SYNOPSIS OF PAPER TO BE PRESENTED AT THE GENERAL ELECTRIC GAS TURBINE CONFERENCE ON MAY 31, 1945

ALTITUDE WIND TUNNEL INVESTIGATIONS OF JET-PROPULSION ENGINES

By Abe Silverstein

SUMMARY

Investigations of the performance and operational charactersitics of several jet-propulsion engines have recently been conducted in the NACA Cleveland altitude wind tunnel and a few of the significant results are summarized in this report. The testing techniques and instrumentation methods are briefly reviewed.

Measured performance data on the General Electric I-40 engine are given for a wide range of altitudes and ram pressure ratios and the applicability of the methods used in reducing the data to standard sea-level conditions is discussed. The drags of windmilling engines are shown to be high and the necessity is stressed for closing the duct inlets of engines that are inoperative in flight.

The difficulties experienced in starting and accelerating jet-propulsion engines at high altitudes are pointed out and the adjustable tail-pipe nozzle is shown to be a useful device for improving the operational characteristics of the engines. The effect of altitude in decreasing the range of stable operating speeds of jet-propulsion engines is shown and the factors

contributing to "combustion blowout" at low engine speeds are outlined.

INTRODUCTION

The advent of the jet-propulsion engine as a prime mover for aircraft has introduced broad new fields for research. A phase of this research is the determination of the effects of altitude and flight speed on the performance and operational characteristics of jet engines, and the efforts of the Cleveland altitude wind tunnel staff during the past year have been largely devoted to this work. The research program has included investigations of the General Electric I-16, I-40, and TG-180 engines and the Westinghouse 19B and 19XB engines.

The performance characteristics of these engines have been investigated whenever possible over a range of pressure altitudes from approximately sea level to 50,000 feet and at tunnel temperatures from 60° F to -50° F. Operational tests have also been conducted which usually include investigations of starting, acceleration, windmilling, and fuel-metering characteristics. At the higher altitudes the engines are tested at ram pressure ratios corresponding to flight speeds as high as 700 miles per hour.

For the tests, the engines are either mounted in aircraft installations, as was the case of the General Electric I-40 engine in the YP-80A airplane, or in specially constructed wing-nacelle installations. The engines are extensively instrumented in order that detailed information can be obtained on the over-all characteristics of the engines as well as of the separate components.

Significant test results have been abstracted to provide a basis for a preliminary presentation of the general effects observed in altitude tests of jet engines.

SYMBOLS

D_w	windmilling drag, lb
F_j	jet thrust, lb
F_j/δ	jet thrust corrected to NACA standard atmospheric conditions at sea level, lb
F_n	net thrust, lb
F_n/δ	net thrust corrected to NACA standard atmospheric conditions at sea level, lb
H_A/p_o	ram pressure ratio
H_H	tail-rake total pressure, lb/sq ft abs.
h	tunnel pressure altitude, ft
N	engine speed, rpm
$N/\sqrt{\theta}$	engine speed corrected to NACA standard atmospheric conditions at sea level, rpm
p_H	tail-rake static pressure, lb/sq ft abs.
T_H	tail-rake indicated temperature, ^{o}R
V	true airspeed, mph
W_a	air flow, lb/sec
$W_a\sqrt{\theta}/\delta$	air flow corrected to NACA standard atmospheric conditions at sea level, lb/sec
W_f	fuel flow, lb/sec

$W_f/\delta\sqrt{\theta}$ fuel flow corrected to NACA standard atmospheric conditions at sea level, lb/sec

$W_f/W_a\,\theta$ fuel-air ratio corrected to NACA standard atmospheric conditions at sea level

$W_f/F_j\sqrt{\theta}$ specific fuel consumption based on jet thrust corrected to NACA standard atmospheric conditions at sea level, lb/(hr)(lb jet thrust)

$W_f/F_n\sqrt{\theta}$ specific fuel consumption based on net thrust corrected to NACA standard atmospheric conditions at sea level, lb/(hr)(lb net thrust)

η_b combustion efficiency, percent

θ ratio of absolute total temperature at the compressor inlet to absolute static temperature of NACA standard atmosphere at sea level

δ ratio of absolute total pressure at the compressor inlet to absolute static pressure of NACA standard atmosphere at sea level

WIND-TUNNEL INSTALLATION AND INSTRUMENTATION

The Cleveland altitude wind tunnel is a single-circuit return passage tunnel with a closed test section 20 feet in diameter. Engines are mounted in the tunnel on wings extending across the tunnel which are attached at their tips to the main balance trunnions. A six-component parallelogram balance equipped with a tape recorder measures the forces on the model, which may be rotated in pitch about the trunnion axes by a motor-driven screw mechanism. An installation of the YP-80A airplane in the tunnel is shown in figure 1.

Altitude conditions are simulated by reducing the tunnel pressure by means of exhausters and by reducing the tunnel temperature by means of refrigerating coils located in the tunnel return passage. The pressure in the tunnel can be reduced to $1\frac{1}{2}$ inches of Mercury absolute and the temperature can be reduced to approximately -50° F. The design airspeed in the tunnel at an altitude of 30,000 feet is approximately 500 miles per hour with the tunnel empty. Large models such as have been tested in the tunnel reduce the speed to a value considerably lower than the design speed. For tests of jet-propulsion engines at high values of ram pressure ratio, a pipe providing dry refrigerated air at slightly less than sea-level pressure is connected directly to the inlet of the engine. The tunnel pressure is then reduced so that a pressure differential between the engine inlet and discharge of more than two can be obtained.

The engines are extensively instrumented, as illustrated in figure 2. Measurements have been taken at 11 stations through the air and gas passages of the I-40 engine corresponding to 245 individual measurements of pressure and temperature. Typical rakes used for measuring the total and static pressures in the air passages of the engine are shown in figure 3. An inconel rake has been developed for measuring the total and static pressures and temperatures at the tail-pipe nozzle. (See fig. 4.) Typical distributions of pressures and temperatures measured by this rake at the tail-pipe nozzle are shown in figure 5. Calibrations have indicated that the thrusts calculated from the readings obtained on the rake are within 3 percent of those obtained by scale measurements.

Temperatures are recorded by means of Brown self-balancing potentiometers and pressures are recorded by photographing banks of liquid-filled manometers. Fuel flows are measured by means of a rotameter.

RESULTS AND DISCUSSION

The detailed results of the investigations on jet engines have thus far been presented as Preliminary Data reports to the AAF Air Technical Service Command and the Bureau of Aeronautics. Approximately fifty of these reports have been submitted to the services and a summary of these data necessarily must omit many interesting and significant facts. The performance results given for the General Electric I-40 and TG-180 engines are representative in general of the results obtained on other engines; however, the operational characteristics of the different engines differ widely.

Performance

Reduction to sea-level conditions.- One of the most important phases of the research has been the determination of the thrust of jet engines at high altitudes and the evaluation of a method by which these thrusts can be predicted from sea-level measurements on the engine. An analysis of static thrust data obtained on the General Electric I-40 engine at altitudes up to 40,000 feet has shown that if the measured speed of the engine is corrected to sea-level conditions by dividing by the square root of θ, and if the measured static thrust at altitude is similarly corrected by dividing by δ, the results for all altitudes can be corrected to a single curve. (See fig. 6.) These results indicate that this conventional method of data reduction is well founded and that it is possible to predict the altitude thrust of an engine without ram at altitude with considerable accuracy.

The fuel flows measured in the static tests of the I-40 engine at different altitudes were corrected to sea-level conditions by dividing the fuel flow by the non-dimensional parameter $\delta\sqrt{\theta}$ (fig. 7). (See reference 1.) The fuel flows did not correct to a single curve except at engine speeds near the design speed. At the lower engine speeds, the fuel flows are higher at high altitudes than at sea level as a result of the lower combustion efficiencies at altitude. An accurate parameter for reducing fuel flows measured at altitude to sea level conditions should include a term to account for the variation of combustion efficiency with altitude. The specific fuel consumption values (fig. 8) show the same discrepancies when corrected to sea-level conditions as were noted for the fuel flows.

<u>Effect of ram.</u>- The effect of ram on the jet thrust of the General Electric I-40 engine is shown in figure 9. The corrected value of jet thrust F_j/δ increases with increasing ram and at rated engine speed with a ram ratio of 1.8, corresponding to a flight speed of about 700 miles per hour at

30,000 feet altitude, the corrected jet thrust is 55 percent higher than the static value. In correcting the values of thrust obtained with ram to sea-level conditions, the value of δ in the parameter F_j/δ is the ratio of the absolute total pressure at the engine inlet, as measured under ram conditions, to the absolute static pressure of the NACA standard atmosphere without ram at sea level.

The corrected values of fuel consumption and specific fuel consumption at different engine speeds and ram pressure ratios are shown in figures 10 and 11. At the lower engine speeds the effect of ram is to reduce the fuel flow to the engine; however, at the design speed the corrected fuel flows with and without ram are approximately the same. The corrected specific fuel consumption obtained from dividing the corrected fuel consumption by the corrected thrust is lower at all speeds under ram conditions. The reduced specific fuel consumption results from recovery of energy by the engine from the pressure of the rammed induction air.

Net thrust.- The net thrust of a jet engine is determined by subtracting the momentum MV_0 of the mass flow of gases passing through the engine from the measured jet thrust. Values of the corrected net thrust of the General Electric I-40 engine for a range of ram pressure ratios from the static condition to a ram ratio of 1.8 are shown in figure 12. The data shown in figure 12 were obtained in tests at 30,000 feet altitude. The effect of ram is to reduce the net thrust of the engine so that at design speed and at a ram pressure ratio of 1.8 the net thrust is approximately three-fourths of the jet thrust.

Corrected specific fuel consumptions based on the net thrust of the engine are shown in figure 13. The net specific fuel consumption increases with ram as a result of the reduction in net thrust with ram. The results shown in figure 13 should not be interpreted as indicating that the over-all efficiency of the jet cycle is reduced at high flight speeds since the thrust horsepower delivered is a product of the net thrust and the flight speed. Values of specific fuel consumption based on thrust horsepower are shown in figure 14 for the General Electric I-40 engine at design speed. The specific fuel consumption reduces with increasing speed to a value of about 0.8 pounds of fuel per net thrust horsepower at a flight speed of 700 miles per hour.

<u>Windmilling</u>.- The designers of jet-propelled airplanes are interested in determining the drag of a jet engine which is inoperative but windmilling. This information is necessary to determine whether closures will have to be provided at the duct inlets to the engine to reduce the windmilling drag. Extensive tests of the General Electric I-40 and TG-180 engines have been made with the engines windmilling and it has been found that the engine windmilling speeds are essentially independent of

the altitude and vary almost linearly with the true airspeed. (See fig. 15.) The windmilling speeds of the TG-180 engine, which is equipped with an axial-flow compressor, are higher than those of the I-40 engine, which is equipped with a centrifugal compressor.

The values of the windmilling drag divided by the rated thrust for the TG-180 and I-40 engines are shown in figure 16. The drag of the I-40 engine is somewhat higher than that of the TG-180 engine. At a flight speed of 600 miles per hour, the windmilling drag of these engines is greater than the rated jet thrust. The high drags measured for all flight conditions indicates that it is imperative that the duct inlets of airplanes equipped with jet engines should be sealed when the engine is inoperative in flight.

The air flow through a windmilling engine is considerably higher than it is for an operating engine. (See fig. 17.) The reduced air flow during the operating condition results from the momentum pressure drop in the combustion chamber due to the addition of heat. The origin of the high windmilling drags of the jet engines is shown in surveys of the total and static pressures through the engine while in the windmilling condition. (See figs. 18 and 19.)

Operational Characteristics

Acceleration.- One of the most serious operational faults found in the investigation of jet engines at altitude conditions was slow acceleration, particularly at low engine speeds. The time required to accelerate the engine rapidly increased with increase in altitude, as shown in figure 20. This increase in acceleration time results from the decreased angular momentum imparted to the turbine by the low-density gases at high altitudes. The mass to be accelerated remains constant with change in altitude, whereas the force available for accelerating the compressor and turbine decreases. A reasonable agreement exists between theoretical studies of this effect and experimentally determined accelerations, as shown in figure 20.

The most promising method for rapidly changing the thrust of a jet engine appears to be an adjustable tail nozzle, by means of which the thrust can be varied greatly without changing engine speed. The theoretical variation of thrust, which may be obtained by varying the tail-pipe nozzle area at a fixed engine speed, is shown in figure 21; it will be noted that thrust can be decreased by approximately one-half by doubling the nozzle outlet area. For tactical use in military operations, the tail pipe can be designed to be opened in cruising flight and snapped shut just prior to beginning an attack.

An experimental model of this type of adjustable tail pipe was tested and the results obtained, as shown in figure 21, are in close agreement with the values predicted by theory. The outlet area of the experimental nozzle was changed by opening and closing hinged doors forming the sides of a square jet nozzle. When the doors were closed quickly by valving compressed air into actuating cylinders, the thrust of the unit increased almost instantly to a higher value, and the speed of the engine when in the governing range remained essentially the same.

The use of an adjustable tail nozzle for jet engines is clearly indicated, not only for purposes of acceleration but also to reduce the thrust in landing and to provide a means for rapidly increasing the thrust in the event of a pilot error in landing. By reducing the jet nozzle size in the take-off condition, higher take-off thrusts can be obtained with higher turbine-inlet temperatures during the take-off run.

Starting and minimum speed operation.- One of the major operational problems of jet engines is the altitude limitation on starting in flight. Increasing the altitude or increasing the flight speed reduces the probability that starting can be accomplished. The General Electric TG-180 has the most favorable starting characteristics of the engines tested thus far and results obtained on the limiting altitudes and flight speeds at which starting can be accomplished are shown in figure 22. Starts were made on the TG-180 engine at 40,000 feet altitude, however, not above a ram ratio corresponding to a flight speed of 300 miles per hour. The high altitude starts on the TG-180, however, required careful nursing of the throttle to avoid burner blowout.

Igniting the cold, low-density fuel-air mixture in the in the combustion chamber is the first problem in altitude starting. When the flight speed is high so that the engine is windmilling at a high speed, conditions in the combustion chamber are aggravated because the air flow through the combustion zone is higher than the air flow that occurs during the operating condition. (See fig. 17.) The spray formation in the combustion chamber is distorted and the fuel-air ratio in the primary burning zone is decreased.

Major improvements in the ignition of the TG-180 engine were effected, however, by minor changes to the spark plugs and combustion chambers. The solution of the ignition problem in windmilling starts at altitude will probably be reached as a result of extensive development now in progress on spray nozzles, combustion chambers, and ignition systems.

A far more serious and fundamental problem is the acceleration of the engines during the start from the speed of the starting motor or windmilling speed to the speed at which the engine will operate in a stable manner. This stable operating speed can not be too accurately defined since it depends on the operator's skill with the throttle and judgment. For the purpose of discussion, it can be defined as the lowest speed from which the engine can be accelerated normally without excessive juggling of the throttle to avoid high tail-pipe temperatures and combustion blowout. Minimum stable operating speeds at different altitudes for the General Electric I-40 engine based on this definition are shown in figure 23.

The acceleration from the starting motor or windmilling speed to the stable operating speed is difficult because the engine is operating in this speed range at its most inefficient condition and far from the design point of all the engine components. The combustion efficiency in this range of speeds is extremely low at high altitudes. (See fig. 24.)

The low combustion efficiency in itself would not be too serious if it did not require that large amounts of fuel be provided to the engines through the burner nozzles into the primary burning zone. The fuel-air ratios measured for the General Electric I-40 engine at different altitudes and engine speeds are shown in figure 25. The results of figure 25 must be extrapolated to lower engine speeds to provide an accurate picture of the high fuel-air ratios occuring at starting speeds.

As a result of overrich mixtures in the primary burning zone of the combustion chamber during the starting cycle at altitude, the addition of the fuel required for acceleration normally results in burner blowout. Practical starts on the General Electric I-40 engine have not been possible above an altitude of 20,000 feet.

Starting at altitude is improved with ram, provided ignition is accomplished, as a result of the energy transfer from the rammed induction air to the compressor. The fuel-air ratios measured on the I-40 engine at different ram pressure ratios at 30,000 feet altitude are shown in figure 26.

The fuel-air ratios decrease with increasing ram ratio so that overloading of the primary burning zone is avoided.

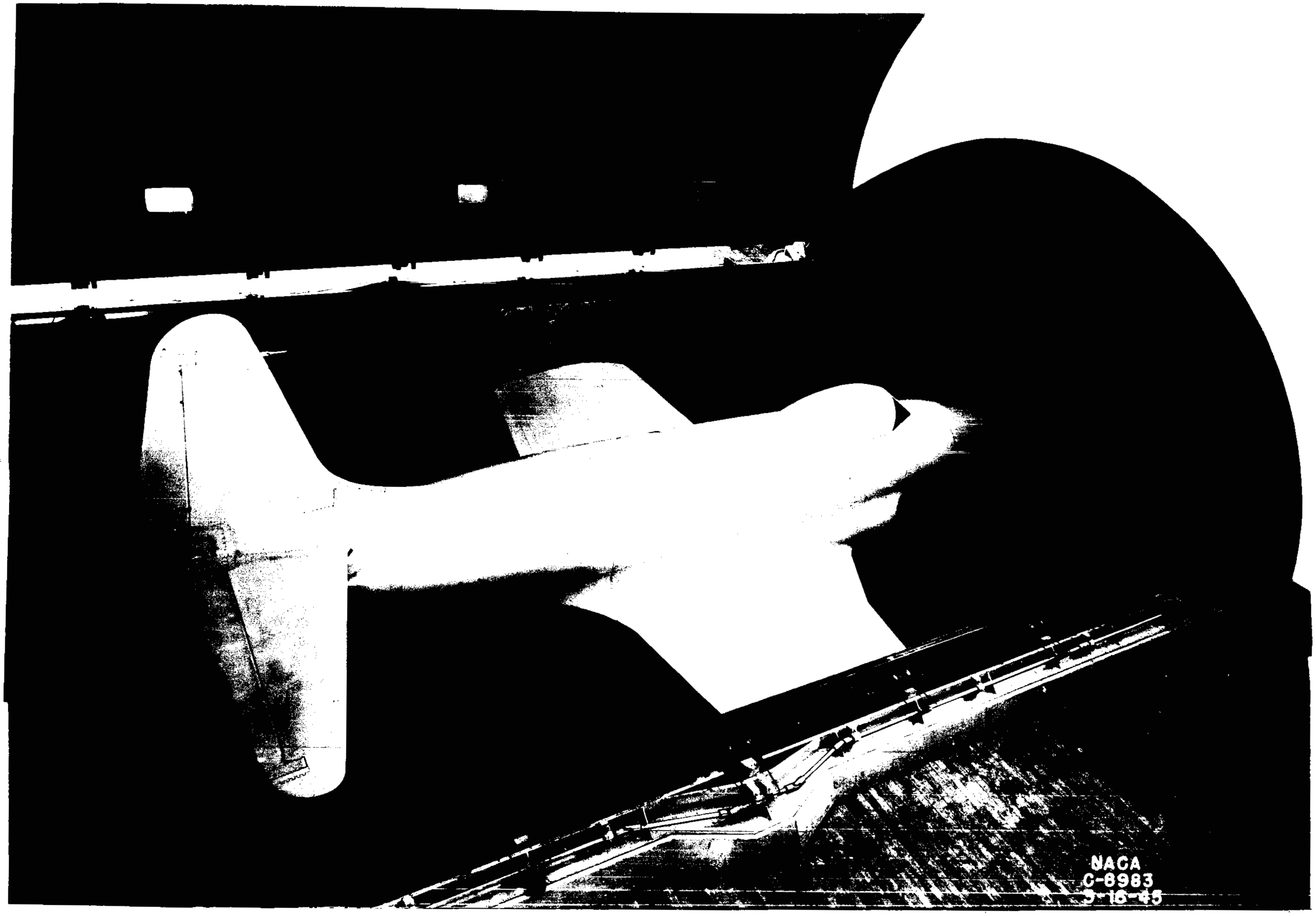

Figure 1. - Lockheed YP-80A airplane installed in the altitude wind tunnel.

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AIRCRAFT ENGINE RESEARCH LABORATORY
CLEVELAND, OHIO

INSTRUMENTATION OF I-40 ENGINE

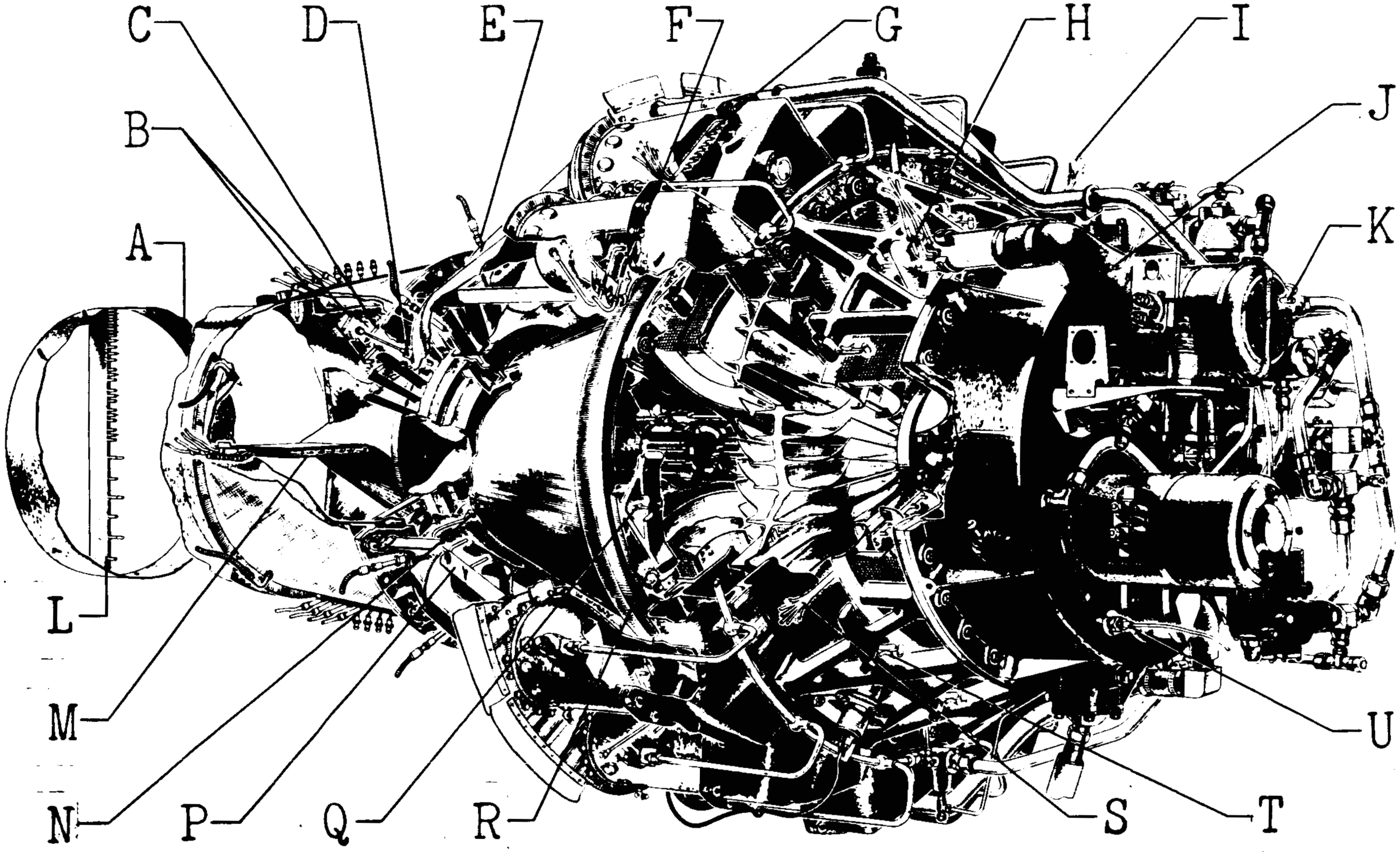


FIGURE 2

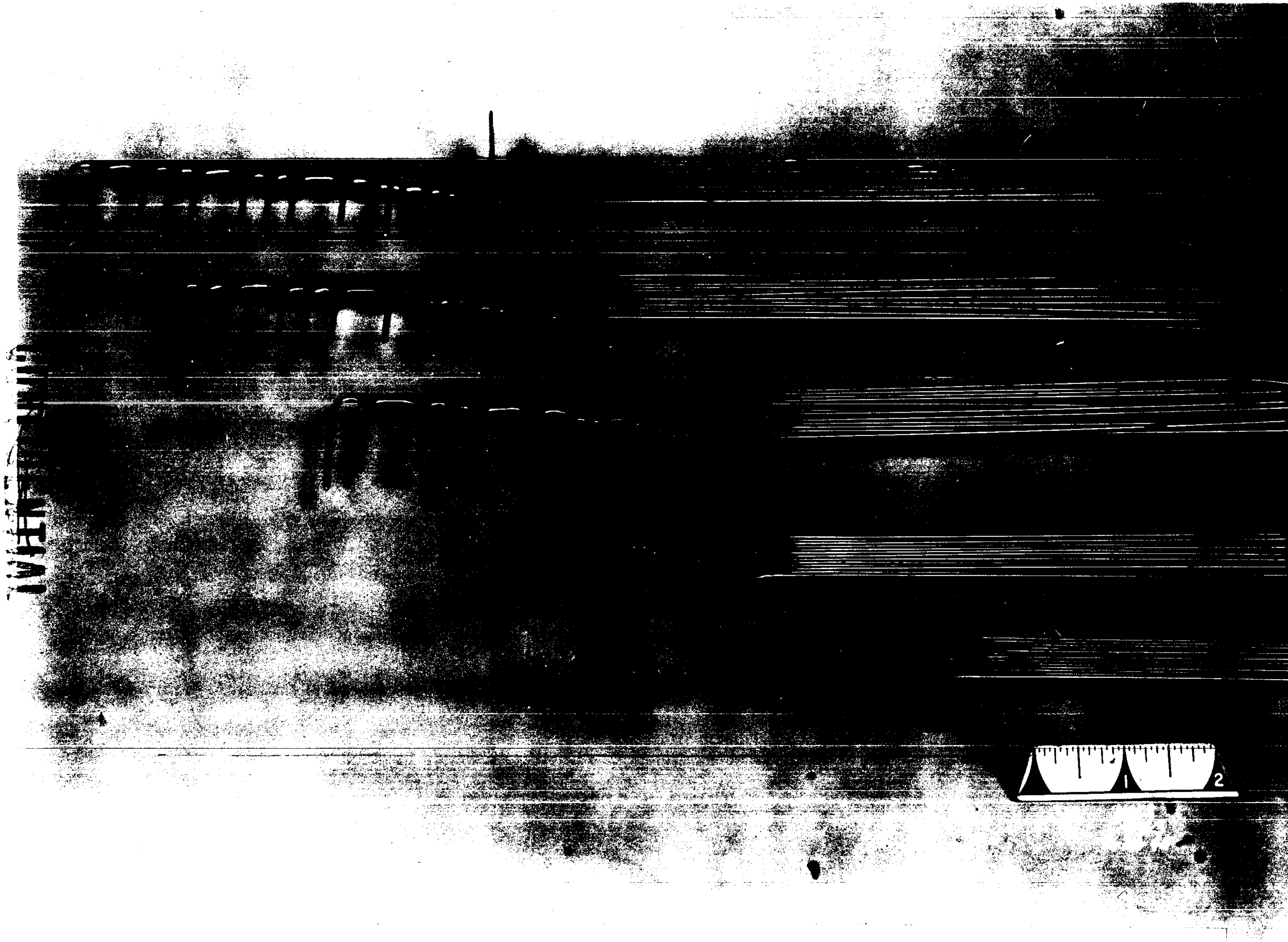
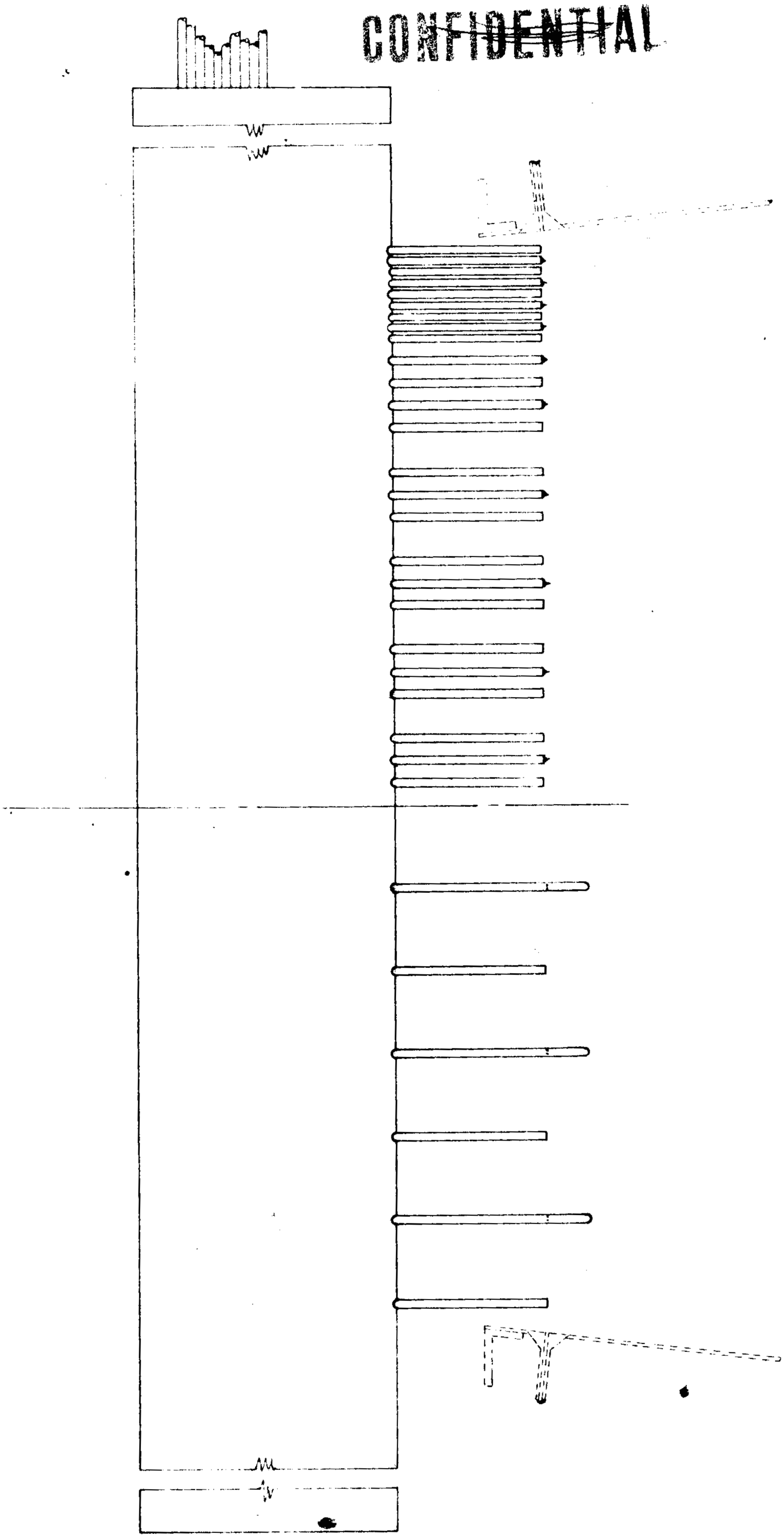
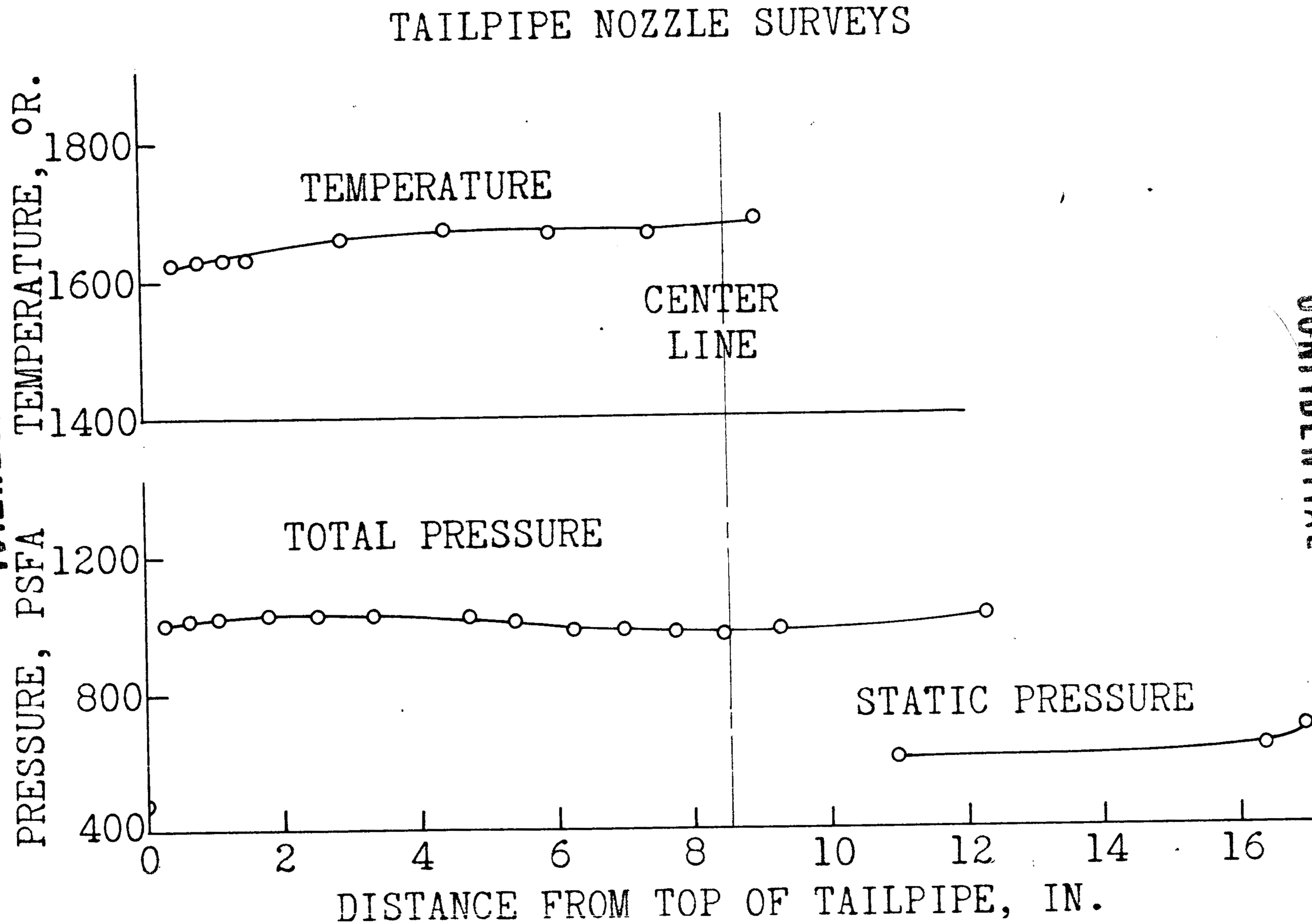


Figure 3.- Typical rakes for measurement of total and static pressures.



TAILPIPE NOZZLE RAKE

FIGURE 4



TAILPIPE NOZZLE SURVEYS
TEMPERATURE, °R.
1800
1600
1400
TEMPERATURE
CENTER LINE
PRESSURE, PSFA
1200
800
400
TOTAL PRESSURE
STATIC PRESSURE
0
2
4
6
8
10
12
14
16
DISTANCE FROM TOP OF TAILPIPE, IN.

FIGURE 5

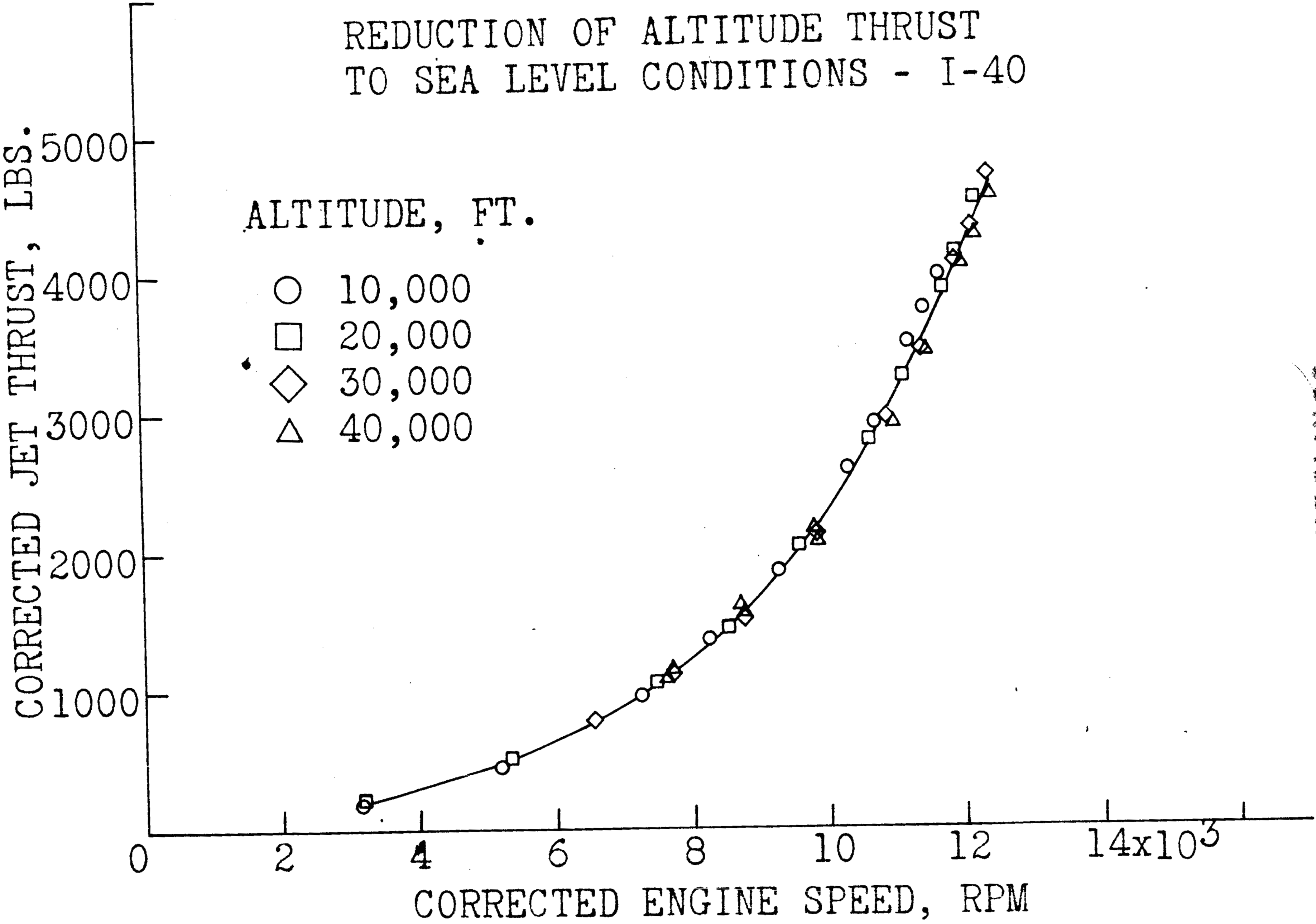

REDUCTION OF ALTITUDE THRUST
TO SEA LEVEL CONDITIONS - I-40
ALTITUDE, FT.
10,000
20,000
30,000
40,000
CORRECTED JET THRUST, LBS.
5000
4000
3000
2000
1000
0
2
4
6
8
10
12
14x10³
CORRECTED ENGINE SPEED, RPM

FIGURE 6

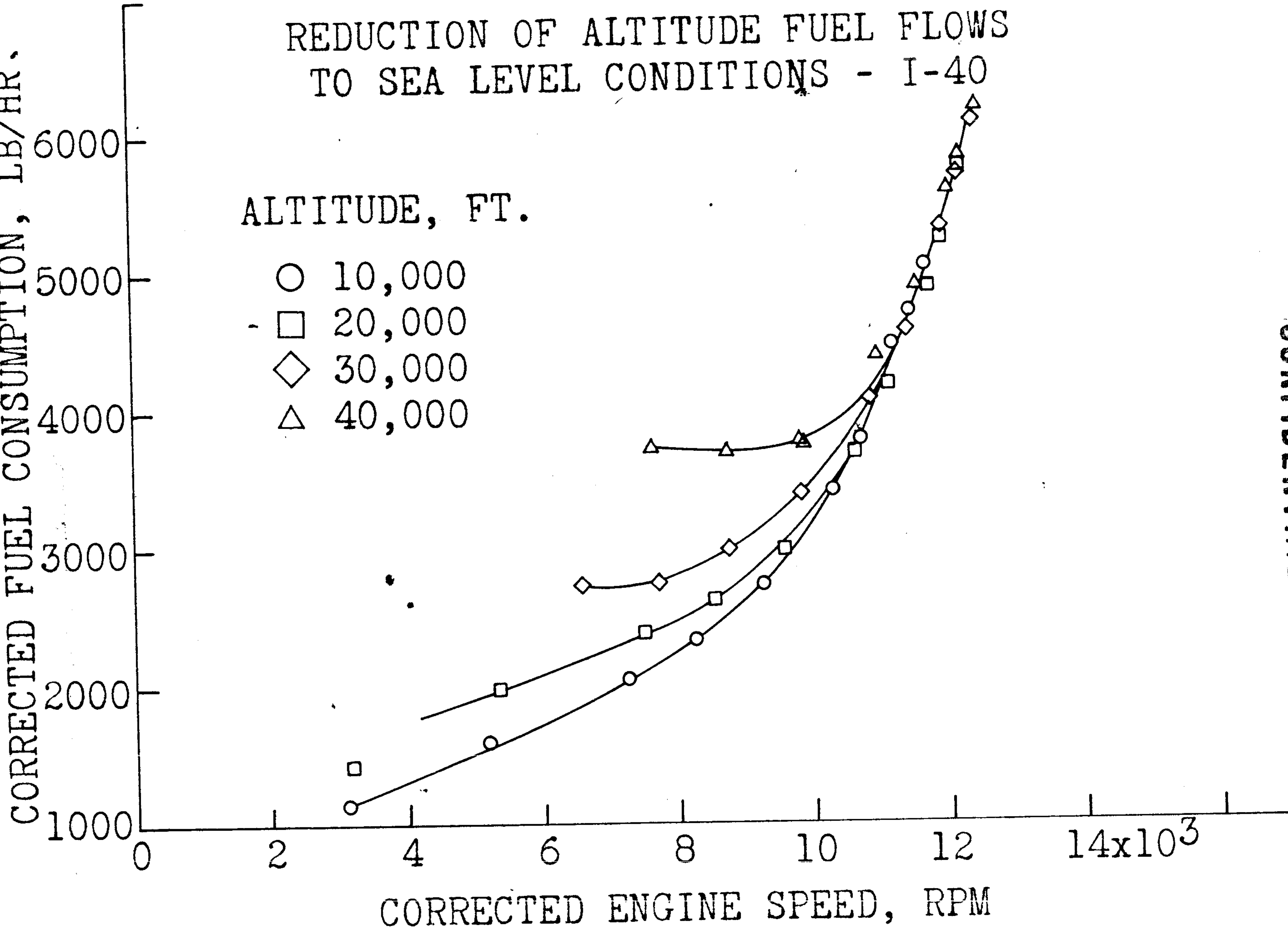

REDUCTION OF ALTITUDE FUEL FLOWS
TO SEA LEVEL CONDITIONS - I-40
ALTITUDE, FT.
10,000
20,000
30,000
40,000
CORRECTED FUEL CONSUMPTION, LB/HR.
1000
2000
3000
4000
5000
6000
0
2
4
6
8
10
12
14x10^3
CORRECTED ENGINE SPEED, RPM

FIGURE 7

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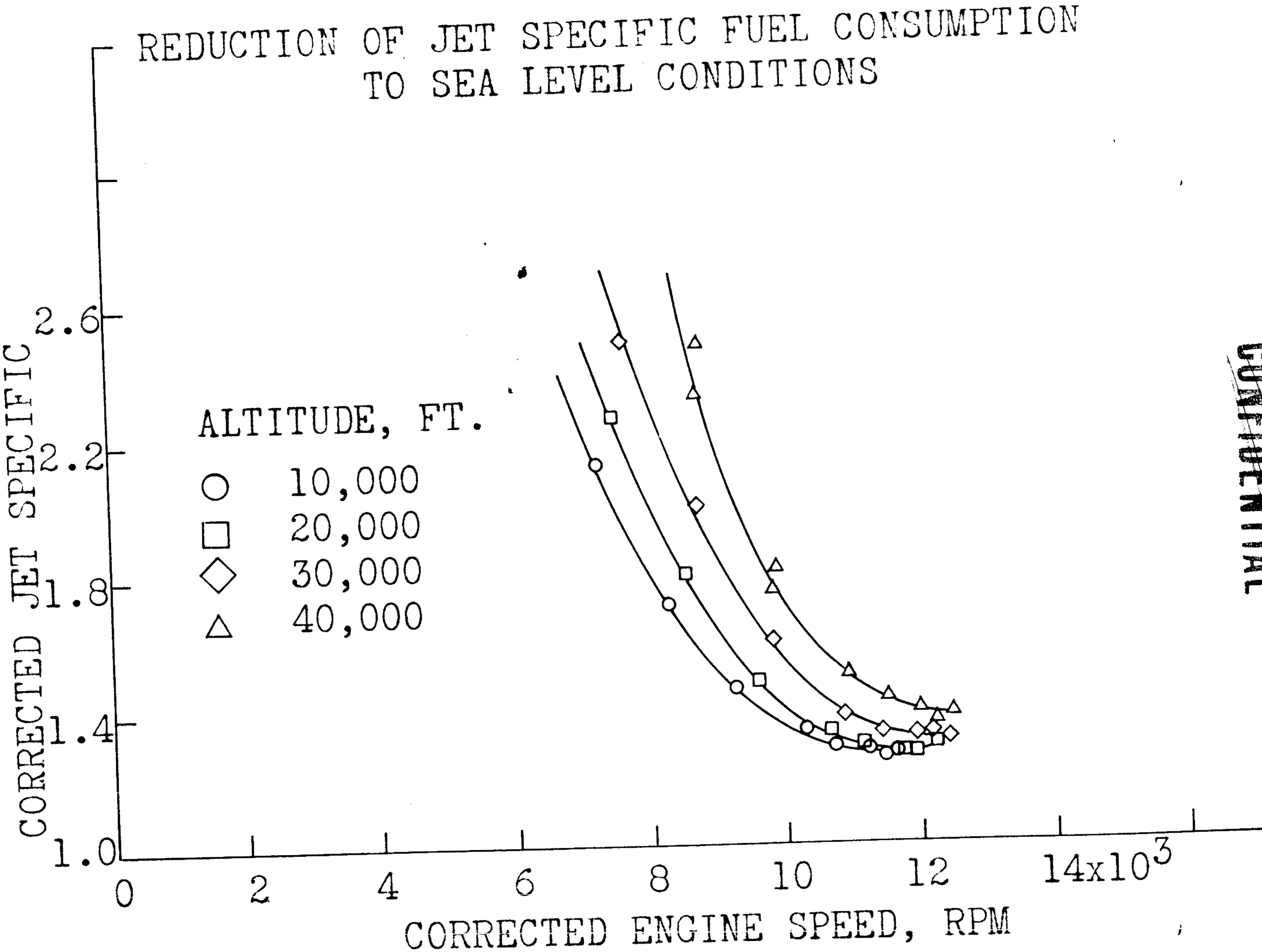

FIGURE 8

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EFFECT OF RAM ON JET THRUST
I-40 AT 30,000 FT. ALTITUDE

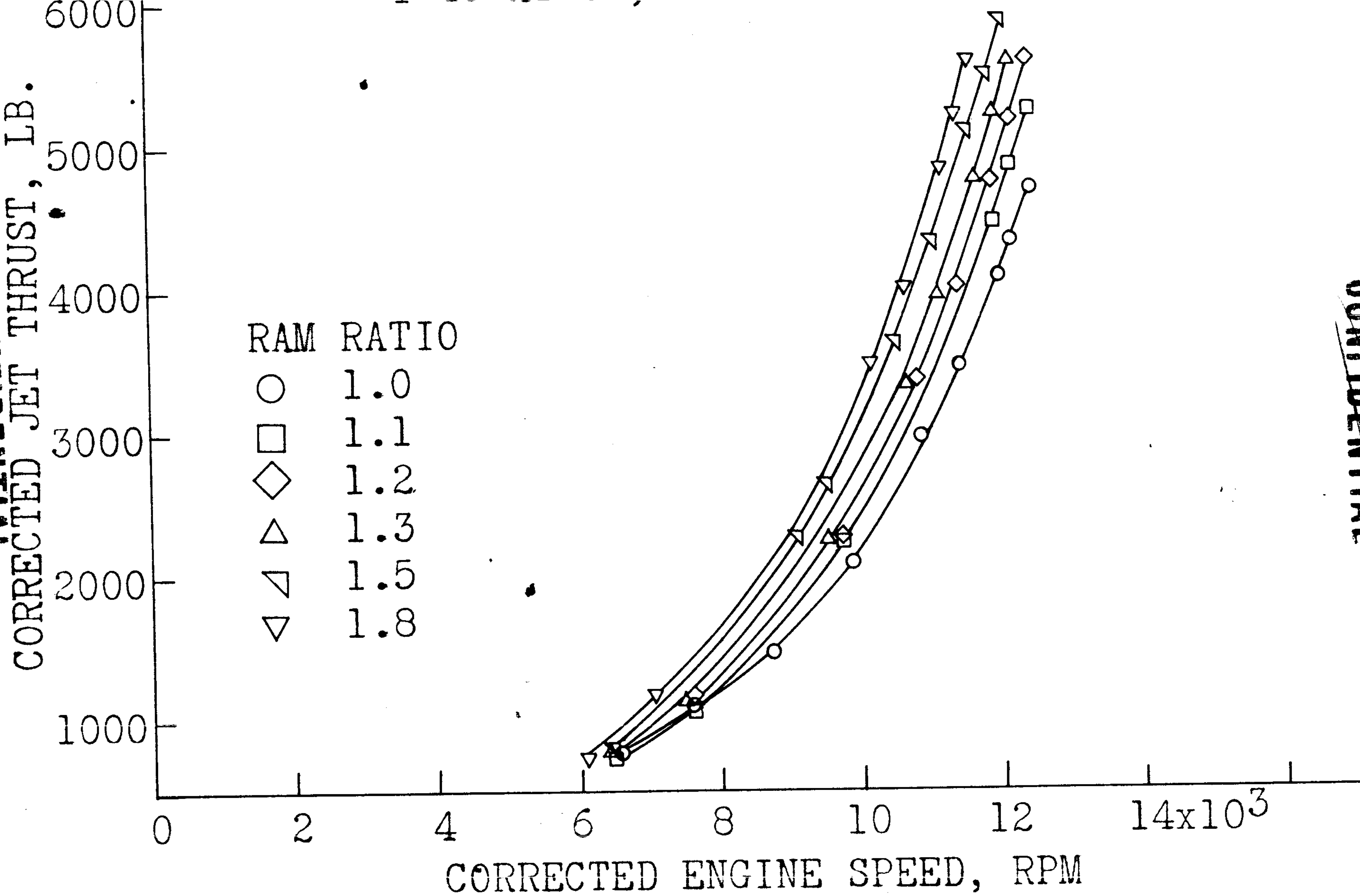

FIGURE 9

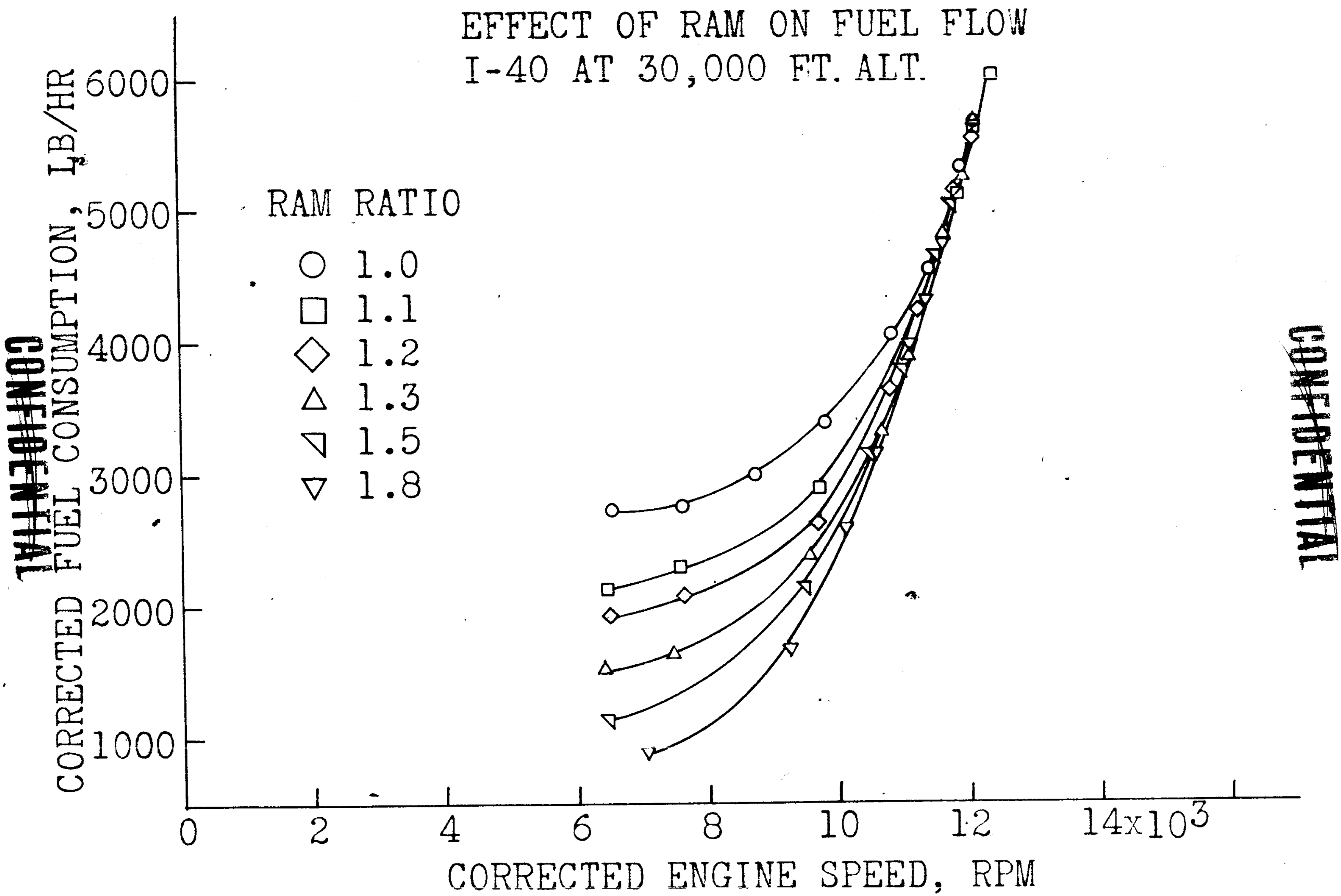
EFFECT OF RAM ON FUEL FLOW
I-40 AT 30,000 FT. ALT.
CORRECTED FUEL CONSUMPTION, LB/HR
6000
5000
4000
3000
2000
1000
RAM RATIO
1.0
1.1
1.2
1.3
1.5
1.8
0
2
4
6
8
10
12
14x10^3
CORRECTED ENGINE SPEED, RPM
CONFIDENTIAL
CONFIDENTIAL

FIGURE 10

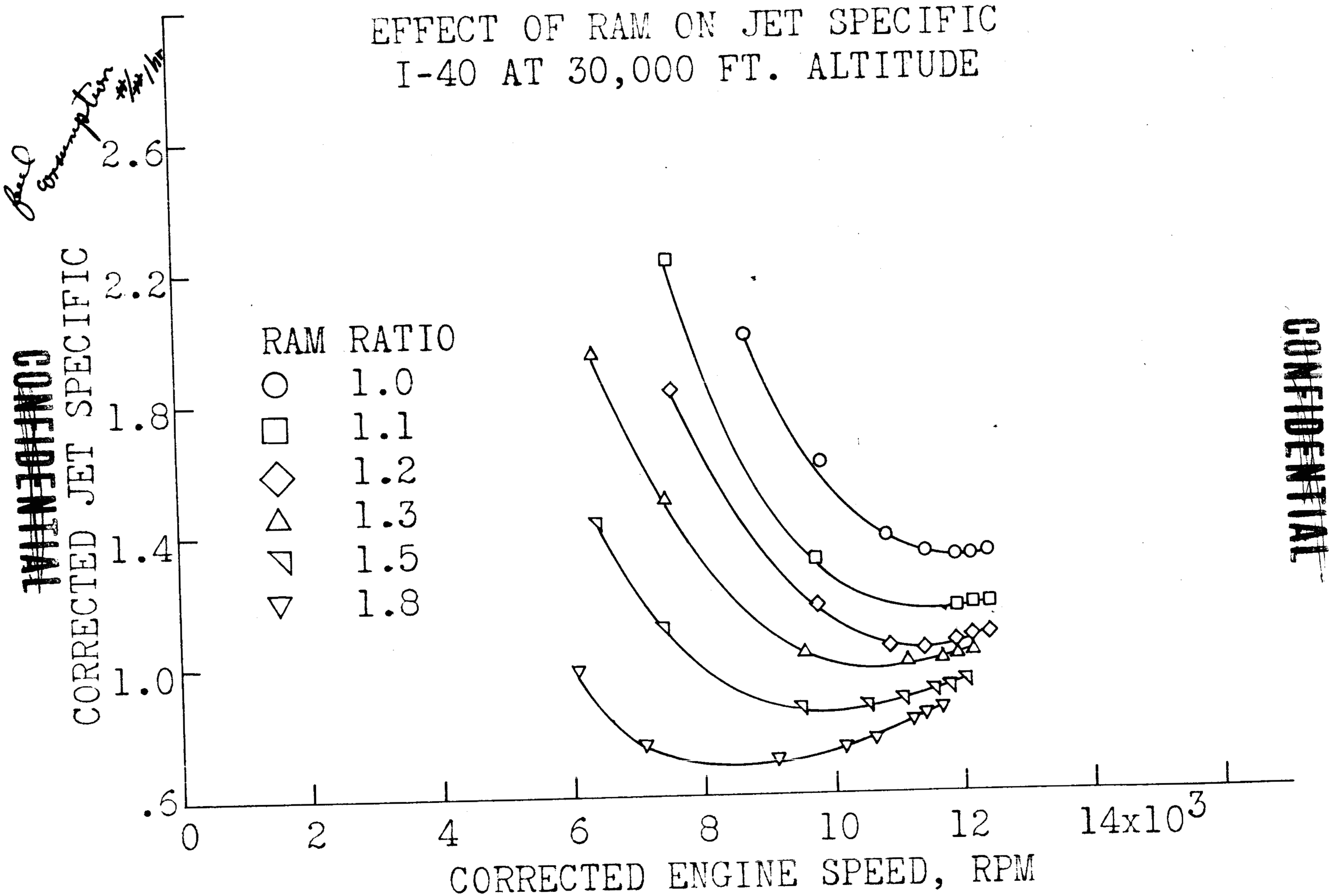
EFFECT OF RAM ON JET SPECIFIC
I-40 AT 30,000 FT. ALTITUDE
fuel consumption #/#/hr
CORRECTED JET SPECIFIC
CORRECTED ENGINE SPEED, RPM
RAM RATIO
1.0
1.1
1.2
1.3
1.5
1.8
.6
1.0
1.4
1.8
2.2
2.6
0
2
4
6
8
10
12
14x10^3
CONFIDENTIAL
CONFIDENTIAL

FIGURE 11

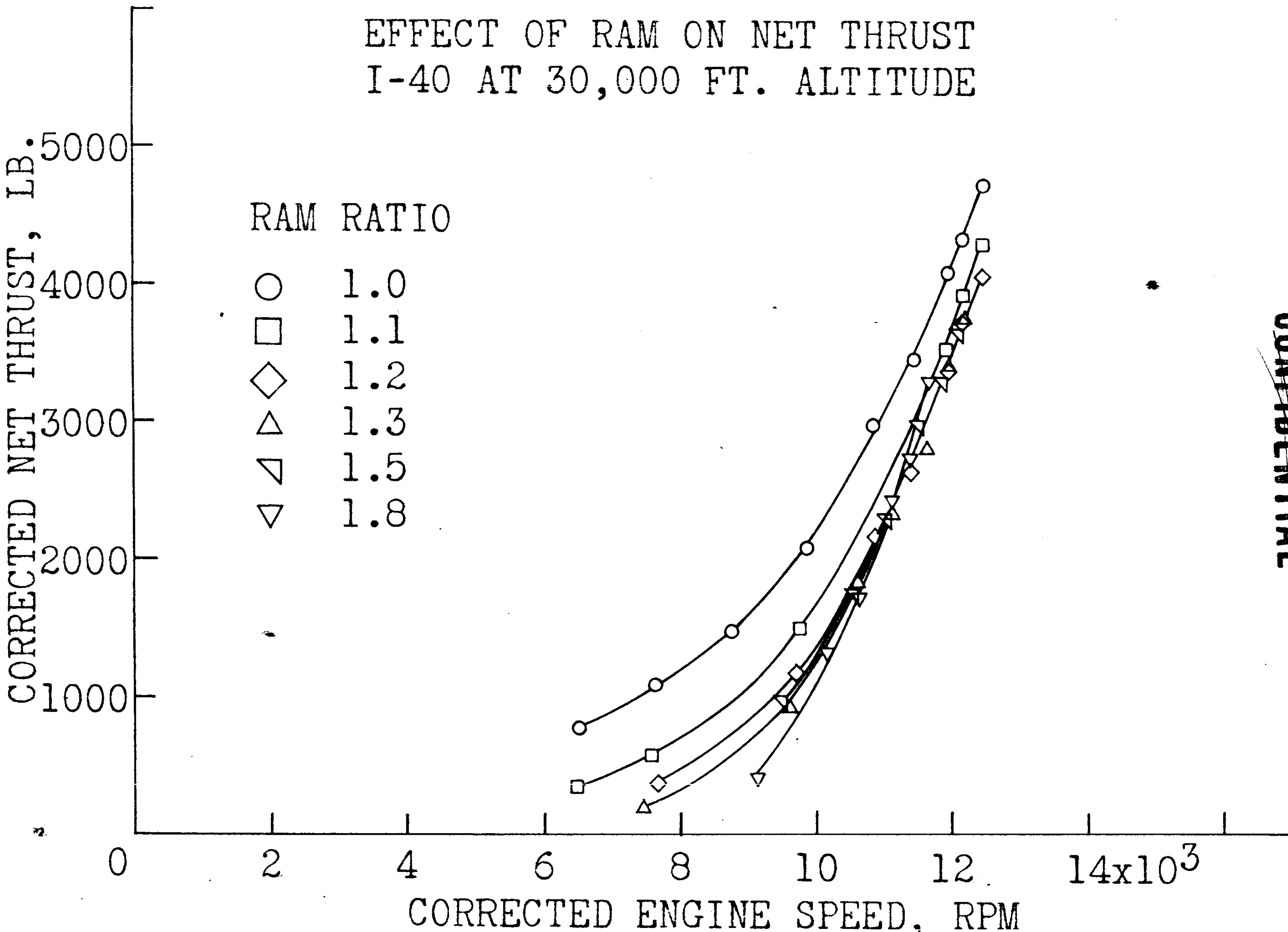
EFFECT OF RAM ON NET THRUST
I-40 AT 30,000 FT. ALTITUDE
RAM RATIO
1.0
1.1
1.2
1.3
1.5
1.8
CORRECTED NET THRUST, LB.
1000
2000
3000
4000
5000
0
2
4
6
8
10
12
14x10³
CORRECTED ENGINE SPEED, RPM

FIGURE 12

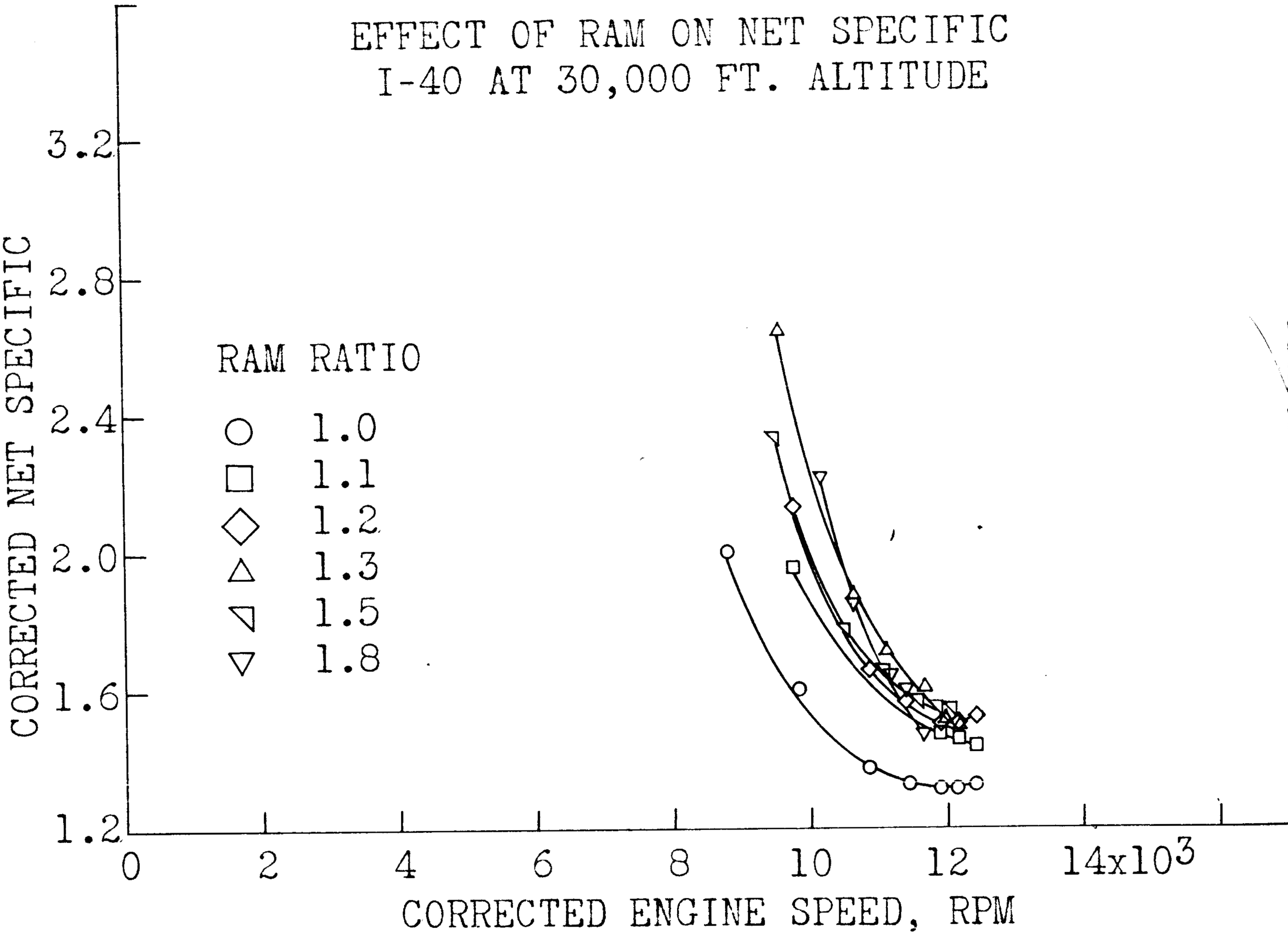
EFFECT OF RAM ON NET SPECIFIC
I-40 AT 30,000 FT. ALTITUDE
CORRECTED NET SPECIFIC
3.2
2.8
2.4
2.0
1.6
1.2
RAM RATIO
1.0
1.1
1.2
1.3
1.5
1.8
0
2
4
6
8
10
12
14x10³
CORRECTED ENGINE SPEED, RPM

FIGURE 13

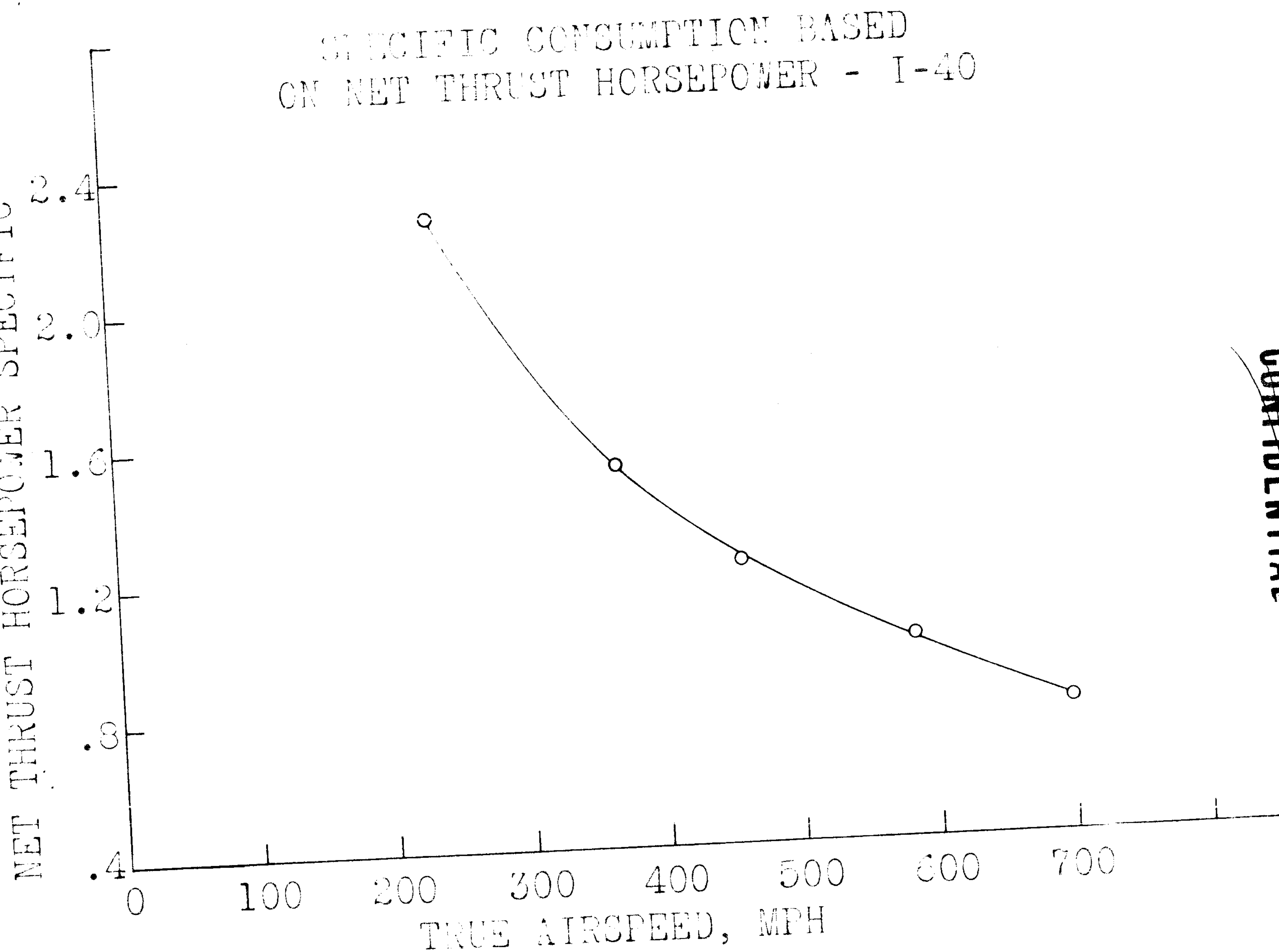

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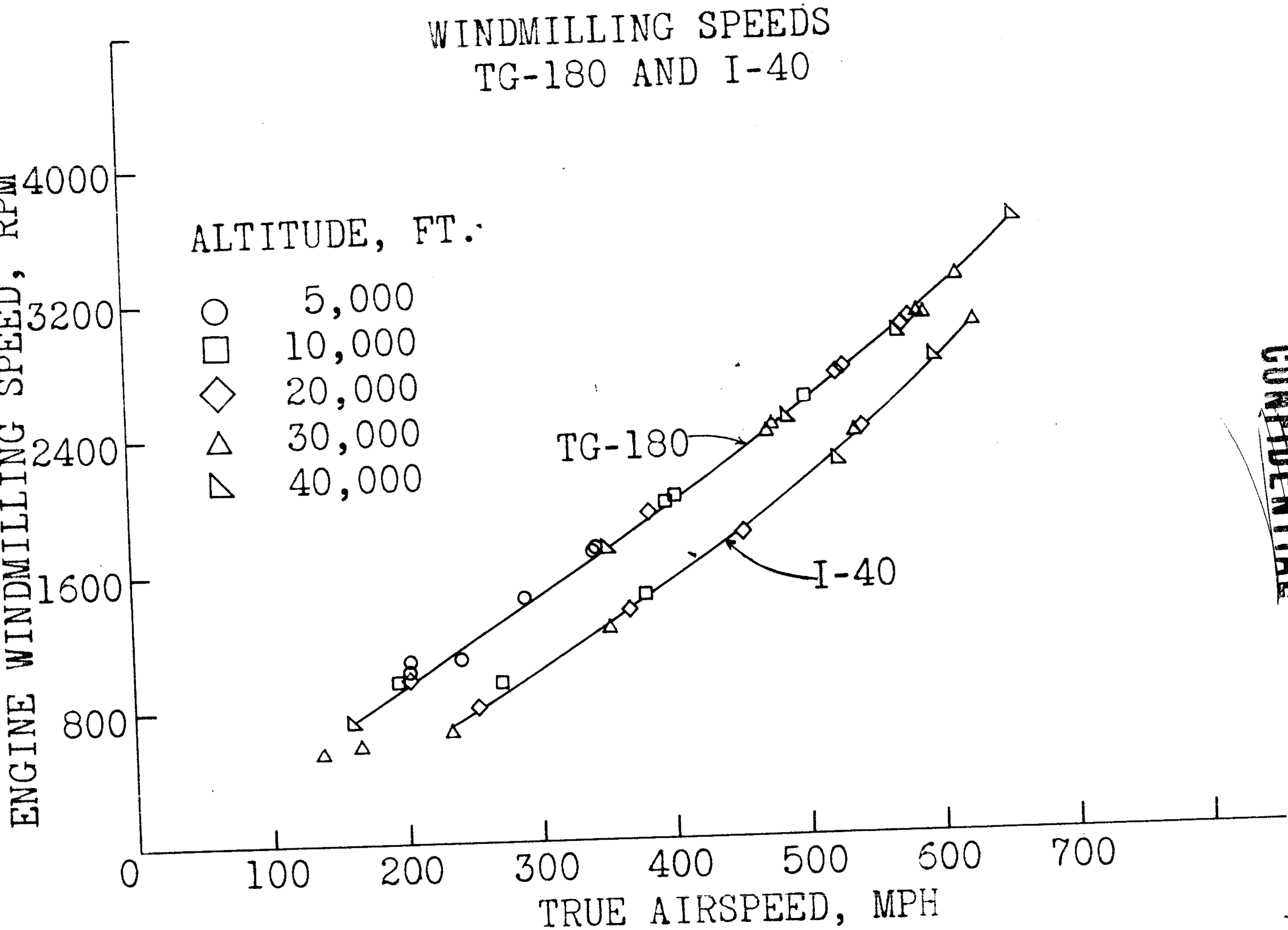
FIGURE 14



WINDMILLING SPEEDS
TG-180 AND I-40
ALTITUDE, FT.:
5,000
10,000
20,000
30,000
40,000
TG-180
I-40
ENGINE WINDMILLING SPEED, RPM
4000
3200
2400
1600
800
0
100
200
300
400
500
600
700
TRUE AIRSPEED, MPH

FIGURE 15

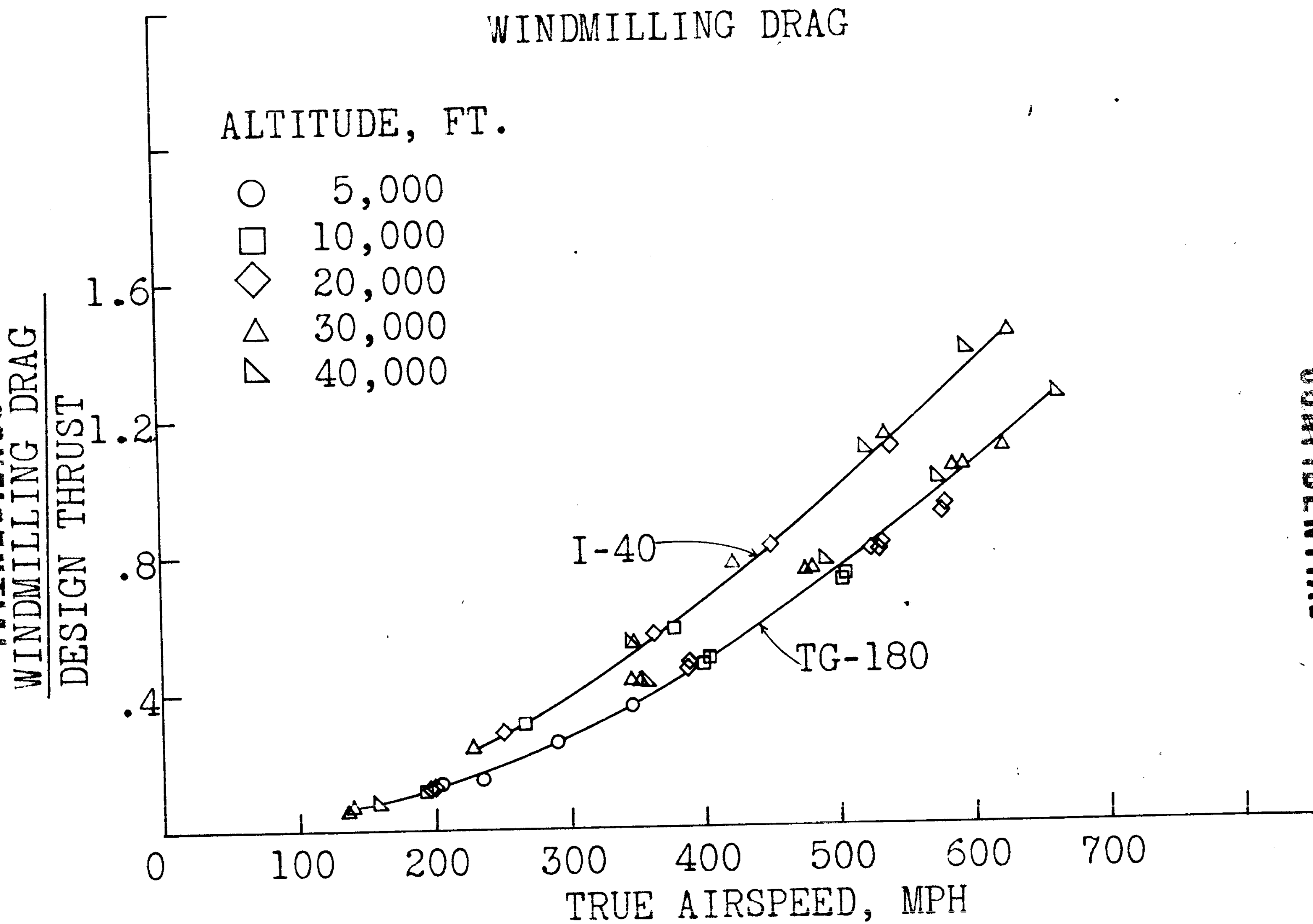


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FIGURE 16

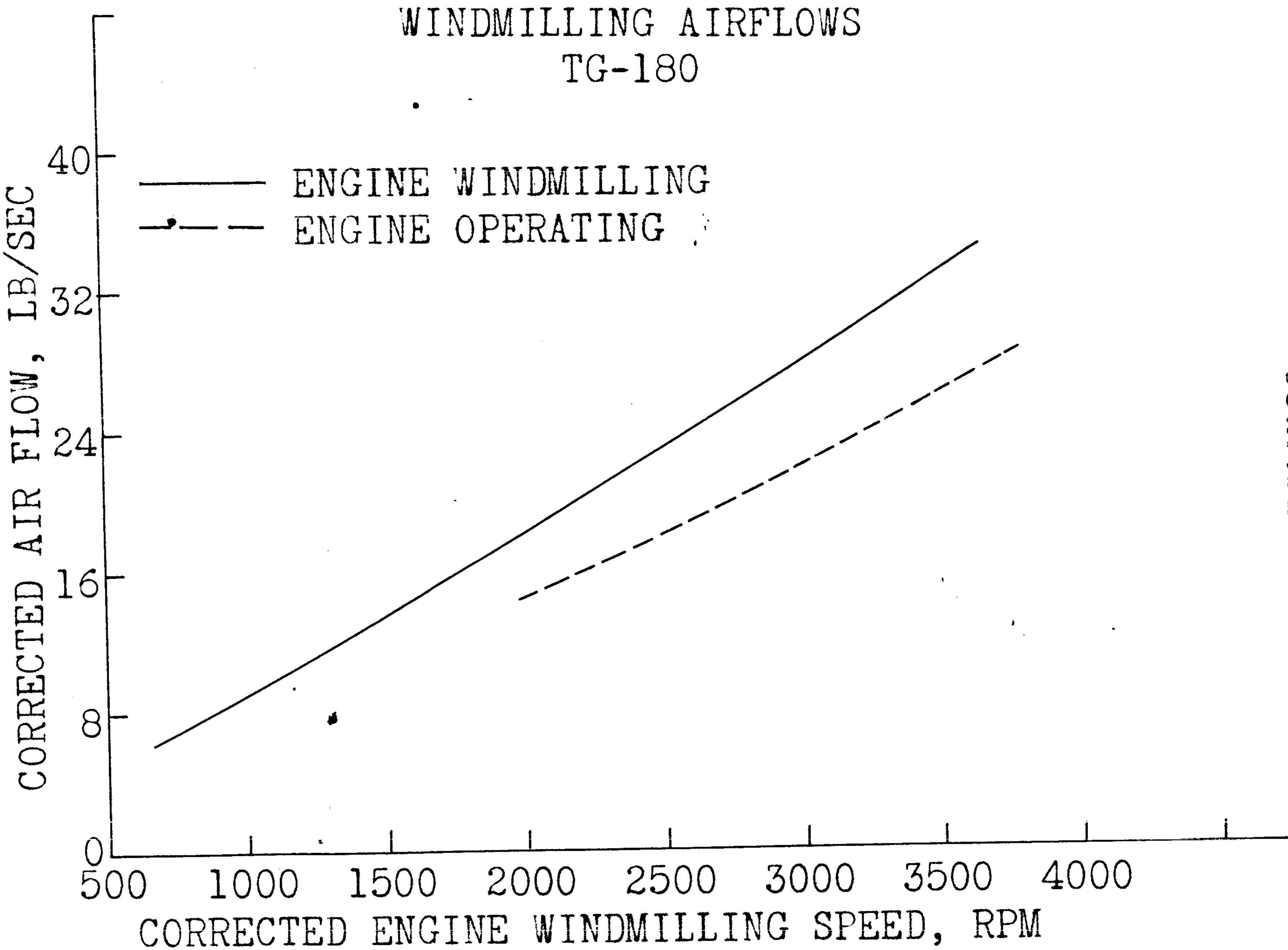

FIGURE 17

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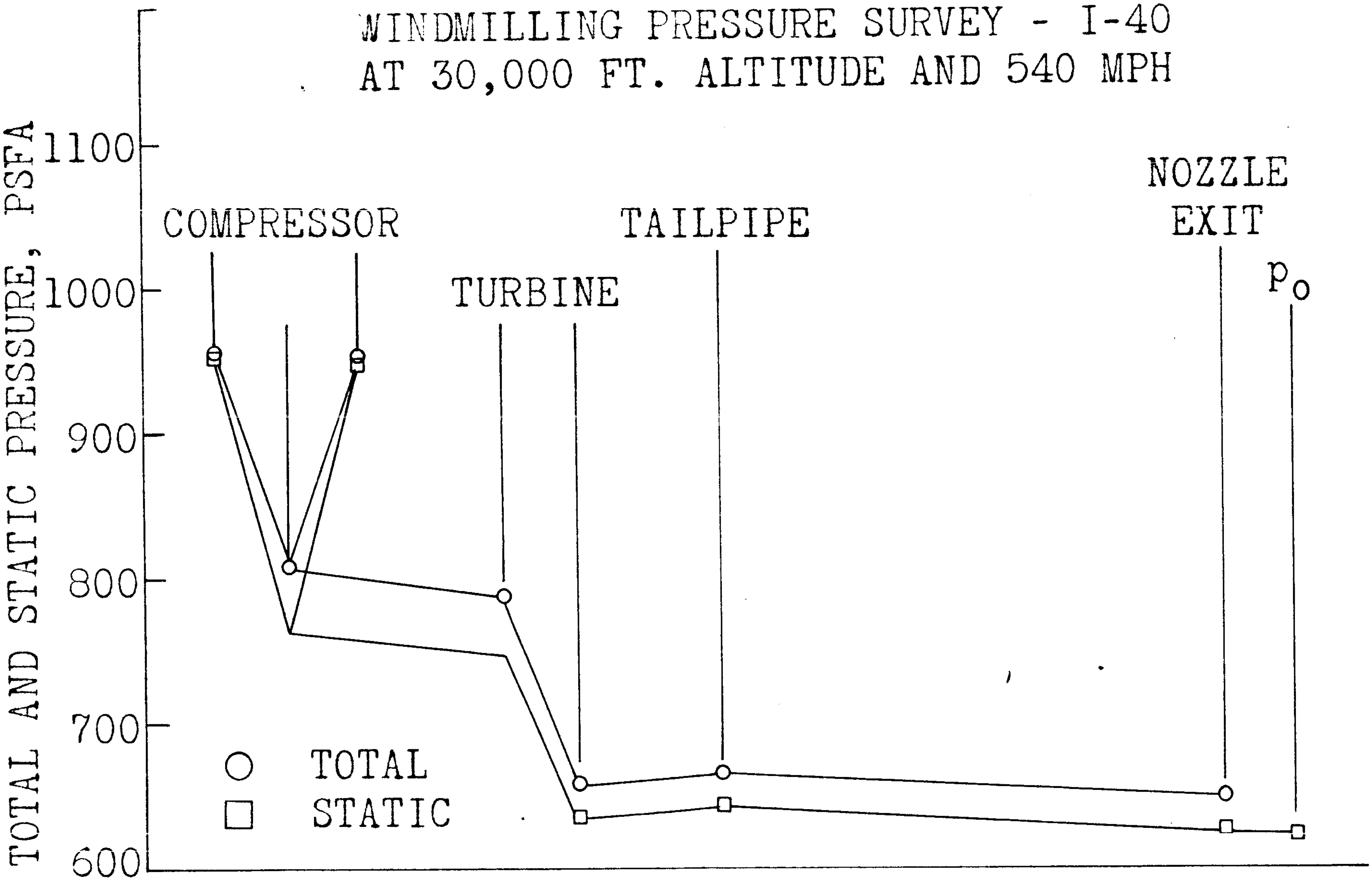

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FIGURE 18

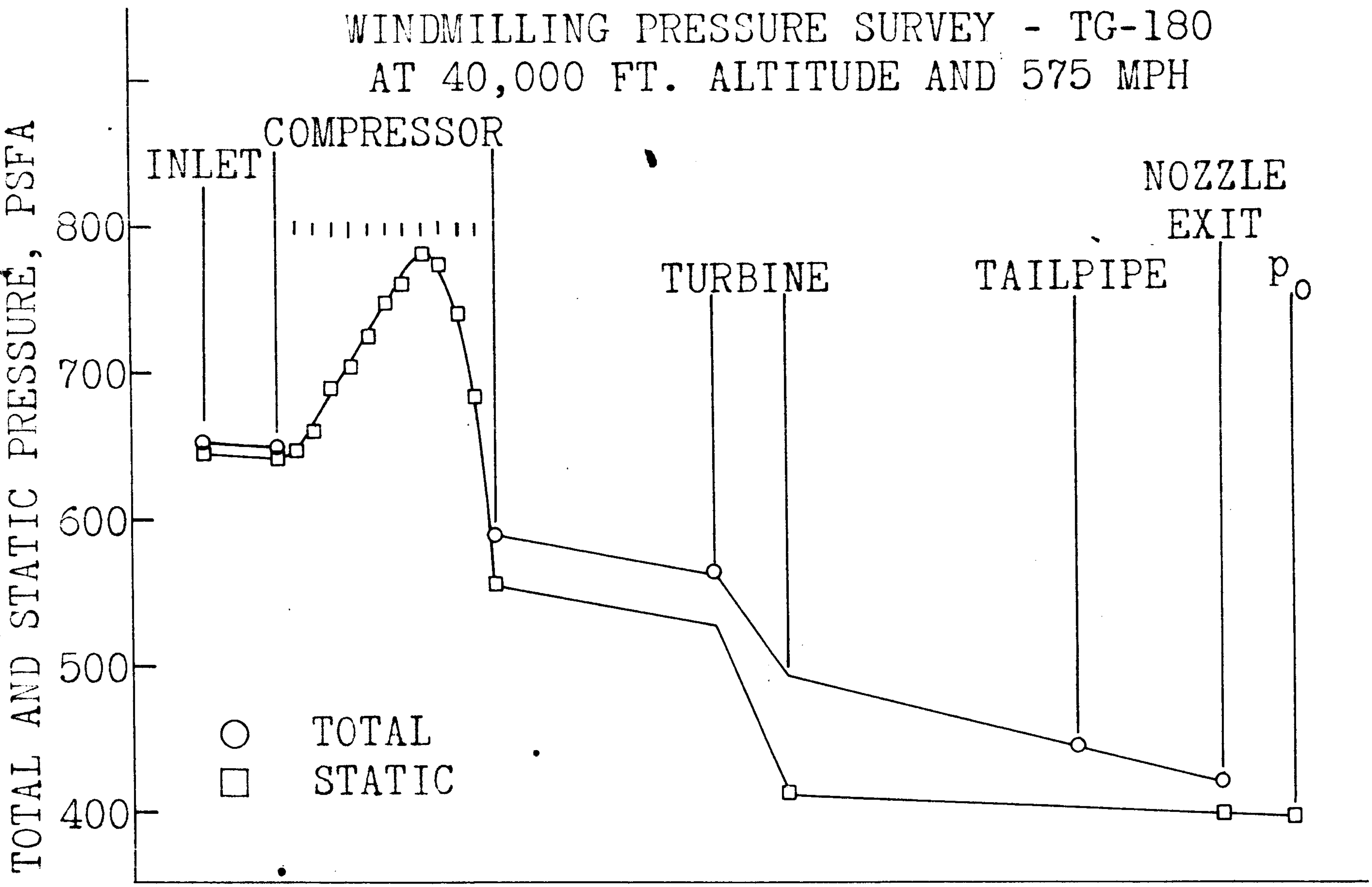
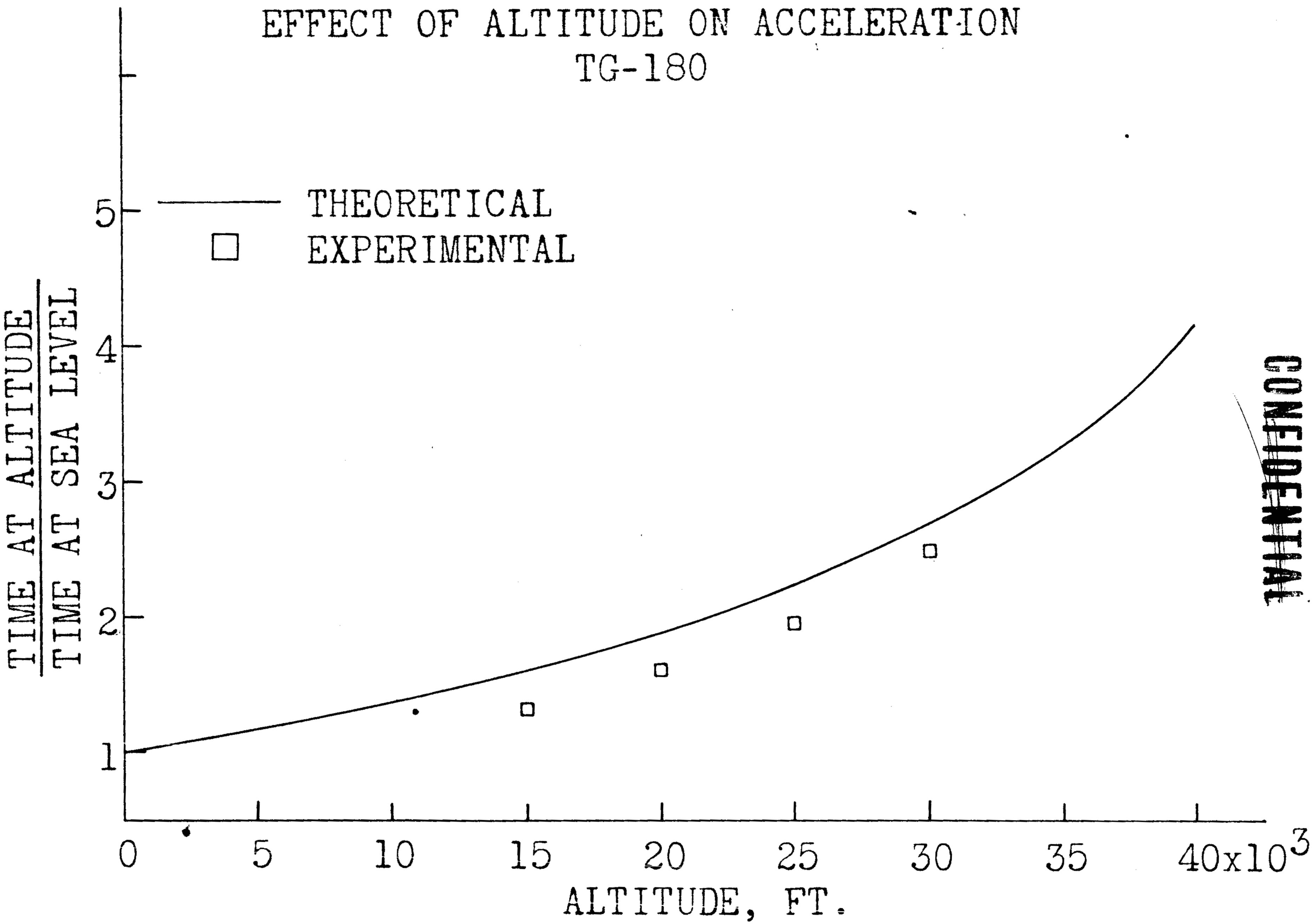
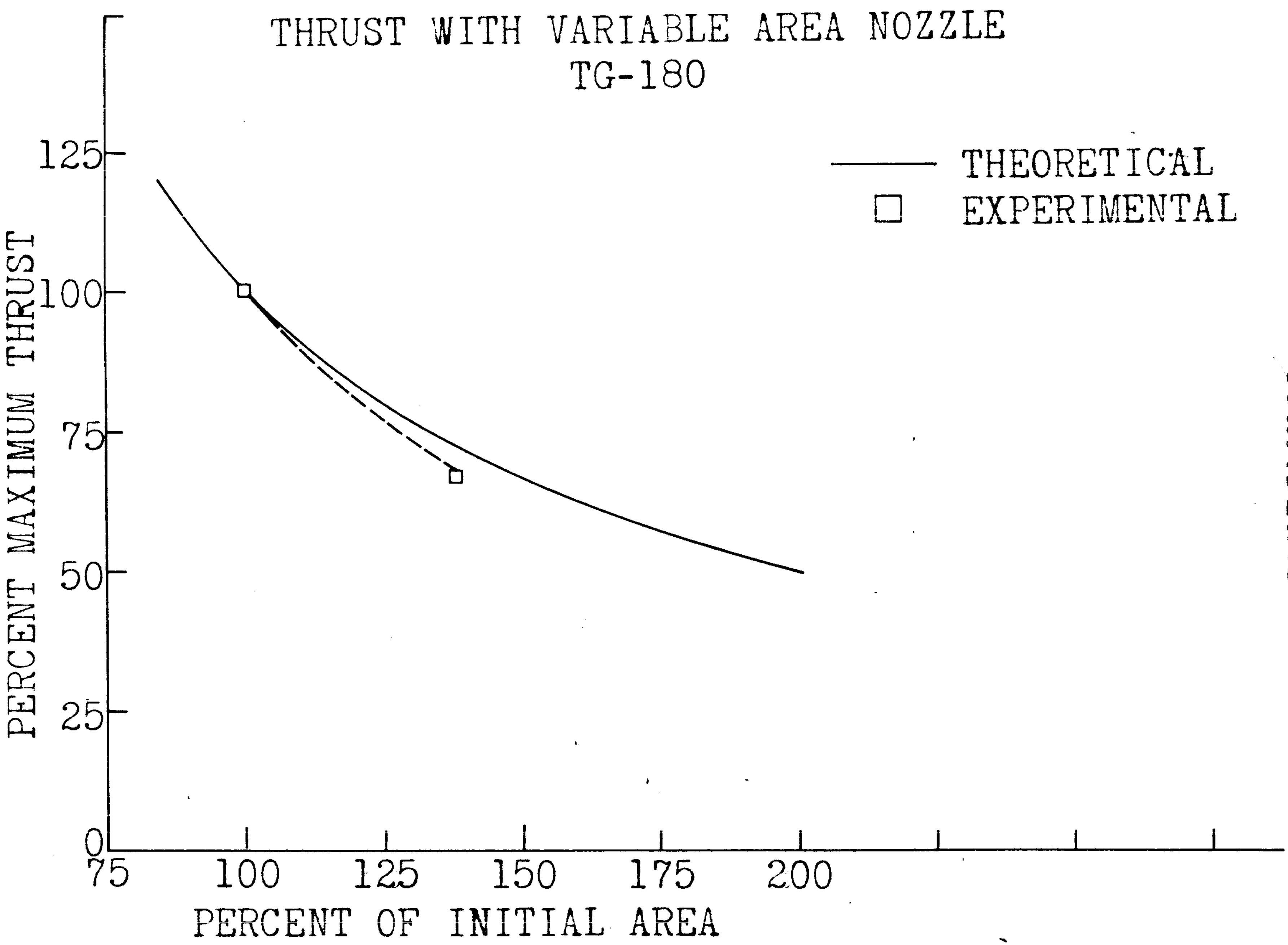

WINDMILLING PRESSURE SURVEY - TG-180
AT 40,000 FT. ALTITUDE AND 575 MPH
TOTAL AND STATIC PRESSURE, PSFA
800
700
600
500
400
INLET
COMPRESSOR
TURBINE
TAILPIPE
NOZZLE
EXIT
p_o
TOTAL
STATIC

FIGURE 19



EFFECT OF ALTITUDE ON ACCELERATION
TG-180
THEORETICAL
EXPERIMENTAL
TIME AT ALTITUDE / TIME AT SEA LEVEL
1
2
3
4
5
0
5
10
15
20
25
30
35
40x10^3
ALTITUDE, FT.

FIGURE 20



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CONFIDENTIAL

FIGURE 21

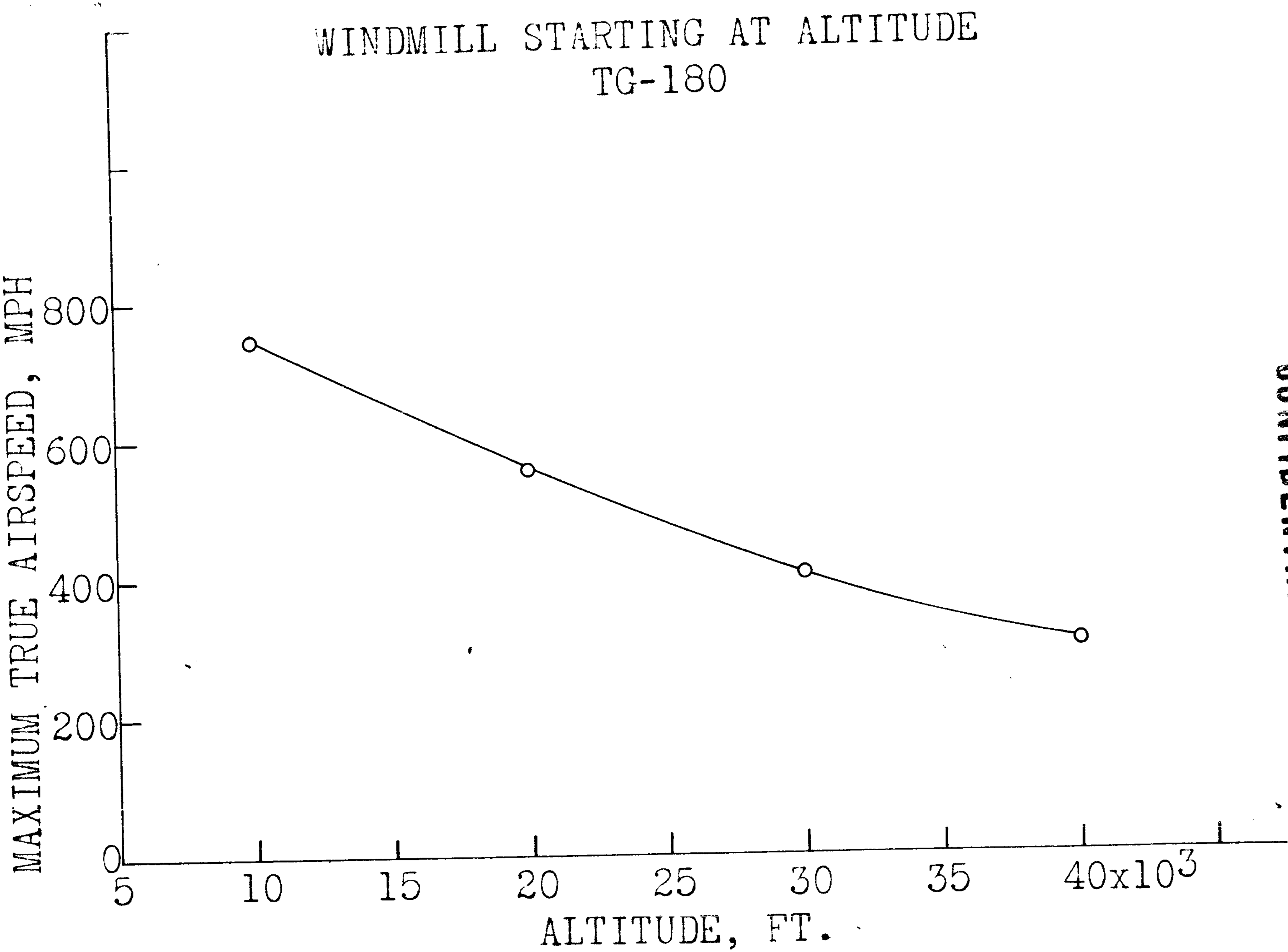
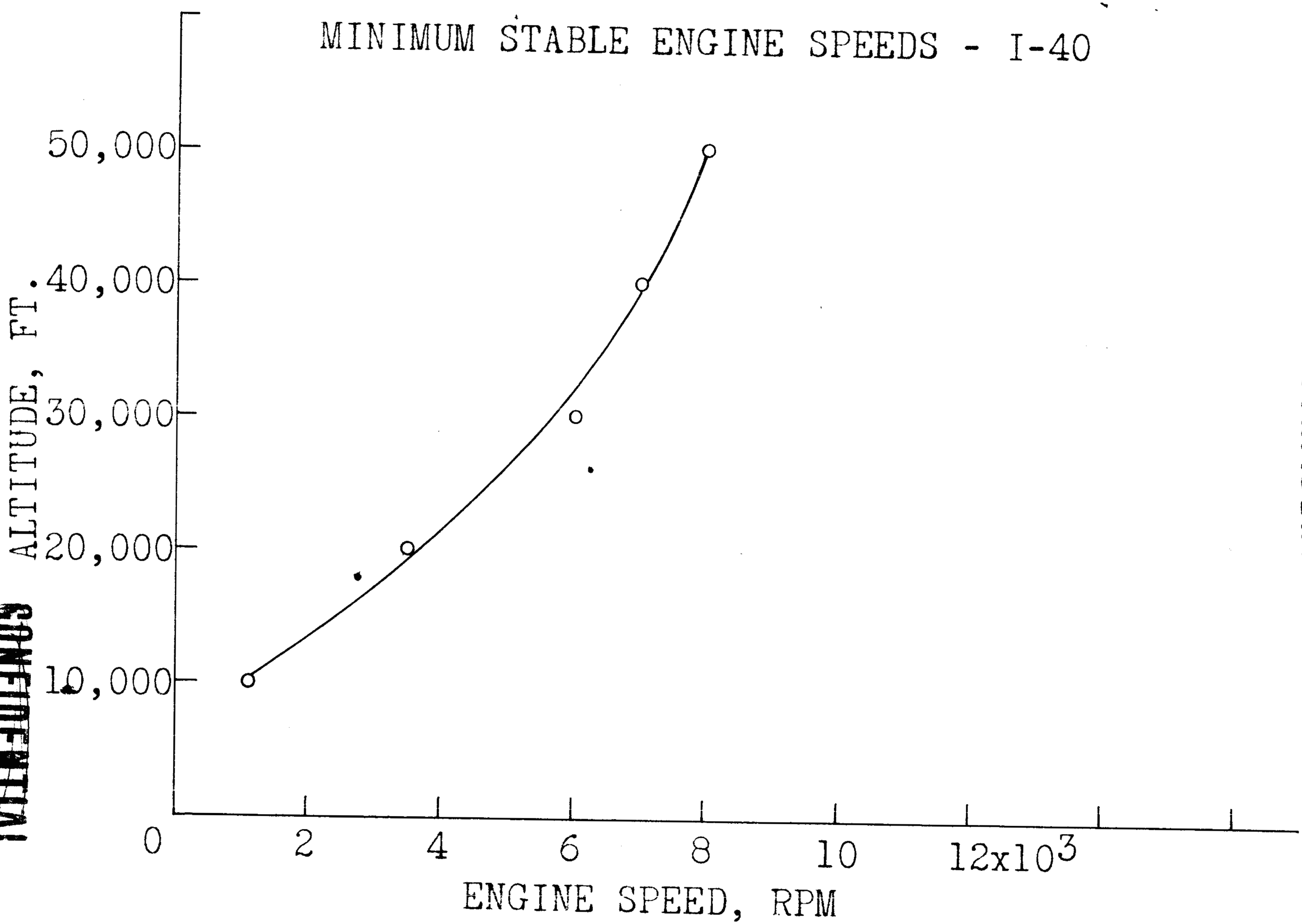

WINDMILL STARTING AT ALTITUDE
TG-180
MAXIMUM TRUE AIRSPEED, MPH
800
600
400
200
0
5
10
15
20
25
30
35
40x10^3
ALTITUDE, FT.

FIGURE 22



MINIMUM STABLE ENGINE SPEEDS - I-40
ALTITUDE, FT.
50,000
40,000
30,000
20,000
10,000
0
2
4
6
8
10
12x10^3
ENGINE SPEED, RPM

FIGURE 23

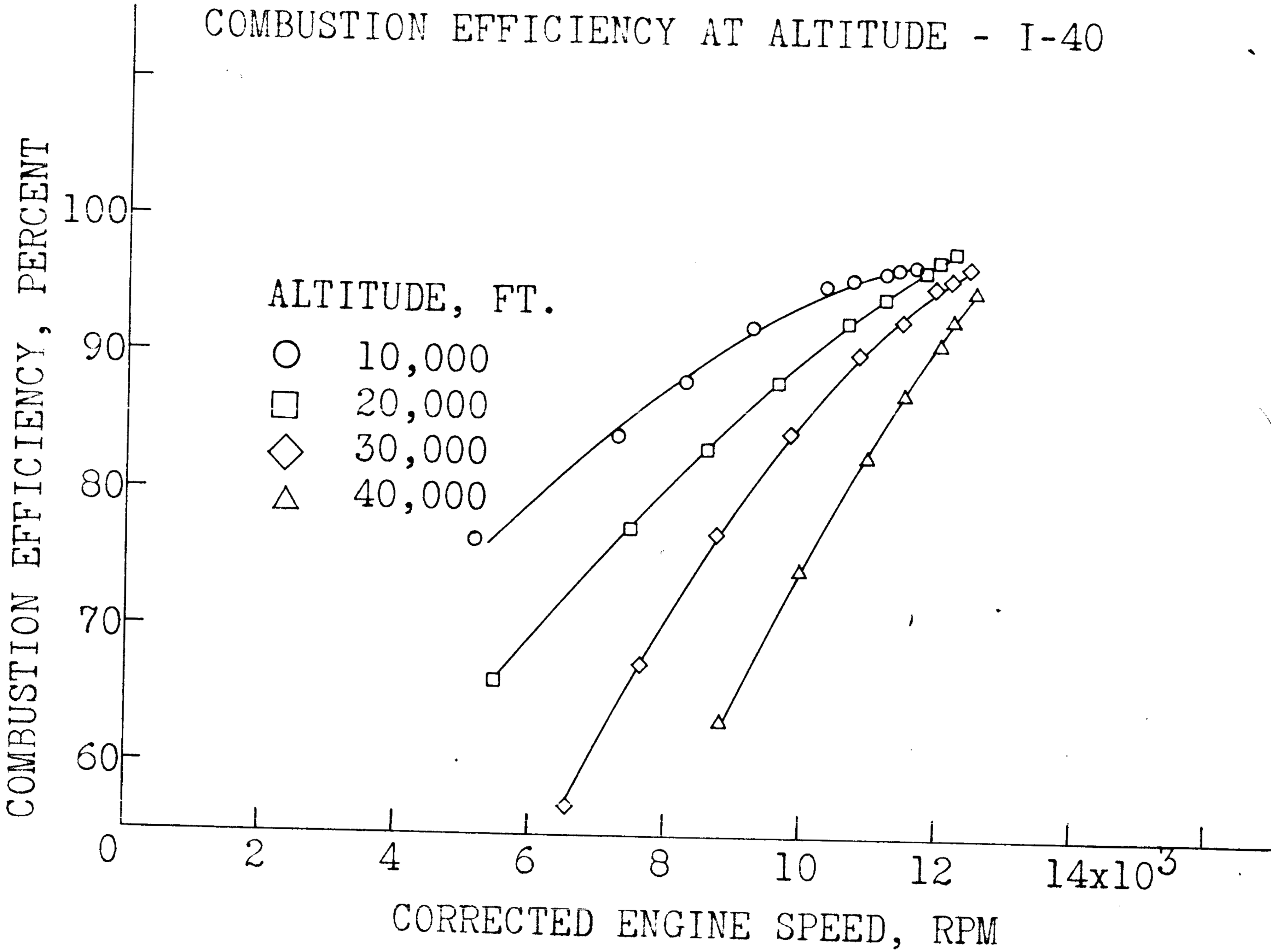

COMBUSTION EFFICIENCY AT ALTITUDE - I-40
COMBUSTION EFFICIENCY, PERCENT
100
90
80
70
60
ALTITUDE, FT.
10,000
20,000
30,000
40,000
0
2
4
6
8
10
12
14x10^3
CORRECTED ENGINE SPEED, RPM

FIGURE 24

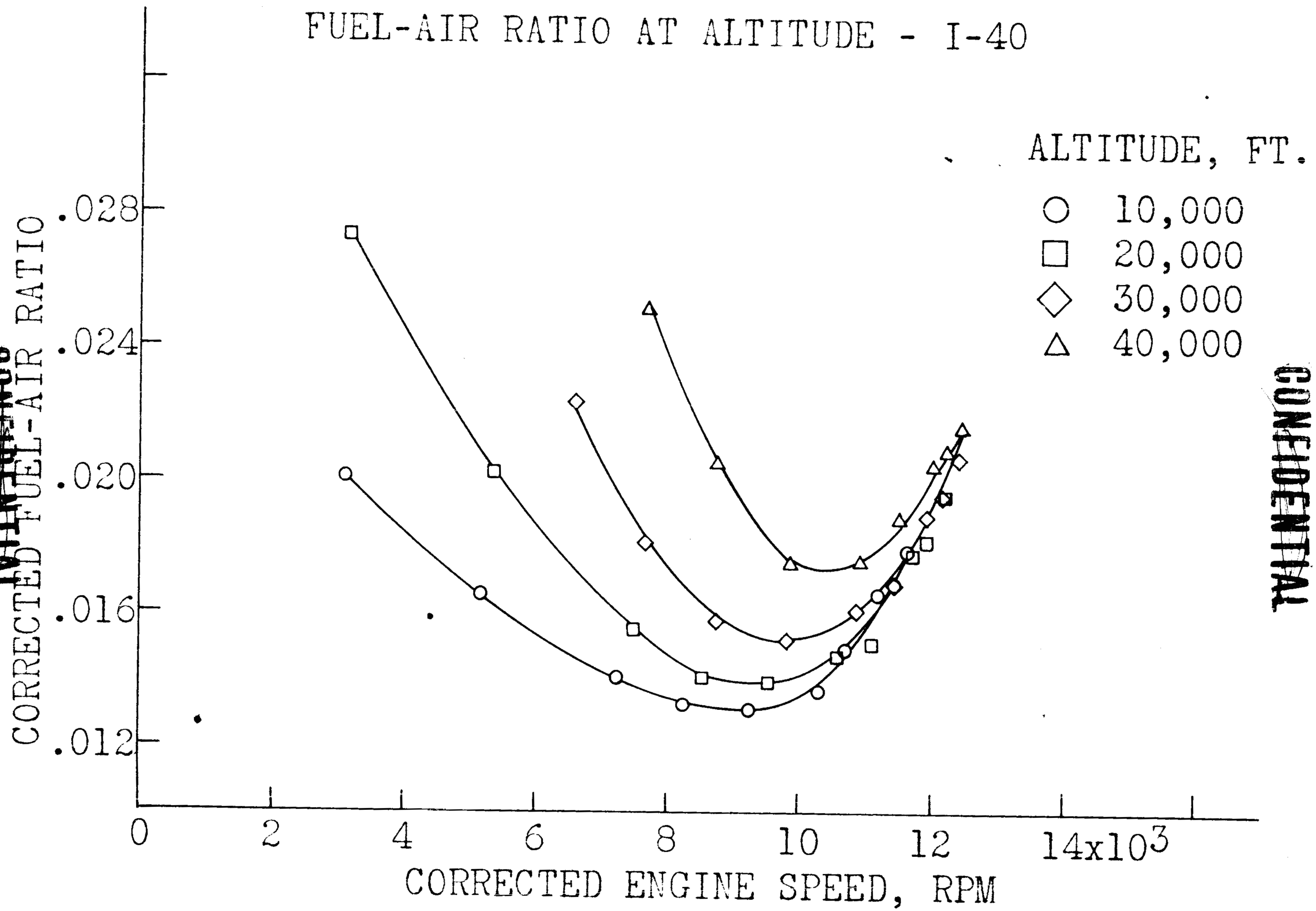


FIGURE 25

CONFIDENTIAL

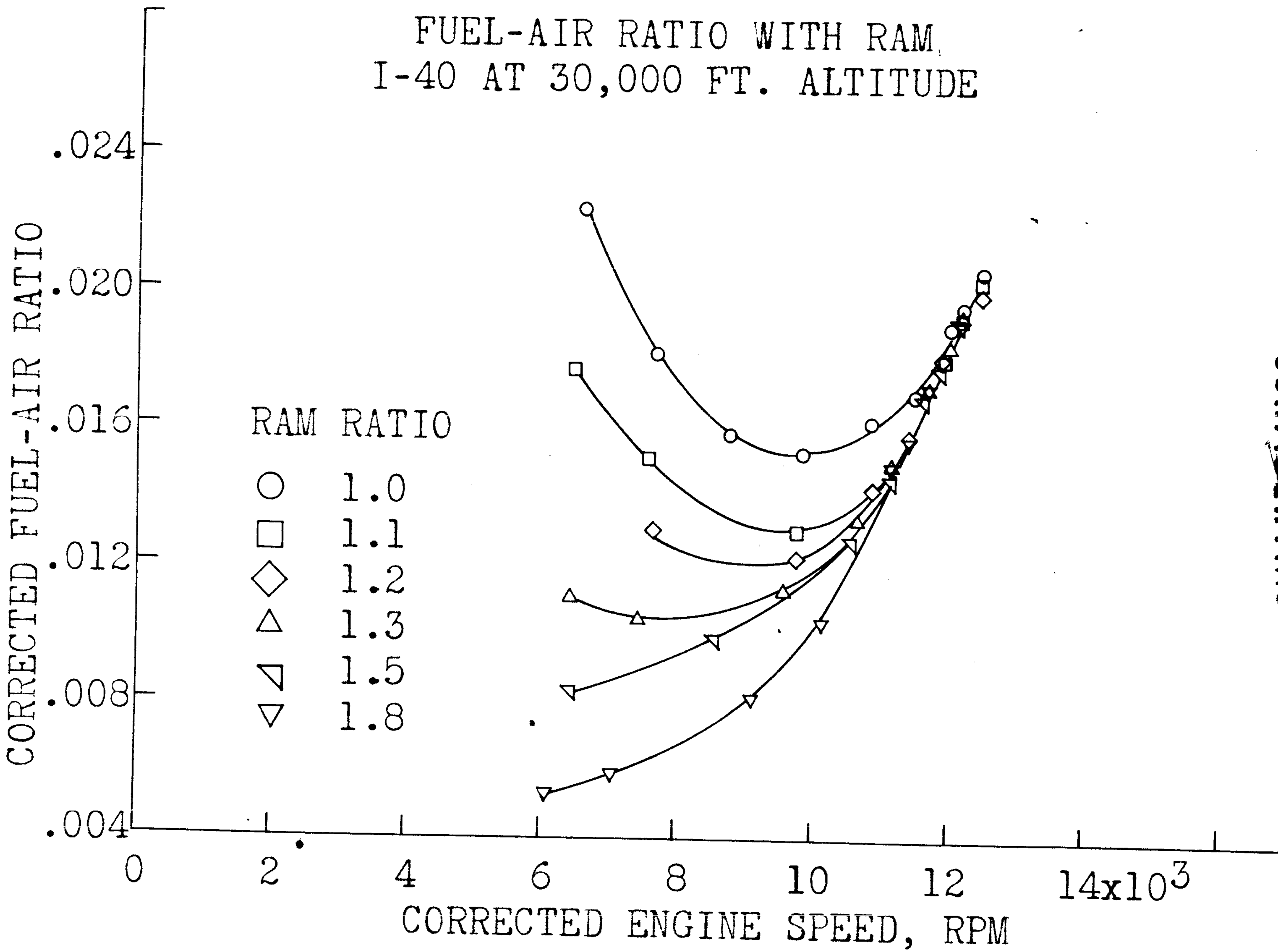

FUEL-AIR RATIO WITH RAM
I-40 AT 30,000 FT. ALTITUDE
.024
.020
.016
.012
.008
.004
CORRECTED FUEL-AIR RATIO
RAM RATIO
1.0
1.1
1.2
1.3
1.5
1.8
0
2
4
6
8
10
12
14x10^3
CORRECTED ENGINE SPEED, RPM

FIGURE 26