AD-A130 777 THE USE OF FUEL ADDITIVES TO CONTROL PLUME OPACITY OF TURBINE ENGINE TEST..(U) AIR FORCE ENGINEERING AND SERVICES CENTER TYDALL AFB FL ENGIN.. 1/1

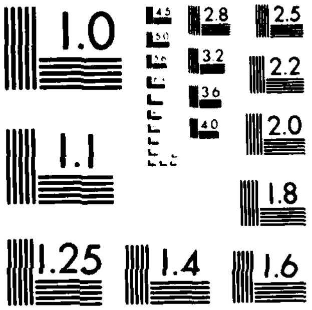
UNCLASSIFIED O M LOVELAND ET AL. APR 83 F/G 21/2 NL

END

DATE
FILMED

[illegible]

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

(12)

ESL-TR-83-08

THE USE OF FUEL ADDITIVES TO CONTROL PLUME OPACITY OF TURBINE ENGINE TEST CELLS

O.M. LOVELAND, A.F. KLARMAN,
J. TARQUINIO, T.L. STODDART
NAVAL AIR PROPULSION CENTER, TRENTON, N.J.
OKLAHOMA CITY AIR LOGISTICS CENTER,
OKLAHOMA CITY, OKLAHOMA

APRIL 1983

FINAL REPORT
MARCH 1978 - OCTOBER 1981

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

ENGINEERING AND SERVICES LABORATORY
AIR FORCE ENGINEERING AND SERVICES CENTER
TYNDALL AIR FORCE BASE, FLORIDA 32403

NOTICE

PLEASE DO NOT REQUEST COPIES OF THIS REPORT FROM HQ AFESC/RD (ENGINEERING AND SERVICES LABORATORY). ADDITONAL COPIES MAY BE PURCHASED FROM:

NATIONAL TECHNICAL INFORMATION SERVICE
5285 PORT ROYAL ROAD
SPRINGFIELD, VIRGINIA 22161

FEDERAL GOVERNMENT AGENCIES AND THEIR CONTRACTORS REGISTERED WITH DEFENSE TECHNICAL INFORMATION CENTER SHOULD DIRECT REQUESTS FOR COPIES OF THIS REPORT TO:

DEFENSE TECHNICAL INFORMATION CENTER
CAMERON STATION
ALEXANDRIA, VIRGINIA 22314

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

1. REPORT NUMBER ESL TR-83-08	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) THE USE OF FUEL ADDITIVES TO CONTROL PLUME OPACITY OF TURBINE ENGINE TEST CELLS		5. TYPE OF REPORT & PERIOD COVERED Final Report March 1978 - October 1981 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) O.M. Loveland, A.F. Klarman, J. Tarquinio, T.L. Stoddart		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Air Propulsion Center, Trenton, New Jersey Oklahoma City Air Logistics Center Oklahoma City, Oklahoma		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS JON 20543A29
11. CONTROLLING OFFICE NAME AND ADDRESS HQ AFESC/RDVS Tyndall AFB, Florida 32403		12. REPORT DATE April 1983 13. NUMBER OF PAGES 39
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release. Distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Availability of this report is specified on reverse of front cover.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Test Cell
Fuel Additive
Opacity
Emission Control
Smoke Abatement
Air Pollution
Pollution Control
Jet Engines
Turbine Engines
Ferrocene
Particulates

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

This research, a joint Air Force/Navy study, evaluated the use of fuel additives to reduce the opacity of turbine engine test cell emissions. Automated smoke abatement system (ASAS) was used to inject ferrocene and XRG fuel additives into J57-43 turbine engines. Data obtained from this study indicate that ferrocene can be used to control test cell opacity without major impact on engine performance. The XRG fuel additive was not effective in reducing opacity. Major problems encountered with the ASAS were resolved during the project. Recommendations for further improvement of the ASAS were reported.

PREFACE

This report was prepared at the Naval Air Propulsion Center, Trenton, New Jersey, The Oklahoma City Air Logistics Center, Oklahoma City, Oklahoma, and the Air Force Engineering and Services Center, Tyndall AFB, Florida, under JON 20543A29.

This report documents work performed between March, 1978, and October, 1981. AFESC/RDV project officers were Captain James Tarquinio and Captain Terry L. Stoddart.

This report has been reviewed by the Public Affairs Office(PA) and is releasable to the National Technical Information Service. At NTIS it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

Terry L. Stoddart
TERRY L. STODDART, Capt, USAF, BSC
Project Officer

John T. Slankas
JOHN T. SLANKAS, Maj, USAF
Chief, Environmental Sciences Branch

Michael J. Ryan
MICHAEL J. RYAN, Lt Col, USAF, BSC
Chief, Environics Division

Francis B Crowley III
FRANCIS B. CROWLEY III, Col, USAF
Director, Engineering and Services Laboratory

A

(The reverse of this page is blank)

TABLE OF CONTENTS

TABLE OF CONTENTS (CONCLUDED)

LIST OF FIGURES

LIST OF TABLES

(The reverse of this page is blank)

SECTION I

INTRODUCTION

The Department of Defense (Navy and Air Force) has for some time sought an environmentally and economically acceptable method to reduce the opacity of turbine engine test cell emissions. Based on the results of previous research and economic studies, a review committee comprised of Air Force Logistics Command, Air Force Systems Command, and U.S. Navy representatives determined that fuel additives, particularly ferrocene, merited further investigation.

This research addresses the use of an Automated Smoke Abatement System (ASAS) to control the injection of fuel additives into the engine being tested. The ASAS responds to the opacity of exhaust smoke; automatically increasing or decreasing the volume of fuel additive flow. The ultimate purpose of the system is to reduce visible smoke in order to comply with environmental regulations. Currently, Ringelmann 1 (20 percent opacity) is the National Standard. The results of this research can be applied to many Air Force and Navy aircraft engines when new environmental regulations dictate.

This joint Air Force/Navy study was conducted at the Oklahoma City Air Logistics Center, an engine overhaul facility.

SECTION II

FACILITIES, EQUIPMENT AND MATERIALS

1. TEST CELL

Test Cell Number 8, Building 3703, at Tinker Air Force Base, was selected as the project cell. This is the eighth or end cell in a block of eight test cells whose intakes and exhaust stacks are oriented east to west. Test Cell 8 is located at the south end of the complex. This test cell would be influenced least by a predominant southerly wind, thereby making it the most desirable of the eight. One distinctive feature of all these test cells is that the front wall of the exhaust stack extends above and curves slightly towards the back wall to form a partial hood over the exhaust stack exit. To properly position the transmissometer in the stack it was necessary to cut a hole in the front wall of the stack and insert one of the transmissometer units, while the other transmissometer unit was mounted over the top of the back wall. Figure 1 shows the installation of the transmissometer units in the stack.

2. ADDITIVES

Ferrocene was purchased from Arapahoe Chemicals, Inc., of Boulder, Colorado, in 55-gallon drums under the trade name, PD 1471®. This material consists of ferrocene dissolved in xylene at a concentration of 10 percent ferrocene by weight. The additive was used as purchased from the manufacturer.

XRG was purchased from Natural Resources Guardianship International, Inc., of Clayville, New York, in 55-gallon drums. The exact chemical formulation of this additive was not provided by the manufacturer, but they did indicate that it contains ferrous sulfate, pitric acid, nitrobenzene, toluene, isopropyl alcohol, and water. The additive was used as purchased from the manufacturer.

3. SMOKE MEASUREMENT

The degree of smoke (plume opacity) emitted from the test cell exhaust stack was rated using a visual (observer) opacity method (Ringelmann Numbers) and a transmissometer. The visual method was used as the primary means of evaluating plume opacity because most state air pollution control agencies use this method for determining visible emission violations. The visual determinations were made by a representative from the Aircraft Environmental Support Office located at the Naval Air Rework Facility, North Island, San Diego, California. The representative was certified by the State of California.

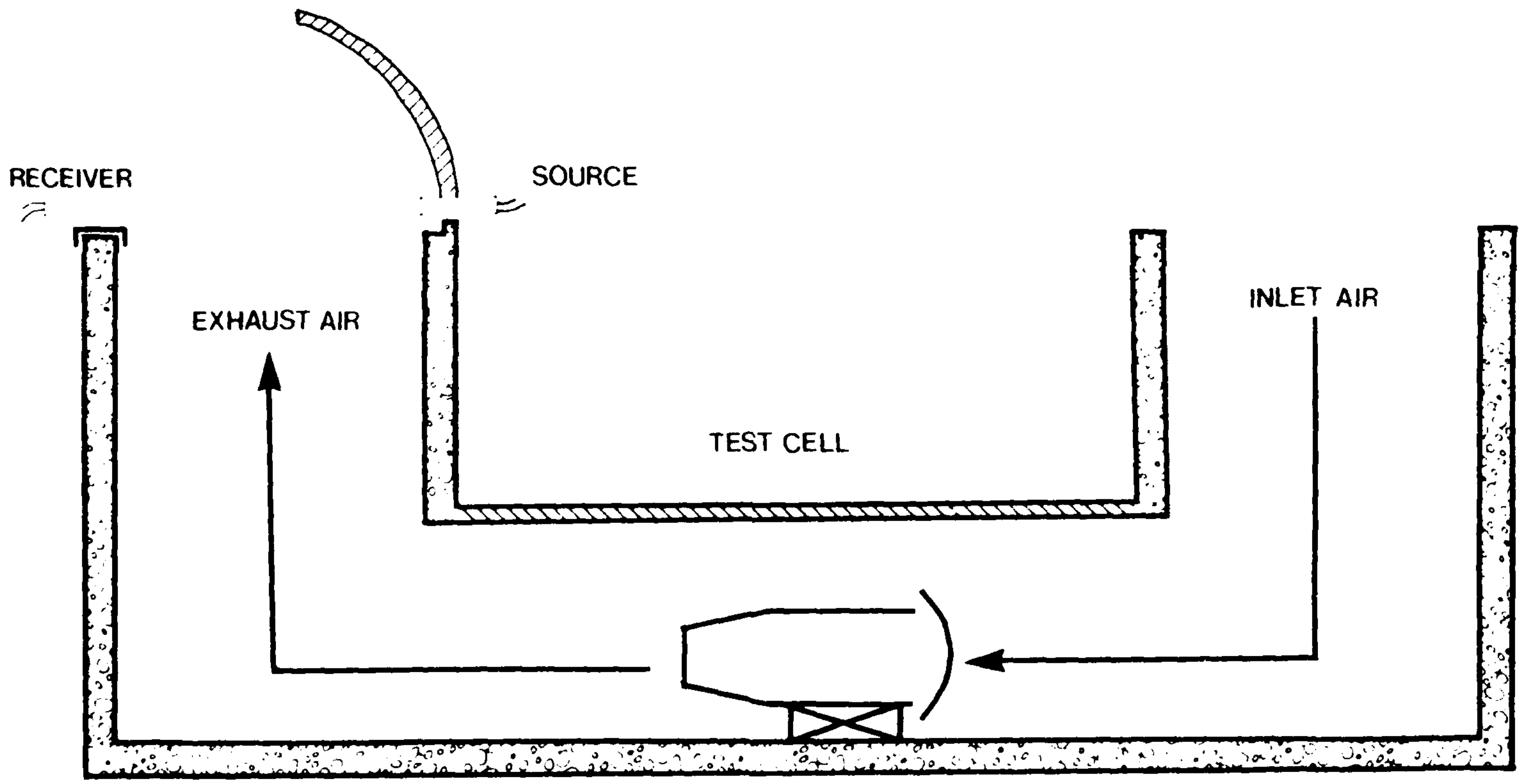


Figure 1. Tinker Air Force Base Stack Installation

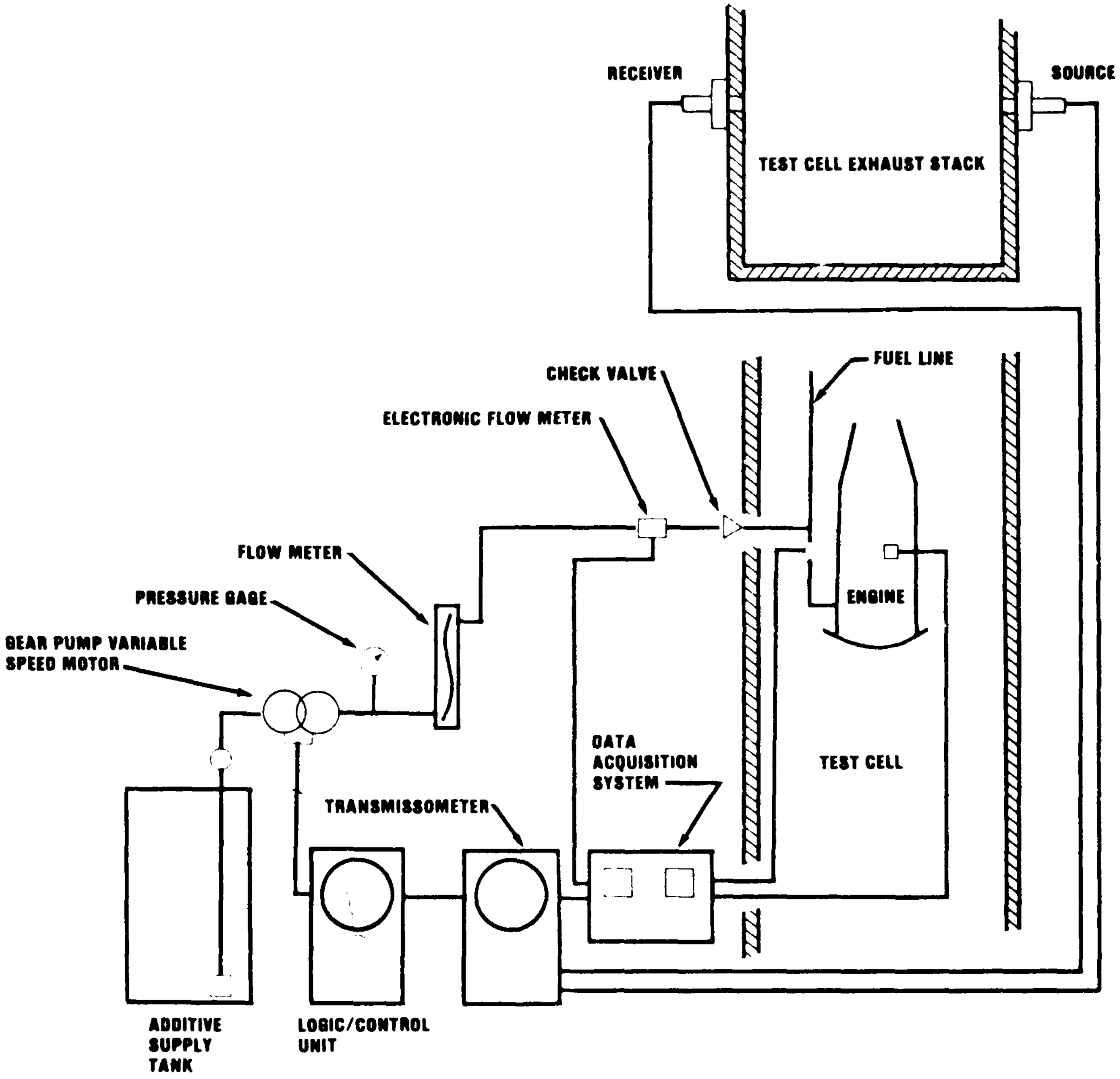
4. AUTOMATED SMOKE ABATEMENT SYSTEM (ASAS)

An ASAS was purchased from the Robert H. Wagner Company, Inc., of Chatham, New Jersey. The system contains a transmissometer mounted in the exhaust stack to monitor test cell exhaust plume opacity, a variable speed, variable stroke piston pump to inject the additive into the engine fuel system, and a logic/control unit which compares the test cell plume opacity to a control value or set point. The system can automatically modulate the additive flow rate to maintain the test cell plume opacity at or below the control value. The control value was set just below the local opacity standard. Reference 1 is a detailed report describing the development of this system and how it operates. In addition to the basic system, the following components were added: a rotameter and electronic flowmeter to measure additive flow rate and a data acquisition system to monitor and record plume opacity, additive flow rate, engine fuel flow rate, engine speed and time. Figure 2 is a schematic of a typical installation of this equipment.

5. ENGINES

One engine from each of the following engine models was included in the study to obtain baseline plume opacity levels:

J57-P-43, J75-P-17, TF30-P-100, TF33-P-7 and TF41-A-2. Only the J57 engine model was exposed to ferrocene and XRG. The fuel used during the study was JP-4.



NOTE:

(1) ALL TUBING 3/8" OR 1/2" (DO NOT USE 1/4").

(2) ENGINE FUEL FLOW METER HAS TO BE DOWNSTREAM TO WHERE ADDITIVE IS INJECTED.

(3) INJECT ADDITIVE AS CLOSE AS POSSIBLE TO THE ENGINE.

Figure 2. Automated Smoke Abatement System

SECTION III

TEST PROTOCOL

In view of the plume opacity readings, the committee selected the J57 engine for initial tests in determining the viability of ferrocene as a smoke suppressant. During this period, a new chemical fuel additive (XRG-3) was recommended and accepted for inclusion into the test program. Initial operating sequences were established concerning engine testing:

(a) Engines were of the same type and model (J57-P-43).

(b) All engines were zero-time engines that "sold off" the test cells with an acceptable level of performance. This action excluded poorly performing and inefficient engines from taking part in the test.

(c) Engines were performance tested in Test Cell 8 prior to injection of fuel additive in order to assure intercell compatibility and verify the absolute integrity of the engine's initial performance baseline.

(d) The set point of the ASAS was adjusted until plume opacity was slightly below 20 percent visual opacity. Once the proper set point was established, the engine was operated at various power conditions simulating the post overhaul functional check points, until a total of 10 hours was achieved. Engine performance and ASAS operation parameters were continuously monitored during this period.

(e) Engines were operated for a total of 10 hours. This 10-hour period was broken down into 2-hour segments. A performance test was accomplished at the end of each 2-hour segment. Each 2-hour period was comprised of 15-minute intervals of operation at four different power settings (100 percent, 90 percent, 75 percent and idle). Fuel additive was injected only at 100, 90, and 75 percent of military power settings In fact, the set point on the ASAS had to be reduced to about 14 percent plume opacity to activate additive injection at the 75-percent power setting. Even then, some oscillation between the on and off modes of the ASAS occurred because of the very minimal additive flow required. Initial plans to intentionally inject additive at lower power settings were discarded as they would not represent a true representation of a normal engine undergoing test if the use of fuel additives were to be required in the future.

SECTION IV

BASELINE MEASUREMENTS

Tables 1 through 5 present the results of the baseline smoke tests. Although meteorological conditions and the location of the test cell stack did not offer the optimum condition for reading visible smoke plumes, the values obtained for each engine can be considered representative of what those engine models produce. The short duration of the test program and the production schedules of the overhaul facility made it impossible to wait for the ideal conditions. The high wind speed and cloudy conditions which existed during the test program might tend to lower the visible opacity of the plume.

The J57-P-43 and J79-6E-15 engine models appear to be the main sources of excessive test cell exhaust smoke (greater than 20 percent visual opacity). The TF33-P-7, TF41-A-2 and J75-P-17 engine models are marginally acceptable. The TF30-P-100 engine model does not appear to be a smoke problem engine. Plume opacities for the J57, J75, TF33, and TF41 engines were within ± 5 percent of the 20-percent guideline, therefore additional testing of these engine models is necessary to document the magnitude of any potential test cell smoke problem. Table 6 compares plume opacities of similar engines using JP-4 and JP-5 type fuels. The engines operated using JP-5 had a visual opacity at least 10 percent higher than similar engines operated using JP-4. Since the physical and chemical properties of JP-8 approach those of JP-5, the potential to have an excessive test cell smoke problem in the future will intensify as the Air Force changes to JP-8 fuel.

In Figure 3, the visual opacity determined for each engine tested is plotted against the Smoke Number (SN) reported in Reference 2 for that engine model. The data were fitted to an equation of the form $Y = A+BX^2$ by the method of least squares analysis. The following equation was generated:

$$\text{Visual Opacity} = 0.212 + 7.27 \times 10^{-3} \times SN^2 \qquad \text{Equation (1)}$$

with a correlation coefficient of 0.96 and a standard deviation for visual opacity of ± 2. This equation can be used to predict the plume opacity for any engine operated in this test cell.

To utilize the ASAS for control of test cell plume opacity during J57/ferrocene tests, it was necessary to calibrate the response of the transmissometer to the visual plume opacity reading. Figure 4 is a plot of plume opacity obtained by the transmissometer and visual observer during the baseline engine evaluations. This data was fitted to an equation of the form $Y = A+BX$ by the method of least square analysis. The following equation was generated:

$$\text{Transmissometer Opacity (\%)} = 2.890 + 0.715 \; \text{Visual Opacity (\%)} \qquad \text{Equation (2)}$$

TABLE 1. BASELINE SMOKE - J57-P43 (S/N 627112)

Time	Power Condition	N_2 RPM (% max N_2)	Fuel Flow (lb/hr)	Transmissometer %	Ringelmann #	Ringelmann %
13.33	I	60.0	980	11.8	3/4	15
13.34	75%	89.2	5070	11.4	3/4	15
13.37	NR	93.0	7050	18.9	1	20
13.40	MAX	95.7	9620	18.1	1-1/4	25

Sky Condition - Cloudy

Wind - 15-20 mph

TABLE 2. BASELINE SMOKE - J57-P17 (S/N 611770)

Time	Power Condition	N_2 RPM (% max N_2)	Fuel Flow (lb/hr)	Transmissometer %	Ringelmann	
					#	%
12:07	JI	57.4	1490	1.8	0	0
				1.6		
				1.5		
12:12	75%	95.7	8144	15.2	3/4	15
				15.2	3/4	15
				15.2	3/4	15
12:15	NR	100.6	11373	20.2	1	20
				19.9	1	20
				19.4	1	20
12:18	MIL	102.9	12845	19.7	1	20
				19.7	1	20
				19.7	1	20
12:21	I	62.0	1460	0.9	0	0
				1.2		
				1.5		

Sky Condition - Partly Cloudy

Wind - 0 mph

TABLE 3. BASELINE SMOKE - TF30-P100 (S/N 679611)

Time	Power Condition	N_2 RPM (% max N_2)	Fuel Flow (lb/hr)	Transmissometer %	Ringelmann	
					#	%
17:27	I	69.3	1260	3.8	0	0
17:30	75%	88.7	5830	8.7	1/4	5
				8.0	1/4	5
				8.2	1/4	5
17:34	NR	92.1	7580	7.7	1/4	5
				7.7	1/4	5
17:37	MAX	95.9	9580	5.8	1/4	5
				5.9	1/4	5
17:40	I	70.0	1260	1.5	0	0

Sky Condition - Partly Cloudy

Wind - 0-5 mph

TABLE 4. BASELINE SMOKE - TF33-P7 (S/N 659662)

Time	Power Condition	N_2 RPM (% max N_2)	Fuel Flow (lb/hr)	Transmissometer	Ringelmann	
				%	#	%
16:19	I	57.2	1110	5.6	0	0
16:22	75%	90.5	5500	17.1	1/2	10
				16.5	1/2	10
16:25	NR	92.8	6300	15.4	3/4	15
16:28	MIL	95.7	7860	13.7	3/4	15
				13.3	3/4	15
16:32	TAKEOFF	98.8	9820	11.0	3/4	15
				10.6	3/4	15
16:35	I	60.6	1060	0.6	0	0
				0.3	0	0

Sky Condition - Partly Cloudy

Wind - 0 to 5 mph

TABLE 5. BASELINE SMOKE - TF41-A2 (S/N 141908)

Time	Power Condition	N_2 RPM (% max N_2)	Fuel Flow (lb/hr)	Transmissometer %	Ringelmann #	Ringelmann %
09:08	I	7081	1070	-0.3	0	0
				-0.3	0	0
09:12	75%	11680	5920	9.1	1/4	5
				8.8	1/4	5
				9.1	1/4	5
09:16	NR	12020	7100	10.6	3/4	15
				10.1	3/4	15
				10.0	3/4	15
09:19	(Intermediate)	12575	9270	14.5	1	20
	MIL			14.2	1	20

Sky Condition - Overcast

Wind - 0-5 mph

TABLE 6. COMPARISON OF NAVY AND AIR FORCE ENGINES

Engine Model		Plume Visual Opacity (%)	
Air Force	Navy	JP-4	JP-5
J57-P-43		25	
	J57-P-10		35
J79-GE-15		26 (EST)	
	J79-GE-8		55
TF41-A-2		20	
	TF41-A-2		30

This equation has a correlation coefficient of 0.92 and a standard deviation of 12.3. The high standard deviation is probably due to visual opacity which is measured in intervals of 5 percent while the transmissometer measures the opacity as continuum (different response to frequency yields different attenuation). The maximum allowable transmissometer opacity can be predicted from Equation (2) by substituting 20 percent for visual opacity and solving. A transmissometer opacity value of 17.2 percent is obtained. To control the exhaust plume opacity for the test cell at or below 20 percent visual opacity, the set point on the ASAS was adjusted so that the transmissometer opacity reading would not exceed 15 percent.

A J79 engine model was,orginally,to have been included in this test series, but it was not available at Tinker Air Force Base during the test period. The plume opacity for a J79-GE-15 engine can be predicted by Equation (1). Souza and Daley (Reference 1) reported that the J79-GE-15 engine model has a Smoke Number of 60. Using a Smoke Number of 60, Equation (1) predicts that the test cell plume capacity for this engine model, at the worst engine smoke condition, would be 26 percent. During the course of this project, several J79 engines were operated in Test Cell 8. Although these engines were undergoing testing in support of different projects, plume opacity was evaluated as being between 25 and 30 percent, confirming this prediction.

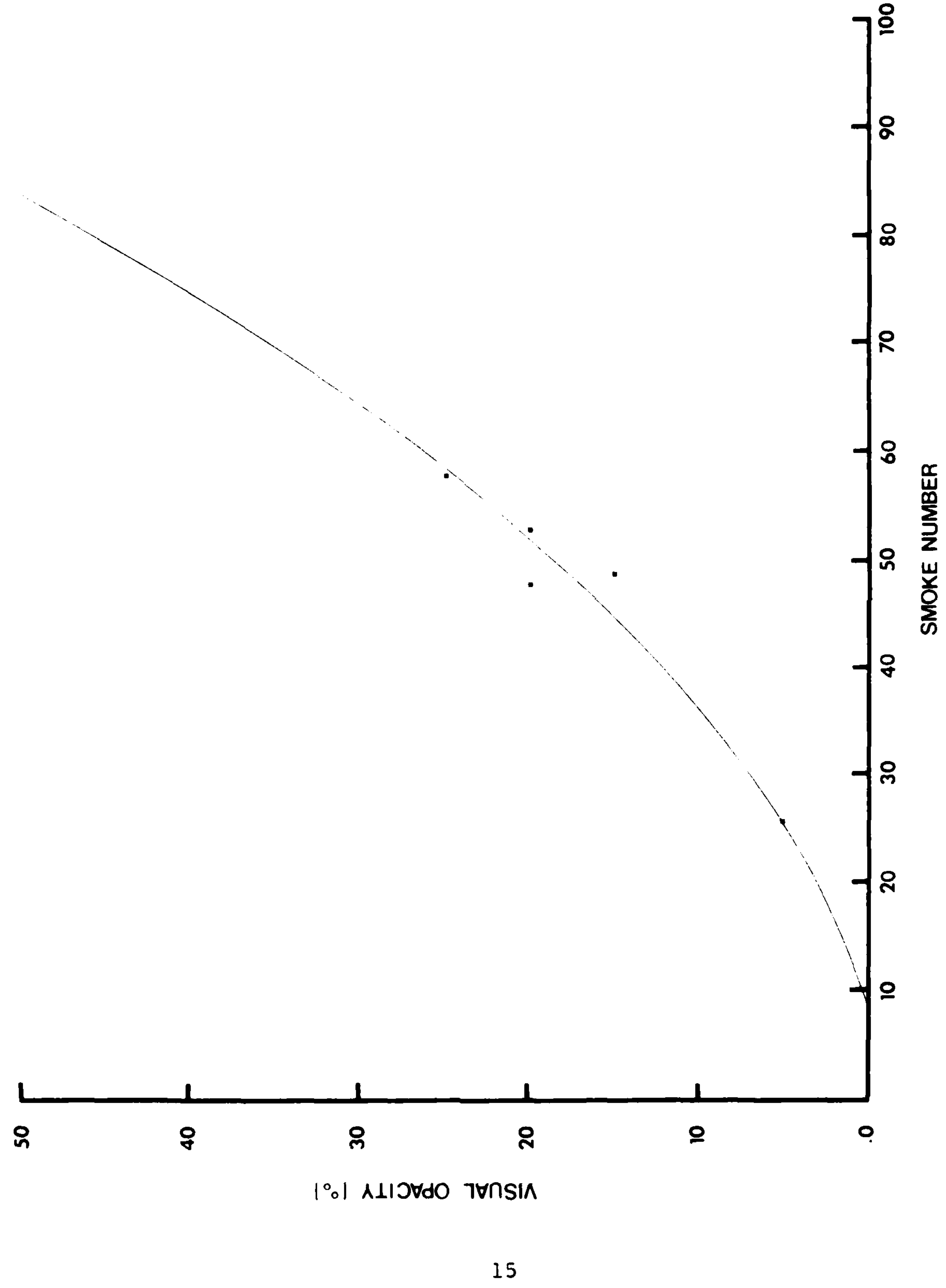


Figure 3. Visual Opacity/Smoke Number Correlation

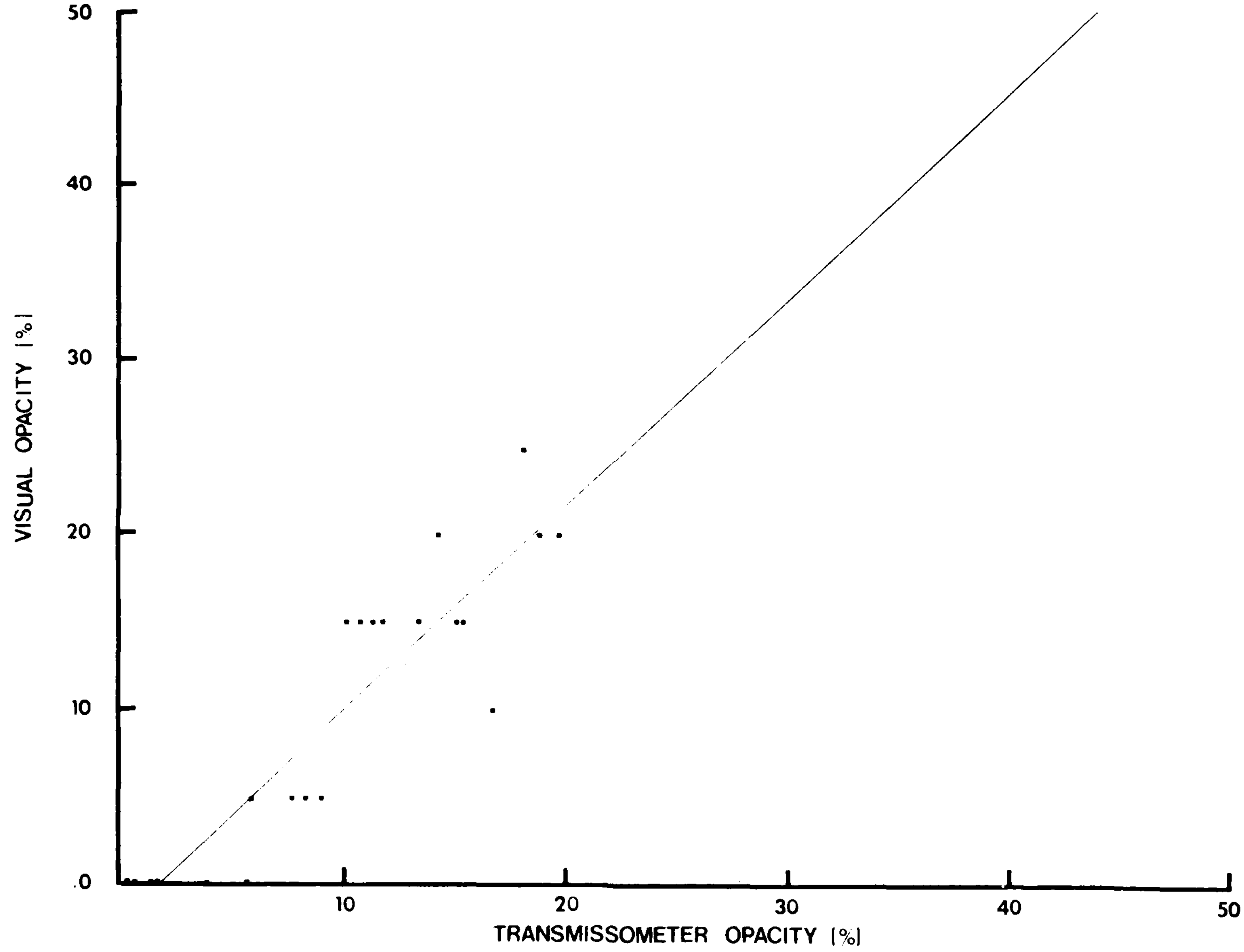


Figure 4. Transmissometer vs Visual Opacity

SECTION V

RESULTS AND DISCUSSION

1. PERFORMANCE BASELINE

All engines were performance-tested in Test Cell 8 prior to additive injection. These tests verified the engine integrity and established the engine's initial performance baseline. The initial baseline in each of the following figures is identified by the plot points being encircled and the plot line drawn in relation to the points. Figures 9 and 11 have two plotted lines depicted on each graph. The significance of these additional lines will be discussed further in this report. All data are corrected to standard conditions and are plotted, utilizing thrust as a constant.

a. Engine Pressure Ratio. Figure 5 reveals the following data:

(1) The repeatability of the test cell configuration, thrust stand and instrumentation is excellent.

(2) The initial performance baseline is documented as true and accurate.

(3) The operating characteristic of the thrust/engine pressure ratio does not change when the engine utilizes fuel diluted with ferrocene.

b. Low Rotor Speed. Figure 6 shows a trend toward higher rotor speed indicating the engine is required to operate at higher rpm to produce the same thrust.

(1) The speed increase averages approximately 30 rpm for any given value of thrust.

(2) The increase is readily discernible at the end of the first 2-hour period and increases at the end of 4 and 6 hours.

(3) At the end of the 6-hour interval, the rate of increase appears constant.

c. High Rotor Speed. The high-speed rotor also trended toward higher speeds, Figure 7.

(1) The speed increase averaged approximately 25 rpm. This increase varied slightly from the low-speed rotor in that the low-speed rotor increase appeared to be uniform throughout the power range and the high-speed rotor rpm increase was slightly less at slower speeds.

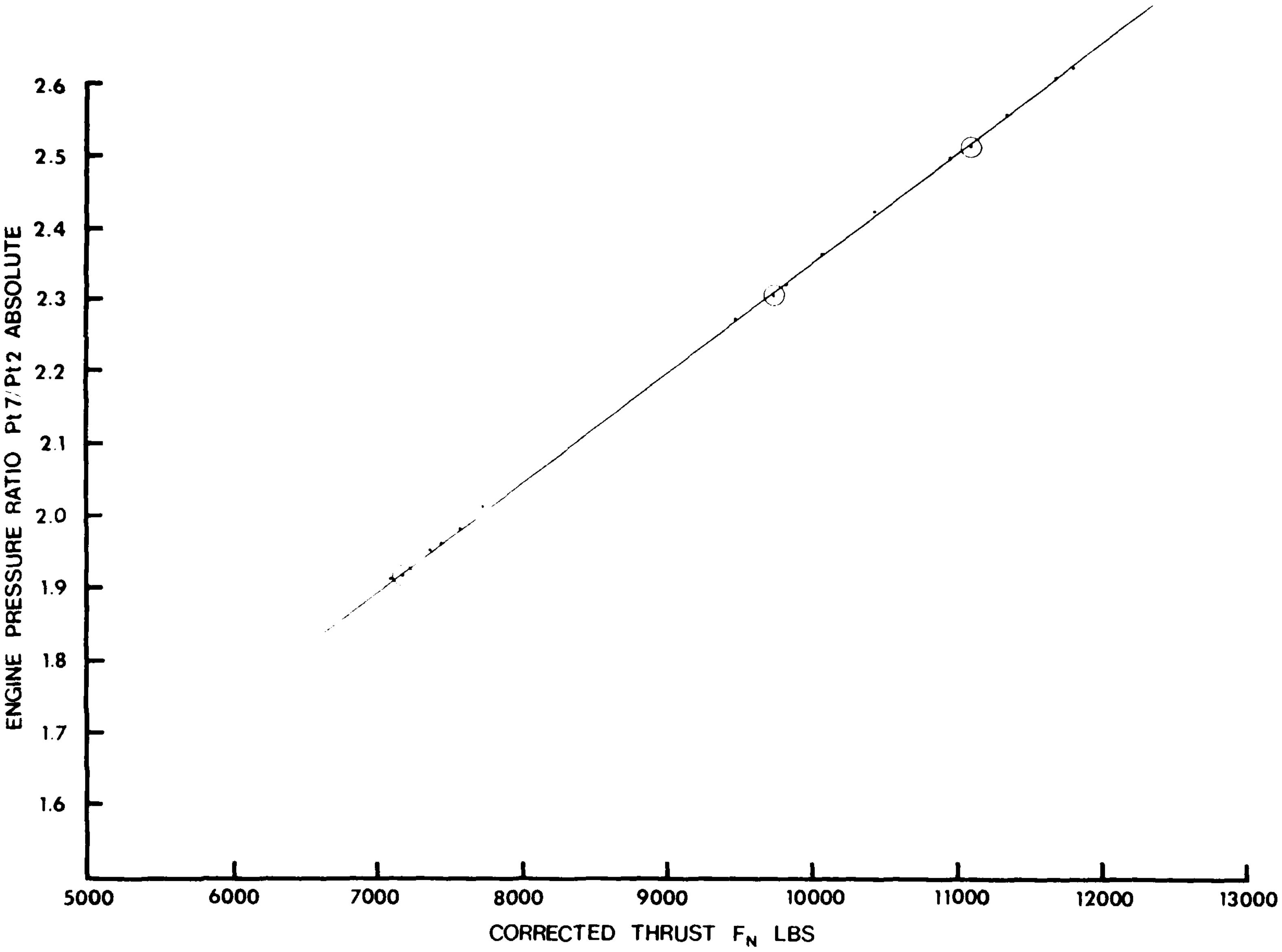


Figure 5. Engine Pressure Ratio vs Corrected Thrust

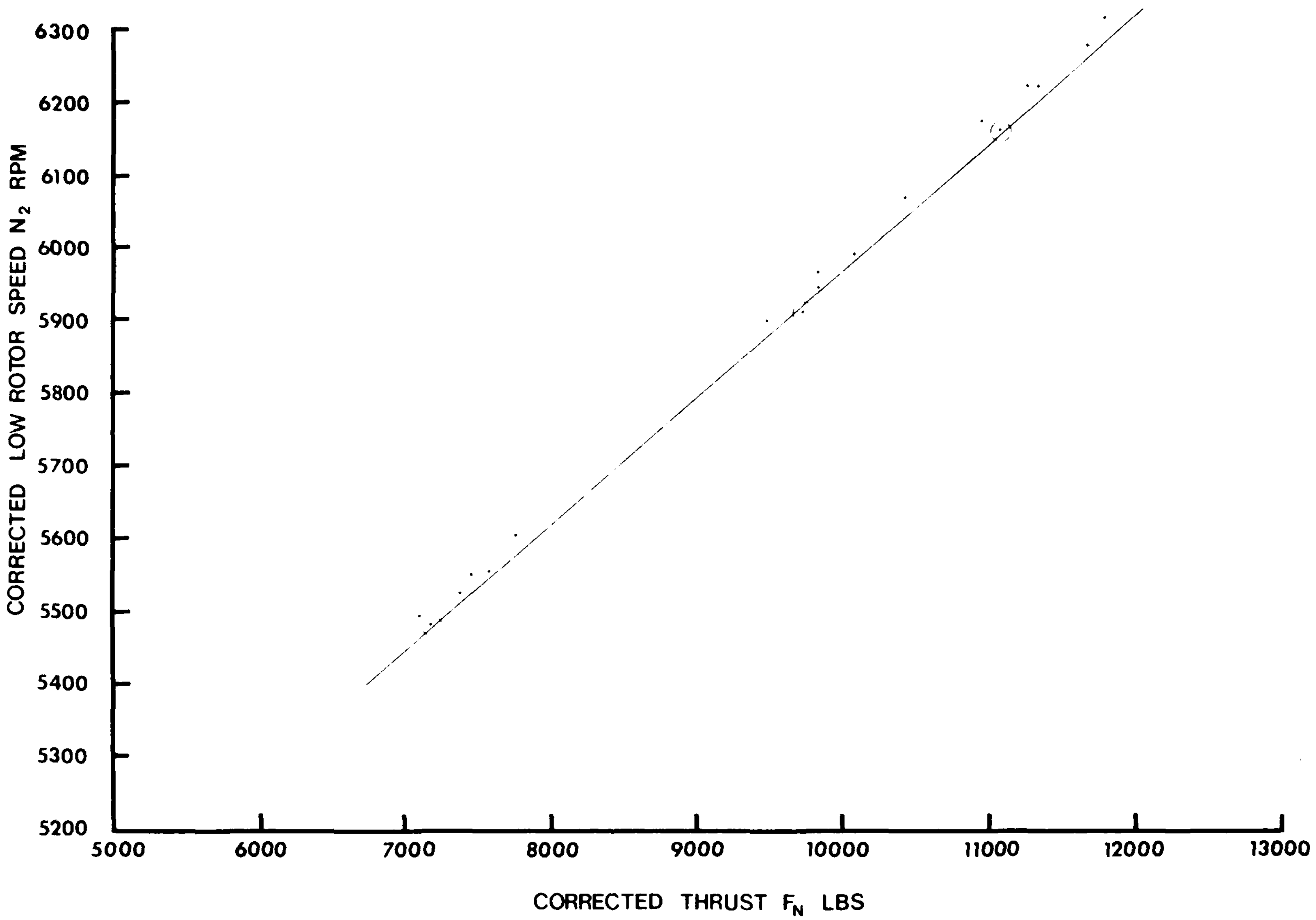


Figure 6. Corrected Low Rotor Speed vs Corrected Thrust

(2) Like the low-speed rotor, the high-speed rotor rpm increase was also immediately discernible and seemed to stagnate at the end of 6 hours.

d. Thrust-Specific Fuel Consumption. Thrust-Specific Fuel Consumption (TSFC), plotted in Figure 8, is a ratio of pounds of fuel to pounds of thrust. In effect, one can view TSFC as an indication of "miles per gallon."

(1) The shift in TSFC was much more dramatic than in previously discussed areas. The amount of shift was approximately .010 to .015 as depicted by the second line or an actual increase of 1.4 to 2.03 percent in fuel consumption.

(2) The increase, while seemingly small, is significant because it would increase the engine test reject rate by approximately 27 percent. However, a correction factor might be established that would consider this shift in the TSFC curve. To establish this factor would require more testing as initial testing indicates a gradual building of the error as testing is accomplished. One should also note that this error is induced by the injection of ferrocene. The rate at which the error is induced is not linear. The bulk of the shift appears to take place during the first 4 hours of operation. After that the rate of change slows very dramatically and, in some instances, stops.

e. Exhaust Gas Temperature. As shown in Figure 9, the exhaust gas temperatures (EGTs) ran uniform throughout the test. The temperature normally did not vary more than 2 or 3 degrees from the established baseline. This substantiates normal engine performance in that usually, for a given EGT, a given thrust corresponds to that value.

f. Fuel Flow. Like TSFC, total fuel flow revealed a substantial increase of about 1.5 to 2 percent for a given thrust value. This is demonstrated by the second line in Figure 10.

(1) Some engines will operate near the allowable fuel flow maximum. This figure reveals an increase of 75 to 125 pounds per hour depending upon the engine power setting.

(2) The seriousness of the impact of increased fuel flow must be determined initially as an amount of increase attributed to the engine reject rate and not merely as a percent of increase or decrease of overall engine efficiency. The predicted increase in engine rejects for this engine, as previously estimated in paragraph d (2) above, is 27 percent (based on an actual 6-month sample of engine performance data for the J57-P-43 engine).

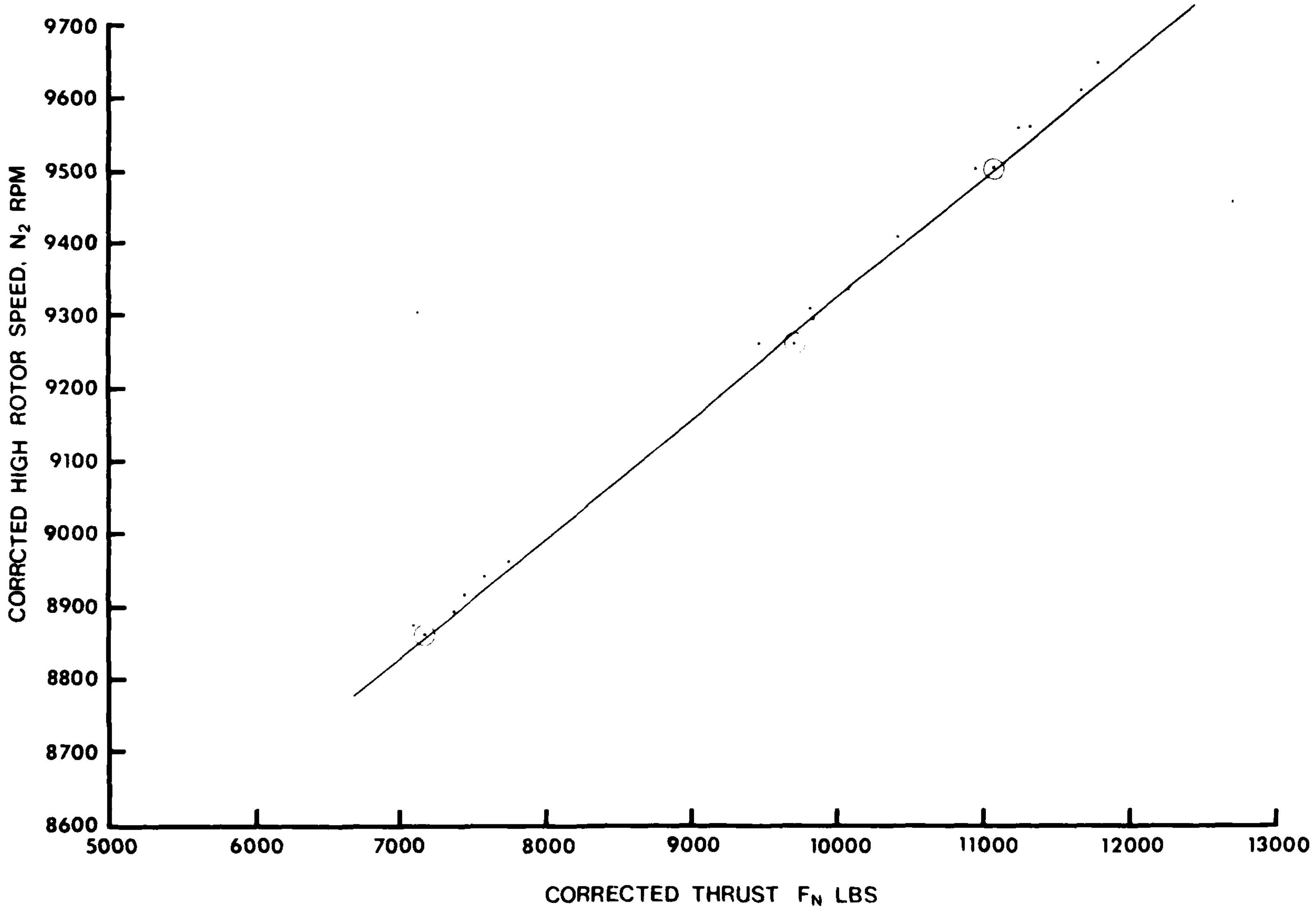


Figure 7. Corrected High Rotor Speed vs Corrected Thrust

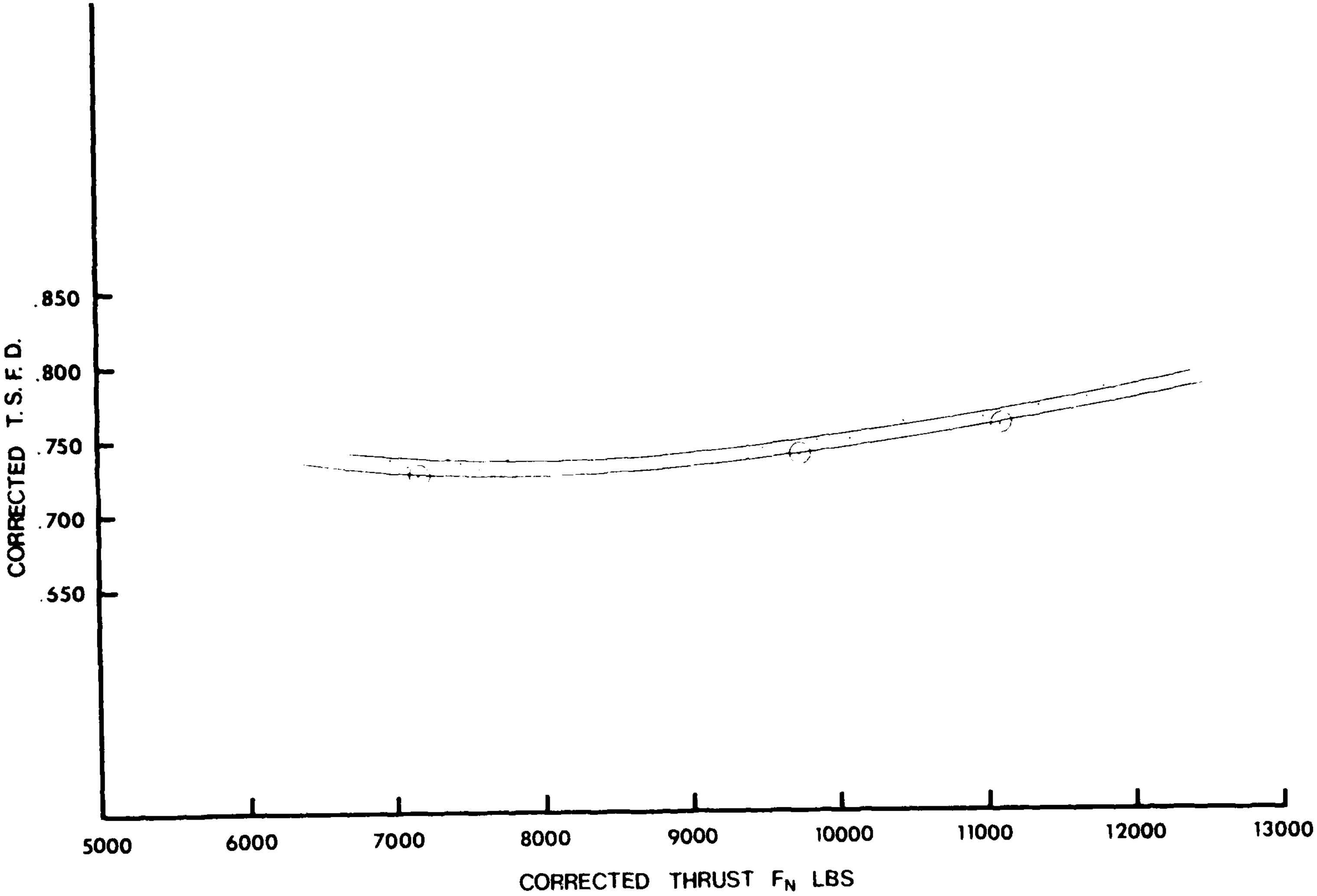


Figure 8. Corrected Thrust-Specific Fuel Consumption vs Corrected Thrust

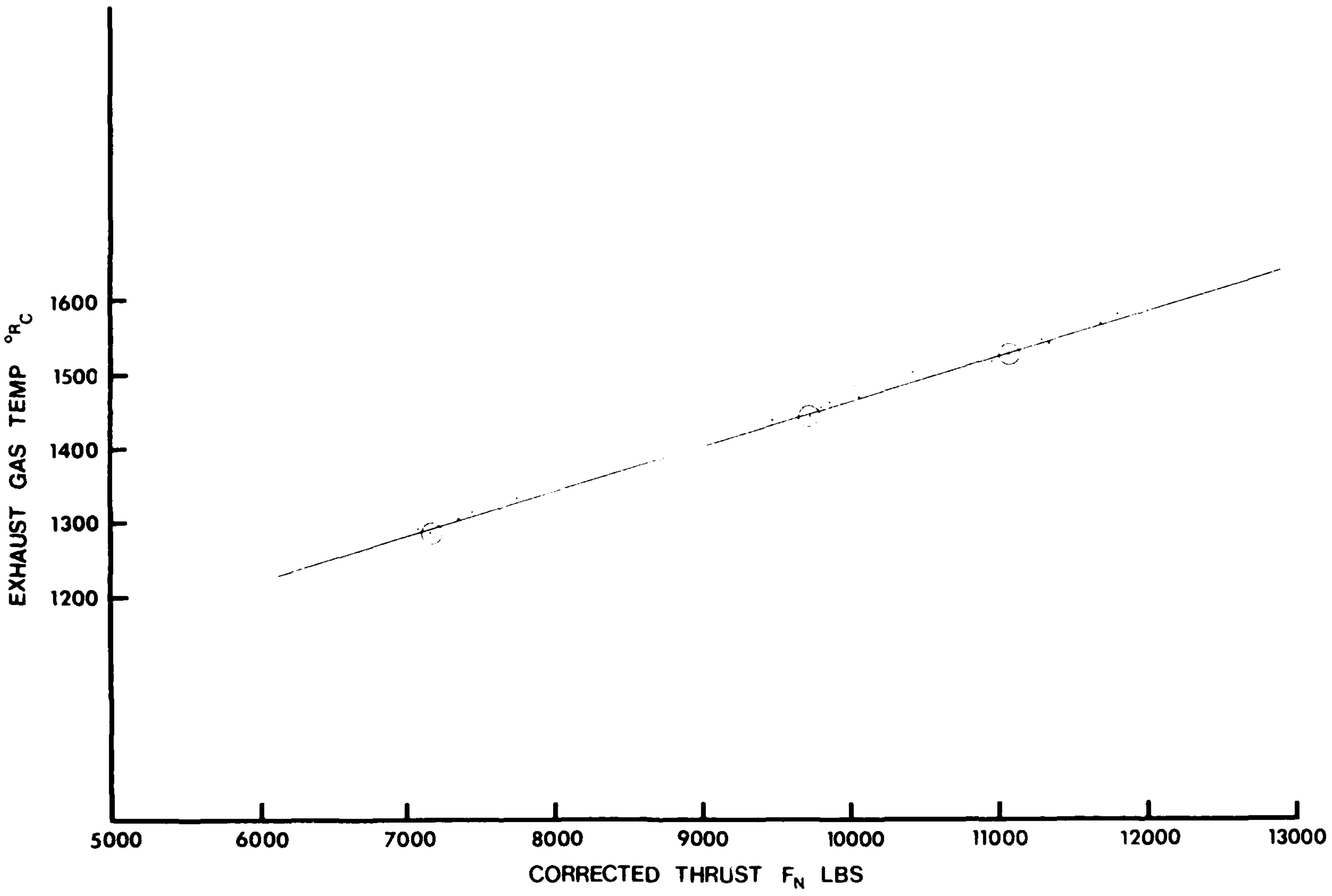


Figure 9. Exhaust Gas Temperature vs Corrected Thrust

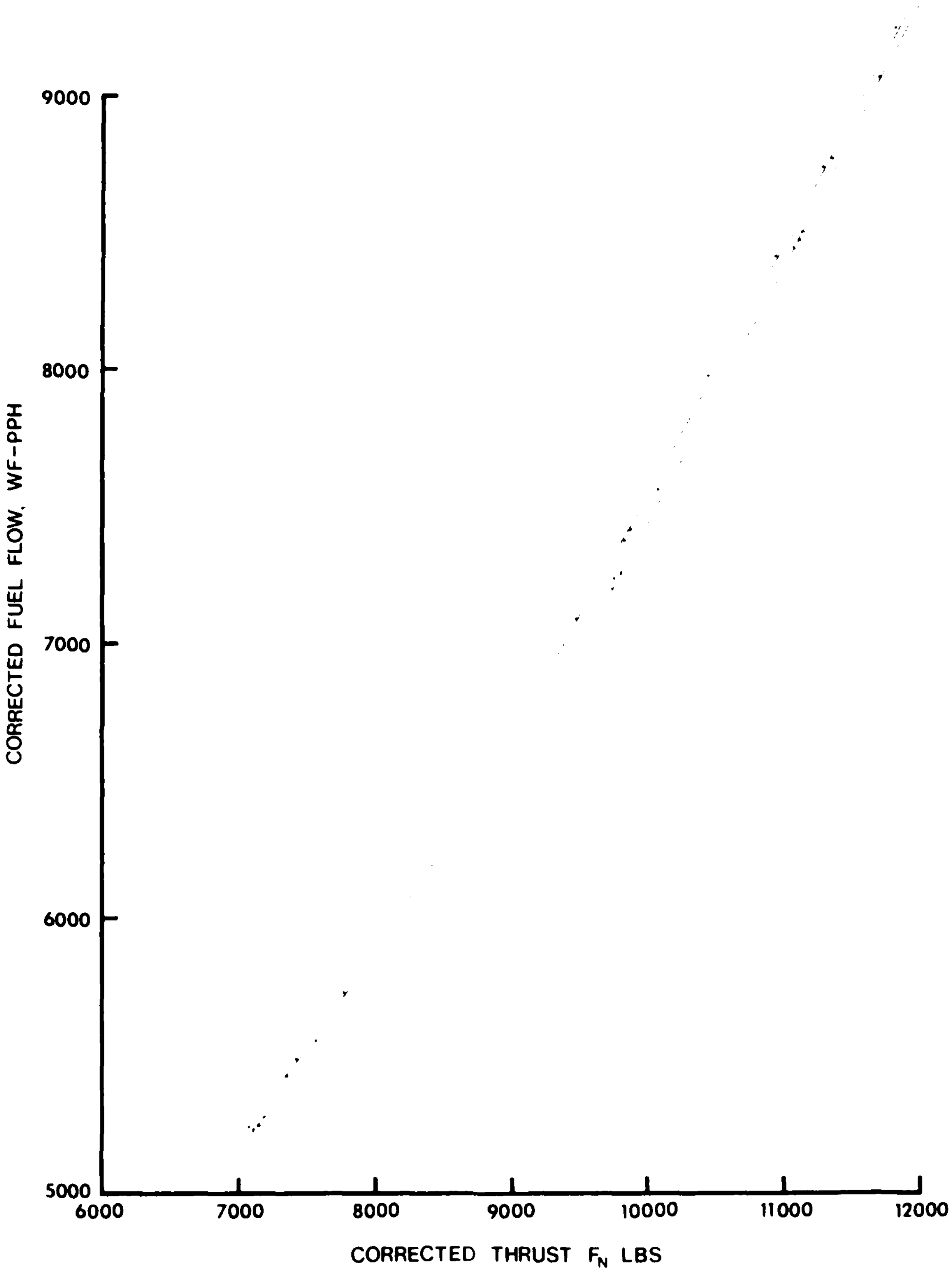


Figure 10. Corrected Fuel Flow vs Corrected Thrust

g. Ferrocene Additive Test. A J57-P-43 engine (S/N 627112) was used to evaluate the effectiveness of ferrocene for control of test cell exhaust plume opacity. During this test period, the ASAS was used to regulate the flow of ferrocene into the engine fuel system. The engine was operated over a test cycle simulating past overhaul performance checkruns . This cycle was repeated until 9.5 to 10 hours had accumulated on the engine. Ferrocene was required for controlling the plume opacity at engine power ratings of 75 percent military or greater. Table 7 presents typical engine performance, additive concentration and plume opacity data obtained during this test sequence.

h. XRG Additive Test. Prior to the start of the ferrocene test, a new additive sold under the trade name XRG® by Natural Resources Guardianship International, Inc., of Clayville, New York, was tested, using a J57 engine to determine its smoke reduction capability. The exact formulation of XRG® was not revealed by the manufacturer, who maintains that the additive uses an oxidizer to increase the burning rate of small soot particles. XRG® was included in the test program as a possible means of eliminating deposit buildup in engine hot sections resulting from the use of metal base smoke abatement additives. Additive flow rates up to 1 percent of engine military fuel flow rate were tested using the ASAS. This additive had no effect on smoke levels produced by the J57 engine. A subsequent retest of XRG® using a different additive batch had similar test results.

2. INITIAL TEST AND INSPECTION

a. The first engine (S/N627112) that received ferrocene injection was delivered to the OC-ALC teardown area for disassembly and inspection. In view of the fact that the smoke suppressant additive is injected only into the fuel system, the Committtee recommended engine disassembly and inspection to include primarily only the engine hot section. In addition, fuel manifold and nozzle assemblies were included in the inspection, along with other combustion-related parts.

b. This engine initially was injected with XRG®-3 in an effort to confirm the validity of the product as a smoke suppressant. This fluid was injected at a concentration rate of ten (10) times that of ferrocene with little or no effect. Samples of this fluid were forwarded for laboratory analysis at the manufacturer's plant to confirm the XRG®-3 batch integrity. Ferrocene testing was then initiated with the same engine in accordance with the previously outlined test program.

c. Inspection of the hot section of this engine revealed a residue with an orange discoloration on almost every part. This discoloration was uniformly distributed in most areas. In most instances, this residue was easily rubbed off. As expected, the residue generated by the ferrocene additive was identified as iron oxide. It was noted that the iron oxide residue appeared to be

TABLE 7. FERROCENE/J57 ENGINE TEST

Power Condition	N_2 (%)	Fuel Flow (lb/hr)	PD 1471 Flow Rate (lb/hr)	Concentration (lb (iron)/ 1000 lb fuel)	Plume Opacity (%)
Idle	62.9	1100	0	0	1.0
75% MIL	88.4	5390	3.4	0.019	14.7
90% MIL	91.5	7170	7.3	0.031	14.6
MIL	94.8	8700	9.2	0.032	14.3

concentrated in the high speed turbine section rather than elsewhere within the engine.

d. Conclusions drawn from this inspection were that the ferrocene additive produced no unusual effects on the engine hot section components other than the discoloration left by the iron oxide. The inspection served to confirm inspection data previously generated by Navy personnel.

e. Although engine performance did not appear to be affected during this test, lengthy delays and equipment problems influenced the Committee to disregard this engine as one of the projected five engine tests. This was largely due to the fact that the ASAS was virtually operated in a manual mode throughout the test. Therefore, a truly representative sample of a production engine, tested in a smoke plume-controlled mode, was not initially achieved.

SECTION VI

EQUIPMENT PROBLEMS

1. GEAR PUMP

During tests of the first engine, the ASAS seemed to require constant adjustment each time the engine power lever was moved to a different power setting. At first it appeared that the gain and sensitivity pots just required fine tuning. However, as the test progressed, it became apparent that the ASAS gear pump was too large for Air Force use. Since the ASAS was built in accordance with newly developed Navy specifications and the Air Force was just entering smoke plume control from a research and production testing viewpoint, no thought was given to changing the pump size at this time.

Primarily the problem with the pump was internal fluid slippage. In order for the pump to overcome the fuel inlet pressure, normally 45 psi, the pump rpm was increased so that when sufficient pressure was obtained the volume of the additive became excessive with regard to actual requirements. Possible solutions to this problem were determined to either dilute the additive supply with JP-4 or buy a lower concentration additive from the manufacturer.

Upon activation of the ASAS for testing of the second engine, the gear pump failed. Verification of operation of all other related parts,plus adequate additive supply, led to disassembly of the pump. This disassembly revealed that several gear teeth were missing from the fibrous gear. Subsequently, the ASAS manufacturer was contacted and the pump gear was replaced under warranty. Upon reactivating the ASAS after repairs were made, the transmissometer malfunctioned, rendering the system inoperable. At this point a service call was initiated to the manufacturer for onsite technical assistance.

Subsequent repair of the transmissometer, reactivation of the system, (the transmissometer problems will be discussed later in this report), and further testing, resurrected previous control problems initially attributed only to the pump. During this testing period, ferrocene was used in a dilution of 50 percent ferrocene and 50 percent JP4. It became obvious that the pump was still substantially quite large. Additionally, the control problems were further identified and attributed to absence of an accurate tachometer which forced the controller to make coarse and insensitive adjustments as it tried to control the smoke plume to the preset value. At this point, a recommendation was made to purchase a variable speed/variable displacement pump as well as an accurate tachometer. Subsequently, funding was approved and modification was accomplished.

During the ASAS manufacturer's onsite visit a malfunction in the rotameter (rotary flow meter) was discovered. Disassembly of this unit by the manufacturer indicated probable deformation of parts. This malfunction was attributed to the gear failure in the pump; causing gear teeth fragments to enter the rotameter. This unit was returned tor repair.

2. TRANSMISSOMETER

Activation of the ASAS prior to operating the second engine revealed a problem in the transmissometer. The unit would not zero or calibrate. A thorough check of all electrical circuits indicated that the system was operable. In checking one of the units atop the exhaust stack, the lens appeared foggy or moisture-covered. Subsequent disassembly revealed that the unit contained approximately 1/4 cup water. This unit was thoroughly cleaned and reinstalled atop the exhaust stack. During operation, immediately following reinstallation, the unit performed as designed.

During the next activation of the ASAS, the transmissometer again failed. A check of the unit atop the exhaust stack, which had previously failed, revealed more moisture contamination. This unit was returned to the manufacturer for repair at the same time the motor, pump, rotameter, and instrumentation were returned for repair or modification.

An attempt to repair this unit was accomplished by cementing the lens cover glass in place with silicone. Following repair, this unit exhibited the same problem; though the electrical plug was also removed and cemented in place. During each test, the unit, upon reinstallation, was required to be completely realigned both mechanically and electrically. Condensation, apparently caused by the dramatic heating and cooling of the unit within the test cell, was responsible for the failure. The only apparent solution to the moisture problem was to remove the unit from the exhaust stack after each test, thereby minimizing its exposure to jet engine testing conditions for which it was apparently not designed.

3. TRANSIT PROBLEMS

a. Vertimeter. A minor malfunction was noted in the vertimeter,during operation,shortly after the modified system was installed. The float within the vertimeter, which presents a visual indication of flow, was inoperative. Disassembly of this unit revealed a deformed float. This condition was also attributed to the gear pump failure. The float was replaced and no further problems were encountered with this unit.

b. Tachometer Belt. The tachometer belt furnished with the modified system has failed three times. The belt is constructed of a cable with plastic teeth molded to it. These teeth provide a positive link between the tachometer and the motor to preclude belt slippage. The cable failed by separating at the end connection where the two ends are joined. It has not been certain whether the belts are of poor quality or whether an alignment problem or some other undiscovered deficiency exists. The belt is operated quite loosely as it must be installed by rolling it on over the tachometer gear. The belt tension cannot be adjusted after the belt is installed because the adjustment screw is located behind the tachometer drive gear.

c. Ferrocene Crystallization. Minor problems developed related to the intermittent utilization of the ASAS. It was discovered that ferrocene will crystalize if not flushed from the ASAS additive supply line, injection line and other system component parts. In some instances, this crystallization occurred within 7 to 10 days. It was not determined if this problem was unique to the OC-ALC ASAS. However, the Navy provided no data to indicate their experience with similar problems. Therefore, this problem was not anticipated but it can be solved simply by flushing the system with fuel after usage if a forthcoming delay is anticipated. It is not known if this crystallization also occurs within the barrels as supplied by the additive manufacturer. This would merit investigation in order to determine the product's effective shelf life.

d. Pump Failure. The variable speed/variable displacement pump failed after a short operational period. The pump diaphragm disintegrated after being exposed to the ferrocene. Teardown of the pump revealed installation of a Hypalon® composition seal. This material is not impervious to ferrocene. The manufacturer replaced the defective seal with one composed of Viton®. Following repair, the pump operated without additional problems.

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

A. Baseline test cell exhaust plume opacity data were obtained for the J57-P-43, J75-P17, TF30-P-100, TF33-P-17 and TF41-A-2 engine models:

(1) The J57 was the only engine model which produced a plume opacity greater than 20 percent.

(2) Maximum plume opacity for the J75 and TF41 engines was 20 percent.

(3) Maximum plume opacity for the TF33 was 15 percent.

(4) Maximum plume opacity for the TF30-P-100 was 5 percent.

b. The test cell smoke plume from a J79-GE-15 engine model was not measured but was predicted to be approximately 25 percent.

c. For any given engine, JP-4 operation produces less smoke than JP-5. Changing to JP-8 should produce smoke similar to JP-5, since these fuels have similar properties.

d. Arapahoe Chemicals additive, PD 1471 (ferrocene), was effective in controlling plume opacity caused by the J57 engine.

e. Natural Resources Guardianship International, Inc., additive, XRG®, had no effect on plume opacity caused by the J57 engine.

f. Robert H. Wager Company's Automated Smoke Abatement System was capable of controlling plume opacity to a preselected value.

g. Ferrocene should be flushed from the ASAS if delays in operation are anticipated.

h. Engine performance is definitely affected through the use of ferrocene in the area of total fuel flow and thrust-specific fuel consumption (T.S.F.C.).

i. Improvement could be made in regard to the ASAS.

j. Ferrocene is not a major expense relative to test cell operating costs. Ferrocene consumption averages approximately 1 gallon per hour. Current estimated cost is 20 dollars per gallon.

k. Engine hot section inspection revealed no apparent engine damage or unusual effect other than discoloration.

l. An engine such as the TF41, whose fuel pump is lubricated and cooled by the fuel itself, might sustain damage when exposed to a fuel additive carrying iron particles.

m. Future production testing would require performance adjustment factors to correct total fuel flow and TSFC parameters.

n. The projected 27-percent increase in reject rate is based on an actual 6-month sample of engine performance data for the J57-43 engine.

o. In view of the shift in engine rpm, the engine Data Plate rpm could be suspect as it is not known whether the shift is permanent or temporary.

2. RECOMMENDATIONS

a. The ASAS basically performed the function for which it was designed. However, some deficiencies should be corrected.

(1) Transmissometers should be designed to prevent condensation entrapment and buildup.

(2) Tachometer installation should allow for belt adjustment.

(3) Air Force personnel installed a pressure gauge in the output side of the pump. This gauge provides a handy reference to verify pump output pressure and is recommended for future systems.

(4) The use of a flow totalizer is recommended to determine the total amount of fuel additive processed by an engine. This measurement might also correlate to the TSFC shift in regard to establishing a graphical correction.

(5) The pump, although variable speed/variable displacement, is too large for Air Force use in a production type of environment. The pump was operated with the percent displacement indicator set at approximately 8. This presented problems because the pump had difficulty in displacing enough fluid output pressure to overcome the fuel inlet pressure. Increases in the displacement indicator resulted in too much additive being injected. A smaller pump that could be operated at midrange appears to be more desirable.

b. Further testing is required to define the parameters of the shifts in fuel flow and TSFC. This testing would be required to accurately assess the impact of utilizing ferrocene during production testing. The parameter shift related to fuel requires further testing to determine if the shift is permanent or temporary. It is not known if the engine will return to baseline after a certain number of operating hours.

c. In view of the circumstances surrounding the Hypalon® seal failure, composition of seals within any engine type should be examined before introducing ferrocene.

d. The effective storage/shelf life of ferrocene should be determined.

e. Extended testing would be required to determine if iron oxide buildup affects the immersion pressure probes aft of the combustion chamber on engines that utilize PT7 or similar probes. Additionally, iron oxide, being a metal residue, might have an affect on thermocouples.

f. The flight operation of five J57 engines subjected to ferrocene during post overhaul checkruns should be monitored and a hot section inspection performed during the next scheduled maintenance period. This inspection should provide information on any long-term effects of ferrocene usage.

g. The Air Force Test Cell Smoke Abatement Program should be extended to include the J75, J79 and TF41 engine models.

REFERENCES

1. Klarman, A. F., Evaluation of an Automated Smoke Abatement System for Test Cells. NAPTC-PE-118, Naval Air Propulsion Center. 1977.

2. Sonza, A. F. and Daley, P.S., U.S. Air Force Turbine Engine Emission Survey, Vol. I, Test Summaries. CEEDO-TR-78-34, Air Force Civil and Environmental Engineering Development Office, Tyndall Air Force Base, Florida, 1978.

DAT

FILM