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EVALUATION OF A THRUSTMETER FOR MEASURING IN-FLIGHT THRUST OF TURBOJET ENGINES

TECHNICAL REPORT

APRIL 1966

by

Robert F. Salmon

National Aviation Facilities Experimental Center

FEDERAL AVIATION AGENCY

AIRCRAFT DEVELOPMENT SERVICE

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SUMMARY

An airborne type thrust measuring instrument was developed and subsequently tested on both a General Electric J79-GE-8 turbojet engine mounted on a thrust stand in a laboratory altitude cell and a Pratt and Whitney JT3C-7 turbojet engine aboard a Boeing 720 aircraft. The thrustmeter system using measurements of internal engine pressures, ambient altitude pressure and total air temperature, computed engine gross thrust, net thrust and percent of maximum continuous rated thrust at the operating flight condition.

Laboratory tests indicated that: (1) the gross thrust value computed theoretically from the measured pressures were within $\pm 2.0\%$ of the thrust stand measured gross thrust, (2) the thrustmeter gross thrust values were within $\pm 3.0\%$ of the thrust stand measured values, (3) the net thrust values computed theoretically from the measured pressures were within $\pm 3.9\%$ of the thrust stand measured net thrust, and (4) the thrustmeter net thrust values were within $\pm 4.2\%$ of the thrust stand measured net thrust. The gross thrust computer module malfunctioned for a series of tests at a simulated altitude condition of 40,000 feet and Mach 1.2.

Flight test results indicated that the system functioned properly aboard the aircraft and was responsive to small changes in engine power setting. The thrustmeter gross thrust and net thrust values agreed with the computed gross and net thrust of the engine within $\pm 2.2\%$ and $\pm 2.8\%$ respectively. In measuring net thrust during the flight tests, some difficulty was encountered in obtaining consistent static pressure readings at the compressor inlet station thus causing errors in the computation of ram drag.

INTRODUCTION

The Federal Aviation Agency in June 1962 initiated a program to investigate the feasibility of various proposed methods of measuring in-flight thrust of turbojet engines. The initial study was conducted by Franklin Institute under the direction of the FAA. The results of that study indicated that the measurement of in-flight thrust could be achieved with considerable accuracy by careful measurement of the engine's external environment and various internal pressures developed by the engine. The results of this preliminary study are covered in Reference 1.

A second phase of the program involved the development, procurement and performance testing of an airborne thrust measuring system which made use of the general design principles recommended in the Reference 1 report and described in Appendix I of this report. This phase of the program involved the installation of the thrust measuring system on a General Electric J79-GE-8 turbojet engine in a laboratory and on a Pratt and Whitney JT3C turbojet engine in a Boeing 720 airplane. The thrust measuring systems tested were procured from Telectro Mek, Inc., Fort Wayne, Indiana under contract with the FAA. Tests on the GE engine were conducted by the U. S. Navy at the Naval Air Turbine Test Station (NATTS), Trenton, N. J. in January 1965 and flight tests on the P&W engine were conducted by the FAA in June 1965.

DISCUSSION

Purpose

The effort described in this report was intended to further the development of a practical airborne instrument system for measuring and indicating gross thrust, percent of rated thrust and net thrust of turbojet engines.

The thrustmeter system consists of the following components:

- Pressure probes - 5 each
- Pressure transducers - 5 each
- Temperature probe - 1 each
- Gross thrust computer module - 1 each
- Ram drag computer module - 1 each
- Reference thrust computer module - 1 each
- Comparator indicator - 1 each

The system makes use of the above equipment to develop a value of gross thrust, net thrust and percent of maximum continuous rated thrust of a turbojet engine. A schematic of the method used by the system to generate these values is shown in Figure 1.

The gross thrust of the engine is determined by measurements of the total and static pressure of the exhaust gas stream at a station in the exhaust cone of a fixed cross-sectional area. With the additional measurement of ambient atmospheric pressure, the gross thrust computer module calculates the gross thrust and sends a proportional electrical signal to the comparator indicator.

The ram drag of the engine is determined by measurements of total and static pressure in the inlet duct of the engine. With the additional measurement of ambient atmospheric pressure, the ram drag computer module calculates the ram drag of the engine and sends a proportional electrical signal to the gross thrust module.

The net thrust of the engine is determined by the subtraction of the ram drag value from the gross thrust value. This takes place in the gross thrust computer module and an electrical signal proportional to the net thrust is then sent to the comparator indicator which displays the resultant net thrust in digital form.

The reference thrust computer module uses electrical signals proportional to compressor inlet total temperature, compressor inlet total pressure and ambient atmospheric pressure. With these three parameters which are indicative of aircraft flight speed, altitude and temperature, the reference computer determines the engine manufacturer's predicted thrust under these conditions for the maximum continuous rated power setting. In effect, it is a computerized version of the model specification of the engine. The output of the computer is sent to the comparator which compares it to the measured value of thrust received from the gross thrust computer module. The result of this comparison is shown on the indicator in the form of a percent of the rated value on a dial which has a range from zero to 120 percent of maximum continuous rated thrust.

The specifications of the thrustmeter system components and the details of the design principles incorporated in the system hardware are covered in Appendices I and II. Figure 2 is a photograph of the components of the thrustmeter system and indicates the general compactness of the design. The overall weight of the system for one engine including cables and mounting pads is about 20 pounds.

Subsequent to the procurement of all hardware, the thrustmeter equipment was tested in a laboratory using a turbojet engine mounted on a thrust stand in an altitude test cell at NATTS, Trenton, N. J.

There were several specific points investigated in the laboratory tests. They were: (1) determination of the accuracy of the aerodynamic system when subjected to practical considerations of installation on an engine, (2) determination of the instrument accuracy of the system components, (3) determination of the overall accuracy of the complete thrust measuring system, and (4) determination of the practical requirements involved in the measurement of representative pressures in the engine.

In the discussion of the tests, certain terms are used which require precise definition. They are:

1. "Load Cell" thrust and "Load Cell" ram drag: the measured value of engine thrust and engine ram drag as determined by the use of a load cell and the measurement of momentum and pressure forces. This was considered the standard or base line to which the thrustmeter system was compared. A detailed description of the load cell measurement system is covered in Appendix I.

2. "Computed" thrust and "Computed" ram drag: the value of thrust and ram drag determined from the measurement of internal pressures in the engine and the ambient atmospheric pressure. These pressures after being converted to proportional electrical signals were used in a digital program to compute engine thrust and ram drag. The digital program used the same aerodynamic equations as those incorporated in the design of the thrustmeter's analog computer modules.

3. "Thrustmeter" thrust (net or gross): the value of engine thrust as determined by the complete thrustmeter system hardware. The pressure inputs to the thrustmeter system hardware were the same as those used in the digital computer for determination of the "computed" thrust value.

The laboratory tests were conducted under the following conditions:

Sea level, 5000 feet, 6000 feet: Mach 0, 0.2, 0.5, 0.6
10,000 feet: Mach 0.6
35,000 feet: Mach 1.2
40,000 feet: Mach 1.2
50,000 feet: Mach 1.4

Figure 3 is a schematic of the laboratory test instrumentation.

Laboratory Test Results:

In analyzing the results of the laboratory tests, the data was subjected to a first degree curve fit in order to establish the line which would best represent the data points and also to establish the standard deviation (one sigma deviation) of the data. The results of this curve fit program are shown in Figures 4 thru 11. In analyzing the graphical presentation of the data shown in these figures, it can be seen that the slope of the first degree curves developed from the data is approximately 1.0 and the Y intercept is approximately zero except for Figure 8. In this type of plot, the ideal curve slope should be 1.0 with a zero intercept. Figure 8 which compares "computed" ram drag with "thrustmeter" ram drag has a slope of 1.13 and an intercept of -220 lbs. The slope difference from the ideal of 1.0 results from the fact that the "computed" value of ram drag used a digital input of 420 in.^{2} as the flow area at Station 2 and the "thrustmeter" ram drag computer module had a 13 percent higher area inadvertently set in its calibrated potentiometer. The intercept value of -220 lbs. indicates that there was a bias in the instrument zero setting. With this bias removed and the air flow area at Station 2 corrected, the slope of the curve fit for the data would be 1.00 and the intercept would be zero. The standard deviation of $\pm$99 lbs. shown in Figure 8 would remain the same. The instrument bias of -220 lbs. was not detected on the meter since the meter could not show a minus value.

A summary of the results obtained from the laboratory tests is shown in Table I. In this table, there is a column showing the root mean square value of thrust for the data used in each comparison. This value was used to compute the percent difference between the ideal value in each comparison. For instance, in comparison Number 1, the root mean square value of "load cell" thrust for all the data used in the comparison was 6937 lbs. The standard deviation (one sigma) was $\pm$135 lbs. and the agreement between "load cell" thrust and "computed" gross thrust was therefore $\pm$1.95%. Comparisons numbered 1, 2, 4 and 6 indicate the maximum agreement which could be obtained from the system when instrument inaccuracies are eliminated. Comparisons 3, 5 and 7 are indications of the thrustmeter instrument performance. Comparison Number 8 is an indication of the overall accuracy which could be obtained from the system when measuring engine net thrust. A complete tabulation of the laboratory test data is shown in Appendix III.

During the laboratory tests of the thrustmeter system, there were a series of points when the gross thrust computer module malfunctioned. This occurred during simulated altitude conditions (40000 feet and Mach 1.2) and resulted in a step change in the gross thrust computed output. After about twelve such data points were taken, the computer returned to normal operation. The malfunction was attributed to a hang-up in a follower of one of the non-linear potentiometers incorporated in the computer design. The ram drag computer displayed no such inconsistency during the laboratory tests.

The comparison of the results when two different measuring stations were used to compute the gross thrust indicated that the choice of location of the pressure measuring station in the exhaust section of the engine was not critical. The agreement between computed gross thrust values when measured at Stations 5 and 7 (See Figures 4 and 5) was within $\pm$37 lbs. as shown in comparison Numbers 1 and 2 of Table I. This indicates that the location of a satisfactory pressure measuring station in the exhaust section would not require an extensive survey of the section.

Flight Test Results

The purpose of the flight tests was to ascertain the performance of the thrustmeter system when operating under true environmental conditions.

The flight tests were conducted aboard an FAA Boeing 720 aircraft at the FAA Aeronautical Center in Oklahoma City. The test engine was a JT3C-7 turbojet. A schematic presentation of the flight test instrumentation is shown in Figure 12. The engine was instrumented with total and static pressure pickups at Station 2 (compressor inlet) and Station 5 (turbine discharge). The flight engineer's static system was used to provide the altitude ambient pressure input and a total temperature probe was mounted on the nose section of the fuselage to provide the total temperature input to the reference computer module. A parallel electrical switching system was installed aboard the aircraft to monitor the six inputs to the thrustmeter system computer modules. These inputs were recorded by a digital voltmeter. The gross thrust and net thrust of the engine was computed from the pressure values recorded by the digital voltmeter in accordance with the engine manufacturer's recommended procedure (Reference 2). This "computed" thrust value was then compared to the gross and net thrust output of the thrustmeter system.

The flight tests encompassed a range of conditions from sea level static to 39000 feet and Mach .88. A total of thirty-seven test points were taken. The graphical presentation of the data is shown in Figures 13 and 14. It is noted that the slope of the curves derived from the curve fit program is not exactly 1.0 and the curves do not go through the origin as they ideally should. This results from the same causes as described for the laboratory tests, i.e. the flow areas set in the computer modules were not exactly accurate (affecting the slope) and the meter reading was not zeroed out (causing a shift in the origin). The setting of flow areas in the computer modules is done by a fine adjustment of set screws on the calibrated potentiometer. This setting can be made precisely with the use of known resistors in the circuits, but during the tests, this special equipment was not available. The offset in the dial reading was undetectable without the use of this special test equipment and was only discovered as a result of the data analysis.

The significant information shown in Figures 13 and 14 is the linearity of the data which is indicative of the consistency which could be expected when using the thrustmeter to set engine power. An essential element contributing to the effectiveness of the reference thrust portion of the thrustmeter system is a reliable engine gross thrust measurement. The reference thrust system compares the thrustmeter value of gross thrust to the engine model specification maximum continuous rated gross thrust for the prevailing flight conditions. This comparison is displayed on a dial ranging from 0 to 120% and indicates the percentage of the maximum continuous rated thrust which is being produced by the engine.

The reference thrust computer read 117% $\pm$1% at all times at take-off over a fairly wide range of temperature and pressure conditions on the runway. At altitude, the percent dial indicated 89% of maximum continuous rated thrust for most of the test points. This was considered to be a representative value of the power level at which the engine was operating since it was at approximately maximum cruise power during most of the tests. The response characteristics of the system were very good. Whenever an engine power setting was changed, the percent of thrust dial reacted promptly. A malfunction of the reference system occurred for a short period during these tests, but it was found to be caused by a damaged wire which carried the temperature input signal to the reference computer module.

A summary of the flight test results is shown in Table II. The root mean square value of the "computed" net and gross thrust are calculated and compared to the "thrustmeter" values of net and gross thrust. Dividing the standard deviation (one sigma deviation) obtained from the first degree curve fit program by the root mean square "computed" thrust value the percentage shown in Column 5 in Table II was obtained. A complete tabulation of the flight test results is shown in Appendix III.

Some difficulties were encountered during the flight test work. The static pressures measured in the inlet duct and used in computing the ram drag were erratic during some of the tests. This resulted in fairly wide fluctuations in the thrustmeter reading of net thrust ($\pm$200 lbs.). This situation could have resulted from inlet distortion or non-axial flow at the pressure measuring station. The digital voltmeter records indicated stable readings for the total pressure and fluctuations in the static pressure despite the fact that all test points were taken during steady state flight and power conditions. The static measuring system at this station consisted of two manifolded wall static pressure pickups located at the 3 and 9 o'clock positions. The instability described above did not affect the measurement of gross thrust and percent of reference thrust since they are computed without inlet static pressure as inputs to the system. More extensive static pressure instrumentation in the engine inlet duct would provide more consistent and reliable values for the thrustmeter system's determination of in-flight net thrust.

CONCLUSIONS

1. As a result of the laboratory and flight tests, it is concluded that the thrustmeter can measure the gross thrust of turbojet engines within ± 3 percent of the actual engine gross thrust.

2. The reference thrust concept used by the thrustmeter system is an effective and simple means of setting engine power and monitoring engine performance.

3. Some improvements in the mechanical design of the thrustmeter components are required to improve the reliability of the equipment.

4. The thrustmeter system offers a pilot an opportunity to detect small changes in engine performance. This could prove worthwhile from the standpoint of detecting engine performance deterioration.

5. In order to measure representative values of static pressure in the engine inlet duct, a more extensive survey of the air flow pattern at this point will be necessary. The measurement of in-flight net thrust would be more consistent and reliable as a result of such an effort.

TABLE I

LABORATORY TEST RESULTS
Test Engine: J79-GE-8 Turbojet

Comparison Number	Type of Comparison	Root Mean Square Value	Standard Deviation 1	Standard Deviation as Percent of RMS Value	See Figure No.
1	"Computed" Gross Thrust vs "Load Cell" Gross Thrust (Sta. 5)	6937 lbs.	±135 lbs.	±1.95%	4
2	"Computed" Gross Thrust vs "Load Cell" Gross Thrust (Sta. 7)	6937 lbs.	±98 lbs.	±1.41%	5
3	"Thrustmeter" Gross Thrust vs "Computed" Gross Thrust (Sta. 5)	6731 lbs.	±111 lbs.	±1.65%	6
4	"Computed" Ram Drag vs "Load Cell" Ram Drag	2351 lbs.	±35 lbs.	±1.50%	7
5	"Thrustmeter" Ram Drag vs "Computed" Ram Drag	2364 lbs.	±99 lbs.	±4.20%	8
6	"Computed" Net Thrust vs "Load Cell" Net Thrust	4795 lbs.	±187 lbs.	±3.90%	9
7	"Thrustmeter" Net Thrust vs "Computed" Net Thrust	5722 lbs.	±185 lbs.	±3.23%	10

TABLE I (Continued)

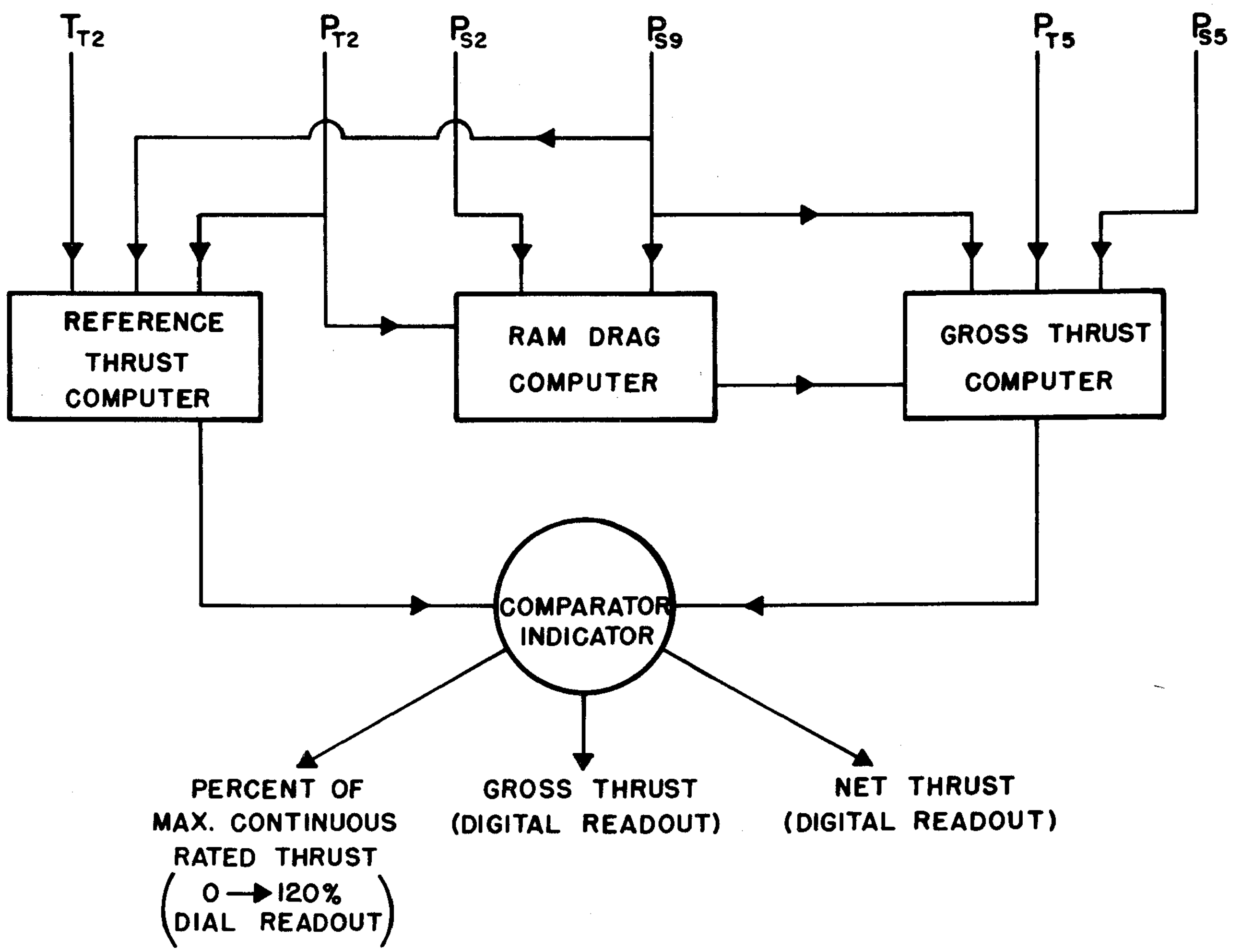
LABORATORY TEST RESULTS
Test Engine: J79-GE-8 Turbojet

Comparison Number	Type of Comparison	Root Mean Square Value	Standard Deviation 1	Standard Deviation as Percent of RMS Value	See Figure No.
8	"Thrustmeter" Net Thrust vs "Load Cell" Net Thrust	5104 lbs.	$\pm$213 lbs.	$\pm$4.20%	11

TABLE II

FLIGHT TEST RESULTS
Test Engine: JT3C-7 Turbojet

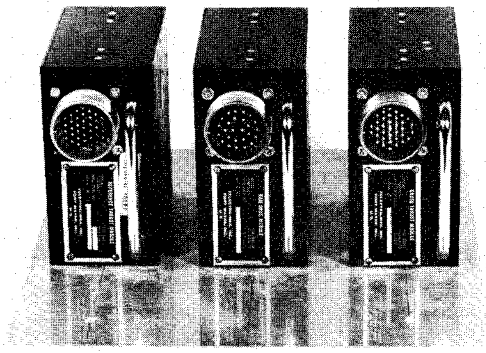
Comparison Number	Type of Comparison	Root Mean Square Value	Standard Deviation 1	Standard Deviation in % of RMS Value	See Figure No.
1	"Thrustmeter" Gross Thrust vs "Computed" Gross Thrust at Take-Off	11080 lbs.	$\pm$131 lbs.	$\pm$1.20%	13
2	"Thrustmeter" Gross Thrust vs "Computed" Gross Thrust at Altitude	5889 lbs.	$\pm$131 lbs.	$\pm$2.20%	13
3	"Thrustmeter" Net Thrust vs "Computed" Net Thrust at Altitude	3375 lbs.	$\pm$95 lbs.	$\pm$2.83%	14



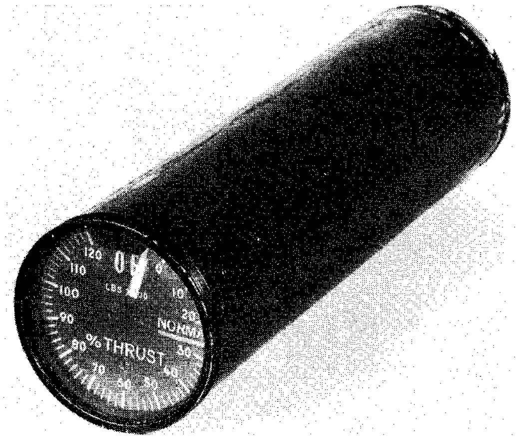
T_{T2} = COMPRESSOR INLET TOTAL TEMPERATURE
P_{T2} = COMPRESSOR INLET TOTAL PRESSURE
P_{S2} = COMPRESSOR INLET STATIC PRESSURE
P_{S9} = ALTITUDE AMBIENT PRESSURE
P_{T5} = TURBINE DISCHARGE TOTAL PRESSURE
P_{S5} = TURBINE DISCHARGE STATIC PRESSURE

THRUSTMETER SYSTEM SCHEMATIC

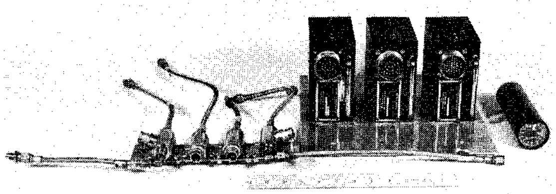
FIG. 1 THRUSTMETER SYSTEM SCHEMATIC



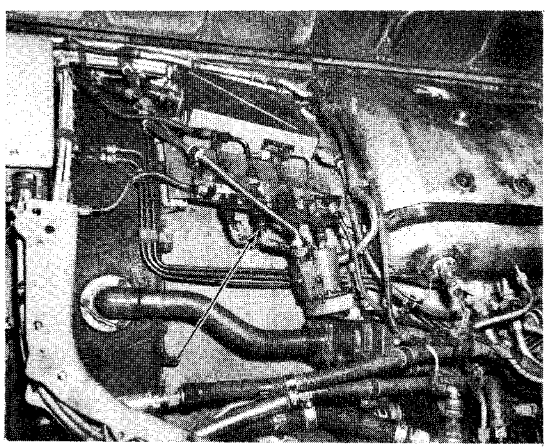
1. COMPUTER MODULES



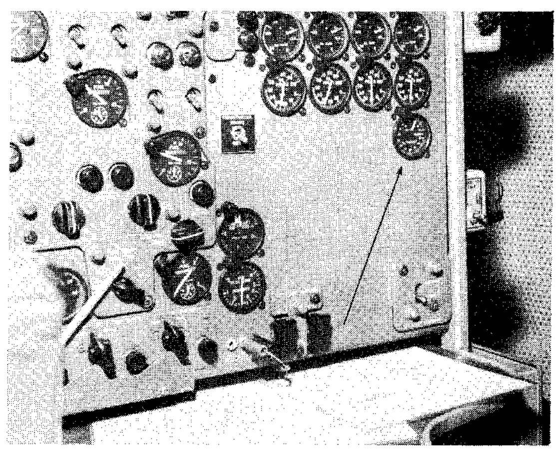
2. THRUSTMETER COMPARATOR INDICATOR



3. THRUSTMETER SYSTEM



4. TRANSDUCERS MOUNTED ON JT3C-7 ENGINE



5. THRUSTMETER INDICATOR ON FLIGHT ENGINEER'S PANEL

FIG. 2 THRUSTMETER SYSTEM COMPONENTS

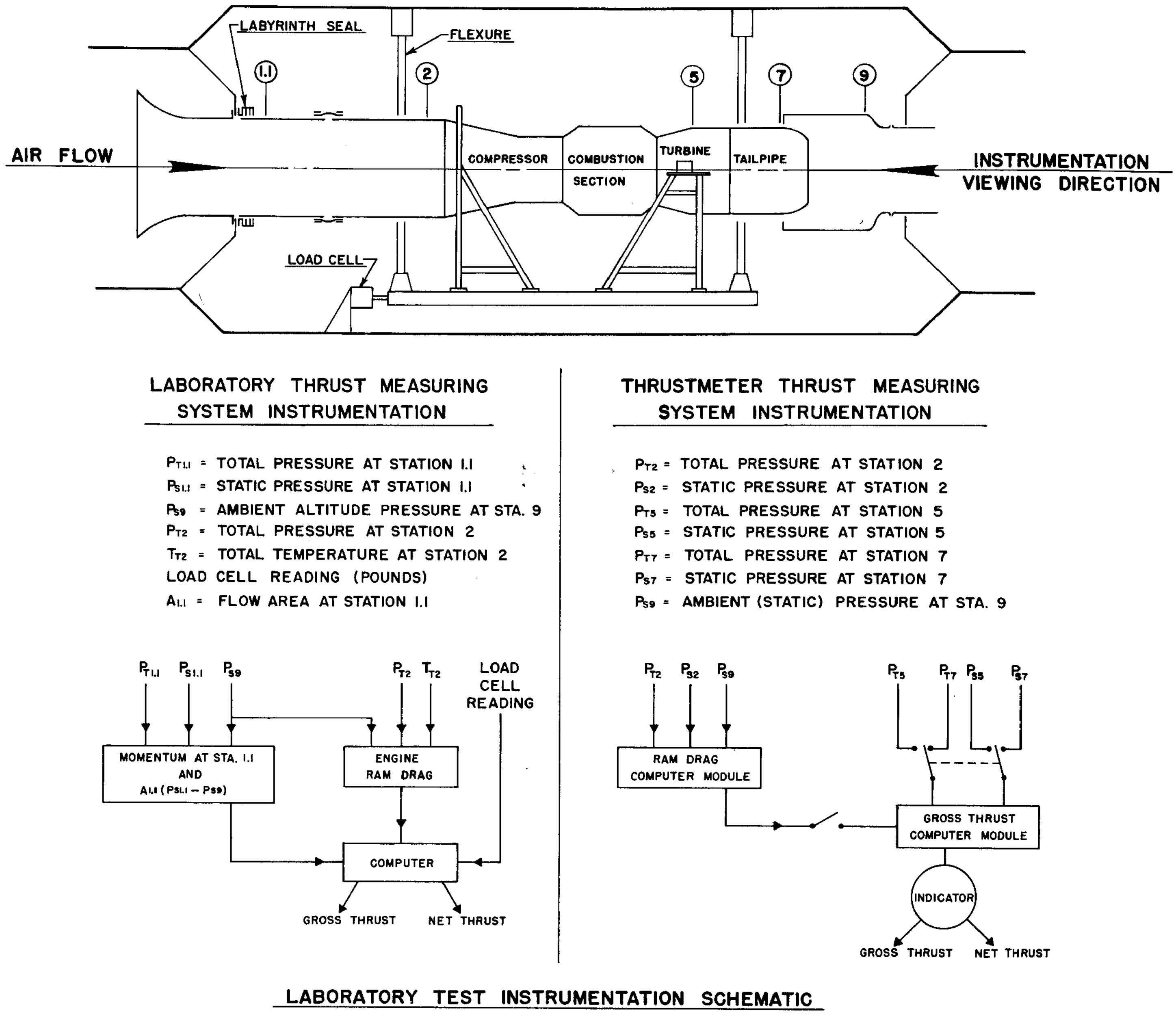


FIG. 3 LABORATORY TEST INSTRUMENTATION SCHEMATIC

LABORATORY TEST RESULTS

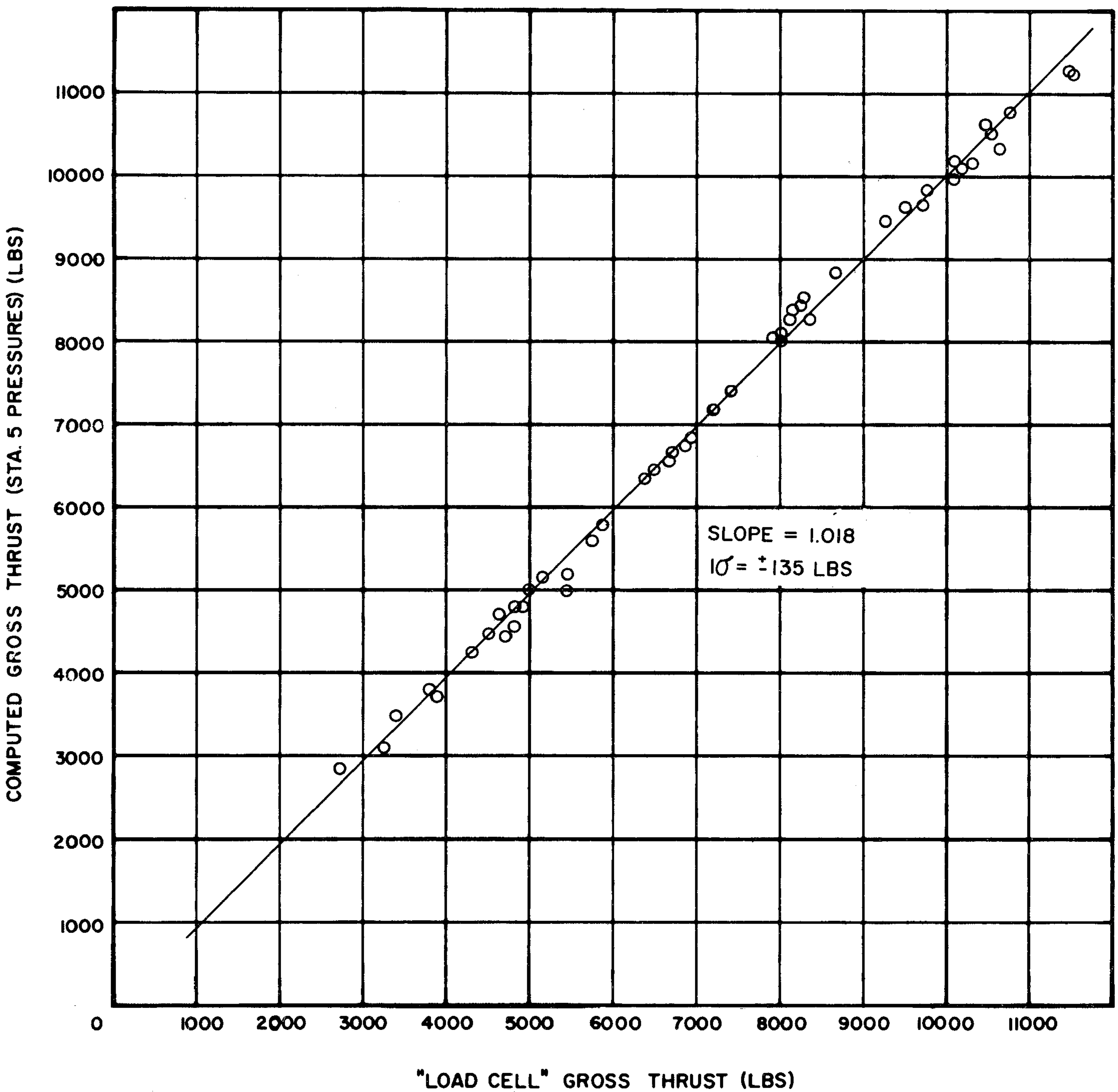


FIG. 4 COMPARISON OF "COMPUTED" GROSS THRUST (STA. 5 PRESSURES) WITH "LOAD CELL" GROSS THRUST

LABORATORY TEST RESULTS

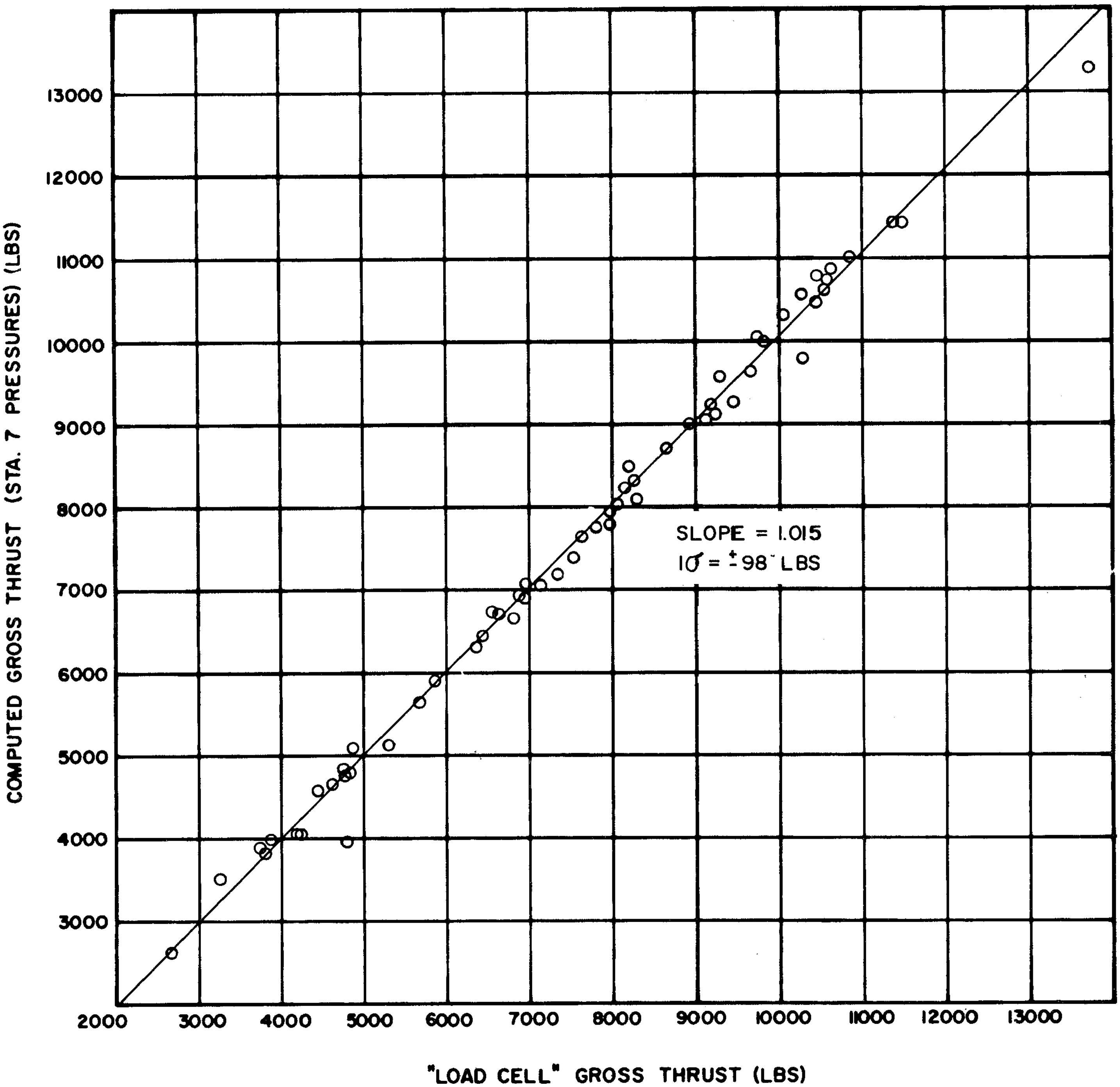


FIG. 5 COMPARISON OF "COMPUTED" GROSS THRUST (STA. 7 PRESSURES) WITH "LOAD CELL" GROSS THRUST

LABORATORY TEST RESULTS

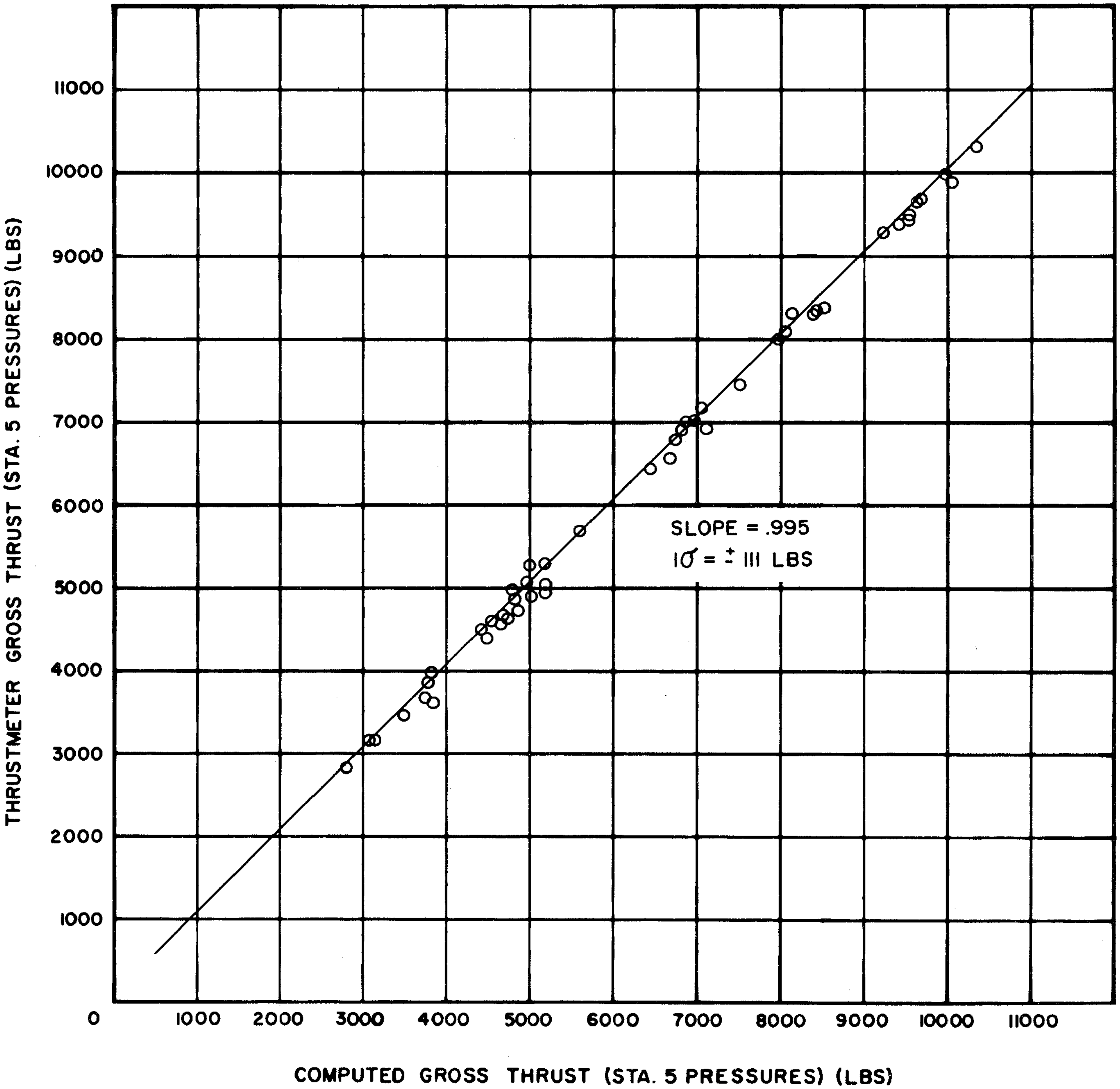


FIG. 6 COMPARISON OF "THRUSTMETER" GROSS THRUST WITH "COMPUTED" GROSS THRUST (STA. 5 PRESSURES)

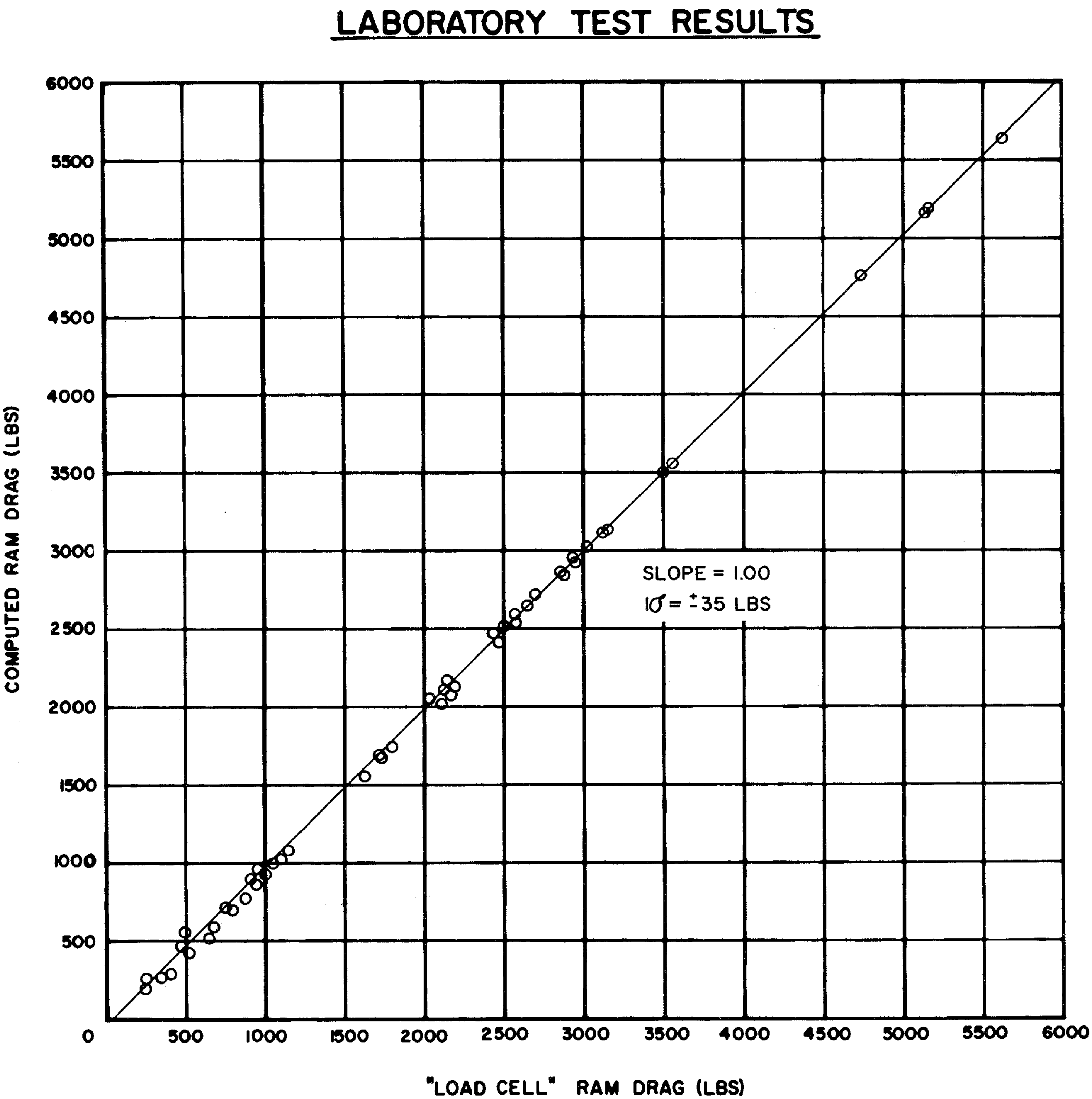


FIG. 7 COMPARISON OF "COMPUTED" RAM DRAG WITH "LOAD CELL" RAM DRAG

LABORATORY TEST RESULTS

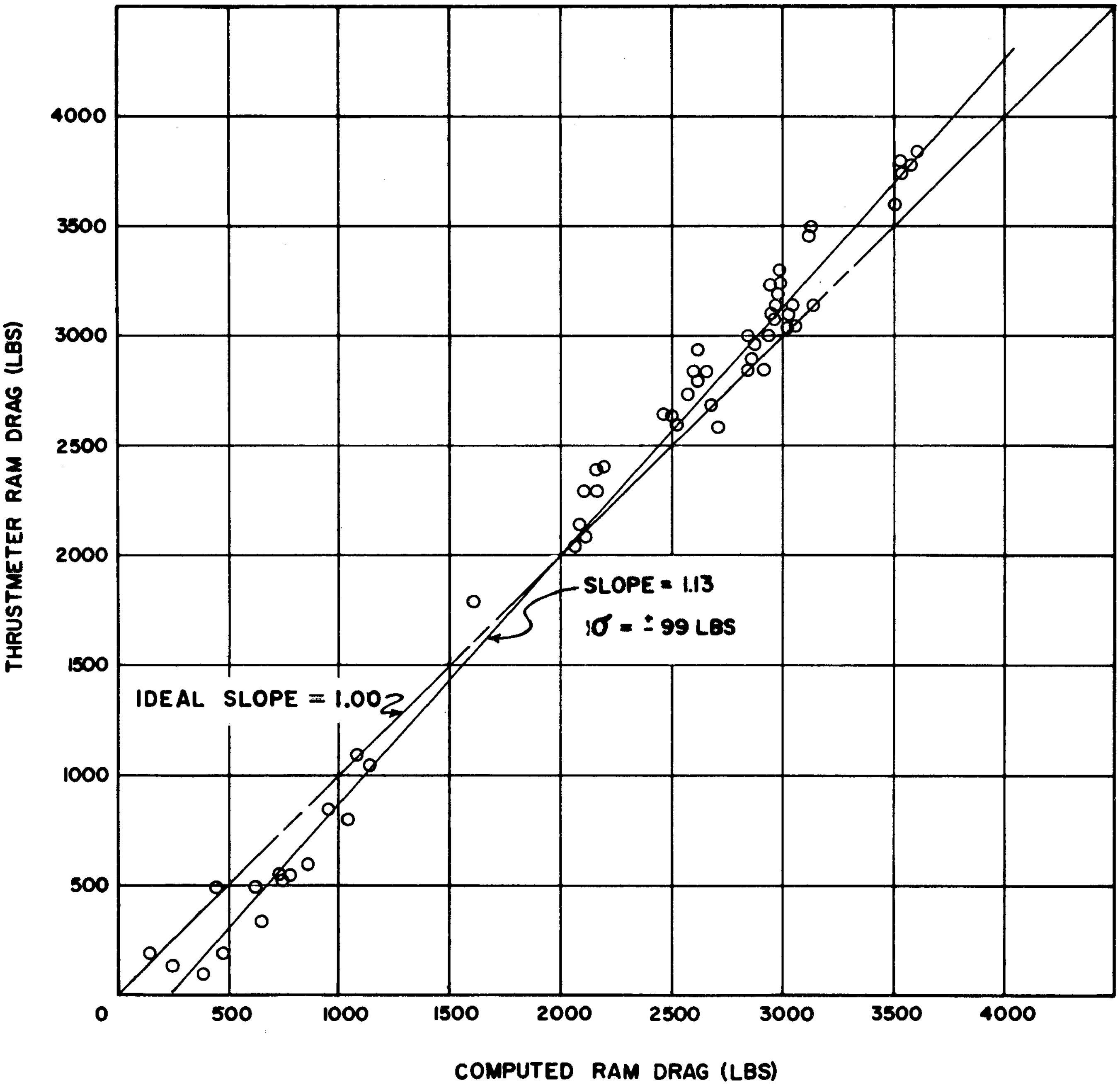


FIG. 8 COMPARISON OF "THRUSTMETER" RAM DRAG WITH "COMPUTED" RAM DRAG

LABORATORY TEST RESULTS

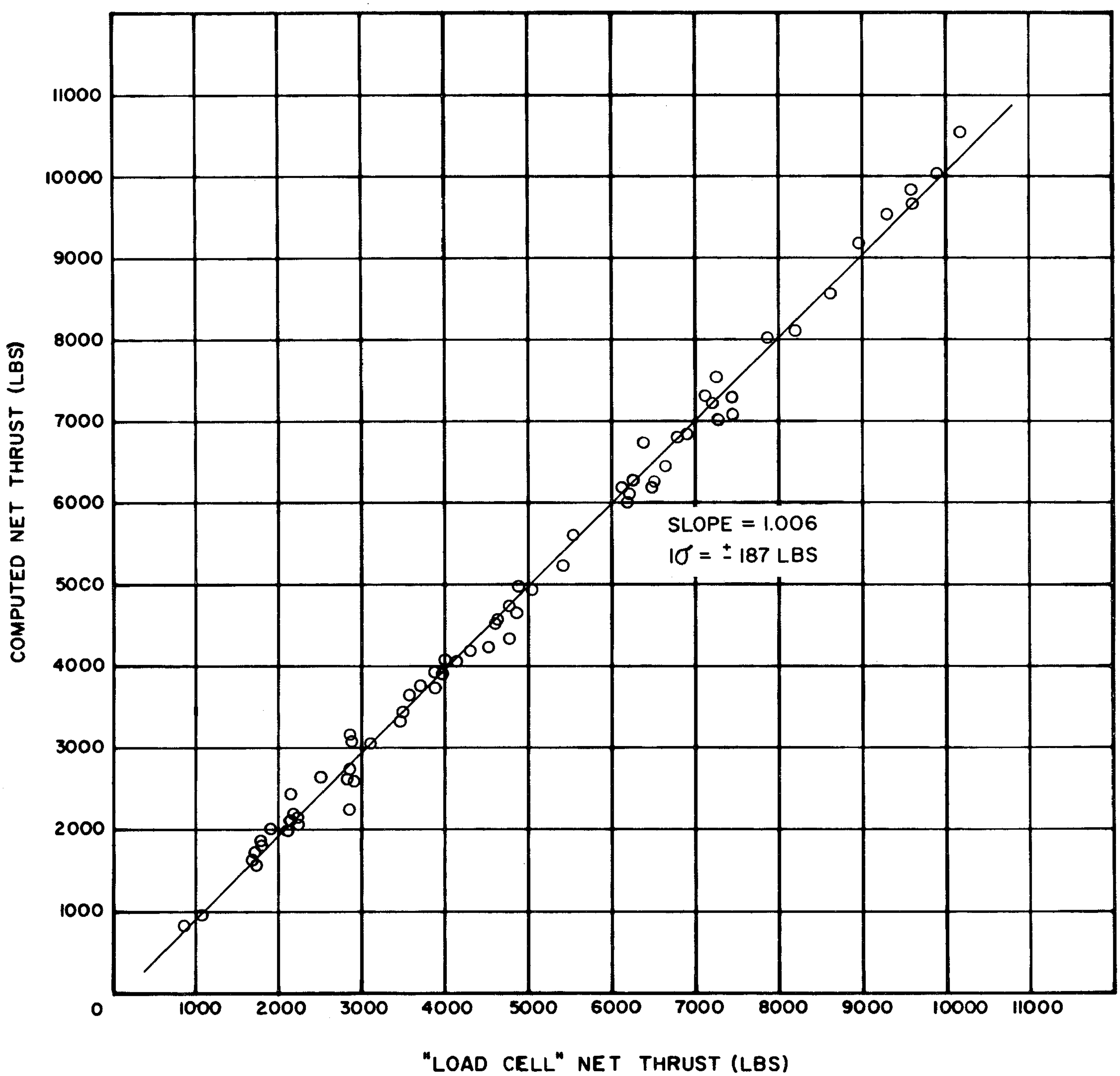


FIG. 9 COMPARISON OF "COMPUTED" NET THRUST WITH "LOAD CELL" NET THRUST

LABORATORY TEST RESULTS

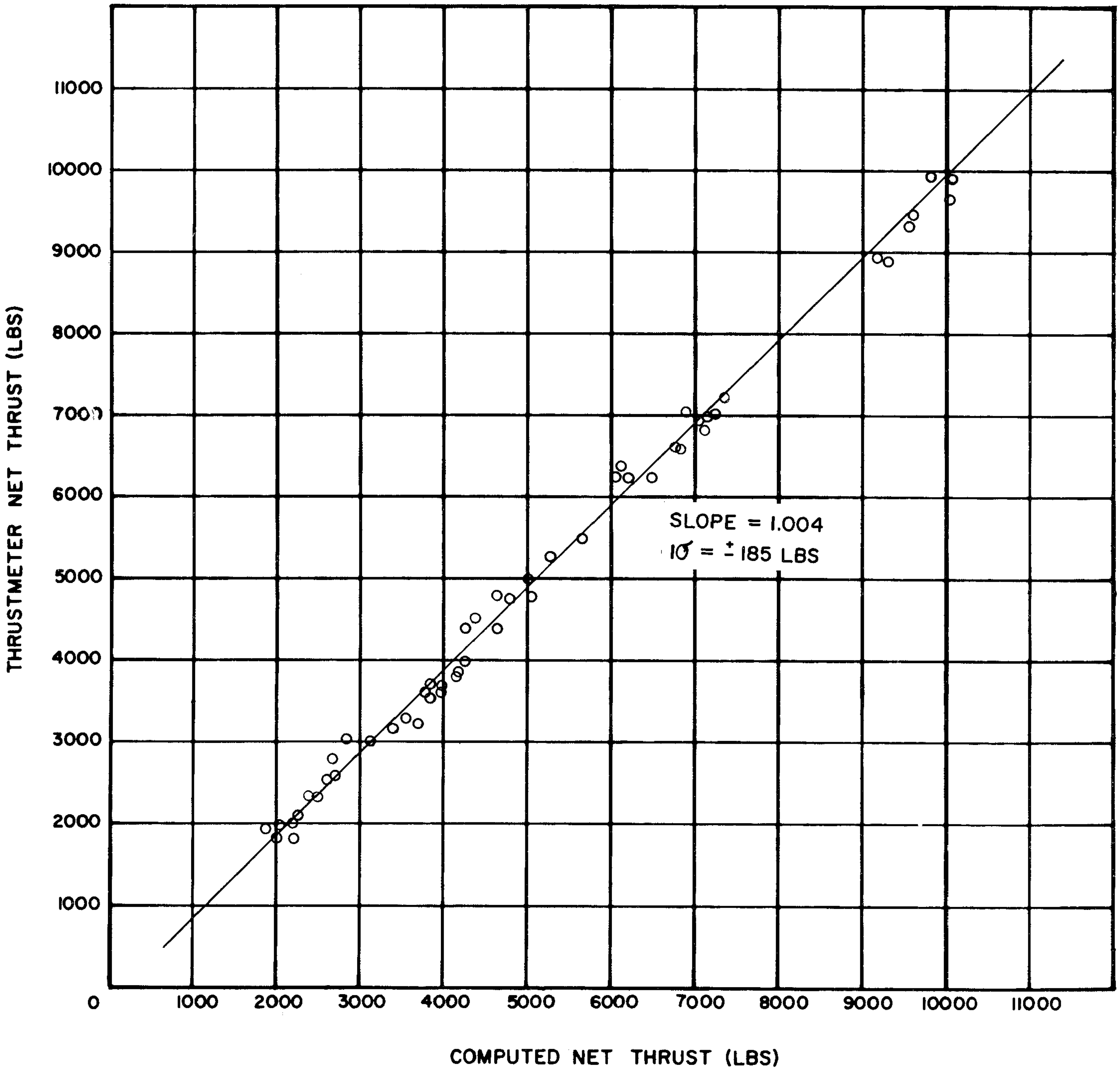


FIG. 10 COMPARISON OF "THRUSTMETER" NET THRUST WITH "COMPUTED" NET THRUST

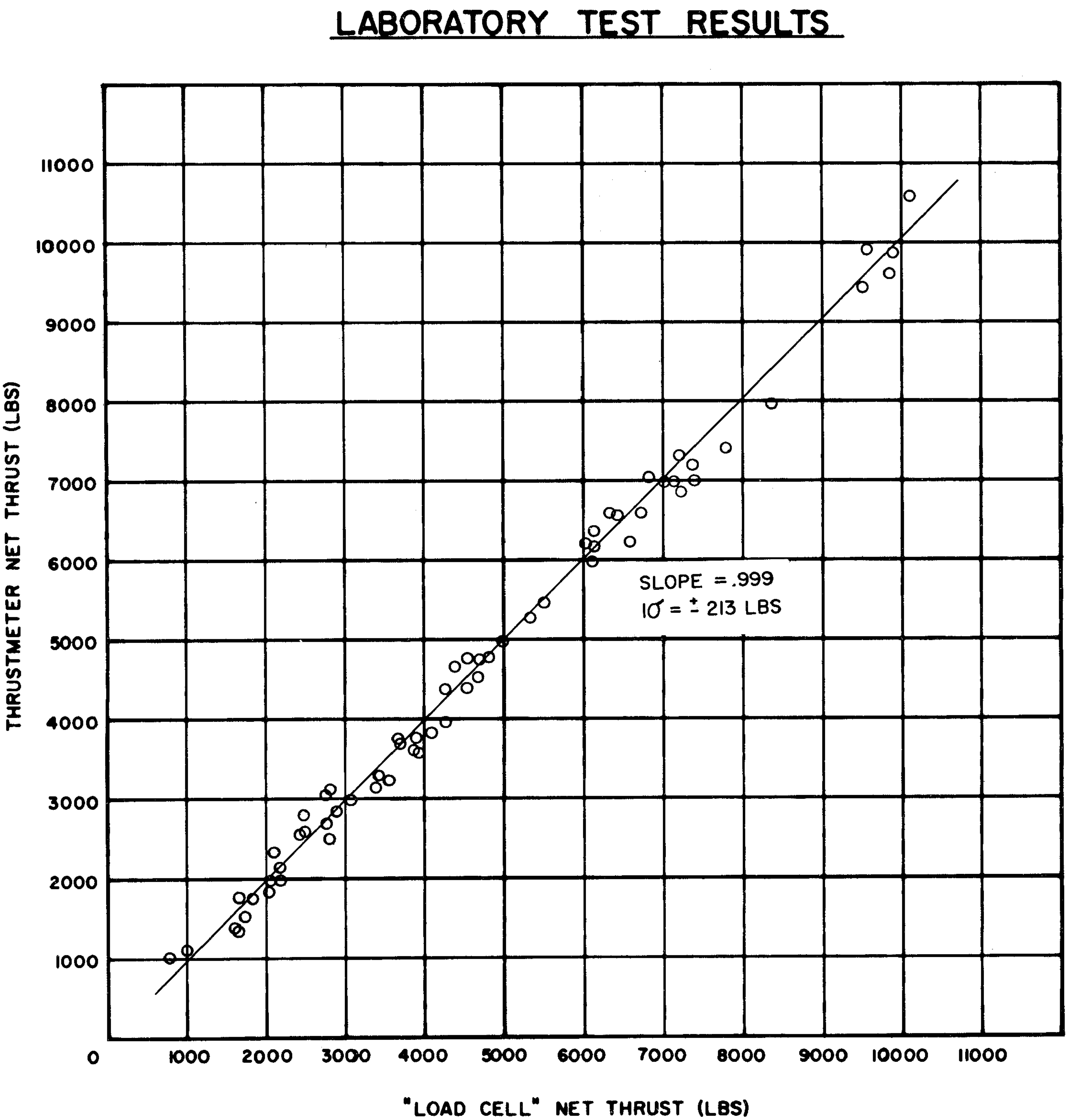
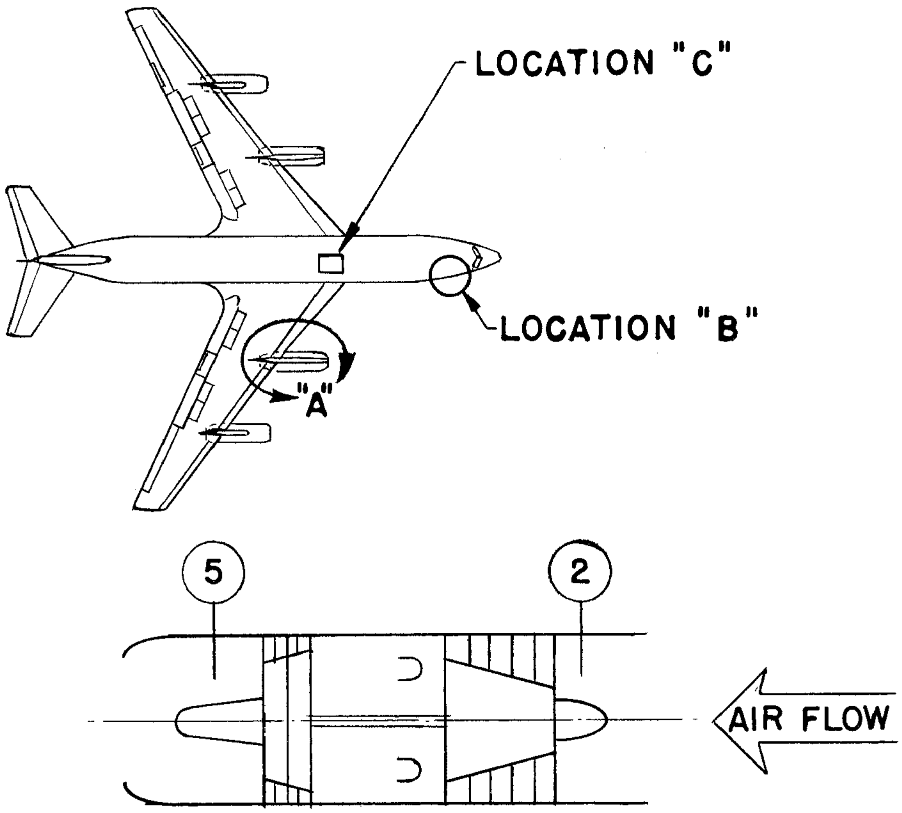


FIG. 11 COMPARISON OF "THRUSTMETER" NET THRUST WITH "LOAD CELL" NET THRUST

BOEING 720B AIRCRAFT



SECTION "A": JT3C-6 TURBOJET

ENGINE PRESSURE MEASUREMENTS

STATION 2: COMPRESSOR INLET TOTAL AND STATIC PRESSURES.

STATION 5: TURBINE DISCHARGE TOTAL AND STATIC PRESSURES.

AIRCRAFT MEASUREMENTS AT LOCATION "B"

SHIP'S SYSTEM STATIC PRESSURE (ALTITUDE AMBIENT PRESSURE)

RAM AIR TEMPERATURE (TOTAL TEMPERATURE)

COMPUTER MODULES LOCATED IN INSTRUMENT COMPARTMENT LOCATION "C".

FLIGHT TEST THRUSTMETER INSTALLATION

FIG. 12 FLIGHT TEST THRUSTMETER INSTALLATION

FLIGHT TEST RESULTS

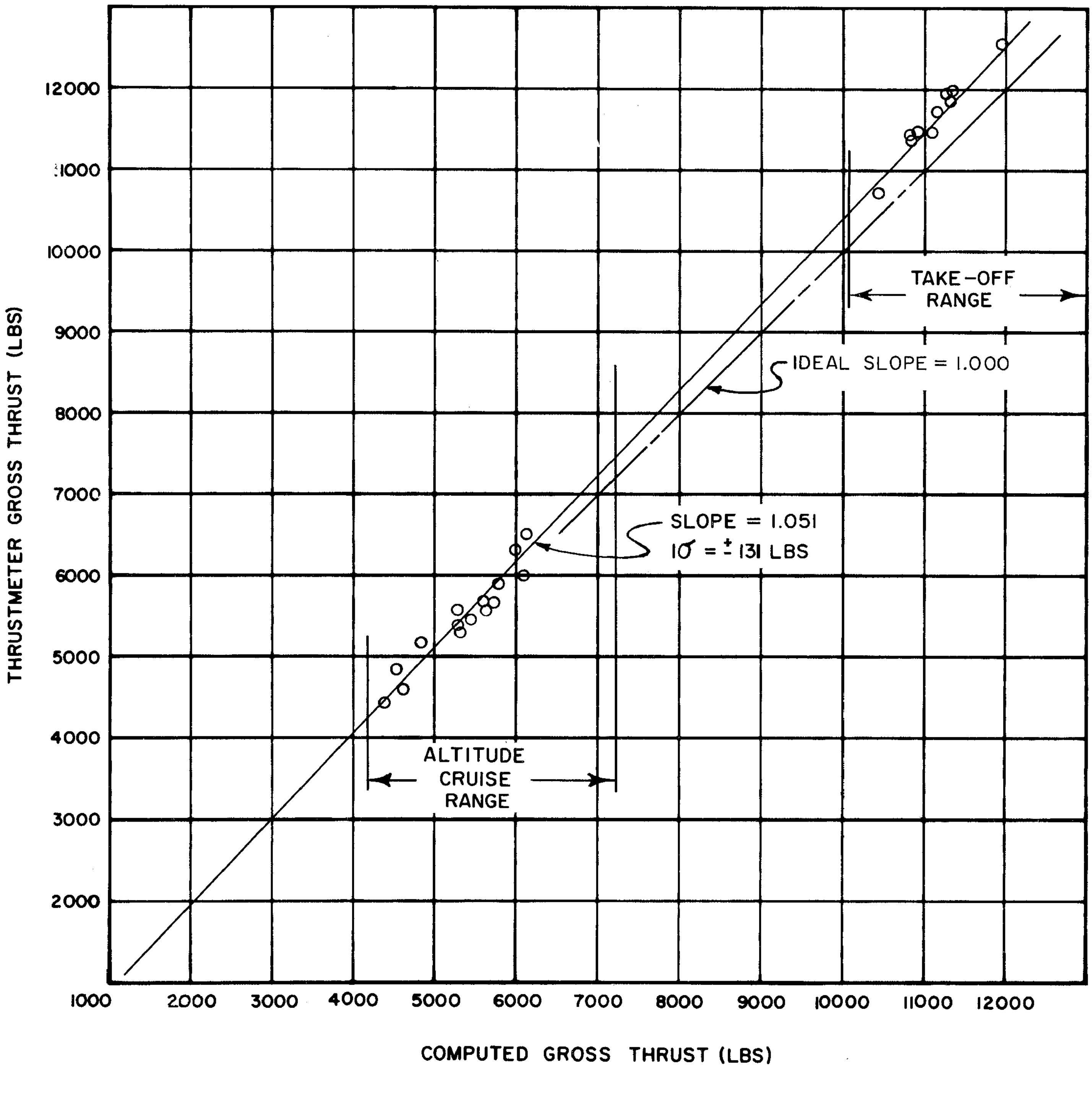


FIG. 13 COMPARISON OF "THRUSTMETER" GROSS THRUST WITH "COMPUTED" GROSS THRUST

FLIGHT TEST RESULTS

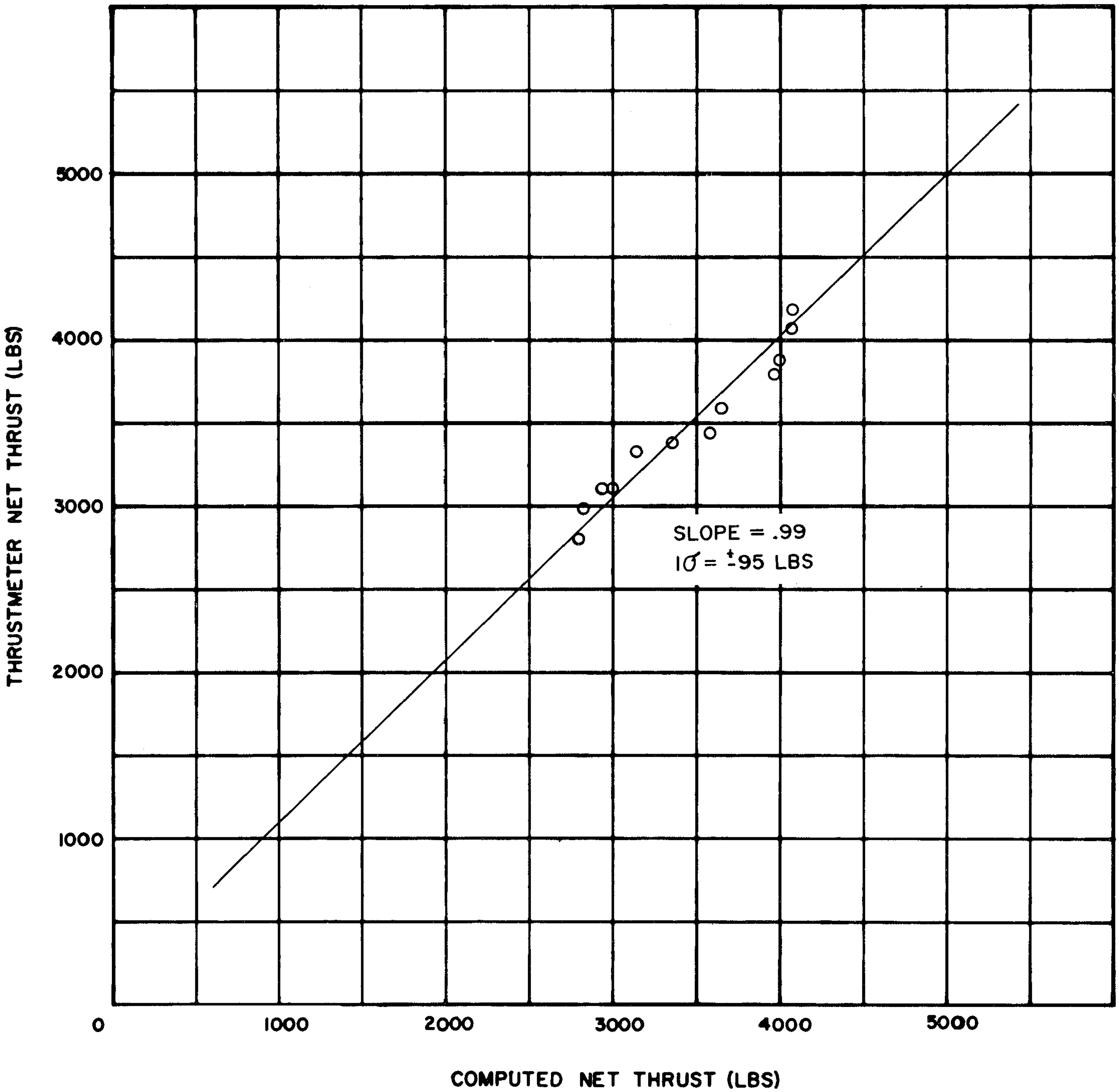


FIG. 14 COMPARISON OF "THRUSTMETER" NET THRUST WITH "COMPUTED" NET THRUST

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3. R. F. X. Salmon, "Evaluation of the Grumman Exhaust Nozzle Traversing Rake as an In-Flight Measuring Device for Turbojet Aircraft," U. S. Naval Air Turbine Test Station, Trenton, N. J., Aeronautical Turbine Laboratory, Report NATTS-ATL-75 BuWeps Problem Assignment ATTS-RAPP-2020, January 1962.

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GLOSSARY OF TERMS AND SYMBOLS

Alt.	-	Pressure altitude in feet
P_{s0} or P_{s9}	-	Ambient pressure in inches HgA
P_{t2}	-	Compressor inlet total pressure in inches HgA
P_{s2}	-	Compressor inlet static pressure in inches HgA
T_{t2}	-	Compressor inlet total temperature in ^{o}F
P_{t5}	-	Turbine discharge total pressure Station 5 in inches HgA
P_{s5}	-	Turbine discharge static pressure Station 5 in inches HgA
P_{t7}	-	Nozzle inlet total pressure Station 7 in inches HgA
P_{s7}	-	Nozzle inlet static pressure Station 7 in inches HgA
$Fg_{L.C.}$	-	Laboratory value of gross thrust in pounds
$Fn_{L.C.}$	-	Laboratory value of net thrust in pounds
$R.D._{L.C.}$	-	Laboratory value of ram drag in pounds
Fg_{TM7}	-	Thrustmeter gross thrust value using Station 7 pressures in pounds
Fn_{TM7}	-	Thrustmeter net thrust value using Station 7 pressures in pounds
RD_{TM}	-	Thrustmeter ram drag in pounds
$Fg_{com.7}$	-	Gross thrust ideally computed from Station 7 pressures in pounds
$Fn_{com.7}$	-	Net thrust ideally computed from Station 7 pressures in pounds
$R.D._{com.}$	-	Ram drag ideally computed from Station 2 pressures in pounds

GLOSSARY OF TERMS AND SYMBOLS (Continued)

$Fg_{com. 5}$	-	Gross thrust ideally computed from Station 5 pressures in pounds
Fg_{TM5}	-	Thrustmeter gross thrust using Station 5 pressures in pounds
RPM	-	Engine rotor speed
Bleed Air	-	Engine bleed air; pounds/second
$Wa_{1.1}$	-	Engine airflow calculated by pressures measured at Station 1.1; pounds/second
Mach Number	-	Flight Mach Number

ACKNOWLEDGMENTS

Appreciation is expressed for the cooperation of the personnel of the U. S. Naval Air Turbine Test Station at Trenton, New Jersey, and the personnel of the FAA Aeronautical Center, Oklahoma City, Oklahoma, expecially the personnel of the Aeronautical Engineering Branch at Oklahoma City for their fine work in the installation and testing of the equipment aboard the 720 aircraft.

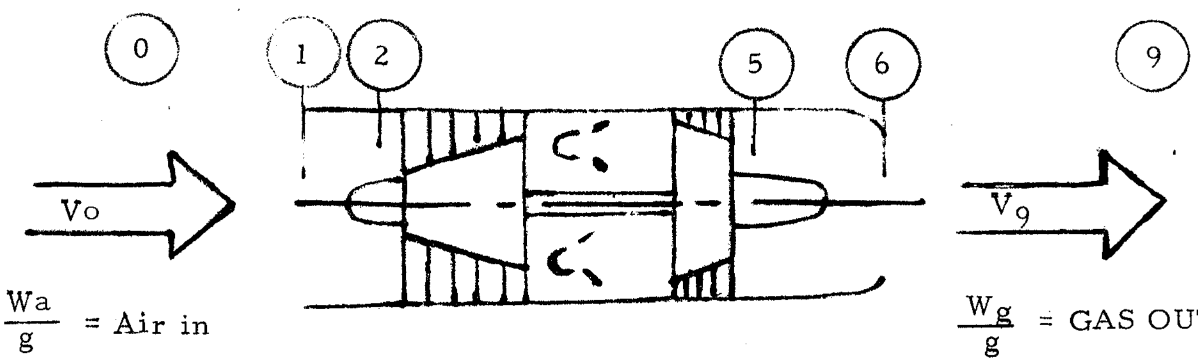
APPENDIX 1

DESIGN PRINCIPLES OF THRUSTMETER SYSTEM
AND
LABORATORY MEASUREMENT OF "LOAD CELL" THRUST

APPENDIX 1

Design Principles of Thrustmeter System

The following is the basis for the thrustmeter design. The net thrust of a turbojet engine is a force resulting from the change of momentum of the air entering and leaving the engine. This is shown graphically below:



$$\text{Net Thrust} = Fn = \frac{Wg}{g}(V_9) - \frac{Wa}{g}(Vo) \qquad (1)$$

where $\frac{Wg}{g}$ = Mass of gas; V_9 = Velocity of gas relative to engine

$\frac{Wa}{g}$ = Mass of air; Vo = Velocity of air relative to engine

This equation is true for a fully expanded gas i.e. a gas whose potential energy at nozzle inlet is converted completely to velocity at nozzle exhaust. For a choked flow nozzle, the equation is:

$$Fn = \frac{Wg}{g}(V_9) + A_9 \; (Ps_6 - Ps_9) \qquad (2)$$

where A_9 = Area at nozzle exit

Ps_6 = Static pressure at nozzle exit

Ps_9 = Ambient atmospheric pressure = Pso

a. Ram Drag

In equation (1), the portion of the equation, $\frac{Wa}{g}$ Vo, is the ram drag force. The measurement of the quantities Wa and Vo, however, cannot be made directly. They are expressed in terms of pressures and temperatures.

$$Wa = Wa_2 = \rho s_2 \; V_2 \; A_2 \tag{3}$$

where Wa = Wa_2 in a continuous flow process

ρs_2 = Static density of air at Station 2

A_2 = Flow area at Station 2

V_2 = Velocity of air at Station 2

It can be shown that (4)

$$V_2 = \sqrt{\frac{2g \; \gamma \; R \; T_2}{\gamma - 1} \left[\left(\frac{Pt_2}{Ps_2} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right]}$$

where g = Gravitational constant

γ = Ratio of specific heats; 1.4 for air

R = Gas constant for air; 53.35

Ts_2 = Static temperature at Station 2

$P_{t,2}$ = Total pressure at Station 2

Ps_2 = Static pressure at Station 2

$$\rho s_2 = Ps_2 \; X \; RTs_2 \tag{5}$$

$$\frac{Wa_2}{g} = \frac{\rho s_2 \quad A_2}{gR \quad Ts_2} \sqrt{\frac{2g \quad \gamma \; RTs_2}{\gamma - 1} \left[\left(\frac{P_{T2}}{Ps_2} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right]} \tag{6}$$

Ram drag is the product of the mass flow entering the engine and the velocity of the entering air. The velocity of the entering air is the velocity of the air relative to the engine which is the engine or aircraft velocity (Vo).

If it is assumed that the inlet duct of the engine is 100% efficient, then $T_{T_O} = T_{T2}$ = total temperature at Station 2 and $P_{T_O} = P_{T2}$ = total pressure at Station 2. It can be shown that

$$T_{t2} = Ts_o \left[\frac{P_{t2}}{Ps_2} \right]^{\frac{\gamma - 1}{\gamma}} \quad \text{and} \tag{7}$$

$$Vo = \sqrt{\frac{2g \quad RTs_o}{\gamma - 1} \left[\left(\frac{P_{t2}}{Ps_2} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right]}$$

and the ram drag is:

$$\text{Ram Drag} = \frac{Ps_2 \, A_2 \, 2 \; \gamma}{\gamma - 1} \sqrt{\left[\left(\frac{P_{t2}}{Ps_2} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right] \left[\left(\frac{P_{t2}}{Ps_o} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right]} \; X$$

$$\sqrt{\left(\frac{Ps_o}{Ps_2} \right)^{\frac{\gamma - 1}{\gamma}}}$$

In equation 8, it is shown that the ram drag can be calculated by taking measurements of:

Pt_2 = Total pressure at compressor inlet
Ps_2 = Static pressure at compressor inlet
Ps_o = Ambient atmospheric pressure

These are the three inputs used by the ram drag computer module of the thrustmeter.

In the above equations, the inlet duct has been considered to be 100% efficient in pressure and temperature recovery. For cases of less than 100% pressure recovery, the ram drag equation would be:

(9)

$$\text{Ram Drag} = \frac{Ps_2 A_2 2\gamma}{\gamma - 1} \sqrt{\left[\left(\frac{Pt_2}{Ps_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\left[\left(\frac{1}{\eta_T}\ \frac{Pt_2}{Ps_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

$$\sqrt{\left(\frac{Ps_2}{Pso}\right)^{\frac{\gamma-1}{\gamma}} \times \eta_T^{\frac{\gamma-1}{2\gamma}}}$$

where η_T = inlet duct efficiency

b. Gross Thrust:

In the station designation diagram, Stations 5 and 6 are turbine discharge and nozzle exit respectively. In the thrustmeter system, the gross thrust is computed from pressures measured at Station 5 upstream of the exhaust nozzle. The development of the gross thrust equation is as follows. For a full expansion nozzle:

where $V_6 = V_9$ and $Ps_6 = Ps_9$ (10)

$$Fg = \frac{W_{g9}}{g} (V_9)$$

The mass flow at Station 5 is the same as at the nozzle exit; therefore $Wg_9 = Wg_5$ and $Wg_5 = \rho s_5 A_5 V_5$ and

$$V_5 = \sqrt{\frac{2g\ \gamma\ gRTs_5}{\gamma g - 1}\left[\left(\frac{P_{t5}}{Ps_5}\right)^{\frac{\gamma g-1}{\gamma g}} - 1\right]} \qquad (11)$$

where
V_5 = Vel. of air at Station 5
ρs_5 = Static density at Station 5
A_5 = Flow area at Station 5
γ_g = Ratio of specific heats of exhaust gas, 1.33
Ts_5 = Static temperature at Station 5
Pt_5 = Total pressure at Station 5
Ps_5 = Static pressure at Station 5
$P s_5 = \frac{\rho s_5}{RTs_5}$

$$\text{therefore } \frac{W_{g5}}{g} = Ps_5\ A5 \sqrt{\frac{2\ \gamma_g}{[\gamma_g - 1]\ [g\ \gamma_g\ R\ Ts_5]}} \times$$

$$\sqrt{\left[\left(\frac{P_{t5}}{Ps_5}\right)^{\frac{\gamma g-1}{\gamma g}} - 1\right]} \qquad (12)$$

If the flow process from turbine discharge (Station 5) to nozzle exit (Station 6) is adiabatic, then $T_{t5} = T_{t6}$ and $P_{t5} = P_{t6}$.

Then $Ts_6 = T_{t5} \left(\frac{Ps_6}{P_{t5}} \right)^{\frac{\gamma_g - 1}{\gamma_g}}$ and nozzle exit velocity

$$V_6 = \sqrt{\frac{2g\,\gamma_g\,RT_{t5}}{\gamma_g - 1} \left[\left(\frac{P_{t5}}{Ps_6} \right)^{\frac{\gamma_g - 1}{\gamma_g}} - 1 \right] \left(\frac{Ps_6}{P_{t5}} \right)^{\frac{\gamma_g - 1}{\gamma_g}}} \tag{13}$$

The gross thrust for full expansion is:

$$Fg = \frac{\dot{W}_{g6}}{g} V_6 = Ps_5 A_5 \; \frac{2\,\gamma_g}{\gamma_g - 1} \left(\frac{P_{t5}}{Ps_5} \right)^{\frac{\gamma_g - 1}{\gamma_g}} \left(\frac{Ps_5}{P_{t5}} \right)^{\frac{\gamma_g - 1}{\gamma_g}} \quad X$$

$$\sqrt{\left[\left(\frac{P_{t5}}{Ps_6} \right)^{\frac{\gamma_g - 1}{\gamma}} - 1 \right] \left[\left(\frac{P_{t5}}{Ps_5} \right)^{\frac{\gamma_g - 1}{\gamma_g}} - 1 \right]} \tag{14}$$

When an allowance for pressure loss between Station 5 and 6 is included as a nozzle efficiency, η_n , the equation for gross thrust is:

$$Fg - Ps_5A_5 \; \frac{2\gamma g}{\gamma g-1} \left(\frac{P_{t5}}{Ps_5}\right)^{\frac{\gamma g-1}{\gamma g}} \left(\frac{Ps_6}{\eta n \; P_{t5}}\right)^{\frac{\gamma g-1}{\gamma g}} \quad X$$

$$\sqrt{\left[\left(\frac{\eta n \; P_{t5}}{Po}\right)^{\frac{\gamma g-1}{\gamma g}} -1\right]\left[\left(\frac{P_{t5}}{Ps_5}\right)^{\frac{\gamma g-1}{\gamma g}} -1\right]} \qquad (15)$$

Equations 9 and 15 are the basic equations which are incorporated in the ram drag and gross thrust computer modules. The interesting feature of the gross thrust measuring system is the fact that the internal pressure measurements are taken at a station upstream of the nozzle throat at a station of constant geometric area. Using this approach, the computation of gross thrust can be made for either a variable geometry or fixed nozzle engine. Equation 15 can be modified to compute a gross thrust for an under-expanded (or choked flow) nozzle as shown in Equation 16.

$$Fg_{choke} = 2\gamma_g \, Ps_5A_5 \sqrt{\left[\left(\frac{P_{t5}}{Ps_5}\right)^{\frac{\gamma g-1}{\gamma g}} -1\right]\left(\frac{P_{t5}}{Ps_5}\right)^{\frac{\gamma g-1}{\gamma g}}} \quad +$$

$$A_5 \sqrt{\frac{2}{\gamma_g - 1}\left[\left(\frac{P_{t5}}{Ps_5}\right)^{\frac{\gamma g-1}{\gamma g}} - 1\right]\left[\frac{1+\gamma g}{2+2\left[\left(\frac{P_{t5}}{Ps_5}\right)^{\frac{\gamma g-1}{\gamma g}} - 1\right]^{\frac{\gamma g+1}{\gamma g-1}}}\right]} \; X$$

$$\left[Ps_6 - Pso\right] \qquad (16)$$

where $Ps_6 = P_{t6}\left[\frac{2}{\gamma_g+1}\right]^{\frac{\gamma g}{\gamma_g+1}}$ and $Pt_6 = Pt_5$

The measured parameters for gross thrust computation are:

Pt_5 = Total pressure at Station 5
Ps_5 = Static pressure at Station 5
Ps_o = Ambient atmospheric pressure

It should be noted that in Equation 15, $Ps_6 = Ps_9$ since the exhaust gases are assumed to be fully expanded at the nozzle exit. For a choked flow nozzle with a pressure loss between Station 5 and 6 ($P_{t5} > P_{t6}$) the gross thrust equation is:

$$Fg_{choke} = 2\,\gamma_g\, Ps_5 A_5 \sqrt{\left[\left(\frac{P_{t5}}{Ps_5}\right)^{\frac{\gamma_g-1}{\gamma_g}} - 1\right]\left(\frac{P_{t5}}{Ps_5}\right)^{\frac{\gamma_g-1}{\gamma_g}}} \; +$$

$$\sqrt{\frac{2}{\gamma_g-1}\left[\left(\frac{P_{t5}}{Ps_5}\right)^{\frac{\gamma_g-1}{g}} - 1\right]} \; X \; \sqrt{\frac{1+\gamma_g}{2+2\left[\left(\frac{P_{t5}}{Ps_5}\right)^{\frac{\gamma_g-1}{\gamma_g}} - 1\right]}} \; X$$

$$\left[\eta\, P_{t5}\left[\frac{2}{\gamma_g+1}\right]^{\frac{\gamma_g}{\gamma_g-1}} - Pso\right] \qquad (17)$$

Laboratory Measurement of "Load Cell" Thrust

In the report, the term "load cell" thrust is used to define the value of thrust (net or gross) as determined by the U. S. Naval Air Turbine Test Station where the laboratory tests were conducted. The term "load cell" is a misnomer in that the load cell which is used in the thrust measurement is an instrument which measures only a portion of the thrust developed by the engine. There is also a pressure/area force and momentum which are aerodynamically measured and which enter into the determination of the engine's thrust. Figure 3, which is the laboratory test schematic, is useful at this point in understanding the laboratory thrust measuring system.

The measurement of "load cell" gross thrust uses the following equation:

$$(1)\ F\ \text{gross} = \text{Load cell reading} + A_{LS}\left(Ps_{1.1} - Ps_9\right) + \frac{Wa_{1.1}}{g} \times V_{1.1}$$

where A_{LS} = Cross-sectional area of inlet duct at the labyrinth seal

$Ps_{1.1}$ = Static pressure at Station 1. 1

Ps_9 = Ambient atmospheric pressure measured at Station 9

$Wa_{1.1}$ = Air flow measured at Station 1. 1

The terms $\frac{Wa_{1.1}}{g} \times V_{1.1}$ and $A_{LS}\left(Ps_{1.1} - Ps_9\right)$ are aerodynamically measured and under high Mach number simulation conditions could constitute as much as 50 percent of the gross thrust value. The experience of the laboratory in measuring thrust in this way extends over a ten year period. The accuracy of the measurement varies over the range of conditions tested with the greatest accuracies at low Mach number and altitude. An approximate value for the accuracy tolerance of gross thrust at sea level static is ± 0.5 percent.

APPENDIX 2

THRUSTMETER SYSTEM MECHANICAL DESIGN DETAILS

APPENDIX 2

Thrustmeter System Mechanical Design Details

The thrustmeter system consists of the following components:

1. Pressure probes
2. Pressure transducers
3. Temperature probe
4. Gross thrust computer module
5. Ram drag computer module
6. Reference thrust computer module
7. Comparator indicator

Pressure probes: Five per engine, measuring total and static pressures at the compressor inlet and turbine exhaust station and the fifth unit measuring ambient atmospheric pressure.

Pressure transducers: Five potentiometer type pressure transducers are used per engine. Details of the transducers characteristics are shown in the following table:

Purpose	P_{t5}	$P_{t5}-P_{s5}$	P_{t2}	$P_{t2}-P_{s2}$	P_{s9}
Size	1"x1.4"x3"	1"x3"x3"	1"x1.4"x3"	1"x3"x3"	1"x1.4"x3"
Weight	8 oz.	8 oz.	8 oz.	8 oz.	8 oz.
Press. Range	0-60 psia	0-30 psid	0-30 psia	0-8 psid	0-15 psia
Type	Absol.	Diff.	Abs.	Diff.	Abs.

Power input: 400 cps, AC or DC, 35 V Max.
Accuracy: $\pm 1\%$ @121°C, $\pm 1.5\%$ @25° and 180°C

Temperature Probe: One total temperature probe with 100% recovery up to Mach 1.5. Accuracy: $\pm .3\%$.

Gross thrust computer module: One gross thrust computer module. The function of the computer is to convert electrical signals from the pressure transducers to a voltage proportional to the gross thrust of the engine. There are three inputs required for this computation, turbine discharge total pressure (P_{t5}), turbine discharge static pressure (P_{s5}), ambient atmospheric pressure (P_{s9}). These inputs are in the form of electrical signals which come from the pressure transducers. The computer circuit uses the electrical signals to drive non-linear potentiometers which develop the mass flow function and the expansion function of the gross thrust equation. A calibrated potentiometer sets the flow area at the pressure measuring station in the engine. The output of the computer module is a voltage proportional to the engine's gross thrust.

Specifications of the gross thrust computer module are shown in the following table:

Size: 2.5" x 6" x 6"
Weight: 3.5
Temp. Range: -65° to +100°C
Power Input: 115 VAC, 400 CPS @30.36 Watt
Signal Inputs: 0-11 VAC, 400 CPS
Signal Outputs: one 0-10 VAC, 400 CPS; One 11.8 VAC three wire torque synchro signal
Accuracy: ±1.5% of full scale thrust

Ram Drag Computer Module: The ram drag computer module converts electrical signals from the pressure transducers to a voltage proportional to the engine's ram drag. There are three inputs to the computer, compressor inlet total pressure (P_{t2}), compressor inlet static pressure (Ps_2) and ambient atmospheric pressure (Ps_9). These inputs are in the form of electrical signals which come from the pressure transducers. The computer circuitry uses the electrical signals to drive non-linear potentiometers which develop the weight flow function and the compression function of the ram drag equation. A calibrated potentiometer sets the flow area at the pressure measuring station in the inlet duct. The output of the computer module is a voltage proportional to the ram drag of the engine.

Specifications of the ram drag computer module are shown in the following table:

Size: 2.5" x 6" x 6"
Weight: 2.5 lbs.
Temp. Range: -65° to +100°C
Power Input: 115 VAC, 400 CPS
Signal Inputs: 0-11 VAC, 400 CPS
Signal Outputs: One 0-10 VAC, 400 CPS
Accuracy: ±1.5% of full scale thrust

Reference Computer Module: The reference computer is an analog computer which incorporates the performance of the engine according to the model specifications over the entire flight spectrum. The inputs to the computer are total inlet temperature (T_{t2}), ambient atmospheric pressure (Ps_9), and total inlet pressure (Pt_2). These three inputs are independent of engine operation and actually provide the reference computer with flight speed, altitude and ambient air temperature. The computer uses these signals to determine the maximum continuous rating of the engine gross thrust according to the engine specifications. This value is then compared with the gross thrust which the engine is producing (as determined by the gross thrust computer module), and the percent of the maximum continuous rated thrust is displayed on the percent thrust indicator dial. The reference computer simulates the non-linear engine performance data curves with non-linear function modules.

Specifications of the reference computer module are shown in the following table:

Size: 2.5 x 6 x 6 inches
Weight: 2.5 lbs.
Temp. Range: -65° to +100°C
Power Input: 115 VAC Single Phase 400 CPS
Signal Inputs: 1) T_{t2}; 38 - 64 ohms
2) P_{t2}; 0 - 10 VAC
3) P_{so}; 0 - 10 VAC
Signal Outputs: Ref. thrust; 1.5 to 5.3 VAC, 400 CPS
Sensitivity: 1% of full scale output
Accuracy: ±1% of full scale thrust equations

<u>Comparator Indicator</u>: The indicator receives signals from the reference and gross thrust computers and displays the following information:

1 - Pounds of thrust (net or gross) as computed by the ram drag and gross thrust computers. This value is displayed in digital form.

2 - Percent of maximum continuous rated thrust developed by the engine. This is a signal proportional to the ratio of the gross thrust developed by the engine to the maximum continuous rated thrust for the flight speed, altitude and ambient conditions at that instant as determined by the reference thrust computer. The percent thrust is shown on a round 2" diameter dial with graduations from 0 to 120%.

The design of the indicator integrates a synchro receiver, a d'Arsonval movement, and a servo system composed of an amplifier, motor gearhead and potentiometer into a single instrument case.

APPENDIX 3

LABORATORY AND FLIGHT TEST RESULTS

APPENDIX III TABLE I
LABORATORY TEST RESULTS

Run No.	Alt. (ft.)	Mach No.	P_{s9}	P_{t2}	T_{t2}	P_{t5}	P_{t7}	$F_{g_{L.C.}}$	$F_{n_{L.C.}}$	$R.D._{L.C.}$	$F_{g_{TM7}}$	$F_{n_{TM7}}$	RD_{TM}	$F_{g_{com\ 7}}$	$F_{n_{com\ 7}}$	RD_{com}	$F_{g_{com\ 5}}$	$F_{g_{TM5}}$	RPM	Bleed Air	$Wa_{1.1}$
1	110	.05	29.79	29.82	65.0	74.60	69.30	10490	10148		10600	10600		10800	10574				7696	.86	172.3
2	-50	.02	30.00	29.98	59.9	75.80	70.40	10729			10750			10974					7693	.70	173.2
3	50	.08	29.86	29.98	58.2	77.00	71.90	10421	9929	492		9900	500	10488	10048	440	10600		7387	.71	169.5
4	20	.10	29.88	30.02	57.8	76.20	71.40	10161	9568	583	10100	9900	200	10276	9808	468	10100		7307	.71	166.7
5	450	.16	29.43	30.02	59.6	68.80	64.50		7440	821		7000	600		7113	851			6908	O	145.3
6	680	.20	29.19	30.06	59.6	68.50	64.30		7291	1007		6850	800		7087	1031			6910		144.3
7	500	.16	29.38	29.91	60.0	64.00	60.10	7365	6618	747		6250	550		6456	765	7390		6806		137.1
8	650	.18	29.24	29.90	61.0	53.60	50.80	5437	4703	734	5100	4550	550	5095	4357	738	5231		6538		118.2
9	350		29.54	29.88	59.1	67.80	63.60	7955	7408	547		7200	350	7965	7324	641	8121				
10	200	.08	29.70	29.88	58.6	56.10	53.10	5738	5397	341	5400	5300	100	5655	5258	397	5692		6604		123.5
11	530	.15	29.35	29.89	59.5	47.85	45.26	4284		579	4200		500	4048		617			6400		110.4
12	370	.13	29.52	29.90	59.7	33.55	35.29	1135	815	320	1150	1000	150	1184	850	334			5773		72.32
13	440	.14	29.45	29.88	60.6	30.86	30.15			228	400		200	415		229			5005		47.8
14	410	.16	29.48	30.01	60.6	76.40	70.70	10843	9878	965		9600	750	11004	10047	957	11008		7693		172.5
15	550	.16	29.33	29.92	58.7	78.00	73.10	10531	9573	958		9450		10627	9651	976	10540		7300		166.6
16	35000	1.20	7.04	16.93	48.8	44.22	40.62	8254	4861	3556	8600	4800		8540	5002	3538	8548	8350	7581		99.1
17	35020	1.20	7.03	16.95	50.3	45.61	42.30	8153	4740	3514		4800	3800	8264	4778	3486	8383	8280	7371		98.0
18	34960	1.20	7.05	16.93	50.1	45.44	42.19	8082	4565	3517		4800	3600	8076	4595	3481	8255		7302		97.0
19	35080	1.20	7.01	16.93	49.2	40.42	38.06	6690	3555	3135	6750	3250	3500	6795	3678	3117	6686	6550	6914		86.4
20	35060	1.20	7.02	17.03	48.5	30.65	28.99	4769	2120	2649	4850	2000	2850	4852	2232	2620	4676	4540	6530		73.0
21		1.20																	6144		57.1
22	34960	1.19	7.05	16.88	45.7	29.39	27.70	4496	1894		4500			4614	2045		4503	4390	6505		72.0
23	50010	1.38	3.40	10.68	83.5	26.02	24.07	5185			5350			5499			5241	4945	7687		59.2
24	49600	1.37	3.49	10.71	84.5	26.03	24.08	5085	2912	2173	5400	2800		5472	2631	2241	5216	5040	7688		59.2
25	49510	1.36	3.50	10.69	84.7	26.45	24.85	4927	2834	2093	5250			5306	3161	2145	4968	4915	7396		57.6
26	49600	1.37	3.49	10.72	84.2	26.31	24.84	4881	2828	2053	5050			5218	3102	2116	4878	4710	7304		56.9
27	49750	1.37	3.46	10.68	85.3	22.72	21.54	3845	2085	1760	4150	1850		3981	2185	1796	3789	3690	6915		48.4
28	49700	1.37	3.47	10.71	85.1	19.59	18.58	3262	1671	1591	3500			3255	1635	1620	3132	3130	6717		43.9
29	49650	1.37	3.48	10.70	84.2	21.19	20.04			1703	3900	1800		3708	1980	1728	3516	3450	6861		47.2
30	49700	1.37	3.47	10.72	81.9	26.52	24.86			2102	5250			5369		2155	5018	4890	7395		58.0
31	9950	.60	20.61	26.24	71.9	65.60	61.20	10259	7216	3043	10400		3100	10585	7575	3010	10192		7685		149.5
32	9950	.60	20.61	26.30	72.8	67.10	62.90	10080	7066	3014	10100		3100	10296	7341	2955	9977	9950	7382		147.4
33	9940	.60	20.63	26.31	73.6	66.90	62.70	9657	6765	2892	9450	6600	2850	9658	6824	2834	9639	9650	7227		141.6
34	9930	.60	20.64	26.28	72.9	66.60	62.20	9263	6392	2871	9600	6600	3000	9585	6759	2826	9635	9550	7235		140.8
35	9900	.60	20.65	26.31	73.4	57.40	53.90	7533	5009	2529	7600	5050	2600	7488	4987	2501	7535	7430	6921		124.2
36	10020	.60	20.55	26.21	71.8	43.79	41.37	4916	2829	2087	5100	3050	2050	4822	2779	2043	4909	4970	6538		102.3
37	9930	.60	20.64	26.35	71.3	44.06	41.65	4939	2837	2099			2100	4876	2784	2092	4933	4890	6541	3.10	103.3
38	9770	.59	20.76	26.38	71.3	43.72	41.36	4851	2769	2082			2100	4788	2718	2070	4837	4910	6541	5.40	103.4
39	9880	.60	20.67	26.36	71.2	43.58	41.24	4868	2763	2105			2100	4772	2684	2088	4820	4890	6541	5.91	103.5
40	10040	.60	20.53	26.30	72.7	31.92	30.02	2743	1040	1703	2900		1800	2680	980	1700	2858	2810	6225		83.6
41	9990	.60	20.58	26.20	72.8	63.10	57.90	9803		3012	10000	6950	3050	10038	7033	3005	10048	9850	7687	4.23	148.7
42		.60						9178	6160	3018			3050	9263	6261	3002	9558	9440	7687	10.71	149.5
43		.60						9207	6166	3041	9450	6400		9139	6115	3024	9450		7685	10.87	149.3
44		.79						5886	3926		6100	3600		5906	3755		5818	5960	6863		93.4
45		.80						6965	4291		7100	4400	2700	6901	4244	2657	6906	7020	[illegible]	O	100.8
46		.79						7883	5008	2875	7900	5000	2900	7834	4961	2873	7985		7230		109.4
47		.80						8643	5517	3126	8650	5500		8739	5614	3125	8844		7685		117.5
48	-30	.80	29.95	45.77	124.4	76.00	71.20		4828	4727					4660	4729			6856		169.9
49	-40	.80	29.97	45.65	126.5	85.00	80.30	11444	6236	5158				11402	6254	5148	11179		7023		186.0
50	-50	.80	30.00	45.75	126.3	85.40	80.70	11393	6223	5170				11454	6314	5140			7022		186.3

APPENDIX III TABLE I (Continued)
LABORATORY TEST RESULTS

Run No.	Alt. (ft.)	Mach No.	P_{s9}	P_{t2}	T_{t2}	P_{t5}	P_{t7}	$F_{g_{L.C.}}$	$F_{n_{L.C.}}$	$R.D._{L.C.}$	$F_{g_{TM7}}$	$F_{n_{TM7}}$	RD_{TM}	$F_{g_{com}}$ 7	$F_{n_{com}}$ 7	RD_{com}	$F_{g_{com}}$ 5	$F_{g_{TM5}}$	RPM	Bleed Air	$Wa_{1.1}$
51	20	.80	29.88	45.60	125.7	97.00	91.80	13737	8118	5620				13806	8178	5628			7218	o	202.6
52	10	.79	29.90	45.07	124.0	102.80	95.20	16260		6390						6394	16647		7689		234.3
53	6070	.24	23.90	24.96	102.9	57.30	53.80	7160		1037	7100			7076		1076	7143		7218		119.8
54	6000	.23	23.97	24.90	103.2	59.30	54.70	8270	7166	1104	8050	7000		8351	7218	1133	8399		7685		134.8
55	5060	.50	29.86	29.47	67.4	74.50	70.20	10563	7841	2722			2600	10722	8031	2691	10325		7229		159.4
56	5100	.50	24.80	29.48	66.1	73.90	68.60	11490	8585	2905			2850	11456	8565	2891	11283		7687		169.2
57	40130	1.22	5.50	13.83	47.1	25.37	24.02	3951	1752	2199	3850		2300	4048	1888	2160	3882		6529	2.87	59.4
58	39970	1.22	5.54	13.82	47.5	25.00	23.65	3886	1679	2187	3800		2400	3898	1742	2156	3804		6529	1.98	59.4
59	40020	1.23	5.52	13.90	47.6	24.73	23.42	3851	1643	2214	3800		2400	3870	1702	2168	3751		6530	3.93	59.9
60	40130	1.23	5.50	13.91	46.8	33.55	31.58	5740	3090	2650	5800	3000	2800	5676	3071	2605	5617	5670	6903	3.09	71.2
61	40130	1.23	5.50	13.82	48.3	36.94	34.39	6805	3865	2940	6700	3600	3100	6692	3772	2920	6754	6790	7303	w 40	79.4
62	42550	1.31	4.90	13.83	47.6	36.91	34.37	6987	3847	3140	7100	3650	3450	7007	3906	3101	6986	7010	7387	3.41	79.8
63	40400	1.24	5.43	13.89	47.4	37.02	34.52	6895	3878	3017	7000	3750	3250	6916	3939	2977	6845	6900	7388	3.44	80.3
64	40060	1.23	5.52	13.88	48.6	35.23	32.81	6648	3673	2973	7000	3750	3250	6736	3810	2926	6560		7388	2.40	80.1
65	40170	1.23	5.49	13.90	49.6	33.01	30.23	6375	3404	2971	6350	3150	3200	6333	3387	2946	6371		7392	5.22	80.0
66	39800	1.22	5.59	13.89	48.8	32.03	28.44	6454	3450	3004	6450	3300	3150	6455	3502	2953	6440	6483	7675	5.52	81.2
67	39800		5.59	13.89	48.4	34.14	31.07														
68	39720	1.21	5.60	13.90	47.9	36.06	33.06	6971	3994	2977	7100	3800	3300	7086	4113		7170	7058	7673	3.66	81.2
69	34660	1.18	7.15	16.92	48.0	39.94	35.51	7825	4270	3555	7800	4000	3800	7786	4243	3543	8090	8064	7671		99.3
70	34930	1.19	7.06	16.95	47.7	42.60	38.71	8179	4597	3582	8250	4400	3850	8208	4625	3583	8330	8428	7669	2.77	99.2
71	34960	1.19	7.05	16.93	47.7	43.98	40.59	7977	4459	3518			3750		4291	3515	8300	8142	7306	2.89	97.4
72	35020	1.19	7.03	16.94	48.2	41.30	37.72	7646	4119	3527	7550	3850	3700	7653	4143	3510	7950	7921	7338	6.61	97.3
73	34930	1.19	7.06	16.97	49.1	29.79	28.18	4694	2077	2617	4800	2000	2800	4625	2033	2592	4500	4470	6535	4.29	72.4
74	34930	1.19	7.06	16.97	48.9	30.32	28.70	4802	2200	2602	4950	2000	2950	4714	2118	2596	4620	4560	6536	2.12	72.4
75	34850	1.19	7.09	16.97	49.0	30.65	29.08	4831	2212	2617	5000	2150	2850	4832	2243	2589	4620	4598	6532	2.91	72.5
76	33370	1.13	7.60	16.96	47.7	44.51	40.64	3794						3931					7666	3.95	99.1
77	51800	1.44	3.14	10.70	83.6	22.24	21.02		1652	2142		1950	2300		1835	2096	3860	3808	6919	2.73	48.8
78	52200	1.46	3.08	10.72	82.6	22.86	21.69	3917	1741	2499		2000	2300	4039	1911	2468	3970	3874	6917	1.63	48.9
79	52200	1.46	3.08	10.63	83.0	24.68	23.08		2136		5000	2350	2650	4943	2483		4640	4738	7299	1.86	56.1
80	52110	1.45	3.09	10.71	83.5	23.62	21.80		1953		5050	2400	2650	4823	2355		4680	4686	7300	3.46	56.3
81	50370	1.40	3.36	10.70	83.3	23.32	20.72			2519	5200	2550	2650	5079	2583	2496	4970	4912	7672	3.66	59.3
82	49470	1.36	3.51	10.61	83.5	24.33	22.09	4896	2463	2433	5250	2600	2650	5122	2677	2445	5050	4971	7674	1.92	58.8
83	9980	.60	20.59	26.26	70.3	67.00	62.40	9798	6880	2918	10050	7050	3000	9778	6875	2903	9950	9966	7294	.74	143.6
84	9980	.61	20.59	26.39	71.8	63.90	59.10	9458	6484	2924			3150	9292	6241	2591	9660	9634	7301	5.05	144.7
85	9980	.60	20.59	26.17	71.5	60.50	55.70	8948	6098	2900	9200	6.50	2950	9044	6159	2885	9270	9224	7302	9.04	143.7
86	10030	.60	20.54	26.23	71.6	58.40	52.20	9142	6111	3031	9400	6250	3150	9070	6037	3033	9380	9423	7670	9.56	146.6
87	10020	.60	20.56	26.22	71.5	58.70	52.60	9256	6194	3062	9350	6200	3150	9136	6112	3024	9440	9498	7674	9.07	149.6
88	490	.15	29.39	29.89	61.1	53.80	51.10	5457	4822	635	5550			5293	4652	641	5290	5196	6527	.77	118.3
89	490	.15	29.39	29.88	60.6	53.00	50.20	5322	4693	628	5550			5163	4530	633	5230	5093	6525	4.17	118.4
90	350	.11	29.53	29.84	61.2	53.00	50.36			466						505	5260	5018	6538	6.83	118.1
91	560	.16	29.31	29.81	59.7	69.10	64.10			911						895			7315	11.08	165.8
92	390	.17	29.50	30.06	60.2	76.00	71.00			999						947			7308	2.11	166.5
93	550	.15	29.34	29.84	59.5	72.10	67.10	9753	8924	833	10000	9400		10082	9193	889			7299	6.63	164.5
94	520	.15	29.36	29.89	62.7	69.60	63.3												7301	1.50	164.8
95	480	.15	29.40	29.90	57.7			9670		914	9800	9400		10162	9258	904			7674		170.9
96	430	.13	29.47	29.83	56.2			10037	9259	779	10230	9800		10349	9524	825			7677	7.17	170.8

APPENDIX III TABLE II
FLIGHT TEST RESULTS

Run No.	Altitude (ft.)	P_{s9} (psf)	Mach No.	P_{s2} (psf)	P_{t2} (psf)	EPR	P_{t5} (psf)	P_{s5} (psf)	Gross Thrust (F_g) TM (lb.)	Gross Thrust (F_g) COMP (lb.)	Net Thrust (F_n) TM (lb.)	Net Thrust (F_n) COMP (lb.)
1	1280	2020			2020	2.63			12000	11344		
2	37100	450	.82	616	703.6	2.55	1830	1487	4700	4530	3100	2990
3	37000	452	.84	619	718.1	2.55	1830	1482	4700	4518	3100	2928
4	37160	449	.835		709.1	2.50	1800	1458	4650	4451		
5	340	2163			2163.4	2.61			12600	11926		
6	39140	408	.87		669	2.61	1752	1421	4400	4394	2800	2794
7	31000	600	.86	846	973	2.50	2420	1968	6000	6007	3900	3987
8	30900	603	.87	850	981	2.50	2450	2000	6200	6052	4100	4052
9	30900	603	.88		998	2.50	2460	1991	6200	6108		
10	300	2101			2101	2.45			10750	10412		
11	35000	498	.79	650	752	2.10	1975	1605	4950	4864	3350	3134
12	30	2130			2130	2.50			11500	11085		
13	31000	600	.81	797	924	2.32	2310	1885	5800	5641	3400	3351
14	31000	600	.81	789	924	2.32	2310	1885	5800	5641	3400	3351
15	720	2075			2075	2.45			11500	10797		
16	26000	752	.69	895	1033	2.10	2600	2095	6100	6152	4200	4082
17	1270	2032			2032	2.61			11900	11267		
18	33100	545	.78	710	814	2.39	2157	1740	5200	5300	3450	3570
19	32800	552	.82		863	2.42	2170	1740	5200	5320		
20	36800	457	.83		718	2.43	1875	1513	4750	4630		
21	37000	452	.80	599	690	2.41	1790	1446	4500	4400	3000	2810
22	31000	600	.79	790	906	2.30	2295	1861	5650	5600	3600	3610
23	30900	603	.82		942	2.30	2360	1920	5950	5780		
24	31000	600	.80	793	915	2.29	2320	1887	5750	5660	3600	3620
25	1270	2041			2041	2.60			12000	11247		
26	29000	658	.68		896	2.16	2300	1867	5500	5480		
27	28900	661	.75		959	2.26	2390	1931	5950	5750		
28	28900	661	.78		987	2.30	2460	1992	5850	5930		
29	29000	658	.81		1012	2.32	2500	2020	6200	6100		
30	29100	655	.82	879	1018	2.32	2490	2008	6250	6100	3800	3960
31	33000	547	.80		834	2.30	2160	1750	5300	5280		
32	32900	550	.81		847	2.30	2180	1763	5500	5360		
33	32900	550	.79		830	2.28	2155	1759	5400	5270		
34	1270					2.60			11750	11110		
35	1280					2.60			11450	10830		
36	1280					2.58			11450	10780		
37	1290					2.58			11700	11160		

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