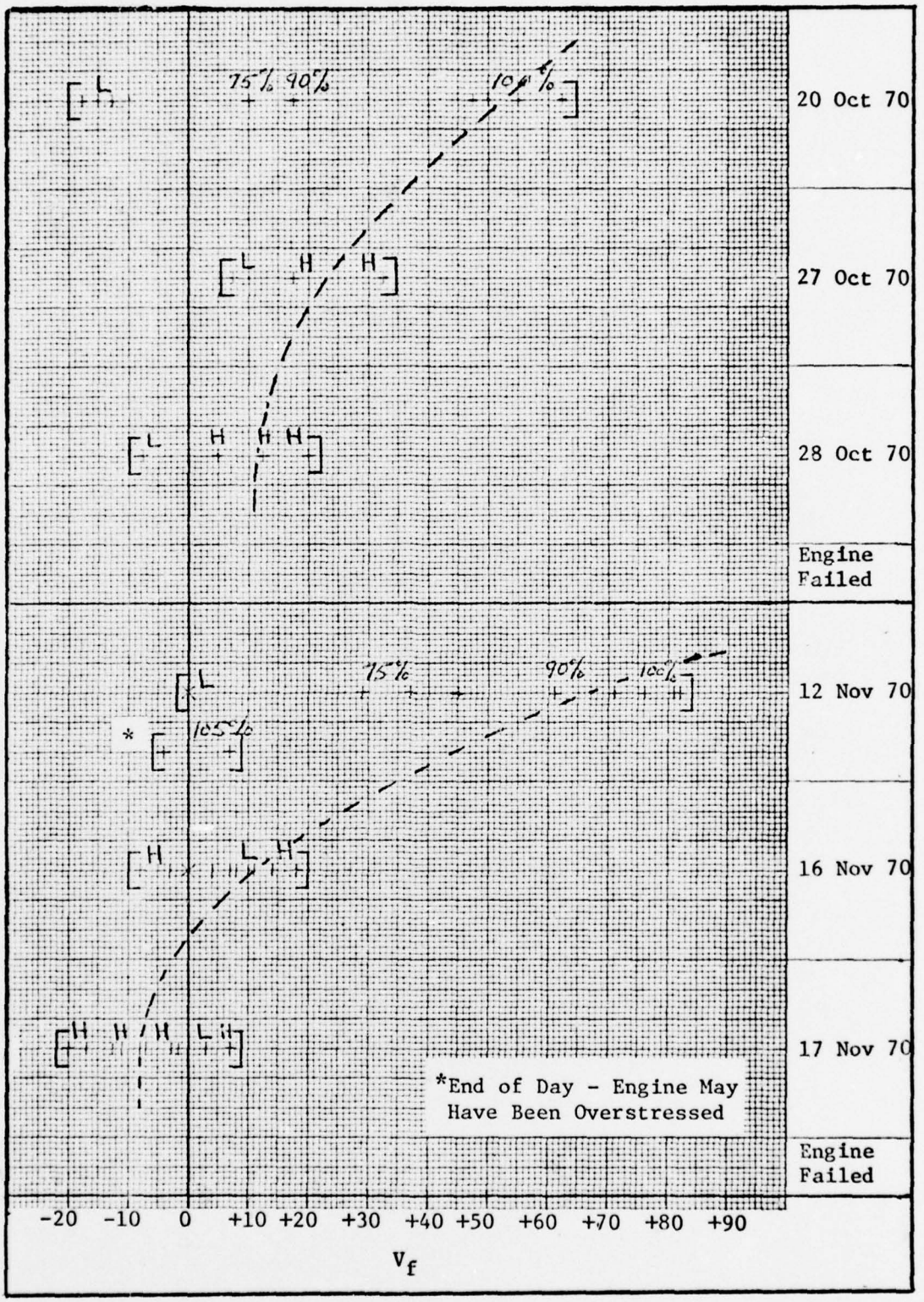


Figure 11. Anomalous D.C. Shifts

in numerous "spikes" increasing with time as shown in figure 12 (a-f). These spikes have since been studied extensively and shown to precede a large number of engine failures. One of the things which was overlooked, however, was the large D.C. shift which was observed. Examining the V_f shift for the 20-28 Oct engine also shows this trend prior to engine failure. An interesting correlation can be made by comparing the V_f versus thrust. In figure 13, the slope of V_f values for 20 Oct 70 and 12 Nov 70 is uniquely different from the slope of V_f values for 16 Nov and 17 Nov 70, which is 2 days prior to engine failure. This data suggests that as originally postulated, particulate matter and perhaps unburnt hydrocarbons could modify the D.C. level as well as NO_2. Substantial data was taken with a probe in a J-60 turbojet engine (Ref. 11) with the result that D.C. level was shifted due to oil ingestion. In the J-60 experiment, oil injected into the engine at the rate of 2 gallons/hour caused the floating potential to increase in a positive direction. Since the slope of the I-V traces was also sensitive to oil ingestion, it was concluded that the predominate ion specie concentration changed (change in ion density). In addition, Capt Dunn (Ref. 12) has shown that particulate matter results in pockets of charge as seen in Figure 14.

The conclusions are that although the D.C. level is related to NO_2 concentrations, it is also governed by particulate and unburnt hydrocarbon levels. Hence, care must be taken to simultaneously monitor all three. Anomalous shifts in D.C. level (as shown by J-57 data) as seen in Figure 11,

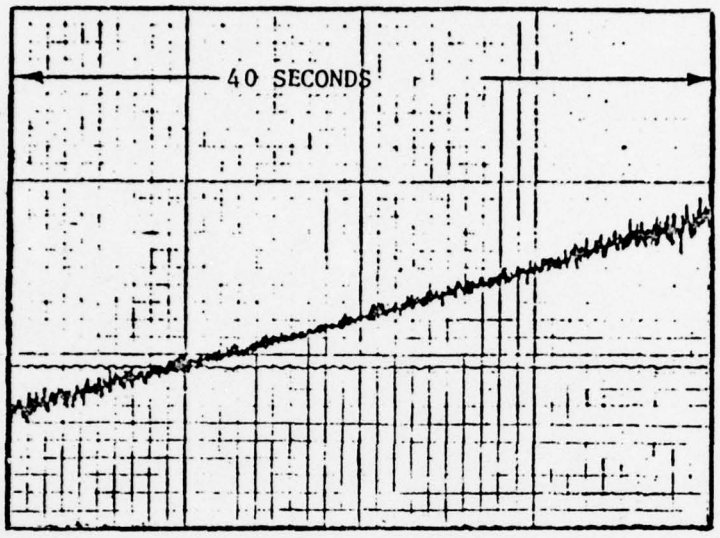


Figure 12 a.

NORMAL I-V TRACE

SLOPE EXPONENTIAL WITH MIXTURE RATIO

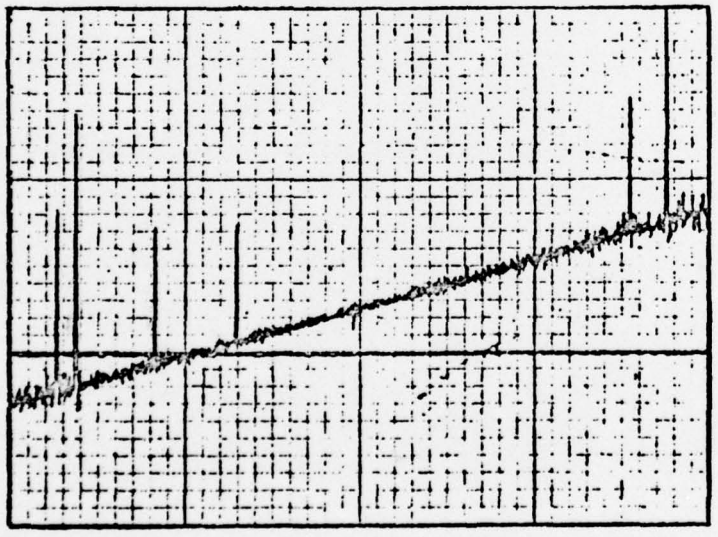


Figure 12 b.

FIRST SPIKES

0900 HRS
17 NOV 1970

Figure 12. I-V Traces With Spikes

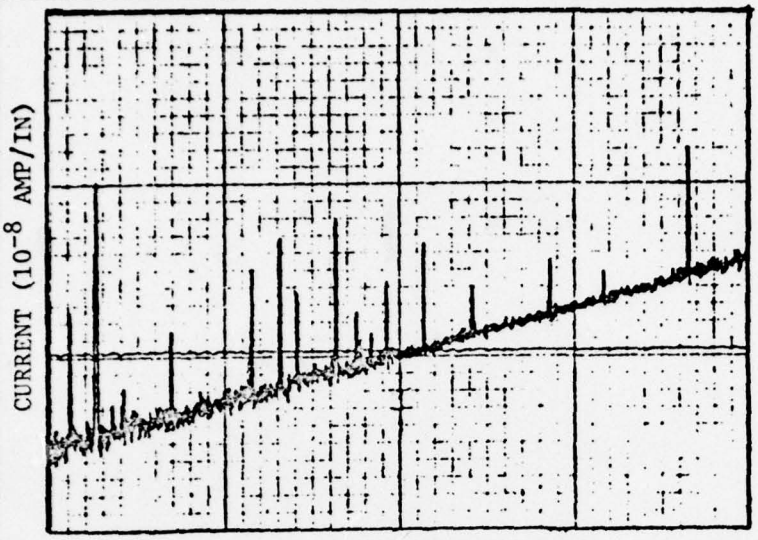


Figure 12 c.

0930 HRS
17 NOV 1970

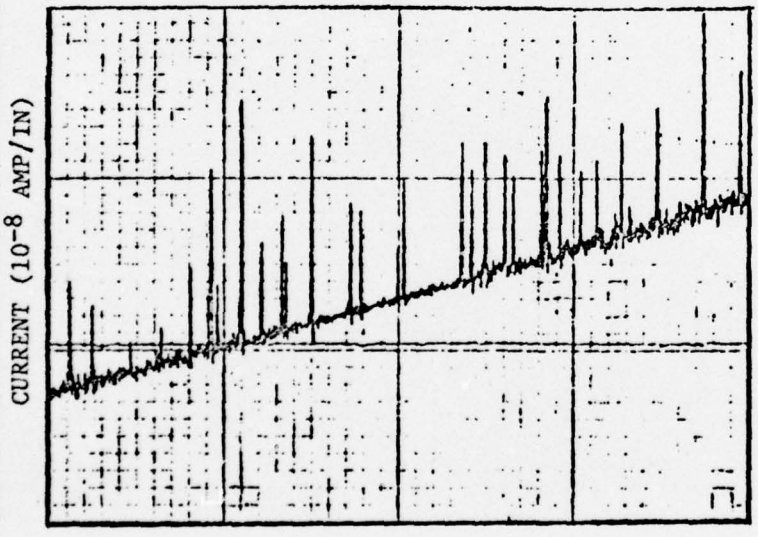


Figure 12 d.

1000 HRS
17 NOV 1970

(Note: Spiking sequence showing increasing spike size and number)

Figure 12. I-V Traces With Spikes

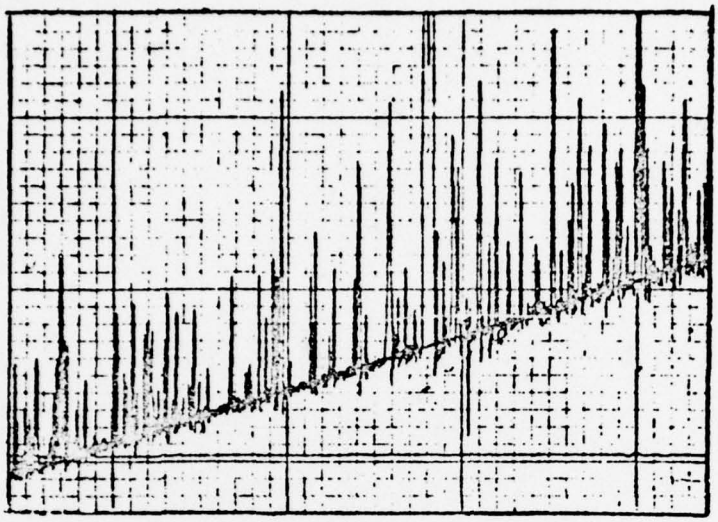


Figure 12 e.

1200 HRS
17 NOV 1970

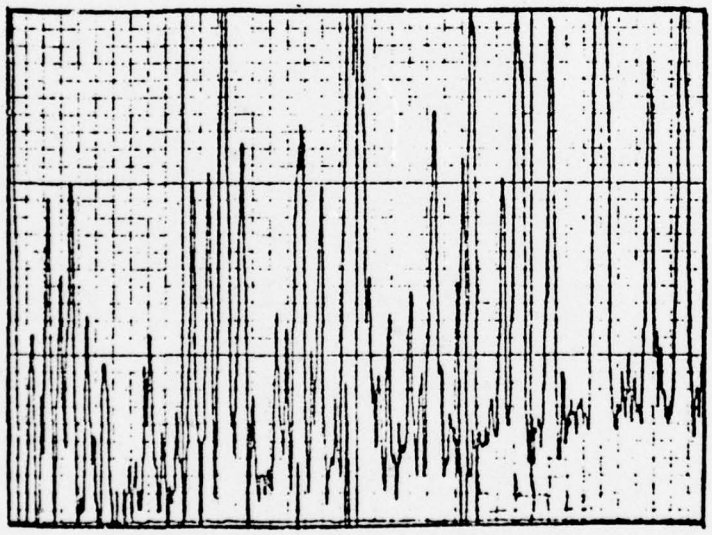


Figure 12 f.

1300 HRS
17 NOV 1970
(5 HOURS PRIOR
TO FAILURE)

[ENGINE FAILURE]
1000 HRS
18 NOV 1970

(Note: Spiking sequence showing increasing spike size and number)

Figure 12. I-V Traces With Spikes

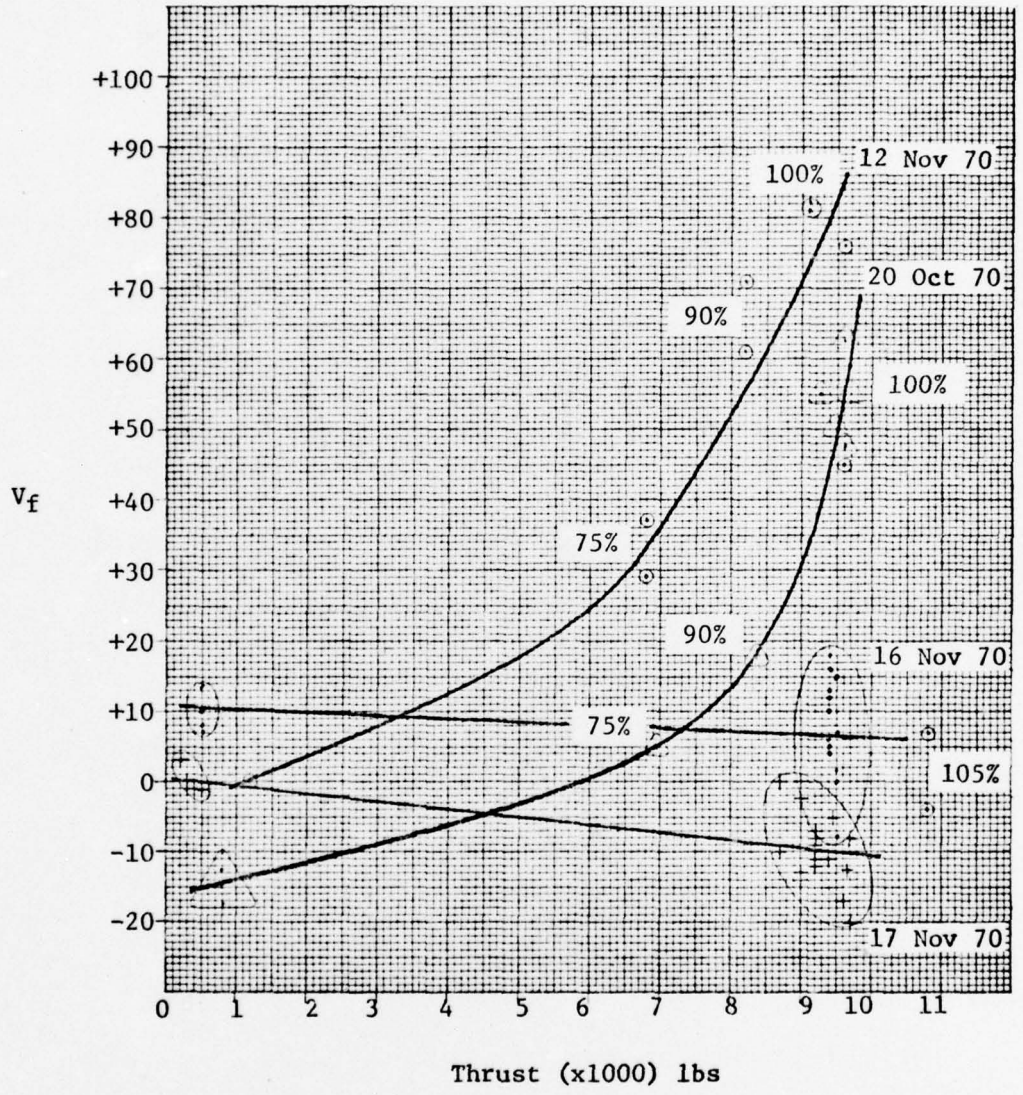


Figure 13. V_f vs Thrust

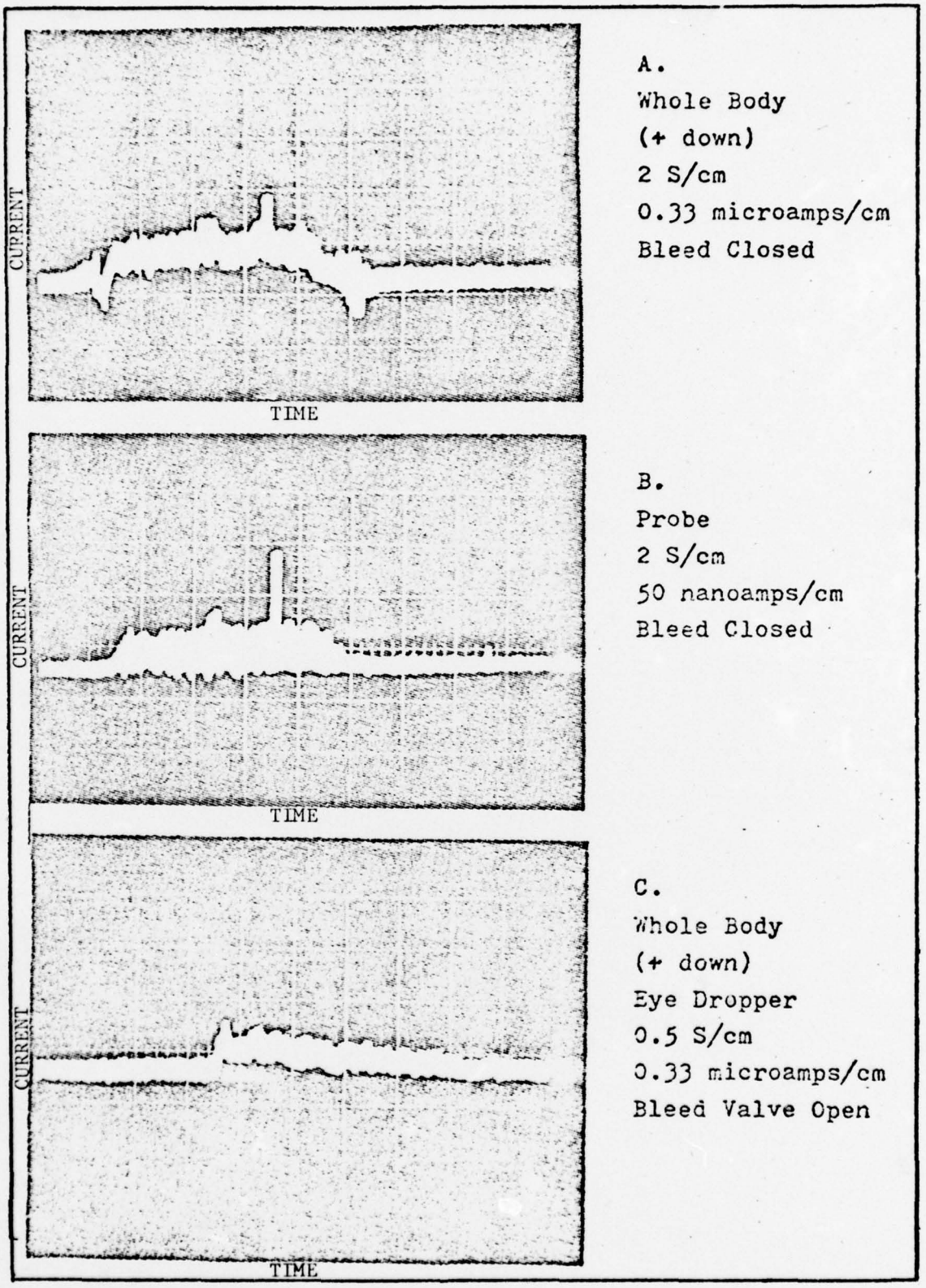


Figure 14. Positive Plasma 37 Micron Nickel (Flow Rate in C Faster than A)

can be indicative of imminent failure since they result in particulates and (in the case of bearings and seals) hydrocarbons in the exhaust. The trend, indicated by figure 11, of the V_f spread for a healthy engine against one prior to failure shows a possible method of sensing engine problems by monitoring the V_f value. Note that the appearance of V_f values of -4 volts and +7 volts on 12 Nov 70 for the 105% thrust is inconsistent with previous V_f values at thrust settings of 90%, 95%(H) and 100%. Because this sudden shift in V_f was then consistent for the next two days prior to engine failure, it is a possibility that this higher than normal thrust caused internal overstress of the engine which eventually resulted in the turbine blade disintegration. This type of anomaly should be examined further for its potential failure predictive capability.

Based upon the above conclusions, possible confirmation could be achieved by a simple oil and particulate experiment on an operational KC-135 aircraft using the whole body method. The whole body method could therefore be used to monitor D.C levels and anomalous shifts used as indications of failure.

A conclusion, to the postulation that a relationship exists between the probe characteristic, exhaust gases, and combustor efficiency, is that definite correlations might be possible if a sufficiently larger data sample size were available. This correlation would be determined from the probe response data in terms of number density which is a function of the engine equivalence ratio and then use the

equivalence ratio to determine amounts of particulates, hydrocarbons, CO and NO emitted from the engine combustion process.

The end result is that the potential exists for the electrostatic probe concept, inserted in the path of jet engine exhaust gases, to indicate both impending engine failure and combustor efficiency and temperature on a real time basis.

VI. RECOMMENDATIONS

Based upon the anomalous D.C. shifts observed in the J-57 data, it is recommended that a few simple whole body type experiments be performed on an operational aircraft with a J-57 engine. These experiments would involve ingestion of oil and particulate matter while simultaneously monitoring the current to ground from the aircraft. Results from this effort would add to understanding the possible factors which effect V_f.

Also worthy of examination is development of a model which can relate the probe response to combustion efficiency through the equivalence ratio. Although the combustion process and the resulting emission of pollutants is not completely known, efforts could be initiated to develop a theory for the probe response in a combustor can and correlate this with corresponding pollutant concentrations.

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APPENDIX A

LABORATORY PROCEDURES FOR NO_2 ANALYSIS

1. This appendix discusses the methodology used to determine the amount of NO_2 pollutant in the exhaust gases of a J-57 jet engine by the analytical Saltzman method.

2. The Saltzman Method:

a. Introduction - When making manual determinations or analysis of nitrogen dioxide or nitric oxide (airborne contaminants) in the atmosphere or the exhaust gases of a jet engine in the range of a few parts per billion (ppb) to approximately 5 ppm, a recommended technique is the Saltzman method. Generally the sampling is performed by using fritted bubblers. Using the method for determining nitric oxide is accomplished by passing the nitric oxide through a permanganate bubbler and converting the NO to an equivalent amount of nitrogen dioxide. Sampling concentrations of NO_x and NO gases in the (5-100) ppm range may be done by using evacuated bottles. A Griess-Saltzman reagent is used in the evacuated bottle which absorbs the nitrogen dioxide and produces a stable pink color within 15 minutes which can then be read visually or in an appropriate instrument (i.e., spectrophotometer or Colorimeter). Interferring effects of other gases present will occur only slightly.

b. Reagents - The reagents utilized are made up from analytical-grade chemicals in nitrite-free water (prepared, if necessary, by redistilling distilled water in an all-glass

still after adding a crystal of potassium permanganate and a crystal of barium hydroxide). The reagents, if maintained in well stoppered brown bottles in a refrigerator, are stable for several months. And, before using the absorbing reagent, it should be brought to room temperature.

c. Preparation of NO_2 Absorbing Agent/Solution - The procedure used during preparation of the absorbing solution, required for determining NO_2 content in exhaust gases, is:

Step 1:
(1) Weigh out 2.5 grams of sulfanilic acid. ($NH_2C_6H_4SO_3H \cdot H_2O$ [99.6%] Crystal 'Baker Analyzed' Reagent)
(2) Add sulfanilic acid to a 500 ml volumetric flask.
(3) Add approximately 300 ml of distilled water.
(4) Then, measure out 70 ml of acetic acid.
(5) Add the 70 ml of acetic acid to the 500 ml flask.
(6) Place 500 ml flask on a hot-plate and warm in order to help dissolve the contents. Shake periodically until all is dissolved.

Step 2:
(1) Weigh out .05 grams of N-(1-Naphtyl-ethylene diamine dihydrochloride)
(2) Add N- to a 50 ml graduated cylinder.
(3) Then, add water to the 50 ml mark.
(4) Place a stopper in the 50 ml cylinder and shake contents until dissolved.

Step 3: (1) Add 10 ml of "step 2" to the contents of "Step 1", then mix.

(2) Add distilled water to bring contents to the 500 ml mark.

(3) Place a stopper in the flask and mix thoroughly.

(4) The result is "Absorbing Reagent for NO_2".

d. Preparation of NO_2 Standard:

Step 4: (1) Weigh out 0.150 grams of pure $NaNO_2$ (Sodium Nitrite).

(2) Carefully transfer 150 mg of $NaNO_2$ to a 100 ml volumetric flask.

(3) Add distilled water through a funnel and dilute carefully until it reaches 100 ml mark. Each ml of this solution contains 1 mg of NO_2.

(4) Place stopper in the flask and shake. Now have a solution of 1 mg NO_2/ml.

e. Preparation of NO_2 Dilute Standard:

Step 5: (1) Pipette 1 ml of "Step 4" solution into a 100 ml volumetric flask.

(2) Dilute by adding distilled water to the 100 ml flask mark. Each .1 ml of this solution contains 10µg of NO_2.

Step 6: (1) Place six 25 ml test tubes in a tube rack and label 0, .2, .4, .6, .8, and 1.0.

(2) Using "Step 5" solution, pipette 0, .2, .4, .6, .8, and 1.0 ml into respectively labeled tubes by using a graduated (tenths) pipette.

(3) Fill six tubes to 25 ml marks with "Step 3" absorbing reagent.

(4) After reagent added, let each tube stand for approximately 10-15 minutes.

Step 7: (1) Transfer some of the 0(blank) solution, from the 25 ml test tube of "Step 6", to the colorimeter's photometric cell.

(2) Place blank cell in the colorimeter (ensure is warmed-up and stabilized) and adjust to 100% transmission.

Step 8: (1) Begin with weakest pink color (i.e., .2).

(2) Transfer some to cell with 0 (.2, .4, .6, .8), by dumping 0 sample (.2, .4, .6, .8) and rinsing with .2 sample (.4, .6, .8).

(3) Add .2 sample (after rinse) to above the mark on photometric cell and record the % transmission.

(4) Continue steps 8(2) and 8(3) until have recorded all samples.

Step 9: (1) Plot % transmission against concentration on single cycle semi-logarithmic paper.

f. Originally during "steps 4-8", the resultant strength of the 25 ml cells, with the varying amounts of μgNO_2, produced a red color that was extremely dark at the .2 ml level. This was based upon a $10\mu gNO_2$ per .1 ml strength. For example, the 25 ml cell with .2 ml strength resulted in 20% transmission. When diluted the 25 ml cell to 50 ml (NO_2 Absorbing

Agent) the transmission was somewhat better at 35%, and was 54% at 75 ml and 68% at 100 ml dilution. Based upon this, it was decided to reduce the $NaNO_2$ strength by a factor of 10. The calculation supporting this are shown in Figure A-1. The final values of % transmission vs μgNO_2 are shown in Figure A-2.

g. NO_2 Sampling/Collection Procedure:

Step 10: (1) Place exactly (pipette) 25 ml of absorbing reagent into a stoppered tube/bottle.

(2) Create a vacuum in tube/bottle (i.e., rule of thumb is to remove approximately twice the amount of gas testing).

(3) Draw 10-to-50cc(ml) of exhaust gas from sampling line.

(4) Place gas into tube/bottle and record the total volume of gas added plus temperature and pressure, if they deviate greatly from 25°C and 760mmHg.

h. NO_2 Sample Determination/Analysis:

Step 11: (1) After sample collected (i.e., gas transferred from the syringe to the tube/bottle with 25 ml of absorbing reagent) and absorption begins, a direct red-violet color should appear.

(2) The absorption process will be complete within 15 minutes at ordinary temperature/pressure.

(3) In laboratory, insert standard (i.e., unexposed absorbing reagent) into colorimeter's photometric cell and adjust to 100% transmission.

1. Original $NaNO_2$ Strength.

   a. $\frac{150mg\ NaNO_2}{100ml} \rightarrow \frac{1mg\ NO_2}{1ml}$ (Solution)

   b. Take 10ml of (1a.) solution and dilute to 100ml.
   Have: $\frac{10mg\ NO_2}{100ml} \rightarrow \frac{.1mg\ NO_2}{1ml} \rightarrow \frac{10\mu g\ NO_2}{.1ml}$

2. Reduced $NaNO_2$ Strength.

   a. Take 1ml of (1a.) solution and dilute to 100ml.
   Have: $\frac{1mg\ NO_2}{100ml} \rightarrow \frac{.01mg\ NO_2}{1ml} \rightarrow \frac{1\mu g\ NO_2}{.1ml}$

3. Measured values of %-transmission from $\mu g\ NO_2$ in 25ml cells.

Cell No.	Solution (ml)	$\mu g\ NO_2$	$\mu g\ NO_2$ per ml	%-Transmission #1 - %	#2 - %	Ave. - %
1	0	0	0	100.00	100.00	100.00
2	.2	2	.08	82.50	81.50	82.00
3	.4	4	.16	66.00	66.50	66.25
4	.6	6	.24	54.50	55.50	55.00
5	.8	8	.32	46.00	47.50	46.75
6	1.0	10	.40	38.50	38.50	38.50

Figure A-1. NO_2 Standard Calculations(27 Oct 70)

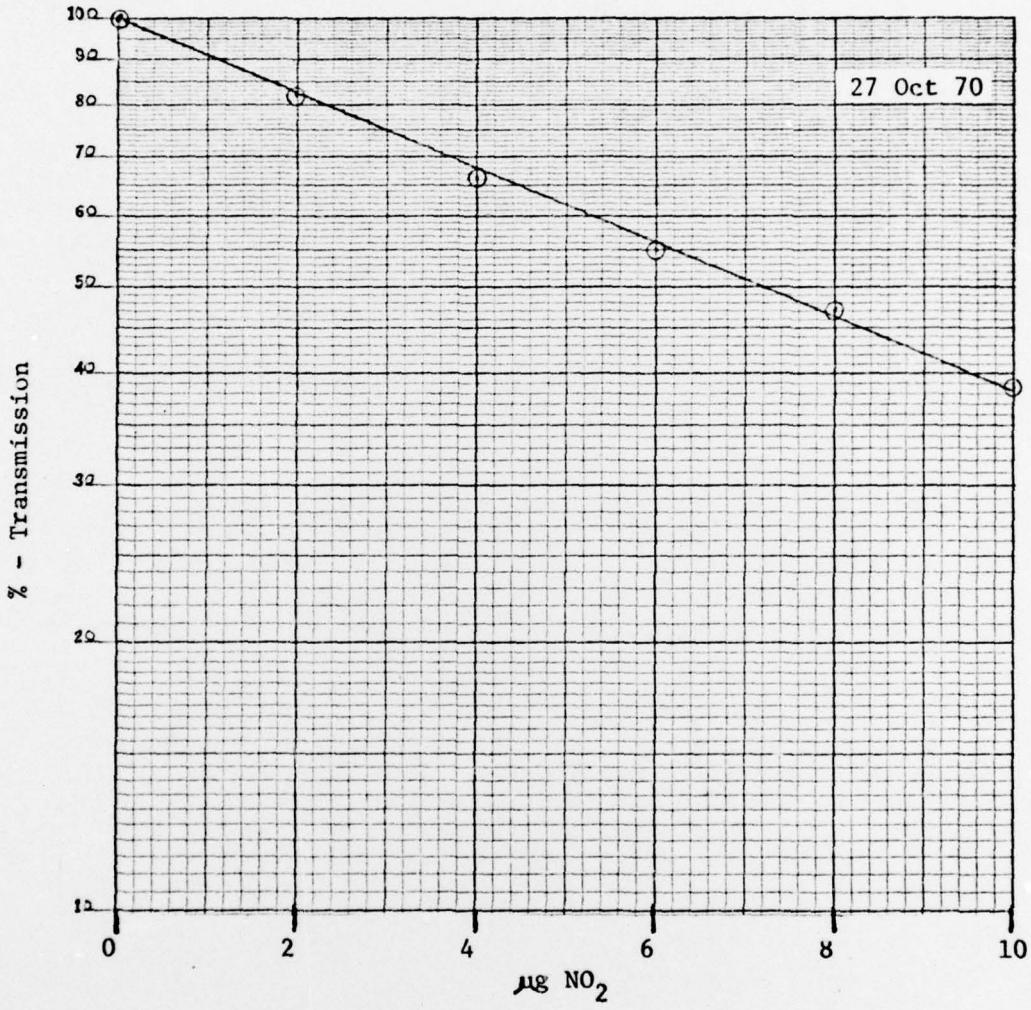


Figure A-2. Percent Transmission vs Micrograms NO_2

(4) Then, wash photometric cell with first gas sample solution and add some of the solution (from the 25 ml tube/bottle) to the rinsed cell.

(5) Insert cell with sample solution into the colorimeter and read the % transmission value.

(6) Take this value and obtain the μgNO_2 value from the standard on the graph.

(7) Take the number of μgNO_2 and multiply by the number of cc(ml)'s of gas that was inserted into the 25 ml(tube/bottle) solution.

(8) The result is the number of μg of NO_2 and this is then used to determine the ppm of NO_2 available at the exhaust exit plane.

3. The equations and calculational procedure are shown in Figure A-3.

4. The sampling hardware is shown in Figure A-4.

5. Gas sample results for 12 Nov 70 and 17 Nov 70 are shown in figure A-5 and figure A-6 respectively.

6. During period when the J-57 engine was operational, the samples were obtained at remote locations from the actual exhaust due to safety considerations. At the remote location, samples were obtained using a 50-cc plastic disposable syringe. The gas samples were obtained from a manifold which had con-

GAS SAMPLE DATA

1. Used 25ml of absorbing reagent solution in test bottle.

2. Test Environment - Standard Conditions - T = 293 ^{o}K
   P = 1 atm.
   MW = 46.01

3. Used 50cc syringe to obtain gas exhaust sample.

4. Value of colorimeter %-transmission is used on graph to determine amount of μg NO_2 in sample.

5. Example: Assume value on graph read 75%.

   Then, $\frac{3\ \mu g\ NO_2}{50cc(ml)} \times \frac{1000ml}{liter} = \frac{60\ \mu g\ NO_2}{liter}$

   And, $\frac{60\ \mu g\ NO_2}{liter} \times \frac{1\ liter}{1.000028 \times 10^{-3}\ m^3} \cong \frac{60000\ \mu g\ NO_2}{m^3}$

   Using a nomograph conversion for

   $\frac{ug}{m^3}$ or $\frac{mg}{m^3}$ to ppm

   Obtain approximately 30 ppm (by volume)

Figure A-3. NO_2 Calculations

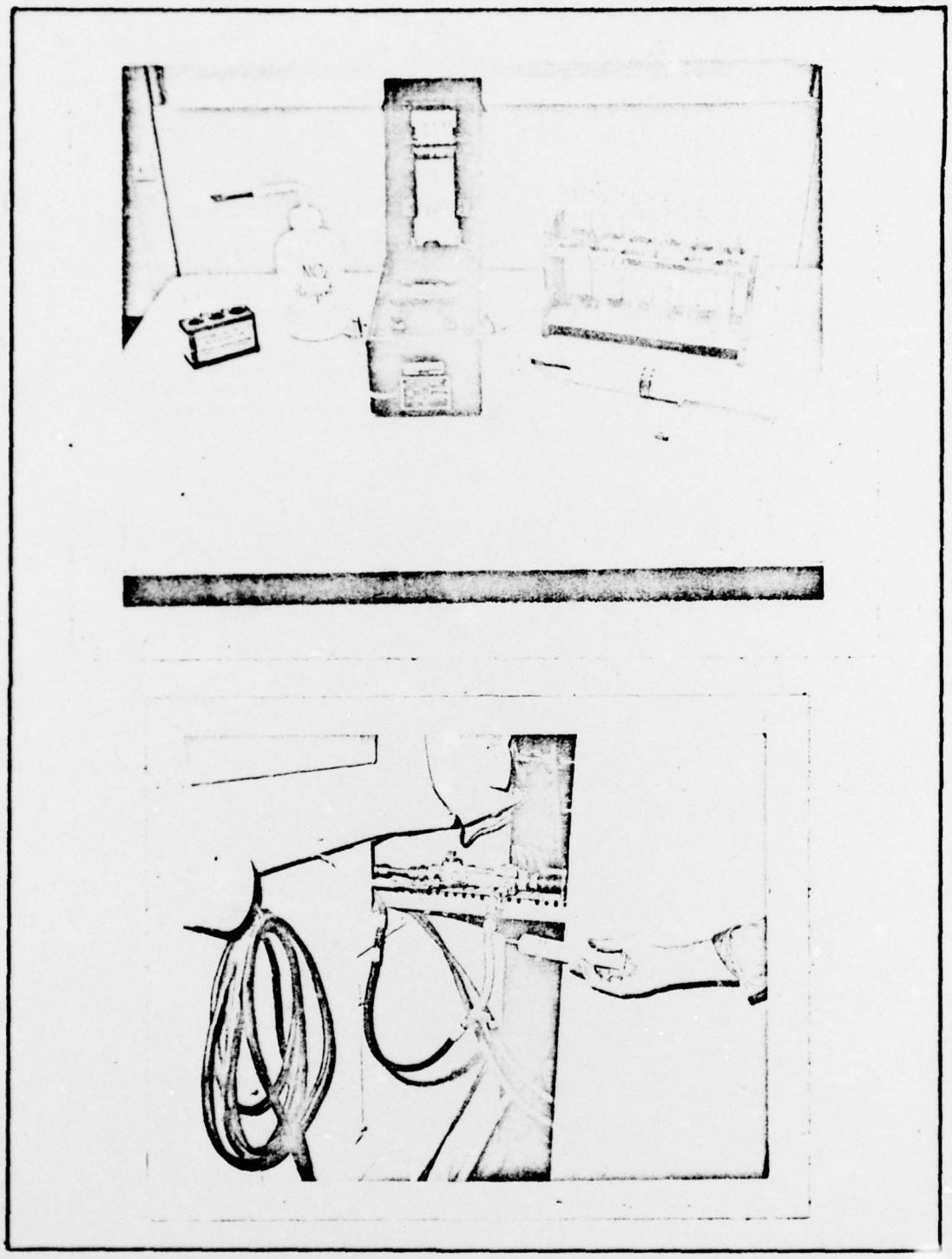


Figure A-4. NO_2 Sampling Hardware

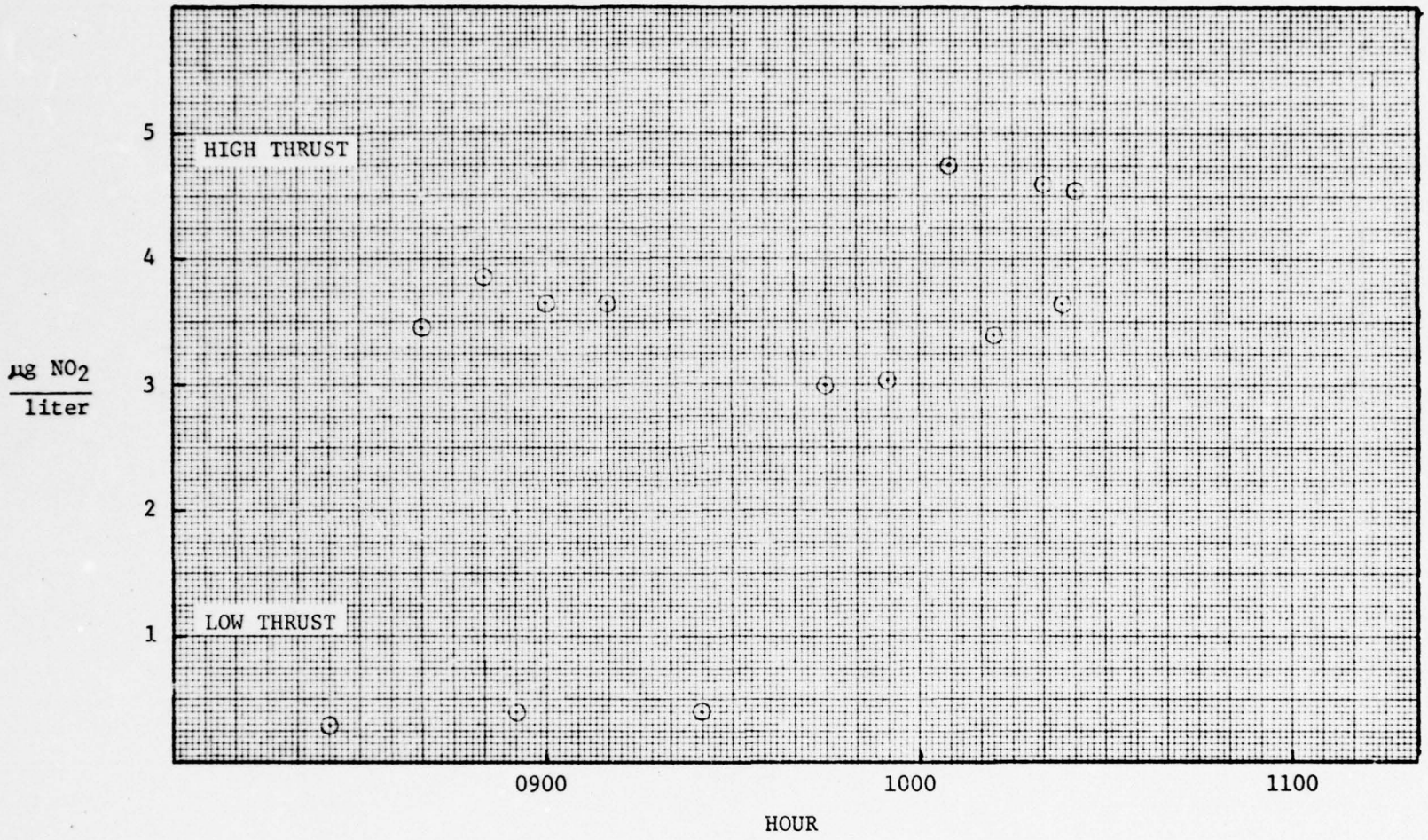


Figure A-5. Gas Analysis Summary(12 Nov 70)

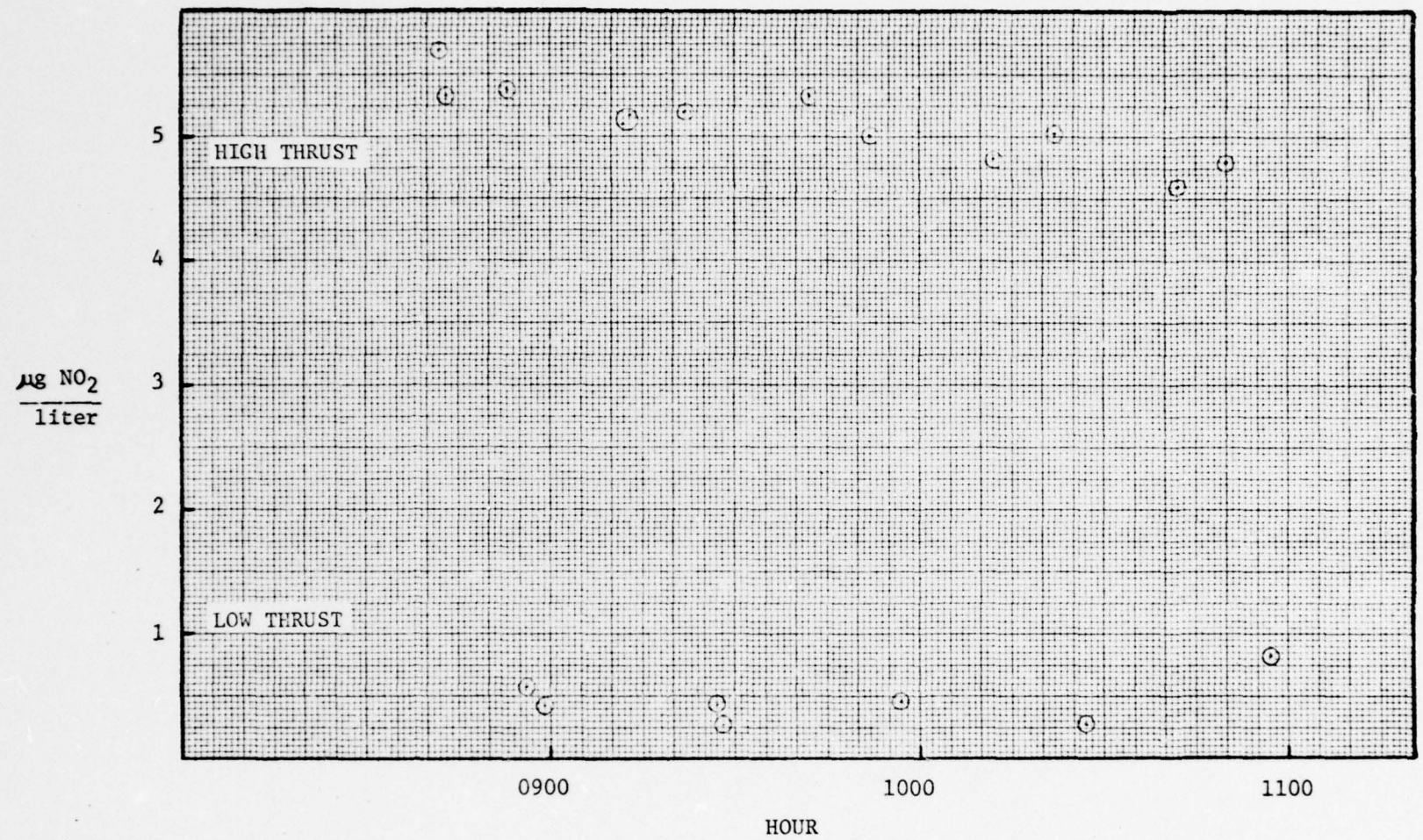


Figure A-6. Gas Analysis Summary(17 Nov 70)

tinuous exhaust flow through it and which had special values and tubing for access with a syringe. Sampling was accomplished at time periods corresponding with probe response measurements. After test shutdown, the samples were taken to the atmospheric lab for evaluation.

7. Based upon trial and error, a number of techniques were tried and subsequently changed due to problems which developed during execution of the techniques.

APPENDIX B

TEST EQUIPMENT LISTING

Instrument	Model	Manufacturers
Insulation Tester	Weston Model 799	Weston Electrical Instrument Corp.
Lumetron Hemoglobin and Glucose Meter (Colorimeter)	Model No. 15 SN 14529	Photovolt Corp.
D.C. Power Supply (0-1000VDC) (0-500 MA)	Model 301C SN 793	John Fluke Mfg Co, Inc., Seattle, WA
Operational Power Supply (0-2000V) (0-10MA)	OPS 2000 SN E71030	Kepco Flushing, NY
Power Supply (26-30VDC)	XR28-7D SN7877	Con-Avionics Westbury, NY
Digital Voltmeter	V64A SN 11.4453	Non-Linear Systems, Inc., Del Mar, CA
Volt-Ohm-Meter	269-AF	Simpson
Humidity Meter		Bacharach Industrial Instrument Co.
VOM-Multimeter	ME-9D/U SN 1188	
Electrometer	600A	Keithley Instruments, Inc., Cleveland, OH
Electrometer	610B	Keithley Instruments, Inc., Cleveland, OH
Oscilloscope	Type 535	Tektronix, Inc.
X-Y Recorder	12D-2	F. L. Moseley Co.
X-Y Recorder	135A	Hewlett-Packard
Thermocouple	Type K	Honeywell
Digital Voltmeter	902	Electro Instruments

VITA

Robert Alan Vopalensky was born on 16 April 1941 in Portland, Oregon. After graduating from high school in Scappoose, Oregon, in 1959, he enrolled at the University of Portland, Portland, Oregon. In June 1964, he graduated in Physics, receiving his degree of Bachelor of Science and a commission in the United States Air Force Reserve. He entered active duty in July 1964, reporting to the 544th Aerospace Reconnaissance Technical Wing-Trajectory Center at Offutt Air Force Base, Omaha, Nebraska. He received his regular commission in the United States Air Force in May 1965.

Permanent address: Route 1, Box 404

Scappoose, Oregon 97056

This thesis was typed by Mrs. Windy Jojola

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Electrostatic Probe
Jet Exhaust
Jet Exhaust Gas Sampling

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this thesis was to experimentally investigate the feasibility of electrostatic probes in determining the ionic number density correlation with pollution concentration in the subsonic J-57 jet engine exhaust gases. A cylindrical electrostatic probe inserted normal to the gas flow was used for this experiment. The ionic number density provides an indication of

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a jet engines over-all efficiency and specifically the efficiency in the combustion chamber region. The pollution concentration is also indicative of an engine's over-all efficiency.

A major contributor to atmospheric contamination or pollution was measured by an off-line grab sampling technique and the application of basic chemical methods. The primary exhaust gas pollutant evaluated was oxide of nitrogen (NO_2), which was shown to correlate with thrust (expected) and, under certain conditions, D.C. potential.

Two new methods of predicting jet engine failure seem possible as a result of the coincidental failure of two engines which were being monitored. The first, counting current "spikes", has been investigated by other authors. The second, observing D.C. shifts, has been overlooked until now, and is reported as a new potential tool.