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A study of the performance characteristics of the General Electric gas turbine.

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A STUDY OF THE PERFORMANCE CHARACTERISTICS OF THE GENERAL ELECTRIC GAS TURBINE

by

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TABLE OF CONTENTS

	Page
I Sections	
1. Summary	1
2. Introduction	3
3. Equipment and Procedure	4
4. Results and Discussion	10
5. Recommendations	14
6. Nomenclature	16
7. Sample Calculations	18
8. References	30
II Tables	
Appendix 1	
Tables Ia-Id - Test Data	
Tables 2a-2d - Results	
III Figures 2	
Appendix	

SUMMARY

1. The purpose of this paper if two-fold. Primarily it is to present the operating characteristics and performance of the Gas Turbine manufactured by the General Electric Company for educational purposes. This educational Gas Turbine is presently installed in the power laboratory of the Mechanical Engineering Department of Rensselaer Polytechnic Institute, Troy, New York. A secondary purpose of this paper is to check the accuracy of the results by use of Orsat Apparatus, that is the final true gas stream temperature of the burner, as found by intensive calculations, was checked by use of exhaust gas analysis.

The gas turbine was operated at all runs with approximately 33% of its original turbine blocked off. This was found in a previous report to give approximately maximum compressor efficiency and improved burner discharge temperatures. The unit was operated over its approximate maximum speed range with various amounts of air bleed. Because the burner temperature was not uniformly distributed over the burner area and to keep the lubricating oil at a safe maximum, a very safe maximum of 13,320 r.p.m.

and 5.5% bleed was used for this report.

It was found that in the first several test runs the unit was unstable. This was found to be due entirely to a dirty partially clogged spray nozzle. In subsequent test runs, after the cleaning of the nozzle, the unit was very stable. It would maintain a steady r.p.m. and burner temperature for as long as two hours.

INTRODUCTION

2. This report is the third in a series done on the General Electric Educational Gas Turbine. All three reports were done under the co-ordinated quidance of Professor Neil P. Bailey and Professor F. J. Bordt. The first report was an analytical report on calculations for the Educational Gas Turbine by L. Cdr's. Dixon and Tugeng and Lt.(j.g.) Bodnaruk, U.S.N. The second report was concerned primarily with operating range, performance, and the determination of turbine area to be blocked off. This report is based primarily on the determination of the performance characteristics, and accuracy of measured gas stream temperatures.

This educational gas turbine was manufactured by the Aircraft Gas Turbine Division of the General Electric Company for use by the Mechanical Engineering Department of Rensselaer Polytechnic Institute, Troy, New York.

EQUIPMENT AND PROCEDURE.

3. The unit used for this report was the General Electric Educational Gas Turbine as described in Reference I. This unit is made up primarily of a B-22 turbo-super-charger consisting of single stage centrifugal compressor and a single stage impulse turbine. The B-22 turbo-super-charger is equipped with a combustion chamber, compressor inlet flow nozzle venturi, compressor discharge bleed off and accessory equipment for use in the study of Gas Turbine Performance. The can type combustion chamber is of reverse flow type and is 92 inches long. The straight section of pipe from the perforated inner lines to the nozzle box inlet has been included in this design to provide for more uniform temperature and pressure measurements over its cross section. Opposite the compressor discharge connection on the combustion chamber is a 4 inch line through which air may be bled for use on other applications and thereby varying the turbine operating conditions. By use of this bleed off, variable fuel air ratios and turbine temperatures can be obtained for constant compressor operating conditions. The inlet air to the compressor is measured with a 7 inch double venturi flow nozzle. The rotor speed is measured

by a tachometer that indicates one revolution for every 9.5 revolutions. Kerosene is supplied to the burner fuel nozzle at 150 psia by an external high pressure pump. Although the fuel nozzle tips are replacable, the same tip was used throughout this investigation. The turbine wheel and bearing housing of the turbine is cooled by an remote blower supplying 200 cfm. Ignition is started by a single electrode spark plug located in the burner near the spray nozzle.

The only method of applying an external load to the unit was by use of the bleed air. Air was bleed off from the compressor discharge to the atmosphere by means of a bleed off valve. The speed of the unit was controlled by a throttle which regulated the fuel supply. The unit had three safety circuits. The maximum burner pressure was 23 pounds gage. A pressure switch was located in the compressor discharge line which was set to trip at 22 pounds gage. The maximum nozzlebox temperature was 1600°F. A thermo switch was located near the nozzlebox inlet on the combustion chamber with a setting to shut off the fuel supply at 1600°F. The turbine exhaust line is equipped with a sensing thermo switch which closes the burner circuit as soon as a temperature of 300°F is reached. This thermo switch operates in conjunction with a delay relay which holds the burner circuit closed for 10 seconds. At the end of 10 seconds if the exhaust temperature is not above 300°F. the ignition and fuel supply is automatically shut off. This minimizes hot starts by preventing long attempts to start the unit. Starting air was obtained from a remote compressor which maintained a continuous supply of air at 90-95 psia gage.

For complete details on the starting and operation of the unit see Reference I. The complete installation was instrumented to obtain all the necessary data to obtain performance characteristics in the following matter.

1.) Compressor Inlet.

The inlet pressure was assumed to be atmospheric and was measured by a standard Navy mercury barometer. The temperature was measured by two Weston Model 226 L 002 testing thermometers placed in the inlet protection screen.

2.) Compressor discharge.

The total discharge pressure was measured by a total impact tube. The temperature was measured by three copper-constantan bare tipped thermocouples placed evenly about the discharge duct of the compressor. The thermocouples were all uniformly inserted to a depth of 2-3/16 inches.

3.) Burner Discharge

The burner gas stream temperature was measured at the discharge end of the burner by three bare tipped chromel-alumel thermocouples placed at 90, 180 and 270 degrees around burner and inserted to a depth of 2-3/8 inches. The static pressure was measured by three static pressure taps in the same plane as the thermocouples: these pressure taps were manifoled together and the pressure indicated on a mercury column gage. The burner wall temperature was measured by a bare tipped iron-constantan fastened securely on the outside burner wall in same plane as gas stream thermocouples by a heat resistant putty. The outside burner wall was thoroughly cleaned with a file and abrasive cloth of all scale, rust and dirt before puttying on the thermocouple.

4.) Inlet Air

- measured by a 7 inch double venturi flow nozzle with a conventional manometer connected to the inner venturi throat.

5.) Bleed Air

The amount of air bleed was measured by a 1.25 inch square edge orifice mounted in the four inch bleed line, with "vena contracta" pressure taps. The temperature of the bleed air was measured by two bare tipped copper constantan thermocouples mounted in the bleed line 20 inches up stream from the orifice and inserted to a depth of 1-13/16 inches.

6.) Speed

The speed was indicated on a standard electric tachometer. The actual r.p.m. was 9.5 times the indicated r.p.m.

7.) Fuel Flow

The fuel was taken from an outside 275 gallon storage tank by an electric driven pump and pumped into a 10 gallon day tank. This tank was calibrated so that fuel used could be measured. The excess fuel from the nozzle was also pumped back into the day tank to keep fuel temperature constant.

All thermocouples led to a selector switch on the control panel. The selector switch was connected to a standard Leeds and Northrup potentiometer.

The compressor discharge, burner discharge, bleed air, and turbine exhaust were measured on 60 inch single leg mercury manometers. The inlet air venturi, bleed air orifice and turbine wheel pressure drops were measured on double leg water manometers.

<u>Exhaust Gas Analysis.</u>

The composition of the exhaust gases was measured by a standard Orsat Analysis Apparatus. The Orsat sample line was connected to an impact tube that was inserted in the turbine exhaust line at the same place where the turbine exhaust pressure was measured. Because of the whirling motion of the gases in the exhaust line, the exhaust line was probably not flowing full. Therefore about 40 different samples were taken at various radii of the exhaust line. Considerably difficulty was encountered in obtaining a true exhaust gas analysis. However with the sampling tube close to the exhaust wall a number of samples were obtained that checked very closely. (See pg. 9a)

The standard procedure followed in all tests was heat the lubricating oil to 100°F prior to starting. After starting the unit was allowed to warm up for 15 to 20 minutes to allow it to reach a stable operating condition. For each run the unit was allowed about 10 minutes to reach a stable operating condition before any data was taken. The r.p.m. was constantly checked during each run. The best method of recording fuel comsumption was to record fuel level at the start of the run and at the end. This usually took about 10 minutes. Runs were made at constant r.p.m. and various air bleed for a number of r.p.m. Also constant air bleed and various r.p.m. runs were made.

Method of Use of Exhaust Gas Analyzer.

1.) Apparatus was completely overhauled. New hoses were installed to insure that there would be no leakage. New chemicals were installed in CO_2, O_2 and CO absorber bottles.

2.) Exhaust gas sample was brought into sample tube and exhausted to atmosphere about 10 times before each sample was analyzed to insure a true gas sample.

3.) Exhaust gas was run through CO_2, O_2 + CO, absorbers twice before recording amount.

4.) After sample was passed through C), it was passed through CO_2 absorber before recorded to remove HCl vapor

RESULTS AND DISCUSSION

4. It was found during the first stage of the investigation that the unit was unstable in its operation. However, after thorough cleaning of the spray nozzle the unit became very stable and would hold a given r.p.m. for as long as two hours with one fuel setting. Also a large variation in temperature distribution occurred in the burner gas stream. At first it was thought that a thermocouple was defective. However, after switching the thermocouples around, it was found that the very same temperature distribution existed. Therefore it was assumed that there was a variation in the burner temperature distribution, as high as 150°F, and the average temperature of the three thermocouples was used in all computations. This variation of burner temperature around its circumference was found to be constant under the same conditions of burner temperature and r.p.m. That is at 10000 r.p.m. the high temperature was always found to be at the same position on the circumference of the gas stream. However as the r.p.m. was increased the high temperature moved in a counterclockwise manner. This change was uniform and always in the same direction. However at higher r.p.m. the variation in gas stream temperature became less. In other

words, as the r.p.m. increased the burner gas stream temperature tended to become more uniform. It is felt by the author that there is room for an intensive study of the temperature distribution over a cross section of the burner area.

Figure No. 1 shows the compressor test pressure ratio, P_c/P_1 vs. Compressor Speed. All test data fitted in very well.

Figure No. 2 shows the compressor air flow in CFM at standard conditions plotted vs. r.p.m. Again all the test data fell along curve very well.

Figure No. 3 shows the compressor efficiency plotted vs. corrected compressor speed.

Figure No. 4 shows the fuel rate vs. fraction of inlet air bleed for various r.p.m. The data fell in quite well.

Because the performance of the gas turbine was desired as a function of speed and burner temperature only, the effect of inlet temperature was eliminated by reducing the air flow in CFM to standard conditions. Where weight flow was used in computations it was also converted to standard conditions. The effect of compressor inlet temperature upon compressor work was eliminated by determining the work as a function of compressor pressure ratio and compressor efficiency and assuming a standard inlet temperature of 59°F.

Figure No. 5 shows the relationship between, Burner temperature, Compressor Pressure ratio, Turbine Pressure ratio, Inlet Air flow and Compressor efficiency vs. ~~portion~~ ratio of inlet air bleed. P_2/P_1 was practically constant for all values of portion of air bleed. The compressor efficiency dropped off slightly for higher values of air bleed.

Figure No. 6 shows the effect of rotor speed and burner inlet temperature upon Compressor efficiency, turbine efficiency and Machine efficiency. Compressor efficiency increases with speed but decreases slightly with an increase in turbine inlet temperature. The turbine efficiency decreased with speed. However it increased with temperature from 1400°F to 1450°F, then dropped off again for 1500°F. The machine efficiency increased slightly with speed.

Figure No. 7 shows gross turbine power, net turbine powers, and Turbine Air rates vs. turbine speed for various turbine inlet temperatures. The gross turbine power increased greatly with r.p.m. and temperature. The net turbine power remained almost constant, the turbine air rate decreased slightly with temperature and speed.

Orsat Results. (See Sample Calculations)

The air fuel ratio as obtained from the Orsat Analysis checked very well with the one obtained by the actual measuring of the fuel and air during the run. Therefore, it was assumed that the Orsat Analysis was accurate. Also the true gas stream temperature checked very well with that obtained from a heat balance set up from the exhaust gas analysis. The true burner gas stream temperature was found to be 1365°F. From the exhaust gas analysis, the burner gas stream temperature was found to be 1340°F.

RECOMMENDATIONS

5. It was found during the operation of the unit that 800 indicated r.p.m. was a critical speed. That is at 800 indicated r.p.m. a vibration was set up that would trip one of the automatic shut-off circuits and the unit would automatically shut down. This did not happen at any other r.p.m. Therefore, it is recommended that the unit be warmed up at a greater speed, one of at least 1,000 indicated r.p.m. Also because of the fuel system used when fuel is constantly flowing from the day tank to the burner nozzle and the excess fuel discharging back into the day bank, there is some oscillation in the fuel level. Therefore to obtain accurate fuel consumption, fuel measurements should be measured over periods of at least 10 minutes, preferably 15 minutes. This will give adequate accuracy in fuel measurements.

It is also suggested that the bleed valve be checked for faulty operation. There was considerable oscillation in the bleed air manometer at high bleed. Perhaps inserting about 10 to 20 additional feet of flexible tubing in the line would overcome this. Also additional burner wall temperature thermocouples could be advantageously used around the burner, also it is felt that there might be a study carried out of burner temperature distribution. Also a study of burner temperature and unit operation might be made using various burner spray nozzle tips. The burner spray nozzle should be taken out and cleaned after each 10 or 15 hours of operation.

It is felt that the unit is in good operating condition but it takes an operator about 10 operating hours before he is familiar enough with the installation to use it to its ulmost advantage.

NOMENCLATURE

6. The following nomenclature is used in this report.

A - pipe or duct area - ft.^{2}

D - pipe or duct diameter - ft.

G - mass flow per unit of cross-section area - lb.m/ft.^{2} sec.

g - acceleration of gravity = 32.2 ft./sec.^{2}

HP - horsepower

h - enthalpy - BTU/lb or BTU/Mol.

Δh - differential manomenter pressure - inches of water.

K - orifice coefficient

L - mechanical work - BTU/Min.

m_v - potentiometer reading - millivolts

N - rotative speed - R.P.M.

N_R - Reynolds' number

p - pressure - inches of Hg.

P - Pressure - lb./ft.^{2}

Q - volumetric flow rate - CFM

R - gas constant = 53.4 for air

T - temperature - °R

t - temperature - °F

t^* - t (star) = actual burner gas temperature

V - forced convection film coefficient
BTU/hr - ft.^{2} - °F.

v - velocity - fps.

w - weight rate of flow - lb./min.

β - orifice - pipe diameter ratio

η - efficiency, expressed as decimal

γ - ratio of specific heat at constant pressure to specific heat at constant volume
= 1.395 for air at low temperatures

ρ - mass density - slugs/ft.^{3}

ρ_m - mass density - lb.$_m$/ft.^{3}

absolute viscosity - lb.$_m$/ft.-hr.

SUBSCRIPTS

a - actual or test conditions

av. - average

b. - bleed air

c. - compressor

f. - fuel

i. - indicated

m. - mass or mean

o. - orifice

s. - standard inlet temperature conditions of 59°F.

s=c - constant entropy process

t. - turbine or thermocouple

w. - wall

SAMPLE CALCULATIONS

7. This calculation is for run No. 8a - all other runs were calculated in exactly the same manner.

1. $N_a = N_1 \times 9.5 = 1260 \times 9.5 = 12,000$

2. $t_a = \frac{78.2 + 86}{2} = 82.1°F$

3. $N_S = N_a \sqrt{t_{is}/t_{ia}} = N_a \sqrt{\frac{t_{is} + 460}{t_{ia} + 460}}$

$= 12,000 \quad \frac{519}{542.1}$

$= 11,770$ r.p.m.

4. To find W_a

h (inlet air venturi) = $3.4+4.6=8.0"H_2O$

Inlet air temperature $t_{ia} = 82.1°F$

$P_S = P_{bar} = P_1 = 29.712"$ Hg.

$\therefore$ from curve No. P-1097802 of reference 1

$W_a = 86$ lbs.per minute.

5. $Q_a = \frac{W_a R t_{ia}}{P_1} = \frac{68 \times 53.3 \times 542.1}{29.712 \times 70.73} = 1125$ C.F.M.

6. $Q_S = Q_a \sqrt{\frac{t_{is}}{t_{ia}}}$

$= 1125 \sqrt{\frac{519}{542.1}}$

$= 1100$ C.F.M.

7. P_2 = 7.2 " Hg. gage

$= 29.712 + 7.2 = 36.912$" Hg. abs

8. $P_2/P_1 = \frac{36.912}{29.712} = 1.355$

9. Compressor discharge temperature

M_v. av. $= \frac{2.18 + 2.08}{2} = 2.13\ M_v$,

from reference No. 8

$t_2 = 98$ + potential temperature

$= 98 + 78 = 176°F$

10. To find Compressor efficiency

$$\eta_c = \frac{(P_2/P_1)^{\frac{\gamma-1}{\gamma}} - 1}{\frac{t_2}{t_1} - 1} \qquad \frac{\gamma-1}{\gamma} = .283$$

$$\eta_c = \frac{(1.355)^{.283} - 1}{\frac{636}{542.1} - 1} = .545 = 54.5\%$$

11. To find the weight of bleed air - W_b

(a) av. M_v. from thermocouples 4 and 5

M_v. (av) $= \frac{1.4 + 1.4}{2} = 1.4$

from reference No. 8

$t_3 = 66 + 78 = 144°F.$

(b) For a standard square edged orifice

$$V_o = K \sqrt{\frac{2 \Delta P_o}{\rho_o}}$$

where ρ_o is measured on the upstream side of orifice in the bleed air pipe,

Since $\rho_o = \rho_3 = \frac{P_3}{g R T_3}$

$$V_o = K \sqrt{\frac{2 \Delta P_o}{\frac{P_3}{g R T_3}}}$$

$h = 2.0'' \; H_2O$

$P_3 = 406.5 '' \; H_2O$

$T_3 = 604°R$

V_o is found by trial and error. Since K is a function of Reynolds' number.

For first trial assume K = .605

$$V_o = .605 \sqrt{\frac{\Delta h \times 3330 \; T_3}{P_3}}$$

$$= .605 \sqrt{\frac{2.0 \times 3330 \; (604)}{406}}$$

$$= .605 \sqrt{9,900}$$

$$= .605 \times 99.6$$

$$= 60.3'/sec.$$

but $N_{R_o} = \frac{3600 \times V_o \times \rho_m \times D_o}{\mu}$ $\qquad \mu = .0490$

where $\rho_m = \frac{P_3}{R \; T_3} = \frac{406'' H_2O \times 5.204}{53.3 \times 604}$

$= .0656$ pounds mass per cu. ft.

From table of reference 5 value of K = .605 for

$$\beta = \frac{\text{diam orifice}}{\text{Inside Bleed pipe}} \quad , \; N_R \simeq 30{,}000$$

$$\beta = \frac{1.25}{3.94} = 0.319$$

therefore V_o = 60.3'/sec.

$$\therefore \; W_b = \rho_m A_o V_o \times 60$$

where $A_o = \pi/4 \left(\frac{1.25}{12}\right)^2$

$$\therefore \; W_b = .0656 \times .51 \times 60.3$$

$$W_b = 2.02 \text{ lb per min.}$$

12. Fraction of inlet air bleed

$$W_b/W_a = \frac{2.06}{86} = .0235$$

13. Calculation of burner gas stream temperature

From reference 4 a graphical solution for finding the thermocouple radiation was used.

$(M_{v_{av}})$ for thermocouple 6, 7 and 8,

$$M.V._{av.} = \frac{26.4 + 29.8 + 29.0}{2} = 28.4 \text{ M.V.}$$

from reference 8

$$t_{t5} = 78 + 1233 = 1311°F$$

for wall temperature

$$M_v = 22.9$$

$$t_{w5} = 78 + 757 = 835°F$$

The weight flow at the burner discharge

$$W_5 = W_a - W_b + W_f$$

$$= 86 - 2.02 + 1.36$$

$$= 85.34 \text{ lbs. per min.}$$

$$\therefore G = \frac{W_s \text{ lbs./sec}}{\text{Area}}$$

$$= \frac{85.34}{60} \times \frac{1}{\pi/4 \left(\frac{7.69}{12}\right)^2}$$

$$= 4.39 \text{ lb m/ft.}^2\text{-sec.}$$

The determination of U from Figure 8 is by trial and error.

Estimating a gas stream temperature of 1400°F

from Figure 8 $\frac{G'}{G} = 0.92$

$\frac{U}{U'} = 1.15$

$$\therefore G' = g \times 92 = 4.39 \times .92 = 4.04 \text{ lb./ft}^2\text{-sec.}$$

from Figure $U' = 96$

$$U = U' \times 1.15 = 96 \times 1.15 = 110 \text{B.T.U./Hr.-ft}^2\text{-°F.}$$

From Figure 9 $t_m - t_a = 10°F$

$$t_{av.} = \frac{1311 + 835}{2} = 1073$$

$$\therefore t_m = 1073 + 10 = 1083°F$$

$$t_t - t_w = 1311 - 835 = 476°F$$

Consequently using

$$U = 110, \quad t_m = 1083°, \quad t_t - t_w = 476°F$$

From Figure 10 $\quad t_g - t_t = 97°F$

therefore $\quad t_g = t_t + 97°F = 1311 + 97 = 1408°F$

14. $\quad P_5 = 29.712 + 10.4 = 40.112$ " Hg

15. $$P_6 = 29.712 + \frac{H''H_2O}{13.6} = 29.712 + .607$$

$$= 30.319$$

16. $$P_5/P_6 = \frac{40.112}{30.319} = 1.325$$

Performance Data Computations

From Figure 5 - See Table 2

For a speed of 13,300 r.p.m. t_{o5} = 1400

W_b/W_a	= .03	Standard Conditions
Q_s	= 1100	Assumed
P_2/P_1	= 1.352	t = 59°F
η_c	= .525	P = 30.00 " Hg.
W_t	= 1.38	
P_5/P_6	= 1.325	

17. $$W_s = Q_s \times \frac{P_{is}}{R\,T_{is}}$$

$$= 1100 \times \frac{\frac{30.00}{12} \times 13.6 \times 62.4}{53.4 \times (519)}$$

$$= 84.5 \text{ lb./Min.}$$

18. $$W_b = W_s \times W_b/W_g = W_s \times W_b/W_s$$

$$= 84.5 \times .03 = 2.54 \text{ lb./min.}$$

19 $$\eta_t = \frac{\text{Actual turbine work}}{\text{ideal turbine work}} = \text{turbine efficiency.}$$

The ideal turbine work is defined as the work of a constant entropy turbine operating between the actual turbine pressure ratio. The actual turbine work is assumed to be equal to the compressor work.

Actual turbine work $L_{t_a} = W_a \ (h_2 - h_1)$

Ideal turbine work $(L_t)_{s=c} = W_t \ (h_5 - h_6)$

In order to find $h_2 - h_1$, and $h_5 - h_6$

where $T_1 = 519$, $T_5 = 1860$, T_2 and T_6 must be found.

$$T_2 = T_1 \left[1 + \frac{(P_2/P_1)^{\frac{\gamma-1}{\gamma}} - 1}{\eta_c} \right]$$

$$= 519 \left[1 + \frac{(1.352)^{.283}}{.525} \right]$$

$$= 608°R$$

Therefore using Table 1, reference 11,

$L_{T_a} = 84.5(2136) = 1805$ BTU per min.

To find T_6

Using table 4 of reference 11

$$P_{r_6} = \frac{P_{r5}}{P_5/P_6} = \frac{146.5}{1.352} = 107.4$$

$\therefore$ from Table 4

$T_6 = 1736°R$

From Tables of reference 11, M.w of fuel = 28.925

$$W_t = W_a - W_b + W_f$$

$$= 83.34 \text{ lbs/min}$$

$$\therefore (L_T)_{s=c} = \frac{W_T}{28.95} (\Delta H) = 2900 \text{ BTU/Min.}$$

$$\therefore \eta_t = \frac{1805}{2900} = .623 = 62.3\%$$

20. $\eta_m = \eta_t \times \eta_c$

$= .623 \times .525 = .328$

21. Turbine Horsepower is equal to L_{T_a}

$$\therefore = \frac{1805}{42.43} = 42.7$$

22. The net horsepower is equal to work of compressing bleed air.

$$HP_{net} = \frac{W_b\ (h_2-h_1)}{42.43}$$

$$= \frac{2.54\ (21.36)}{42.43} = 1.95$$

23. Air rate = W_t/HP_t

$$= \frac{83.34}{42.7} = 1.95 \text{ lb/min.-HP.}$$

Sample Calculations for determing A/F ratio and burner gas stream temperature from exhaust gas analysis.

Exhaust Gas Composition from Orsat Analysis

CO_2 = 2.4%

O_2 = 16.2%

CO = 0.6%

		Moles C	Moles O_2	Moles H_2
CO_2	22.4	2.4	2.4	-
O_2	16.2	-	16.2	-
CO	0.6	0.6	0.3	-
N_2	80.8(by difference)			
H_2O	5.2	2.6		5.2
TOTALS	105.2	3.0	21.5*	5.2

Total $O_2 = 80.8 \times \frac{21}{79} = 21.5$* moles

lbs. air = 102.3 x 28.8 = 2950 lbs.

lbs. fuel- 10.41 x 36.0 = 46.4 lbs.

$A/F = \frac{2950}{46.4} = 64.5$

Air fuel ratio as measured by actual fuel loss and weight of inlet air.

Weight of fuel used per minute = .1490x7=1.044

To find W_a

$P_s = P_1$ = 29.620 " Hg. abs.

Inlet air Temperature = 80°F

Inlet air venturi h = 1.9 + 2.9 = 4.8 " H_2O

From Curve W_a = 68#/Min.

$\therefore$ $A.F = \frac{6.8}{1.044} = 65$

64.5 = 65 therefore Orsat Analysis Assumed to be correct.

To solve for Burner Temperature.

This is a trial and error solution.

Knowing T_2 and estimating T_5

$L.H.V.(W_t) = W \Delta H$

$L.H.V.(W_t) = W_{CO_2} + H_{CO_2} + W_{O_2} + H_{O_2} + W_{CO} + H_{CO} + W_{N_2} + H_{N_2}$

$+ W_{H_2O} + H_{H_2O}$

			h_2	h_5 for T_{05}=1800°R	
lbs.	CO_2	= 101.1	14	326.4	31,500
	O_2	= 52	15	304.6	150,000
	CO	16.8	17	332.4	53,000
	H_2	225°	16.9	328.9	650,000
	H_2O	93.5	52.9	617.9	46,000
				Total	880,500

$$L.H.V.(W_t) = W\ h$$

$$46.4(19,000) = 880,500$$

$$880,000 = 880,500$$

$\therefore$ Burner temperature is 1800°R = 1340°F

True gas temperature was calculated by method previously explained to be 1365°F.

Therefore both methods check fairly well. So calculations previously used for burner gas stream temperature can be assumed to be accurate.

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TABLE Ia (TEST DATA)

Test No.	Total Time	Comp. inlet °F (a)	(b)	Pot. Temp. °F	Comp. Disch. (a) (1)	(b) (3)	(a) Bleed air (4)	(b) Burner (5)	(a) Discharge (6)	(b) (7)	(c) Turb. Exh. (8)	(a) (9)	(b) (10)	(c) (11)	Burner wall (12)	Ex. wall (13) ... Thermocouple Number all readings in M.V.
1a																
2a		84	86	81	1.5	1.5	.8	.8	27.2	25.4	26	23	23.2	23.2	20.8	20.2
b		84	86.2	82.5	1.5	1.5	1.3	1.32	28.0	26.0	26.2	23.5	23.5	23.5	21.3	20.4
c		84.2	85	83.0	1.5	1.5	1.58	1.58	29.4	26.	27	24.2	24.4	24.4	22.4	21.0
d		84	85	83.0	1.52	1.52	1.7	1.69	29.7	25.2	27.2	24.1	24.1	24.1	22.8	21.6
e		86	89	83.5	1.53	1.51	1.71	1.71	29.8	25.2	27.1	24.1	24.2	24.2	23.0	21.0
f		81	83.5	82.3	1.39	1.35	1.66	1.66	29.42	24.6	26.4	23.8	23.6	23.6	22.6	20.9
g		83.5	86	83	1.41	1.41	1.71	1.71	30.2	25.4	26.8	24.2	24.2	24.2	23.0	21.2
3a		76.5	77	7.4	1.83	1.75	1.33	1.32	28.2	26.5	27.5	23.75	24.2	23.8	22	21
b		77	76	77	2.19	2.1	2.12	2.12	29.3	27.0	27.8	24.4	24.9	24.6	22.9	22
c		76	75	78.2	2.15	2.1	2.29	2.27	29.8	27.1	27.9	24.5	25.0	24.7	23.2	22.1
d		78	77.5	80	1.85	1.79	1.95	1.95	30.1	26.8	28.0	24.4	25.0	24.7	23.2	22.0
e		78	77.5	84	1.90	1.86	2.05	2.05	31.7	26.7	28.0	24.6	25.1	24.8	23.9	22.1
4a		1.69	1.61	78.1	1.69	1.61	1.0	1.0	25.4	26.6	26.8	23.5	23.0	23.2	21.5	20.1
b		1.10	1.65	78.0	1.70	1.65	1.45	1.45	26.3	27.1	27.1	24.0	23.5	23.6	21.9	20.6
c		1.69	1.60	80.5	1.69	1.60	1.65	1.65	26.3	28.0	27.0	24.4	23.9	24.0	22.1	20.85
d		1.69	1.65	82.0	1.69	1.65	1.80	1.80	26.8	28.9	27.4	24.8	24.3	24.7	23.0	21.4
e		1.61	1.60	83.0	1.61	1.60	1.60	1.60	25.6	27.0	26.8	23.7	23.2	23.4	21.6	20.4
f		1.80	1.75	82.1	1.80	1.75	1.5	1.45	25.4	27.1	26.8	23.5	23.6	23.2	21.9	20.5
g		2.0	2.	84.5	2.0	2.1	1.52	1.50	25.4	27.4	27.3	23.6	23.2	23.3	22.6	20.0

TABLE Ia (TEST DATA)

		Idle Speed	Bar. Press. "Hg	Comp. Disch. "Hg ga.	Burner Disch. "Hg ga.		Turbine wheel static "H2O − L	+ R	Bleed air Orifice "H2O + L	− R	Inlet air Venturi "H2O + L	− R	Fuel level gals 2/min. Start	Stop	Bleed air "Hg.
2a	22.6	1000	29.909	6.42	6.2	0	4.55	1.78	0	0	2	3	8.2	7.8	0
b		975		6.1	5.9	0	4.3	1.65	.6	.9	2	3	8.2	7.8	–
c	24.4	990		6.3	6.05	0	4.15	1.35	2.4	2.6	2	3	8.2	7.8	.3
d	24.4	990		6.12	5.09	0	4.25	1.45	3.0	3.3	2.2	3.1	7.25	6.95	.4
e	24.4	1000		6.30	6.05	0	4.3	1.5	3.4	3.6	2.3	3.3	7.95	7.65	.45
f	23.7	990		6.3	6.05	0	4.3	1.5	4.6	5	2.3	3.3	6.85	6.55	.6
g	24.4	1000		6.3	6.1	0	4.3	1.5	6.0	6.5	2.4	3.4	4.45	4.1	.8
							−	+	+	−	+	−			
3a	25.2	1150	29.439	8.33	8.14		5.5	1.8	1.05	0.9	2.8	3.8	7.45	7.15	0.1
b	26.2	1150		8.45	8.30		5.6	1.25	2.1	2.0	2.95	4.05	4.65	4.32	.22
c	26.4	1150		8.56	8.36		5.55	1.70	3.05	3.0	3.0	4.15	5.8	5.49	.32
d	26.4	1150		8.40	8.20		5.4	1.55	3.90	3.75	2.9	4.05	9.2	8.85	.49
e	22.0	1150		8.38	8.10		5.25	1.45	5.55	5.5	3.0	4.1	6.35	5.85	.70
4a	24.7	1050	29.851	7.2	7.04		5.6	0.9	0	0	2.25	3.30	9.5	7.2	0
b	25.7	1050		7.12	6.95		5.55	0.8	.9	.7	2.30	3.40	5.6	5.25	.1
c	26.0	1050		7.05	6.90		5.40	0.65	1.65	1.4	2.3	3.40	9.25	8.88	.2
d	26.75	1050		7.02	6.90		5.25	0.5	2.80	2.70	2.25	3.35	7.05	6.75	.35
e	25.	1030		6.88	6.70		5.4	0.65	0	0	2.1	3.1	8.55	9.20	.58
f															
f	24.9	1125		8.25	8.0		6.25	1.5	0	0	2.7	4.2	10.0	9.25	
g	25.1	1200		9.40	9.16		6.70	1.95	0	0	3.2	4.3	7.45	7.15	

TABLE Ib (TEST DATA)

	(a)	(b)	(c)	(1)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
5a	82	84.2	84	1.65	1.65	0.9	0.9	25.2	26.4	25.9	22.8	23.0	22.0	21	21.8	22.6
b	78	80	79	1.65	1.63	1.55	1.55	27.0	29.5	28.5	24.6	25.2	24.8	22.5	23.6	26.3
	80	80	80	1.65	1.63	1.65	1.65	26.8	29.6	28.4	24.6	25.2	24.8	22.2	23.5	26.1
c	81	84	82.5	2.18	2.12	2.16	2.16	27.2	28.7	29.0	24.4	25.0	24.6	22.55	23.6	25.8
	81	84	84	2.12	2.10	2.18	2.18	27.0	28.8	29.2	24.4	25.0	24.7	22.60	23.8	25.8
d	82	86	84.4	2.18	2.08	2.18	2.18	26.8	28.5	28.95	24.2	24.6	24.4	22.6	23.75	25.5
	84	88.5	86	2.12	2.08	2.18	2.18	26.7	28.5	28.85	24.2	24.6	24.4	22.6	23.55	25.5
e	80	83	85	1.8	1.75	2.0	2.0	26.7	28.4	28.2	24.0	24.55	24.2	23.3	23.4	25.55
	81	85	86	1.8	1.70	2.0	2.0	26.8	28.2	28.2	24.0	24.55	24.25	23.2	23.4	25.6
f	80	83	86	1.5	1.45	1.8	1.8	26.0	28.3	28.1	24.0	24.50	24.2	21.8	23.1	25.4
	80	82	86	1.58	1.58	1.8	1.8	26.4	28.7	28.4	24.2	24.75	24.4	22.0	23.2	25.4
6a	79	89	79	2.5	2.42	1.28	1.28	26.4	28.4	29.3	24.0	24.4	24.1	22.6	22.8	25.2
b	80	92	81	2.55	2.5	1.9	1.9	27.0	28.8	29.65	24.3	24.8	24.4	23.0	23.4	25.9
c	81	90	82	2.65	2.5	2.2	2.2	27.4	29.0	29.8	24.6	25.0	24.8	23.4	23.8	26
d	80	91	83	2.52	2.49	2.42	2.42	28.1	29.55	29.9	24.9	25.4	25.1	23.75	24.2	26.4
e	82	93	84	2.58	2.48	2.5	2.5	28.5	29.72	29.72	25.0	25.6	25.3	24.0	24.4	26.6

TABLE Ib (TEST DATA)

	(1)	(2)	(3)	(4)	(5)	(6)	6		+ (7)	-	(8)		(9)
5a	1050	29.941	7.25	7.10	8.4	1.0	0	0	2.45	3.5	7.5	7.2	-
b	1050	29.908	7.20	7.05	8.3	2.4	2.3	2.2	2.2	3.4	8.2	7.85	0.3
	1050	29.908	7.10	6.9	8.2	2.6	2.3	2.2	2.15	3.3	9.1	8.7	0.3
c	1260	29.908	10.40	10.3	9.9	0.8	3.4	3.2	3.70	4.95	6.85	6.45	0.4
	1250	29.908	10.40	10.3	9.8	0.95	3.4	3.2	3.70	4.5			0.4
d	1255	29.908	10.46	10.22	9.9	0.8	2.2	2.3	3.75	4.9	9.45	9.05	0.34
	1250	29.908	10.32	10.1	9.9	0.8	2.6	2.3	3.75	4.9			0.32
e	1150	29.908	8.63	8.42	9.1	1.7	3.4	3.2	3.1	4.2	9.1	8.75	.42
	1150	29.908	8.60	8.42	9.1	1.7	3.4	3.2	3.05	4.15			.42
f	1050	29.908	7.1	6.9	8.5	2.3	3.4	3.1	2.4	3.55	6.65	6.35	.42
	1050		7.2	7.0	8.6	2.2	3.4	3.1	2.5	3.65			.42
6a	1390	30.072	13.1	12.85	6.2	5.2	0.3	0	4.5	5.9	7.2	6.8	0
b	1395	30.072	13.15	12.9	6.0	5.05	1.2	1	4.7	6.0	6.2	5.79	0.1
c	1390	30.072	13.05	12.8	5.9	4.9	2.4	2.2	4.75	6.0	9.4	8.97	0.3
d	1395	30.072	13.12	12.9	5.9	4.85	4.0	3.8	4.8	6.1	8.62	8.20	0.5
e	1395	30.072	13.1	12.8	5.7	4.7	5.1	4.9	4.9	6.2	6.5	6.08	0.63

TABLE Ic (TEST DATA)

	(1)	(2)		(3)		(4)			(5)		(6)		(7)	(8)	(9)
7a	80	91	83	2.52	2.42	2.5	2.5	28.2	33.3	29.8	26.0	26.6	26.5	25.4	25.1
b	82	94	83	2.5	2.42	2.62	2.62	28.0	32.4	29.4	25.8	26.2	26.0	25.1	24.9
8a	78.2	86	78	2.18	2.08	1.4	1.4	26.4	29.8	29.0	24.4	25.0	24.8	22.9	23.81
b	80	85	78.5	2.1	2.1	2.02	2.02	27.0	30.6	29.2	25.1	25.8	25.5	23.6	24.4
c	78.2	88	80	2.2	2.15	2.28	2.28	28.4	31.6	30	26	26.5	26.4	24.4	25.2
d	,81	90	81	2.18	2.1	2.38	2.38	27.7	31.2	29.6	25.6	26.2	26.0	24.2	25.1
e	79	92	82	2.19	2.09	2.30	2.30	26.9	30.4	29.1	25.0	25.4	25.2	23.6	24.4

TABLE Ic (TEST DATA)

7a	1390	29.712	12.75	12.42	4.4	4.3	6.1	6.1	4.4	5.7	.228
b	1380	29.712	12.8	12.58	4.5	4.3	7.3	6.9	4.6	5.9	.228
8a	1260	29.712	10.62	10.4	4.2	4.05	1.1	0.9	3.4	4.6	.194
b	1260	29.712	10.5	10.29	3.95	3.8	4.2	4.1	3.5	4.8	.200
c	1262	29.712	10.55	10.32	3.9	3.8	7.0	7.0	3.5	4.8	.214
d	1260	29.712	10.42	10.21	3.9	3.75	9.4	9.1	3.8	5.0	.222
e	1260	29.712	10.40	10.18	4.1	3.9	5.6	5.7	3.7	4.95	.1985

TABLE Id

ORSAT ANALYSIS DATA (10,000 r.p.m.)

RUN NO.	CO_2	O_2	CO	
1	3.1	12.9	0.8	
2	2.6	11.1	0.4	
3	3.0	14.0	0.9	
4	3.0	12	1.1	
5	2.5	16.2	0.6	
6	2.4	16.1	0.7	
7	2.4	16.2	0.6	Sample taken at
8	2.4	16.2	0.6	same distance from
9	2.4	16.2	0.6	outside of gas stream

TABLE Ie

VALUES OF K

REYNOLDS NUMBERS	15,000	25,000	35,000	50,000	75,000	100,000
			K			
.300	.6081	.6054	.6039	.6027	.6015	.6008
3.50	.6123	.6069	.6081	.6067	.6055	.6047

TABLE 2a (RESULTS)

Test	N_a	N_s	t_{1a}	t_2	t_3	t_5	t_6	t_{w5}	t_{w6}
2a	9500	9260	85	151	119.0	1223.1	1090	779.7	750
b	9250	8800	85.1	152.5	144.1	1242.5	1106.7	787.5	748.2
c	940	8950	84.6	153	150.6	1276.5	1142.2	823.7	778
d	9400	8950	84.5	153.8	161.6	1276.5	1132.6	836.7	797.7
e	9500	9220	87.5	154.3	168.7	1277.0	1136.9	843.5	778.5
f	9400	9060	82.75	146.3	159.5	1231.5	1114.3	829.3	774.3
g	9500	9260	84.75	149	162.2	1276.4	1136.8	843	784.7
3a	10920	10750	76.75	156.8	135.6	1263.2	1122.8	801.7	769
b	10920	10750	76.5	173.8	174.2	1291.6	1147.4	834	803.7
c	10920	10750	76.5	176.2	182.2	1305.2	1153.2	844.9	809.2
d	10920	10740	77.75	164	169.6	1307	1155	846.7	807.7
e	10920	10740	77.75	170.8	178.0	1319.8	1163.2	873.3	815
4a	10000	9780	80.5	154.1	125.3	1220.1	1090.0	789.4	744.4
b	10000	9780	81	156.0	145.6	1241.4	1109.2	802.3	760
c	10000	9775	82	156.5	157.1	1257.1	1130.1	811.8	770.5
d	10000	9780	81	159.6	165.2	1283.6	1156.4	842	790.3
e	9800	9600	80.5	157.6	157.4	1233.8	1103	797.7	758.7
f	10680	10400	82	164.2	151.2	1228.4	1098	806.5	760.9
g	11400	11100	82	178.5	154.9	1243.7	1104.5	831.5	747.2
5a	10000	9760	83.1	160.5		1205		779	
b	10000	9800	79.3	160	154	1315		820	
c	11920	11660	80	180.8	183	1312		830	
d	11900	11620	85.1	183	185	1303		832.3	
e	10920	10700	82.3	167	178.5	1295.5		864.5	
f	10000	10700	81.3	155	169	1286		811	

TABLE 2a (RESULTS)

Test	W_a	Q_a	Q_s	P_2/P_1	c	P_5/P_6	W_b	W_b/W_a	W_t	t_5
2a	69.0	945	921	1.215	.472	1.189	0	0	1.05	1353.1
b	69.0	945	921	1.205	.452	1.180		.0254	1.05	1372
c	69.0	943	920	1.210	.451	1.185	3.15	.0456	1.05	1392
d	70.5	961	939	1.205	.434	1.180	3.65	.0518	1.05	1386
e	72.0	995	968	1.210	.454	1.185	3.72	.0517	1.05	1387
f	72.0	985	964	1.210	.462	1.185	4.36	.0606	1.05	1351
g	72.0	988	965	1.210	.466	1.188	5.04	.0698	1.25	1401
3a	75.0	1030	1010	1.279	.48	1.254	2.0	.0267	1.05	1393
b	81.0	1110	1090	1.286	.407	1.260	2.81	.0347	1.165	1421
c	82.0	1125	1105	1.290	.404	1.261	3.40	.0414	1.05	1435
d	81.0	1115	1095	1.285	.408	1.258	3.87	.0477	1.25	1427
e	82.0	1128	1108	1.283	.429	1.255	4.61	.0564		1450
4a	73.0	995	975	1.242	.483	1.218	0	0	1.05	1350
b	73.5	1004	985	1.237	.443	1.215	1.825	.0248	1.25	1371
c	73.5	1005	986	1.236	.4445	1.212	2.042	.0295	1.295	1387
d	73.0	1000	979	1.235	.434	1.213	3.34	.0458	1.05	1413
e	71.0	965	945	1.230	.4255	1.204	0	0	1.225	1364
f	80.5	1100	1078	1.275	.484	1.	0	0	1.225	1358
g	83.6	1140	1117	1.313	.448	1.280	0	0	1.05	1374
5a	73	995	970	1.24	.436	1.212	0	0	1.05	1305
b	72	985	965	1.238	.407	1.219	3.02	.042	1.35	1410
c	88	1095	1075	1.349	.475	1.316	3.66	.0416	1.40	1405
d	88	1205	1175	1.347	.495	1.311	3.07	.0349	1.40	1398
e	82	1120	1094	1.289	.471	1.258	3.68	.0449	1.35	1385
f	76	1032	1010	1.238	.455	1.214	3.59	.0472	1.05	1366

TABLE 2b (RESULTS)

Test No	N_a	N_s	T_{1a}	T_2	T_3	T_5	T_{W_5}	T_{g_5}* (actual)	W_a
6a	13200	12900	84	196		1294	826	1390	97
b	13220	12950	86	201	169	1303	841	1410	99
c	13200	12900	85.5	200.5	182	1326	856	1418	100
d	13220	12900	85.5	199.5	193	1348	868	1432	101
e	13220	12900	87.5	202.5	198	1354	878	1440	102
7a	13200	12900	85.5	194	197	1401	920	1500	103
b	13200	12900	88	197	201	1382	911	1480	104
8a	12000	11770	82.1	176	144	1311	835	1400	86
b	12000	11770	82.5	175	171.5	1327	858.5	1420	87.5
c	12000	11760	83.1	180	184	1380	886	1480	87.5
d	12000	11750	85.5	179	189	1361	880	1458	90
e	12000	11750	85.5	180	187	1330	862	1426	89

TABLE 2b RESULTS)

Test No.	Q_a	Q_s	P_2/P_1	η_c	P_5/P_6	W_b	W_b/W_a	W_t
6a	1315	1285	1.435	.567	1.385	0	0	1.4
b	1350	1315	1.437	.564	1.386	2.29	.0231	1.435
c	1362	1330	1.434	.562	1.386	3.00	.030	1.45
d	1380	1345	1.436	.563	1.387	3.89	.0385	1.47
e	1400	1360	1.435	.562	1.388	4.00	.0392	1.47
7a	1360	1330	1.420	.544	1.390	4.93	.0513	1.585
b	1380	1342	1.425	.537	1.393	5.20	.0536	1.595
8a	1125	1100	1.355	.545	1.325	2.02	.0235	1.36
b	1144	1114	1.350	.542	1.321	3.98	.0455	1.40
c	1145	1114	1.350	.542	1.322	5.25	.0599	1.50
d	1183	1155	1.345	.540	1.318	5.86	.0651	1.52
e	1170	1141	1.344	.540	1.316	4.69	.0526	1.39

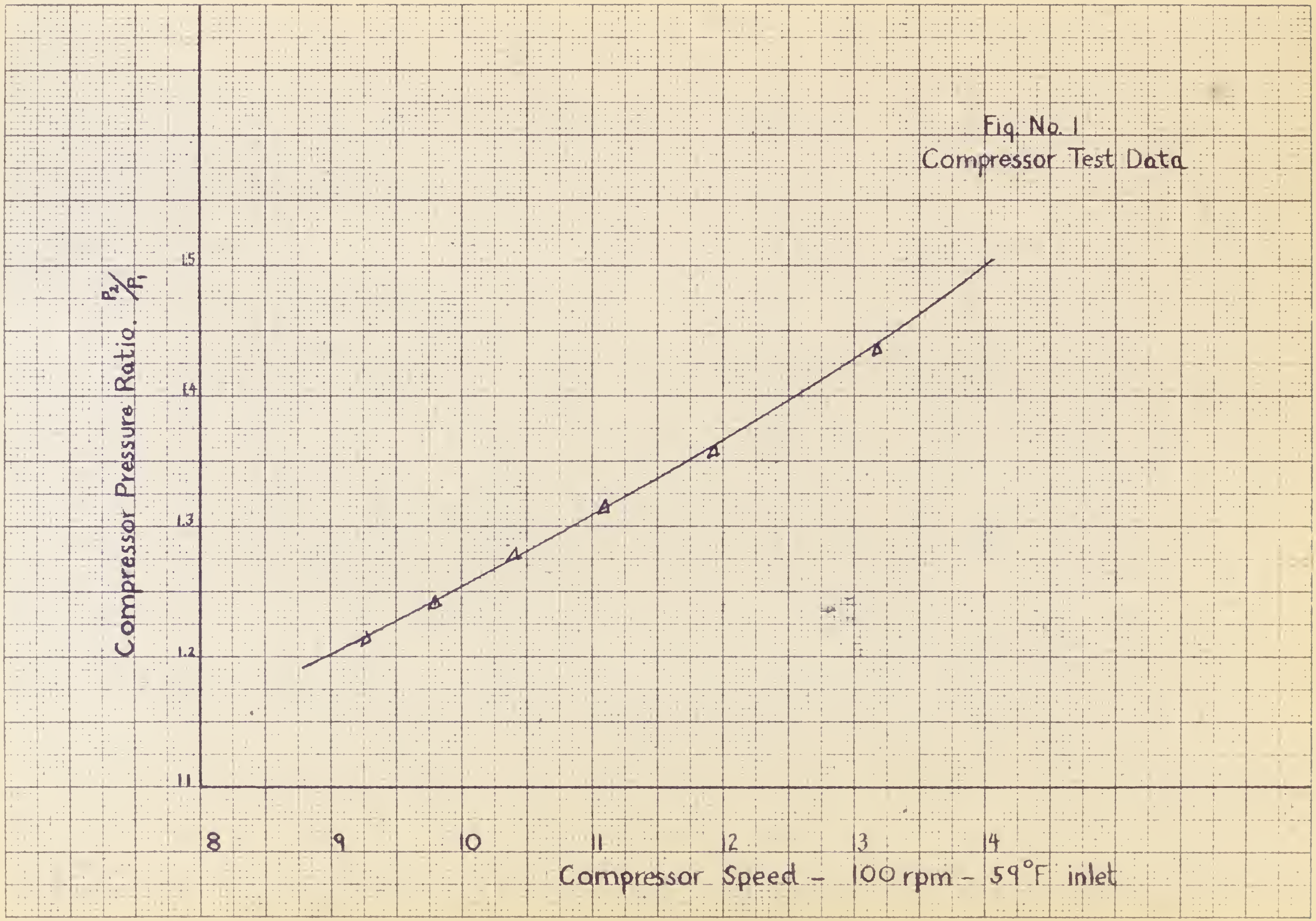


Fig. No. 1
Compressor Test Data

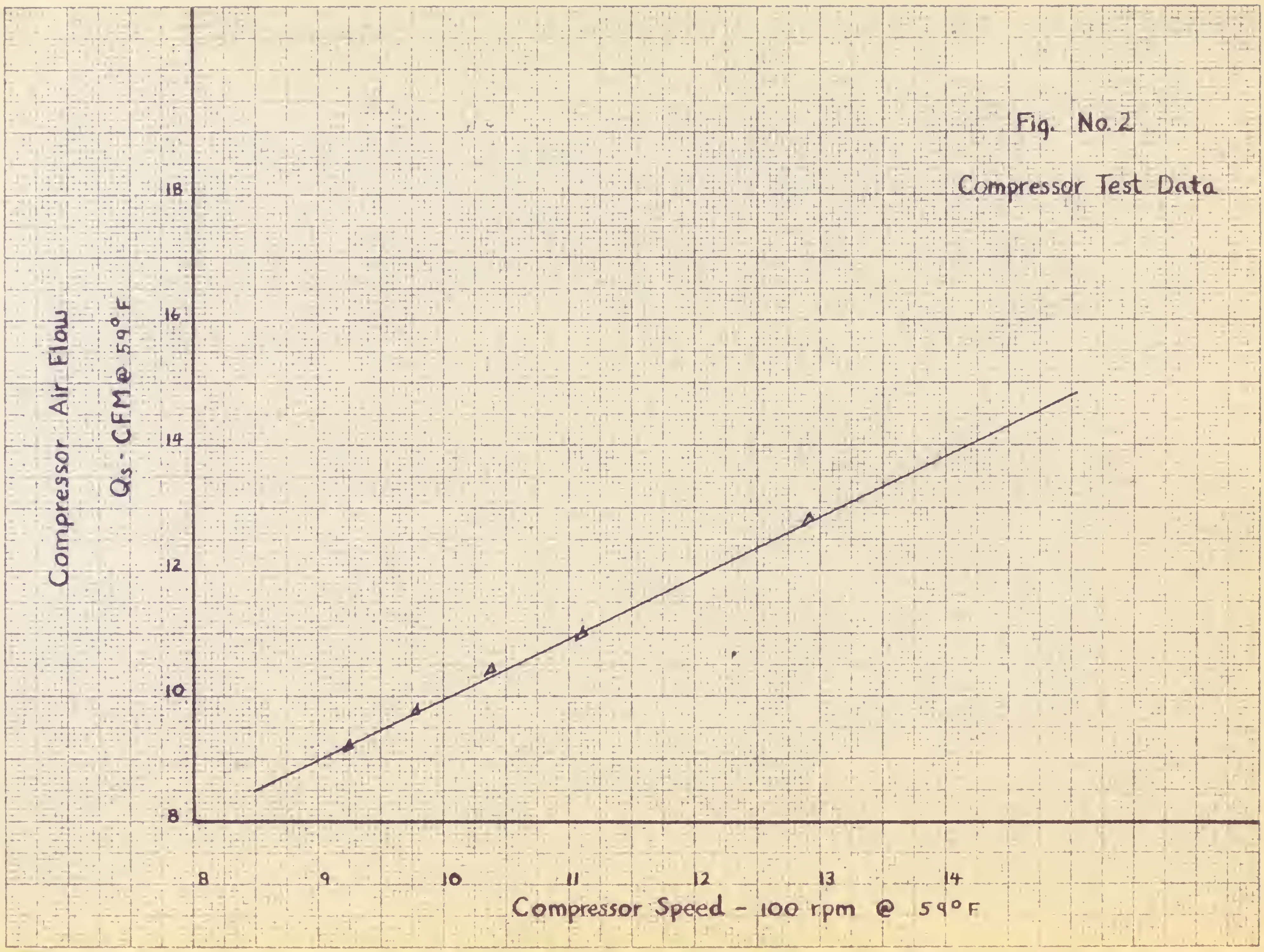


Fig. No. 2
Compressor Test Data
Compressor Air Flow
Qs - CFM @ 59°F
18
16
14
12
10
8
8
9
10
11
12
13
14
Compressor Speed - 100 rpm @ 59°F

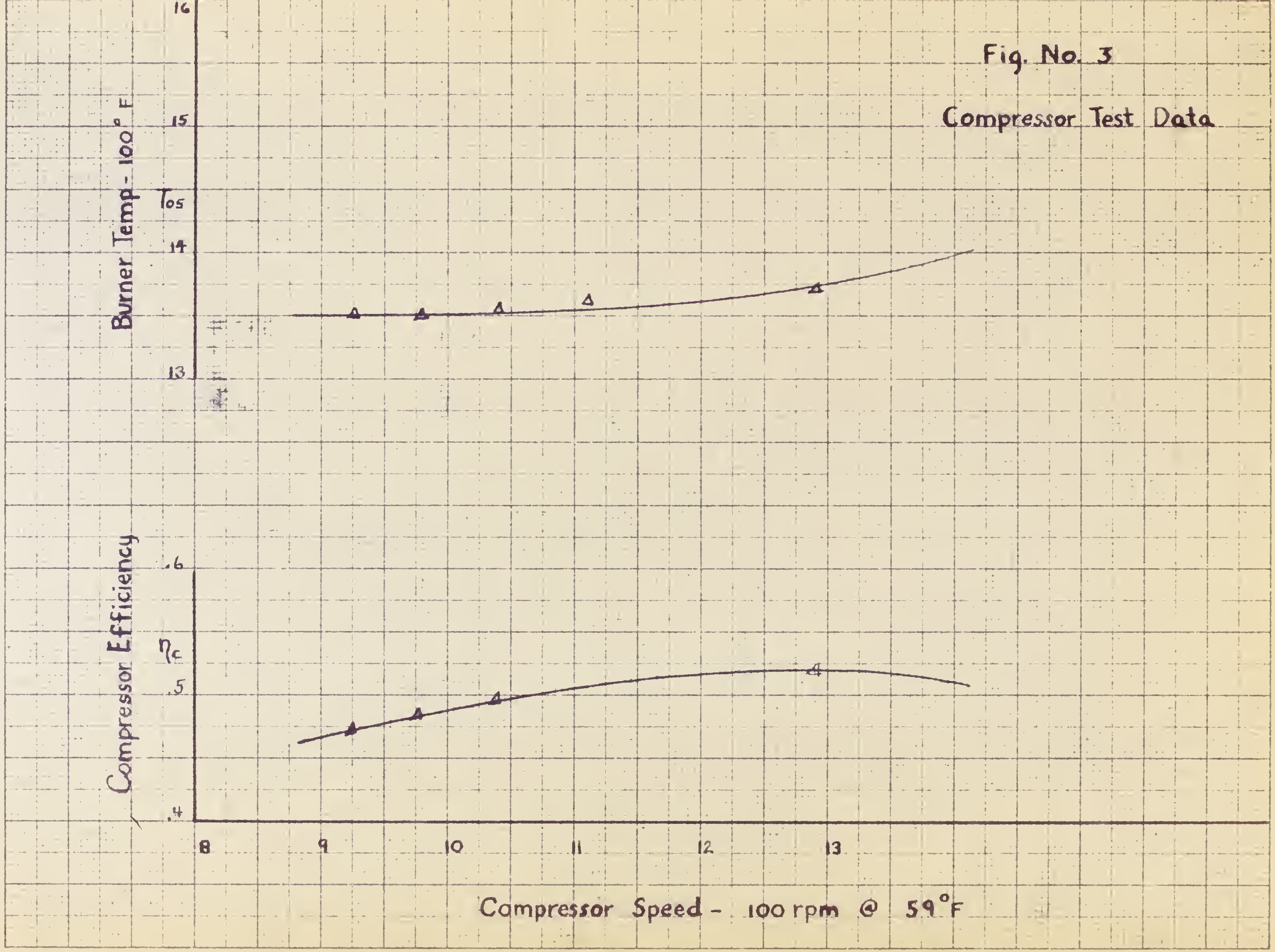


Fig. No. 3
Compressor Test Data
Burner Temp - 100° F
T_{os}
16
15
14
13
Compressor Efficiency
η_c
.6
.5
.4
8
9
10
11
12
13
Compressor Speed - 100 rpm @ 59°F

Fig. No. 4

Performance Data

Fuel Rate vs W_b/W_a

Fig. No 5
Performance Data

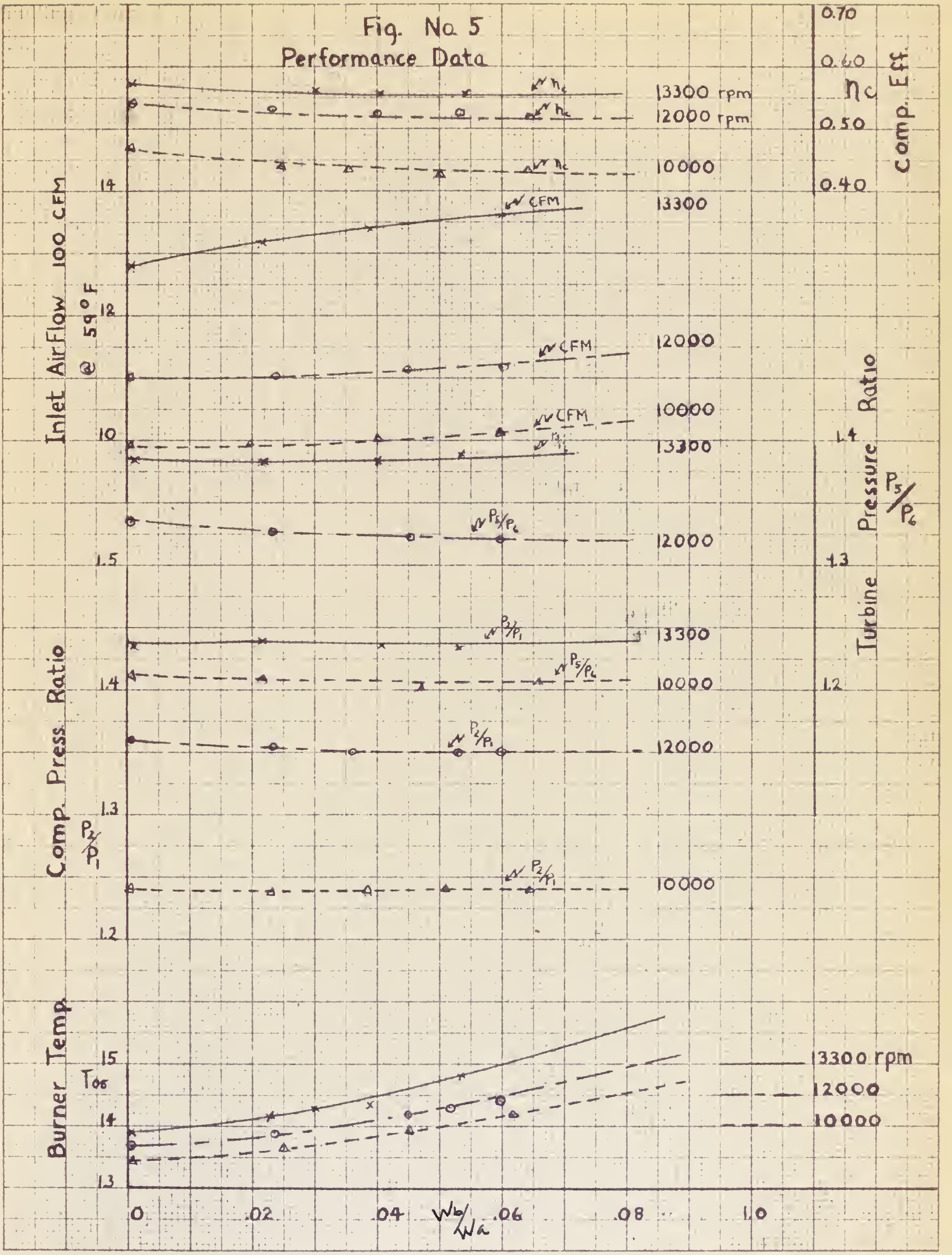
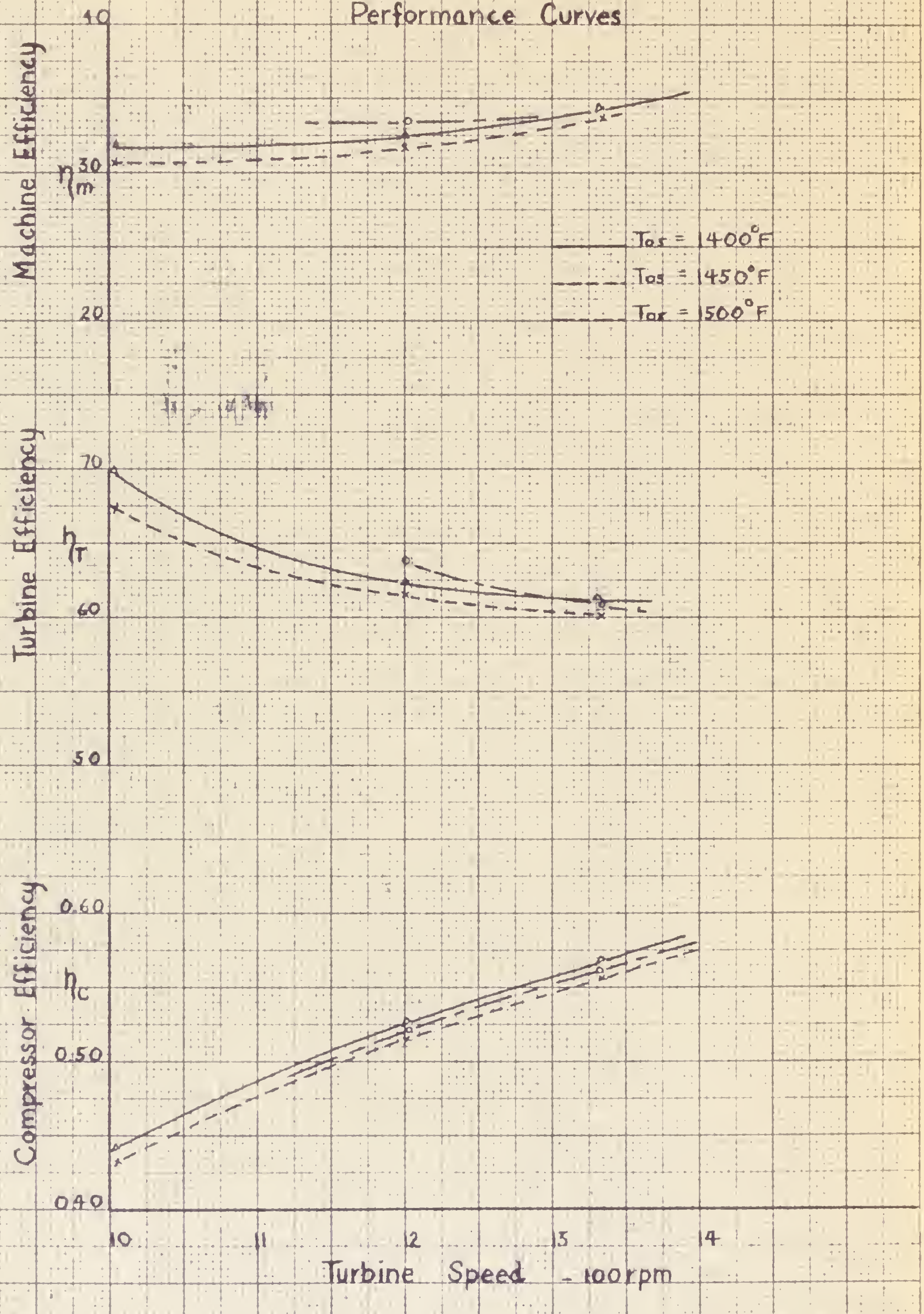


Fig. No. 6

Performance Curves



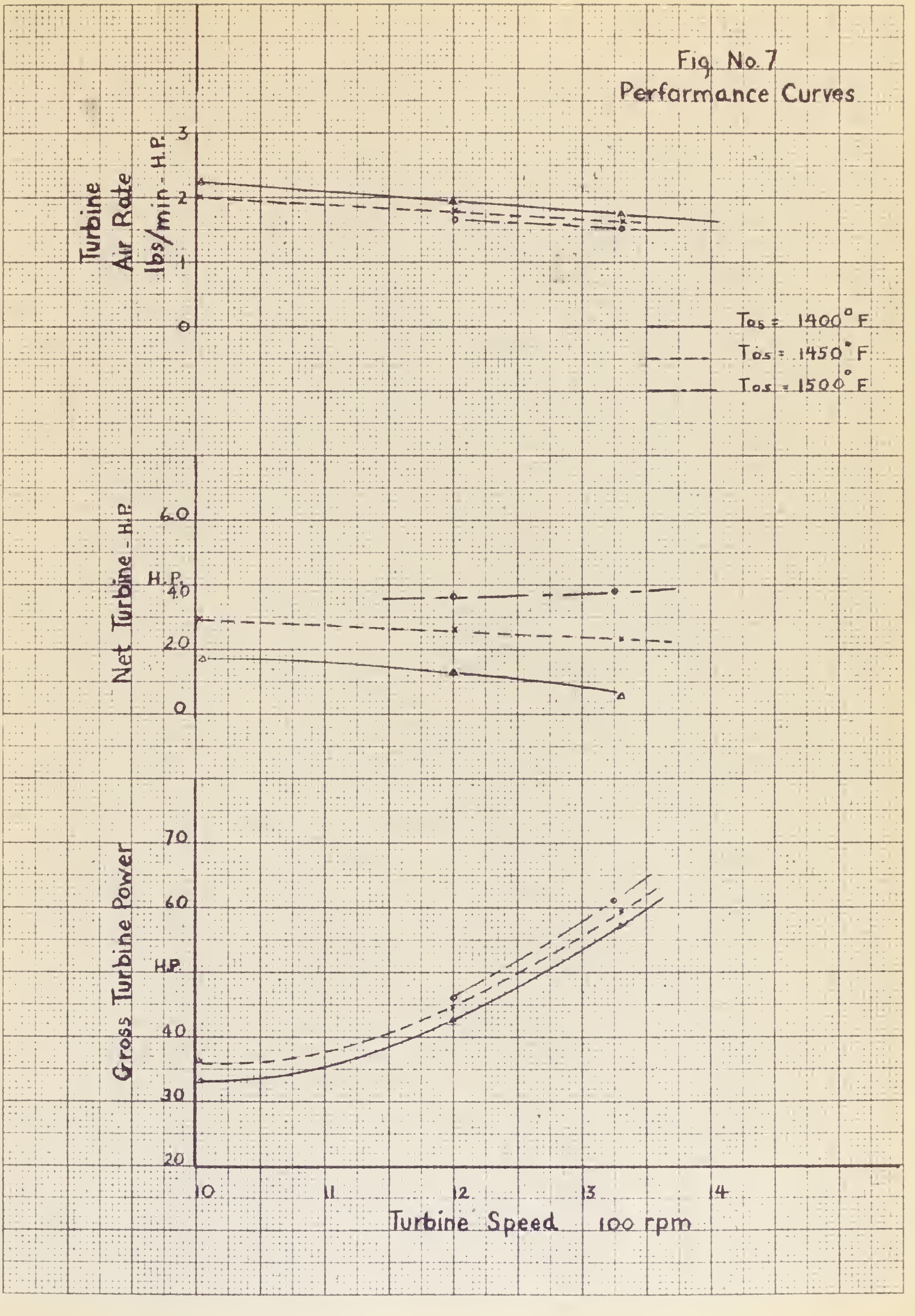


Fig. No. 7
Performance Curves
Turbine Air Rate lbs/min - H.P.
3
2
1
0
Tos = 1400° F
Tos = 1450° F
Tos = 1500° F
Net Turbine - H.P.
H.P.
6.0
4.0
2.0
0
Gross Turbine Power
H.P.
70
60
40
30
20
10
11
12
13
14
Turbine Speed 100 rpm

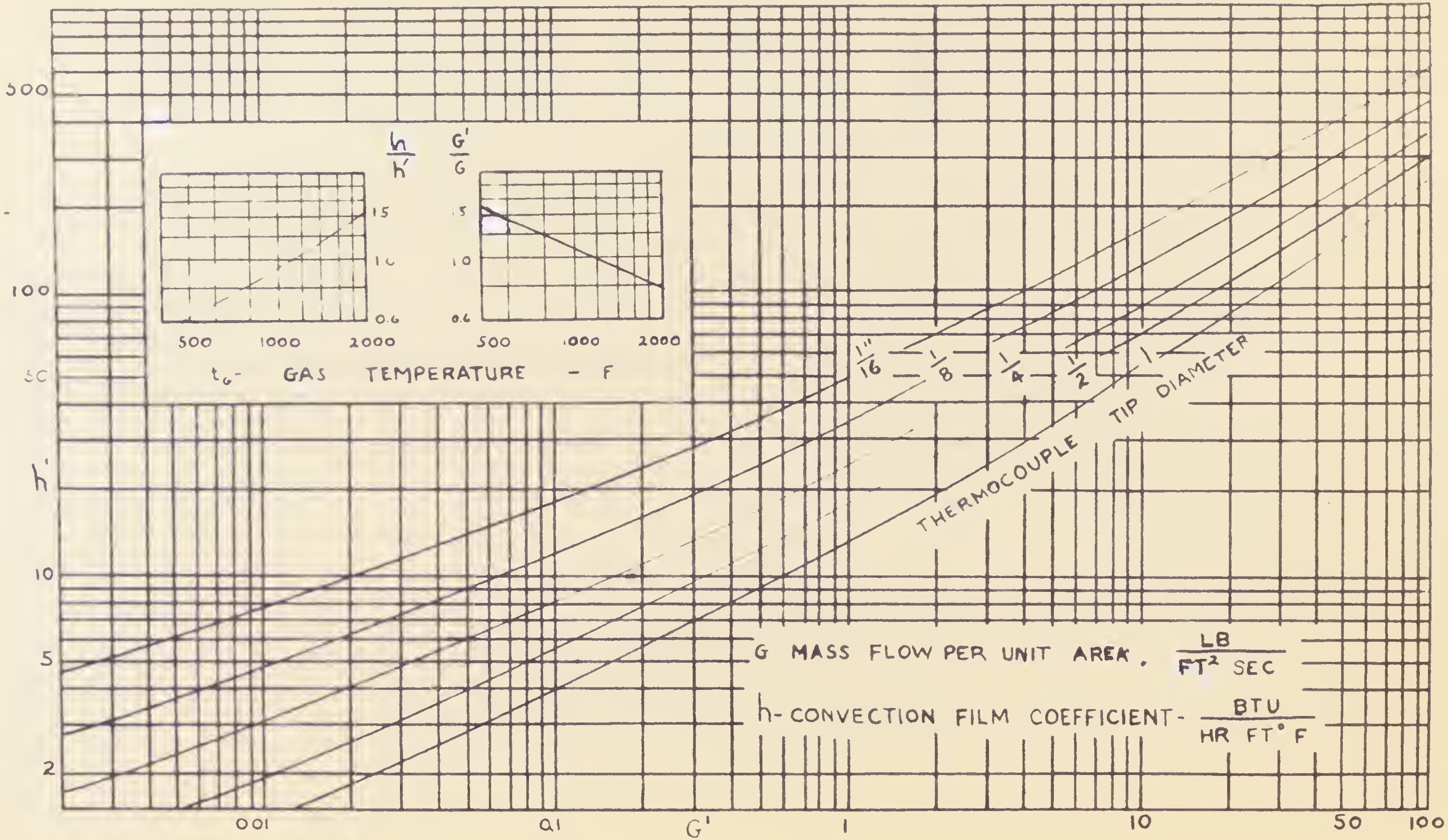


DIAGRAM FOR DETERMINING FILM COEFFICIENT OF HEAT TRANSFER FOR SINGLE CYLINDERS NORMAL TO GAS STREAM

FIGURE 8

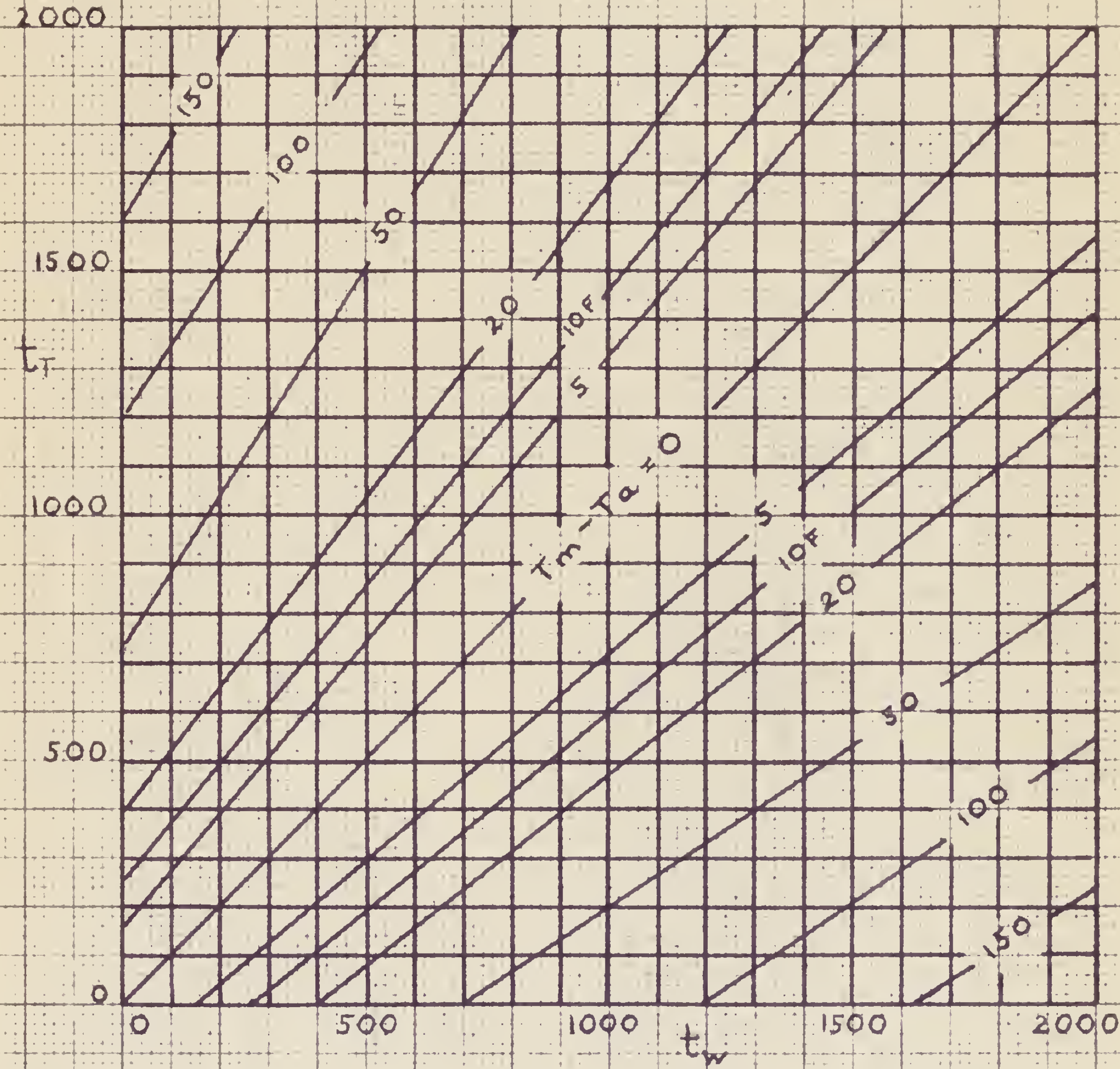


DIAGRAM FOR DETERMINING Tm − Ta

Figure 9

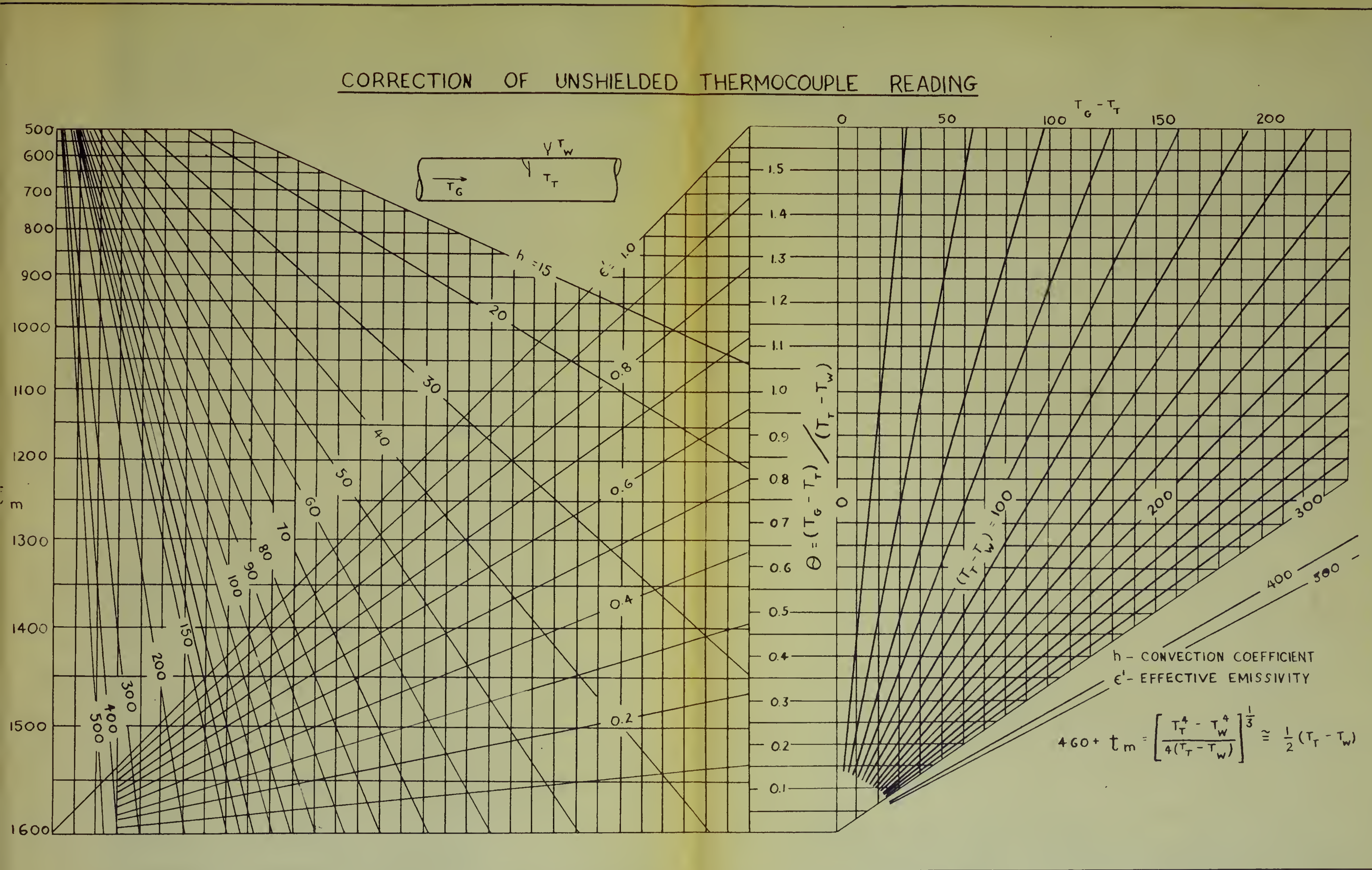


DIAGRAM FOR UNSHIELDED-THERMOCOUPLE CORRECTION

FIGURE 10

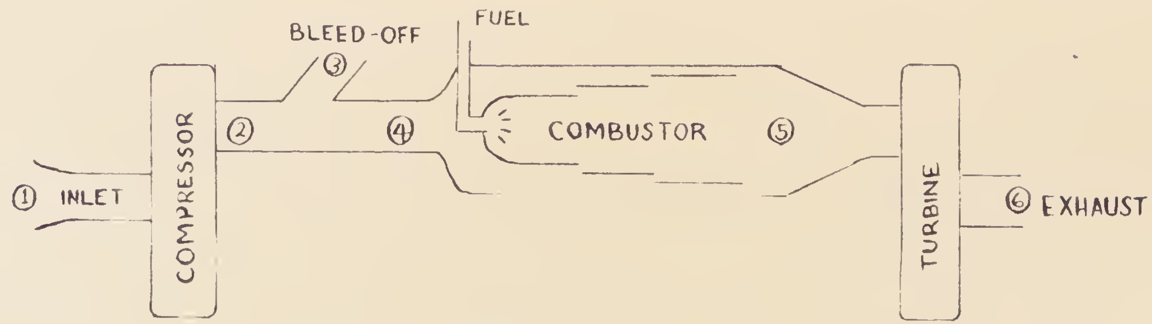


FIGURE II
SCHEMATIC DIAGRAM OF UNIT

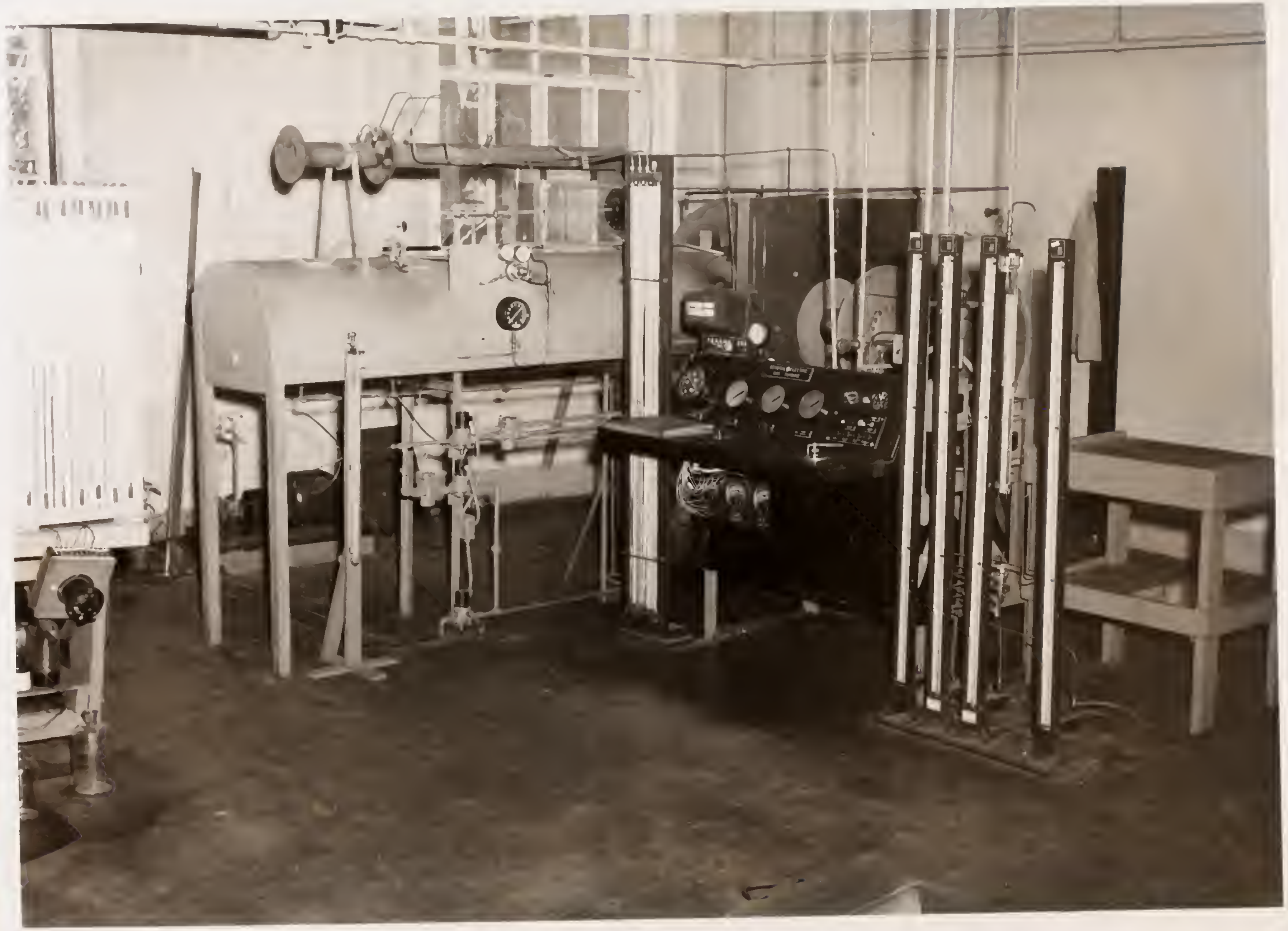


Figure 12
Control Panel, Bleed line, and Burner Shield

Figure 13
Inlet air shield to Compressor

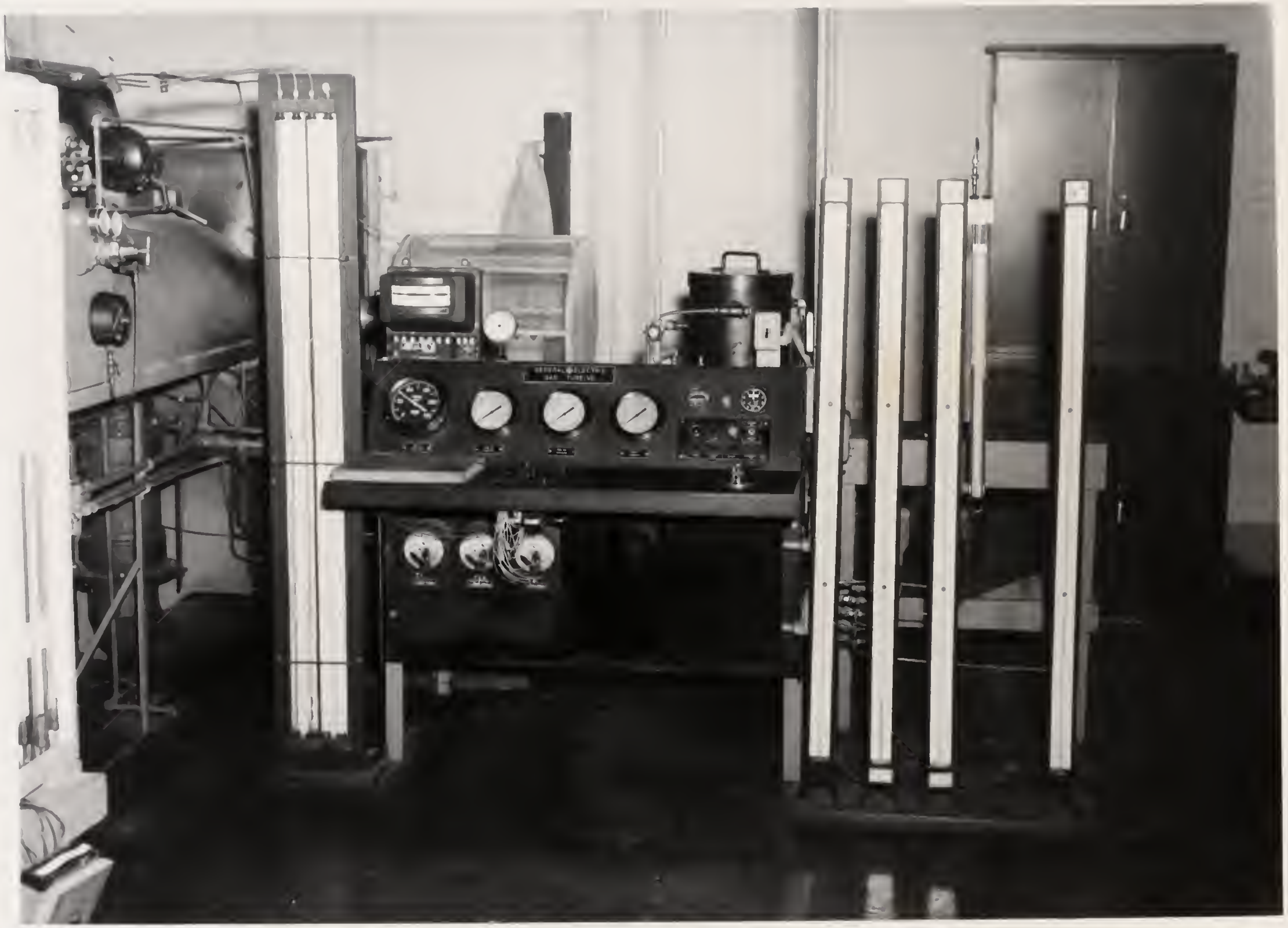


Figure 14
Control Panel and Pressure Manometers

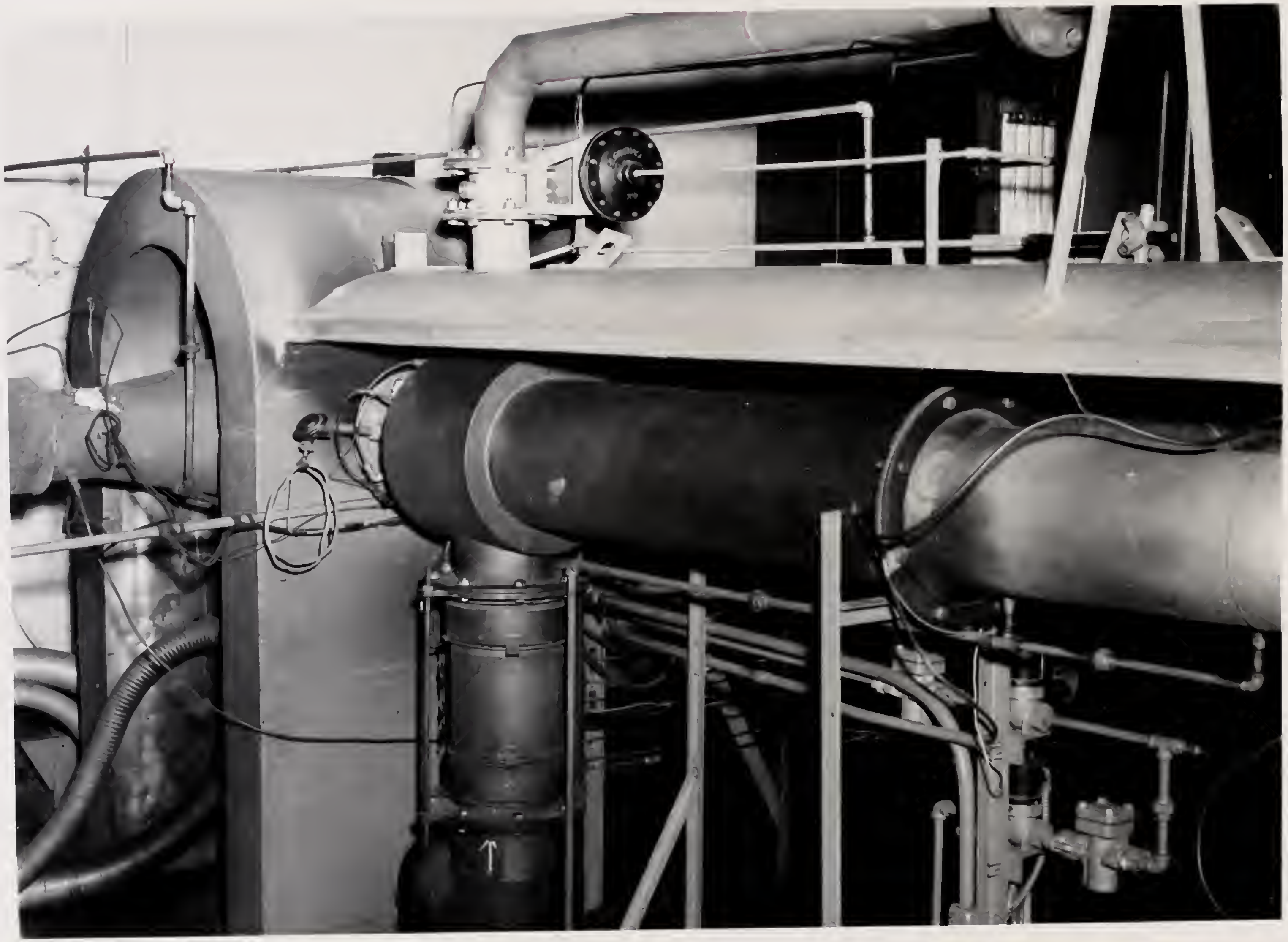


Figure 15
Burner and Turbine Wheel Shield