A REPORT ON INCREASING THE THRUST OF A TURBOJET ENGINE BY COMBUSTION OF FUEL IN THE TAIL PIPE

Thesis by

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I. SUMMARY AND ACKNOWLEDGEMENTS

The purpose of this work was to develop a means of increasing the thrust of a turbojet engine by burning kerosene in the tail pipe.*

A combustion system was developed which gave the following results:

(1) Maximum thrust increase using a G.E. I-14 engine was 64 per cent over straight tail pipe thrust corresponding to 42 per cent increase over the normal engine thrust. This increase was accomplished at an engine rpm of 12,000.

(2) Increase of maximum thrust obtained was 51 per cent over the straight tail pipe thrust corresponding to 23 per cent over the normal engine thrust. This increase was accomplished at an engine rpm of 16,000.

(3) For the thrust increases mentioned in (1) and (2) above, increases of Specific Fuel Consumption were 66 per cent and 78 per cent respectively over normal engine SFC.

This experimental work was performed at the California Institute of Technology Thermojet Laboratory during the period March, 1945 to June, 1945.

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velopments originated by him.

II. INTRODUCTION

Since the thrust variation of a turbojet with forward speed is quite small, a unit designed for flight operation will have available for take-off only a slightly greater thrust than that developed at top speed. Comparing this with a conventional engine where the thrust decreases radically with increasing speed, it can readily be visualized that the take-off thrust of the turbojet will be much less than that of a conventional engine-propeller combination, with approximately the same or even inferior high speed performance. This characteristic of the turbojet results in notably poor take-off characteristics.

It is the object of this investigation to achieve an increase in the thrust delivered by a turbojet unit by developing means of reheating of the exhaust gases leaving the turbine. This method, usually referred to as "tail pipe injection", permits the further addition of heat, with its resultant increase of stream energy, without raising the temperature of the turbine blades, which are already operating near their ultimate margin of safety with present day materials.

Some research has been undertaken on this and other means of thrust boosting (Cf Refs 1 and 2) with positive results. This report discusses some of the theoretical aspects of the problem and presents test results of increase in thrust obtained by the development of a tail pipe injection system.

III. THEORETICAL ANALYSIS

SYMBOLS

Values or units used in computations are given with appropriate items.

$(\ )_1$	Subscript referring to conditions before combustion
$(\ )_2$	Subscript referring to conditions after combustion
A	Area, sq ft
a	Velocity of sound, ft/sec
C_H	Heating ratio = $\frac{\text{Heat added per unit mass}}{\text{Total energy per unit mass}}$
C_p	Specific heat at constant pressure, 0.276 Btu/(lb)($^{\circ}$R)
F	Thrust, lb
H	Total heat added, Btu
h	Heat added per unit mass, Btu/Slug
M	Mach number
m	Mass flow per unit time, Slugs/sec
P	Total pressure, lb/sq in
p	Static pressure, lb/sq in
R	Gas constant, 53.6 ft lb/(lb)($^{\circ}$R)
T	Absolute temperature, Degrees Rankine
v	Local velocity, ft/sec
γ	Ratio of specific heats, 1.33
ρ	Density (Mass per unit volume), Slugs/cu ft

With combustion in the tail pipe, there will be a great increase in the volume of gas to be handled. However, the normal turbojet unit is so designed that, with its nozzle installed, near sonic velocities are attained at the throat at maximum designed outputs. Such a condition would prevent the increase of maximum designed thrust by tail pipe injection, once a Mach number of one was reached in the nozzle throat. For this reason the nozzle was considered to be removed and the analysis was based on the addition of heat in a tail pipe of constant cross-sectional area.

Certain assumptions were made to simplify the problem so that a direct analytical approach could be taken. Namely, the assumptions made were:

(1) Constant specific heat throughout.

(2) Mass of fuel added is negligible compared to that of the gases from the turbine.

(3) Friction losses along the pipe are neglected.

(4) Mixing of gases occure without loss in such a manner that the entire stream is heated uniformly.

The following discussion is based on the theory outlined in Ref 3. Fig 1 illustrates the conventions used.

From the condition of continuity of flow,

$$\rho_1 v_1 A_1 = \rho_2 v_2 A_2$$

since $A_1 = A_2$

$$\rho_1 v_1 = \rho_2 v_2 \tag{1}$$

Equating the change of momentum to the forces,

$$\rho_2 v_2^2 A_2 - \rho_1 v_1^2 A_1 = A_2(p_1 - p_2)$$

$$\text{or,}\quad \rho_2 v_2^2 - \rho_1 v_1^2 = p_1 - p_2 \tag{2}$$

The energy equation, if H equals the heat added, becomes:

$$A_1 \rho_1 v_1 (C_p T_1 + \frac{1}{2} v_1^2) + H = A_2 \rho_2 v_2 (C_p T_2 + \frac{1}{2} v_2^2) \tag{3}$$

From the equation of state,

$$\frac{p}{\rho} = RT \quad \text{or} \quad C_p T = \frac{\gamma}{\gamma - 1} \frac{p}{\rho} \tag{4}$$

Introducing Eq (4) into the energy equation and eliminating the temperature,

$$\rho_1 v_1 A_1 (\frac{\gamma}{\gamma-1} \frac{p_1}{\rho_1} + \frac{1}{2} v_1^2) + H = \rho_2 v_2 A_2 (\frac{\gamma}{\gamma-1} \frac{p_2}{\rho_2} + \frac{1}{2} v_2^2) \tag{5}$$

Since the mass flow is given by,

$$m = \rho_1 v_1 A_1 = \rho_2 v_2 A_2 \tag{6}$$

we can rewrite the momentum equation in the following form:

$$m (v_2 - v_1) = A_2 (p_1 - p_2) \tag{7}$$

Let h be the heat added per unit mass, i.e.,

$$h = H/m \tag{8}$$

then Eq (5) may be written as follows:

$$\frac{\gamma}{\gamma-1}\frac{p_1}{\rho_1}+\frac{1}{2}v_1^2+h=\frac{\gamma}{\gamma-1}\frac{p_2}{\rho_2}+\frac{1}{2}v_2^2 \tag{9}$$

or by rewriting

$$\left[\frac{\gamma}{\gamma-1}\frac{p_1}{\rho_1}+\frac{1}{2}v_1^2\right]\left[1+\frac{h}{\frac{\gamma}{\gamma-1}\frac{p_1}{\rho_1}+\frac{1}{2}v_1^2}\right]=\frac{\gamma}{\gamma-1}\frac{p_2}{\rho_2}+\frac{1}{2}v_2^2 \tag{10}$$

The heating ratio C_H will be defined in the form

$$C_H = \frac{\text{Heat added per unit mass}}{\text{Total energy of entering gas per unit mass}}$$

or

$$C_H = \frac{h}{\frac{\gamma}{\gamma-1}\frac{p_1}{\rho_1}+\frac{1}{2}v_1^2} \tag{10a}$$

Since

$$\gamma\frac{p}{\rho} = a^2 \tag{10b}$$

the expression in Eq (10)

$$\frac{\gamma}{\gamma-1}\frac{p_1}{\rho_1}+\frac{1}{2}v_1^2 = \frac{a_1^2}{\gamma-1}+\frac{1}{2}v_1^2 = \left(1+\frac{\gamma-1}{2}M_1^2\right)\frac{a_1^2}{\gamma-1} \tag{10c}$$

then using Eqs (1) and (2) to replace p_2 and ρ_2 in the expression below

$$\frac{\gamma}{\gamma-1}\frac{p_2}{\rho_2}=\frac{\gamma}{\gamma-1}\left[\frac{p_1-\rho_2 v_2^2+\rho_1 v_1^2}{\rho_1\frac{v_1}{v_2}}\right]$$

$$\frac{\gamma}{\gamma-1}\,\frac{p_2}{\rho_2} = \frac{1}{\gamma-1}\left[\frac{\gamma p_1}{\rho_1}\left(\frac{v_2}{v_1}\right) - \gamma v_1^2\left(\frac{v_2}{v_1}\right)^2 + \gamma v_1^2\left(\frac{v_2}{v_1}\right)\right]$$

$$\frac{\gamma}{\gamma-1}\,\frac{p_2}{\rho_2} = \frac{a_1^2}{\gamma-1}\left[\frac{v_2}{v_1} - \gamma M_1^2\left(\frac{v_2}{v_1}\right)^2 + \gamma M_1^2\left(\frac{v_2}{v_1}\right)\right]$$

$$\frac{\gamma}{\gamma-1}\,\frac{p_2}{\rho_2} = \frac{a_1^2}{\gamma-1}\left[\frac{v_2}{v_1}\left(1+\gamma M_1^2\right) - \gamma M_1^2\left(\frac{v_2}{v_1}\right)^2\right] \qquad (10d)$$

and also

$$\frac{1}{2}v_2^2 = \frac{a_1^2}{\gamma-1}\left(\frac{\gamma-1}{2}\right)M_1^2\left(\frac{v_2}{v_1}\right)^2 \qquad (10e)$$

Substituting the five Eqs (10a) to (10e) in Eq (10), we obtain:

$$(1+C_H)\left(1+\frac{\gamma-1}{2}M_1^2\right)\frac{a_1^2}{\gamma-1} = \frac{a_1^2}{\gamma-1}\left[\left(1+\gamma M_1^2\right)\frac{v_2}{v_1} - \gamma M_1^2\left(\frac{v_2}{v_1}\right)^2\right] + \frac{a_1^2}{\gamma-1}\left(\frac{\gamma-1}{2}\right)M_1^2\left(\frac{v_2}{v_1}\right)^2$$

or grouping terms,

$$\frac{\gamma+1}{2}M_1^2\left(\frac{v_2}{v_1}\right)^2 - \left(1+\gamma M_1^2\right)\frac{v_2}{v_1} + \left(1+\frac{\gamma-1}{2}M_1^2\right)(1+C_H) = 0 \qquad (11)$$

The solution of this quadratic equation will give two roots for the velocity ratio, $\frac{v_2}{v_1}$; one representing supersonic flow. The following discussion rules out the use of this larger root.

Using the energy equation,

$$dh = d\left(\frac{1}{2}v^2 + C_p T\right) \qquad (12)$$

Bernoulli's equation,

$$\rho v\, dv = -dp \qquad \text{or} \qquad \frac{dp}{\rho} = -v\, dv \tag{13}$$

the continuity equation,

$$d(\rho v) = 0 \qquad \text{or} \qquad \frac{dv}{v} = -\frac{d\rho}{\rho} \tag{14}$$

the equation of state,

$$\frac{p}{\rho} = RT \tag{15}$$

and rewriting the energy equation (12) in the form

$$dh = v\, dv + \frac{C_p}{R} d(RT)$$

$$dh = v\, dv + \frac{\gamma}{\gamma - 1} d\left(\frac{p}{\rho}\right)$$

$$dh = v\, dv + \frac{\gamma}{\gamma - 1}\left[\frac{dp}{\rho} - \frac{p}{\rho}\frac{d\rho}{\rho}\right] \tag{16}$$

we obtain, on substituting Eqs (13) and (14) into Eq (16),

$$dh = v\, dv + \frac{\gamma}{\gamma - 1}\left[-v\, dv + \frac{p}{\rho}\frac{dv}{v}\right]$$

$$dh = v\, dv\left[1 - \frac{\gamma}{\gamma - 1} + \frac{1}{\gamma - 1}\left(\frac{\gamma p}{\rho}\right)\frac{1}{v^2}\right] \tag{17}$$

Then, since

$$\gamma \frac{p}{\rho} = a^2$$

Eq (17) becomes,

$$dh = v\,dv\left[1 - \frac{\gamma}{\gamma - 1} + \frac{1}{\gamma - 1}\,\frac{1}{M^2}\right]$$

or collecting terms and rewriting,

$$v\,dv = \frac{\gamma - 1}{\left[\frac{1}{M^2} - 1\right]}\,dh \qquad (18)$$

This expression gives the variation of velocity with the addition of heat.

A similar relationship for the variation of Mach number with heat addition is obtained in the following analysis:

$$d\,(M^2) = d\,(\frac{v^2}{a^2}) = \frac{2v}{a^2}\,dv - \frac{v^2}{a^4}\,d\,(a^2) \qquad (19)$$

where

$$d(a^2) = \gamma\,d\,(\frac{p}{\rho}) = \gamma\left[\frac{dp}{\rho} - \frac{p}{\rho}\,\frac{d\rho}{\rho}\right]$$

$$d(a^2) = \gamma\left[-v\,dv + \frac{p}{\rho}\,\frac{dv}{v}\right]$$

$$d(a^2) = -\gamma v\,dv + \frac{a^2}{v}\,dv$$

$$d(a^2) = -\gamma v\,dv + \frac{v\,dv}{M^2} \qquad (19a)$$

Substituting Eq (19a) in Eq (19), we obtain

$$d(M^2) = \frac{2v}{a^2}\,dv - \frac{v^2}{a^4}\left[-\gamma v\,dv + \frac{v\,dv}{M^2}\right]$$

$$d(M^2) = \frac{v\,dv}{a^2}\left[1 + \gamma M^2\right] \tag{20}$$

and finally, substituting this in Eq (18) and rewriting, we have

$$d(M^2) = \frac{\gamma - 1}{\left[\frac{1}{M^2} - 1\right]} \; \frac{1 + \gamma M^2}{a^2}\, dh \tag{21}$$

Eqs (18) and (21) show that for subsonic flows both the velocity and Mach number will increase with the addition of heat. However, for Mach numbers greater than unity, the denominators of both expressions become negative, showing that heat must be subtracted from the flow for either the velocity or Mach number to further increase. From these facts, the impossibility of obtaining supersonic velocities by continuous heat addition to subsonic velocity flows in a uniform pipe becomes evident. For this reason we can disregard the larger root of the solution of Eq (11), and the solution for the smaller root takes the form,

$$\frac{v_2}{v_1} = \frac{1 + \gamma M_1^2}{(\gamma + 1) M_1^2} - \sqrt{\left[\frac{1 + \gamma M_1^2}{(\gamma + 1) M_1^2}\right]^2 - 2\,\frac{1 + \frac{\gamma - 1}{2} M_1^2}{(\gamma + 1)\, M_1^2}\,(1 + C_H)} \tag{22}$$

It can be seen that an increase of the heating ratio, C_H, will cause a continual gain in velocity up to the point where the value under the radical becomes zero. Any further increase in C_H results in complex velocity ratios and is thus impossible. Therefore, the maximum increase of velocity, which corresponds to the attainment of sonic velocity after combustion, is given by

$$\frac{v_2}{v_1} = \frac{1 + \gamma M_1^2}{(\gamma + 1) M_1^2} \tag{22a}$$

and

$$\left(\frac{v_2}{v_1}\right)^2 = 2 \frac{1 + \frac{\gamma - 1}{2} M_1^2}{(\gamma + 1) M_1^2} (1 + C_H) \tag{23}$$

By assuming a constant ratio of specific heats, ($\gamma = 4/3$), it is possible to plot curves of the velocity ratio against Mach number for various values of the heating ratio. Such a plot is shown in Fig 2, which gives the velocity increases theoretically obtainable by addition of heat in the tail pipe.

A similar set of curves, showing velocity ratio attainable vs rpm with fuel burned in the tail pipe (gal per hr) as a parameter, were made using General Electric Company test data for an I-14B unit. These curves (Cf Fig 3) were determined using the following assumptions: (1) combustion 100 per cent complete; (2) thorough and complete diffusion of the heat added over the entire mass of air in the tail pipe takes place instantaneously; (3) no losses due to friction.

An effort was made to obtain actual measured values of mass flow for the unit with the nozzle off. However, satisfactory static pressure readings along the length of the tail pipe could not be obtained, probably because of the turbulent flow and severe warpage conditions existing along the tail pipe. An assumption was made that the mass flow remained the same with the nozzle removed, and thus General Electric Company data could be used. From the data given in Ref 4, values of mass flow, total energy, and Mach number of the gases entering the tail pipe for various engine speeds were determined. Using these values and assuming various quantities of fuel injected in gal per hr, velocity ratios v_1/v_2 were computed, using Eq (22) derived previously. Since the mass of fuel injected in the tail pipe was neglected in the derivation of Eq (22), the ratio of thrust with burning to the thrust without burning is directly proportional to the calculated ratio v_1/v_2 and is shown in Fig 3.

A pressure drop across the combustion flame occurs as a direct result of the increase of momentum of the stream by the addition of energy as heat. This pressure drop may be computed in the following manner.

The loss in total pressure is given by:

$$P_1 - P_2 = p_1 - p_2 + \frac{1}{2}\rho_1 v_1^2 - \frac{1}{2}\rho_2 v_2^2 \qquad \text{or}$$

$$P_1 - P_2 = p_1\left(1 - \frac{p_2}{p_1}\right) + \frac{1}{2}\rho_1 v_1^2\left(1 - \frac{v_2}{v_1}\right) \tag{24a}$$

$$\frac{P_1 - P_2}{p_1} = \left(1 - \frac{p_2}{p_1}\right) + \frac{\gamma}{2}\frac{\rho_1}{\gamma p_1} v_1^2\left(1 - \frac{v_2}{v_1}\right)$$

$$\frac{P_1 - P_2}{p_1} = \left(1 - \frac{p_2}{p_1}\right) + \frac{\gamma}{2} M_1^2\left(1 - \frac{v_2}{v_1}\right) \tag{24b}$$

The momentum equation in the form given by Eq (7) may be modified to:

$$\frac{\gamma \rho_1}{\gamma p_1} v_1^2 \left(\frac{v_2}{v_1} - 1\right) = 1 - \frac{p_2}{p_1}$$

or

$$\left(1 - \frac{p_2}{p_1}\right) = \gamma M_1^2 \left(\frac{v_2}{v_1} - 1\right) \tag{25}$$

Substituting (25) in (24b):

$$\frac{P_1 - P_2}{p_1} = \frac{\gamma M_1^2}{2} \left(\frac{v_2}{v_1} - 1\right)$$

or

$$\frac{P_1 - P_2}{\frac{1}{2}\gamma M_1^2 p_1} = \frac{v_2}{v_1} - 1 = \frac{P_1 - P_2}{q} \tag{26}$$

Pressure drops across the flame front were observed, varying from about 2 lb/sq in at 12,000 rpm to 5 at about 16,000 rpm. These were of a qualitative nature and could not be checked accurately with the theoretical values.

IV. COMBUSTION PROBLEMS

One of the major problems encountered in tail pipe combustion is the completion of burning before the fuel has been swept out of the tail pipe or has passed a combustible mixture ratio zone. Since normal velocities and temperatures encountered in the tail pipe are of the order of 1000-1200 ft/sec and 1000°F respectively, a given particle of gas or fuel will be inside the 4 ft pipe for only three to four thousandths of a second. This interval is on the border line of ignition lags for most fuels, even at this temperature.

There are several suggested means of solving this problem; these are:

(1) Mechanical - Introduction of turbulence to retain a given fuel-air mixture in a desired location for longer times. This can be accomplished by the use of flame holders, baffles, and flame tubes. Such devices can and usually do attempt to control mixture ratios by proper design to obtain maximum combustion rates. Another method would increase tail pipe length, thus affording a greater length of time available for combustion. Such systems inherently introduce drag losses in the stream with consequent losses of thrust.

(2) Increase the gas temperature - The normal effect of raising the temperature on any fuel is to decrease the ignition lag. One method of increasing the temperature in the tail pipe is found in the use of pilot burners where air and fuel are mixed, ignited, and burned under well-controlled conditions, the products of combustion then being used to raise the temperature of and ignite the larger or main fuel-air mass. The degree of drag losses attributable to a system of this type will largely depend on the method of installation.

(3) Chemical - The ignition lags of fuels can be greatly de-

creased by the use of certain chemical compounds. The use of additives is the subject of a current research at the Jet Propulsion Laboratory.

(4) Selection of fuels - Ignition lag is a specific property of a given fuel and should be considered when a selection is made. The heating value of the fuel must, however, be kept in mind at the same time, inasmuch as several fuels with low lags and excellent mixture ratio characteristics have poor heating values.

It might be mentioned that these latter two methods, being concerned with the fuel alone, will cause no losses of thrust when the unit is in normal operation. Should a fuel other than that used in the engine burners be employed, the fuel system of an aircraft installation might become prohibitively complicated and cumbersome. Additives may, in addition to improving tail pipe burning characteristics, improve the combustion characteristics of the regular unit.

Another problem associated with auxiliary combustion is the effect of flame instability. This not only causes rapid thrust variations but produces moderately severe buffeting conditions in the region adjacent to the jet exhaust. This problem might be solved by proper fuel selection.

V. EQUIPMENT

With the exception of a few preliminary combustion investigations which were conducted on a General Electric I-A Turbojet engine, the installations and tests described were made on G.E. I-14 unit No. 36 at the

Jet Propulsion Laboratory.

The unit was instrumented in the following manner:

(1) Pressures:

(a) Compressor discharge to burners No. 2 and No. 7

(b) Main fuel to unit burners

(c) Turbine exhaust, static*

(d) Tail pipe entering, static*

(e) Tail pipe exit, static*

(f) Tail pipe exit, total*

(g) Pilot burner, air supply, static*

(h) Pilot burner fuel

(i) Main auxiliary injector fuel

(j) Nitrogen pressure of auxiliary fuel tanks

(k) Ambient pressure.

(2) Temperatures:

(a) Compressor discharge to burners No. 2 and No. 7

(b) Turbine exhaust

(c) Tail pipe entering

(d) Tail pipe exit

(e) Bearings

(f) Ambient temperature.

Most temperatures were measured using thermocouples with cold junctions in ice water. Fig 4 shows the instrument

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* Measured by mercury manometers; others by bourdon type gauges.

panel used in these experiments.

(3) Fuel flow rates were measured by timed observations on tank sight glasses, the main unit fuel and the auxiliary fuel having separate supply systems (Cf Figs 5 and 6).

(4) Thrust was measured on a conventional Caltech hydraulic thrust jack.

Because of severe warpage encountered in the thin material of the tail pipe and tail cone walls, it was found that the static pressures were totally unreliable, except as indications of relative changes. All indications pointed to the presence of considerable turbulence throughout the tail pipe, with some evidence of separation near the entrance. Because of this, there exists the possibility of error in the thermocouple temperature indications.

VI. TAIL PIPE COMBUSTION SYSTEM

The installation as finally developed is shown in Fig 7. This system was the result of a gradual development from injectors alone to the use of a pilot burner, flame tubes, and a fuel wash system on the cone. Some of the modifications employed will be touched on briefly in a discussion of experimental development.

The pilot burner is shown in detail in Fig 8 and the general method of installation is shown in Figs 7 and 9. The air supply to the burner is provided by a semi-circular air scoop of 1.75 in diameter riveted to the tail cone about 8 in aft of the turbine. This scoop feeds ram air from the turbine exhaust to the air inlet passages shown in Fig 8. These passages force the air into the pilot burner tangential to the walls, giving it a violent swirling motion which gives a well defined helical path down the tube of the pilot burner. An M-6 injector, manufactured by Spraying Systems Company, Chicago, Illinois, is centrally located in the forward wall of the burner, and a spark plug is located about 4 in aft of the injector. Fuel and ignition lines to the pilot burner pass down through the tail cone supporting bolts inside the straightening vanes and thus introduce no drag into the stream.

The four main injectors, fitted with GG-5 nozzles, also manufactured by the Spraying Systems Company, Chicago, Illinois, are located one behind each straightening vane. The injection is upstream and slightly inward toward the pilot burner and flame tube.

Additional fuel is run on the tail cone from four 1/16 in nozzles discharging directly on the cone surface in the space between the cone and the inner edge of the straightening vanes. Fuel lines supplying these four nozzles are led in through the straightening vanes and thus offer no drag in the tail pipe.

Fuel flow to the tail pipe combustion unit was controlled through separate valves for each of the injector systems from pressurized tanks.

The fuel used in both the main unit and the tail pipe during these tests was kerosene with the following properties:

A.P.I.	44.1
Color	30
Sulphur	0.1

Engler Distillation

Initial	360°F
10 Per Cent	388°F
50 Per Cent	418°F
90 Per Cent	460°F
95 Per Cent	488°F
End	498°F

VII. EXPERIMENTAL DEVELOPMENT

As mentioned before, there was a considerable amount of work done before satisfactory combustion characteristics were obtained. While data were taken during these investigations, they have not been presented, inasmuch as the development at that time had not progressed to the point of offering tangible results in thrust increase.

The first attempt was direct upstream injection, with only the four main injection nozzles installed. There was no evidence of combustion with this attempt, nor after a spark plug was installed in what was hoped to be the vicinity of a combustible mixture. Very little experimentation clearly dictated the necessity of some type of pilot burner.

Several ideas for pilot burners were contemplated. The pilot burner finally selected was developed by Ivan Weeks, of the Jet Propulsion Laboratory staff. Fig 10 shows the setup used for preliminary investigations on this burner to determine the optimum scoop and injector size. Inasmuch as this particular type of burner operates well over wide variations of inlet air flow, and because of the fact that it could be conveniently buried in the tail cone structure, it was selected over other types that project directly into the stream.

When the pilot burner was installed in the tail cone structure, the tail cone wash injectors were installed in an attempt to utilize the heated surface of the tail cone to assist in raising the temperature and vaporization of the fuel. Such a system should have additional advantages, in that some of the fuel and vapor will lie within whatever boundary layer exists, thus greatly reducing the translation velocity of those particular portions. This fuel and vapor passing along the skin of the cone should pass directly into the turbulent wake astern of the pilot burner into the best region for combustion.

The next attempt, utilizing the pilot burner and the cone wash and the main injectors, produced some, but limited, results. General ignition of the fuel from all injectors was obtained, but at very low thrusts only. Even slight increases of velocities over those corresponding to 200 lb thrust exceeded the blow-out point of the general combustion. It should be mentioned here that the pilot burner continued to burn up to the maximum output of the unit and would ignite at any rpm.

From these tests it became evident that a greater volume in which the fuel/air ratios and temperatures could be reasonably controlled was required. Some type of flame tube was thus necessary, preferably being of such a design as to pick up the cone wash, some of the fuel from the main injectors, and not permit excessive quantities of air in the mixture. The straight cylindrical flame tube previously described was selected first, but while this was being fabricated, a divergent conical perforated tube which was available was tested. This conical flame tube as installed is shown in Figs 11 and 12.

The divergent tube brought about a little improvement but still failed to support combustion with thrusts in excess of 300 lb, about 10,000 rpm. While a part of the fuel almost certainly entered the cone, too much air was also entering to maintain necessary inflammability ratios. Fig 12 shows burning in the conical flame tube.

The installation of the straight perforated tube seemed to clear up a greater part of the difficulties encountered. From runs made with the tail pipe removed, the path of the wash was visible and appeared to behave as predicted, a major portion of the wash fuel running down the cone and into the flame tube. Fig 13 shows the straight flame tube with burning being carried on. The spray angles of the main injectors were reset to point in more toward the cone, to keep the atomized fuel closer to the pilot burner heat source.

With the system developed to this point it was possible to hold combustion up to 16,000 rpm, within 500 rpm of the upper design limit of the unit, with every indication that it could have been pushed higher. As a safety measure and to prevent excessive deterioration of the engine, 16,000 rpm was set as the upper limit of the operation under any conditions.

With the installation as above, burning appeared to be quite satisfactory, with blue flame filling a greater portion of the tail pipe. At the same time, however, the exhaust flame projected beyond the end of the tail pipe, representing a useless loss of energy. To obviate some of this loss the tail pipe length was doubled by the addition of an extra pipe. This act alone brought about practically a 100 per cent increase in thrust gain. This installation is shown in Fig 14.

VIII. OPERATING TECHNIQUE

As mentioned previously, fuel was supplied to the tail pipe combustion system from pressurized tanks. For operation of the system, three valves were used: one to control fuel to the pilot burner, one to control fuel to the cone wash, and one to control fuel to the main injectors. Fuel tank pressure could be varied as desired. Fig 4 shows the control panel for the tail pipe combustion system.

For operation of the tail pipe combustion system, fuel pressure to the pilot burner was reduced by a reducer valve from main tank pressure to about 5 to 10 lb/sq in and the fuel valve opened slightly until ignition was started by means of the spark plug.

With the pilot burner lighted, the cone wash, which was at main tank pressure, was then started, the control valve being opened until combustion started. With a smooth combustion established in the flame tube by burning of the cone wash fuel, the main injector valve was opened slowly until the main injector fuel ignited. One point is noteworthy here. If combustion was not established by the cone wash fuel first, the main injector fuel could not be burned at all. Also, at low rpm the cone wash fuel could be increased to the point where the main fuel flame could be extinguished, apparently due to flooding the area of the flame tube. At higher rpm, say 14,000 to 16,000, this could not be done, probably because of greater air flow rate. Hence, the flame tube and cone wash are indispensable for successful operation of the present system.

Once combustion was started, the control valves to the main injector and cone wash were opened until the maximum combustion was established in the tail pipe. A further opening of the main fuel valve would then cause all combustion except the pilot burner to be extinguished. Just prior to the point of extinguishing the combustion by excessive fuel, a noticeable vibration of the flame could be felt and heard. From experience, the intensity of this vibration was used to judge when the maximum fuel was being injected at any rpm.

Pressures used to the various nozzles varied about as follows:

Pilot burner: 10 lb at 12,000 rpm to 30 lb at 16,000 rpm.

Cone wash: no gauge, equal to main tank pressure minus drop through control valve and lines ($\frac{1}{4}$ in copper tubing).

Main injectors:

10 lb at 12,000 rpm to 50 lb at 16,000 rpm.

Main tank pressure:

100 to 150 lb/sq in.

At rpms in the vicinity of 12,000, when fuel injection rate was the maximum used, some visible blue flame was emitted from the end of the 8 ft tail pipe, such flame extending perhaps 1 ft beyond the tail pipe. At higher rpm, say 16,000, the flame length was shortened until little or none was visible at the end of the tail pipe, indicating that with increased temperature and pressure across the flame front, burning time decreased and the flame front probably moved closer to the injectors.

IX. RESULTS AND DISCUSSION

After all data were corrected to standard conditions by methods outlined in Ref 5, the final results showed a net gain in thrust of 23 per cent with tail pipe combustion over that of the normal unit. A corresponding gain in thrust of 51 per cent over the unit with a straight tail pipe was obtained. Both figures quoted correspond to operation at 16,000 rpm. Curves of percentage thrust increase plotted against rpm are shown in Fig 15. For the above gains in thrust, corresponding increases of 78 per cent and 54 per cent in specific fuel consumption were required. The actual thrusts obtained are shown in Fig 16. Curves of specific fuel consumption are shown in Fig 17. Thrust calibration curves for the original unit with nozzle on and nozzle off are shown in Fig 18. Calibration runs of the unit with the auxiliary tail pipe combustion system installed showed a negligible loss of thrust due to internal drag, as compared with the original unit. This curve is shown in Fig 19. Engine fuel consumptions for various conditions of tail pipe combustion are shown in Fig 20. Curves showing relative fuel consumption of the engine and tail pipe are shown in Fig 21.

Fig 3 shows that the maximum possible thrust increase over the straight tail pipe is 84 per cent at 16,000 rpm. In this investigation the maximum increase in thrust obtained at 16,000 rpm was 51 per cent or, in other words, 61 per cent of the theoretical maximum increase was obtained.

Going again to Fig 3, it is found that a 51 per cent increase of thrust at 16,000 rpm requires 100 per cent efficient combustion of 85 gal per hr of fuel in the tail pipe. This value, when compared to 270 gal per hr actually injected gives a heat addition efficiency of about 32 per cent. This low value can be explained by any or all of the several following reasons:

(1) Incomplete combustion.

(2) Loss of unignited fuel.

(3) Incomplete mixing of the streams, with resultant non-uniform heat distribution throughout the mass of gas in the tail pipe.

(4) The failure to contain the combustion within the tail pipe, which is evidenced by the existence of flame areas outside of the pipe.

Some of the above mentioned losses might be reduced by further extension of the tail pipe. As discussed before, doubling of the tail pipe length doubled the thrust gain. The calibration of the unit with and without tail pipe burning in a single 4 ft tail pipe is shown in Fig 27, which may be compared to the similar calibration for the 8 ft pipe as shown in Fig 16. Any increase in tail pipe length will increase the time available for combustion, subsequent heat distribution, and stream mixing, thus improving the heat addition efficiency, with consequent gains in thrust and reduction of specific fuel consumption. Comparison of Figs 16 and 22 will show that the losses attributable to the increased length are negligible.

The fact that the installation of the tail pipe combustion system caused no appreciable decrease in thrust appears rather strange. However, it is felt that there existed a region of considerable turbulence just aft of the unmodified tail cone of the unit. The pilot burner exit and flame tube were installed in just this region and thus would cuase very little additional loss. Likewise the main injector nozzles being installed in the wake of the straightening vanes would produce small losses while the remainder of the system was buried in existing structures.

It was found that the effect of combustion in the tail pipe was to reduce the engine speed by about 1000 rpm. It is thought that this was due to the fact that the combustion increased the back pressure on the turbine and thus decreased the work output of the turbine. This requires a decrease in rpm to reestablish equilibrium conditions between the compressor work required and the turbine output. The pressure drop due to combustion is due to the acceleration of the gas in the tail pipe. To restore the engine rpm to its previous value, the throttle must be opened, which results in higher turbine temperatures at a given engine speed than would be encountered without tail pipe burning. This requires a greater fuel consumption on the part of the engine to maintain the given speed. The magnitude of the necessary increase is shown in Fig 20. It should be noted that these events may lead to excessive turbine blade temperatures.

X. CONCLUSIONS

As a result of this work the following conclusions have been drawn:

(1) As installed in a G.E. I-14 turbojet unit with the exhaust nozzle removed, the tail pipe combustion system developed here is capable of burning kerosene over the entire operating range of the engine.

(2) The maximum thrust increases obtained were 64 per cent over the straight tail pipe and 42 per cent over the normal unit with the nozzle installed; both maximums occurring at 12,000 rpm. Corresponding specific fuel consumption increases of 53 per cent and 66 per cent were required.

(3) The increases of maximum thrust obtained were 51 per cent over the straight tail pipe and 23 per cent over the normal unit with the nozzle installed, both values representing operation at 16,000 rpm. Corresponding specific fuel consumption increases of 54 per cent and 78.5 per cent were required.

(4) Doubling tail pipe length improved the thrust gains obtainable with tail pipe injection approximately 100 per cent.

XI. RECOMMENDATIONS

In view of the results obtained, the authors submit the following recommendations:

(1) That the tail pipe fuel injection system be modified and amplified to permit greater rates of fuel flow for the tail cone wash. At full rpm the cone wash valves were

fully opened. It is possible that more fuel to the cone wash would permit further fuel to be added through the main injectors.

(2) Further investigation of the effect of additional increase in tail pipe length should be made.

(3) At 16,000 rpm it was noticed that the outer tail cone in the vicinity of the cone wash lead-in lines was at a dull red heat, indicating the possibility that because of increased temperature and pressure across the flame front, the flame front moves nearer the fuel injectors. As a check on this hypothesis, it is suggested that experiments be carried out using quartz inserts in the tail pipe to facilitate actual observation of the flame front during the combustion.

(4) Further experimentation should be made to determine if the pilot burner size used is the optimum, since there exists the possibility that a larger pilot burner would be beneficial.

(5) In further investigations, it is recommended that more main injector nozzles be placed in the stream, these to be used at high rpm to obtain a more even and more symmetrical distribution of fuel flow in the tail pipe. Similarly, the distribution from the cone wash should possibly be made more symmetrical.

(6) Further investigation to determine whether other fuels

might be selected which would improve tail pipe combustion should be made. This should include investigation of certain additives to decrease combustion time lags.

REFERENCES

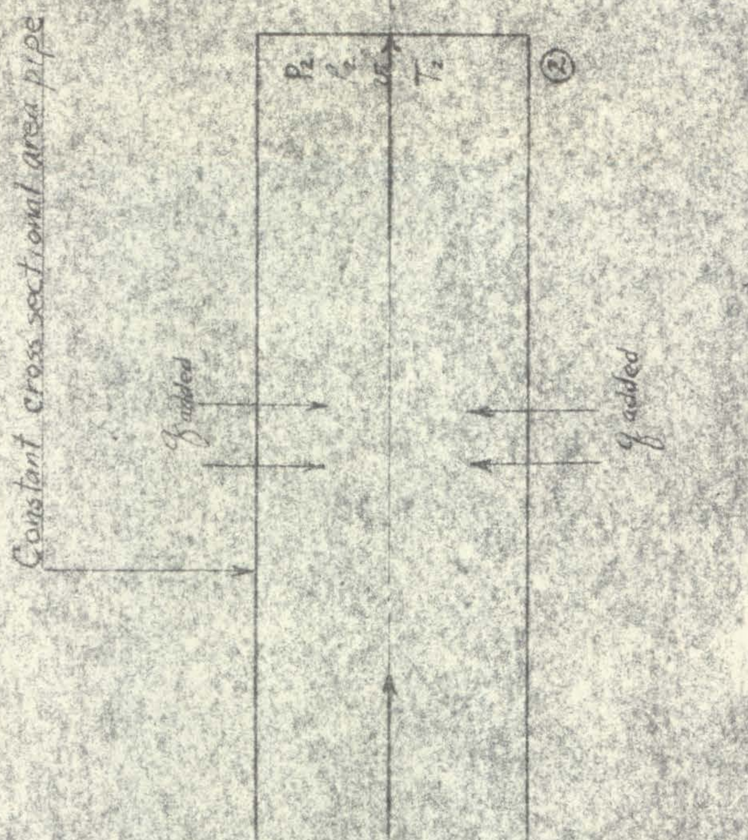
1. Cohen, H., "Experiments on Thrust Boosting of a Simple Jet Propulsion Engine (W.I.A. No. 3) by Exhaust Reheat Methods", T. N. No. Eng. 307, R.A.E., June, 1944.

2. Willcock, R. M., "The Boosting of the Thrust of a Simple Jet Propulsion Turbine Engine", Report No. E 4104, R.A.E., February, 1944.

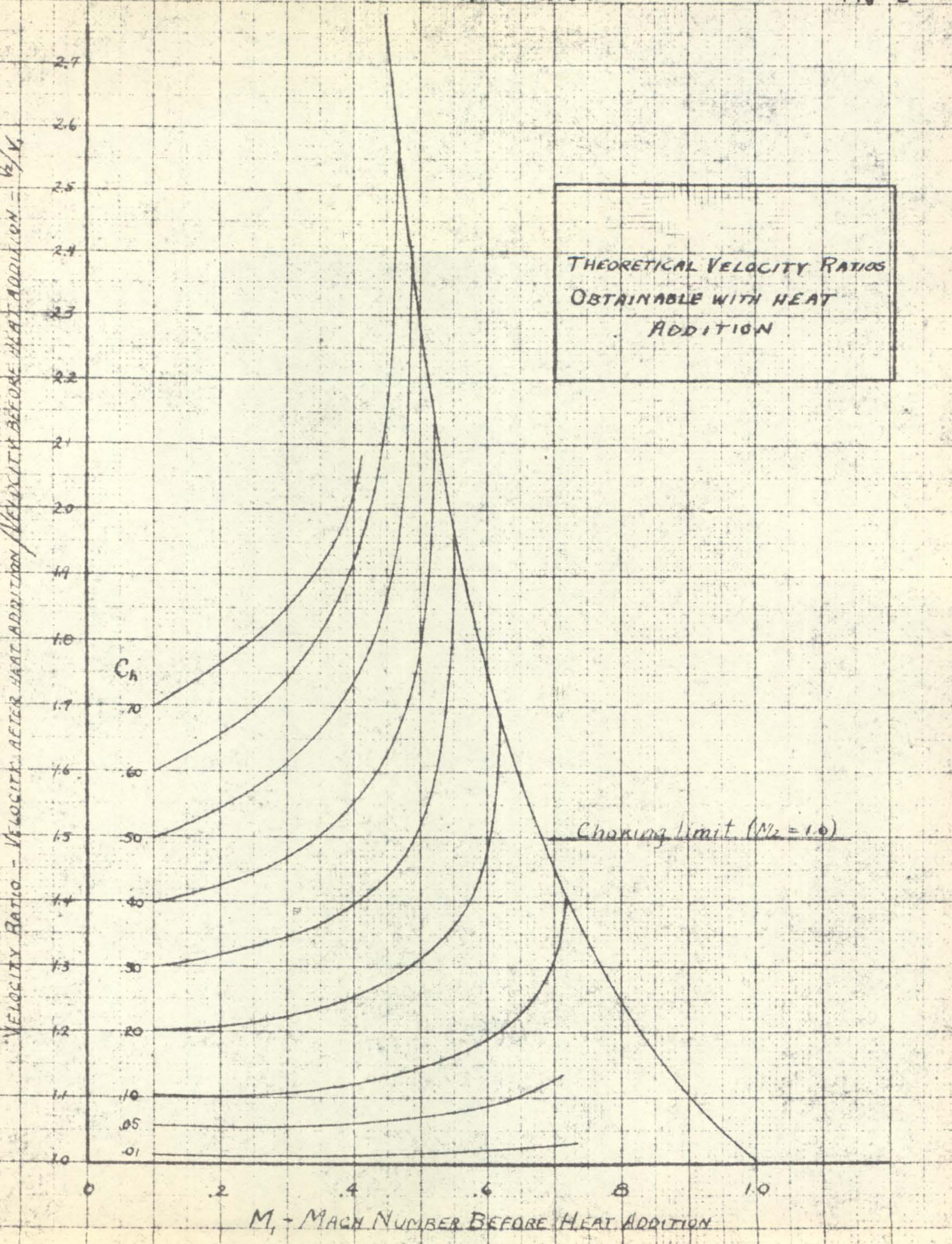
3. Jet Propulsion Course Lecture Notes, Prepared by Staff of GALCIT and JPL-GALCIT, California Institute of Technology, 1945.

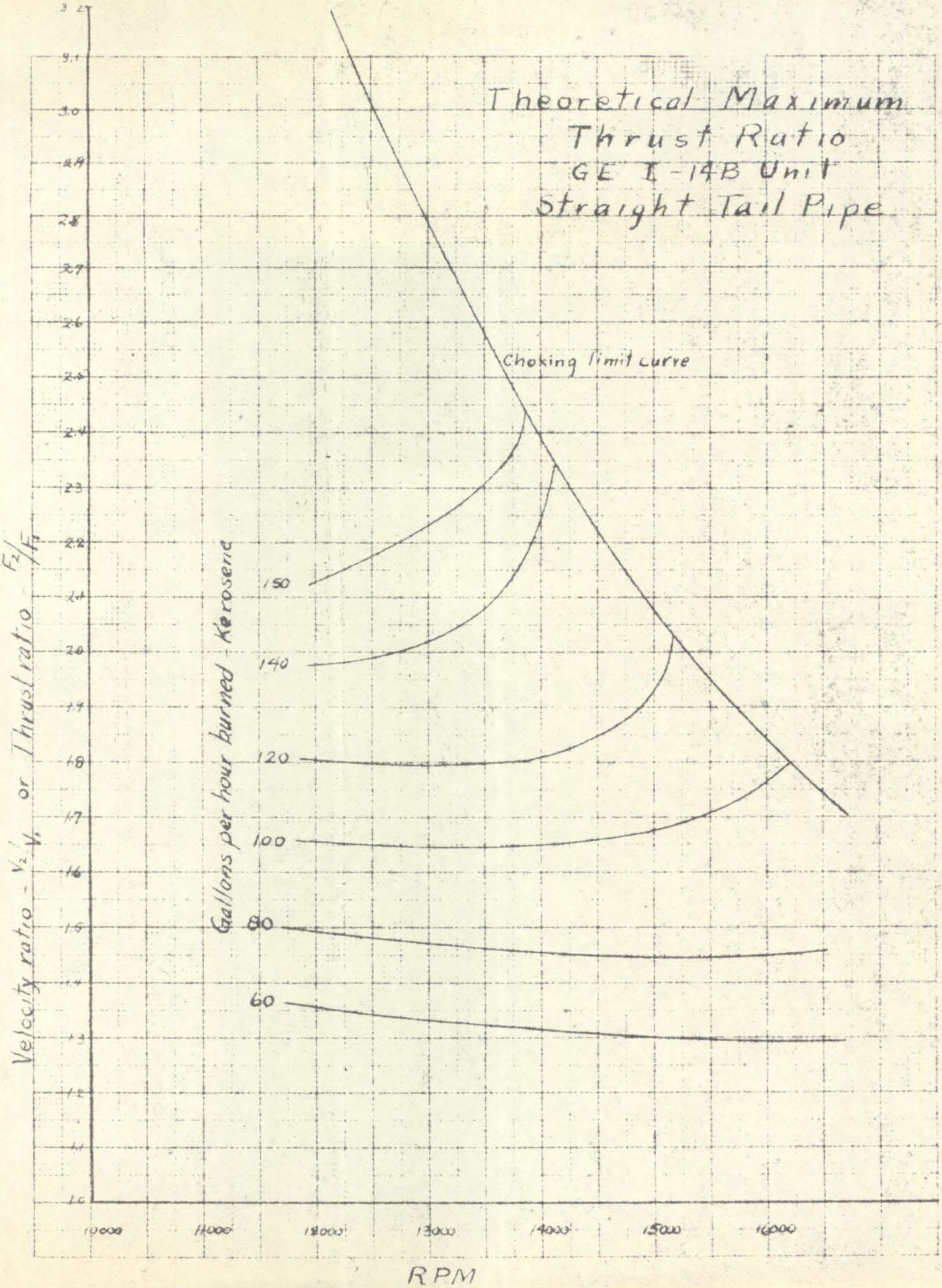
4. Type I Supercharger Test Report, Type I-14B, Unit No. 3, Data Folder No. 47370, General Electric Company, Schenectady, N.Y., January, 1944.

5. "Type I Supercharger - Basis of Correction of Test Results and Extrapolation to Altitude Performance", Data Folder No. 47318, General Electric Company, Schenectady, N.Y., October, 1943.



Showing nomenclature used in theoretical analysis


THEORETICAL VELOCITY RATIOS OBTAINABLE WITH HEAT ADDITION
VELOCITY RATIO - VELOCITY AFTER HEAT ADDITION / VELOCITY BEFORE HEAT ADDITION = V_2/V_1
M_1 - MACH NUMBER BEFORE HEAT ADDITION
C_h
.70
.60
.50
.40
.30
.20
.10
.05
.01
Choking limit ($M_2 = 1.0$)
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
0
.2
.4
.6
.8
1.0


Theoretical Maximum
Thrust Ratio
GE I-14B Unit
Straight Tail Pipe
Choking limit curve
150
140
120
100
80
60
Gallons per hour burned - Kerosene
Velocity ratio - V_2/V_1 or Thrust ratio - F_2/F_1
10000
11000
12000
13000
14000
15000
16000
RPM

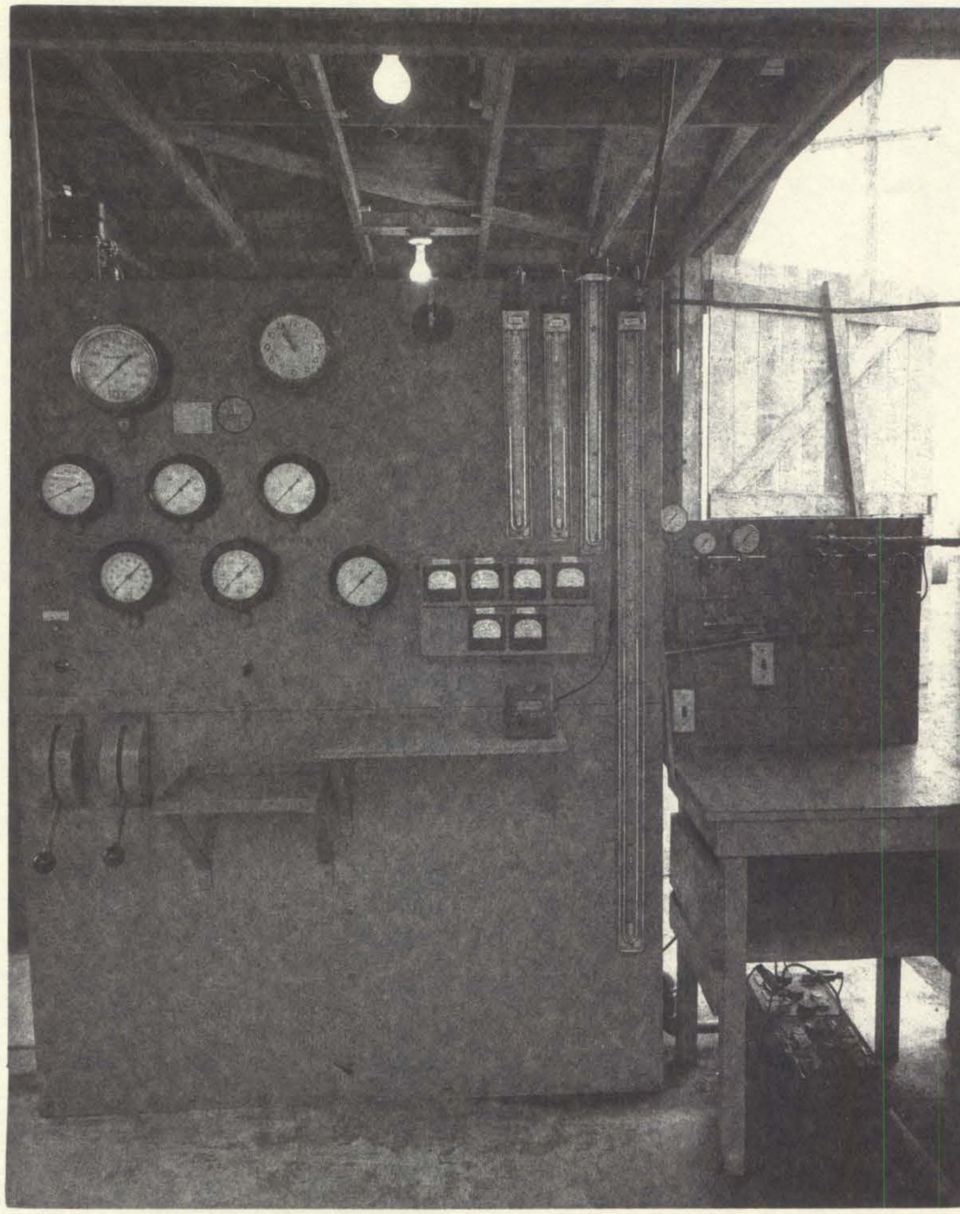


FIGURE 4. CONTROL PANELS.

FIGURE 5. FUEL TANKS.

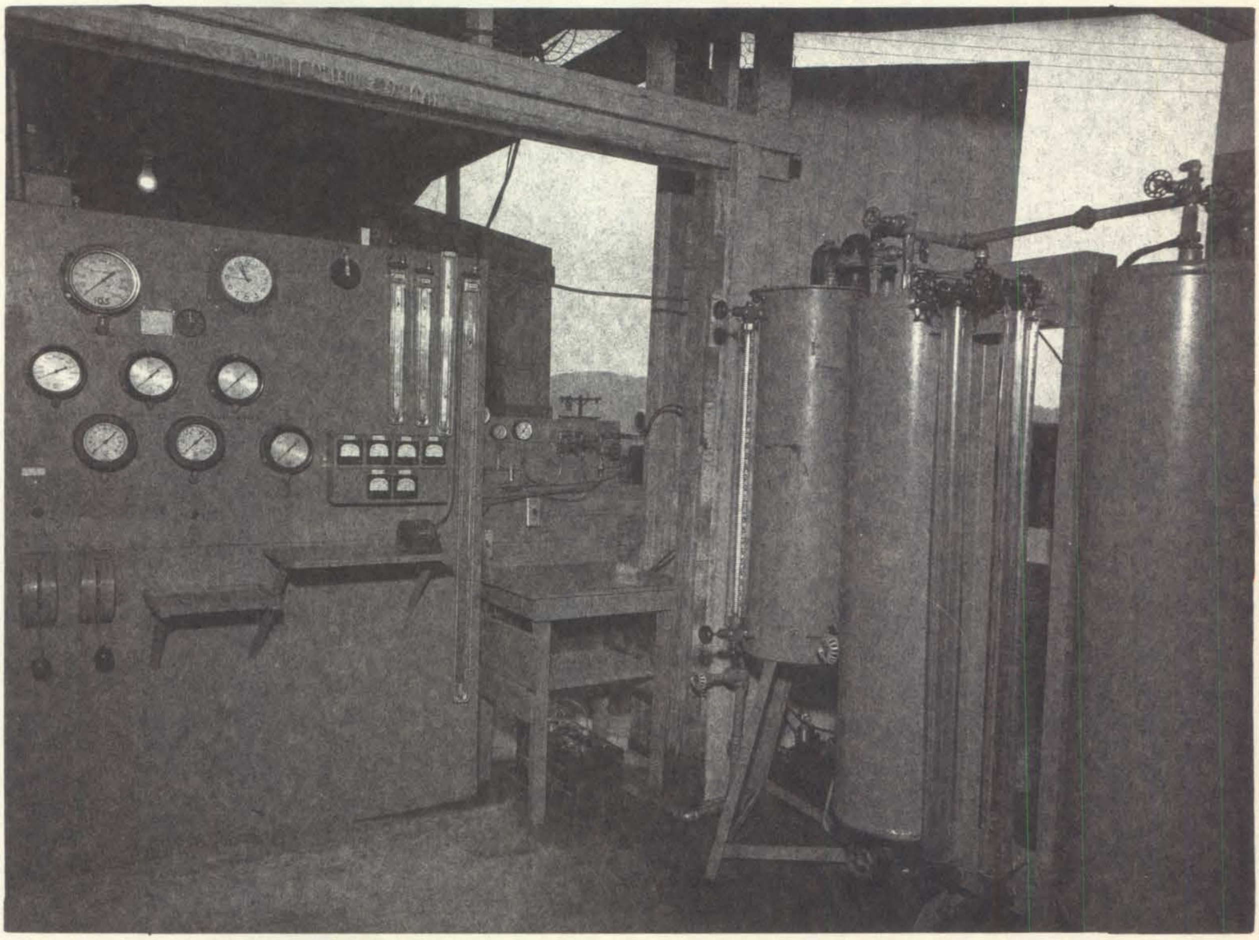
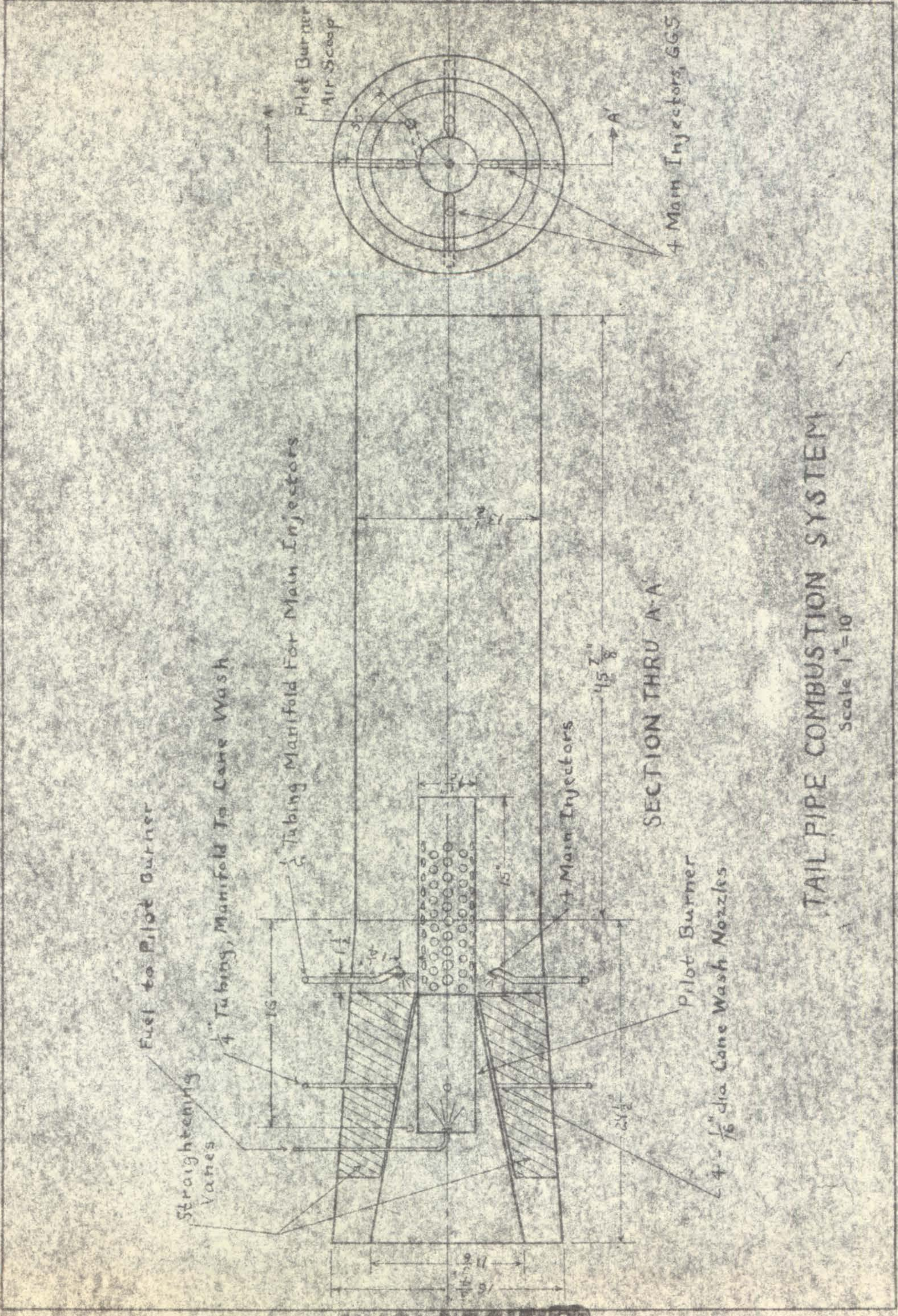


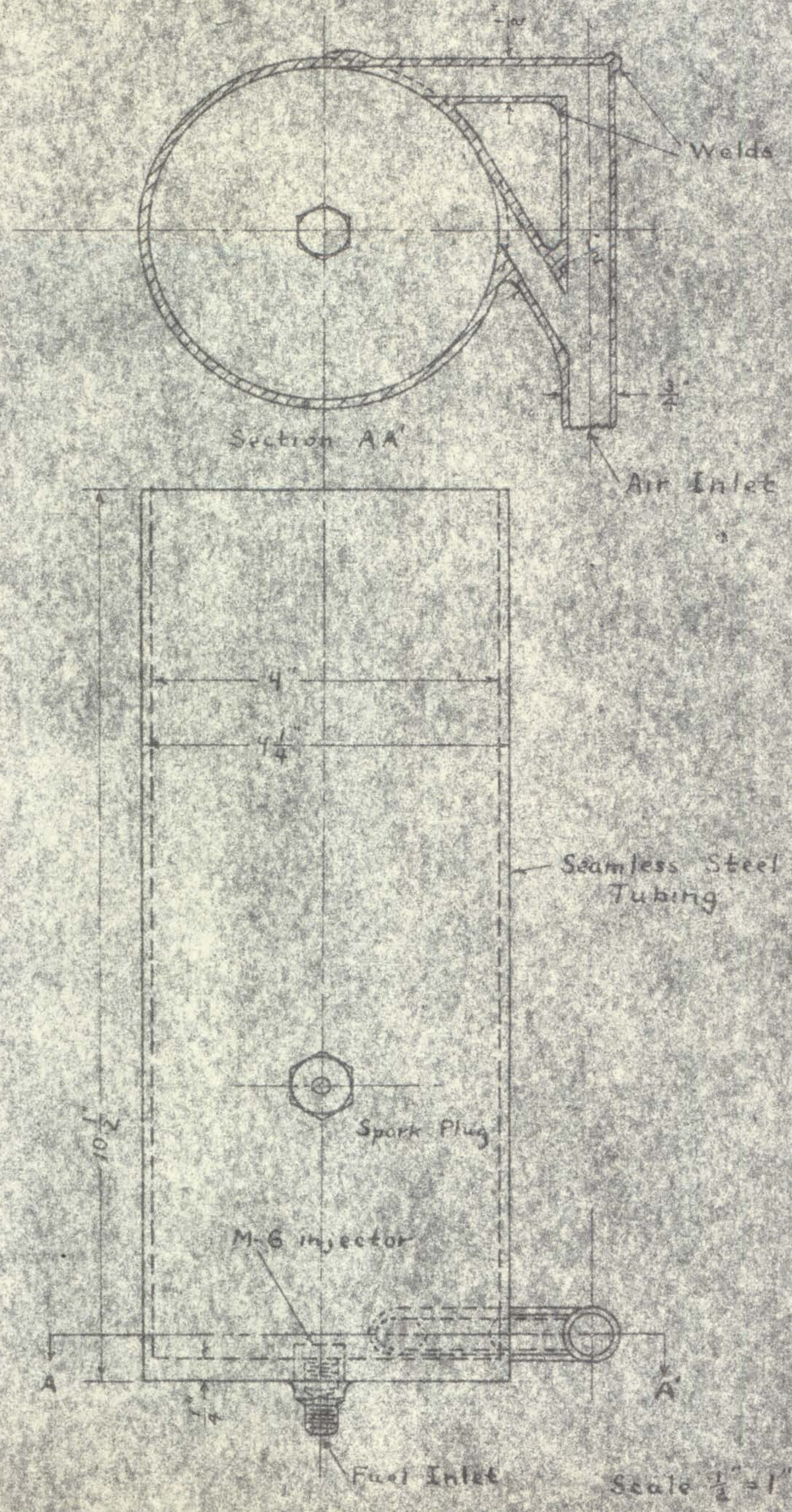
FIGURE 6. CONTROL PANELS AND FUEL TANKS.



TAIL PIPE COMBUSTION SYSTEM
Scale 1" = 10"

RESTRICTED

PILOT BURNER



RESTRICTED

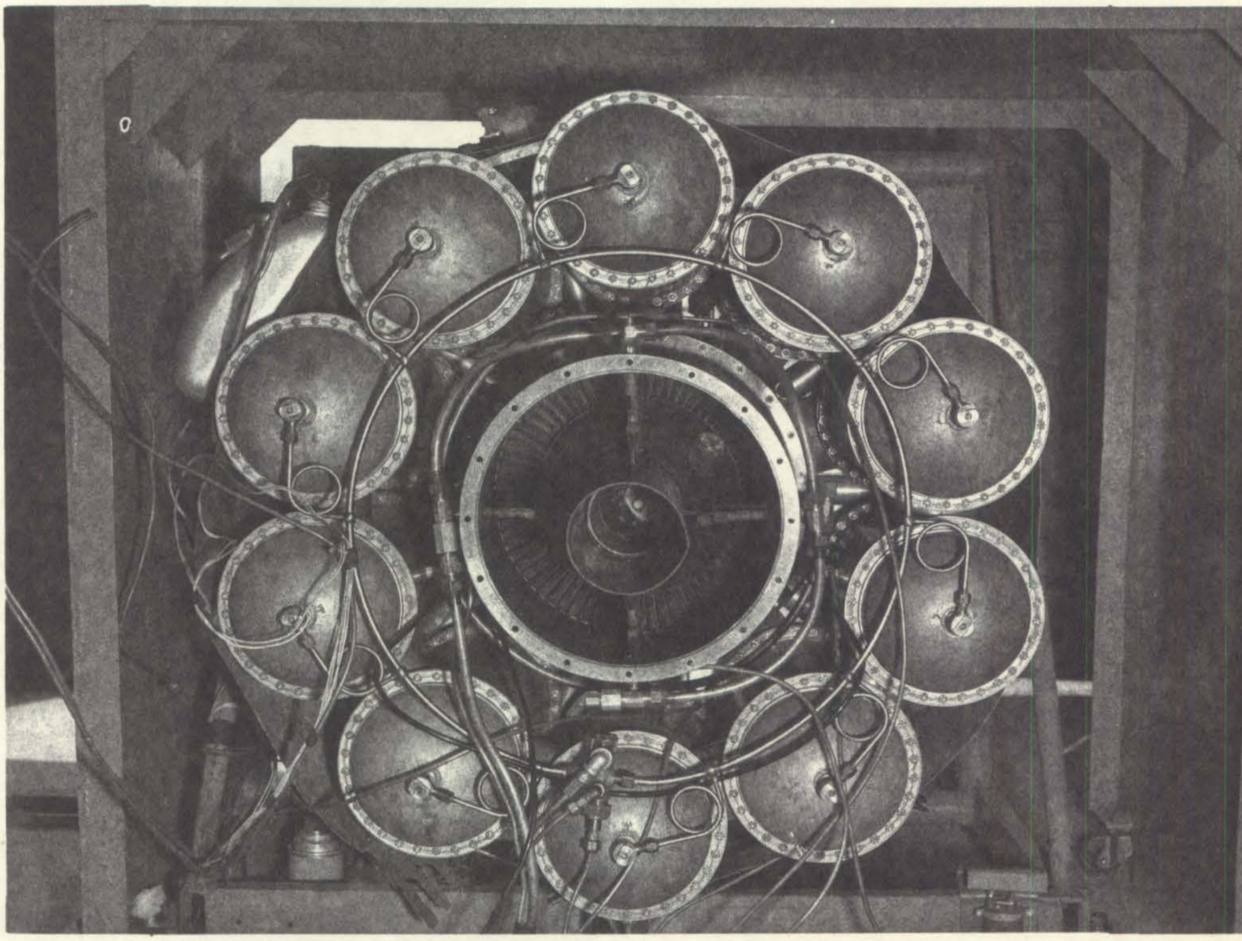


FIGURE 9. END VIEW OF STRAIGHT FLAME TUBE AND PILOT BURNER.
(PILOT BURNER AIR SCOOP IS VISIBLE IN UPPER RIGHT HAND QUADRANT OF EXHAUST ANNULUS)

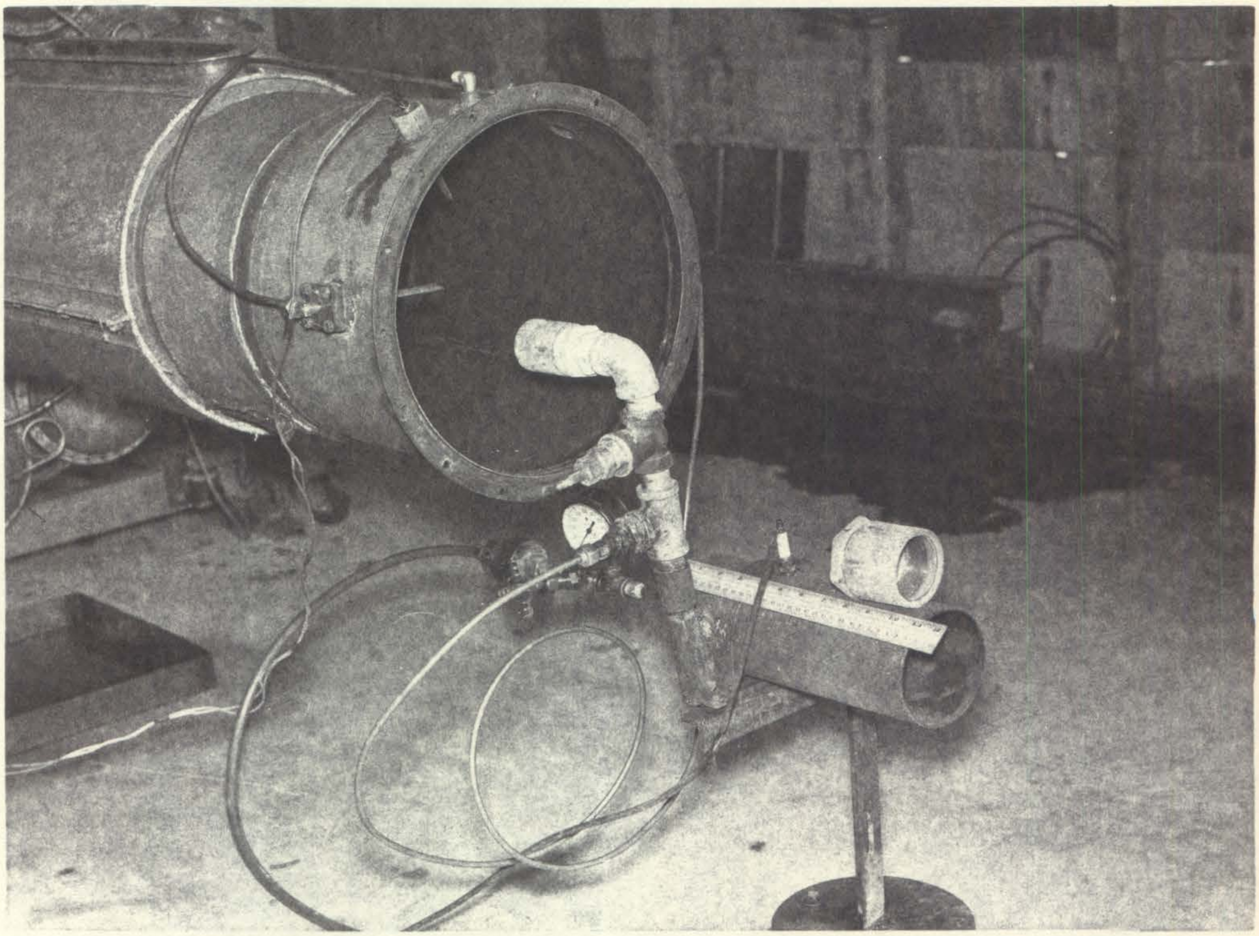


FIGURE 10. PILOT BURNER TEST.

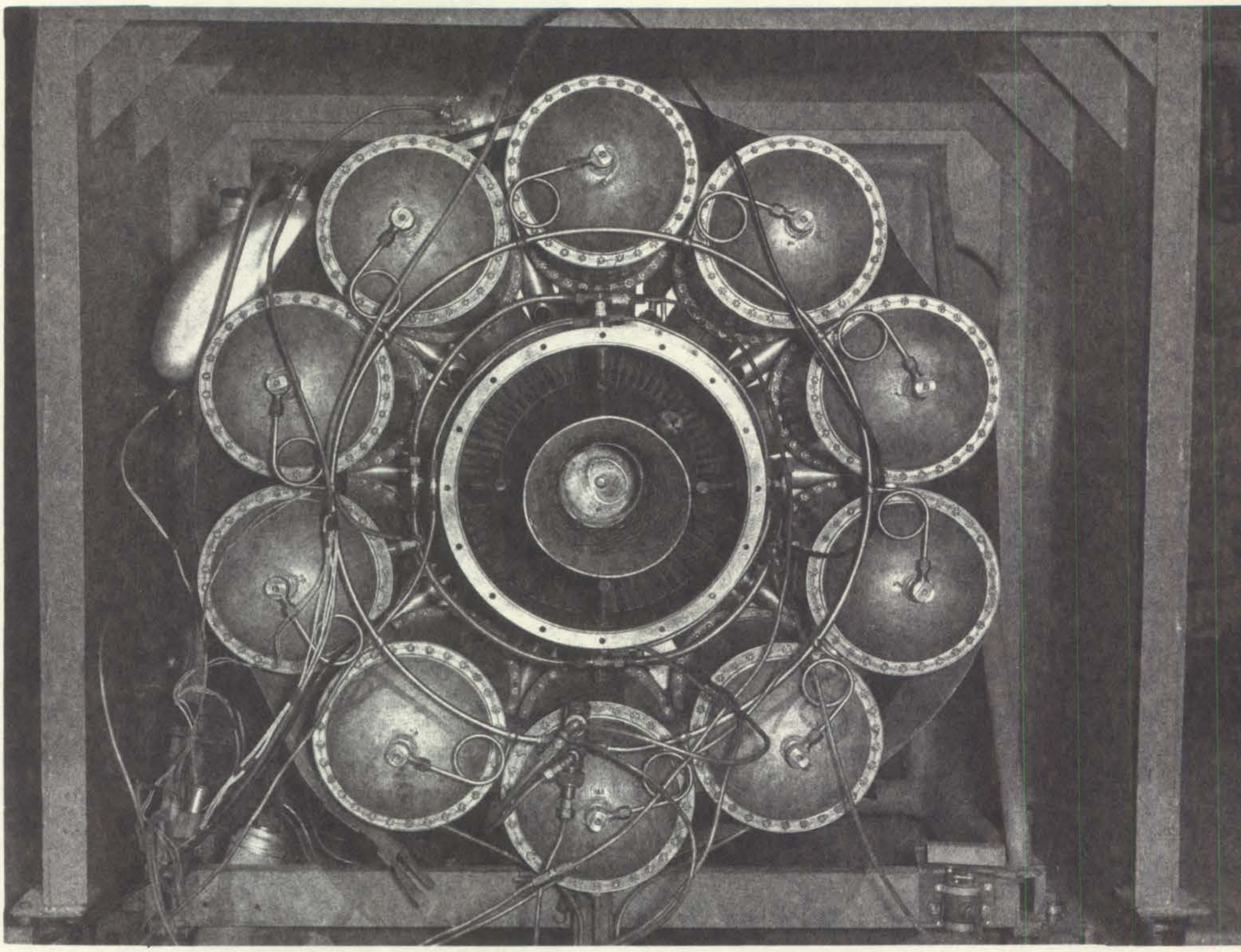


FIGURE 11. END VIEW OF DIVERGENT FLAME TUBE AND PILOT BURNER. (PILOT BURNER AIR SCOOP IS VISIBLE IN UPPER HAND QUADRANT OF EXHAUST ANNULUS; NOTE THE MANNER IN WHICH THE FACE OF THE PILOT BURNER HAS BEEN ETCHED BY THE SCOURING ACTION OF THE SWIRLING FLAME.)

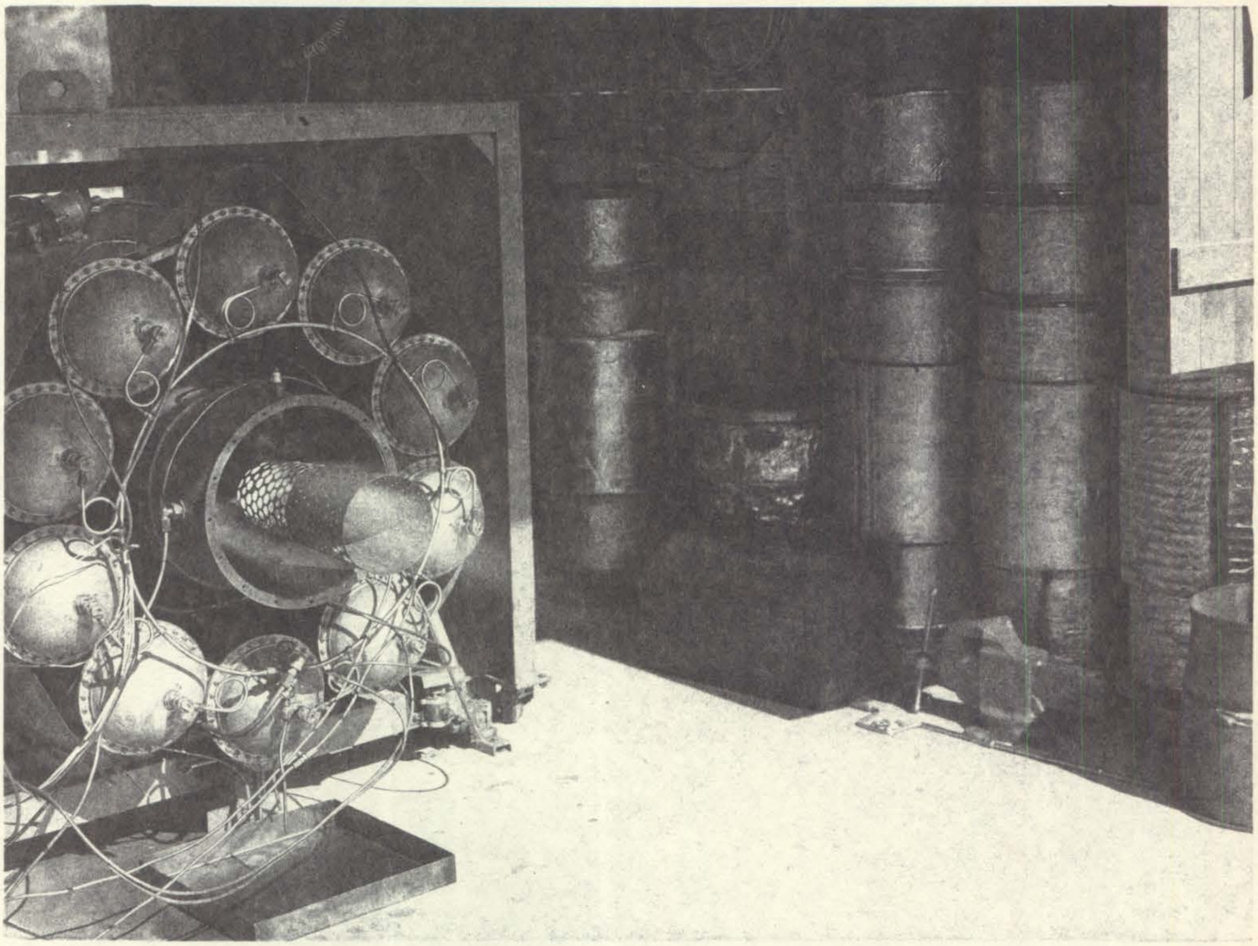


FIGURE 12. SIDE VIEW OF DIVERGENT FLAME TUBE WITH BURNING.
(NOTE SPRAY PATTERN FROM MAIN INJECTORS.)

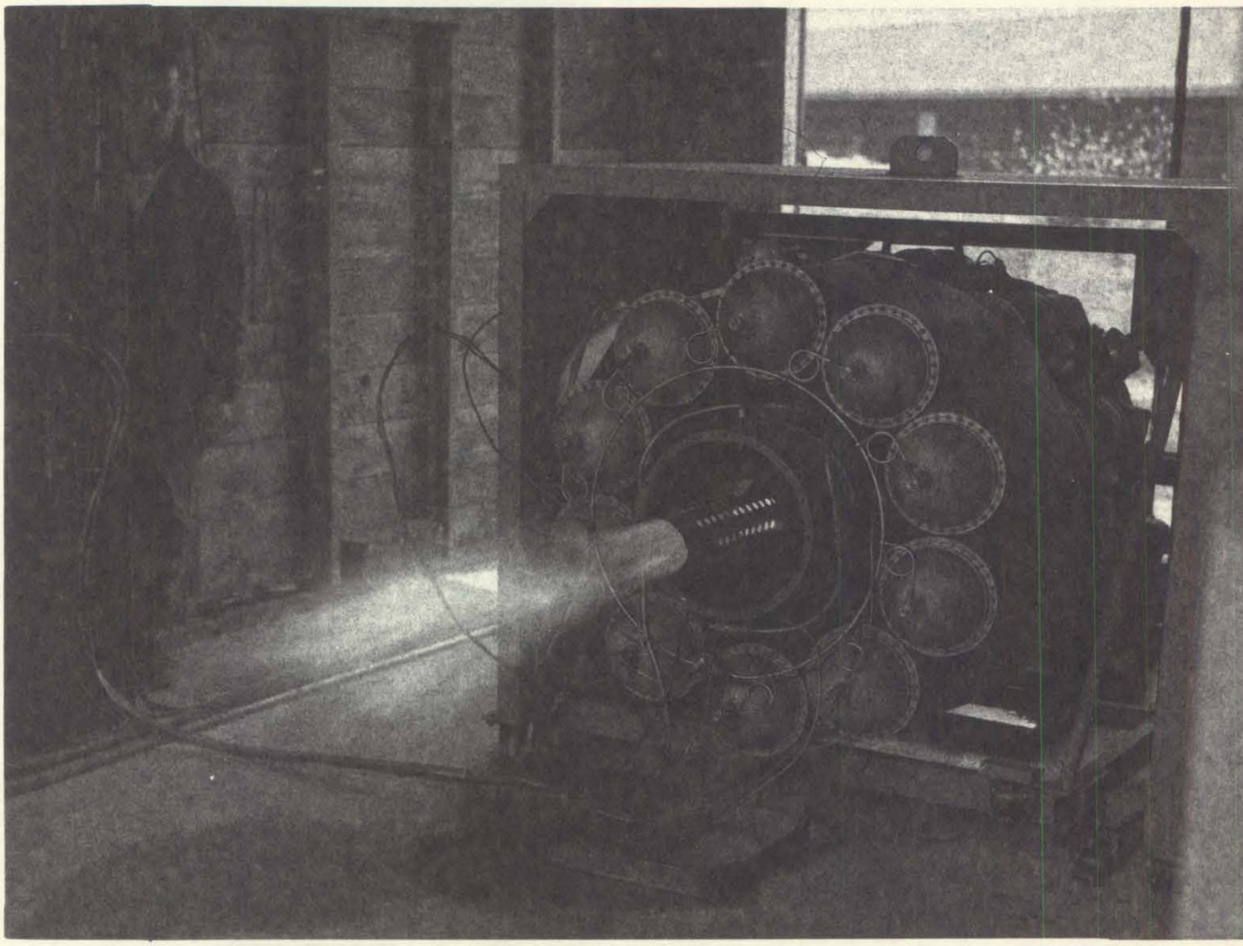


FIGURE 13. SIDE VIEW OF STRAIGHT FLAME TUBE WITH BURNING.
(NOTE SPRAY PATTERN FROM MAIN INJECTORS AS COMPARED TO THAT SHOWN IN FIG. 12.)

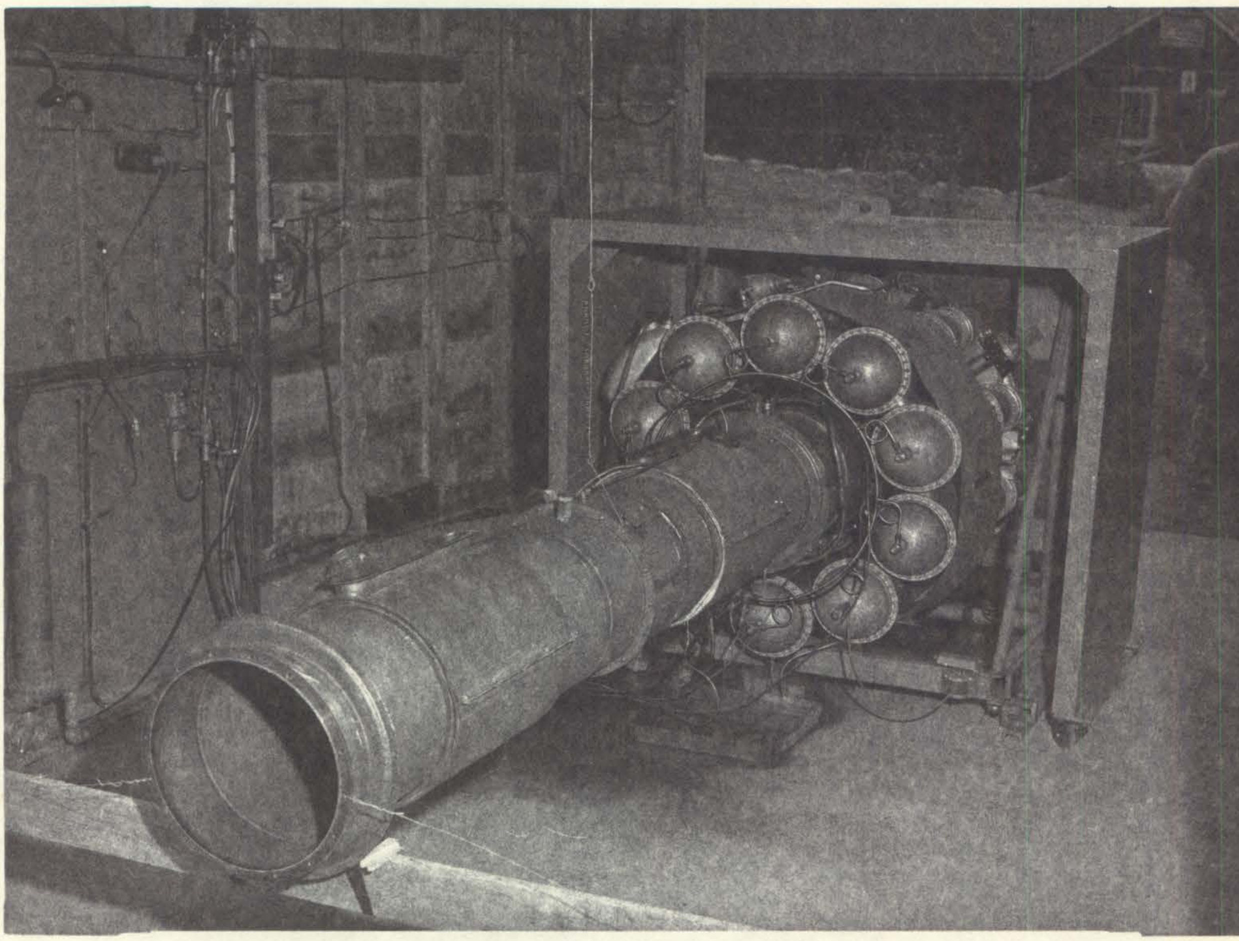
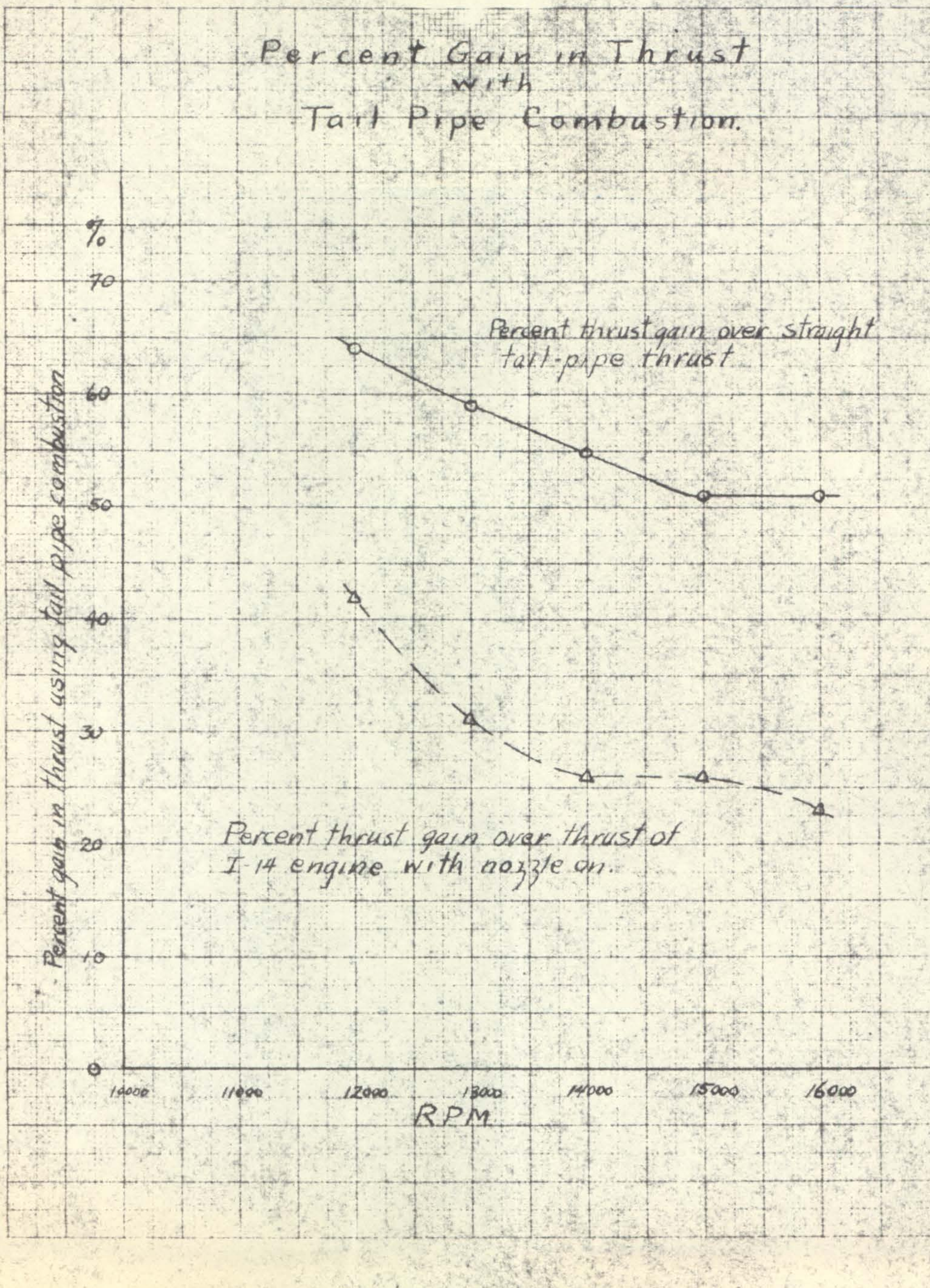
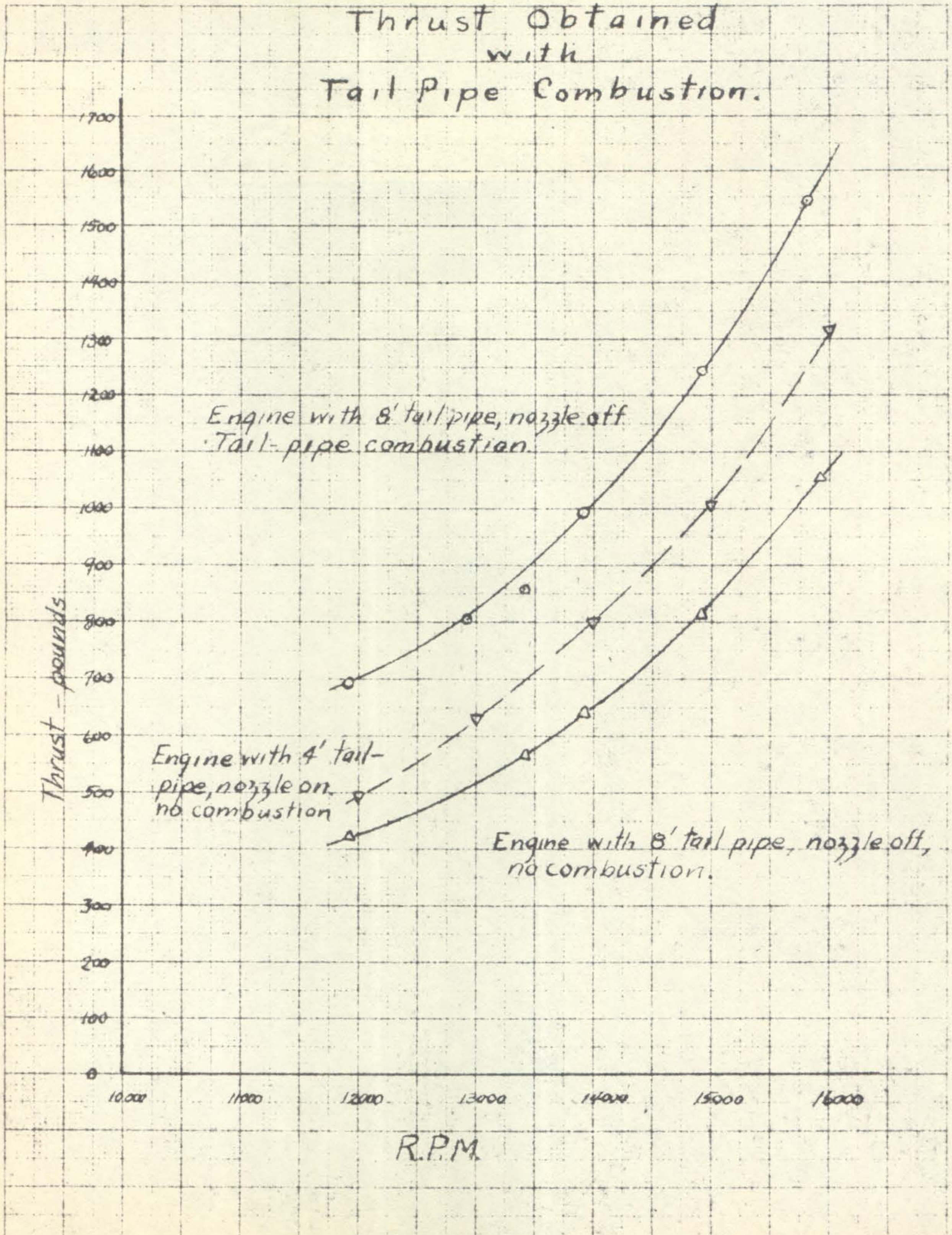
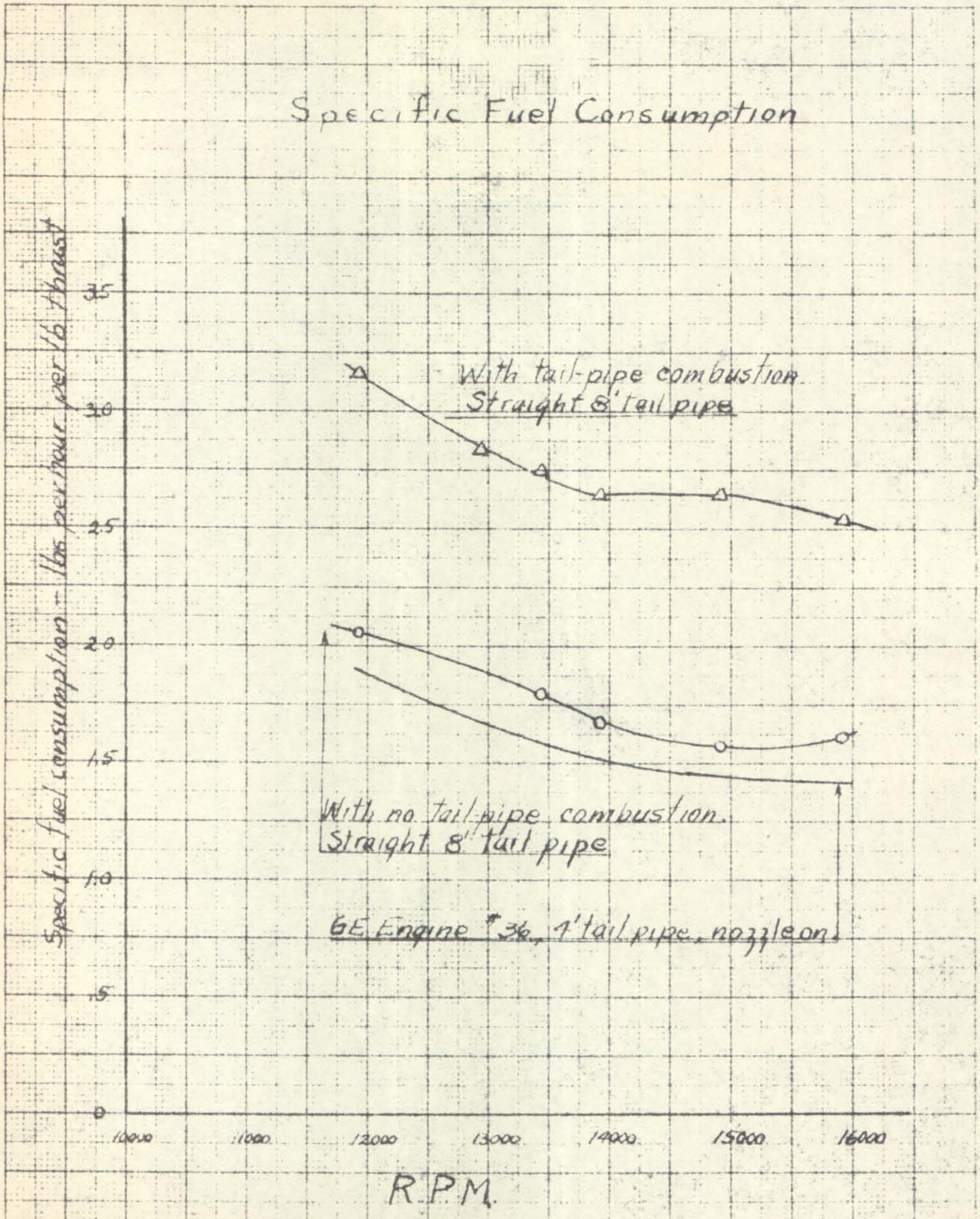
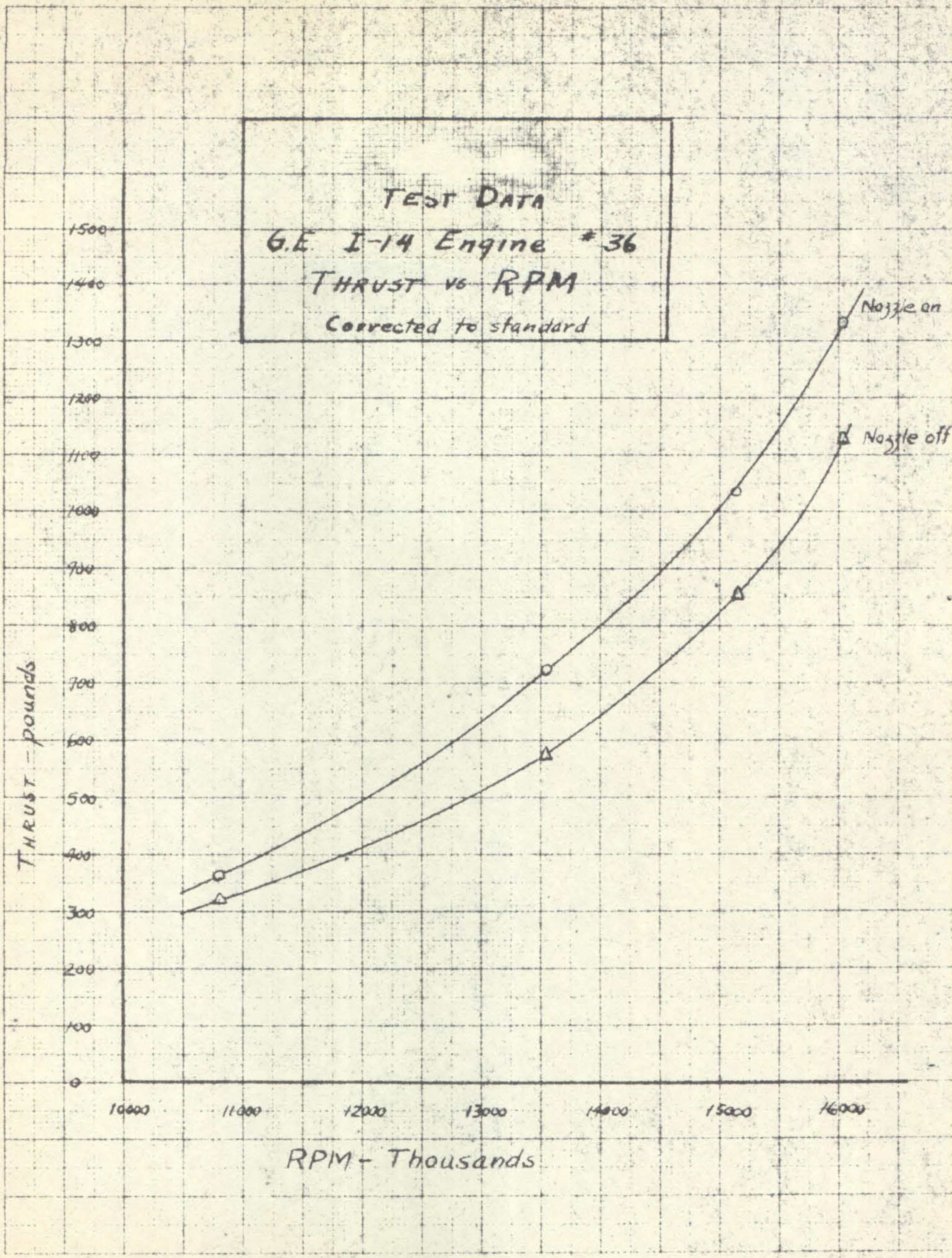


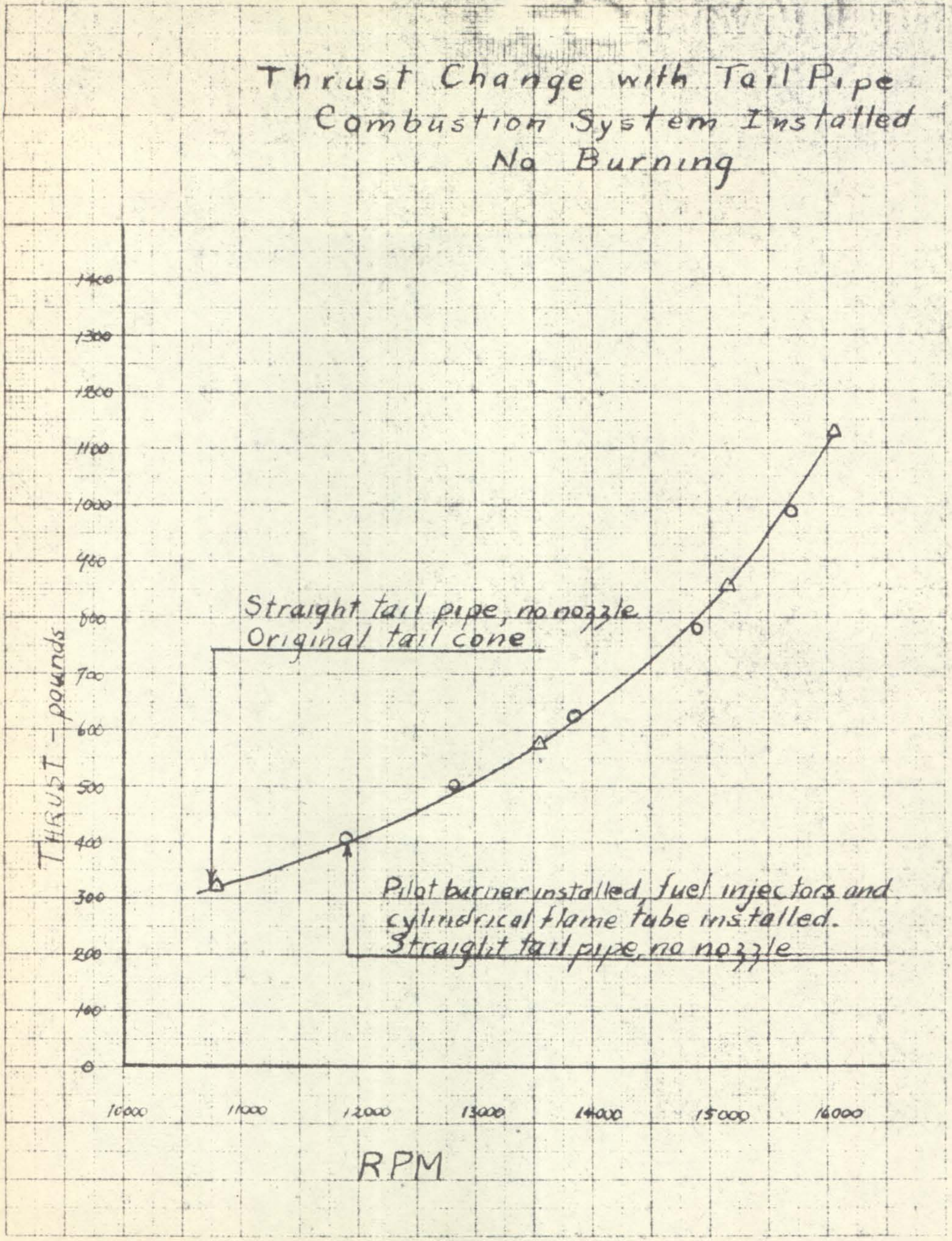
FIGURE 14. EIGHT FOOT TAIL PIPE INSTALLATION.

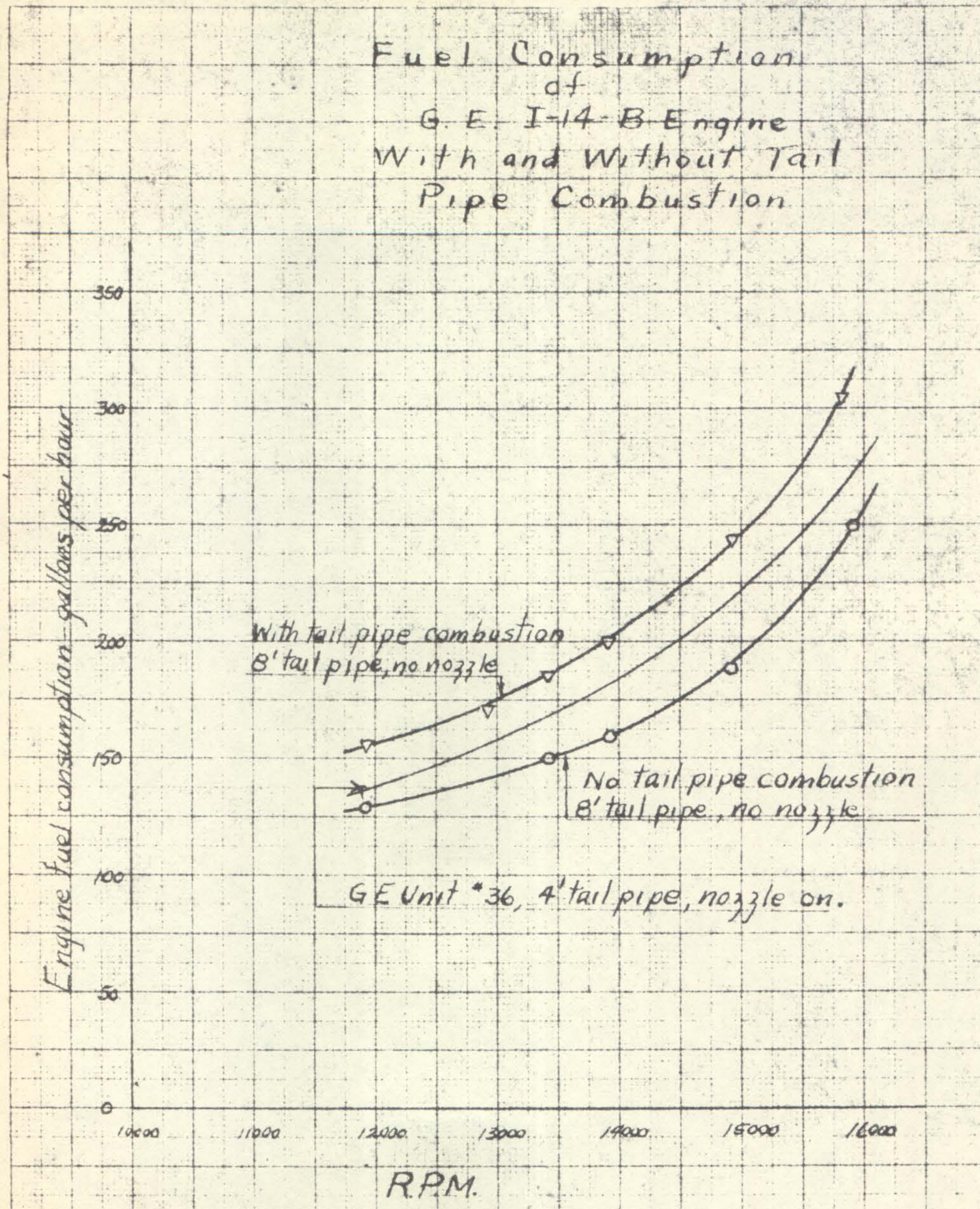

Percent Gain in Thrust
with
Tail Pipe Combustion.
%
70
60
50
40
30
20
10
0
Percent gain in thrust using tail pipe combustion
Percent thrust gain over straight tail-pipe thrust
Percent thrust gain over thrust of I-14 engine with nozzle on.
10000
11000
12000
13000
14000
15000
16000
RPM

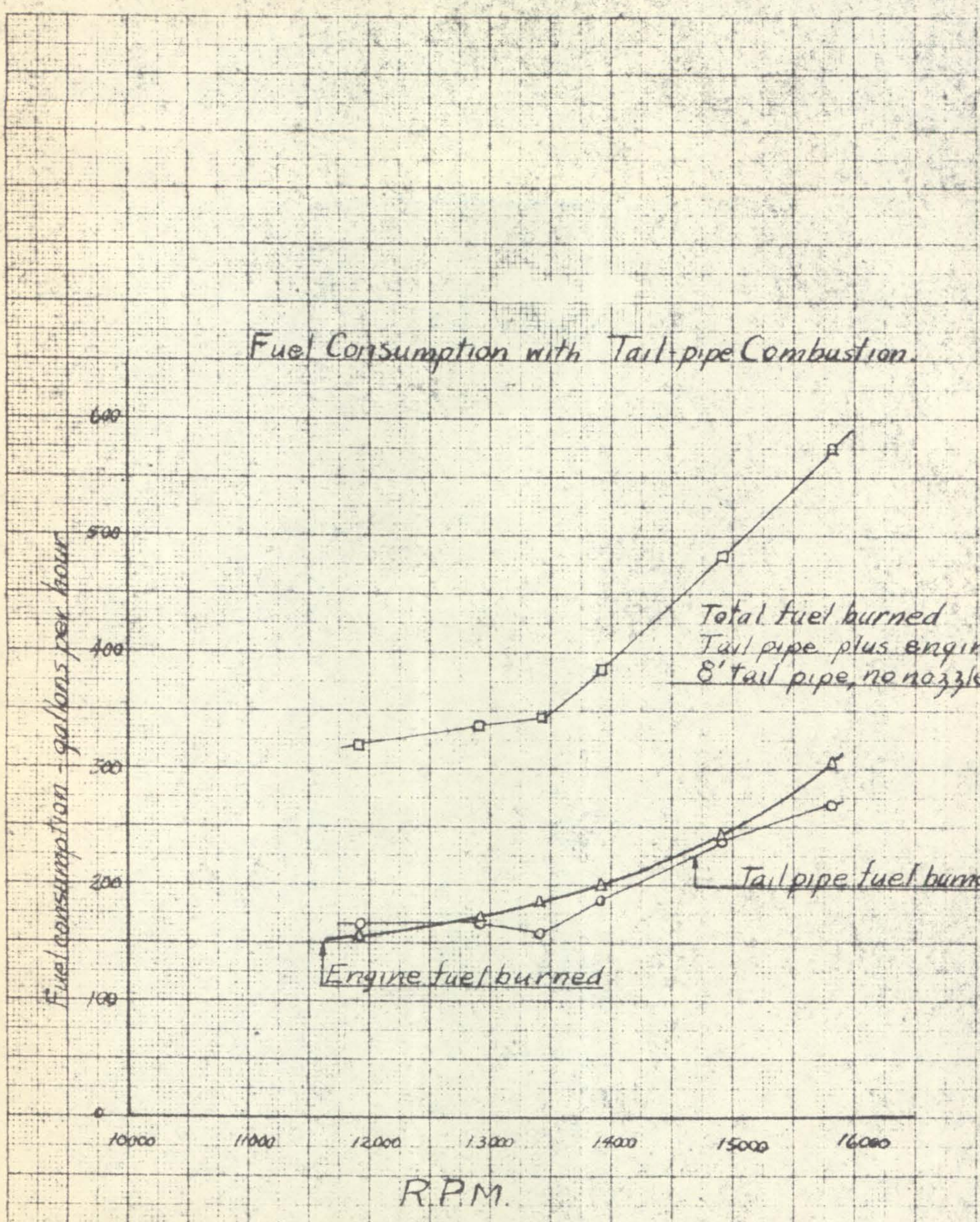

Thrust Obtained
with
Tail Pipe Combustion.
Thrust - pounds
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
10,000
11000
12000
13000
14000
15000
16000
R.P.M.
Engine with 8' tail pipe, nozzle off
Tail-pipe combustion.
Engine with 4' tail-pipe, nozzle on.
no combustion
Engine with 8' tail pipe, nozzle off,
no combustion.

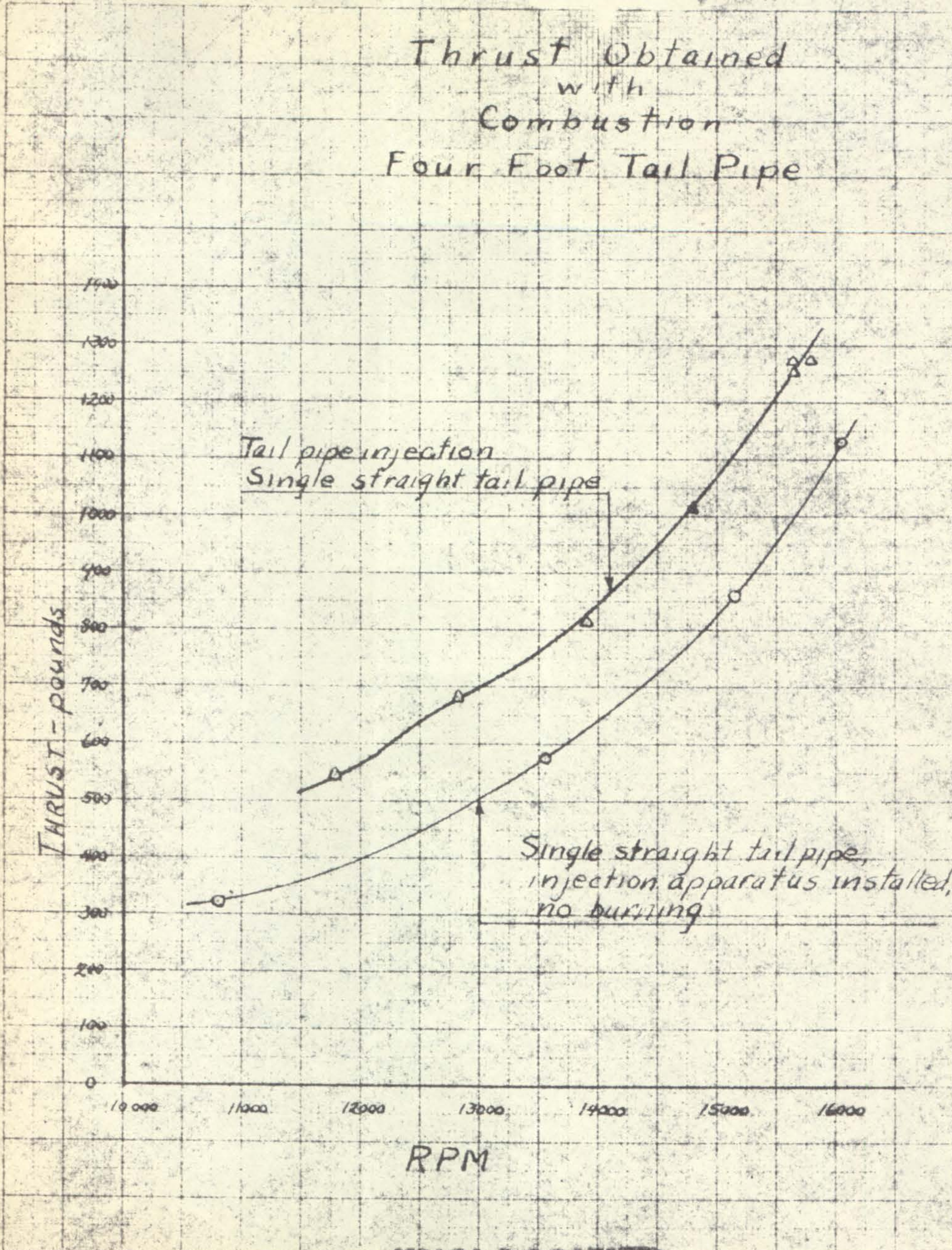

Specific Fuel Consumption
Specific fuel consumption - lbs per hour per lb thrust
With tail-pipe combustion.
Straight 8' tail pipe
With no tail-pipe combustion.
Straight 8' tail pipe
GE Engine #36, 4' tail pipe, nozzle on.
35
30
25
20
15
10
5
0
10000
11000
12000
13000
14000
15000
16000
R.P.M.


TEST DATA
G.E. I-14 Engine #36
THRUST vs RPM
Corrected to standard
Nozzle on
Nozzle off
THRUST - pounds
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
10000
11000
12000
13000
14000
15000
16000
RPM - Thousands


Thrust Change with Tail Pipe
Combustion System Installed
No Burning
THRUST - pounds
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Straight tail pipe, no nozzle
Original tail cone
Pilot burner installed, fuel injectors and
cylindrical flame tube installed.
Straight tail pipe, no nozzle.
10000
11000
12000
13000
14000
15000
16000
RPM


Fuel Consumption
of
G. E. I-14-B Engine
With and Without Tail
Pipe Combustion
Engine fuel consumption - gallons per hour
350
300
250
200
150
100
50
0
10000
11000
12000
13000
14000
15000
16000
R.P.M.
With tail pipe combustion
8' tail pipe, no nozzle
No tail pipe combustion
8' tail pipe, no nozzle
GE Unit #36, 4' tail pipe, nozzle on.


Fuel Consumption with Tail-pipe Combustion.
Total fuel burned
Tail pipe plus engine
8' tail pipe, no nozzle
Tail pipe fuel burned
Engine fuel burned
Fuel consumption - gallons per hour
600
500
400
300
200
100
0
10000
11000
12000
13000
14000
15000
16000
R.P.M.


Thrust Obtained
with
Combustion
Four Foot Tail Pipe
Tail pipe injection
Single straight tail pipe
Single straight tail pipe,
injection apparatus installed,
no burning
THRUST - pounds
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
10000
11000
12000
13000
14000
15000
16000
RPM