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TELEDYNE CONTINENTAL MOTORS MOBILE AL AIRCRAFT PRODU--ETC F/G 21/7  
COMPUTER SIMULATION OF AN AIRCRAFT ENGINE FUEL INJECTION SYSTEM--ETC(U)  
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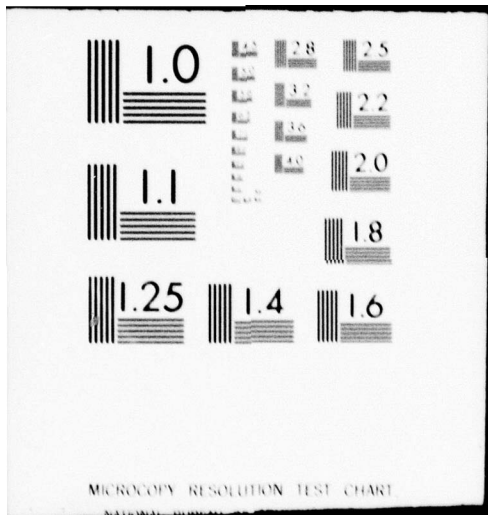
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**10** David D. Hester

**9** FINAL REPORT



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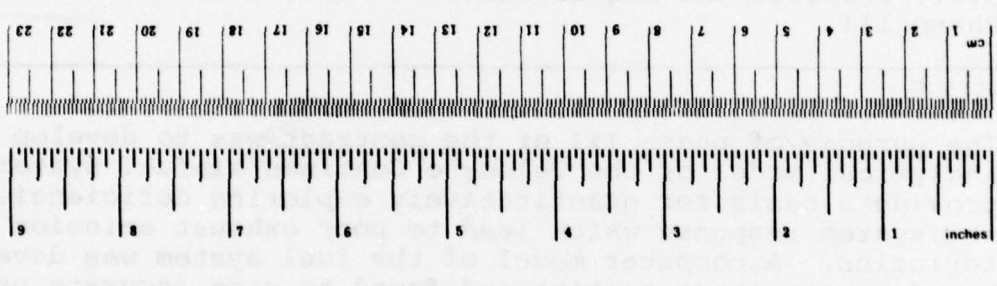
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16. Abstract The purpose of phase III of the contract was to develop an analytical model of the Teledyne Continental fuel system to provide a basis for quantitatively exploring deficiencies in the system response which lead to poor exhaust emission characteristics. A computer model of the fuel system was developed based on component testing and found to give accurate predictions for pressures and flow rates within the system. The model has been used to investigate modifications to the system for improved fuel management and reduced exhaust emissions. The effect of improved fuel management on engine exhaust emissions was evaluated.					
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# METRIC CONVERSION FACTORS

When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>			
millimeters	0.04	inches	in
Centimeters	0.4	inches	in
meters	3.3	feet	ft
meters	1.1	yards	yd
kilometers	0.6	miles	mi
<b>AREA</b>			
square centimeters	0.16	square inches	in <sup>2</sup>
square meters	1.2	square yards	yd <sup>2</sup>
square kilometers	0.4	square miles	mi <sup>2</sup>
hectares (10,000 m <sup>2</sup> )	2.5	acres	ac
<b>MASS (weight)</b>			
grams	0.035	ounces	oz
kilograms	2.2	pounds	lb
tonnes (1000 kg)	1.1	short tons	ton
<b>VOLUME</b>			
milliliters	0.03	fluid ounces	fl oz
liters	2.1	pints	pt
liters	1.06	quarts	qt
liters	0.26	gallons	gal
cubic meters	35	cubic feet	ft <sup>3</sup>
cubic meters	1.3	cubic yards	yd <sup>3</sup>
<b>TEMPERATURE (exact)</b>			
Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>			
inches	*2.5	centimeters	cm
feet	30	centimeters	cm
yards	0.9	meters	m
miles	1.6	kilometers	km
<b>AREA</b>			
square inches	6.5	square centimeters	cm <sup>2</sup>
square feet	0.09	square meters	m <sup>2</sup>
square yards	0.8	square meters	m <sup>2</sup>
square miles	2.6	square kilometers	km <sup>2</sup>
acres	0.4	hectares	ha
<b>MASS (weight)</b>			
ounces	28	grams	g
pounds	0.45	kilograms	kg
short tons (2000 lb)	0.9	tonnes	t
<b>VOLUME</b>			
teaspoons	5	milliliters	ml
tablespoons	15	milliliters	ml
fluid ounces	30	milliliters	ml
cups	0.24	liters	l
pints	0.47	liters	l
quarts	0.96	liters	l
gallons	3.8	liters	l
cubic feet	0.03	cubic meters	m <sup>3</sup>
cubic yards	0.76	cubic meters	m <sup>3</sup>
<b>TEMPERATURE (exact)</b>			
Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

\*1 in = 2.54 exactly. For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price \$2.25, SD Catalog No. C13.10.286.

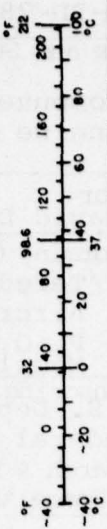


TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
Purpose	1
Background	1
Overview	2
DISCUSSION	6
Description of the Continental Fuel Injection System	6
Description of the Fuel System Model	9
CONCEPTS TO IMPROVE FUEL INJECTION	49
CONCLUSIONS	59
REFERENCES	60
APPENDIX	A-1

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LIST OF ILLUSTRATIONS

<u>Figure</u>	<u>Title</u>	<u>Page</u>
1	Fuel Flow Limits for TSIO-360-E	3
2	Generalized Mixture Ratio Curve	4
3	Fuel Injection System Hardware	7
4	Fuel Injection System Schematic	8
5	Metered Fuel Assembly Calibration	12
6	Fuel System Model	13
7	Friction Factors for Fully Developed Flow	16
8	Variation of Fuel Viscosity with Temperature	17
9	Specific Weight of 100/130 Avgas	18
10	Vane Pump Calibration	20
11	Vane Pump Calibration	21
12	Vane Pump Flow Map	22
13	Vane Pump Leakage	23
14	Fuel Pump Assembly	24
15	Variable Orifice Flow Characteristics	25
16	Variable Orifice Flow Area	26
17	Variable Orifice Loss Factor	28
18	Aneroid Test Results	29
19	Aneroid Deflection Due to Axial Force	30
20	Effect of Relief Valve Adjustment on Valve Pressure Loss	33
21	Effect of Turbo Discharge Pressure on Relief Valve	34

List of Illustrations - Cont'd.

<u>Figure</u>	<u>Title</u>	<u>Page</u>
22	Vapor Separator Flow Rate	35
23	Air Throttle and Fuel Metering Assembly	37
24	Throttle Orifice Area	38
25	Throttle Orifice Pressure Loss	39
26	Throttle Orifice Discharge Coefficient	40
27	Metered Fuel Assembly Calibration	42
28	Fuel Nozzle Design	43
29	Simulated High Power Trim Adjustment	44
30	Comparison of Fuel System Simulation with Fuel Bench Test Data	45
31	Comparison of Fuel System Simulation with Fuel Bench Test Data	47
32	Comparison of Fuel System Simulation with Engine Calibration Data	48
33	Effect of Ambient Air Temperature on Engine Fuel/Air Ratio	51
34	Temperature Sensing Aneroid Design	52
35	Bellows Movement Required for Temperature Compensation	53
36	Fuel System Modification for Improved Fuel Vaporization During Acceleration	55
37	Fuel System Modification for Off-Idle Enrichment During Acceleration	56
38	Delayed Reference Pressure Response During Engine Acceleration	57

LIST OF SYMBOLS

<u>Symbol</u>	<u>Meaning</u>	<u>Units</u>
A	Area	Square Inch
$A_e$	Relief Valve Diaphragm Effective Area	Square Inch
$A_v$	Valve Area	Square Inch
CHT	Cylinder Head Temperature	Degrees Fahrenheit
$C_d$	Orifice Discharge Coefficient	-
D	Line Diameter	Inch
DISP	Pump Displacement	Cubic Inch
EGT	Exhaust Gas Temperature	Degrees Fahrenheit
F	Objective Function	-
F1-F11	Remainder Terms from Flow Equations	-
F ( $\Delta P$ )	Pump Leakage function	Pounds per Hour
F/A	Fuel to Air Mass Ratio	-
$K_f$	Line Loss Factor	-
$K_o$	Line Loss Factor for Bends, Valves and Fittings	-
$K_s$	Spring Constant	Pounds per Inch
L	Line Length	Inch
N	Pump Speed	Revolutions per Minute
PAMB	Ambient Pressure	Pounds per Square Inch Absolute
P1	Pump Inlet Pressure	Pounds per Square Inch Absolute
P2	Pump Discharge Pressure	Pounds per Square Inch Absolute

List of Symbols - cont'd

<u>Symbols</u>	<u>Meaning</u>	<u>Units</u>
P3	Ambient Pressure	Pounds per Square Inch Absolute
P4	Nozzle Inlet Pressure	Pounds per Square Inch Absolute
P5	Turbo Discharge Pressure	Pounds per Square Inch Absolute
P6	Variable Orifice Discharge Pressure	Pounds per Square Inch
P7	Vapor Return Line Pressure	Pounds per Square Inch
Pds	Downstream Pressure	
Q	Fluid Dynamic Head	
Re	Reynolds Number	-
R <sub>r</sub>	Orifice Rod Radius	Inch
R <sub>o</sub>	Variable Orifice Radius	Inch
RF	Fuel Pressure Force on Variable Orifice Rod	
RPM	Pump or Engine Rotational Speed	Revolutions per Minute
T	Temperature	Degrees Fa
W	Mass Flow Rate	Pounds per Hour
Z0	Supply Line Elevation at Tank	Inch
Z1	Supply Line Elevation at Pump	Inch
ΔLS	Relief Valve Spring Compression	Inch
ΔP	Pressure Differential	Pounds per Square Inch
ΔP <sub>v</sub>	Valve Pressure Differential	Pounds per Square Inch

List of Symbols - cont'd

<u>Symbols</u>	<u>Meaning</u>	<u>Units</u>
$\Delta P_t$	Throttle Pressure Drop	Pounds per Square Inch
$\delta$	Variable Orifice Displacement from Closed Position	Inch
$\delta_{ADJ}$	Variable Orifice Adjustment	Inch
$\epsilon$	Surface Roughness	Inch
$\eta$	Pump Efficiency	-
$\mu$	Fluid Viscosity	Pounds Mass per Foot Per Second
$\rho$	Fluid Density	Pounds Mass per Cubic Foot

## INTRODUCTION

### Purpose

The purpose of this report is to develop a computer simulation of the TCM fuel injection system to serve as a tool for the evaluation of schemes for improved fuel management. Using the simulation, the effects of fuel system modifications on fuel flow rate are evaluated at various engine operating and environmental conditions. The impact of modifications on emissions and fuel economy are determined.

### Background

This report describes work performed under the first option of Phase III of National Aviation Facilities Experimental Center (NAFEC) contract DOT FA74NA-1091 by Teledyne Continental Motors (TCM). Prior testing of TCM engines under Phase I of this contract has shown that a significant reduction in emissions is available through improved fuel management. Phase II of the contract entitled "Corrective Measures Determination" involves an investigation of concepts which offer the most promise toward achieving the emissions levels required by proposed Environmental Protection Agency (EPA) standards. However, analysis accomplished under a National Aeronautics and Space Administration (NASA) contract (NASA contract NAS3-19755) fulfilled the purpose of Phase II, eliminating the need for duplicating this effort under NAFEC contract (reference 1). Phase III of the NAFEC contract DOT FA74NA-1091 was concerned with the analysis, design, construction and testing of fuel injection system based on the system currently manufactured at Continental.

Phase III was divided into three options. The objectives of the first option were:

- (1) Define the fuel system requirements.
- (2) Develop a generalized analytical model of the TCM fuel injection system.
- (3) Measure the response of the TCM fuel injection system to varied operational conditions.
- (4) Refine the analytical model to correlate with system measurements.
- (5) Use the model to predict component requirements for fuel/air ratio control.

This report describes the work performed under the first option of Phase III. The second and third options were concerned with the modification of the current system and subsequent testing. These options were cancelled due to a proposed elimination of the emissions standards for aircraft piston engines.

### Overview

To understand the Continental fuel injection system and its effects on aircraft engine emissions, it is necessary to understand the operating limitations of the air-cooled aircraft internal combustion engine. These limitations are primarily imposed by cooling requirements, detonation limits, and acceleration characteristics of the engine. The Continental fuel injection system was designed to avoid over-heating and detonation by supplying excess fuel at high power. A typical fuel flow schedule is shown in figure 1, which shows an increase in the slope of the fuel flow schedule above 75 percent power to provide additional fuel for cooling. At cruise power (75 percent) and below, the primary consideration is engine acceleration, although cooling can be a problem during aircraft ground operations (taxi).

In order to obtain better cruise economy for steady state operation, the Continental system is equipped with a manual mixture control. This control is a fuel pump bypass which is used at the option of the pilot at 75 percent power and below to reduce fuel flow. Figure 2 shows the benefits of leaning. Although power drops with increasingly lean fuel/air ratios, specific fuel consumption drops approximately 15 percent from best power fuel/air to best economy fuel/air. Below 75 percent power, manual leaning is limited by instructing the pilot to lean no more than 50° Fahrenheit (F) rich of peak exhaust gas temperature (EGT). Figure 1 shows the region of the fuel schedule where manual leaning is permitted.

The effect of leaning on engine emissions was investigated during phase I of (NAFEC) contract DOT FA74N1091 (reference 2) where it was found that leaning generally reduces hydrocarbons (HC) and carbon monoxide (CO) while increasing nitrogen oxides (NO). For the baseline engines, HC and CO emissions exceed (EPA) standards. However, NO emissions are considerably below the standards. Therefore, leaning is a means of reducing the emissions which exceed the EPA standards. Improvement must be

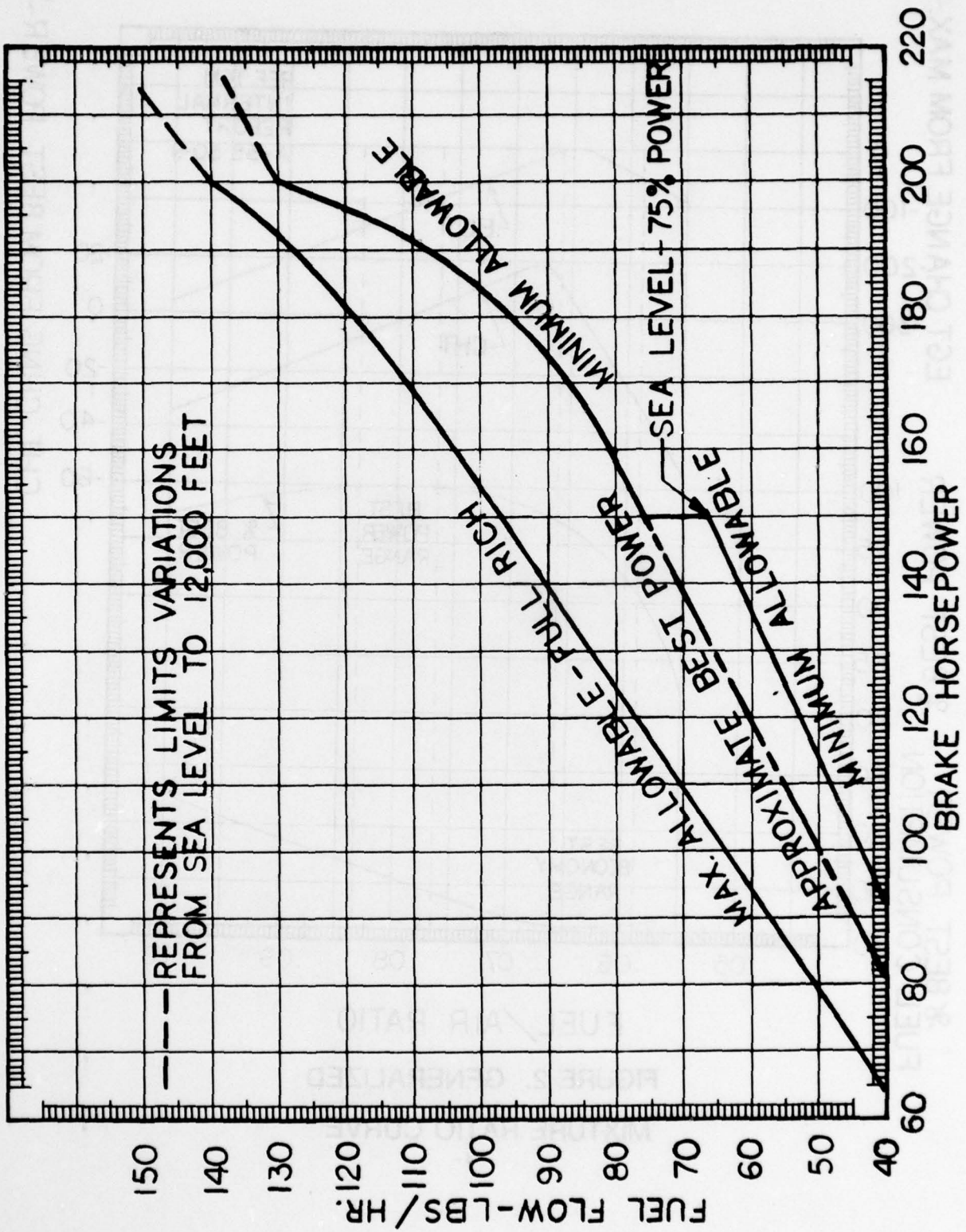


FIGURE 1. FUEL FLOW LIMITS FOR TSIO-360-E ENGINE

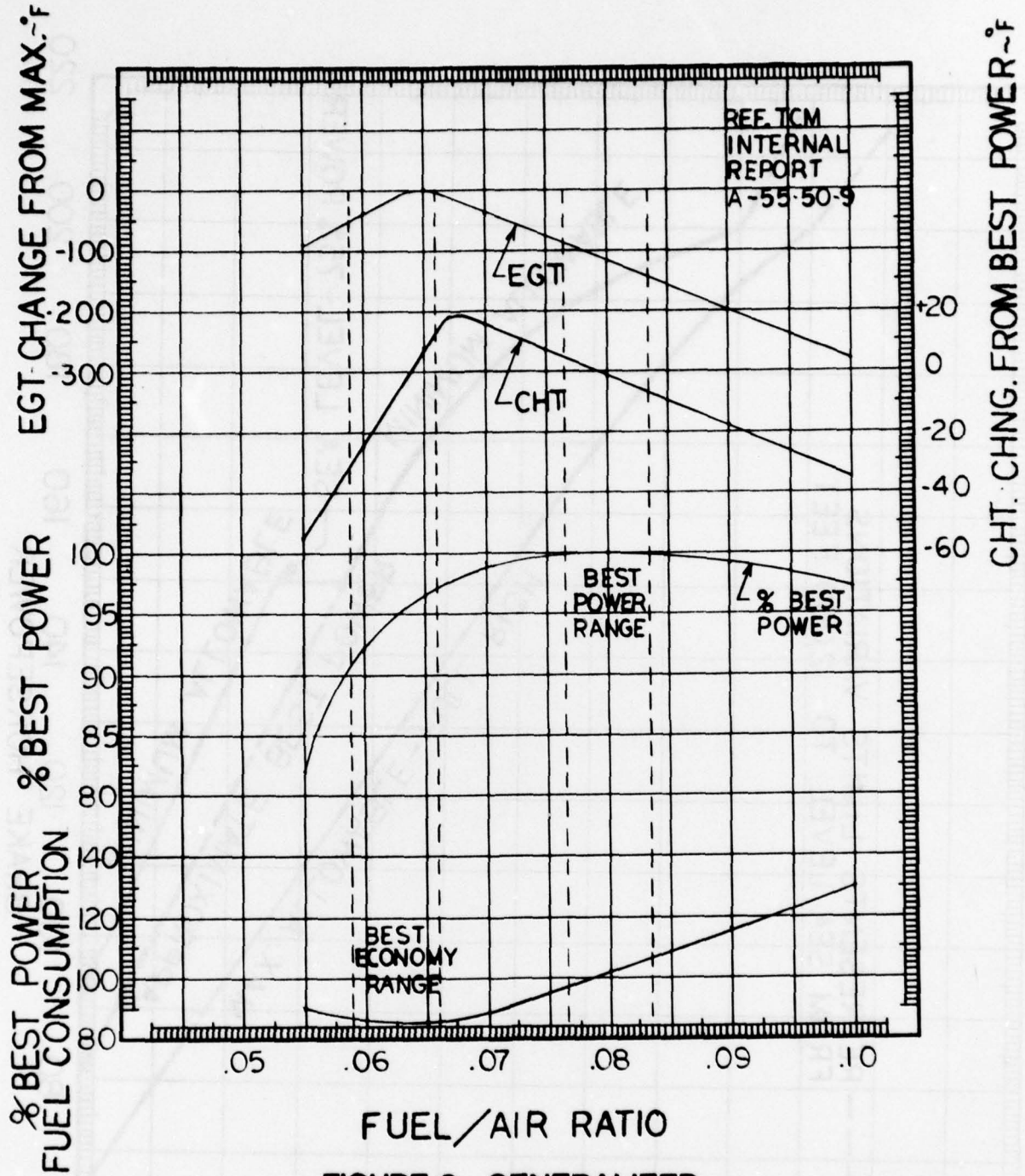


FIGURE 2. GENERALIZED  
MIXTURE RATIO CURVE

made to the current fuel injection system and perhaps the air intake manifold to safely lean for reduced emissions during the landing and takeoff (LTO) cycle, where the engines are operated full rich.

Improvements to the fuel system in the form of additional or modified hardware cannot be made without an understanding of the fluid behavior within the system. Phase III, Option I, of the NAFEC Contract DOT-FA74NA1091 was awarded to Teledyne Continental Motors (TCM) to investigate the current fuel injection system and develop an analytical simulation. This simulation is to serve as the basis for quantitatively exploring deficiencies in the fuel system which lead to poor exhaust emissions characteristics. The simulation was based on component behavior as determined from component bench tests. The model was written in modular format to readily allow simulation of fuel system hardware changes for improved fuel management.

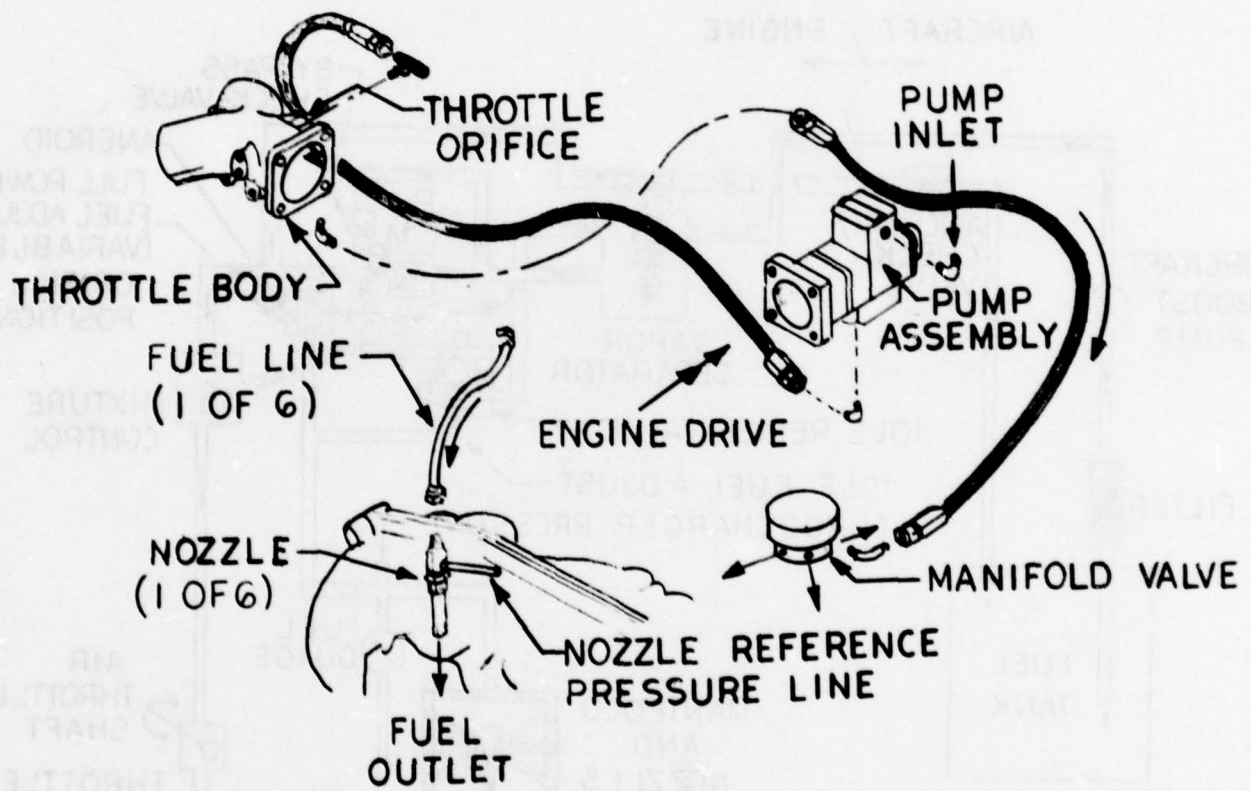
## DISCUSSION

### Description of the Continental Fuel Injection System

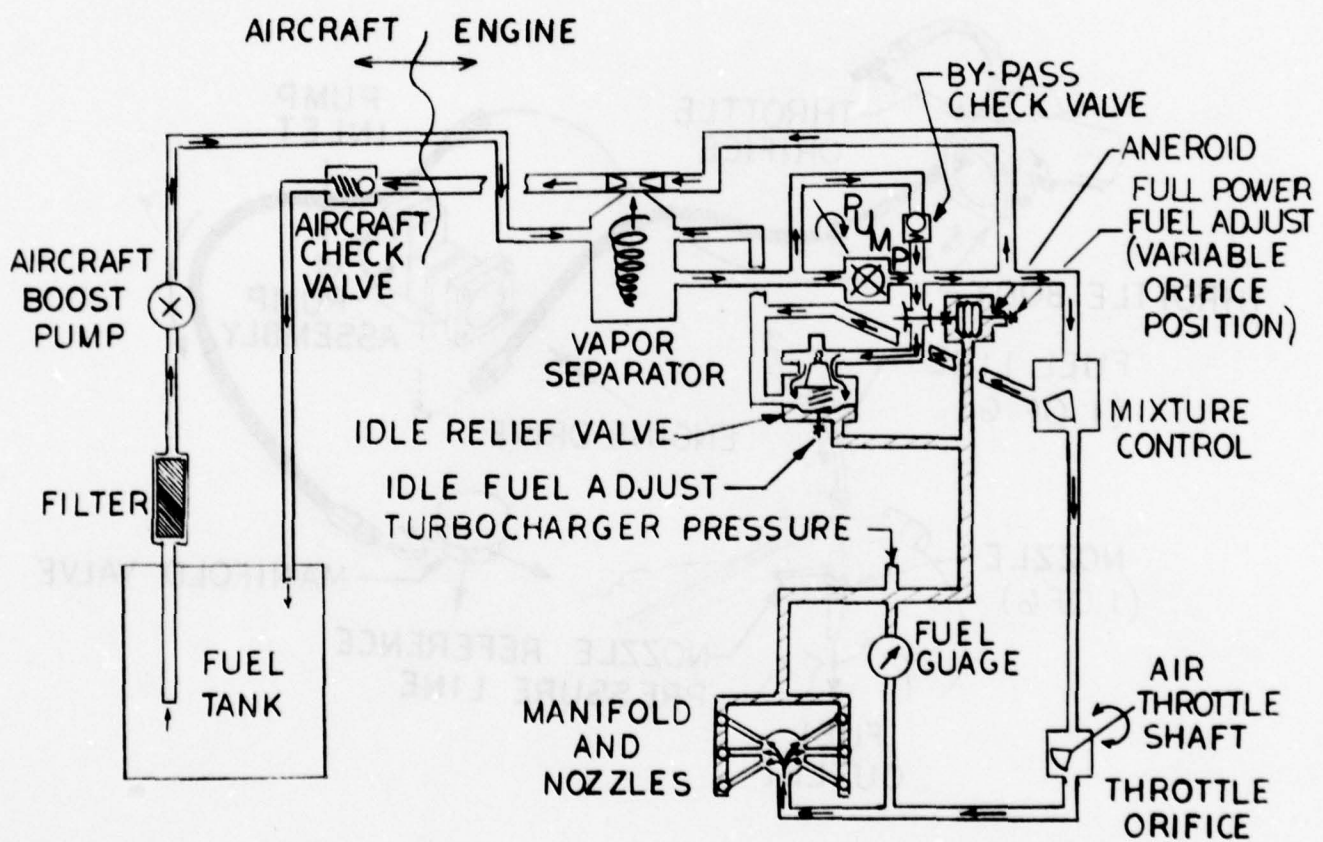
The fuel injection system chosen for simulation is designed for the TSIO-360-E and LTSIO-360-E engines. These engines currently lead Continental's line of turbocharged engines for rate of production. The LTSIO-360-E and TSIO-360-E are counter-rotating 200 horsepower engines produced for the rapidly expanding twin engine aircraft market. The fuel system used on these engines was developed by modifying previous Continental designs and shares many common components with other Continental fuel systems. The components of the system are shown in figure 3. Injector nozzles spray fuel continuously into the intake port of each cylinder where the fuel is further vaporized by cylinder air intake. The fuel/air mixture enters the combustion chamber when the intake valve opens. The amount of fuel delivered is determined by engine speed, turbocharger discharge pressure, throttle angle, and ground trim adjustments.

A schematic of the fuel injection system used on Continental turbocharged engines is shown in figure 4. The heart of the system is a rotary vane pump which is driven at a 1:1 ratio by the engine and delivers flow in direct proportion to engine speed. The pump is bypassed by the variable orifice and idle relief valve which to a large extent govern the output pressure of the pump. As more flow is bypassed at a constant pump speed, pump pressure drops. The idle relief valve is effective at low pump speeds and is ground adjusted to set the minimum pump discharge pressure at idle. The variable orifice is ground-adjusted to trim pump pressure at full power. The action of the aneroid adjusts the variable orifice rod to increase pump discharge pressure with increasing turbocharger discharge pressure. This aneroid action tends to increase fuel flow as air density increases with turbocharger pressure, tending to hold a constant fuel/air ratio. However, no compensation for ambient air temperature effects on air density are made, as the aneroid is insensitive to temperature.

From the pump, fuel flow to the engine is metered by an orifice which is directly linked to the air throttle. The size of the orifice is a function of the throttle position. Orifice size tends to increase as the throttle is opened, increasing fuel flow as manifold pressure and engine airflow increase. Fuel pressure downstream of the throttle valve (metered fuel pressure) is fed to the manifold valve and nozzle. The rate of fuel flow entering the cylinders depends on the fluid pressure



**FIGURE 3. FUEL INJECTION SYSTEM HARDWARE**



**FIGURE 4. FUEL INJECTION SYSTEM SCHEMATIC**

of the fuel relative to the reference pressure of the nozzles. For turbocharged engines, turbocharger discharge pressure is used as a nozzle reference pressure. The manifold valve, nozzle lines, and nozzles are factory calibrated as a unit so that fuel flow rate is a set function of metered fuel pressure (figure 5). The function of the manifold valve is to distribute fuel flow to the individual fuel nozzles and to abruptly chop the fuel flow when metered fuel pressure drops below the idle cutoff level.

Fuel/air mixture ratio is manually leaned by the pilot by opening a fuel pump bypass valve which reduces fuel pump discharge pressure. Since this action reduces fuel flow without affecting airflow, the fuel/air ratio is reduced.

#### Description of the Fuel System Model

Simulation of the fuel injection system involves the solution of a fluid flow network to determine the flow rate and pressures within the system. The approach used to simulate the fuel system is described in detail in reference 3. Using this approach, the flow versus pressure drop relationship for each component of the system was first established using an equation or curve fit based on component flow testing. Next, a set of governing equations was established using two basic hydraulic principles:

$$\begin{array}{l} \text{Flow continuity} \\ \Sigma(\text{flows entering a junction}) = 0 \end{array} \quad (1)$$

$$\begin{array}{l} \text{Continuity of Potential} \\ \Sigma(\text{pressure changes across a closed flow path}) = 0 \end{array} \quad (2)$$

These equations form a set of nonlinear simultaneous equations which can be solved with the help of a computer iterative technique. The technique employed, Rosenbrock's algorithm, uses initial guesses for the unknowns and improves the guesses using the set of simultaneous equations. Successive iteration leads to a set of pressures and flow rates which satisfy equations 1 and 2. The accuracy of the initial guesses is not critical and satisfactory solutions can be obtained within about 5,000 iterations.

The fuel system model employed is shown in figure 6. There are 11 unknowns for the system, six pressures and five flow rates:

- P1 - Pump inlet Pressure, X(1)
- P2 - Pump discharge pressure, X(2)
- P3 - Fuel metered pressure, X(3)
- P4 - Nozzle inlet pressure, X(4)
- P6 - Variable orifice discharge pressure, X(5)
- P7 - Vapor return line pressure, X(6)
- WA - Supply line flow rate, X(7)
- WB - Pump flow rate, X(8)
- WC - Vapor separator flow rate, X(9)
- WD - Variable orifice flow rate, X(10)
- WE - Fuel system output flow rate, X(11)

Of course, one of the unknowns is the desired fuel output of the system, WE. In order to solve for the 11 unknowns, there must be a set of 11 simultaneous equations. These are composed of two flow continuity equations and nine continuity of potential equations:

$$\begin{aligned} \text{Flow continuity at junction 0} \\ \text{WA-WE-WC=0} \end{aligned} \quad (3)$$

$$\begin{aligned} \text{Flow continuity at junction 1} \\ \text{WB-WA-WD=0} \end{aligned} \quad (4)$$

$$\text{PAMB-P1-(DP)}_{\text{SL}} = 0 \quad (5)$$

Where  $(DP)_{\text{SL}}$  = Supply Line Pressure drop  
PAMB = Ambient pressure (known)

$$\text{P2-P1- Pump Pressure Rise} = 0 \quad (6)$$

$$\begin{aligned} \text{P2-P6- Variable Orifice Pressure} \\ \text{Drop} = 0 \end{aligned} \quad (7)$$

$$\begin{aligned} \text{P6-P1- Idle Relief Valve Pressure} \\ \text{Drop} = 0 \end{aligned} \quad (8)$$

$$\begin{aligned} \text{P2-P7- Vapor Separator Pressure} \\ \text{Drop} = 0 \end{aligned} \quad (9)$$

$$\begin{aligned} \text{P2-P3- Control Unit Pressure} \\ \text{Drop} = 0 \end{aligned} \quad (10)$$

$$\begin{aligned} \text{P3-P4- Mainfold Valve Pressure} \\ \text{Drop} = 0 \end{aligned} \quad (11)$$

$$P4-P5- \text{ Nozzle Pressure Drop} = 0 \quad (12)$$

Where P5 = Turbocharger discharge pressure (known)

$$P7-P0- \text{ Return Line Pressure Drop} = 0 \quad (13)$$

Where P0 = Ambient pressure (known)

These 11 equations were formed into 11 separate computer sub-routines. Each subroutine is used to calculate the value of one of the sums based on assumed values for the 11 unknowns and known boundary values. The correct assumptions for the unknowns will yield 11 sums which each equal zero. To find a solution to the problem using Rosenbrock's algorithm, an objective function is formed using the remainder terms from each of the 11 functions:

$$F = F1^2 + F2^2 + \dots + F11^2$$

Where F1 = WA-WE-WC

F2 = WB-Wa-WD

F3 = P0-P1 - Supply line pressure drop

.  
.  
.

F11 = P7-P0- Return line pressure drop

After calculating the objective function (F) based on assumptions for the 11 variables, new values for the unknowns are formed within the algorithm. A new value of the objective function is calculated using the 11 subroutines. If the magnitude of the objective function is less than the previous value, the new values for the unknowns are accepted. Successive iterations are continued until the objective function is reduced to a small positive value. The magnitude of the objective function is a measure of the error of the solution, and can be used as a criteria for convergence. For this study, the maximum value of the objective function was set at 0.001 which gave flow rates correct to within approximately 0.10 pounds per hour.

The use of subroutines within the computer code gives the simulation the flexibility needed to allow evaluation of modifications to the fuel system. Changes which would require extensive bench and flight testing of the entire fuel system

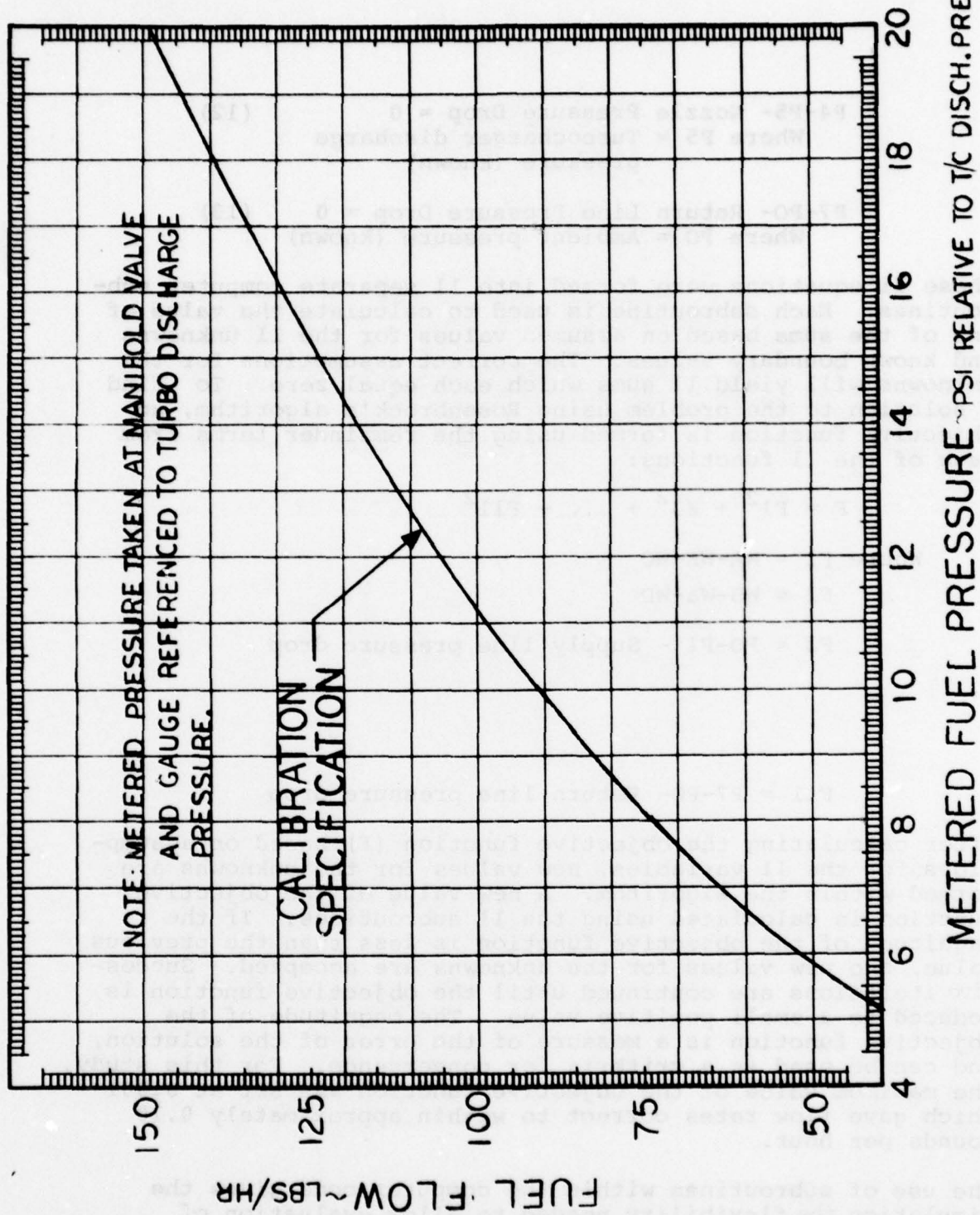
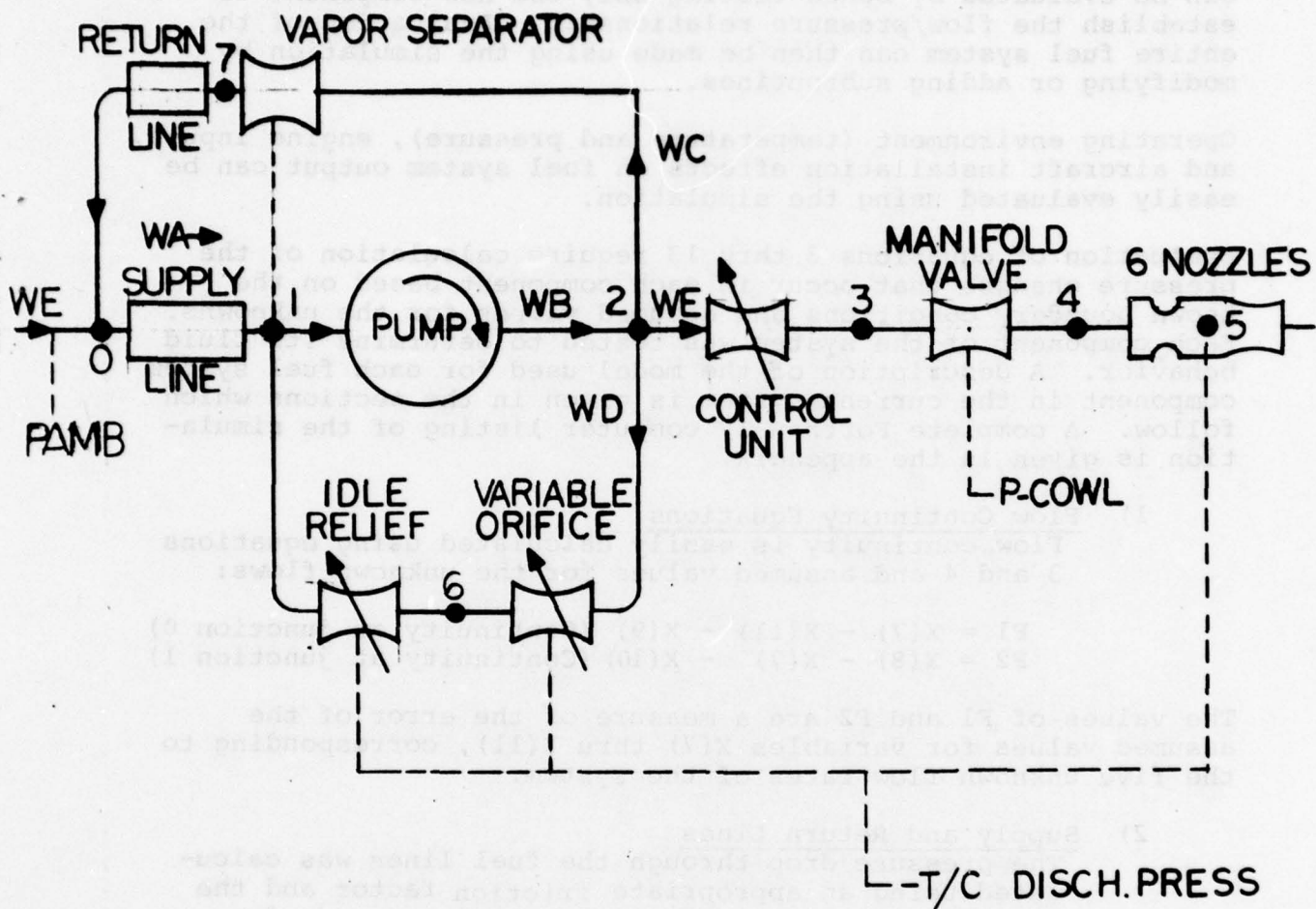


FIGURE 5. METERED FUEL ASSEMBLY CALIBRATION



**FIGURE 6. FUEL SYSTEM MODEL**

can be evaluated by bench testing only the new component to establish the flow/pressure relationship. Evaluation of the entire fuel system can then be made using the simulation by modifying or adding subroutines.

Operating environment (temperature and pressure), engine inputs, and aircraft installation effects on fuel system output can be easily evaluated using the simulation.

Evaluation of equations 3 thru 13 require calculation of the pressure changes that occur in each component based on the known boundary conditions and assumed values for the unknowns. Each component of the system was tested to determine its fluid behavior. A description of the model used for each fuel system component in the current system is given in the sections which follow. A complete Fortran IV computer listing of the simulation is given in the appendix.

1) Flow Continuity Equations

Flow continuity is easily calculated using equations 3 and 4 and assumed values for the unknown flows:

$$F1 = X(7) - X(11) - X(9) \text{ (Continuity at junction 0)}$$

$$F2 = X(8) - X(7) - X(10) \text{ (Continuity at junction 1)}$$

The values of F1 and F2 are a measure of the error of the assumed values for variables X(7) thru X(11), corresponding to the five unknown flow rates of the system.

2) Supply and Return Lines

The pressure drop through the fuel lines was calculated using an appropriate friction factor and the methods given in reference 4. Line pressure drop is calculated as:

$$\Delta P = K_f * Q + \frac{\rho * (Z1-Z0)}{1728}$$

Where  $K_f = FF * L/D + K_o$

$$FF = 64./Re \text{ for laminar flow (Re < 3000)}$$

$$FF = \text{Value from Moody diagram (figure 7) for turbulent flow}$$

$$L = \text{Line length (inches)}$$

$$D = \text{Line diameter (inches)}$$

$K_o$  = Dimensionless experimental coefficient accounting for head loss in bends, valves, fittings, etc. Available in numerous handbooks, (reference 4)

Re = Reynolds number

$$Re = \frac{W \times D}{\mu \times A} \times \frac{12.}{3600.}$$

$\mu$  = Fluid viscosity,  $Lb_m / ft\text{-sec}$

$\rho$  = Density of fluid ( $lbm/ft^3$ )

Z0 = Elevation of line at fluid inlet (inches)

Z1 = Elevation of line at flow exit (inches)

Q = Fluid dynamic head (psi)

$$= \frac{1}{2} * \frac{W * |W| * 144.}{(3600)^2 (\rho) (A^2) (32.2)}$$

W = Fluid flow rate (pph)

A = Cross-sectional area of line ( $in^2$ )

The friction factor (FF) for turbulent flow is a function of the line surface roughness relative to the line diameter and Reynolds number, as explained in reference 4. Surface roughness (EPSP) was estimated to be 125. microinches.

Fuel viscosity and density for low lead 100 Octane (LL100) aviation gasoline (Avgas) are built in functions of temperature as shown in figures 8 and 9 (reference 5).

For turbulent flow, friction factor is determined by interpolation of figure 7, which was built into the computer code. The friction factor for laminar flow is given by the equation:

$$FF = 64./Re \quad (\text{reference 4})$$

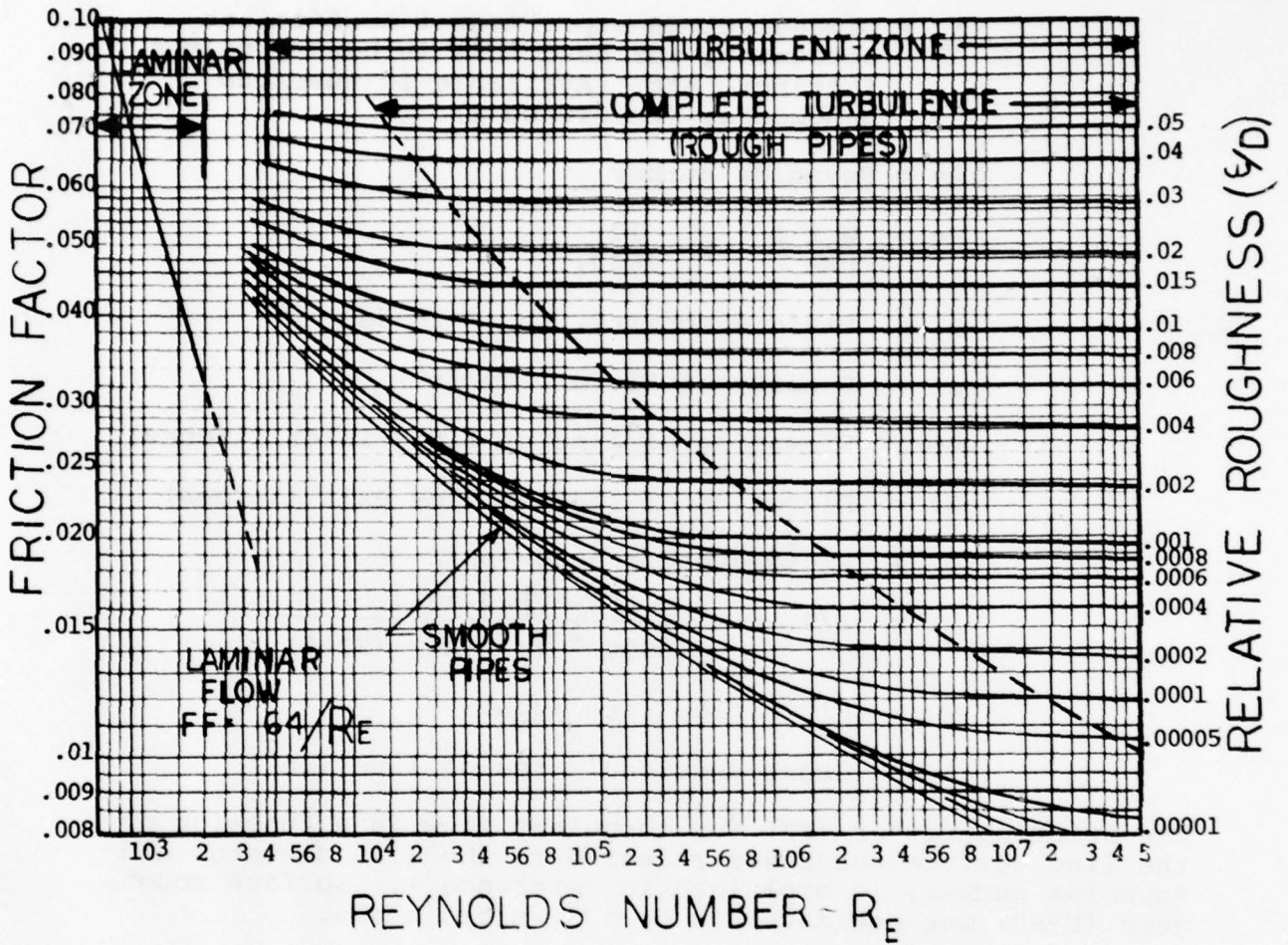


FIGURE 7. FRICTION FACTORS FOR FULLY DEVELOPED FLOW

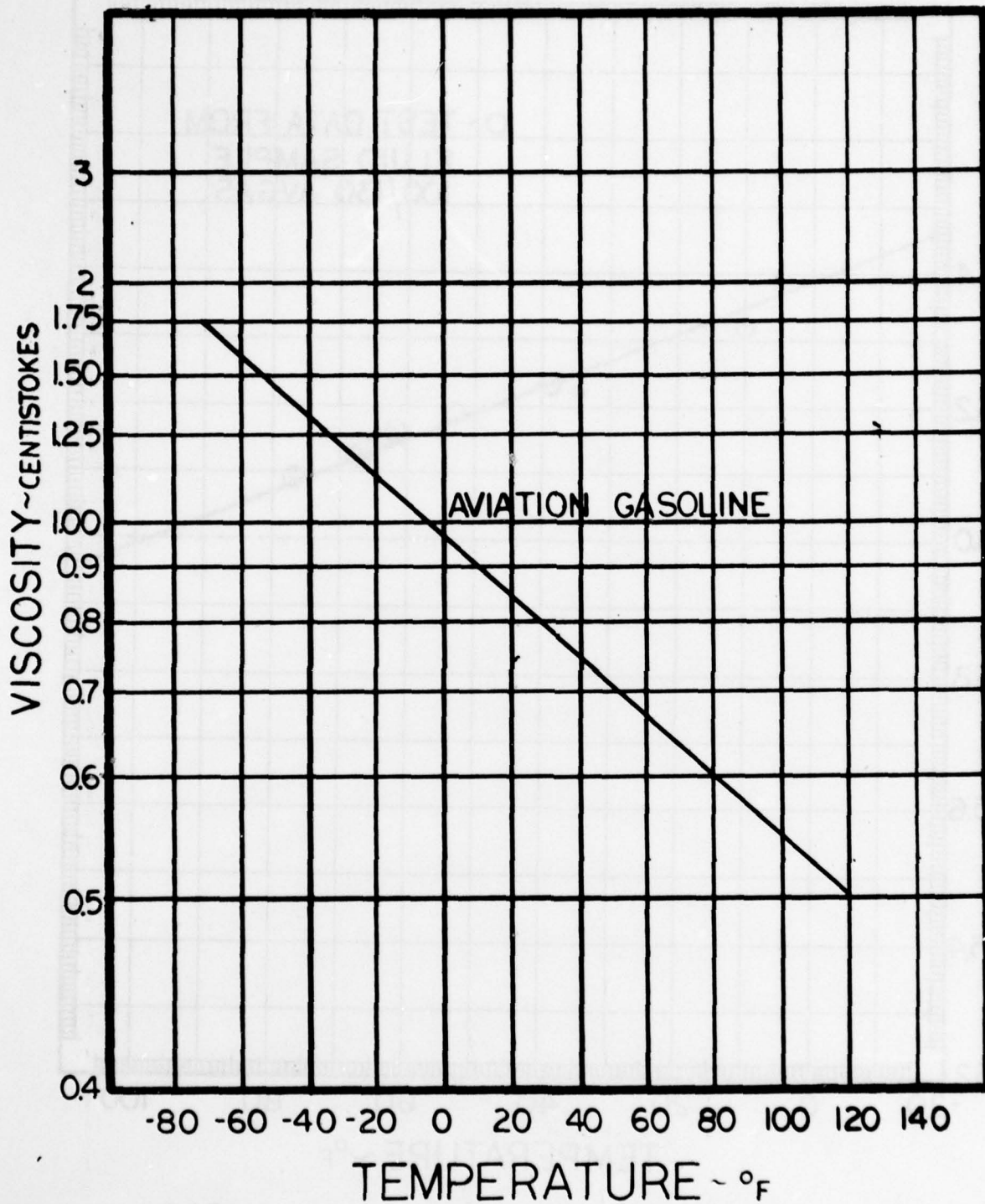


FIGURE 8. VARIATION OF FUEL VISCOSITY WITH TEMPERATURE

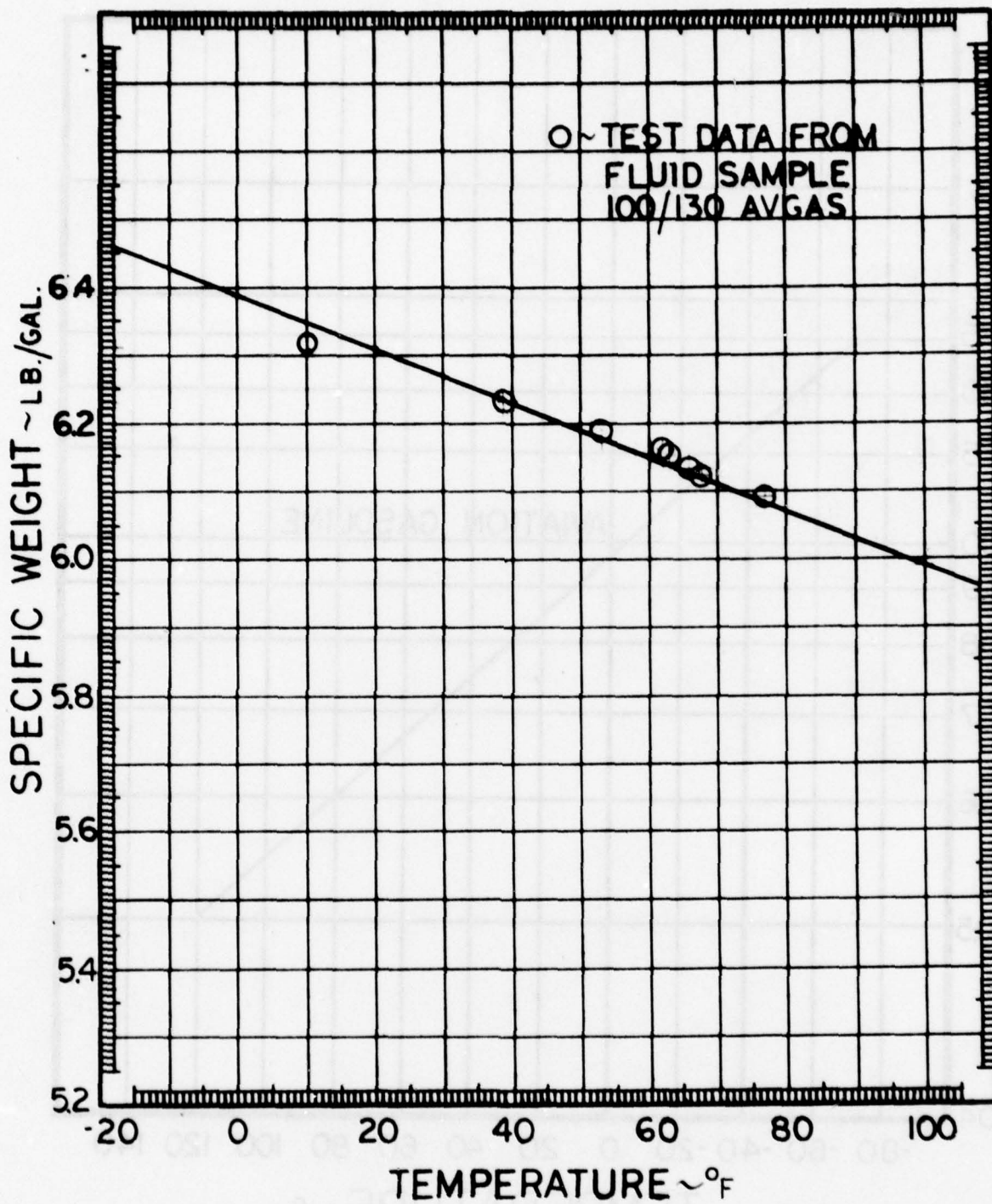


FIGURE 9. SPECIFIC WEIGHT OF 100/130 AVGAS

### 3) Fuel Pump

Bench tests were used to establish the fluid behavior of the rotary vane pump. Data from these tests is plotted in figures 10 and 11. Cross plots of the data show that pump output is proportional to pump speed for a given pump pressure rise (figure 12). An equation for the pump output was developed based on pump displacement and experimentally determined flow rate:

$$W = \left( \frac{\eta * \rho * DISP}{1728} \right) * (60 * N) - F(\Delta P)$$

Where  $\eta$  = pump efficiency (93.7 percent for the pump tested)

$\rho$  = fluid density

DISP = pump displacement (in<sup>3</sup>)

N = pump speed (RPM)

F( $\Delta P$ ) = pump leakage flow rate (PPH) (figure 13)

Pump leakage is due to internal pump flow used for bearing lubrication plus vane leakage. This flow is independent of pump speed and is a function of the pressure rise across the pump and vane tolerances as shown in figure 13.

### 4) Variable Orifice

A cross-sectional view of the variable orifice is shown in figure 14. Pressure loss through the variable orifice depends on the position of the orifice rod relative to the body of the orifice. Figure 15 shows the effect of varying flow rate and orifice position on orifice pressure loss as determined from bench tests. For constant orifice position, orifice pressure loss is proportional to the square of the flow rate. Orifice flow area varies as shown in figure 16, calculated from the known orifice and rod radii:

$$A = \pi [(Ro)^2 - (Rr)^2]$$

Where  $Ro$  = radius of unblocked orifice  
 $Rr$  = radius of orifice rod

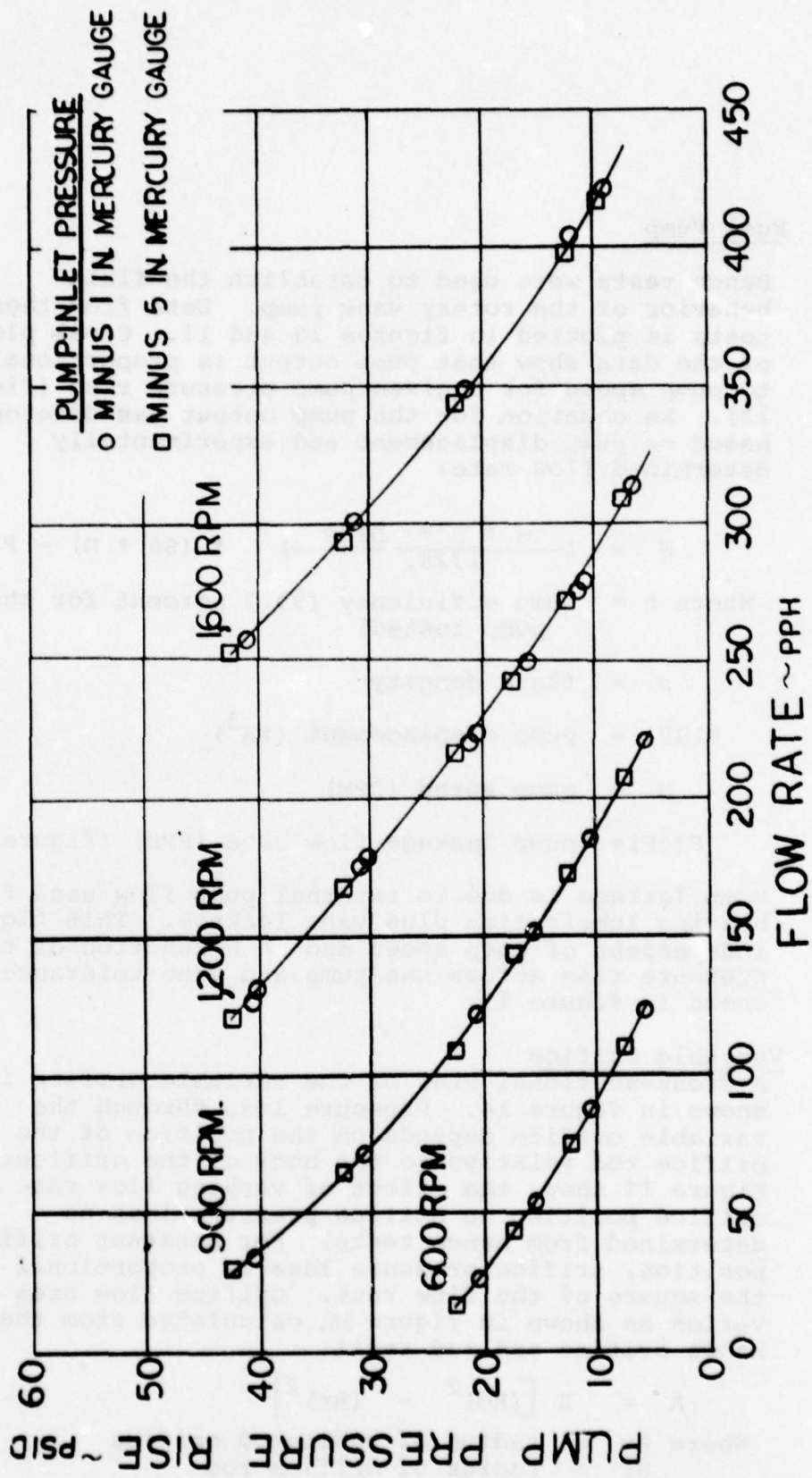
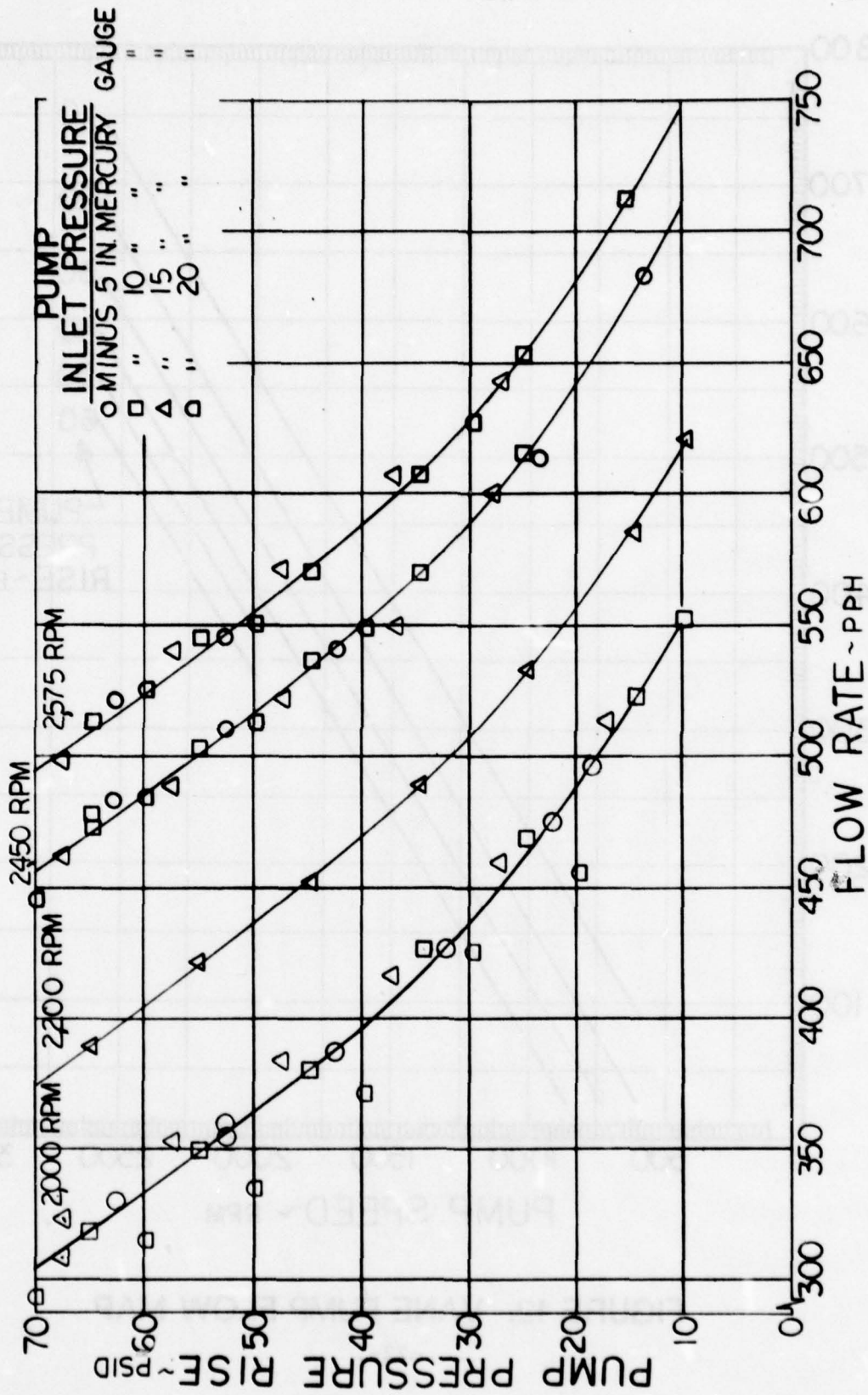


FIGURE 10. VANE PUMP CALIBRATION



**FIGURE 11. VANE PUMP CALIBRATION**

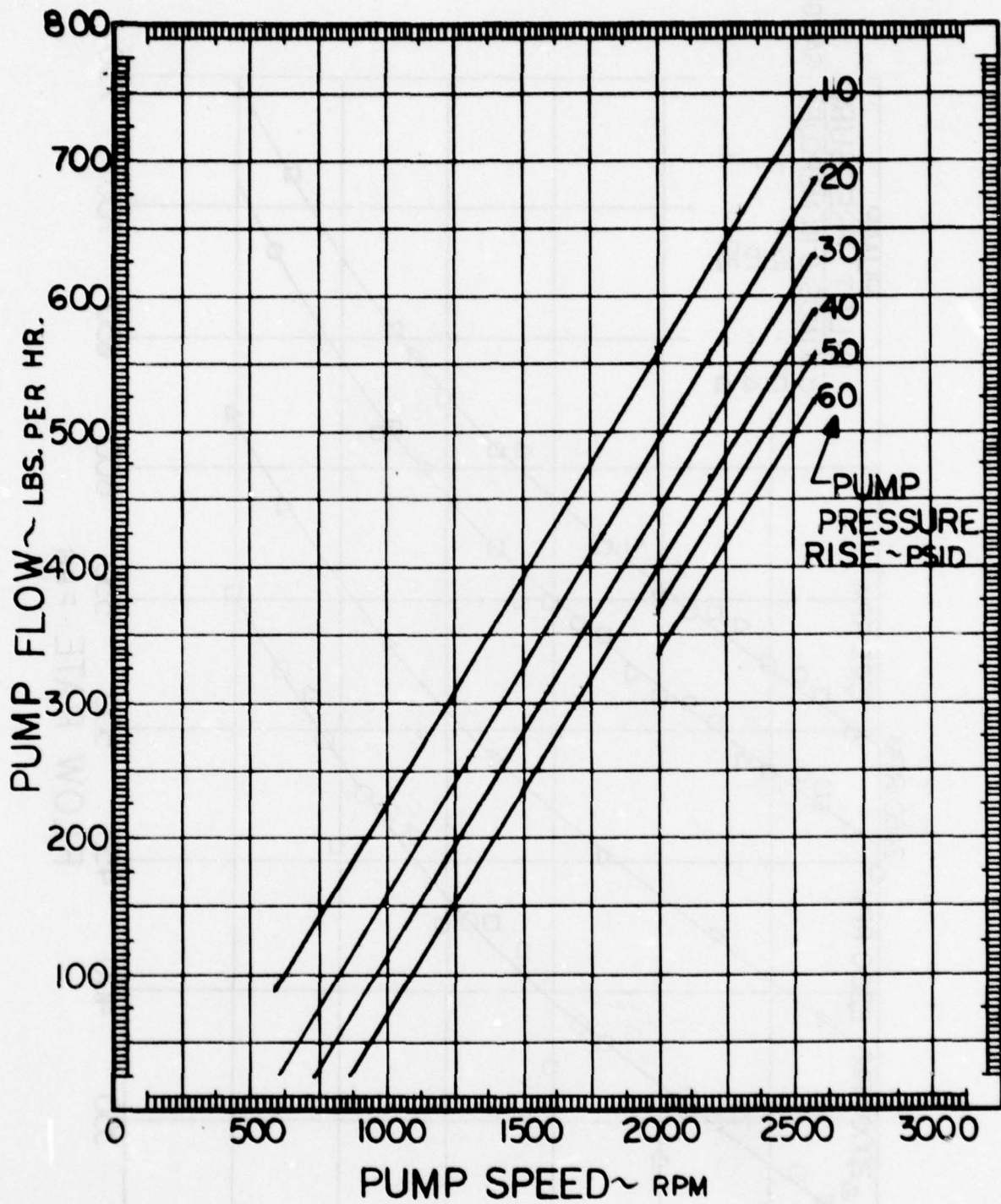


FIGURE 12. VANE PUMP FLOW MAP

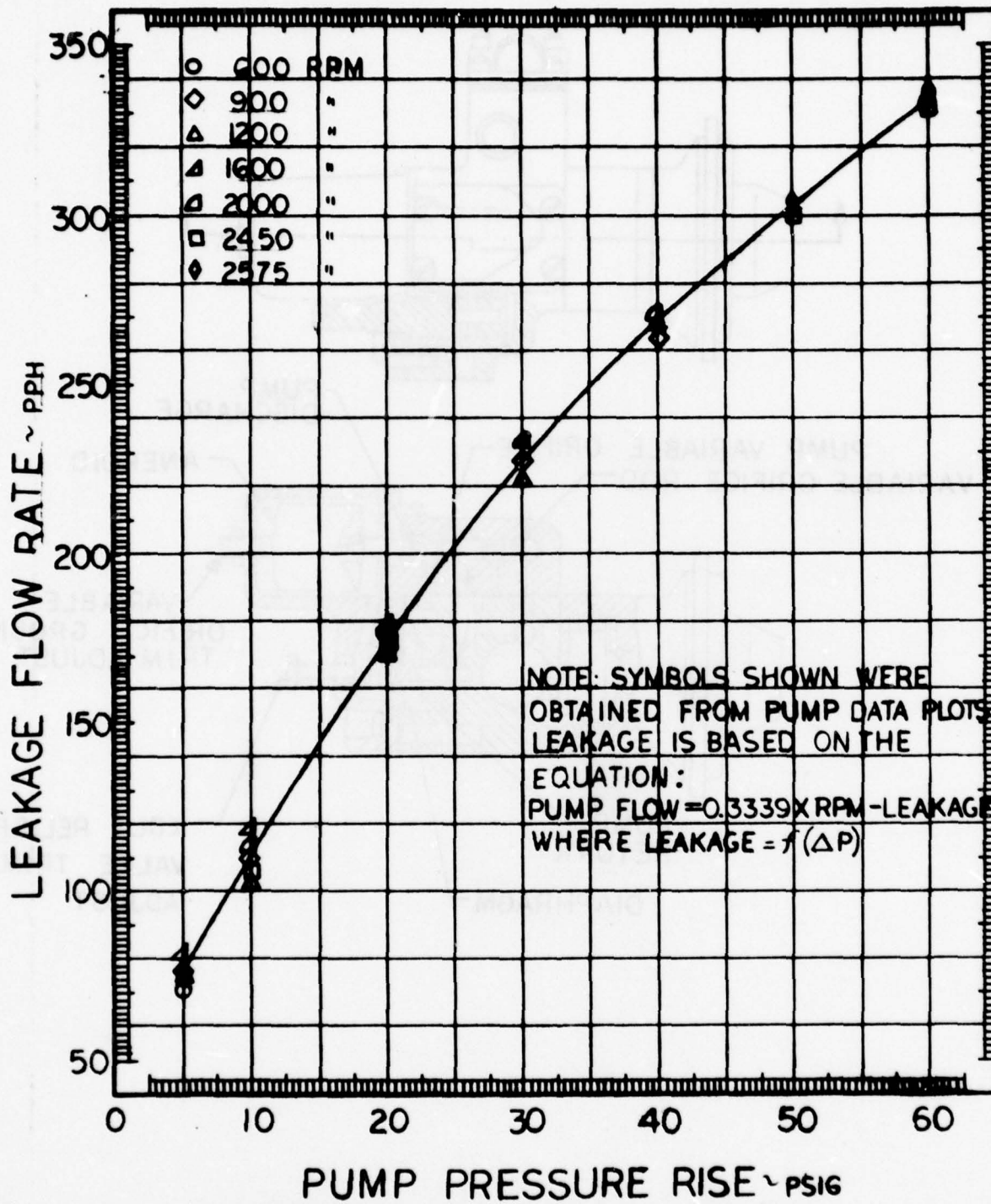
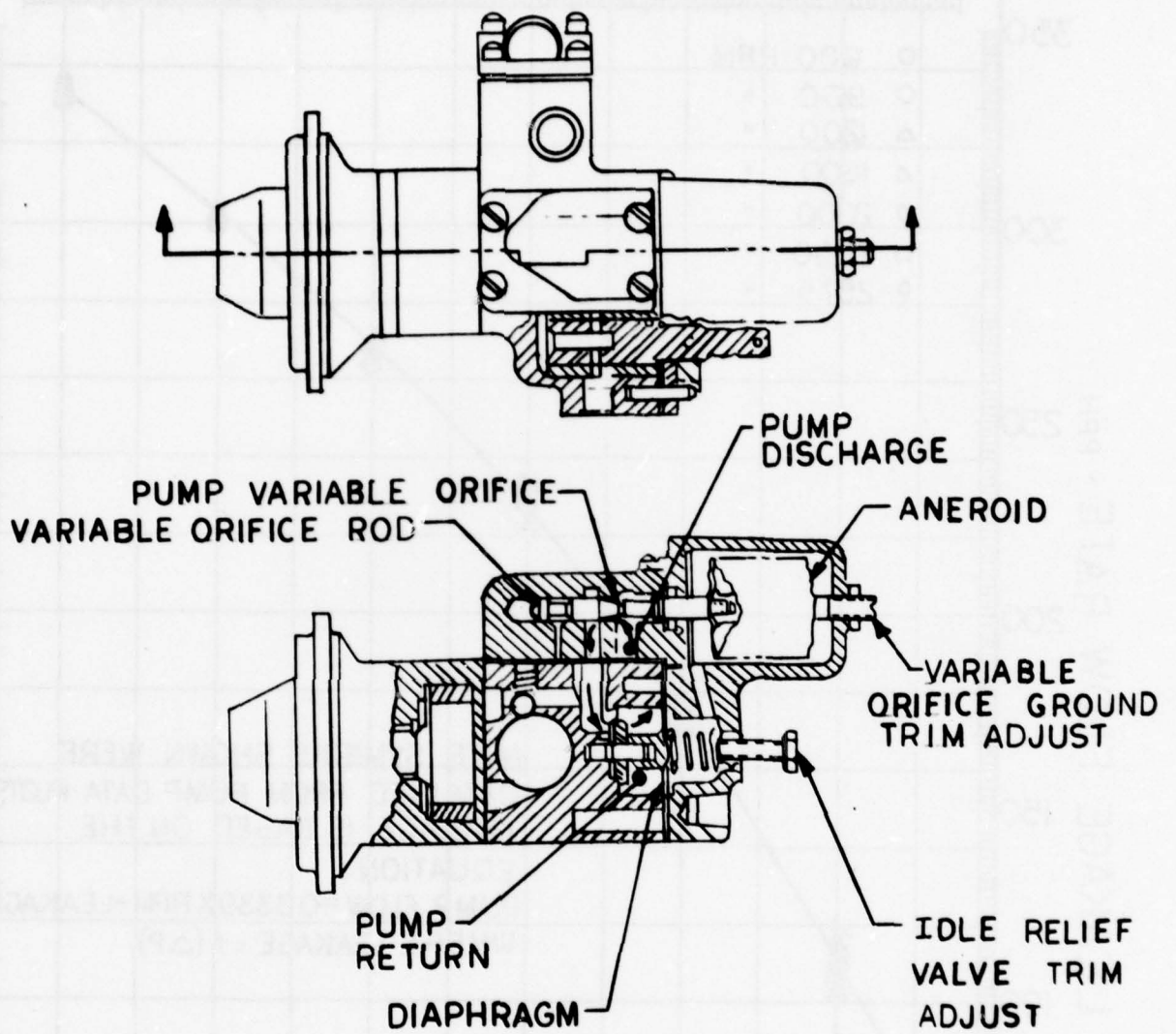


FIGURE 13. VANE PUMP LEAKAGE



**FIGURE 14. FUEL PUMP ASSEMBLY**

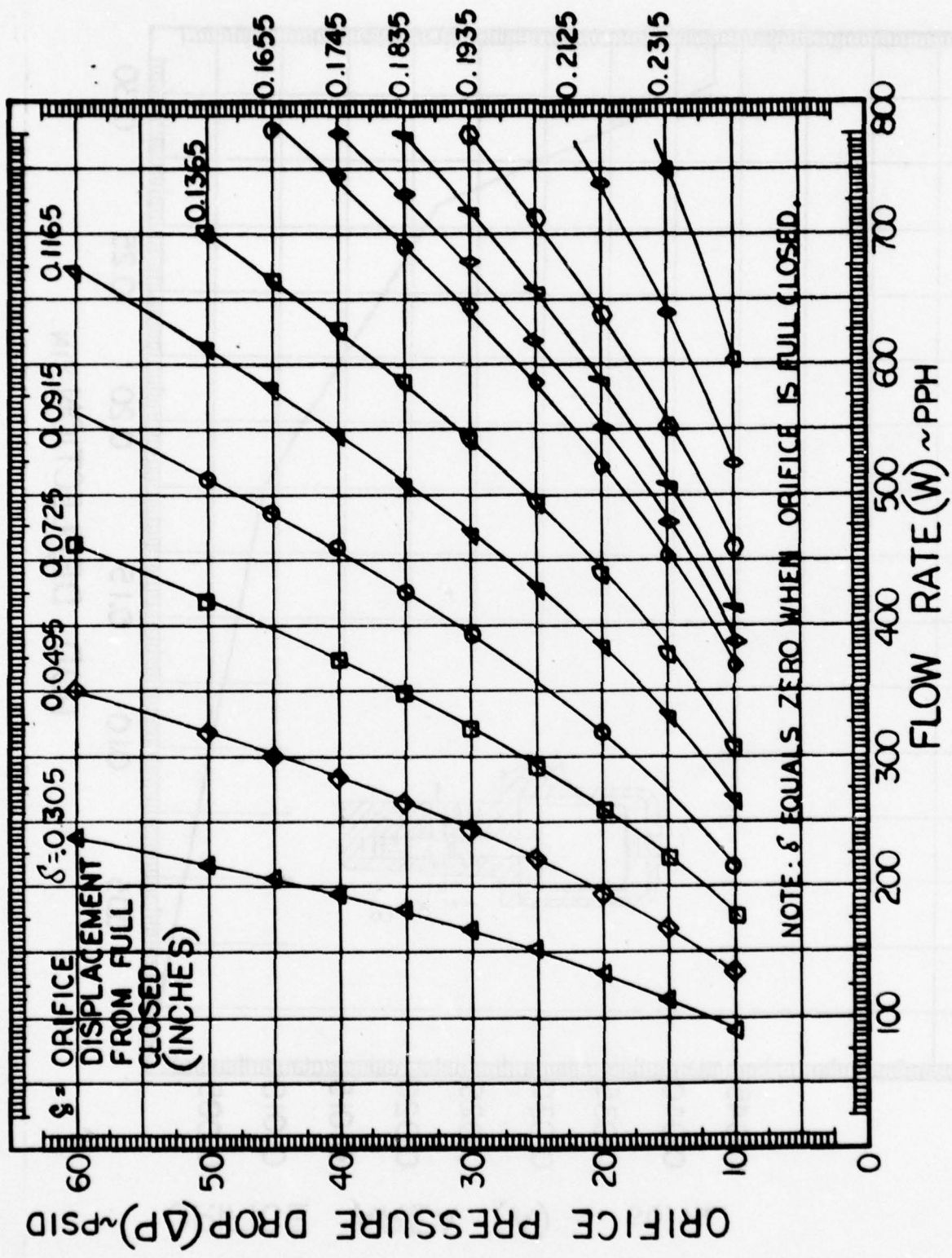


FIGURE 15. VARIABLE ORIFICE CHARACTERISTICS

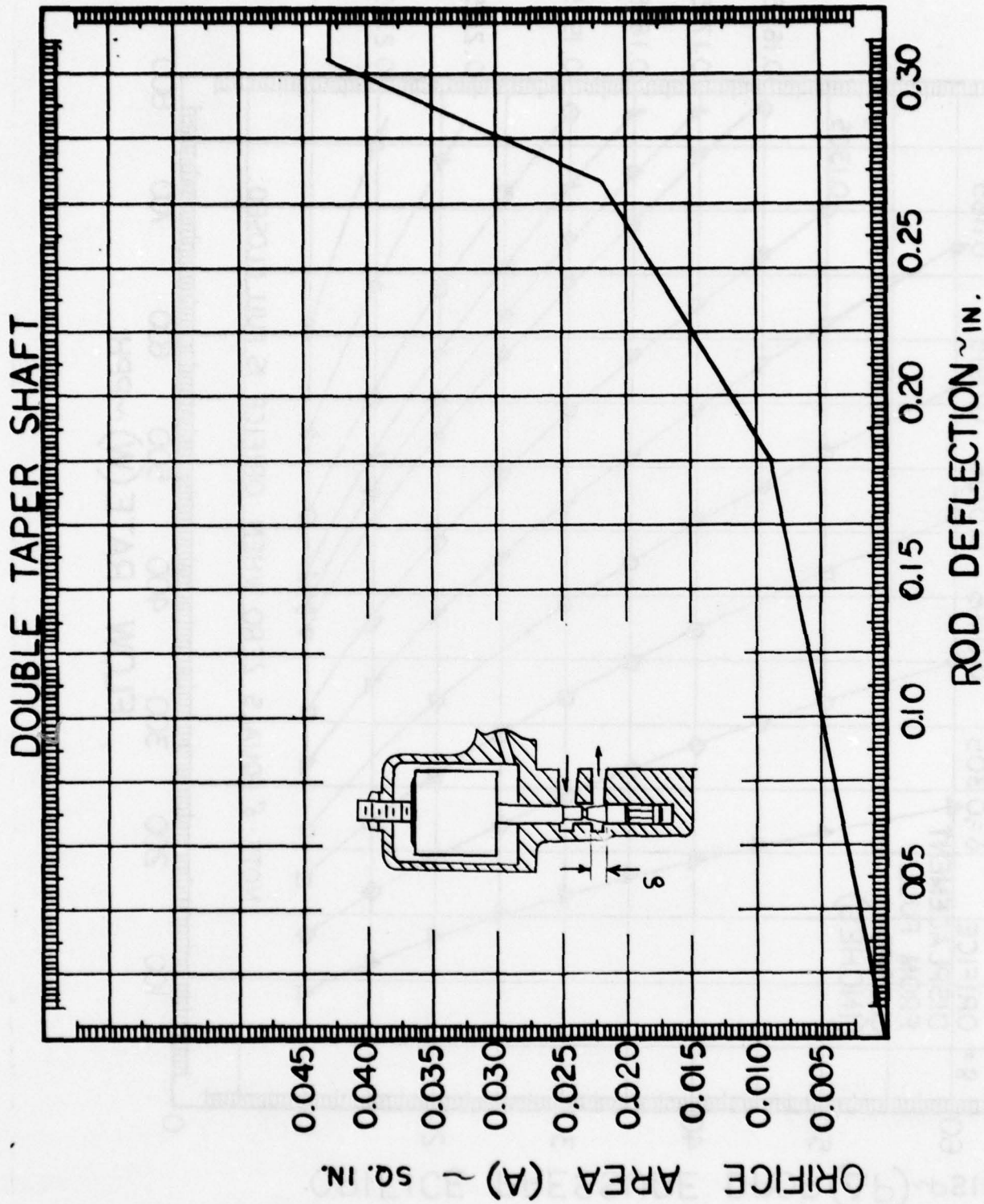


FIGURE 16. VARIABLE ORIFICE FLOW AREA

Based on the experimental data and analytical area calculations, an orifice dimensionless K-factor can be determined as a function of orifice area as shown in figure 17. Orifice pressure loss is then calculated using:

$$DP = K * Q$$

Where

Q = Orifice dynamic head (psi)

$$= \frac{1/2 \rho * V^2}{(32.3) (144.)}$$

and V = mean flow velocity

$$V = \frac{W * 144.}{\rho * A * 3600.}$$

W = Flow rate (pph)

$\rho$  = Density (lbm/ft<sup>3</sup>)

A = Orifice area (in<sup>2</sup>)

This equation gives an orifice pressure drop proportional to the square of the orifice flow rate, in agreement with the data in figure 15.

In order to determine the orifice pressure loss, the position of the orifice must be known. The effect of reference pressure on aneroid movement is shown in figure 18. Tests indicate that changes in temperature do not produce significant aneroid movement. Changes in temperature from 80° F to 150° F cause aneroid movements on the order of 0.005 inches. Aneroid temperature insensitivity is ideal, since the temperature of the aneroid is not representative of induction air temperature.

Fuel pressure on the orifice rod produces movement of the rod, since the aneroid behaves as a linear spring (figure 19). Because of the interaction of fuel pressure forces on aneroid movement and vice versa, orifice pressure loss must be determined by iteration. The final orifice rod position is given by:

$$\delta = \delta \text{ adj.} + AMS (P_{\text{adj}} - P_5) - \frac{RF}{K} \quad (14)$$

Where  $\delta$  adj = Orifice rod adjusted position

### DOUBLE TAPER ROD

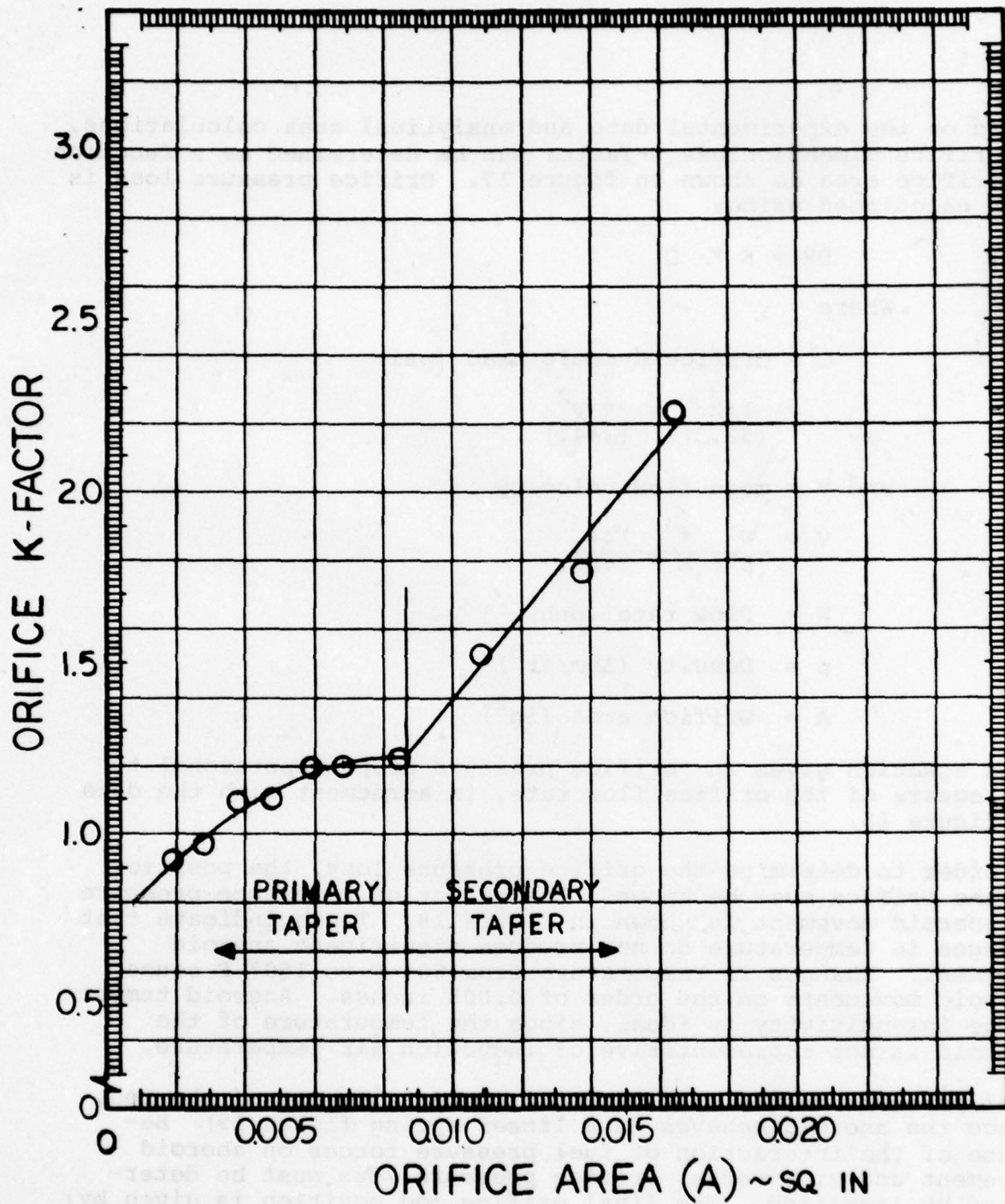


FIGURE 17. VARIABLE ORIFICE LOSS FACTOR

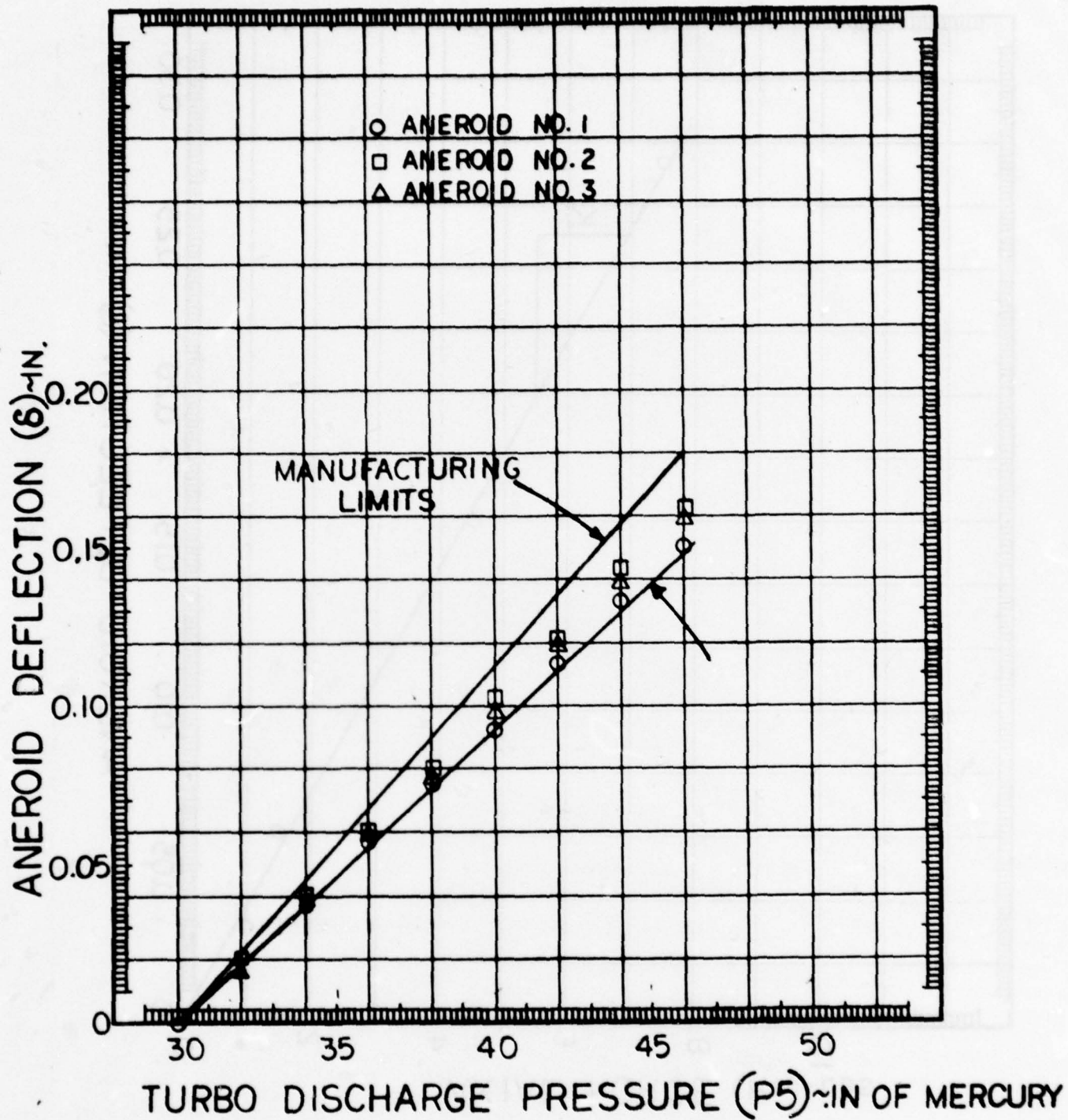


FIGURE 18. ANEROID TEST RESULTS

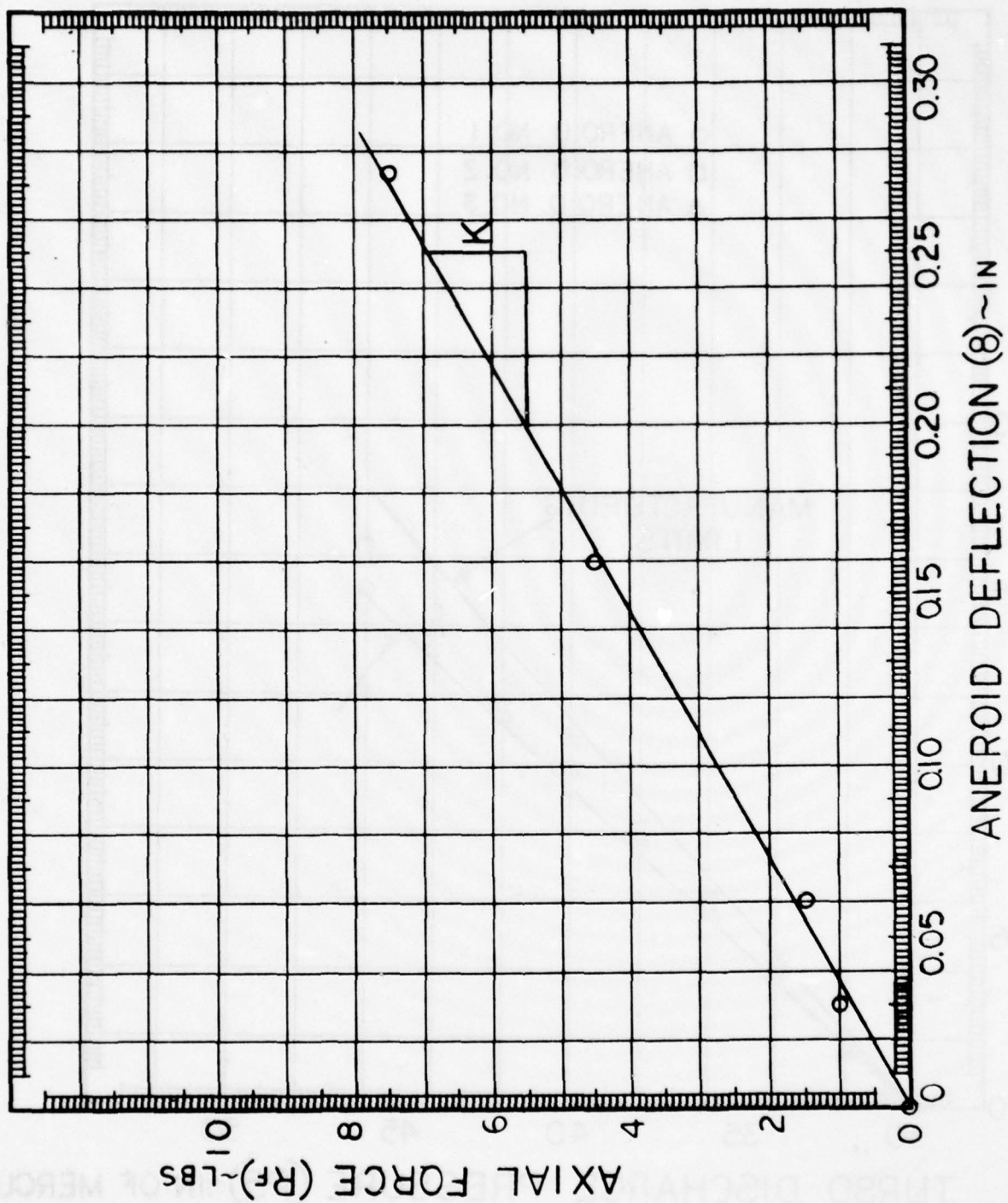


FIGURE 19. ANEROID DEFLECTION DUE TO AXIAL FORCE

- $P_{adj}$  = Turbo discharge pressure when orifice was adjusted  
 $P_5$  = Turbo discharge pressure for present operating conditions  
 $AMS$  = Slope of aneroid movement versus pressure (figure 18)  
 $K$  = Spring constant of the aneroid (figure 19)  
 $RF$  = Fuel pressure force on variable orifice rod

Orifice position ( $\delta$ ) as obtained from equation 14 is zero when the orifice is full closed (see figure 16).

#### 5) Idle Relief Valve

The idle relief valve is a spring-loaded valve used to set a minimum discharge pressure for the pump. A cross-sectional view of the relief valve is shown in figure 14. An adjustable spring and the action of the pump reference pressure (turbo discharge pressure,  $P_5$ ) on the valve diaphragm act to close the valve. The fluid pressure of the Avgas is higher at the valve inlet than at the valve discharge, producing a force across the valve orifice ( $A_v$ ) which tends to open the valve. Static equilibrium of forces on the valve yields equation 15 for the valve pressure drop:

$$\Delta P_v = \frac{K_s * \Delta LS + (P_5 - P_{ds}) A_e}{A_v} \quad (15)$$

Where  $\Delta P_v$  = Valve pressure drop ( $Lb_f/in^2$ )

$A_v$  = Valve flow area ( $in^2$ )

$A_v = \pi R_l^2$

$R_l$  = Valve orifice radius (0.31 inches)

$P_5$  = Turbo discharge pressure ( $Lb_f/in^2$ )

$P_{ds}$  = Valve downstream pressure ( $Lb_f/in^2$ )

$A_e$  = Diaphragm effective area (sq in)

$K_s$  = Valve spring constant ( $Lb_f/inch$ )

$\Delta LS$  = Ground-adjusted spring compression (inch)

Note that the valve pressure drop is independent of flow rate. This was found to be true from testing and is due to the rather large orifice area and relatively weak valve spring (low spring constant,  $K_s$ ). A small movement of the valve provides sufficient flow area for the required bypass flow (at relatively low pressure drop across the valve). Increase of the spring force due to this movement is small compared to the initial spring force typical of correct idle adjustment.

The unknown constants in equation 15 were determined from bench tests. Partial differentiation of this equation at constant turbo discharge and valve exit pressure gives:

$$\frac{d(\Delta P_v)}{d\Delta LS} = \frac{K_s}{A_v} \quad (P_5 \text{ and } P_{ds} \text{ Constant})$$

which is the slope of the pressure drop versus spring adjustment curve given in figure 20. From the slope of the curve and known valve area, the spring constant was determined to be 13.7  $lb_f/inch$ .

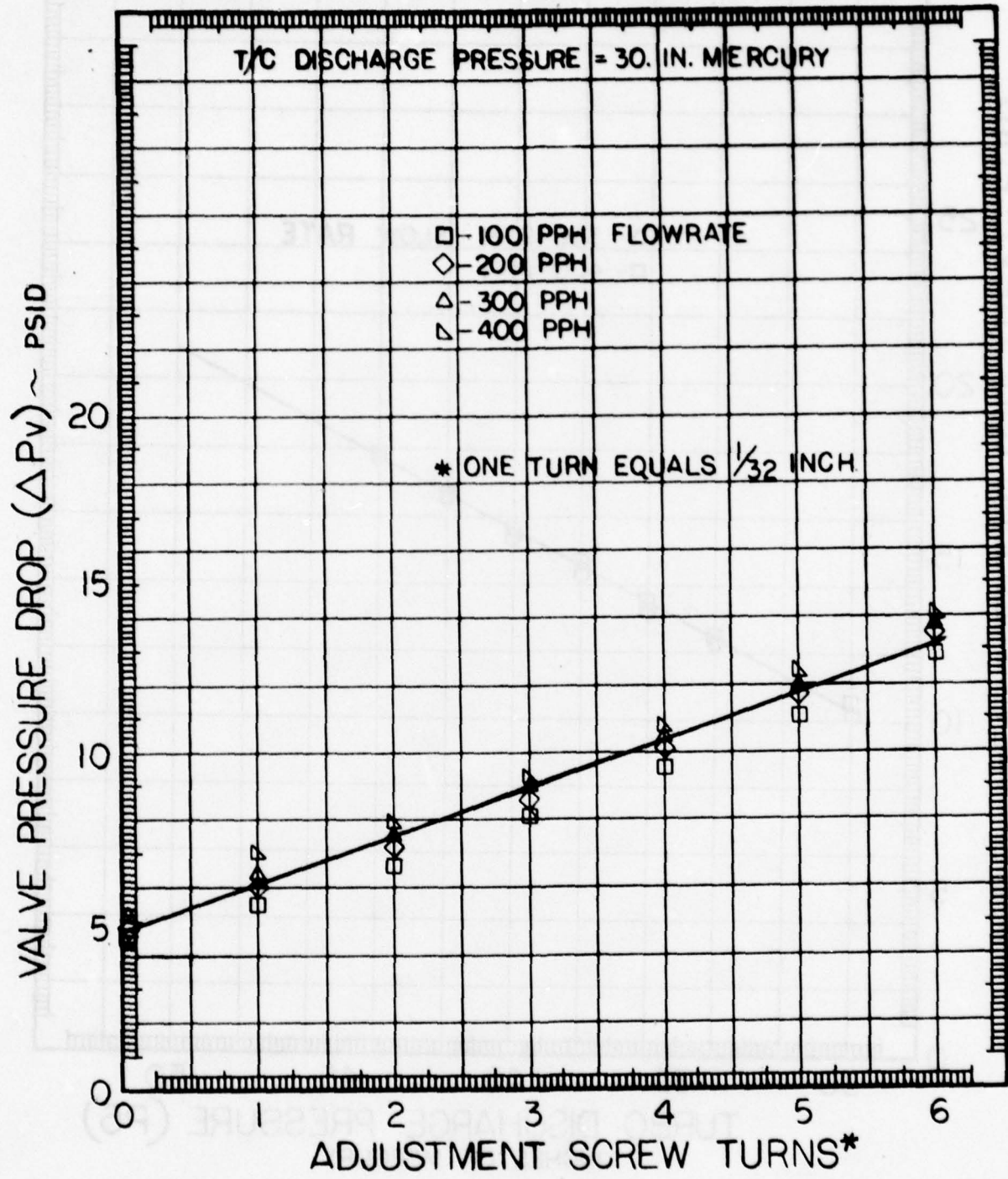
Similarly, the effect of turbo discharge pressure on valve pressure drop at constant spring load and valve exit pressure can be expressed as:

$$\frac{d(\Delta P_v)}{d P_5} = \frac{A_e}{A_v} \quad (\delta_{adj} \text{ and } P_{ds} \text{ Constant})$$

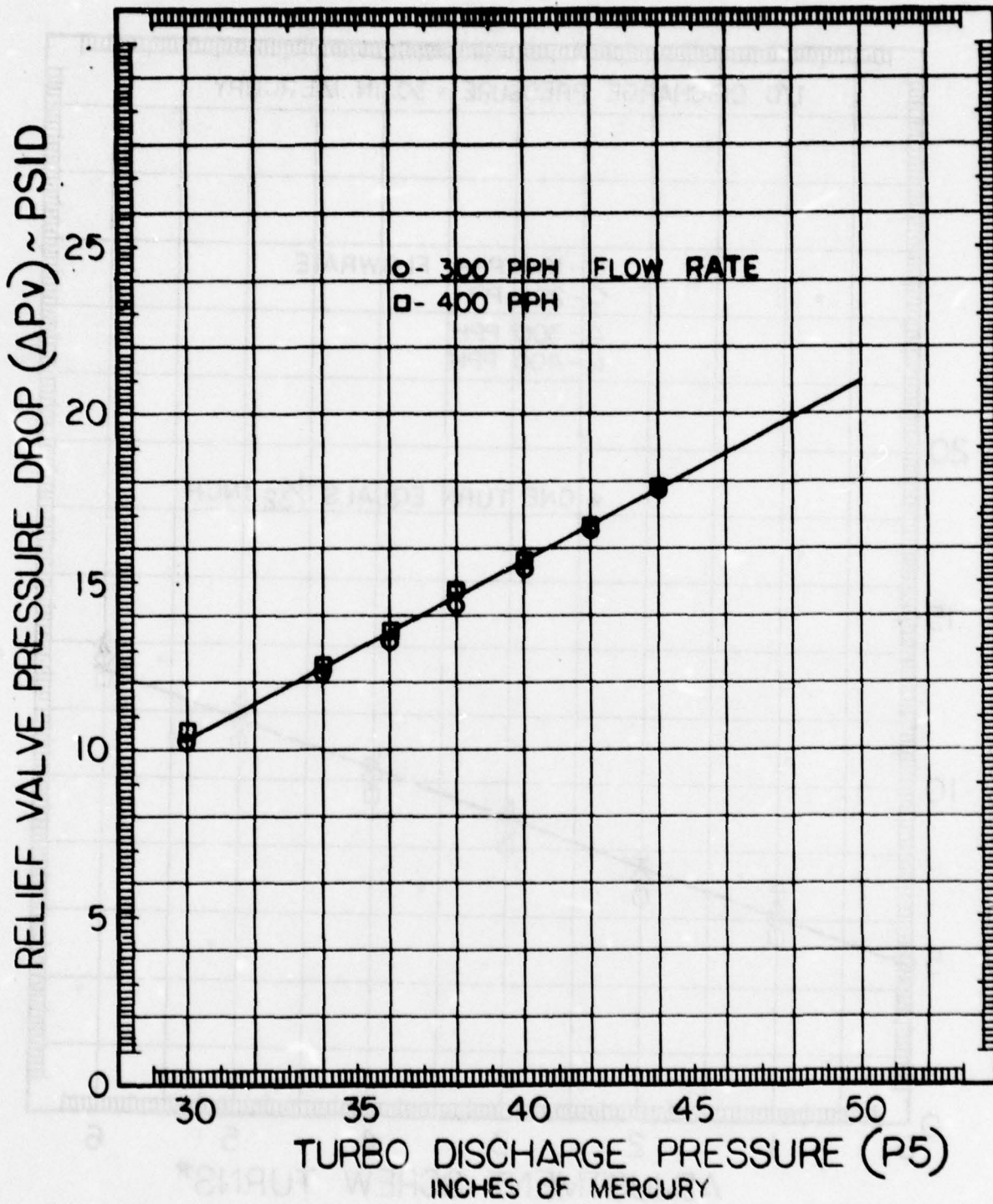
which is the slope of the line of data in figure 21. From the slope of the curve and known valve area, the diaphragm effective area was determined to be 0.334  $in^2$ . With the constants determined from bench tests, equation 15 can be used to calculate the relief valve pressure drop.

#### 6) Vapor Separator

The vapor separator pressure/flow relationship was determined experimentally and is given in figure 22. The internal passage connecting the pump discharge and inlet to the vapor separator was blocked and tapped to measure vapor separator flow rate. Flow rate was found to be insensitive to small changes in pump inlet pressure or vapor separator back pressure. Figure 22 was built into the computer model using a data block with linear interpolation between data points.



**FIGURE 20. EFFECT OF RELIEF VALVE ADJUSTMENT ON VALVE PRESSURE LOSS**



**FIGURE 21. EFFECT OF TURBO DISCHARGE PRESSURE ON RELIEF VALVE**

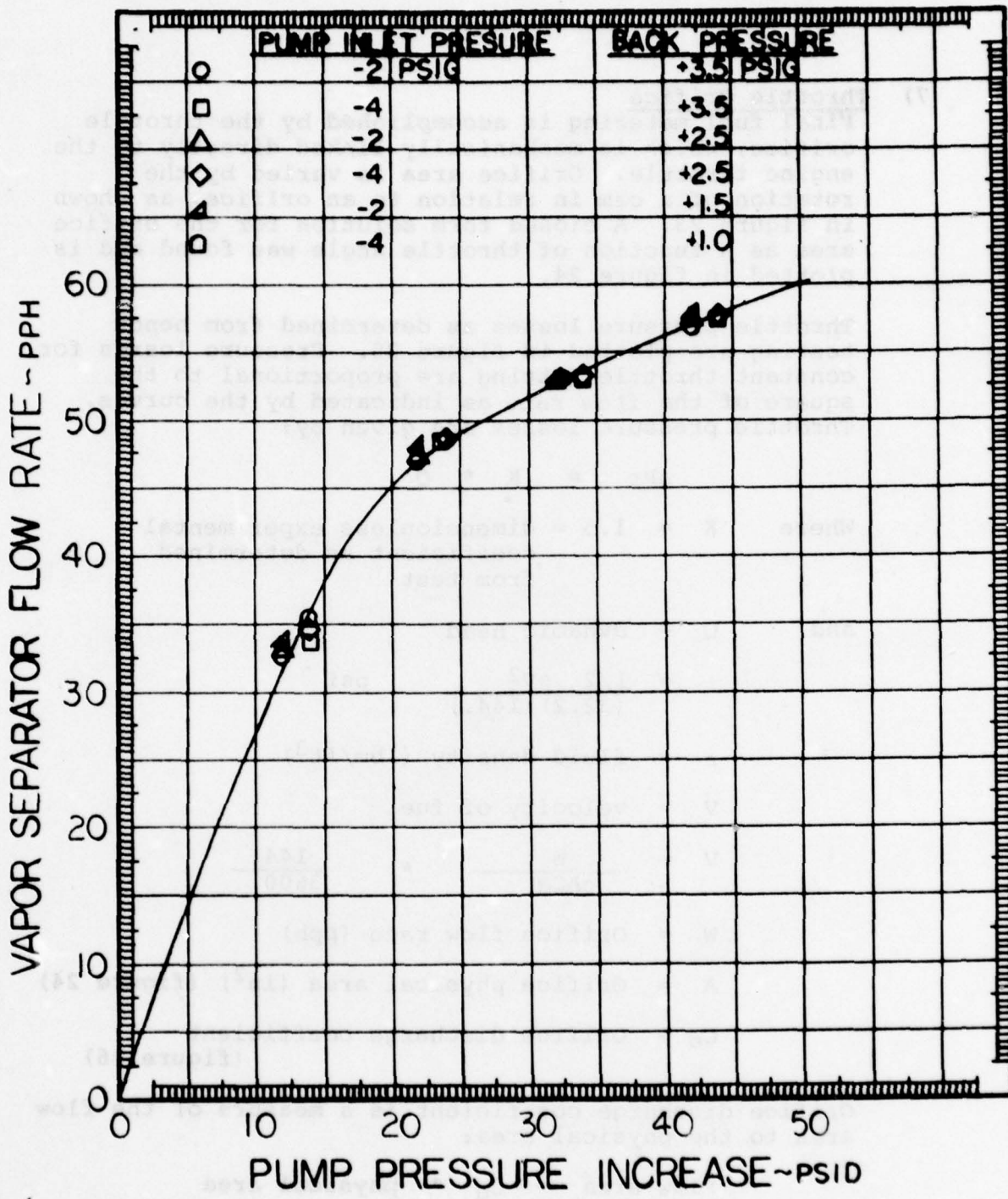


FIGURE 22. VAPOR SEPARATOR FLOW RATE

### 7) Throttle Orifice

Final fuel metering is accomplished by the throttle orifice, which is mechanically linked directly to the engine throttle. Orifice area is varied by the rotation of a cam in relation to an orifice, as shown in figure 23. A closed form solution for the orifice area as a function of throttle angle was found and is plotted in figure 24.

Throttle pressure losses as determined from bench testing are plotted in figure 25. Pressure losses for constant throttle setting are proportional to the square of the flow rate as indicated by the curves. Throttle pressure losses are given by:

$$\Delta P_t = K * Q$$

Where  $K = 1.5 =$  dimensionless experimental coefficient as determined from test

and  $Q =$  dynamic head  
 $= \frac{1/2 \rho V^2}{(32.2)(144.)}$  psi

$\rho =$  fluid density (lbm/ft<sup>3</sup>)

$V =$  velocity of fuel

$$V = \frac{W}{\rho A C_d} * \frac{144.}{3600.}$$

$W =$  Orifice flow rate (pph)

$A =$  Orifice physical area (in<sup>2</sup>) (figure 24)

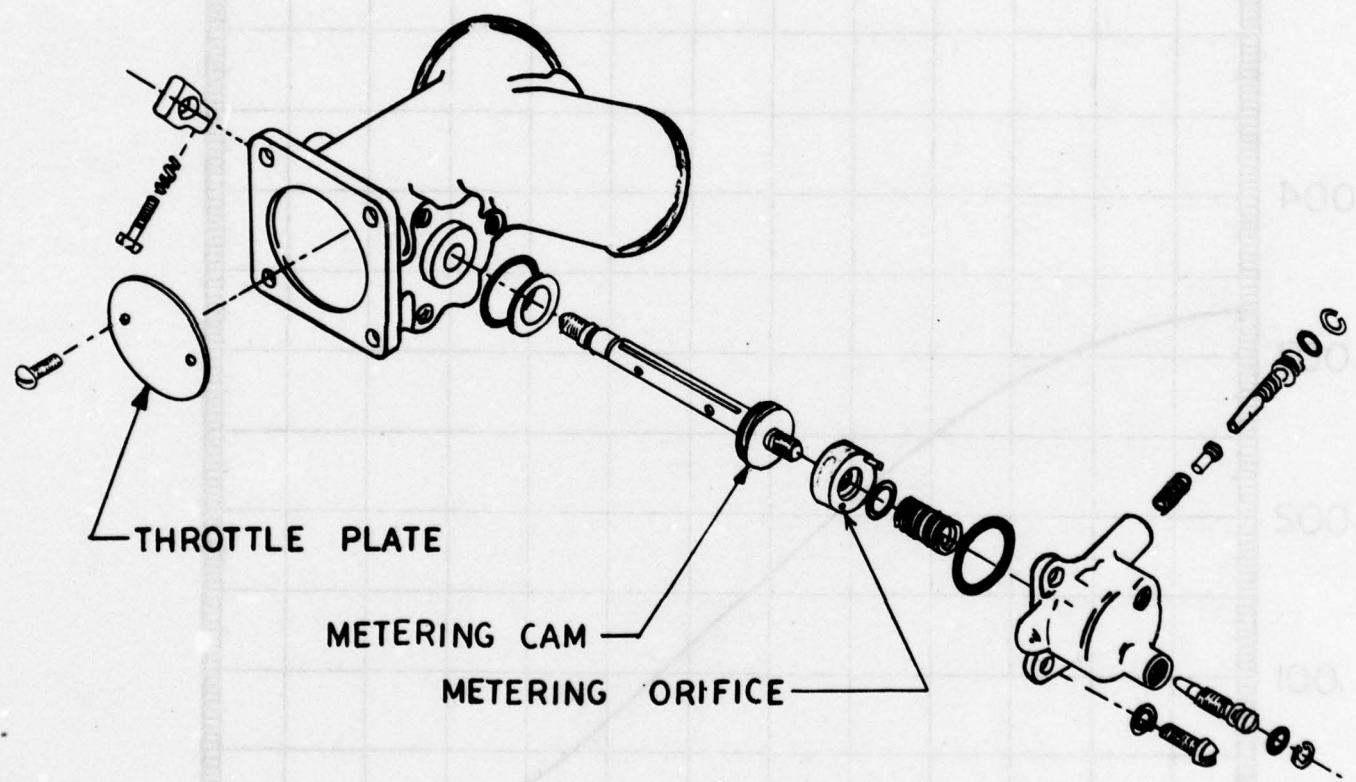
$C_d =$  Orifice discharge coefficient  
(figure 26)

Orifice discharge coefficient is a measure of the flow area to the physical area:

$$\text{Flow area} = C_d * \text{physical area}$$

Figure 26 gives the experimentally determined discharge coefficient for the throttle orifice as a function of orifice physical area.

THROTTLE ORIFICE AREA  
T810-360-E



150 100 80 60 40 20 0

ANGLE OF ROTATION  
DEGREES

FIGURE 24. THROTTLE ORIFICE AREA

**FIGURE 23. AIR THROTTLE AND FUEL METERING ASSEMBLY**

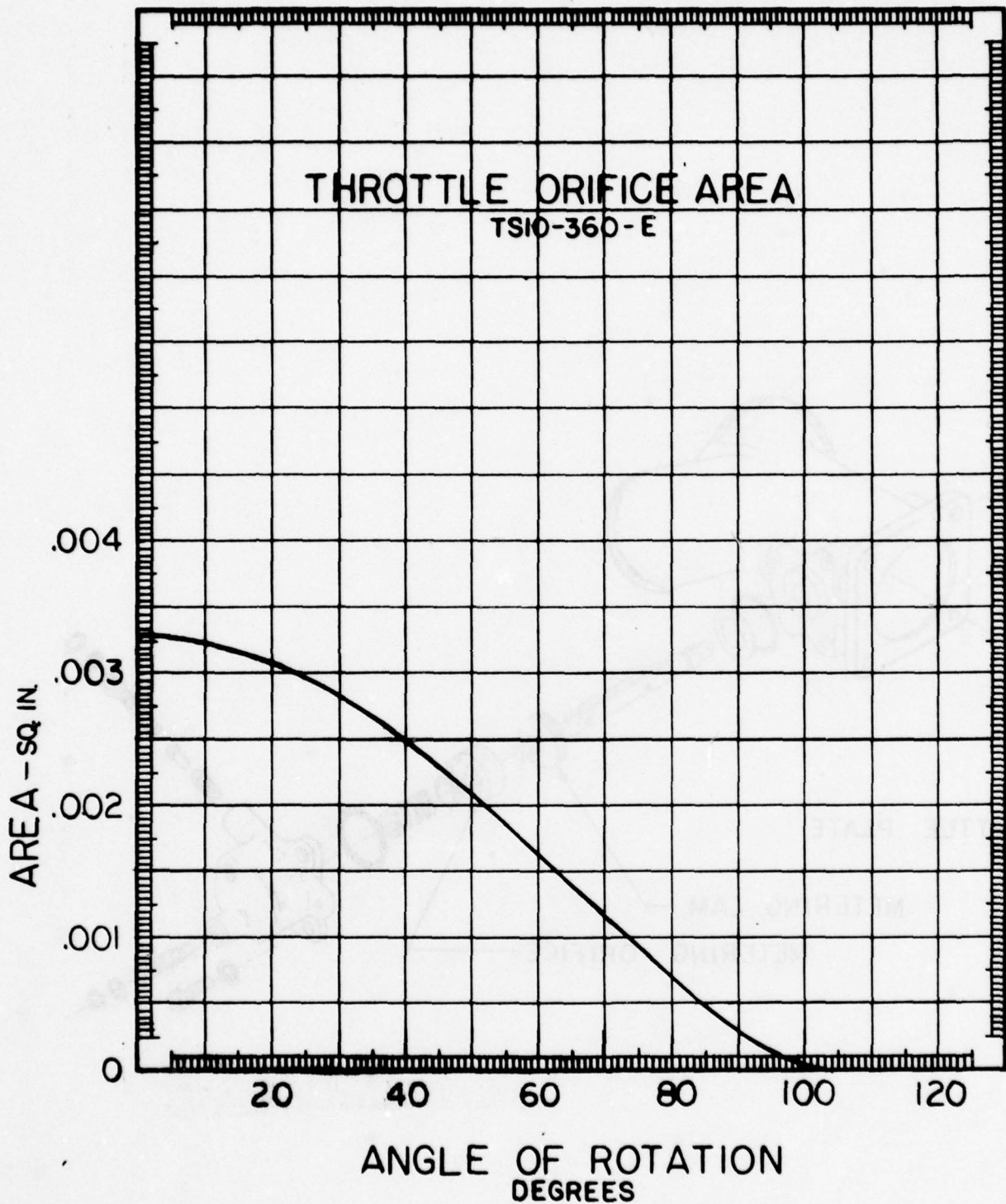


FIGURE 24. THROTTLE ORIFICE AREA

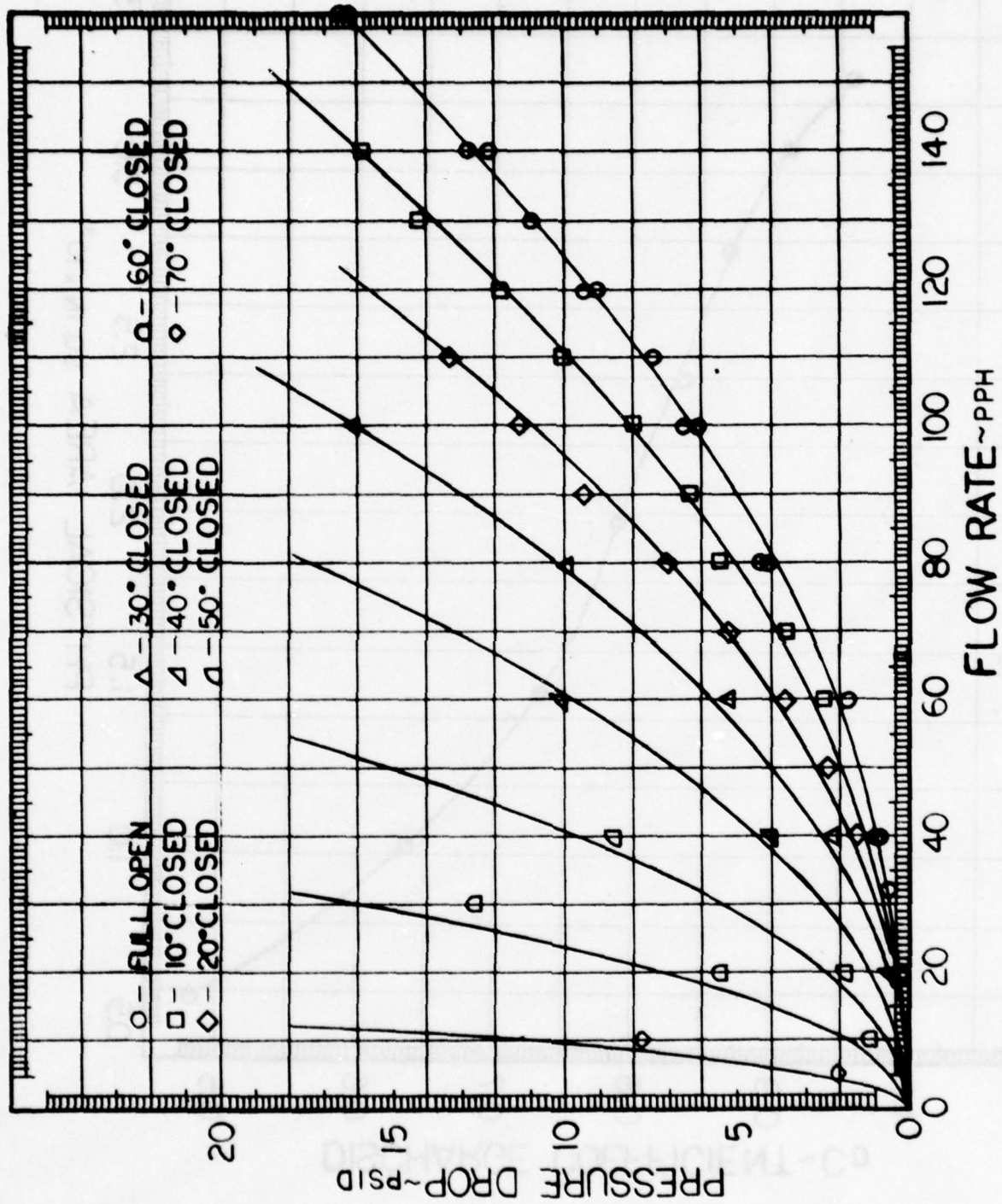


FIGURE 25. THROTTLE ORIFICE PRESSURE LOSS

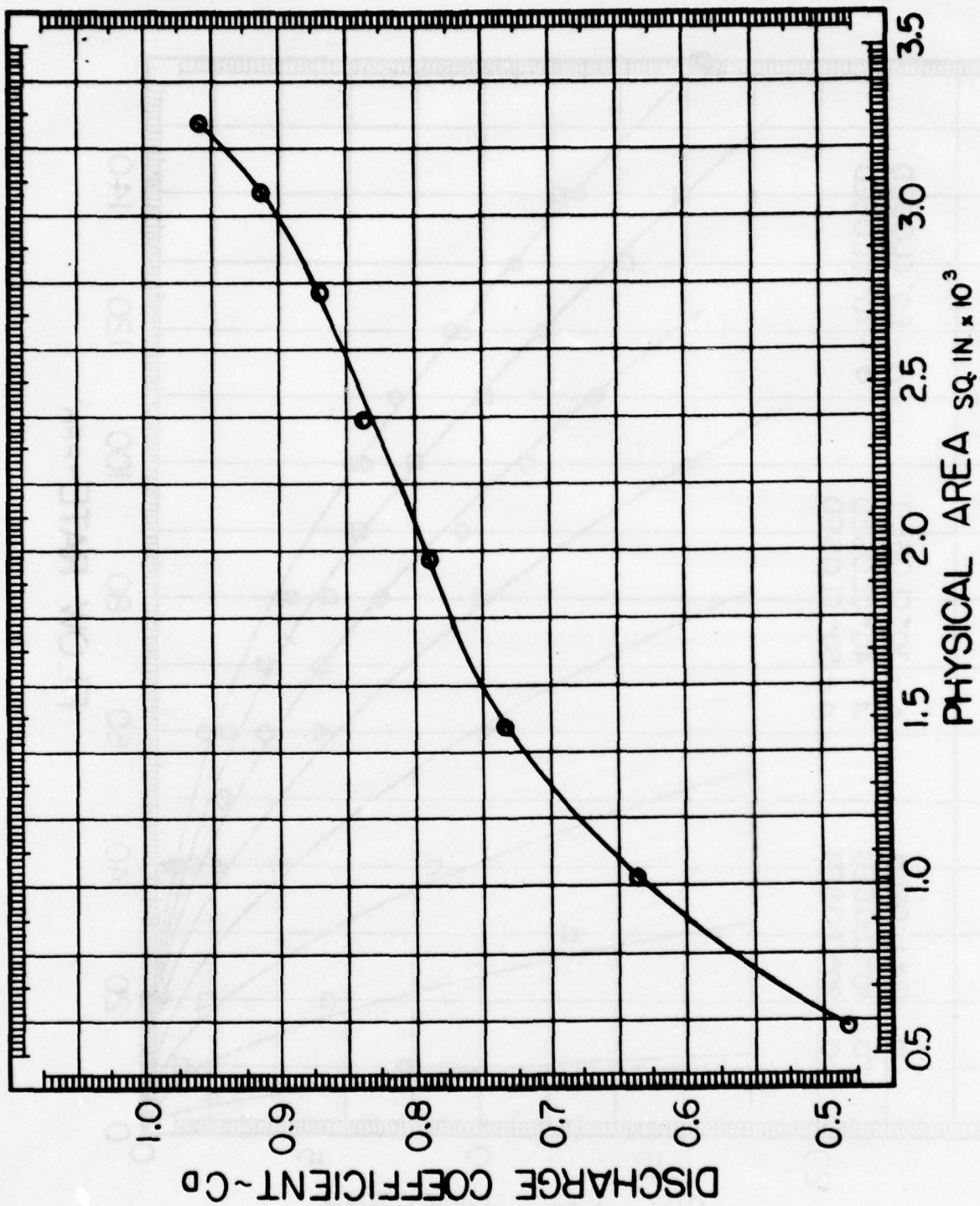


FIGURE 26. THROTTLE ORIFICE DISCHARGE COEFFICIENT

#### 8) Manifold Valve and Nozzles

The manifold valve, nozzle lines and nozzles are factory calibrated as a unit. Figure 27 gives the relationship between fuel flow and metered pressure. Metered fuel pressure is defined as the difference between fuel pressure at the manifold inlet and nozzle reference (turbo discharge) pressure. Fuel flow through the nozzle was found to be independent of manifold pressure. Turbo discharge pressure is fed to the fuel jet as shown in figure 28 and prevents manifold pressure from affecting fuel flow.

#### Simulation Checkout

A number of comparisons between simulation predictions and test data were made to check the computer simulation. Fuel bench tests of the entire fuel system were made to generate data for comparison. When possible, the simulation was compared directly with recorded engine data. However, throttle angle is rarely recorded during engine tests, and the accuracy of the throttle readings are questionable. Bench tests of the complete fuel system were made to simulate engine data by matching engine speed, turbo discharge pressure, and metered fuel pressure as recorded during engine calibration testing (reference 6). Careful measurements of the throttle angle were then made for input to the simulation.

The simulation was first "trimmed," using the variable orifice adjustment corresponding to ground trim on the actual system. Figure 29 shows the manufacturer's recommended flow rate and pressure at high power, as a function of the variable orifice ground trim. The simulation was trimmed to the middle of the recommended bands for fuel flow, metered fuel pressure, and pump discharge pressure. Idle flow rate was trimmed by adjusting the idle relief valve to 7.1 pph at 700 rpm. Fuel pump discharge pressure at idle was 6.7 psig. Continental's spec idle trim is 6 to 8 pph at 700 rpm, with a pump pressure of  $6.5 \pm 0.25$  psig.

After trimming, the simulation predictions were compared to test data. Figure 30 shows the simulation predictions (connected by solid line) compared to fuel bench test data. The engine conditions simulated on the fuel bench correspond to engine prop load conditions, with horsepower ranging from 20 to 100 percent of maximum continuous power. The difference between the predicted and measured flow rate is within the accuracy of the bench measurements. Pump discharge pressure agreed well with measured values.

The effect of turbo discharge pressure on fuel system output is

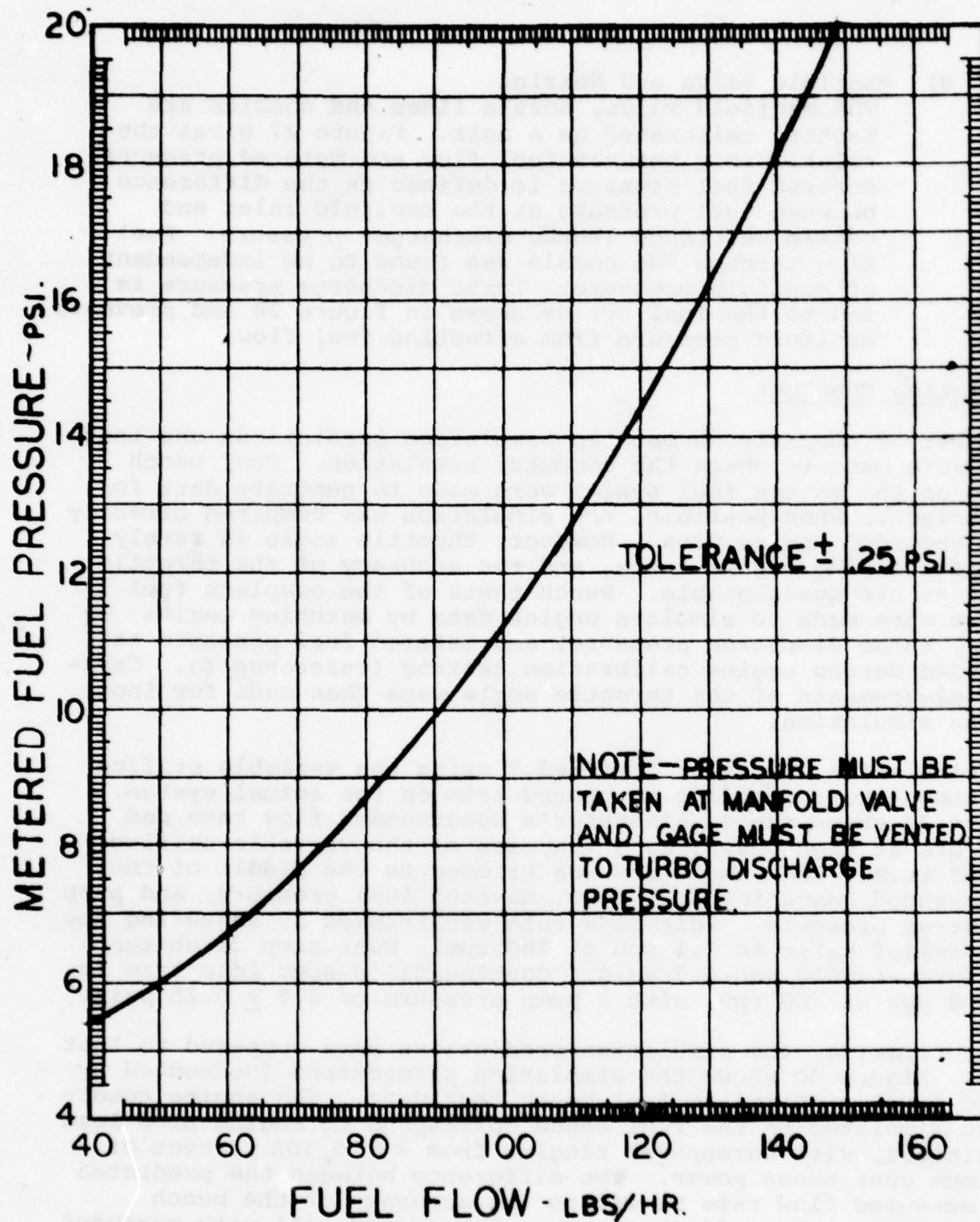
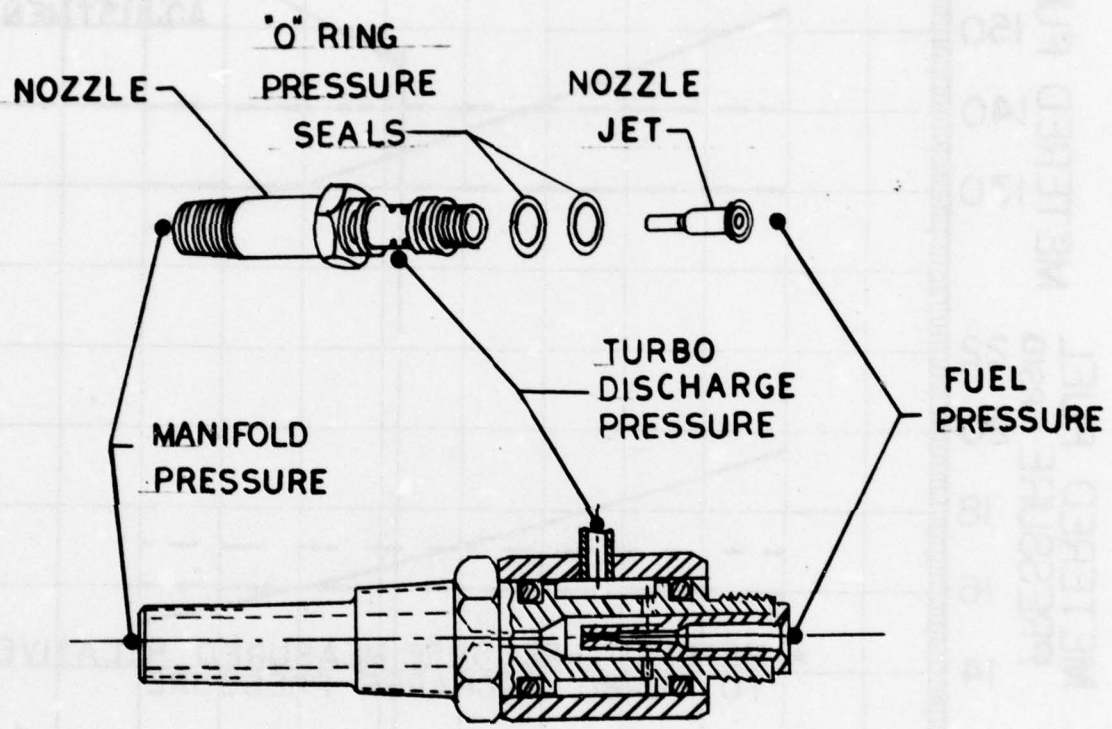
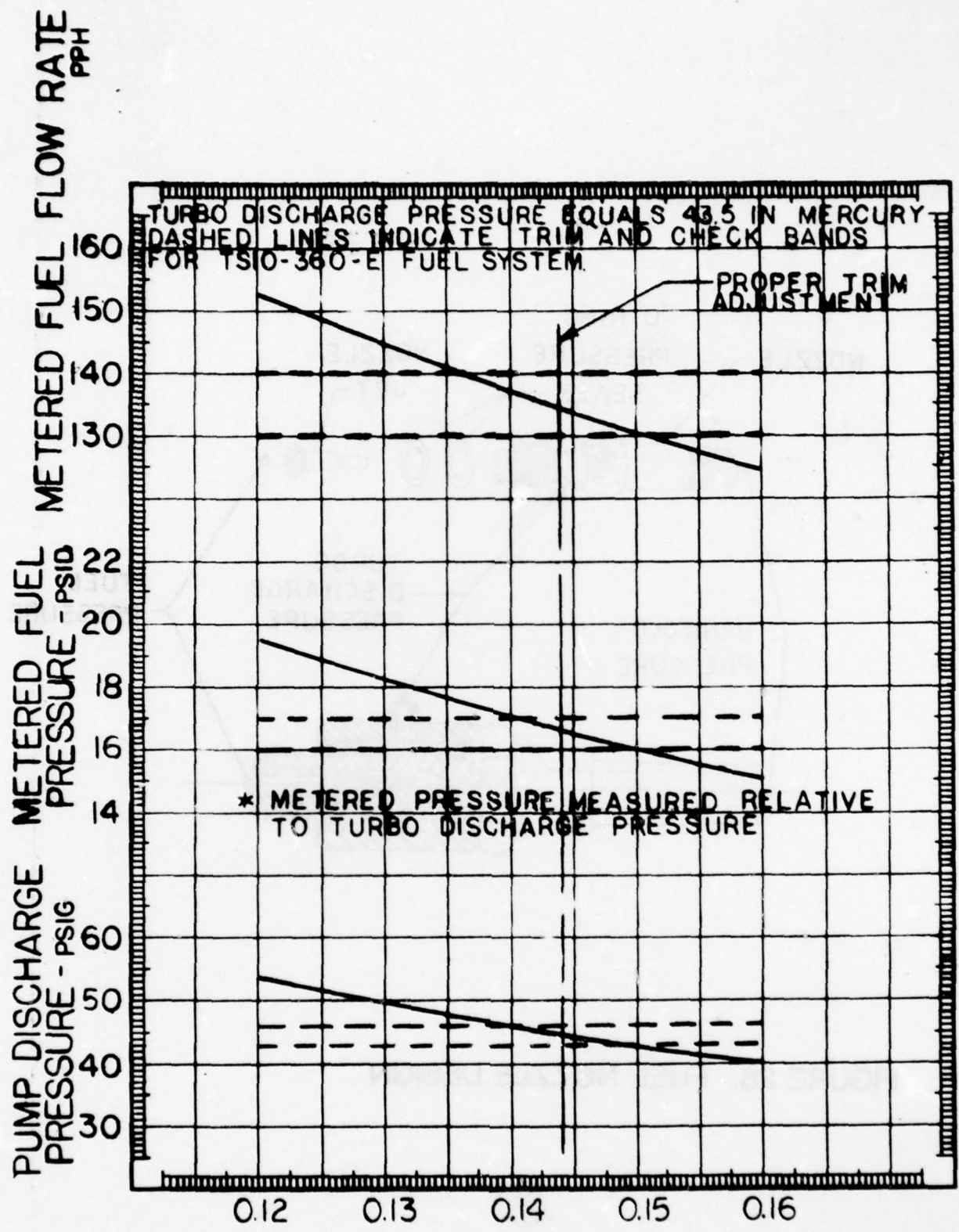


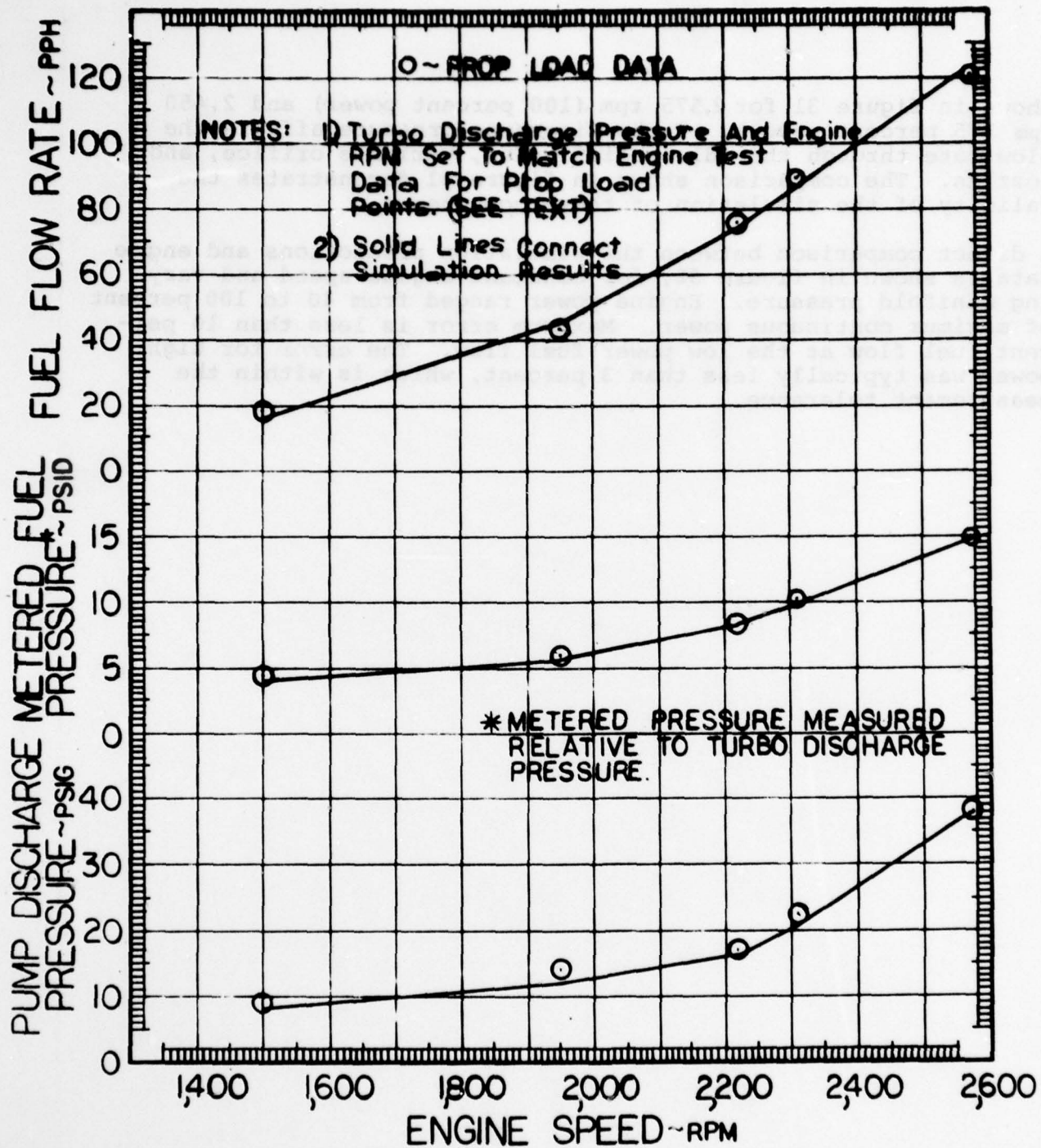
FIGURE 27. METERED FUEL ASSEMBLY CALIBRATION



**FIGURE 28. FUEL NOZZLE DESIGN**



VARIABLE ORIFICE ROD ADJUSTMENT - IN.  
 FIGURE 29. SIMULATED HIGH POWER TRIM ADJUSTMENT



**FIGURE 30. COMPARISON OF FUEL SYSTEM SIMULATION WITH FUEL BENCH TEST DATA**

shown in figure 31 for 2,575 rpm (100 percent power) and 2,450 rpm (75 percent power). Turbo discharge pressure affects the flow rate through the idle relief valve, variable orifice, and nozzles. The comparison shown in figure 31 demonstrates the validity of the simulation of these components.

A direct comparison between the simulation predictions and engine data is shown in figure 32, for constant engine speed and varying manifold pressure. Engine power ranged from 40 to 100 percent of maximum continuous power. Maximum error is less than 10 percent fuel flow at the low power fuel flow. The error for high power was typically less than 3 percent, which is within the measurement tolerance.

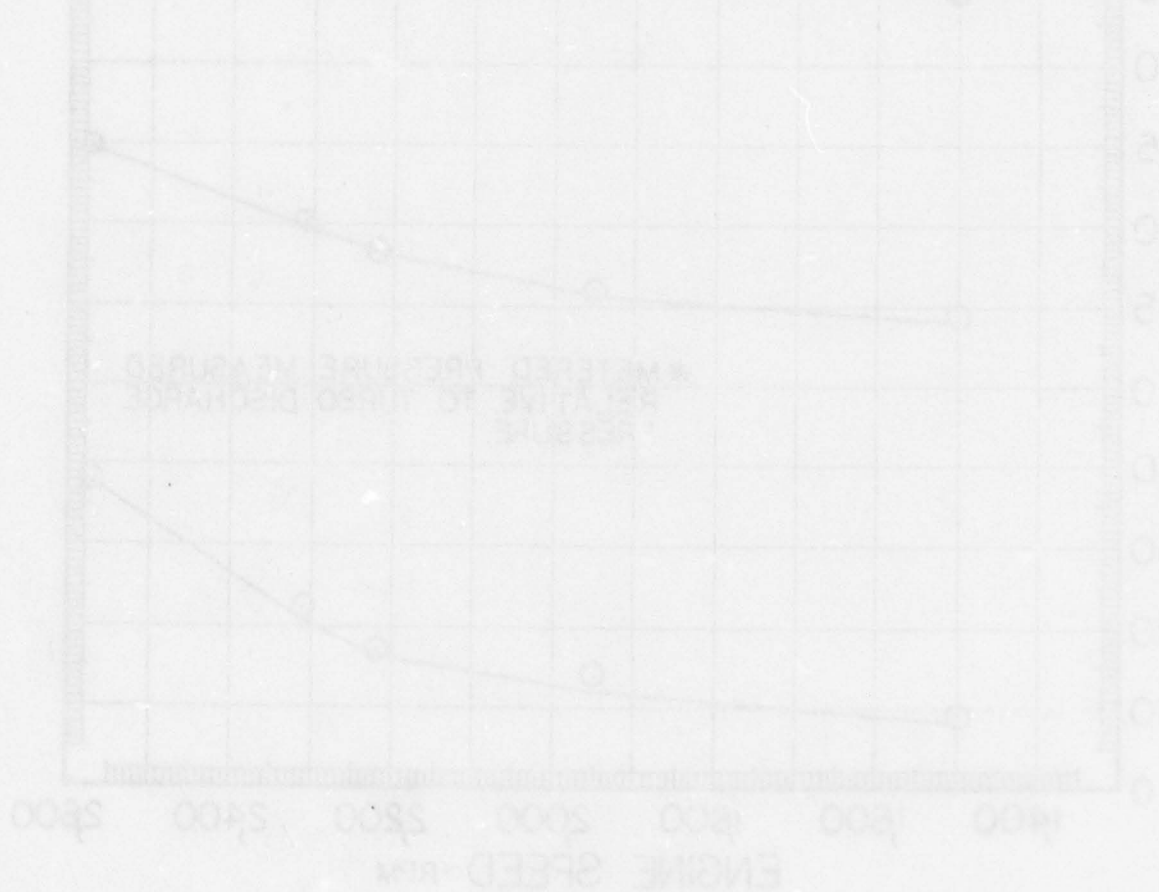


FIGURE 30. COMPARISON OF FUEL SYSTEM SIMULATION WITH FUEL BENCH TEST DATA

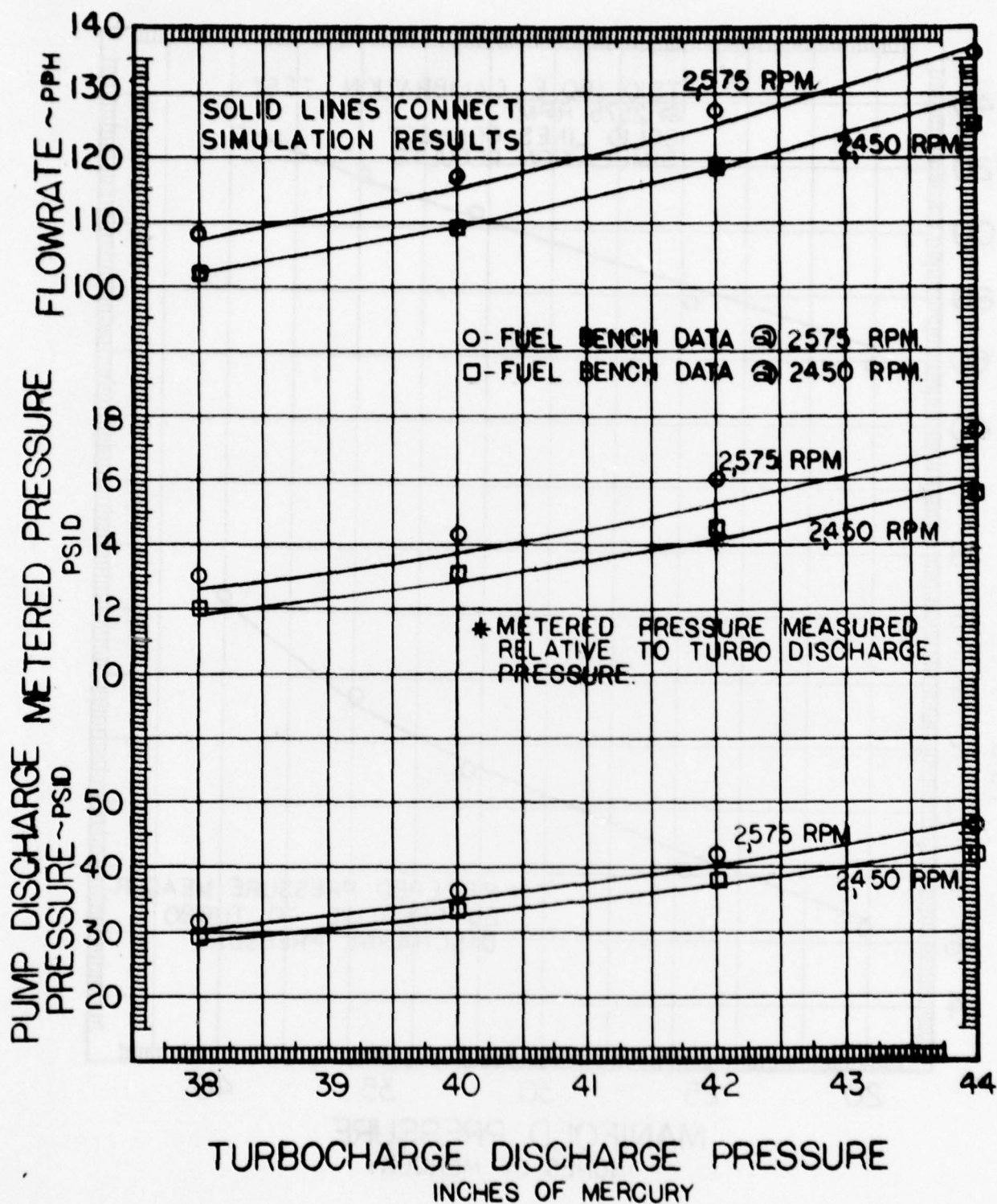


FIGURE 31. COMPARISON OF FUEL SYSTEM SIMULATION WITH FUEL BENCH TEST DATA

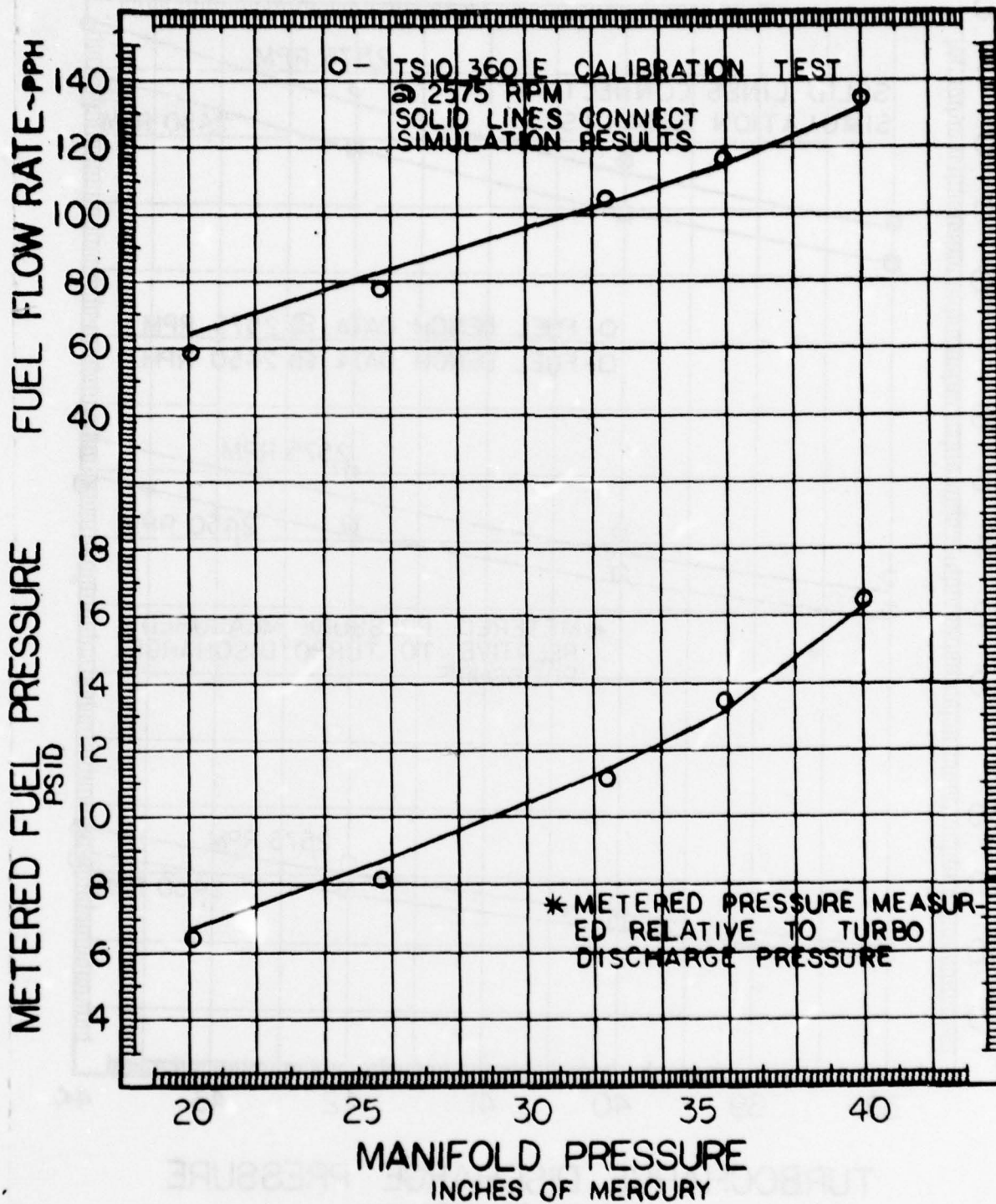


FIGURE 32. COMPARISON OF FUEL SYSTEM SIMULATION WITH ENGINE CALIBRATION DATA

## CONCEPTS TO IMPROVE FUEL INJECTION

During phase 1 of the contract, an investigation of the effects of leaning on engine emissions for the NAFEC seven-mode LTO cycle was completed. A review of this study was made to determine the reduction of emissions that could be expected for a TSIO-360-C engine, assuming a means of reducing the engine acceleration lean limit could be found. Table 1 repeats the information for the baseline emissions of the engine reported in reference 1, and shows hydrocarbons to be 212 percent of the proposed standards. Emissions of carbon monoxide and oxides of nitrogen were found to be 193 percent and 9 percent of the proposed standards, respectively. Table 1 also shows the emissions predicted provided the engine acceleration lean limit was reduced to 0.065 fuel/air ratio at low power. These predictions, based on the results found in phase I of the contract, show that the hydrocarbon emissions would be reduced from 212 percent to 48 percent of the proposed EPA standards. Carbon monoxide emissions would be reduced to 140 percent of the EPA standards, and emissions of nitrogen oxides would remain below the EPA standards, increasing to 46 percent. Take-off and climb fuel flows were assumed to be mean values (baseline flows) within the current fuel flow band. These high power conditions are engine temperature limited and the engine must be cooled with sufficient fuel as determined by flight testing a particular installation. The target value of 0.065 fuel/air ratio was picked as a value obtainable by modifying the current Continental fuel system and air intake manifold. Continental engines have demonstrated acceptable acceleration below 0.065 fuel/air ratio with more sophisticated fuel systems and intake manifolds.

Some methods for reducing the engine lean limit for acceleration and improving fuel/air ratio control are given below. The transient response of the turbocharger discharge pressure and flow rate during acceleration must be known in order to tailor the fuel system response to sensed parameters.

### 1) Temperature Compensation

The current fuel system has no means of temperature compensation. This means the fuel system must be adjusted for acceptable engine acceleration at the lowest expected ambient temperature. The effect of ambient temperature on fuel/air ratio for constant fuel flow is shown in figure 33. Given a minimum fuel/air ratio acceleration limit at 0° F, increasing ambient temperature increases the operating fuel/air ratio. Temperature compensation can be added to the Continental system using a N-Propyl Alcohol filled aneroid (figure 34). The aneroid movement necessary to maintain constant fuel/air ratio with varying

TABLE I  
 BREAKDOWN OF EMISSIONS BY ENGINE  
 OPERATING CONDITION  
 TSIO-360-C ENGINE

All Values Are Percent of Proposed EPA Standards

HC EMISSIONS

Operating Condition	(1)		Limit
	Baseline Emissions (%)	Leaned Emissions (%)	
Taxi	154.5	10.5	Accel
Idle	24.0	11.0	Accel
Climb	20.4	20.4	Temp
Approach	11.9	4.9	Accel
Take-off	1.3	1.3	Temp
<b>Total</b>	<b>212.1</b>	<b>48.1</b>	

CO EMISSIONS

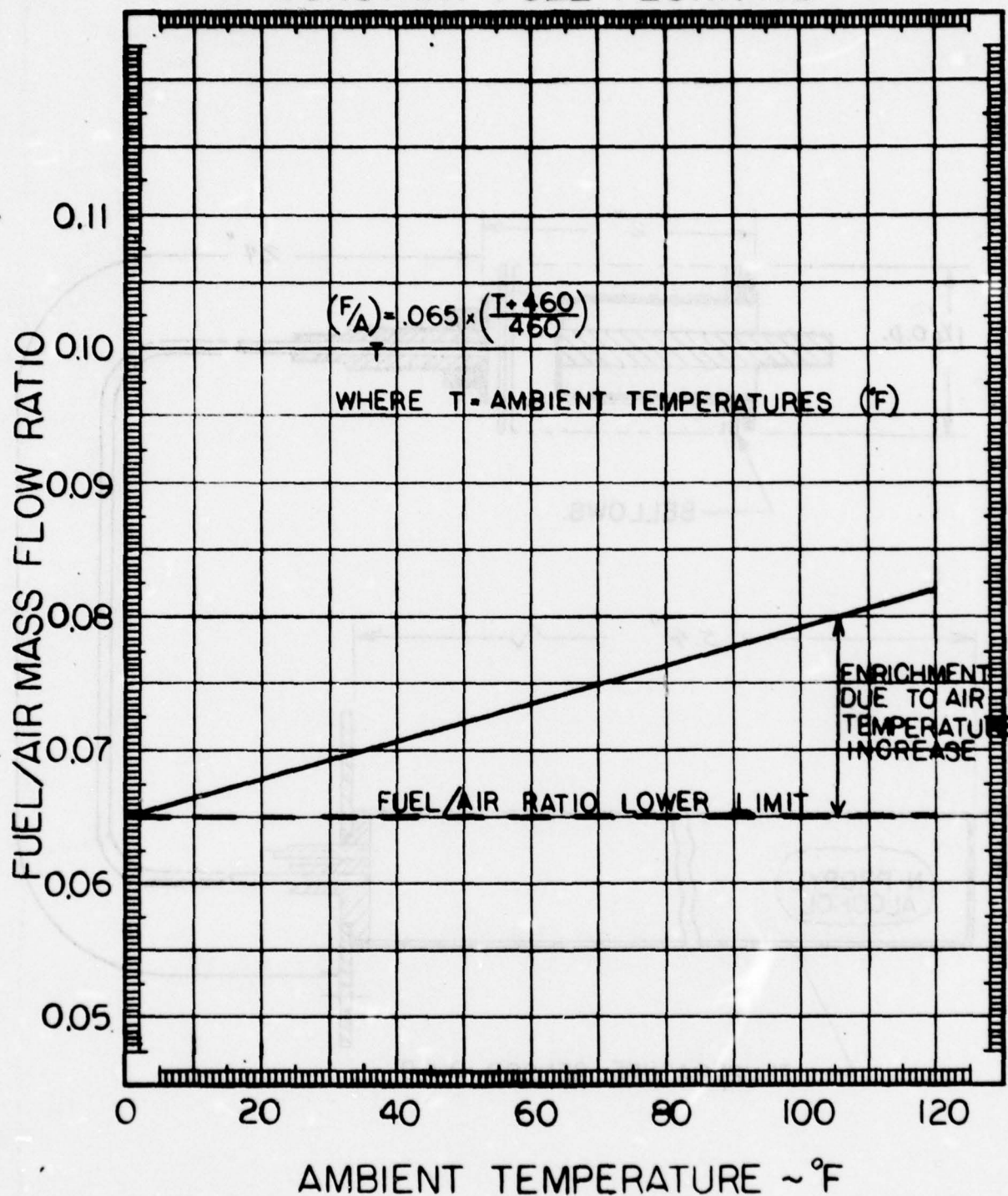
Operating Condition	(1)		Limit
	Baseline Emissions (%)	Leaned Emissions (%)	
Climb	102.3	102.3	Temp
Approach	54.8	15.9	Accel
Taxi	26.4	12.3	Accel
Take-off	9.5	9.5	Temp
Idle	Neg	Neg	Accel
<b>Total</b>	<b>193.0</b>	<b>140.0</b>	

NO EMISSIONS

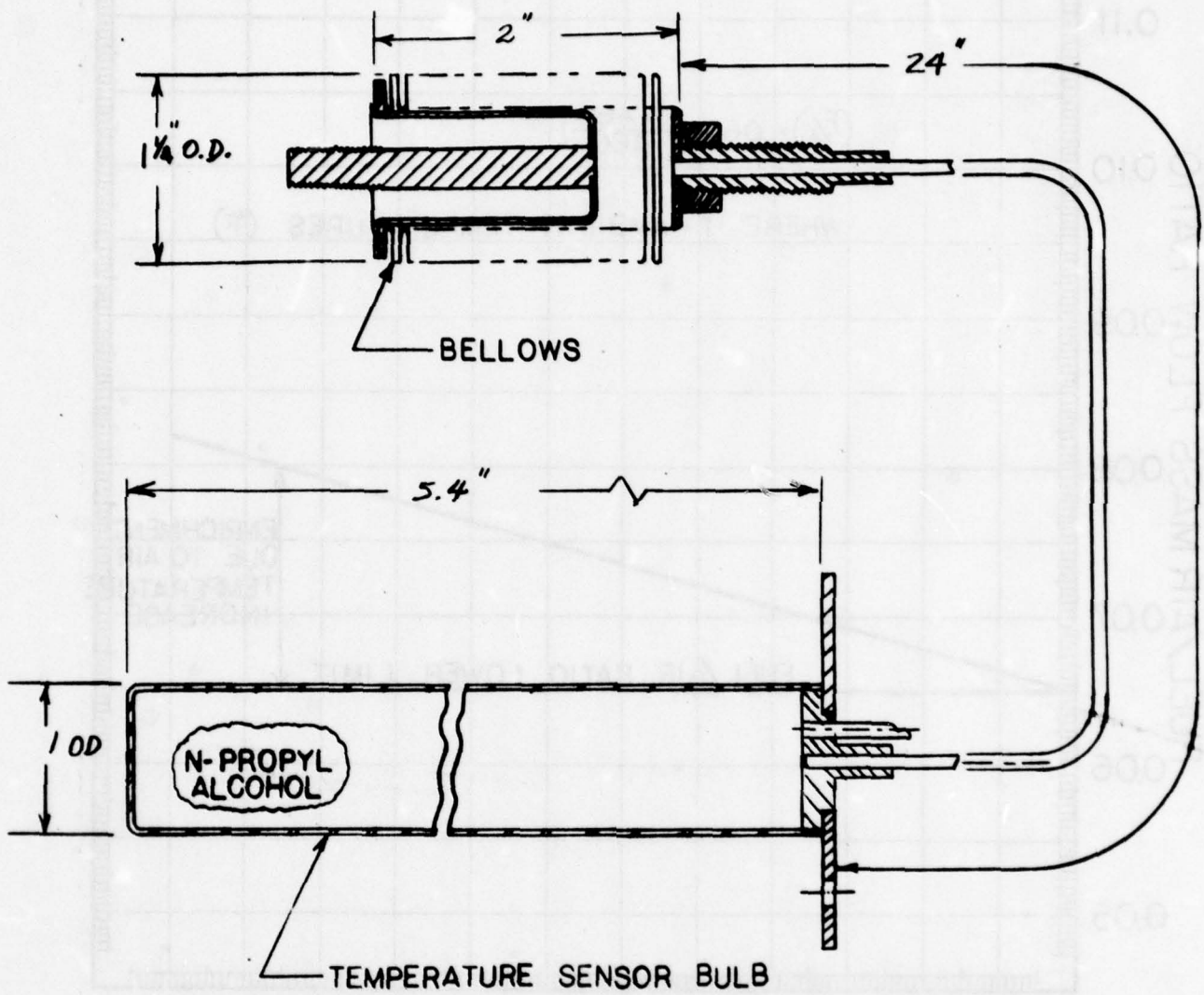
Operating Condition	(1)		Limit
	Baseline Emissions (%)	Leaned Emissions (%)	
Approach	7.1	38.8	Accel
Climb	0.4	3.3	Temp
Taxi	0.7	1.9	Accel
Idle	0.6	2.0	Accel
Take-off	Neg	Neg	Temp
<b>Total</b>	<b>8.8</b>	<b>46.0</b>	

(1) Acceleration limit assumed to be reduced to 0.065 fuel/air ratio by improving manifold and fuel management.

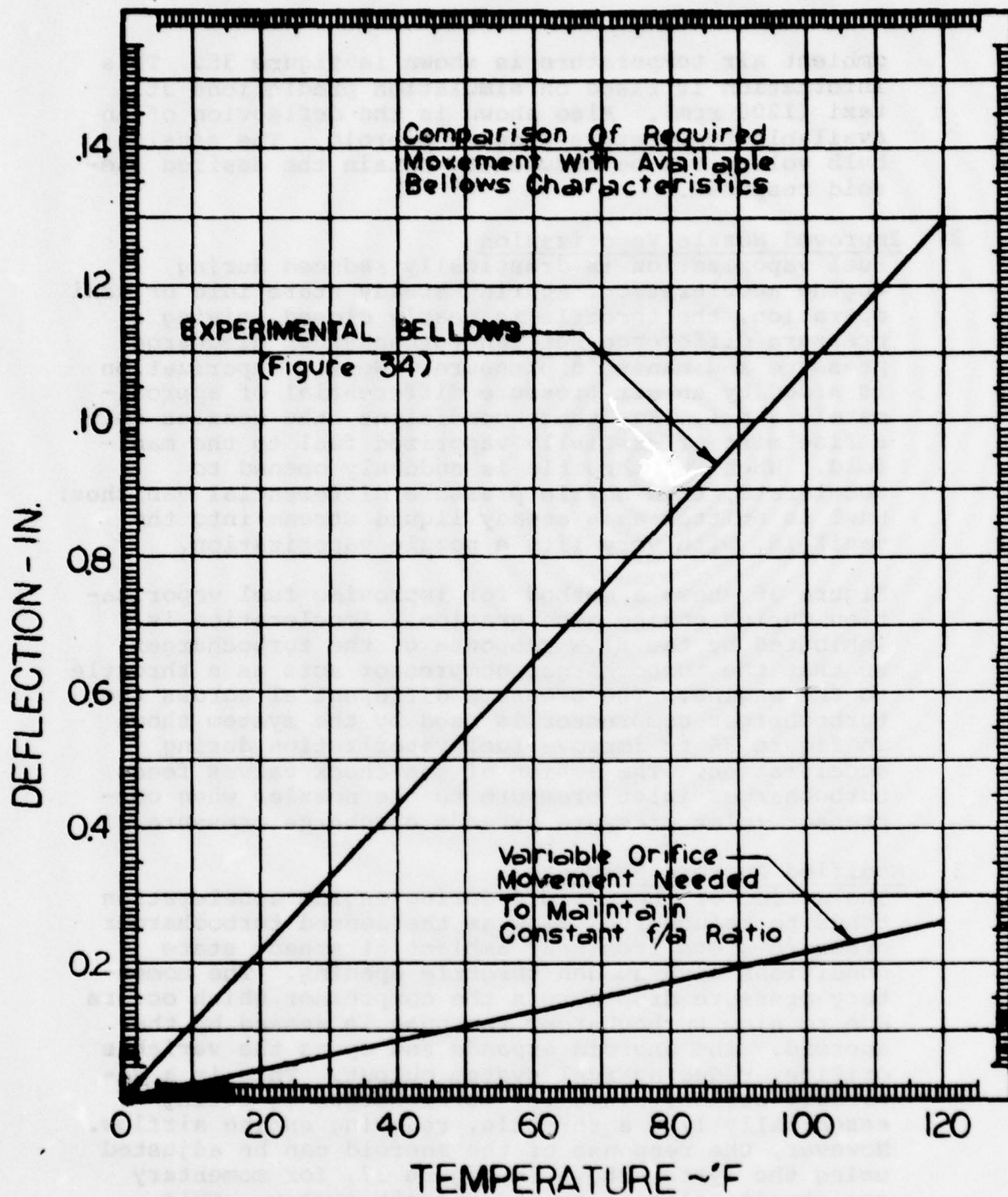
### CONSTANT FUEL FLOWRATE



**FIGURE 33. EFFECT OF AMBIENT AIR TEMPERATURE ON ENGINE FUEL /AIR RATIO**



**FIGURE 34. TEMPERATURE SENSING ANEROID DESIGN**



**FIGURE 35. BELLOWS MOVEMENT REQUIRED  
FOR TEMPERATURE COMPENSATION**

ambient air temperature is shown in figure 35. This information is based on simulation predictions at taxi (1200 rpm). Also shown is the deflection of an available temperature-sensing aneroid. The sensing bulb volume can be reduced to obtain the desired aneroid response.

2) Improved Nozzle Vaporization

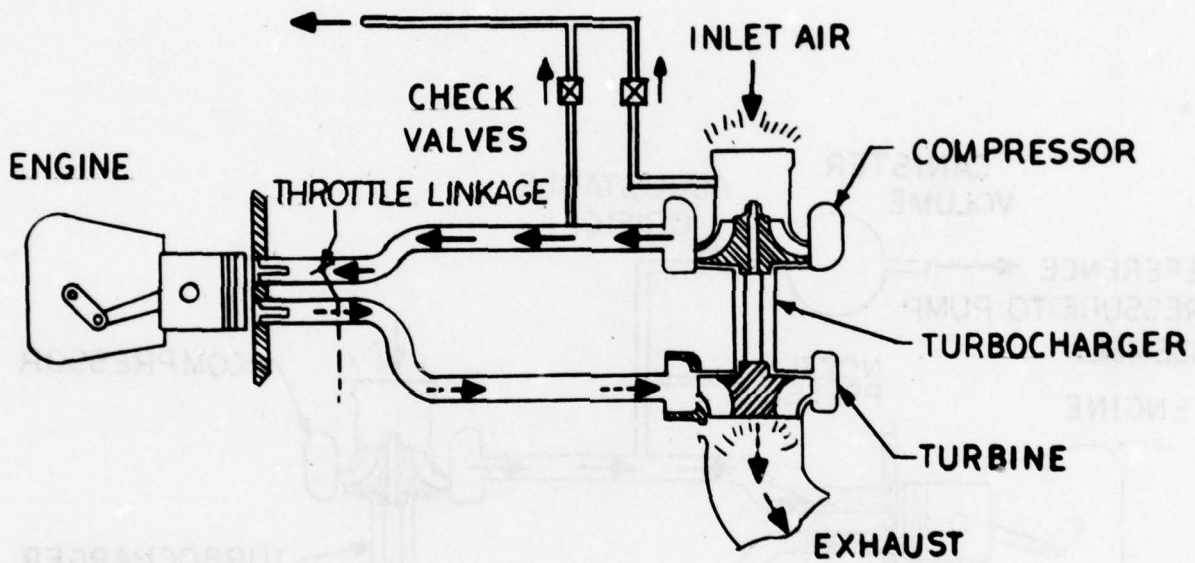
Fuel vaporization is drastically reduced during engine acceleration. During steady state idle or taxi operation, the throttle is nearly closed, giving a pressure difference between turbocharger discharge pressure and manifold pressure. Nozzle vaporization is aided by an air pressure differential of approximately 5 psi. For these conditions, the nozzles emit a fine mist of partially vaporized fuel to the manifold. When the throttle is suddenly opened to accelerate, this nozzle pressure differential vanishes. Fuel is emitted as a steady liquid stream into the manifold, with very little nozzle vaporization.

Figure 36 shows a method for improving fuel vaporization during engine acceleration. Acceleration is inhibited by the slow response of the turbocharger, so that the turbocharger compressor acts as a throttle to the engine. The pressure differential across the turbocharger compressor is used by the system shown in figure 36 to improve fuel vaporization during acceleration. The action of the check valves feeds turbocharger inlet pressure to the nozzles when compressor inlet pressure exceeds discharge pressure.

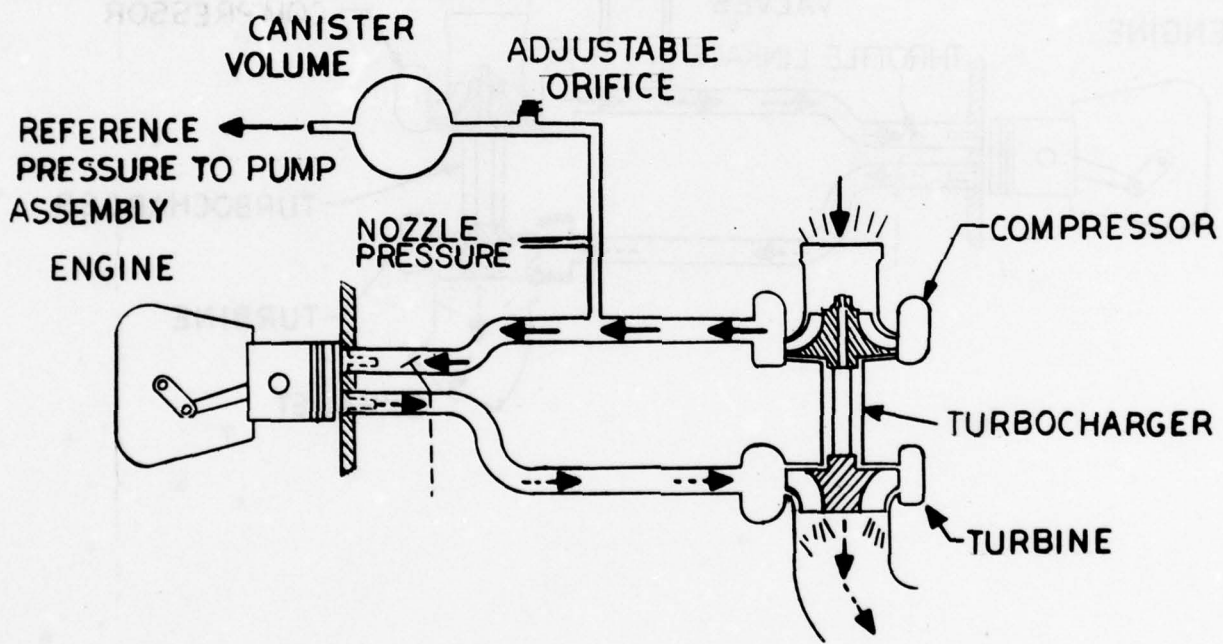
3) Modified Aneroid Response

The action of the aneroid during engine acceleration tends to reduce fuel flow as the sensed turbocharger pressure drops from near ambient at steady state conditions with sudden throttle opening. The momentary pressure drop across the compressor which occurs due to slow turbocharger response is sensed by the aneroid. The aneroid expands and opens the variable orifice, reducing fuel system output. This is a desirable action, since the turbocharger is acting essentially like a throttle, reducing engine airflow. However, the response of the aneroid can be adjusted using the system shown in figure 37, for momentary enrichment relative to the current system. This could be used to counter the effects of leaning at steady state conditions, and thus reduce the acceleration lean limit. The probable response of such a system would be as shown qualitatively in figure 38.

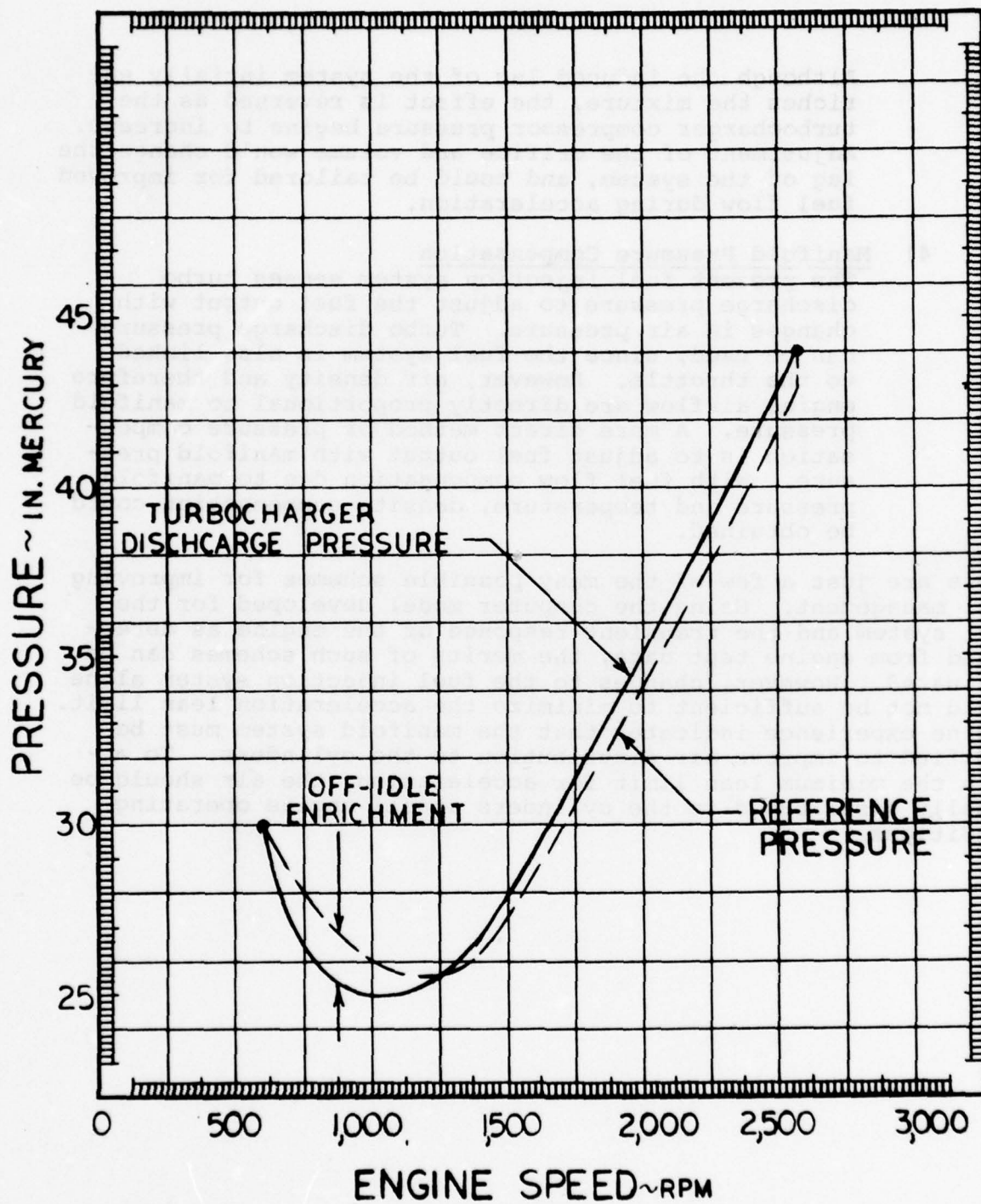
REFERENCE PRESSURE  
TO NOZZLES



**FIGURE 36. FUEL SYSTEM MODIFICATION FOR IMPROVED FUEL VAPORIZATION DURING ACCELERATION**



**FIGURE 37. FUEL SYSTEM MODIFICATION FOR OFF-IDLE ENRICHMENT DURING ACCELERATION**



**FIGURE 38. DELAYED REFERENCE PRESSURE RESPONSE DURING ENGINE ACCELERATION**

Although the induced lag of the system initially enriches the mixture, the effect is reversed as the turbocharger compressor pressure begins to increase. Adjustment of the orifice and volume would change the lag of the system, and could be tailored for improved fuel flow during acceleration.

4) Manifold Pressure Compensation

The present fuel injection system senses turbo discharge pressure to adjust the fuel output with changes in air pressure. Turbo discharge pressure can be used, since the fuel system is also linked to the throttle. However, air density and therefore engine airflow are directly proportional to manifold pressure. A more direct method of pressure compensation is to adjust fuel output with manifold pressure. With fuel flow compensation due to manifold pressure and temperature, density compensation could be obtained.

These are just a few of the many possible schemes for improving fuel management. Using the computer model developed for the fuel system and the transient response of the engine as determined from engine test data, the merits of such schemes can be evaluated. However, changes to the fuel injection system alone would not be sufficient to minimize the acceleration lean limit. Engine experience indicates that the manifold system must be modified to improve air distribution to the cylinders. To attain the minimum lean limit for acceleration, the air should be equally distributed to the cylinders at all engine operating conditions.

## CONCLUSIONS

From the results, it is concluded that:

- 1) A computer simulation of the TCM fuel injection system has been developed which predicts accurately the fuel flow for the TSIO-360-E system. Changes in fuel flow due to varying engine conditions, ambient conditions, and fuel system adjustments can be predicted.
- 2) Reduced emissions and improved fuel economy at the full rich setting for cruise power and below can be attained by adding temperature compensation to the fuel system. Temperature compensation would reduce fuel flow for engine operation at high intake temperature.
- 3) Improved fuel management during acceleration along with better airflow distribution would reduce the acceleration lean limit and emissions in the aircraft landing and take-off (LTO) cycle. If modifications are sufficient to reduce the acceleration lean limit to 0.065 fuel/air ratio, hydrocarbon emissions can be reduced to 61 percent of the EPA emission standards for the NAFEC seven-mode LTO cycle. Carbon monoxide emissions would be reduced from 193 percent to 140 percent of the standards. Emissions of nitrogen oxides would remain below the standards at 46 percent.

#### REFERENCES

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- 3). Huebner, Kenneth H., "A Simplified Approach to Flow Network Analysis: Application to Engine Lubrication Systems," SAE Report No. 750080, 1975.
- 4). Crane Engineering Division, "Flow of Fluids Through Valves, Fittings, and Pipe," Crane Technical Paper No. 410 Crane Engineering Co., 4100 S. Kedzie Avenue, Chicago, Ill., 1976.
- 5). "Texaco Aviation Products," Texaco Inc., International Aviation Sales Dept., 135 East 42nd Street, New York, N.Y., 1975.
- 6). Teledyne Continental Motors, "F.A.A. Type Test and Calibration of the Teledyne Continental Model LTS10-360-E Aircraft Engine," TCM Report No. 640, 1974.

APPENDIX  
OPERATING INSTRUCTIONS  
FOR  
TSIO-360-E FUEL INJECTION SYSTEM COMPUTER SIMULATION

Input to the computer simulation of the Continental TSIO-360-E fuel injection system consists of the engine operating conditions and fuel system adjustments necessary to establish the operating conditions of the system. A complete listing of the input is given in Table A-1. Several computer runs are necessary to establish the input values for valve positions required to simulate a particular fuel system trim. This process is analogous to the actual trimming of the fuel injection system. Two trims are required:

(1) Idle Trim. Computer runs are made simulating idle speed (700 rpm) and throttle position (72° from full open throttle) with several values for idle relief valve adjustment (SAL). These results can be used to determine the approximate relief valve setting required to give the desired idle pump discharge pressure (X2 minus ambient pressure, PAMB). This pressure is generally set to be 6.0 to 6.5 psig. Next, the idle fuel flow adjustment (ADJCU) is varied to establish the correct input to give the desired metered fuel pressure at idle. This pressure is calculated from the computer output for absolute metered fuel pressure (X3, psia) minus turbo discharge pressure (P5, psia), turbo discharge pressure at idle is normally equal to ambient pressure. Idle metered fuel pressure is generally set to be 3.5 to 4.0 psid (referenced to turbo discharge pressure).

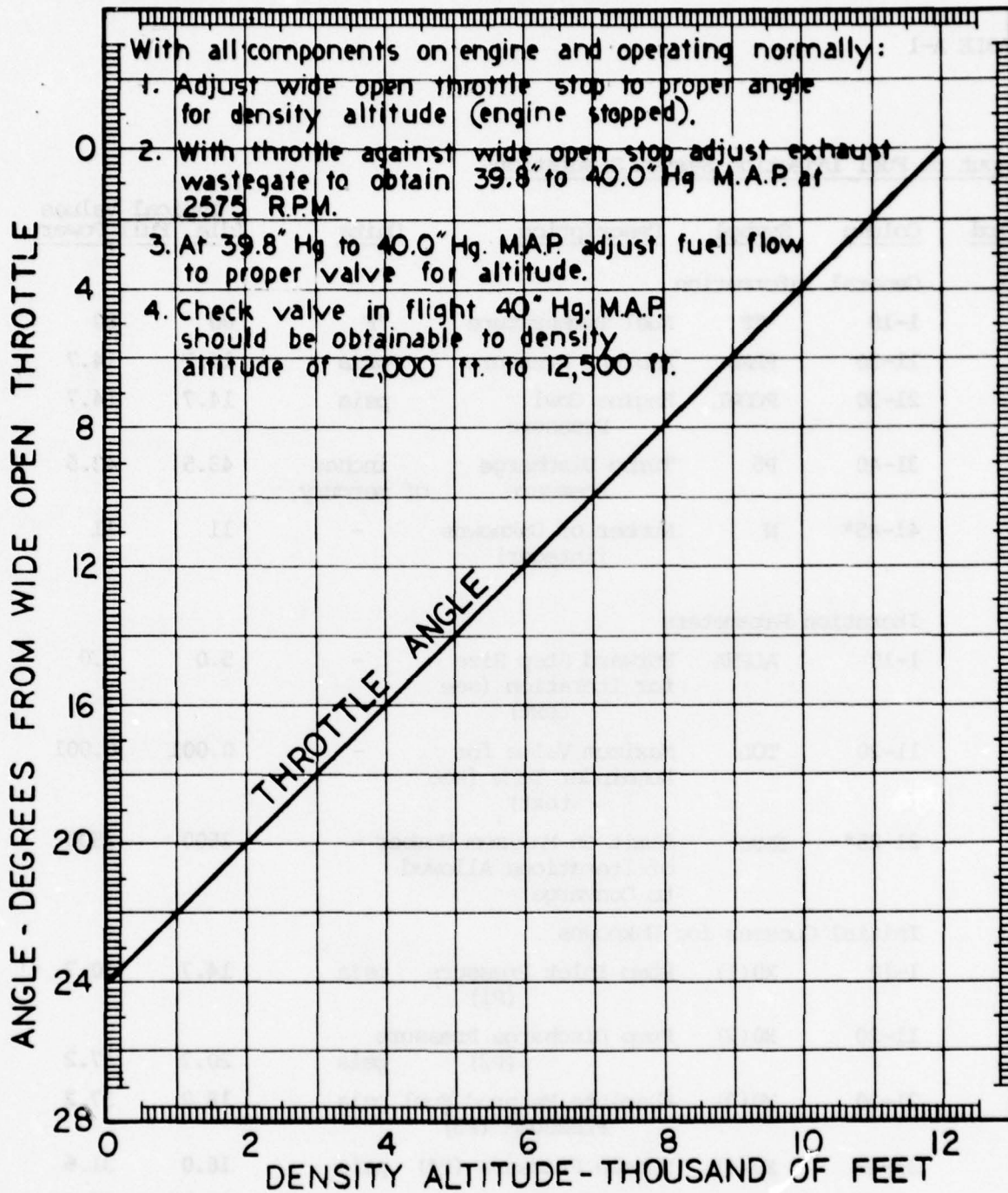
(2) Full Power Trim. The simulation is next adjusted at full power (defined as 2575 rpm, 40. inches manifold pressure) using the variable orifice adjustment input. The throttle settings for full power can be determined from actual engine data. Correct full power throttle settings are specified by Continental as a function of density altitude. For engine ground trims, the exhaust waste gate is adjusted to obtain 40 inches of manifold pressure at a specified throttle setting. This full throttle set-

ing is a function of density altitude as specified in figure A-1. Using the full throttle setting (ALFA) as established from engine data or from figure A-1, the variable orifice position (ADJVO) is varied to obtain the desired metered fuel pressure (X3 minus P5) or metered fuel flow (X11). Full power metered fuel pressure is generally set between 16.0 and 17.0 psid (relative to turbo discharge pressure, P5). Corresponding metered fuel flows are 130 to 140 pph. During the trim at idle and full power, aneroid reference pressure (PREF) is set equal to trim full power turbo discharge pressure (approximately 43 to 44 inches of mercury). This pressure should be held constant for subsequent simulations for the same trim setting. Aneroid movement with changes in turbo discharge pressure is referenced to PREF, which may be regarded as a trim parameter.

After trimming the simulation, subsequent simulations can be made varying altitude, engine speed, turbo discharge pressure, throttle angle, or any other input parameter desired to match a given operating condition.

Deck output consists of the results of the iteration process (X1 thru X11) after every 100 completed iteration loops, along with a parameter labeled "B". This parameter is the magnitude of the objective function as described in the discussion section of this report. The iteration continues until the value of the objective function is less than the value input of TOL (Card 2) or until the number of iterations exceeds NMAX. The values of X1 thru X11 corresponding to the sample output are given below, followed by a complete listing of the FORTRAN source program.

Computer Output	Fuel System Parameter	Units	Idle Value	Full Power Value
X1	P1, Pump Inlet Pressure	psia	14.63	10.82
X2	P2, Pump Discharge Pressure	psia	21.40	59.15
X3	P3, Absolute Metered Fuel Pressure	psia	18.59	38.88
X4	P4, Nozzle Pressure	psia	14.79	33.21
X5	P6, Variable Orifice Discharge Pressure	psia	20.96	28.80
X6	P7, Vapor Separator Discharge Pressure	psia	14.77	15.39
X7	Supply Line Flow Rate	pph	26.20	199.6
X8	Pump Flow Rate	pph	149.1	574.8
X9	Vapor Separator Flow Rate	pph	19.05	58.77
X10	Variable Orifice Flow Rate	pph	122.9	375.2
X11	Metered Fuel Flow Rate	pph	7.14	140.8
B	Remainder Term	-	0.00094	0.0085
N	Number of Iterations	-	1891	2500



**FIGURE A-1. INSTRUCTIONS FOR ADJUSTMENT OF EXHAUST GAS WASTEGATE**

TABLE A-1

Input to Fuel Injection System Simulation

<u>Card</u>	<u>Column</u>	<u>Symbol</u>	<u>Description</u>	<u>Units</u>	<u>Typical Values</u>	
					<u>Idle</u>	<u>Full Power</u>
1	General Information					
	1-10	TF	Fuel Temperature	°F	80	80
	11-20	PAMB	Ambient Pressure	psia	14.7	14.7
	21-30	PCOWL	Engine Cowl Pressure	psia	14.7	14.7
	31-40	P5	Turbo Discharge Pressure	inches of mercury	43.5	43.5
	41-45*	N	Number of Unknowns (integer)	-	11	11
2	Iteration Parameters					
	1-10	ALPHA	Forward Step Size for Iteration (see text)	-	5.0	5.0
	11-20	TOL	Maximum Value for Remainder Term (see text)	-	0.001	0.001
	21-25*	NMAX	Limit on Maximum Number of Iterations Allowed to Converge	-	2500	2500
3	Initial Guesses for Unknowns					
	1-10	X0(1)	Pump Inlet Pressure (P1)	psia	14.7	10.7
	11-20	X0(2)	Pump Discharge Pressure (P2)	psia	20.7	47.2
	21-30	X0(3)	Absolute Metered Fuel Pressure (P3)	psia	18.2	37.2
	31-40	X0(4)	Nozzle Pressure (P4)	psia	16.0	31.6
	41-50	X0(5)	Variable Orifice Discharge Pressure (P6)	psia	20.0	27.8
	51-60	X0(6)	Vapor Separator Discharge Pressure (P7)	psia	14.7	14.7
	61-70	X0(7)	Supply Line Flow Rate	pph	23.0	181.0

\* Integer Value. Input Right Adjusted in Input Field.

Table A-1 (cont'd)

Card	Column	Symbol	Description	Units	Typical Values	
					Idle	Full Power
4	71-80	X0(8)	Pump Flow Rate	pph	150.	617.
	Initial Guesses for Unknowns (continued)					
	1-10	X0(9)	Vapor Separator Flow Rate	pph	17.0	53.9
	11-20	X0(10)	Variable Orifice Flow Rate	pph	127.	436.
5	21-30	X0(11)	Metered Fuel Flow Rate	pph	6.0	127.
	Supply Line Data					
	1-10	XK	Line K-Factor (Ref3)	-	4.45	4.45
	11-20	DP	Line Diameter	Inch	0.20	0.20
	21-30	XL	Line Length	Inch	180.	180.
	31-40	EPSP	Line Surface Roughness (Ref 3)	Inch	0.000125	0.000125
	41-50	Z0	Line Elevation at Fuel Tank Relative to an Arbitrary Datum	Inch	0.	0.
	51-60	Z1	Line Elevation at Pump Inlet Relative to Same Datum	Inch	0.	0.
6	Fuel Pump Data					
	1-10	RPM	Pump Speed (Equals Engine Speed for TSIO-360-E)	rpm	700	2575
	11-20	DISP	Pump Displacement	cu.inch	0.226	0.226
7	21-30	EFF	Pump Efficiency	-	0.9371	0.9371
	Variable Orifice Data					
	1-10	ADJVO	Variable Orifice Adjustment	inch	0.145	0.145
	11-20	PREF	Aneroid Reference Pressure	inches mercury	43.5	43.5
21-30	AMS	Slope of Aneroid Movement with Pressure	in/inch mercury	.00925	.00925	

Table A-1 (Cont'd)

<u>Card</u>	<u>Column</u>	<u>Symbol</u>	<u>Description</u>	<u>Units</u>	<u>Typical Values</u>	
					<u>Idle</u>	<u>Full Power</u>
	31-40	EROR	Allowable Error in Variable Orifice Iteration Loop. Maximum position error	in	0.01	0.01
8	Relief Valve Data					
	1-10	XK	Idle Relief Valve Spring Constant	lb/in inch	13.7	13.7
	11-20	RD	Pressure Disk Effective Radius	inch	0.326	0.326
	21-30	SAL	Idle Relief Valve Spring Length Adjustment	inch	0.362	0.362
9	Throttle Data					
	1-10	ALFA	Throttle Angle From Full Open Throttle	degrees	72.0	24.0
	11-20	ADJCU	Idle Fuel Flow Adjustment	degrees	5.0	5.0
10	Manifold Valve Data					
	1-10	SALM	Manifold Valve Spring Adjustment (set at factory)	inch	0.2452	0.2452
11	Vapor Return Line Data					
	1-10	XKR	Line K-Factor (Ref3)	-	16.4	16.4
	11-21	DR	Line Daimeter	inch	0.20	0.20
	21-30	XLR	Line Length	inch	180.	180.
	31-40	EPSR	Line Surface Roughness (Ref 3)	inch	0.000125	0.000125

Computer Program listing is attached.

```

0001 DIMENSION MS(30,2),D(3C),D1(3U),EPS(3U,30),EPS1(30,30),XI(30),
0002 C,XOI(30),EI(30),XO(30),DEMS(5U),VIS(50)
0003 COMMON RHO,VISC,PI,PAMB,PCCL,P5
0004 COMMON/AAA/ M1
0005 COMMON/THREE/ XKF,DP,XL,ZO,Z1,EPSP
0006 COMMON/FOUR/ DISP,EFF,RPM
0007 COMMON/FIVE/ ADJVO,PREF,AMS,ERUK,AMRF,AMDP,NMAX
0008 COMMON/SIX/ XK,RD,SAL
0009 COMMON/EIGHT/ ALFA,ADJCU
0010 COMMON/NINE/ SALM
0011 COMMON/ELEVN/ XKR,DR,XLR,ZOR,ZLK,EPSP
0012 DATA DENS / 1.,1.,5.,0.,-20.,20.,0.,100.,140.,6.,47.,6.,31.,6.,15.,
0013 C 5.99,5.83 /
0014 DATA VIS / 1.,1.,16.,0.,-20.,0.,10.,20.,30.,40.,50.,60.,70.,80.,
0015 C 90.,100.,110.,120.,130.,140.,150.,160.,170.,180.,190.,200.,
0016 C 0.67,0.63,0.60,0.58,0.55,0.52,0.50,0.49,0.48 /
0017 PI=3.14159
0018 BP=0.0
0019 WRITE(3,20)
0020 WRITE(3,15)
0021 15 FORMAT( / 20X, '**** GENERAL INPUT DATA ****', / / / )
0022 READ(1,10) TF,PAMB,PCCL,P5,N
0023 10 FORMAT(4F10.5,15)
0024 READ(1,40) ALPHA,TOL,NMAX
0025 40 FORMAT(2F10.5,15)
0026 WRITE(3,21) ALPHA
0027 21 FORMAT(1H1, ' FORWARD STEP SIZE FOR ITERATION IS ',F10.4)
0028 WRITE(3,41) TOL,NMAX
0029 41 FORMAT( /, ' ITERATION TOLERANCE FOR THIS RUN IS ',F10.5, /,
0030 C, ' MAX NUMBER OF ITERATIONS IS ',15)
0031 BETA=ALPHA/10.
0032 READ(1,11) (XO(I),I=1,N)
0033 THESE ARE THE INITIAL GUESSES FOR THE UNKNOWNS
0034 11 FORMAT(8F10.5)
0035 CALL ENGUNB(DENS,1,TF,C,PHU,11)
0036 CALL ENGUNB(VISC,1,TF,0,VISC,12)
0037 RHO=RHO*7.481
0038 VISC=VISC*1.076E-05*RHC
0039 WRITE(3,12)
0040 12 FORMAT( / 3X, 'FUEL TEMP',10X, 'AMB PRESS',10X, 'COWL PRESS',10X,
0041 C, 'T/C DISCH PRESS',10X, 'FUEL DENSITY',10X, 'FUEL VISC', / )
0042 WRITE(3,13)
0043 13 FORMAT(5X, 'DEG F',14X, 'PSIA',15X, 'PSIA',15X, 'IN. HG. ABS.',13X,
0044 C, 'LBM/CU FT',13X, 'LBM/(FT*SEC)', / )
0045 WRITE(3,14) TF,PAMB,PCCL,P5,RHU,VISC
0046 14 FORMAT(5X,F5.1,14X,F5.2,14X,F5.2,10X,F5.2,18X,F5.2,16X,1PE9.3, / / )
0047 READ(1,11) XK,DP,XL,EPSP,ZO,Z1
0048 WRITE(3,16)
0049 16 FORMAT( / 20X, '**** INLET LINE INPUT DATA ****', / / )
0050 WRITE(3,17) XK,DP,XL,ZO,Z1,EPSP
0051 17 FORMAT(3X, 'LINE K-FACTOR = ',F10.5,3X, 'LINE DIA = ',F10.2,2X, 'IN',
0052 C3X, 'LINE LENGTH = ',F10.2,2X, 'IN',3X, 'TANK FLUID LEVEL = ',F10.2,
0053 C2X, 'IN', /, ' PUMP LEVEL = ',F10.2,2X, 'IN',3X, 'SURF ROUGH = ',F11.4)
0054 READ(1,11) RPM,DISP,EFF

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0045 WRITE(3,18)
0046 18 FORMAT(/,20X,'***** PUMP INPUT DATA ****',/)
0047 WRITE(3,19) RPM,DISP,EFF
0048 19 FORMAT(3X,'PUMP SPEED = ',F10.1,3X,'PUMP DISP = ',F10.4,2X,'CU IN'
C 3X,'PUMP VOLUMETRIC EFFICIENCY = ',F10.3)
READ(1,11) ADJVO,PREF,AMS,ERUK
0049 WRITE(3,30)
0050 30 FORMAT(/,20X,'***** VARIABLE URIFICE INPUT DATA ****',/)
0051 WRITE(3,31) ADJVO,PREF,AMS,ERUR
0052 31 FORMAT(3X,'ADJUSTMENT = ',F10.4,2X,'IN',3X,'REF PRESS = ',F10.2,2X,
C 'IN HG ABS',3X,'ANERCID SLOPE = ',F10.5,2X,'IN/IN HG',
C 3X,'ERROR = ',F10.5)
READ(1,11) XK,RD,SAL
0054 WRITE(3,32)
0055 32 FORMAT(/,20X,'***** IDLE RELIEF VALVE INPUT DATA ****',/)
0056 WRITE(3,33) XK,RD,SAL
0057 33 FORMAT(3X,'VALVE SPRING CONSTANT = ',F10.2,2X,'LB-F/IN',3X,'PRESS D
CISK EFFECTIVE RADIUS = ',F10.3,3X,'SPRING ADJUSTED LENGTH = ',
C F10.3,2X,'IN')
READ(1,11) ALFA,ADJCU
0059 WRITE(3,34)
0060 34 FORMAT(/,20X,'***** CONTRCL UNIT INPUT DATA ****',/)
0061 WRITE(3,35) ALFA,ADJCU
0062 35 FORMAT(3X,'THROTTLE ANGLE = ',F10.1,2X,'DEG',3X,'IDLE ADJUSTMENT = '
C F10.1)
C ALFA IS ANGLE FROM FULL THROTTLE (DEG)
C ADJ IS IDLE ADJUSTMENT FROM MIN FLOW (UEG) MIN IS 0,MAX IS +10.
IF(ADJCU .LT. 0.) ADJCU=0
IF(ADJCU .GT. 10.) ADJCU=10.
ALFA=ALFA + 15. - ADJCU
0064 ALFA=ALFA/57.295787
0065 READ(1,11) SALM
0066 36 FORMAT(/,20X,'***** MANIFOLD VALVE INPUT DATA ****',/)
0067 WRITE(3,37) SALM
0068 37 FORMAT(3X,'ADJUSTED SPRING LENGTH = ',F10.4,2X,'IN')
ZOR=ZO
0069 ZIR=ZI
0070 READ(1,11) XKR,DR,XLR,EPSR
0071 WRITE(3,38)
0072 38 FORMAT(/,20X,'***** RETURN LINE INPUT DATA ****',/)
0073 WRITE(3,39) XKR,DR,XLR,EPSR
0074 39 FORMAT(3X,'LINE K-FACTOR = ',F10.5,3X,'LINE DIA = ',F10.2,2X,'IN',
C 3X,'LINE LENGTH = ',F10.2,2X,'IN',3X,'SURF ROUGH = ',E11.4)
C THE BEGINNING OF ROSENBRACK'S ALGORITHM
C ALPHA=FACTOR BY WHICH LENGTH OF STEP SIZE IS INCREASED.
C BETA=FACTOR BY WHICH LENGTH OF STEP SIZE IS DECREASED.
C E(I)=MAGNITUDE OF INITIAL STEP SIZE.
C THE USER SELECTS VALUES FOR ALPHA AND BETA WHICH LEAD TO RAPID
C CONVERGENCE. TRIAL AND ERROR WITH TWO OR THREE ITERATIONS IS
C USUALLY SUFFICIENT
0080 WRITE(3,20)
0081 20 FORMAT(1M1)
0082 DO 100 NC=1,N

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PAGE 0003

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DOS FORTRAN IV 360N-FD-479 3-8          MAINPOM          DATE 01/09/78          TIME 13.24.12
0083      100 E(NC)=5.
0084      DO 101 NC=1,N
0085      X0(1,NC)=X0(1,NC)
0086      XI(1,NC)=X0(1,NC)
0087      D1(1,NC)=0.
0088      DO 119 NC=1,N
0089      DO 120 NK=1,N
0090      EPS(1,NC,NK)=0.0
0091      119 CONTINUE
0092      M1=0
0093      DO 125 NC=1,N
0094      MS(1,NC)=0
0095      125 MS(1,NC,2)=0
0096      B=F(X0)
0097      NS=0
0098      DO 102 NC=1,N
0099      EPS(1,NC,NK)=1.
0100      WRITE(3,29)
0101      29 FORMAT(14H I X0)
0102      WRITE(3,26) (I,X0(I),I=1,N)
0103      26 FORMAT(15,1PE17.6)
0104      WRITE(3,23) B
0105      23 FORMAT(4H B= ,E15.6)
0106      DO 103 NC=1,N
0107      D1(1,NC)=E(1,NC)
0108      104 CONTINUE
0109      DO 105 II=1,2000
0110      IF (NS .GE. I) GO TO 106
0111      KK=II-1
0112      I=MOD(KK,N)+1
0113      M1=M1+1
0114      IF(M1 .GE. NMAX) GO TO 200
0115      DO 107 NC=1,N
0116      X0(1,NC)=D1(1,NC)+EPS(1,NC)
0117      XI(1,NC)=X0(1,NC)
0118      IF(M1.LT.8) GO TO 108
0119      B=M1
0120      DO 109 NC=1,N
0121      XI(1,NC)=X0(1,NC)
0122      D1(1,NC)=D1(1,NC)+D1(1,NC)
0123      D1(1,NC)=ALPHA*D1(1,NC)
0124      MS(1,1)=MS(1,1)+1
0125      GO TO 110
0126      108 D1(1,NC)=BETA*D1(1,NC)
0127      MS(1,2)=MS(1,2)+1
0128      110 NS=10
0129      DO 111 L=1,N
0130      N2=MS(L,1)+MS(L,2)
0131      NS=MINO(NS,N2)
0132      105 CONTINUE
0133      106 CONTINUE
C GET FILE(10) NEW DIRECTIONS
0134      DO 112 NC=1,N
0135      DO 113 NK=1,N
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PAGE 0004

DDO	FORTRAN IV 360N-FD-479 3-8	MAINPGM	DATE 01/09/78	TIME	13.24.12
0136	113 EPSI(NC,NK)=0.0				000162
0137	112 CONTINUE				000163
0138	DO 114 NC=1,N				000164
0139	114 EPSI(NC,N)=D1(N)*EPS(NC,N)				000165
0140	NI=N-1				000166
0141	123 IF(NI.LT.1) GO TO 124				000167
0142	DO 116 NC=1,N				000168
0143	116 EPSI(NC,NI)=D1(NI)*EPSI(NC,NI)+EPSI(NC,NI+1)				000169
0144	NI=NI-1				000170
0145	GO TO 123				000171
0146	124 CONTINUE				000172
0147	DO 300 I=1,N				000173
0148	DO 301 NC=1,N				000174
0149	301 EPSI(NC,I)=EPSI(NC,I)				000175
0150	JJ=I-1				000176
0151	DO 400 J=1,JJ				000177
0152	RR1=0.				000178
0153	DO 401 NC=1,N				000179
0154	EPSIP=EPSI(NC,I)*EPS(NC,J)				000180
0155	401 RR1=RR1+EPSIP				000181
0156	DO 402 NC=1,N				000182
0157	402 EPSI(NC,I)=EPSI(NC,I)-RR1*EPSI(NC,J)				000183
0158	400 CONTINUE				000184
0159	RR=0.				000185
0160	DO 302 NC=1,N				000186
0161	ESPIP=EPSI(NC,I)*EPS(NC,I)				000187
0162	302 RR=RR+ESPIP				000188
0163	RR=RR/RRR				000189
0164	DO 303 NC=1,N				000190
0165	303 EPSI(NC,I)=EPSI(NC,I)/RR				000191
0166	300 CONTINUE				000192
0167	DO 117 NC=1,N				000193
0168	XO1(NC)=X1(NC)				000194
0169	117 O1(NC)=0.				000195
0170	DO 118 NC=1,N				000196
0171	MSI(NC,1)=0				000197
0172	118 MSI(NC,2)=0				000198
0173	MS=0				000199
	C THE FOLLOWING STATEMENT IS AN ERROR CRITERION THAT CAN BE USER				000200
	C ADJUSTED. B IS THE LATEST VALUE OF THE OBJECTIVE FUNCTION AND				000201
	C THIS VALUE MUST BE LOWER THAN SOME SPECIFIED CCNANT				000202
	C (TOL) BEFORE THE SEARCH PROCEDURE STOPS				000203
	IF(ABS(B) .LT. TOL) GO TO 200				000204
0174	C M1 IS THE NUMBER OF FUNCTION EVALUATIONS THAT HAVE OCCURRED DURING				000205
	C THE SEARCH FOR THE MINIMUM VALUE OF THE OBJECTIVE FUNCTION. IF M1				000206
	C BECOMES TOO LARGE (GE NMAX), THE SEARCH PROCEDURE STOPS				000207
	IF(M1 .GE. NMAX) GO TO 200				000208
	KJ=MOD(M1,100)				000209
0175	IF(KJ .NE. 0) GO TO 104				000210
0176	IF(BP .EQ. 0) GO TO 104				000211
0179	RED=ABS(18P-81/8P)				000212
0180	IF(RED.LT. .05) GO TO 200				000213
0181	BP=B				000214
0182	GO TO 104				000215

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PAGE 0005

13.24.12

TIME

DATE 01/09/78

MAINPGM

360N-FO-479 3-8

DOS FORTRAN IV

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0183 C THIS IS THE MAIN ITERATICA LCOPI RETURN PATH
0184 C ROSENROCH'S ALGORITHM ENDS HERE
0185 200 WRITE(3,25) M1
0186 25 FORMAT(37H NUMBER OF ITERATIONS REQUIRED EQUALS,15)
0187 28 WRITE(3,28) I
0188 WRITE(3,26) (I,XI(I),I=1,N)
0189 WRITE(3,27) 8
0190 27 FORMAT(5H 8=,E15.6)
0191 WRITE(3,42) AMRF,AMDP
0192 C/, ANEROID MOVEMENT DUE TO ROD FORCE EQUALS ',F10.5,
0193 C F10.5)
0194 CALL EXIT
0195 END
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DOS FORTRAN IV 360N-FD-479 3-8      PAINPCM      DATE 01/09/78      TIME 13.24.42      000231
C THE FOLLOWING FUNCTION PROCEDURE DEFINES THE OBJECTIVE FUNCTION. 000232
C EQUATION 15 FROM HUEBNER'S TEXT 000233
FUNCTION F(X) 000234
DIMENSION X(30) 000235
COMMON/AAA/ M1 000236
T=F1(X(7),X(9),X(11))**2 + F2(X(7),X(8),X(10))**2 000237
C + F3(X(11),X(7))**2 + F4(X(11),X(2),X(8))**2 000238
C + F5(X(2),X(5),X(10))**2 + F6(X(11),X(5))**2 000239
C + F7(X(2),X(6),X(9))**2 + F8(X(2),X(3),X(11))**2 000240
C + F9(X(3),X(4),X(11))**2 + F10(X(4),X(11))**2 000241
C + F11(X(6),X(9))**2 000242
F=-T 000243
J=MOD(M1,100) 000244
IF(J.NE.0) GO TO 513 000245
WRITE(3,512) F,M1 000246
512 FORMAT(9H F EQUALS,F17.6,10H M1 EQUALS,I5) 000247
WRITE(3,28) 000248
28 FORMAT(14H I XI) 000249
WRITE(3,26) (I,X(I),I=1,11) 000250
26 FORMAT(15,1PE17.6) 000251
513 CONTINUE 000252
RETURN 000253
END
```

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PAGE 0001

13.25.01

TIME

DATE 01/09/78

MAINPGM

3-B

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C LISTING OF FUNCTION PROCEDURES FOR THE NET-ORP. EACH FUNCTION
C REPRESENTS EITHER THE PRESSURE-FLOW RELATION FOR A FLOW PATH OR
C AN EXPRESSION OF FLOW CONTINUITY AT SOME NODES.
C FOR THE LYSIO-360E FUEL INJECTION SIMULATION I DEFINED
C X(1)=P1
C X(2)=P2
C X(3)=P3
C X(4)=P4
C X(5)=P6
C X(6)=P7
C X(7)=WA
C X(8)=WB
C X(9)=WC
C X(10)=WD
C X(11)=WF
C
C FUNCTION F(X7,X9,X11)
C CONTINUITY AT JUNCTION 0
COMMON/AAA/ M1
F1= X7-X11-X9
JJJ=MOD(M1,100)
IF(JJJ.NE.0) GO TO 1000
WRITE(3,1100) F1
1100 FORMAT( E13.4)
1000 CONTINUE
RETURN
END

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PAGE 0001

13.25.15  
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TIME

DATE 01/09/78

F2

005 FORTRAN IV 360N-FO-475 3-8

```
0001      FUNCTION F2(X7,X8,X1C)
0002      CONTINUITY AT JUNCTION 1
0003      COMMON/AAA/ M1
0004      F2= X8-X7-X10
0005      JJJ=MOD(M1,100)
0006      IF(JJJ.NE.0) GO TO 1000
0007      WRITE(3,1100) F2
0008      1100 FORMAT( E13.4)
0009      1000 CONTINUE
0010      RETURN
0011      END
```

```

0001      FUNCTION F3(X1,X7)
0002      PRESSURE LOSS THROUGH THE SUPPLY LINE
0003      DIMENSION FR1(217),FRIZ( 5),FRIC(273)
0004      COMMON RHO,VISC,PI,PAMB,PCCAL,P5
0005      COMMON/AAA/ MI
0006      COMMON/THREE/(KKO,D,XL,ZO,ZL,EPS)
0007      EQUIVALENCE (FRIC(1),FR1(1)),(FRIC(216),FRIZ(1))
0008      DATA FR1 / 1.,1.,17.,14.,1.,1.,E-05,5.,E-05,1.,E-04,2.,E-04,
0009      C4.,E-04,6.,E-04,8.,E-04,1.,E-03,2.,E-03,4.,E-03,6.,E-03,8.,E-03,1.,E-02,
0010      C1.,5E-02,2.,E-02,3.,E-02,3.,E+05,5.,E+05,8.,E+03,1.,5E+04,3.,E+04,6.,E+04,
0011      C1.,E+05,2.,E+05,4.,E+05,8.,E+05,2.,E+06,4.,E+06,8.,E+06,1.,E+07,.,04.,.037,
0012      C.-032.,.0275,.,023,.,0158,.,0178,.,0125,.,0136,.,012,.,0102,.,0092,.,0083,
0013      C.-0081,.,044,.,037,.,032,.,0275,.,023,.,0158,.,0178,.,0155,.,0138,.,0122,.,
0014      C.-0108,.,0098,.,0092,.,0085,.,044,.,037,.,032,.,0275,.,023,.,0198,.,018,.,016,
0015      C.-0142,.,013,.,0118,.,0112,.,0105,.,0108,.,044,.,037,.,032,.,0275,.,023,
0016      C.-0202,.,0184,.,0164,.,0145,.,0137,.,0128,.,0122,.,0120,.,0120,.,044,.,037,
0017      C.-032,.,0275,.,024,.,0208,.,0190,.,0170,.,0158,.,0149,.,0141,.,0139,.,0138,
0018      C.-0138,.,044,.,037,.,032,.,0275,.,0245,.,0217,.,020,.,0182,.,0172,.,0167,
0019      C.-016,.,016,.,016,.,016,.,016,.,016,.,016,.,016,.,016,.,016,.,016,.,016,
0020      C.-0183,.,0180,.,0175,.,0175,.,0175,.,0175,.,0175,.,0175,.,0175,.,0175,.,0175,
0021      C.-023,.,0215,.,0202,.,0195,.,019,.,0189,.,018,.,0188,.,044,.,038,
0022      C.-034,.,0295,.,0258,.,0235,.,0222,.,021,.,0202,.,02,.,02,.,02,.,02,.,02,.,045,
0023      C.-039,.,0355,.,031,.,028,.,026,.,025,.,0242,.,024,.,0237,.,0237,.,0237,.,0237,
0024      C.-0237,.,047,.,0415,.,038,.,034,.,034,.,0315,.,03,.,0295,.,029,.,029,.,029,
0025      C.-029,.,029,.,029,.,0485,.,0435,.,04,.,0365,.,0348,.,0335,.,033,.,0325,.,032,
0026      C.-032,.,032,.,032,.,032,.,032,.,0495,.,045,.,042,.,0395,.,0375,.,036,.,0358,
0027      C.-0355,.,0355,.,0355,.,0355,.,0355,.,0355,.,0355,.,0355,.,0355,.,0355,.,0355,
0028      DATA FRIZ / .052,.,047,.,044,.,0415,.,040,.,039,.,0382,.,038,.,038,
0029      C.-038,.,038,.,038,.,038,.,055,.,0215,.,049,.,0462,.,045,.,044,.,044,.,044,
0030      C.-044,.,044,.,044,.,044,.,044,.,044,.,044,.,044,.,044,.,044,.,044,.,049,
0031      C.-049,.,049,.,049,.,049,.,049,.,049,.,049,.,049,.,049,.,049,.,049,.,049,
0032      C.-0575,.,0575,.,0575,.,0575,.,0575,.,0575,.,0575,.,0575,.,0575,.,0575,
0033      C.FLOW IN PPH,DIA IN (INCHES,ABS. VIS IN LBH/(FT*SEC),EPS IN INCHES
0034      W=X7
0035      A=PI*(D**2)/4.
0036      REY=IN*W/(A*VISC))*(12./3600.)
0037      REY=ABS(REY)
0038      EDD=EPS/D
0039      CALL ENGUMB(FRIC,1,EDD,REY,FF,IE)
0040      IF(REY.LT.3000) FF =64./REY*.001
0041      Q=0.5*W*ABS(W)*14./((3600.)*92/RHO/(A**2)/32.2
0042      XK=XKO+FF*XL/D
0043      DP=XK*Q
0044      DP=DP+ PHO*(Z1-Z0)/1728.
0045      F3= PAMB-X1-DP
0046      JJJ=MOD(MI,100)
0047      IF(JJJ.NE.0) GO TO 1000
0048      WRITE(3,1100) REY,FF,Q,DP,F3
0049      1100 FORMAT( 5E13.4)
0050      1000 CONTINUE
0051      RETURN
0052      END

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PAGE 0001

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0001      FUNCTION F4(X1,X2,X8)
0002      PRESSURE RISE THROUGH VANE PUMP
0003      EFFICIENCY BASED ON PHO CF 45.41
0004      COMMON PHO,VISC,PI,PAMB,PCCL,PS
0005      COMMON/AAA/ MI
0006      COMMON/FOUR/ DISP,EFF,RPM
0007      DIMENSION PUMP(100)
0008      DATA PUMP /1.,1.,17.,6.,0.,7.,.111.,.145.,.175.,.203.,.5.,.227.,.249.,.
0009      C 268.,.285.,.302.,.318.,.334.,.36.,.39.,.42.,.45.,.48.,.51.,.54.,.57.,.60.,.70.,.80.,.90.,.100./
0010      C 20.,.25.,.30.,.35.,.40.,.45.,.50.,.55.,.60.,.70.,.80.,.90.,.100./
0011      RHOT=45.41
0012      M=X8
0013      C ACTUAL FLOW IS NOW CONVERTED TO MEASURED FLOW
0014      W=W/1.02
0015      WLEAK=(PHO*DISP/1728.*RPM*.60.*EFF - W)*SQRT(RHOT/RHO)
0016      IF(WLEAK.LT.0.) WLEAK=C
0017      CALL ENGUMB(PUMP,1,WLEAK,0.,DP,IE)
0018      F4=(X2-X1)-DP
0019      JJJ=MOD(MI,100)
0020      IF(JJJ.NE.0) GO TO 10CC
0021      WRITE(3,1100) WLEAK,DP,F4
0022      1100 FORMAT( 3E13.4)
0023      1000 CONTINUE
0024      RETURN
0025      END
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DOS FORTRAN IV 360N-FO-479 3-8      FS      DATE 01/09/78      TIME 13.26.00
0001      FUNCTION F5(X2,X5,X10)      000368
0002      PRESSURE DROP THROUGH VARIABLE ORIFICE      000369
0003      COMMON RHO,VISC,PI,PAMB,PCCNL,P5      000370
0004      COMMON/AAA/ MI      000371
0005      COMMON/FIVE/ ADJVO,PREF,AMS,EKOK,AMRF,AMDP,NMAX      000372
0006      DIMENSION AKFCT(100)      000373
0007      DATA AKFCT / 1.,1.,16.,C.,C.,0.0J1,J.,0.02,0.003,0.004,0.005,0.006,      000374
0008      C.,0.07,0.008,0.0687,0.005,0.010,0.012,0.014,0.016,0.018,0.070,0.83,      000375
0009      C.,0.93,1.01,1.08,1.13,1.175,1.20,1.22,1.24,1.36,1.60,1.85,2.11      000376
0010      C.,2.39 /      000377
0011      C ANEROID SPRING CONSTANT      000378
0012      XKA=27.5      000379
0013      C ORIFICE ROD DIAMETERS      000380
0014      DO=0.245      000381
0015      C FLOW IN PPH,PRESS PSI ABS, ADJVO (INCHES, RHO LB MASS/CU FT      000382
0016      C AMS IS SLOPE OF ANEROID DEFL DUE TO T/C PRESS DROP FROM REF VALVE      000383
0017      MD=X10      000384
0018      PZ=X2      000385
0019      AMDP=(PREF-P5)*AMS      000386
0020      N=0      000387
0021      AMRF=C.,0      000388
0022      C INITIATION OF VALUES FOR AREA CALC      000389
0023      DH=0.25      000390
0024      FVDP=0.,0      000391
0025      OS=DO      000392
0026      BETA=3.562      000393
0027      BETAP=12.83      000394
0028      XLTPR=0.180      000395
0029      XLMX=0.240      000396
0030      R3=0.0425      000397
0031      BETA=BETA/57.295787      000398
0032      BETAP=BETAP/57.295787      000399
0033      R1=DS/2.      000400
0034      DELTAS=(DH-DS)*0.50      000401
0035      AH=PI*(DH**2)/4.      000402
0036      DELTA=ADJVO*AMDP      000403
0037      2 CONTINUE      000404
0038      IF(DELTA.LT.0.0) DELTA=0.,0      000405
0039      IF(DELTA.LE.XLTPR) R2=R1-DELTA*TAN(BETA)      000406
0040      IF(DELTA.GT.XLTPR) R2=R1-XLTPR*TAN(BETA)-(DELTA-XLTPR)*TAN(BETAP)      000407
0041      AREA=AH-PI*(R2)**2      000408
0042      GO TO 700      000409
0043      600 R2=R1-XLTPR*TAN(BETA)-(XLMX-XLTPR)*TAN(BETAP)      000410
0044      HL=DELTA-XLMX      000411
0045      IF(R1.EQ.R2) HB=HL      000412
0046      IF(R1.EQ.R2) GO TO 601      000413
0047      HB=R1*(DELTA-XLMX)/(R1-R2)      000414
0048      AREA=PI*R1*SQRTR1**2+HB**2-PI*(R1)**2      000415
0049      C *PI*(R1+DELTA)**2-PI*(R1)**2      000416
0050      A2=PI*(R1)**2-PI*(R3)**2      000417
0051      IF(A2.LT.AREA) AREA=A2      000418
0052      700 AORIF=AREA      000419
0053      CALL ENGUNB(AKFCT,1.,AORIF,0.,AK,IE)      000420
0054      000421

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PAGE 0002

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DOS FORTRAN IV 360N-FD-479 3-8      F5      DATE 01/09/78      TIME 13.26.00
0045      VEL=(W0/3600.1/(RHO*ACRIF)*L4+.
0046      Q=0.5*RHO*(VEL**2)/(144.*32.2)
0047      FVO=Q*AK
0048      P6=P2-FVO
0049      IFIP6 .LT. 0.1 P6=0.0
0050      R2MN=R1-XLTPR*TAN(BETA)-(XLMX-XLTPR)*TAN(BETAP)
0051      PAVG=(P2+P6)/2.
0052      D2=2.*R2MN
0053      RF=(P2-PAVG)*(PI/4.)*(DC**2-D2**2)+P6*(PI/4.)*(DC**2)
0054      AMRF=-RF/XKA
0055      IFIN.EQ. 0) GO TO 4
0056      IF(ABS(FVO-FVOP).GT. ERROR) GO TO 4
6 F5=(X2-X5)-FVO
      JJJ=MOD(M1,100)
0057      IF(JJJ.NE.0) GO TO 1000
0058      WRITE(3,1100) AORIF,AK,G,FVC,F5,DELTA
0060      1100 FORMAT( 6E13.4)
0061      1000 CONTINUE
0062      RETURN
0064      4 N=N+1
0065      FVOP=FVO
0066      IF(N.LE. 1000) GO TO 5
0067      WRITE(3,200) DOLD,DELTA,X2,X5,XLU,AMRF,AORIF
0068      200 FORMAT( / 3X, ' VARIABLE ORIFICE ITERATION FAILURE, DOLD= ',F10.5,
      C , DELTA= ',F10.5/,5F10.5)
0069      M1=NMAX+1000
0070      GO TO 6
0071      5 IF(N.LT.3) GO TO 7
0072      DOLD=DELTA
0073      D2=DOLD
0074      D2=ADJVO+AMDP+AMRF
0075      IF(D02.EQ.D01) GO TO 7
0076      XM=(D2-D1)/(D02-D01)
0077      B=D2-D02*XM
0078      IF(XM.EQ.1.) GO TO 7
0079      DELTA=B/(1.-XM)
0080      D1=D2
0081      GO TO 2
0082      7 DOLD=DELTA
0083      D01=DELTA
0084      D1=ADJVO+AMDP+AMRF
0085      8 DELTA=(ADJVO+AMDP+AMRF+DOLD)/2.0
0086      GO TO 2
0087      END
0088

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PAGE 0001

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DOS FORTRAN IV 360N-FD-479 3-8      F6      DATE 01/09/78      TIME      13.26.15      000468
C                                     000469
FUNCTION F6(X1,X5)                   000470
  IDLE RELIEF VALVE PRESSURE DKUP    000471
  COMMON RHO,VISC,PI,PAPB,PCCAL,P2   000472
  COMMON/AAA/ M1                      000473
  COMMON /SIX/ XK,RD,SAL              000474
  PI=X1                                000475
  R1=0.31                              000476
  SFL=0.50                             000477
  FRV=((SFL-SAL)*XK+(P5*14.696/25.92-P1)*PI*(RD**2))/(PI*(R1**2))
  F6=X5-X1-FRV                         000478
  JJJ=MOD(M1,100)                     000479
  IF(JJJ.NE.0) GO TO 10CC             000480
  WRITE(3,1100) FRV,F6                000481
  1100 FORMAT( 2E13.4)                000482
  1000 CONTINUE                       000483
  END                                  000484
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PAGE 0001

DDO	FORTRAN IV	360N-FO-479	3-8	F7	DATE	01/09/78	TIME	13.26.33	
0001				FUNCTION F7(X2,X6,X5)				000485	
0002				PRESSURE DROP ACROSS VAPOR SEPARATUR				000486	
0003				COMMON RHO,VISC,PI,PAWP,PCCAL,PS				000487	
0004				COMMON/AAA/ M1				000488	
0005				DIMENSION FLO(100)				000489	
				DATA FLO /1.,1.,16.,0.,0.,10.,20.,30.,35.,40.,45.,47.5,50.,				000490	
				C 52.5,55.,57.5,60.,62.5,65.,70.,75.,80.,85.,90.,95.,100.,				000491	
				C 22.5,26.8,31.8,37.5,43.4,50.,57.,63.,69.,				000492	
0006				M=X9				000493	
				C CONVERT TO MEASURED FLCA				000494	
0007				M=W/1.02				000495	
0008				CALL ENGUNB(FLO,1,M,C.,DP,TE)				000496	
0009				RHOT=45.48				000497	
0010				DP=DP*RHOT/RHO				000498	
0011				F7=(X2-X6)- DP				000499	
0012				JJJ=MOD(M1,100)				000500	
0013				IF(JJJ.NE.0) GO TO 1000				000501	
0014				WRITE(3,1100) DP,F7				000502	
0015				1100 FORMAT( 2E13.4)				000503	
0016				1000 CONTINUE				000504	
0017				RETURN				000505	
0018				END				000506	

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PAGE 0001

13.26.47

TIME

DATE 01/09/78

F8

3-B

IV 360N-FD-479

DOS FORTRAN

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0001      FUNCTION F8(XX2,XX3,X11)
0002      PRESSURE DROP ACROSS CONTRL UNIT
0003      COMMON RHO,VISC,PI,PAMB,PCCL,P5
0004      COMMON/AAA/ MI
0005      COMMON /EIGHT/ ALFA,ADJ
0006      DIMENSION THROT( 50)
0007      DATA THROT / 1.1,1.17,C.0.0.5.0.7.0.9.1.1.3.1.5.1.7.1.9.2.1.
0008      C2.3.2.5.2.7.2.9.3.1.3.3.5.1.0.566.0.631.0.683.0.722,
0009      C0.748,0.765,0.790,0.812,0.824,0.834,0.876,0.903,0.941,1.0,1.0 /
0010      RB=0.036
0011      RC=0.44475
0012      D=0.09375
0013      H=0.406
0014      XKFC=1.50
0015      W=X11
0016      XBAR=RB*SIN(ALFA)
0017      YBAR=-R*COS(ALFA)
0018      A=4.*((H-YBAR)**2+XBAR**2)
0019      B=4.*((H+YBAR)**2-RC**2+(D/L)**2+YBAR**2-H**2)
0020      C=(XBAR**2-RC**2*(D/2.))**2+YBAR**2-H**2)**2
0021      C=C+4.*XBAR**2*H**2-D**2*XBAR**2
0022      Y1=(-B-SQRT(B**2-4.*A*C))/(L.*A)
0023      Y2=(-B+SQRT(B**2-4.*A*C))/(L.*A)
0024      X1=-SQRT((D/2.))**2-(Y1-H)**2)
0025      X2=+SQRT((D/2.))**2-(Y2-H)**2)
0026      A=(H-YBAR)/(X2-X1)
0027      A=A+0.5*(X2*SQRT((D/2.))**2-X2**2)+(D/2.))**2*ARCSIN(2.*X2/D)
0028      A=A-0.5*(X1*SQRT((D/2.))**2-X1**2)+(D/2.))**2*ARCSIN(2.*X1/D)
0029      A=A+0.5*(X1*SQRT((D/2.))**2-X1**2)+C**2*ARCSIN(X1/RC)
0030      AEN=1000.*A
0031      CALL ENGUNB(THRUT,1,AEN,0.,CD,IE)
0032      VEL=(PI/RHO/A)*(144./3600.)/CU
0033      Q=(0.5*PHO*VEL*ABS(VEL))/(32.2*144.)
0034      DP=XKFC*Q
0035      F8=(XX2-XX3)-DP
0036      JJJ=MOD(MI,100)
0037      IF(JJJ.NE.0) GO TO 1000
0038      WRITE(3,1100) A,CD,C,DP,F8
0039      1100 FORMAT(5E13.4)
0040      1000 CONTINUE
0041      RETURN
0042      END

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PAGE 0001

13.27.04

TIME

DATE 01/09/78

F5

DOS FORTRAN IV 360N-FD-479 3-R

```
0001 C  
0002 FUNCTION F9(X3,X4,X11)  
0003 MANIFOLD VALVE PRESSURE DRCP  
0004 COMMON RHO,VISC,PI,PAMB,PCCAL,P5  
0005 COMMON/AAA/ M1  
0006 COMMON/XNTINE/ XLADJ  
0007 DIMENSION ZANIF(100)  
0008 DATA ZANIF /1.,1.,4.,0.,0.,.00.,.100.,.200.,.0.,.1.,2.,2.,3.,2.,88/  
0009 XK=0.2070  
0010 XLF=0.70  
0011 RV=0.090  
0012 DPC= XK*(XLF-XLADJ)/(PI*(RV**2))  
0013 W=X11  
0014 W=W/1.02  
0015 CALL ENGUN8(ZANIF,1.,h.C.,DP,IE)  
0016 RHOI=45.41  
0017 DP=DP+RHOI  
0018 F9=(X3-X4)-DP  
0019 JJJ=MOD(M1,100)  
0020 IF(JJJ.NE.0) GO TO 1000  
0021 WRITE(3,1100) DP,F9  
0022 1100 FORMAT(2E13.4)  
0023 1000 CONTINUE  
0024 RETURN  
END
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DD5 FORTRAN IV 360N-FO-479 3-8 FIC DATE 01/09/78 TIME 13.27.18 PAGE 0001

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0001 FUNCTION F10(X4,X11)
0002 NOZZLE PRESSURE DROP
0003 COMMON RHO,VISC,PI,PAMB,PCCWL,P5
0004 COMMON/AAA/ MI
0005 DIMENSION ZOZZ(100)
      DATA ZOZZ / 1.,1.,1E.,0.,1J.,2U.,30.,40.,50.,60.,70.,
C 80.,90.,100.,110.,120.,130.,140.,150.,160.,200.,0.,0.15,0.30,
C 0.551,1.05,1.65,2.4,3.3,4.35,5.5,0.8,0.8,7.95,9.30,10.7,12.15,
C 13.6,15.2,23.75 /
      RHO=45.41
      W=X11
      W=W/1.02
      CALL ENGUNB(ZOZZ,1.,W,0.,DP,1E)
      DP=DP*RHOY/RHO
      F10=X4-P5*14.696/29.92-DP
      JJJ=MDD(M1,100)
      IF(JJJ.NE.0) GO TO 1000
      WRITE(3,1100) DP,F10
      1100 FORMAT( 2E13.4)
      1000 CONTINUE
      1000 RETURN
      1000 END
```

