Navy Department - Office of Research and Inventions

NAVAL RESEARCH LABORATORY
Washington, D.C.

* * *

CHEMISTRY DIVISION - PHYSICAL AND INORGANIC SECTION

March 1946

DISTRIBUTION STATEMENT A APPLIES.
Further distribution authorized by
UNLIMITED only.

STUDY OF FUELS IN THE AERORESONATOR MOTOR
Period: 7-1-45 to 2-1-46.

By: D. S. Burgess, S. H. Smith,
T. K. Rice, K. J. Hayes and
C. G. Lindquist

FR-2777

- Report P-2777 -

* * *

Approved by:

R. R. Miller, Head, Physical and Inorganic Section

Dr. P. Borgstrom
Superintendent, Chemistry Division

Commodore H. A. Schade
Director, Naval Research Laboratory

Preliminary Pages.......a-c
Numbered Pages..........13
Tables.................. 7
Plates..................20
Distribution List.......-d-

NRL Problem No. P-95
as

TABLE OF CONTENTS

ABSTRACT

As a preliminary to fuel studies, performance of a reference fuel (62 octane gasoline), has been studied in six inch aeroresonators. While no attempt has been made to depart from conventional motor design, dimensions have been varied in the design factors of chamber and tailpipe length, tailpipe diameter, valve box area and "throat" shape and area. Air intake valve tensions are also discussed. Measurements taken over the range of operating fuel values include thrust, air consumption, frequency and temperature. The minimum specific fuel consumption obtained was 2.64 lbs/hr/lb. (specific impulse = 1360) and the maximum thrust 33.5 lbs.

INTRODUCTION

A. Authorization

1. This problem was authorized by the Bureau of Aeronautics on Project Order No. 249/46, "Development of Jet Propulsion Propellants for use in Special Aviation Equipment". TED No. NRL-3401.

B. Statement of the Problem

2. The ultimate purpose of the immediate project is to determine what fuels will improve the present performance of gasoline in the aeroresonator. Originally it was planned to work solely on fuels while excluding design considerations from the program; this policy had to be changed, however, when it became apparent that some understanding of design factors would be necessary for establishing a true base performance of the motor with gasoline. A short series of tests on valves for a six inch model eventually grew into a rather complete study of performances. The work to date, limited in scope to a stationary motor of this one maximum diameter, and using 62 octane gasoline as a fuel, is the subject of this report.

PHYSICAL SET-UP

3. For the location of the project at the Chesapeake Bay Annex of the Laboratory, we are indebted to the Mechanics and Electricity Division group under Mr. Campbell, which is occupied with design problems using motors of a larger size. Through their cooperation it was possible to move into a well-equipped workshop with all necessary facilities for immediate experimental work. A six inch motor was placed at our disposal and an engineer temporarily assigned to working with our group on the initial construction problems. The original motor and subsequent variations (see Plate I) have used iron pipe of standard wall thickness for chamber and tailpipe. Sheet iron reducing sections of 3/16 or 1/4 inch thickness are connected with standard pipe flanges. With one exception all valve-boxes were of the type to employ Eichelberger reed valves and were usually set off from the chamber by a 1-1/2 inch length of reduced cross-section, which in this report, has been called the "throat". All data reported here were obtained with the water cooling system in operation.

4. Thrust measurements were obtained by balancing the push of the motor with air pressure behind a leather piston. To minimize the interference of friction, necessary travel of the assembly during measurement was limited to the 0.005 inch separating open and closed positions of a microswitch (Plates I and III). Operation of the switch activated solenoid valves to bleed air into or out of the system.

8. The linearity of air-fuel vs. fuel plots, while plausible, proves nothing as to the absolute accuracy of these air measurements; some effort was taken, therefore, to check the results by an independent method. Orsat analysis of tail-pipe gases, using samples taken over periods of many cycles, showed that at a point close to the juncture of cone and tailpipe the gases are free of combustibles when the exploding mixture is lean and free of oxygen, thereby excluding "suckback", when the mixture is rich. Therefore, if the composition of the fuel is known, gas analysis should provide correct air-fuel ratios. Table II compares air-box and gas analysis figures for one lean and one rich ratio. The agreement is qualitative rather than quantitative because of the low percentage of CO, CO_2 and O_2 in the samples (most of the gas is nitrogen) and the difficulty of precise measurements by the Orsat.

9. A better check on the air-box was obtained by drawing combustion gas samples through a Pauling oxygen meter. This method is valueless for rich mixtures, but good agreement was obtained at slightly lean mixtures (A/F=15.2,15.6). In the resonance region points are obtained which are linear with air-box measurements in the non-resonating range (frequency 6500 cpm, >5500 cpm). In figures XIIIa and XVIIa, Pauling meter determinations are shown as triangles. The sensitivity of this meter to small increments of air-fuel ratio is illustrated on Plate VI.

10. Frequency measurements were obtained with a Westinghouse reed vibrometer which had previously been checked by the M. & E. group against synchronous motors of known frequency. Readings by different observers using two such vibrometers had an average deviation of about 100 cpm.

11. Time has permitted only a limited number of measurements of apparent average temperatures. For these data, platinum-platinum rhodium thermocouples (24 gage wire) are carried into the air stream through 1/8" porcelain insulators, this size being a compromise between excessive fragility of smaller and excessive effect on motor operation of larger insulators. An estimate of the effect on motor operation of having the couples in place is obtained from Plate XIVa where the circled thrust points were obtained in this way. The problem of correcting apparent temperatures to their true values would involve at least four considerations. (1) Conduction of heat away from the couple along the lead wires, negligible for air-stream temperatures, perhaps significant for inside wall temperatures where the lead wires are not themselves being heated. (2) Damming of the air stream by the couple, also thought negligible following some crude tests of couples in an air stream at room temperatures. (3) Radiation losses from the couples, which can be estimated once the approximate wall temperatures are known. (4) Rate of heat input through convection, a figure that cannot be estimated by any of the usual low temperature, low air-speed formulas.

12. It is regretted that other measurements originally planned have not yet been undertaken. Instantaneous pressure measurements presumably can be started upon arrival of Trimount equipment, the order for which was transferred from E.E.S. High speed photographic measurements have been delayed by lack of manpower and will now probably be deferred until warmer weather. An offer of cooperation by the Physical Optics Division on instantaneous temperature determinations has been gratefully accepted. No other instrumentation is now planned.

EXPERIMENTAL DATA

13. The results obtained in this study are given in Tables I - VII and Plates I - XX. Unless otherwise specified the setup used in running motor tests was as follows:

a. Sixteen (Eichelberger) vane valve box.
b. Water-cooled, square "throat", 1-1/2" long, 16-1/2 sq.in. internal cross section.
c. Conical spray fuel jet as shown in Plate VII.
d. Diameter of combustion chamber 6-1/16", length 6".
e. 6" to 4" reducing section, length along axis 12".
f. Tailpipe diameter 4".
g. Air-box connected through the bellows as on Plate I; all thrust measurements corrected for this effect, using data of Table I.
h. Water cooling along length of tube (see par. 33).

Other information such as tailpipe lengths, etc., is contained in the titles of tables and plates. Precision of the various measurements has been discussed in paragraphs 4 - 11.

TREATMENT OF THE DESIGN VARIABLES

A. Air-Intake Valve Box

14. The treatment of design variables by this group started with difficulties in obtaining sufficient operating life of valves. The original motor received from the M. & E. group had a 12" chamber length, 6" I.D.; initial tests were made using sixteen 0.006 inch steel Eichelberger vanes which had remained operative long enough in a thirteen inch diameter motor to obtain performance data. However, in the small motor, vane deterioration was too fast for performance of any useful measurement. Vanes of 0.008 inch thickness then became available and with these, eight life tests were made of an average duration of twelve minutes; a sufficient period (3 - 6 minutes) at the start of each run was suitable for taking data (with their thirteen inch motor, the M. & E. group had close to a one hour running time on these vanes.)

15. Because of the poor thrust obtained with a 12" chamber length, the chamber was cut down to six inches. Then the 0.008 inch vanes were no longer satisfactory, total life being reduced

to 1 - 3 minutes. The first satisfactory solution to this immediate problem was a shod vane (Plate VIIIa); this valve had a total life, in most instances, of 8 - 10 minutes with a relatively flat thrust vs. time relationship until close to the end of operability. Most of the data reported here, including the best determined specific fuel consumption, 2.64 lbs. fuel/hr./lb. thrust, has used the shod vane. The design was of no practical importance because of the laborious construction and since slightly thereafter the M. & E. group developed a "laminated" vane of considerable greater durability. This laminated vane, fully described in reference (a) (also see Plate VIIIb) was found in two tests to last 40 and 42 minutes in the six inch diameter motor with six inch chamber length. The laminated vane was not used extensively in this study because of a sharp drop in efficiency over the first few minutes (perhaps 10% in thrust) followed by a very slow deterioration. Those results which are given were taken with new vanes.

16. Numerous other attempts to improve vane life might be recorded. A steel and leather vane, using .008" steel for flexing and 1/16" leather for closure was found unsatisfactory. A "swinging door" valve box, departing entirely from the Eichelberger reed, was constructed. The sixteen vanes were replaced by four 0.025" hinged doors held in normal closed position by piano wire (springs). Although this valve box was never successfully put in operation, it does have merits and deserves further experimentation. Most recently a weighted vane (Plate VIIIc) has been found promising as to durability though its performance characteristics are still unknown.

17. From inspection of Plate VIII, it is apparent that both shod and laminated vanes would admit less air than a bare vane for given internal suction pressure. The same would appear likely from the data of Plate IX where measured steady flows of air were passed through the vanes. (In connection with Plate IX it should be pointed out that total average air passage for 16 vanes in operation is 1200 - 1500 lbs/hr., and assuming a sine wave opening of the valves the maximum instantaneous air flow would be of the order of 4000 - 5000 lbs/hr. From this a very crude estimate of the maximum operating pressure drops could be drawn). A comparison of engine performance for bare and shod vanes is not available, but Plates XII - XVI compare the relatively flexible shod vanes and somewhat stiffer laminated vanes under identical motor conditions. See also Table IIIA and B. The following generalizations were drawn:

(1) The ranges of operating fuel values are comparable for the two valves.

(2) The lowest specific fuel consumptions differ by about 10% in the two cases (2.64 and 2.90 lbs/hr/lb.), while highest thrusts are nearly equal.

(3) The best operating conditions are displaced toward longer tailpipes for the stiffer vane.

(4) Air fuel ratio curves are steeper for the laminated vanes and optimum conditions of thrust and specific fuel are obtained with richer mixtures.

(5) Frequencies are higher with laminated vanes and in general, the thrust-fuel curve for a particular tail-pipe length resembles that for a shorter tailpipe with shod vanes.

B. Throat

18. The original thought on durable vanes was to compensate for any loss of flexibility by adding to the number of units. The use of larger valve-boxes was not possible, however, without enlarging or removing the "throat" through which the valves were set off from the chamber. See Plate V. (This water-cooled section was first used on the 12" length of chamber as a scheme for improving valve life; since no marked difference in thrust appeared with and without the throat on this particular set-up, the importance of the throat was but recently appreciated). Initial attempts to increase this cross-section while using a six inch chamber length proved the sensitivity of performance to very slight adjustments of geometry in this region of the tube. The problem here was very much analogous to that of flame-catchers in the ram jet in that there is a "dead space" behind the break in the lines of the tube which apparently is necessary for proper combustion; the value of this dead space is to be balanced against the cross-sectional area lost to the valve box.

19. Table IV lists the various throat arrangements used here in attempts to improve thrust or specific impulse. No more effective configuration was found than the original four inch square section, though the optimum cross section may well lie between that of the four inch square and the four inch circle.

20. Considering the importance of this design variable, the treatment given here has been very insufficient. For one thing the increments of dimension in determining optimum cross-section should be narraowed. Also a number of rough designs might have been more carefully constructed. There has been, moreover, no variation in overall length of the throat, the 1-1/2 inch length being maintained to place the break in streamlining of the tube close to the point of fuel injection. Further work was not attempted because major changes in design seemed out of the province of this group and also because of some doubt that an optimum configuration for the 6 inch tube would carry over to larger motors.

C. Fuel Injection

21. The fuel jet used in virtually all work presented here is shown on Plate VII. A conical spray of about 60° apex angle is obtained, with good atomization from about 60 to 150 lbs. per hour of gasoline. For the six inch motor the conical angle seemed important and four modifications of the jet were made before the tube would resonate well. Position of the point of fuel injection is probably critical for any particular configuration of the throat. With the jet shown, fuel is injected close to the juncture of throat and chamber; the only variations of position that were used consisted of extending the same jet two inches farther downstream and using a similar jet an inch closer to the vanes, performance being erratic in both cases.

22. A comparison of results given here and thos reported in EES reports (ref. b) would indicate a somewhat higher fuel capacity with the side spray injection used at Annapolis. The only occasions where side spray has been used here have involved changes in other variables of the system (see Table IV), so a direct comparison of the methods and also a testing of a combination of the two remains to be undertaken. But for the immediate purpose of testing fuels, many of which are difficult in handling, the conical spray jet offers the advantages of easy disassembly for cleaning and also moderate fuel line pressures (10 - 35 psi).

D. Spark Ignition

23. No indication could be obtained with the six inch motor that position of the spark plug is in any way critical to performance.

E. Chamber and Tailpipe Length

24. Some of the data collected with reference to these two variables are condensed in Tables IIIA, C and D, where peak performance for various geometric arrangements are given. For the 6 inch and 7-1/2 inch chamber lengths, measurements over the entire range of operating fuel flows are given graphically in Plates XII, XIV, XVII and XVIII. The most precise results are those with the 6 inch chamber where numerous runs were made when necessary to obtain reproducibility; least dependable are the results with 12 inch chamber where blisters on the inside surface of the cone had an undetermined effect on operation. In some cases, notably with long tailpipe lengths, the motor choked out at relatively low fuel flow rates and only the "lean" side of fuel-thrust curves could be obtained.

25. The original concept of the problem involved a "constant volume explosion" which should most nearly be obtained when the chamber was prefilled to some optimum depth. At a known fuel and air consumption rate, this depth of filling would be determined by temperature and pressure of the initial mixture as well as by frequency of the motor. It was believed, however, that these temperatures and pressure variations would be insignificant, leaving frequency as the sole determining factor. This frequency has been found to be roughly in inverse proportion to overall length of the tube. The expected results, then, with variations in chamber and tailpipe lengths, would contain these generalities:

(1) Peak performances for various chamber lengths would be obtained at a nearly constant ratio of tailpipe (or overall) to chamber length.

(2) Peak performances for a given chamber and various tailpipes would occur at fuel flows inversely proportional to the overall length.

26. In the composite graph of peak thrusts and lowest specific fuels for 6, 7-1/2, and 12 inch chambers and tailpipe lengths from 28 to 64 inches as in Plate X, all other factors were held constant except that bare vanes were used with the 12 inch chamber instead of the shod vanes used elsewhere. It is apparent from the figure that the first expected generality holds as well as the experimental accuracy would allow. The data of Table III, however, is not consistent with the second expected result. For tailpipe lengths of 28 to 64 inches all with a 6 inch chamber, total fuel flow at best specific fuel consumption remains remarkably constant regardless of frequency. Per cycle the charge of fuel at peak specific is 2.1, 2.5, 2.7, 2.9 and 3.2 x 10^{-5} pounds for five tailpipe lengths studied. In other words, if an optimum precombustion filling of the chamber is to be assumed, then marked differences of initial mixture temperature (or pressure) must exist with the different tailpipe lengths. Similar variation of charges occurs at identical thrusts or specific fuels when different tailpipes are used.

27. In connection with this "optimum filling" of the chamber which seemed so reasonable at first, there should be a point of ignition somewhere near the juncture of chamber and cone from which point the flame should strike back toward the valves. This view seemed confirmed by the Wright Field photographs mentioned in ref. (c). Average temperatures taken along the axis of the chamber would show a sharp increase at this point. If the temperature measurements described in Paragraph II are of any physical significance, however, such a point of ignition does not seem evident (see Table V, Plate XI). Temperature seems to rise regularly along the axis of the chamber to approach a maximum which is reasonably consistent with the heat losses described in paragraph 33. Otherwise the temperatures

measured are not very enlightening, although the drop in temperature toward the end of the tailpipe is sharp enough, in conjunction with Orsat oxygen analyses (Table V) to indicate the extent of suck-back. The irregularity of temperature gradient from axis to inside wall of the tailpipe indicates a non-uniform gas velocity at the forward end of the tailpipe; this condition might be improved by streamlining the juncture of cone and tailpipe.

28. Measurements using a shorter chamber than the 6 inch length will be undertaken shortly. There seems, at present, to be no practical usefulness of very short chambers because of the high rate of valve deterioration to be expected. However, the exact dimensions consistent with most efficient burning of gasoline should be of theoretical interest.

F. Tailpipe Diameter

29. A 4 inch diameter tailpipe was chosen for most of the work here, simply because the 6 to 4 inch reduction had been most successfully used elsewhere and most of the information available involved this ratio of cross-sectional areas. Reducing sections for 6 inch diameter chamber and 3 and 5 inch tailpipes were more recently constructed. Two lengths of 3 inch tailpipe were coupled to an otherwise "standard" set-up for the runs of Plate XIX; it seems obvious that with all other parameters (valve box, throat, etc.) adjusted for the 4 inch tailpipe a smaller diameter is markedly less efficient. But when the throat area was reduced from 16.5 sq. in. to 12.6 sq. in. (see Plate XXa) specific fuel consumption with the small tailpipe approaches the order of magnitude of the best found with the four inch pipe. The peak fuel capacity and peak thrust were lower, of course, and there seemed to be small value in pursuing the design further.

30. Should a simple adjustment of valve-box or throat area bring the 6 to 5 inch reducing section to efficient operation, the design might have a considerably larger fuel capacity and thrust. No indication was obtained here that the design could not be worked out, but merely that considerably time might be involved. When 22 vane and 20 vane valve-boxes were used the tube would not resonate without starting air. With the usual 16 vane valve-box, performance was not reproducible, varying in one case from specific fuel consumption of 2.9 to 4.7 lbs/hr/lb. at a constant fuel setting. If the present intuitive ideas on reaction mechanism are correct, the 6 to 5 inch tube (and similar small reductions on larger tubes) may be of great value with doped fuels.

G. Reducing Cone

31. The length of reducing section from chamber to tailpipe has not been varied, and this represents a considerable omission in the study of design factors. However, the steepness of taper of the cone is varied in changing tailpipe diameters and the effect of cone length relative to overall length is contained implicitly in results with different chamber and tailpipe lengths.

MATERIALS

32. The choice of materials for tube construction is of interest from these standpoints: durability under long term operation, as in valve life, which is not of primary importance to this group; possible catalytic effect on rate of reaction, which has been lightly touched here; heat losses through the walls of the tube, which have an easily demonstrated effect on operating performance.

A. Heat Losses

33. In most of the measurements reported here the tube was cooled during operation by a flow of water which varied with line pressure from 6 to 10 liters per minute. Table VI lists the results of some crude calorimetry to determine the portion of total available heat that was dissipated in this way. The figures (15 - 20%) are probably a minimum, with variations caused by different degrees of wetting of the hot tube. There were, in addition, heat losses by radiation and conduction so it would not be surprising if as much as 25% of the heat of reaction were wasted through the motor walls. Attempts to evaluate the loss in thrust associated with this heat loss are listed in Table VII. Rapid vane deterioration in an uncooled motor makes these latter measurements inaccurate but a difference of about 2 pounds in 30 appears evident.

34. The rate of heat loss during measurements with the uncooled motor is very uncertain. A temperature of 788°C was reached on the outside surface of the tailpipe after 2-1/2 minutes of running, but equilibrium had not yet been attained. From this figure a rough estimate of the radiation loss would be 3% of the total heat; loss by convection should be of the same order of magnitude or smaller. In other words, the data would indicate a relatively small difference in thrust (about 7%) associated with a large difference in heat loss (about 20%). The situation with regard to these measurements is very unsatisfactory.

35. Alundum and carbonundum liners of 1/2 inch thickness have been obtained for the purpose of obtaining thrust data with a lower heat transfer through the motor walls. It is presumed that the value of heat retention, as balanced against increased motor weight, has been estimated elsewhere; it would seem, however, that accurate thrust data as a function of heat loss would be of theoretical interest.

B. Catalytic Effects of Materials in Construction

36. Bench testing of flame characteristics (rate of flame propagation, autogenous ignition temperature, etc.) have shown radically different values to exist for identical mixtures in tubes or pots of different materials. There seemed a slight possibility that motor performance might be affected by a plating of the inside walls and that such effects would help the understanding of reaction mechanism. A copper-dipped cone and chamber was used in several runs and the unit subsequently sand-blasted to remove the copper. Any effect on performance was confused by an unusual experimental variation in this series of runs. The work will be repeated.

EVALUATION OF RESULTS

37. It may be observed that greater emphasis is placed in this report on minimum specific fuel consumptions than on peak thrusts to be obtained with the various designs. This arises partly from the fact that specific fuel (or specific impulse) is more clearly understood as a function of combustion efficiency and partly because the measurements are more precise. Minimum specific fuel is obtained at a fuel flow intermediate between the smooth operation of very lean mixtures (usually with light blue flame) and rough running (always with yellow flame) of the rich mixtures. It thus seems to occur at the maximum capacity of the tube for proper combustion. Thrust measurements can be made with confidence at this point and the greatest experimental error is probably in fuel rotameter reading. It is of interest that air-fuel ratios for minimum specific fuels are of the order of 17 or 18 to 1 for a fuel of stoichiometric ratio 15 to 1. Peak thrusts, on the other hand, occur at close to the stoichiometric ratio and sometimes at the rich side "cut-out", where thrust values are the most difficult to obtain; in the cases of short tailpipe lengths there is usually flame appearing beyond the end of the tube at peak thrust condition.

38. The grouping of minimum specific fuel values for the best motor arrangements in the region 2.5 to 3.0 lbs. fuel/hour/lb. thrust suggests a limit on operating efficiency to be obtained with gasoline in this standard design. The same indication might be obtained by comparison of reports from the various investigators in the field. The best specific fuel value that

can be reported by this group is 2.4 lbs/hr/lb, with cooling water (Table III); according to the 2 pound empirical correction of Table VII, this figure could have been reduced to about 2.5 by running the motor hot.

39. The highest reproducible thrust value obtained here was 33.5 lbs. Again applying the 2 lb. correction, this peak value still falls short of the 38 - 40 lbs. reported elsewhere for tubes of this diameter. Therefore no conclusions can be drawn from this work as to the upper limit of thrusts obtainable.

40. Frequencies and air consumption figures were originally considered desirable for fuel comparisons; since gasoline alone has been used in this work, the magnitude of variations has been small and the measurements thus far have been of no great use. Frequency has been shown to vary inversely with fuel consumption in a single tube and with overall length at identical fuel rates, while varying directly with tailpipe diameter. Air-fuel ratios have been striking only in their constancy at optimum fuel rates for the best designs.

WORK IN PROGRESS

41. The work reported here was expected to be finished about January 1, 1946, the major contributing factor to delay being adverse weather. The next phase of the study, now expected to be completed by May (1946), is a "high spot" survey of the many proposed fuels and fuel additives. In this work the measurements of thrust, air and frequency will be continued as reported here and it is hoped that either instantaneous pressure or temperature measurements will be possible with a number of different fuels. Where variations from reference fuel performance exist, the candidate fuel will be tested in several different designs of motors. For present purposes the fuels to be tested are classed in these categories:

(1) Fuels with possibilities from the standpoint of the original "hot particle" theory. A start has been made here with two runs on dilute aluminum borohydride solutions (ref. d).

(2) Fuels that are known to be unusual "knock" agents, such as iso-amyl nitrite, etc.

(3) Fuels with unusual "induction periods" of ignition. In this connection benzene has been tested in a number of motor configurations, always burning with a comparatively low air-fuel ratio.

(4) Fuels with high rates of flame propagation. High thrusts and specific impulses have been reported for propane (ref. b) but the difference from performance with gasoline was ascribed to better fuel volatilization. This group would like to repeat the work, separating this latter varable, if possible, from the known high rate of flame propagation of propane.

Other projected work includes a study of the effect of added oxygen and water on motor efficiency.

42. A number of jobs to be completed at a later date were mentioned in the body of this report. Most of these can be carried out in a short time (short chamber length, copper plated cone, one or two additional throat configurations, performance of the weighted vane). The greatest time consumption will probably be with the insulating liners for minimization of heat loss.

REFERENCES

(a) Partial Report on Gas Pulsator, NRL Report 0-2730.

(b) N.E.E.S. Reports on Aeropulse Project.

(c) NRL letter C-F13-4(1)(452-DSB), C-452-77/45 dated 10 August 1945.

(d) NRL letter F13-4(1), N506/N830-1/46 dated 20 March 46.

Table I

Correction to Measured Thrust Arising from Air-Box Connection

Fuel Flow (lbs/hr)	Thrust (lbs.)		Difference (lbs.)	Air-Box Pressure (in. H_2O)
	Connected	Unconnected		
86.5	29.0			
88		27.1	1.9	-1.42
88	29.0			
95		30.0	1.9	-1.54
95	31.9			
94	31.8			
94		29.7	2.0	* -2.0 to -2.5
94	31.6			

* High suction pressure due to resonance (par. 7).

Table II

Comparison of Air-Box and Orsat Analysis Figures for Air-Fuel Ratio

Fuel (lbs/hr)	Air-Box		Orsat Analysis
	lbs. air/hr	A/F	A/F
85	1390	16.3	15.9
85	1370	16.1	14.5
85	1420	16.7	12.8
98	1335	13.7	13.7
98	1335	13.7	13.3

Stoichiometric ratio for octane = 15.1

Table III

Summary of Results, Various Chamber and Tailpipe Lengths, Motor Described Paragraph 13.

Tailpipe Length (Inches)	Peak Thrust (lbs.)	Fuel at Same (lbs/hr.)	A/F at Same	Best Sp. Fuel	Fuel at Same (lbs/hr.)	A/F at Same
A. 6 inch chamter length, shod vanes.						
28	31.6	99	15.0	2.80	85	16.8
34	33.5	97	18.0	2.75	93	19.3
40	33.2	93	16.0	2.64	85	18.0
46	33.5	94	16.1	2.75	85	17.3
52	31.5	93	16.2	2.80	85	17.8
64	28.5	92	16.5	3.10	85	17.5
B. 6 inch chamber length, laminated vanes.						
28	26.5	97.5	13.8	3.35	84	15.8
40	32.0	103.0	14.3	3.00	83	(18.5)
52	32.5	97.5	14.5	2.90	92	15.5
64	31.6	104.0	-	3.3	104	-
C. 7-1/2 inch chamber length, shod vanes.						
40	29.5	98	14.0	3.2	90	15.8
52	32.5	105	13.5	3.1	95	15.1
64	26.4*	86	-	3.3*	86	-
* Thrust still rising at maximum operating fuel rate, 86 lbs/hr.						
D. 12 inch chamber length, bare vanes.						
40	21.9	102	13.0	4.4	86	15.0
52	29.1	106	15.4	3.7	106	15.4
					86	17.3
76	28.2	105	15.3	3.7	85	17.7

Table IV

Data Comparing Various Throat Dimensions, Otherwise Standard Tube

No. of Vanes	Throat		Fuel Spray	Lowest Spec. Fuel	Remarks
	Shape	Dimensions			
I 16	Square	4 x 4-1/8	Conical	2.64	"Standard"
II 24	None	-	Conical	?.	Failed to resonate
III 24	None	-	Side spray		Failed to resonate
IV 16	None	-	Conical	3.8	
V 16	Circle	6" diam.	Conical		Failed to resonate
VI 16	Circle	4" diam.	Conical	3.1	See Plate XX
	some vanes overlapped				
VII 22	Circle	5" diam.	Conical		Failed to resonate
VIII 16	Rectangle	4-1/8 x 5-1/2	Conical	3.6	Narrow range of fuel value
IX 24	Rectangle	4-1/8 x 5-1/2	Conical		Failed to resonate
X 24	Rectangle	4-1/8 x 5-1/2	Side spray		Failed to resonate
XI 16	Square	4-1/8 x 4	Conical		Failed to resonate
	plus 2 air-foils between throat and chamber				
XII 16	Circle	6" diam.	Conical	3.7	Very hard on vanes
	plus orifice 4 x 4-1/3 between throat and chamber				
XIII 20	Square	4-1/3 x 4	Side spray	3.7	Much higher operating fuel range

Table V

Apparent Average Temperatures (°C) in Aeroresonator

Region of Tube	Inches from Air Inlet	Temperature			% O_2 * (Orsat Anal.)
		Along Axis**	1/2" From Wall ***	Wall ***	
Throat	0				
	1/8	700			
	1-3/8(Fuel Inlet)				
	2	830			
Combustion Chamber	2	830			
	3	1060			
	4	1190			
	5	1210			
	6	1220			
	7	1230			
	8	1240			
Reducing Cone	8				
	20				
Tailpipe	20				
	30	1500			
	36	1480	1230		
	42	1460		730	
	48	1460	1350		0.6
	54		1390		0.8
	60	1280	1240	780	3.4
	66	970	930		
	72	End of tailpipe			

* Measured 8/11/45
** Chamber measurements 12/20/45
Tailpipe measurements 10/22/45
*** Tailpipe measurements 9/27/45

Table VI

Heat Losses to Cooling Water in Typical Set-up

Length of Test	Water Flow Rate (liters/min.)	Total Loss (kg C.)	Fuel Flow Rate (lbs/hr.)	Total Heat of Combustion (kg C.)*	% Loss Thru Walls
62	9.7	1355	.86	7400	19
60	10	1087	86	7150	15
90	6.7	2110	86	10725	20

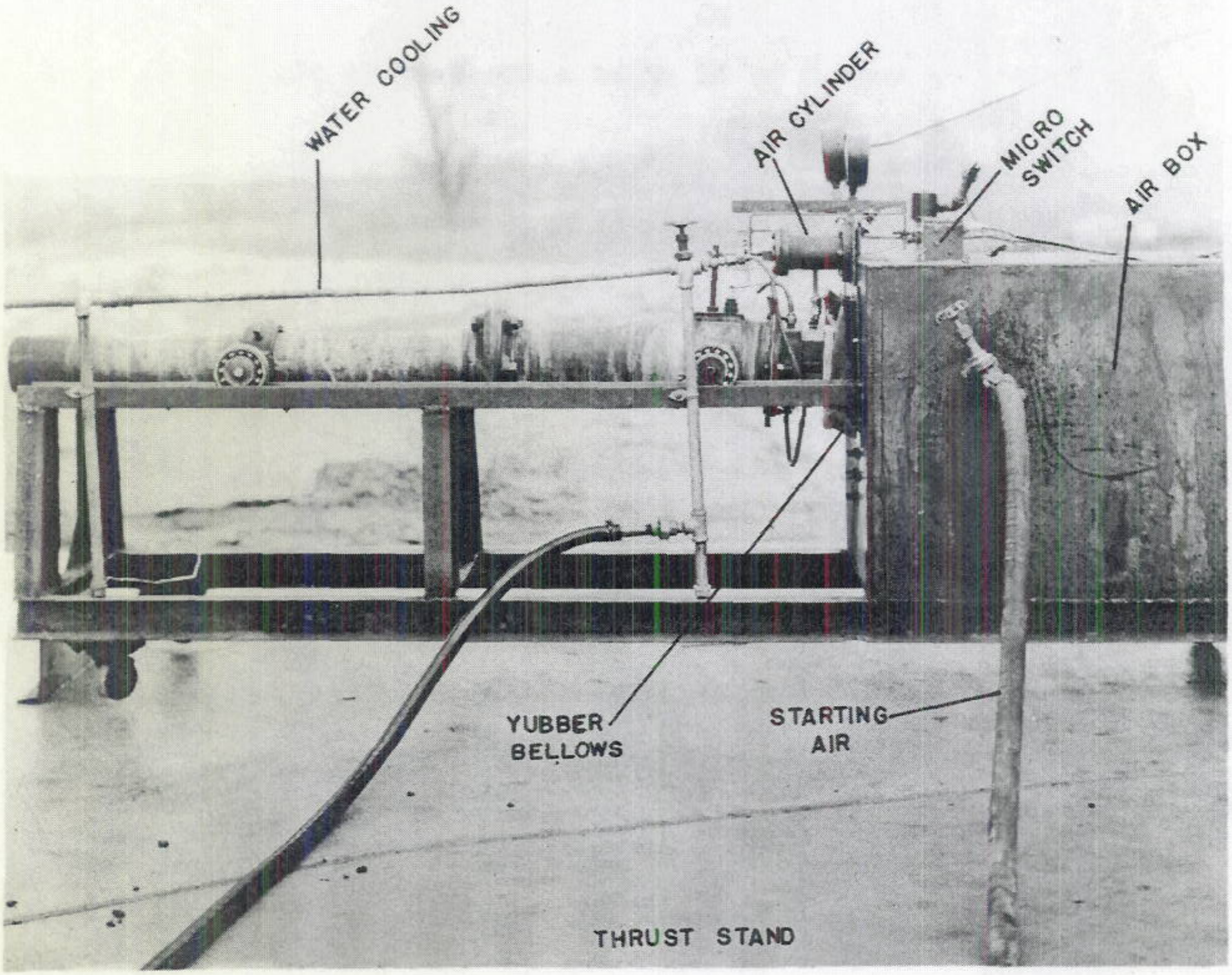
* Assuming heat of combustion to be 11 kg C. per gram of fuel.

Table VII

Differences in Thrust With and Without Water Cooling

Test Series	Thrust (lbs.)		Difference
	With Water	Without Water	
I	27.7 23.8	27.8	2.0
II	29.3 24.5	29.0	2.1
III	28.7	31.1	2.4
IV	31.5	32.8	1.3

Av. = 2.0 lbs.



THRUST STAND

PLATE I

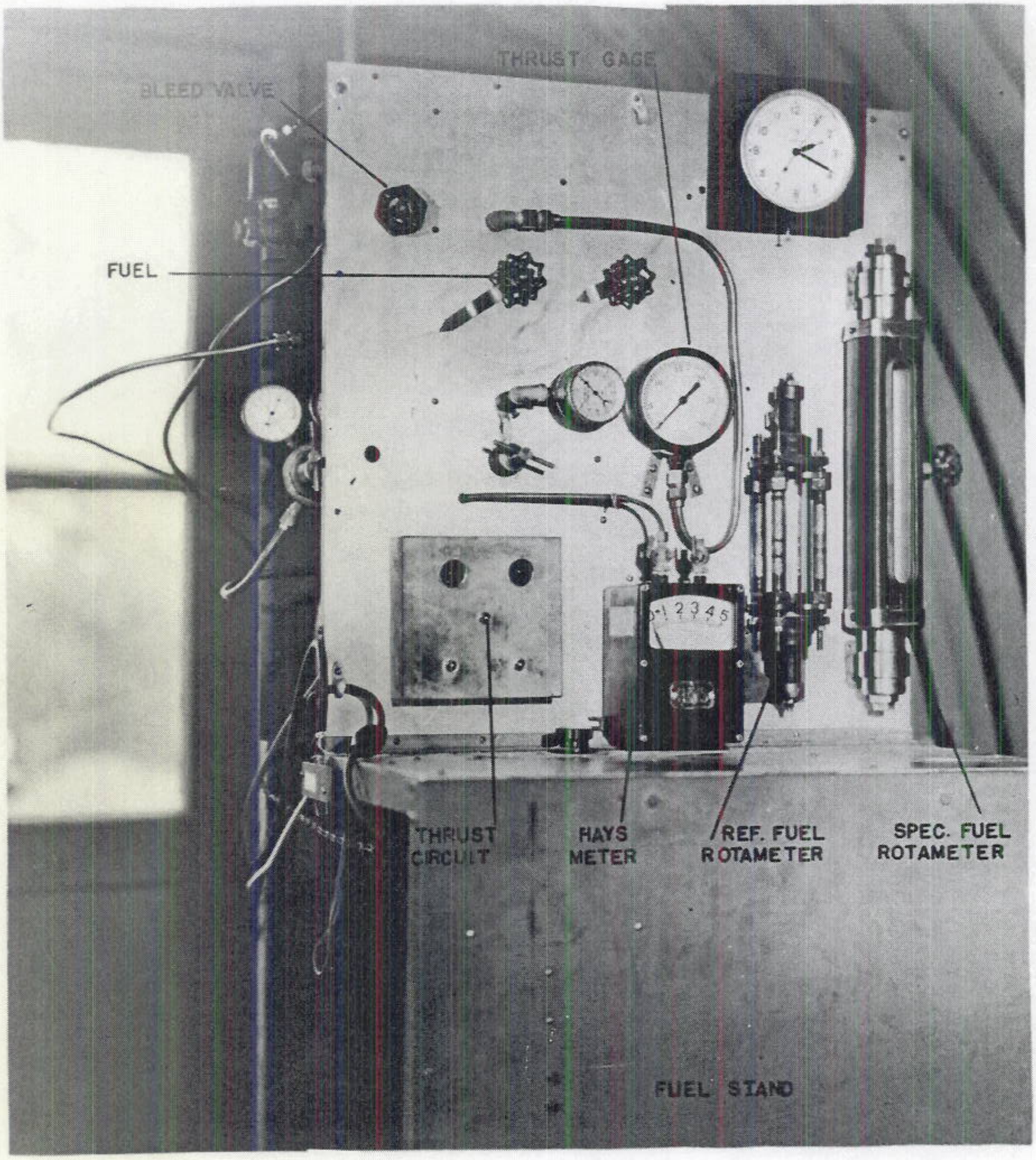
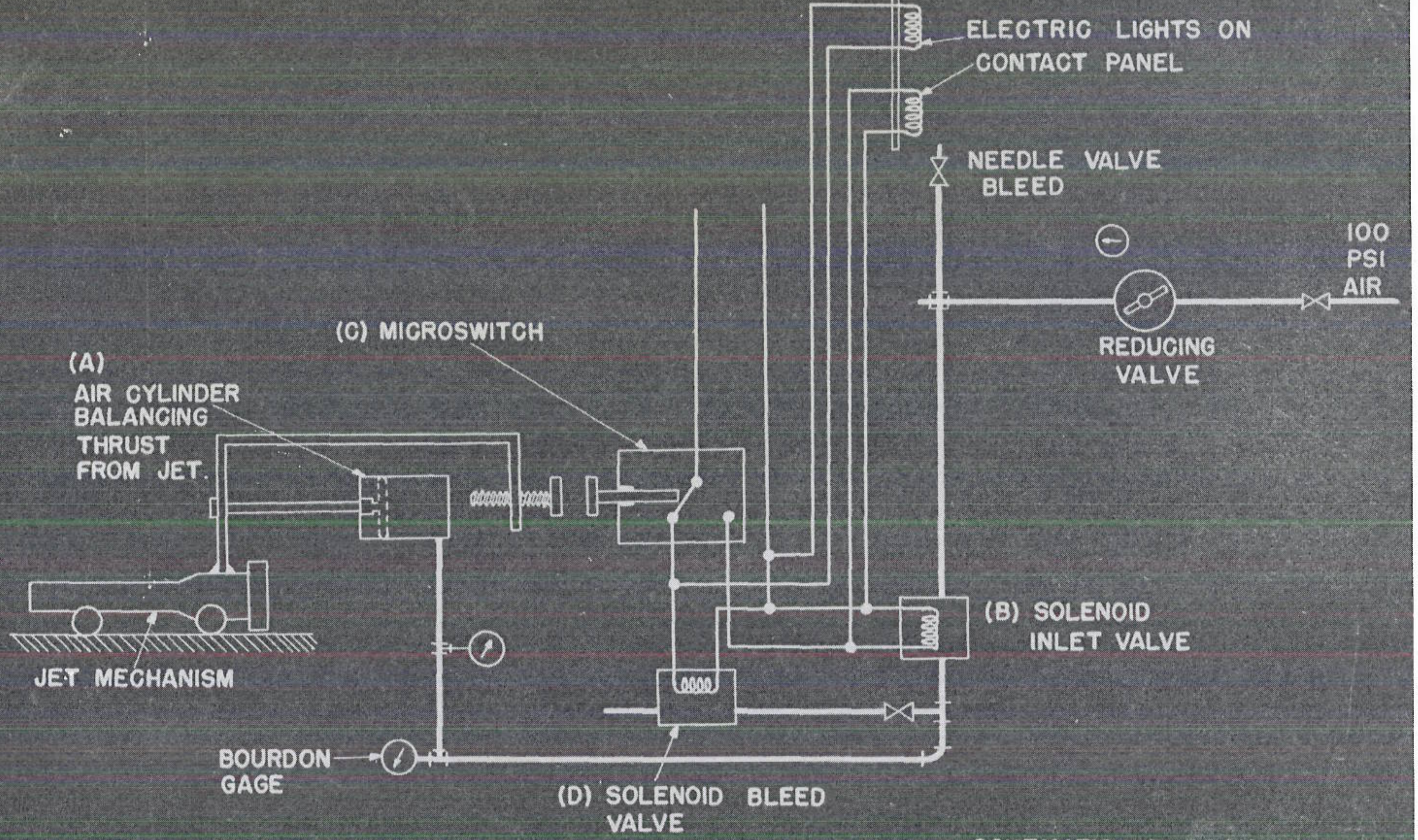

THRUST GAGE
BLEED VALVE
FUEL
THRUST CIRCUIT
HAYS METER
REF. FUEL ROTAMETER
SPEC. FUEL ROTAMETER
FUEL STAND

PLATE 2



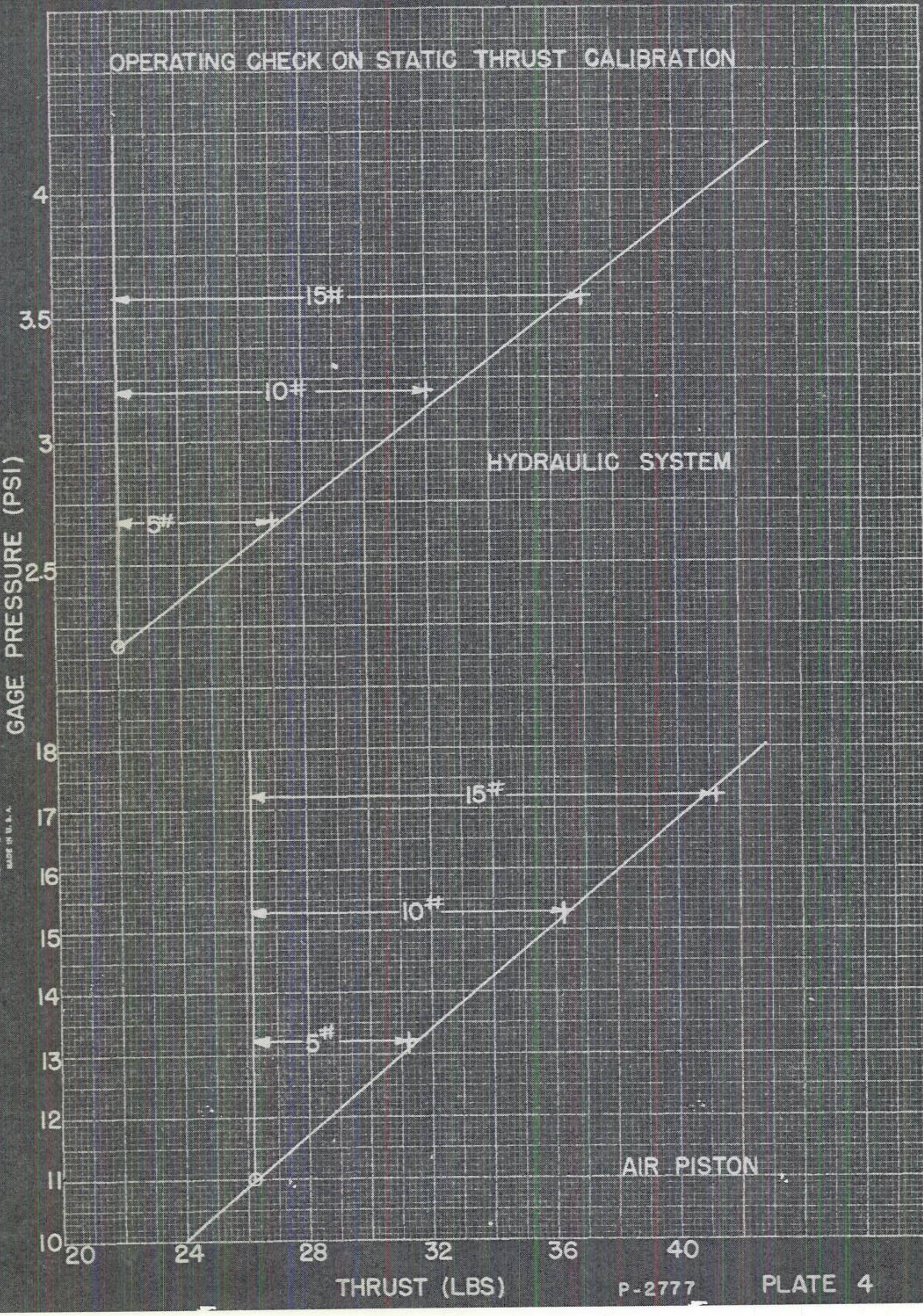
SCHEMATIC DIAGRAM

OF

THRUST BALANCING MECHANISM

AIR PISTON METOD

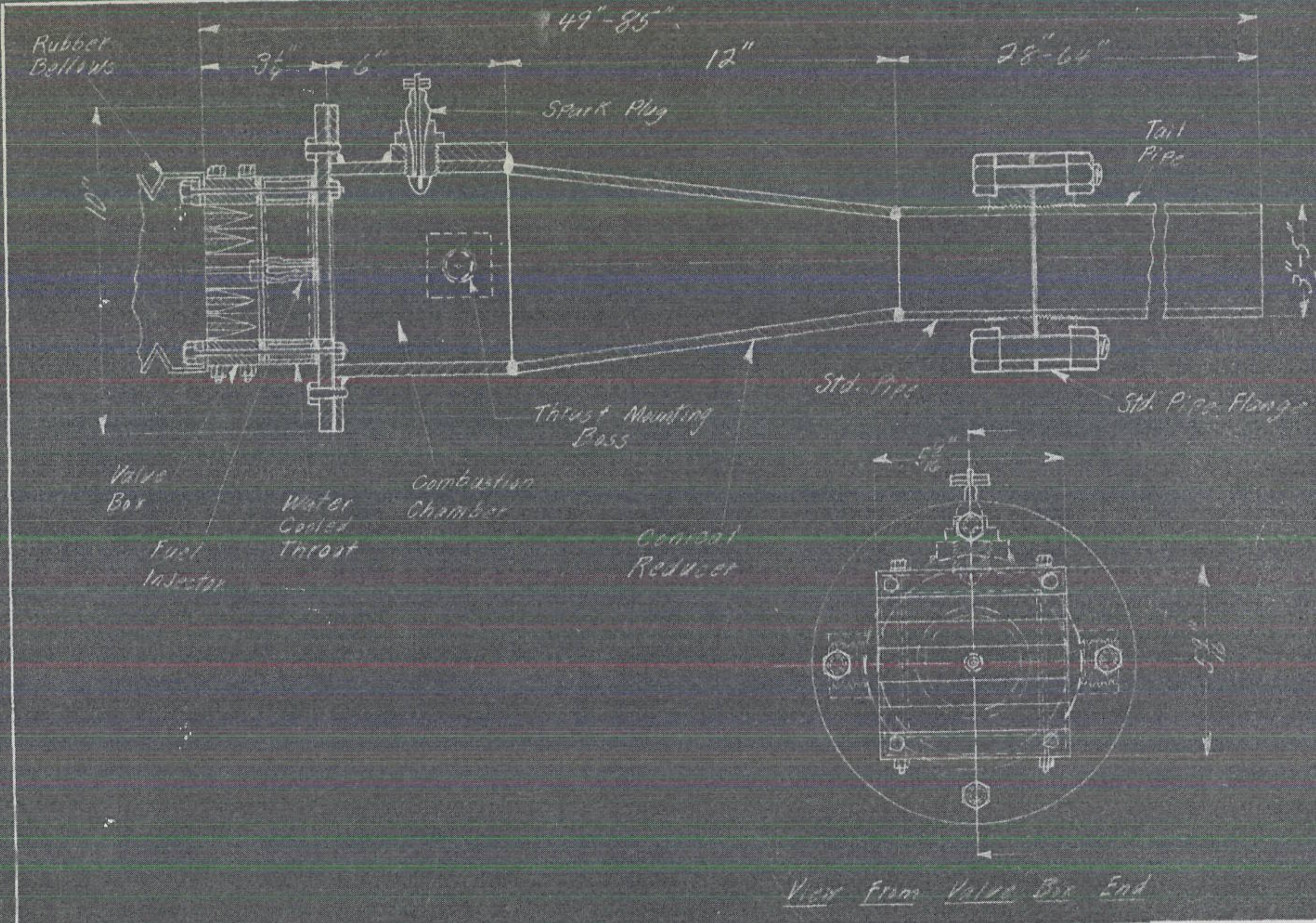
PLATE 3



OPERATING CHECK ON STATIC THRUST CALIBRATION

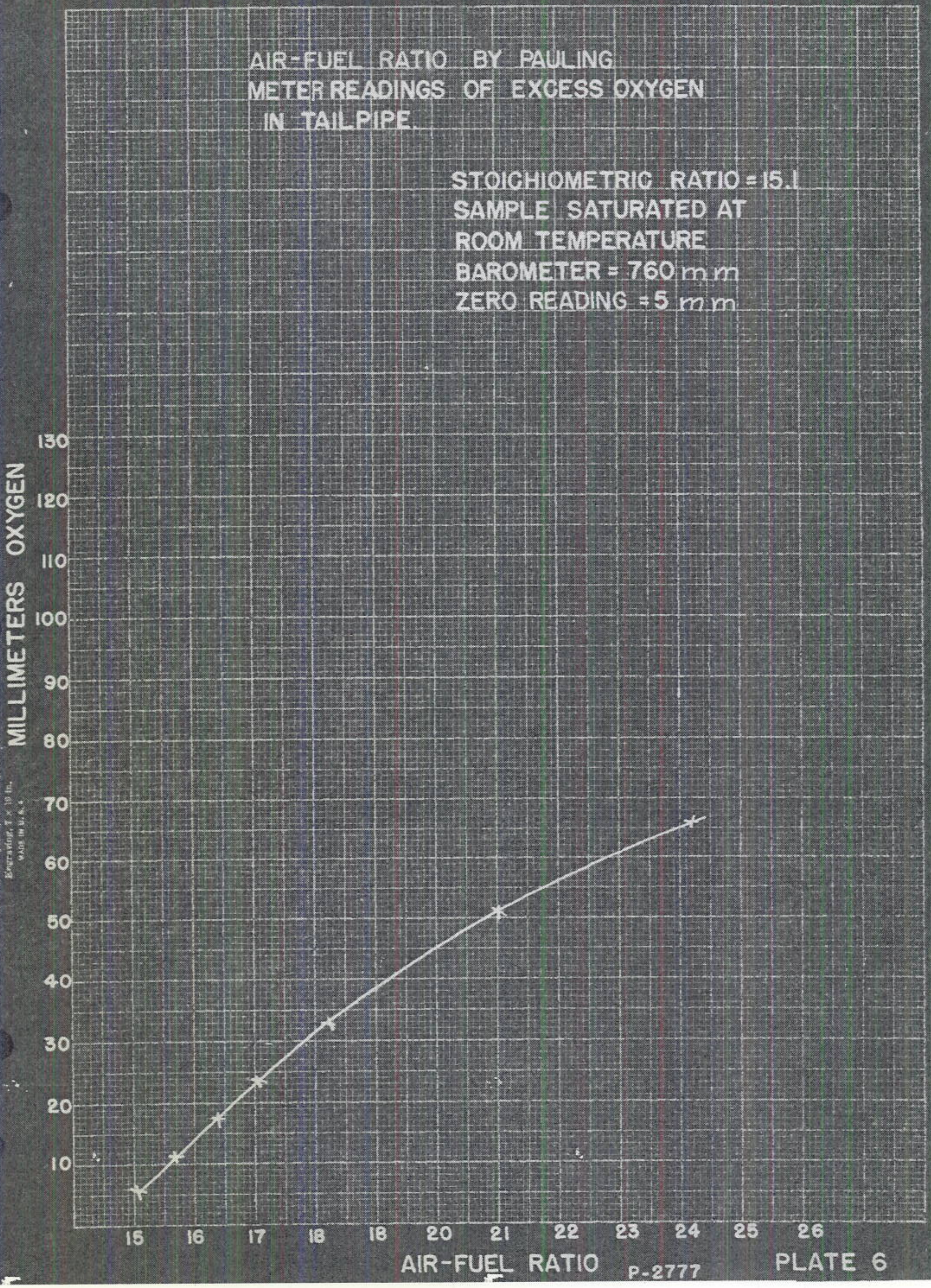
P-2777 PLATE 4

KEUFFEL & ESSER CO., N.Y. NO. 359-11
10 × 10 to the ½ inch, 5th lines accented.
Engraving 7 × 10 in.
MADE IN U.S.A.



U. S. NAVAL RESEARCH LABORATORY WASHINGTON 20, D. C.		SCALE	TYPICAL MODEL OF AERORESONATOR
		DR'WN.	
B'LD'G.	PHONE	CH'K'D.	

PLATE 5



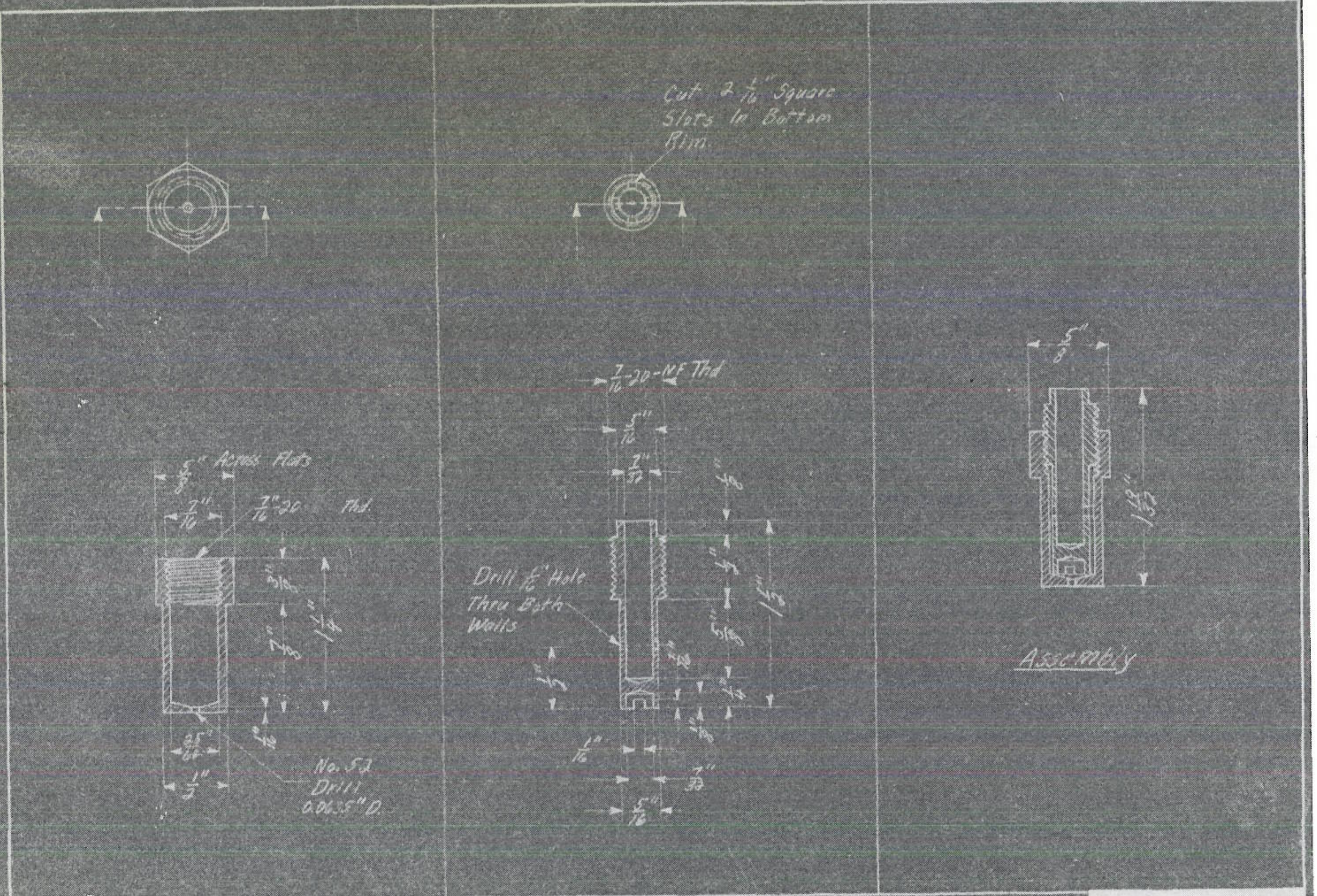
AIR-FUEL RATIO BY PAULING METER READINGS OF EXCESS OXYGEN IN TAILPIPE.

STOICHIOMETRIC RATIO = 15.1
SAMPLE SATURATED AT
ROOM TEMPERATURE
BAROMETER = 760 mm
ZERO READING = 5 mm

P-2777

PLATE 6

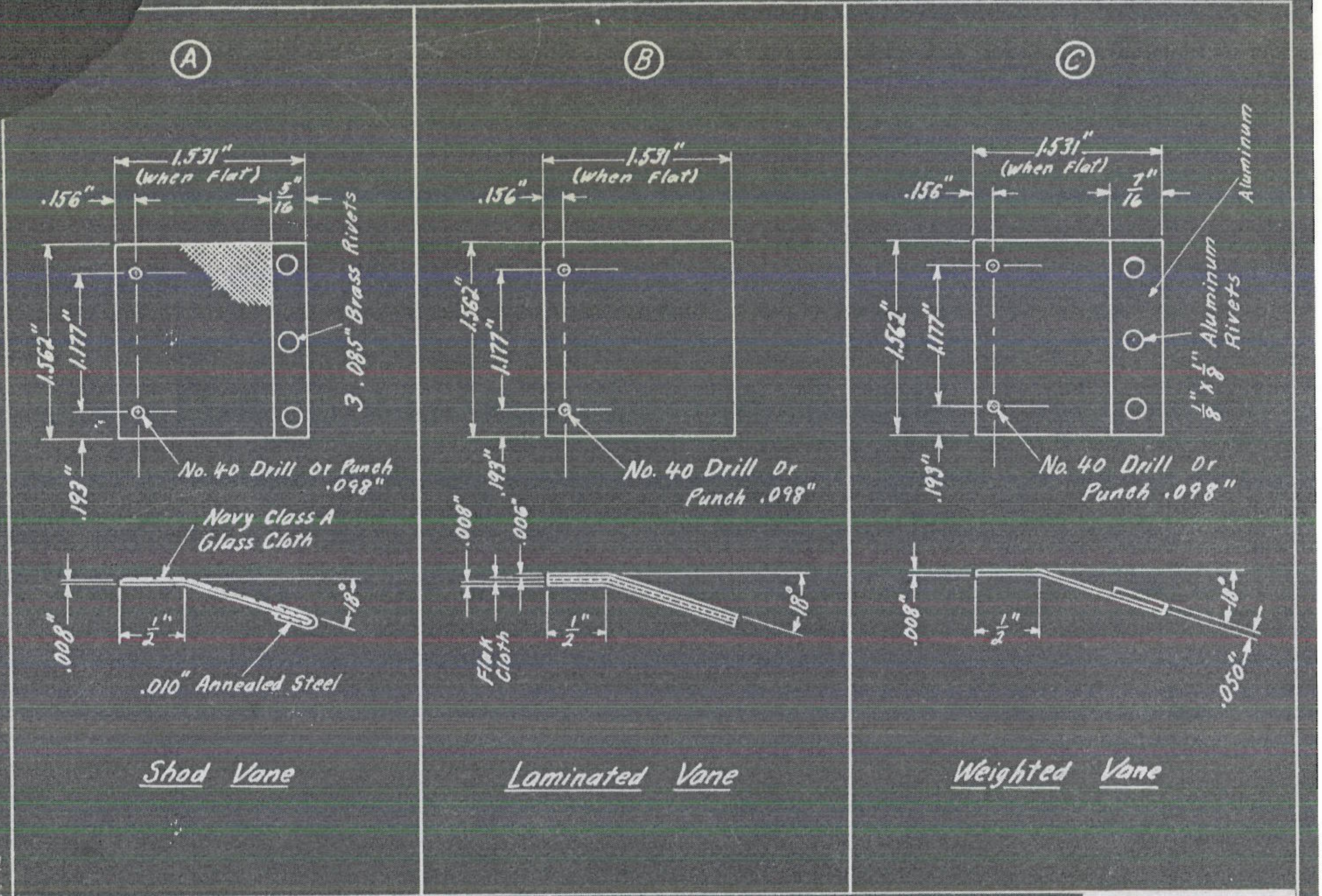
KEUFFEL & ESSER CO., N. Y. NO. 359-11
10 X 10 to the ½ inch, 5th lines accented.
Engraving, 7 X 10 in.
MADE IN U.S.A.



U. S. NAVAL RESEARCH LABORATORY WASHINGTON 20. D. C.		SCALE Full Size DR'WN. JKM	Conical Spray Fuel Injector
B'LD'G.	PHONE	CH'K'D.	
ROOM	DATE 11-14-45	APPR'V'D.	UNLESS OTHERWISE SPECIFIED, TOLERANCES ARE ±

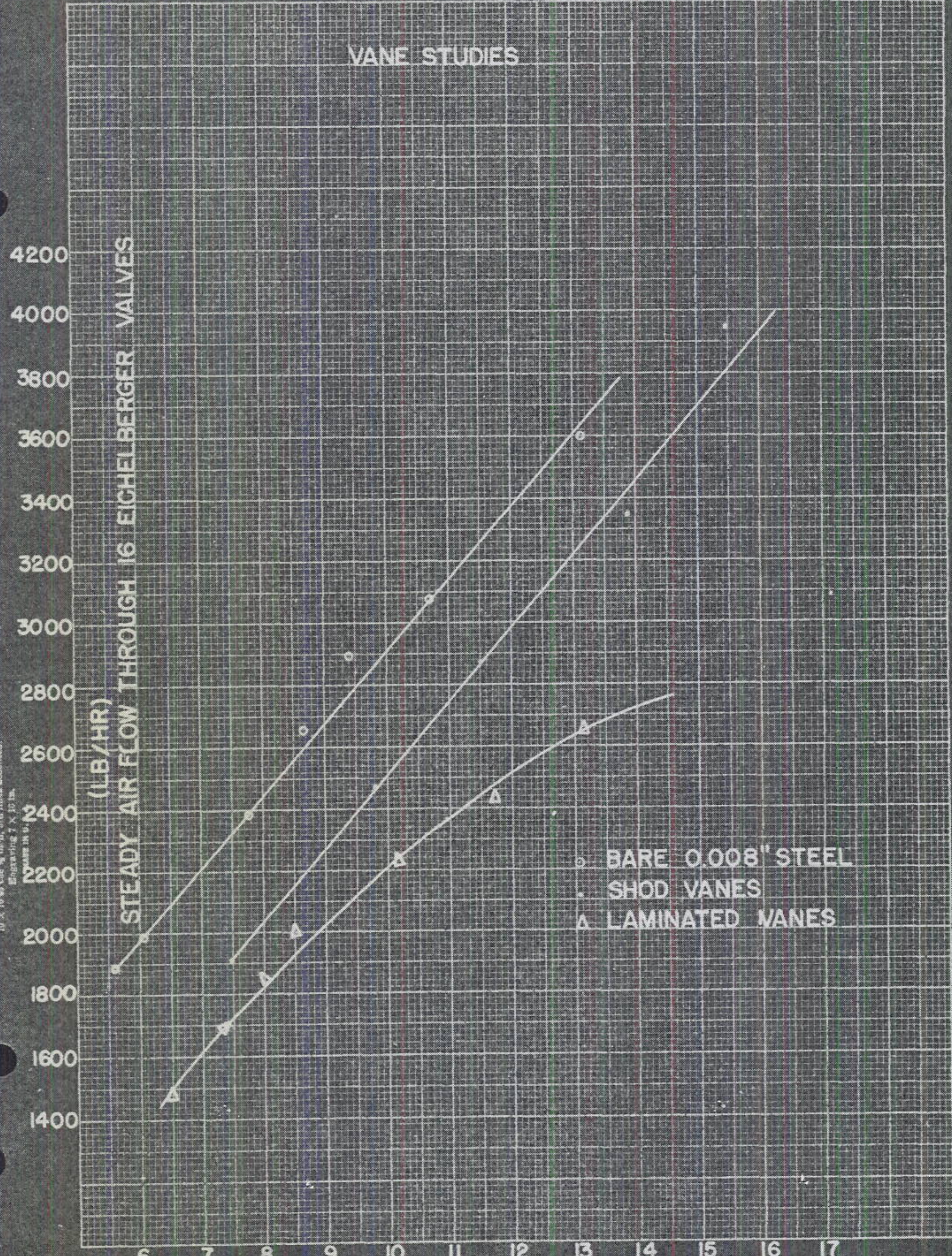
P-2777

PLATE 7



U. S. NAVAL RESEARCH LABORATORY WASHINGTON 20. D. C.	SCALE	VANE DESIGNS
B'LD'G. / PHONE	DR'WN.	
	CH'K'D.	

P-2777



P-2777 PLATE 9

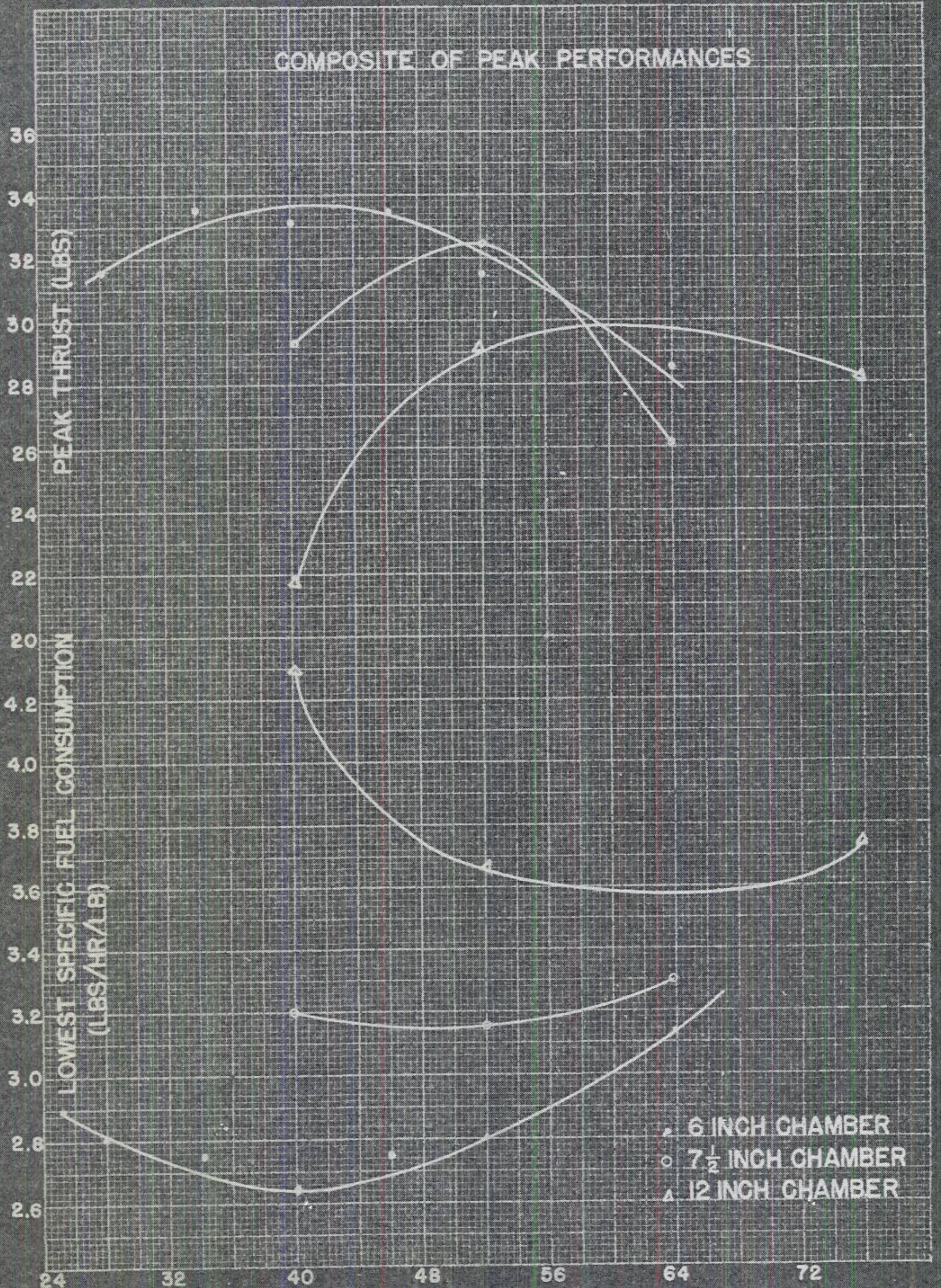
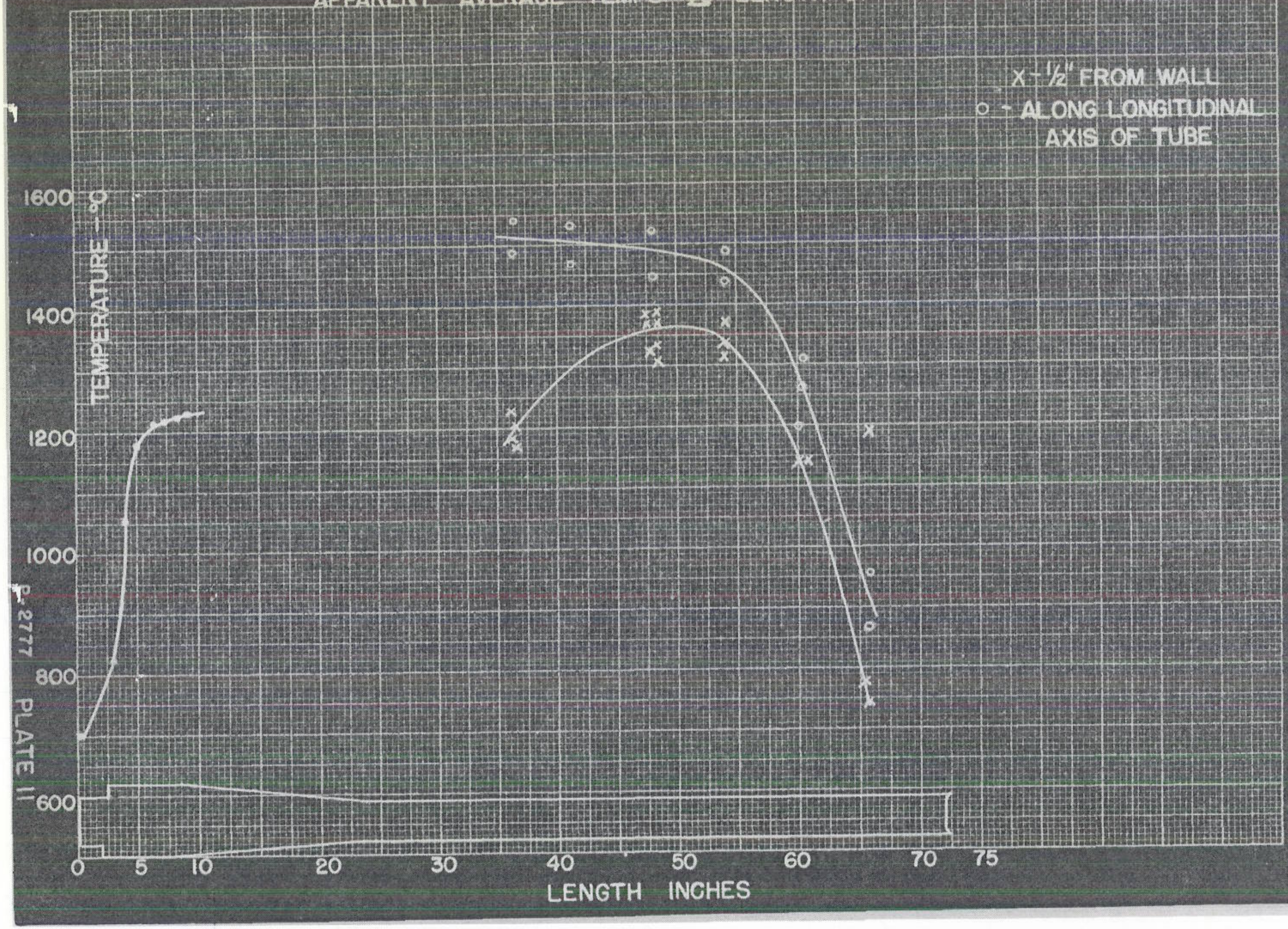


PLATE 10

KEUFFEL & ESSER CO., N. Y. NO. 359-11
10 × 10 to the ½ inch, 5th lines accented.
Engraving, 7 × 10 in.
MADE IN U. S. A.

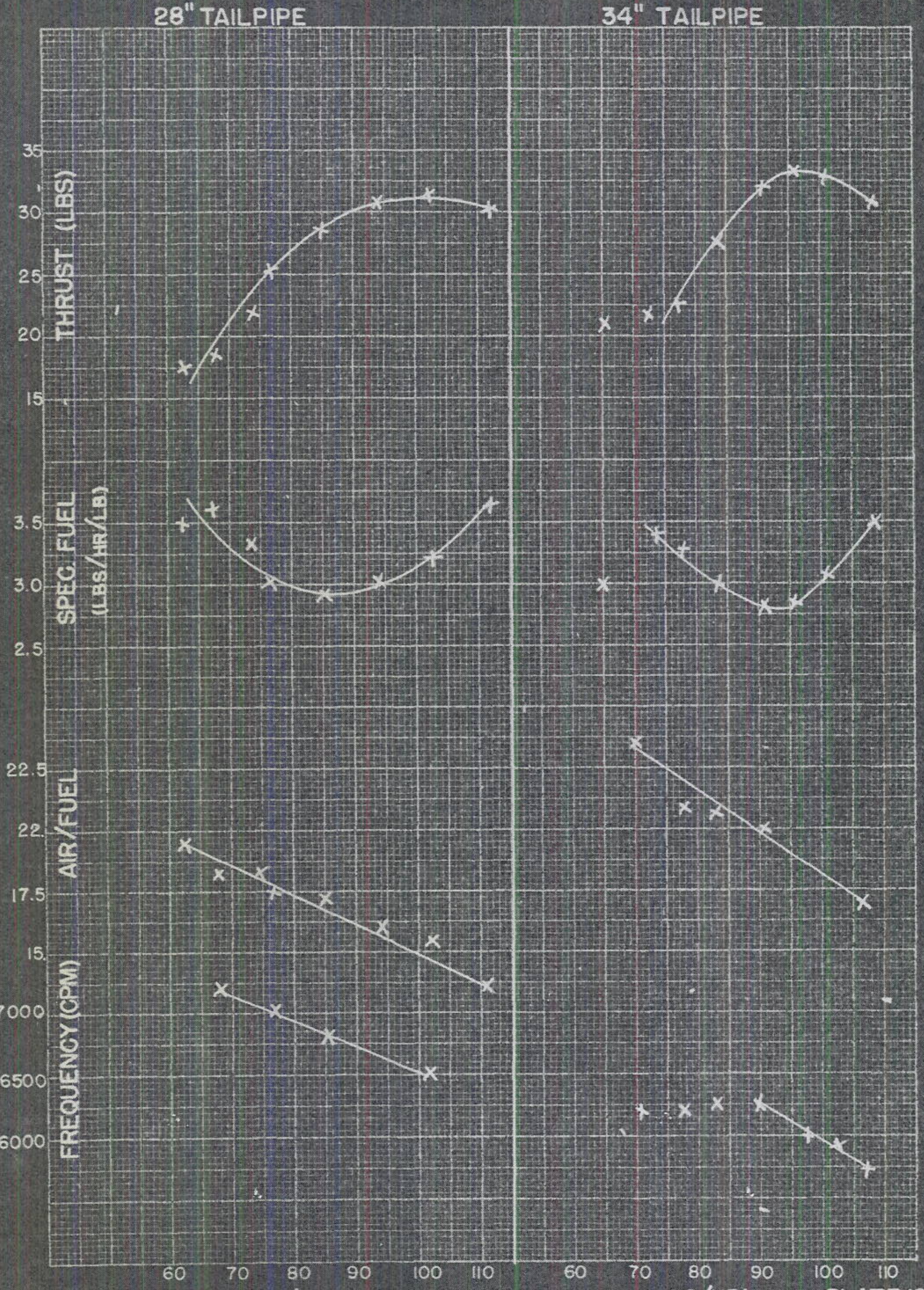
KEUFFEL & ESSER CO., N. Y. NO. 359-11
10 × 10 to the ½ inch, 5th lines accented.
Engraving 7 × 10 in.
MADE IN U. S. A.

APPARENT AVERAGE TEMPS VS. LENGTH OF AERORESONATOR



P-2777 PLATE II

SHOD VANES



P-2777

PLATE 12

KEUFFEL & ESSER CO., N. Y. NO. 359-11
10 × 10 to the ½ inch, 5th lines accented.
Engraving, 7 × 10 in.
MADE IN U.S.A.

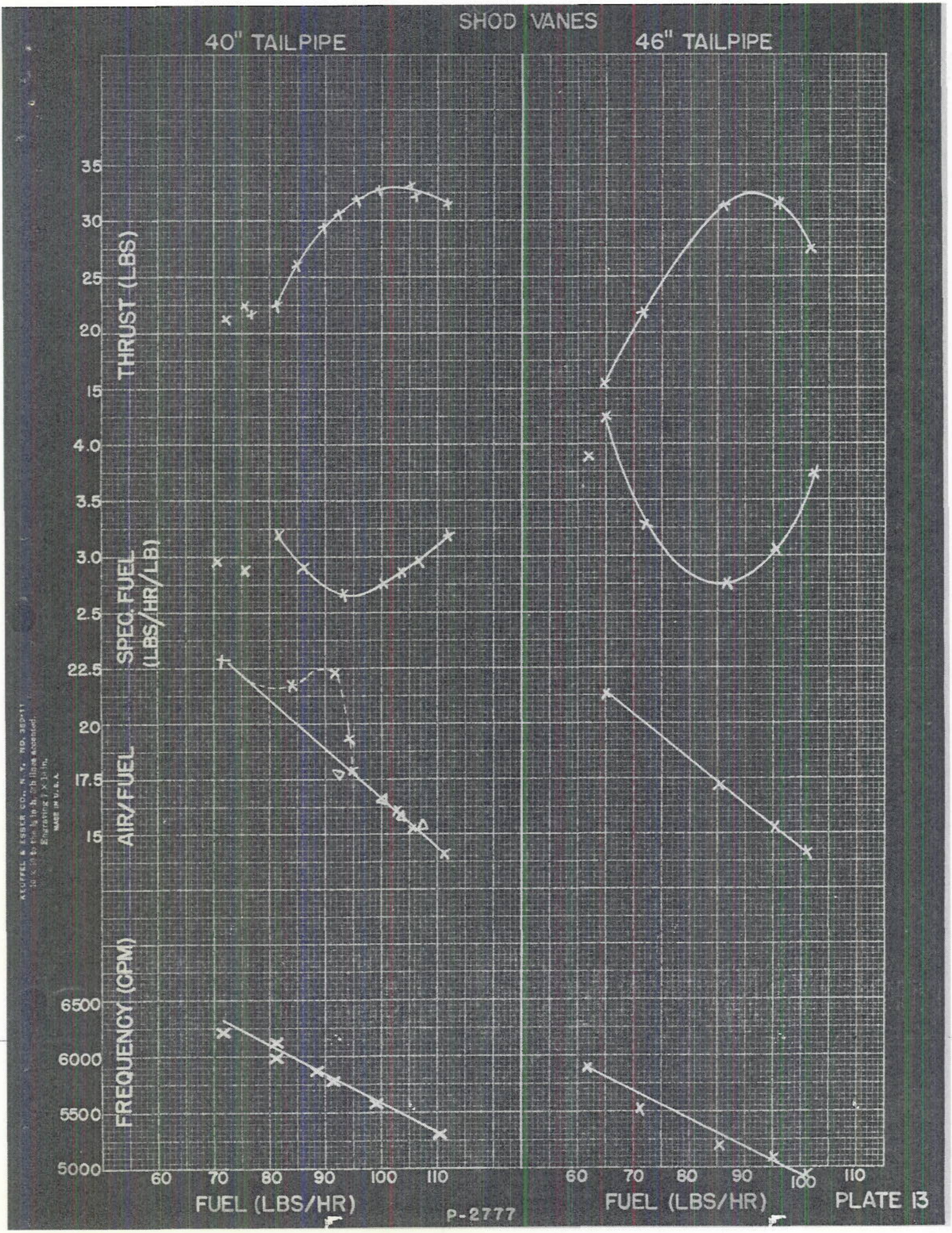
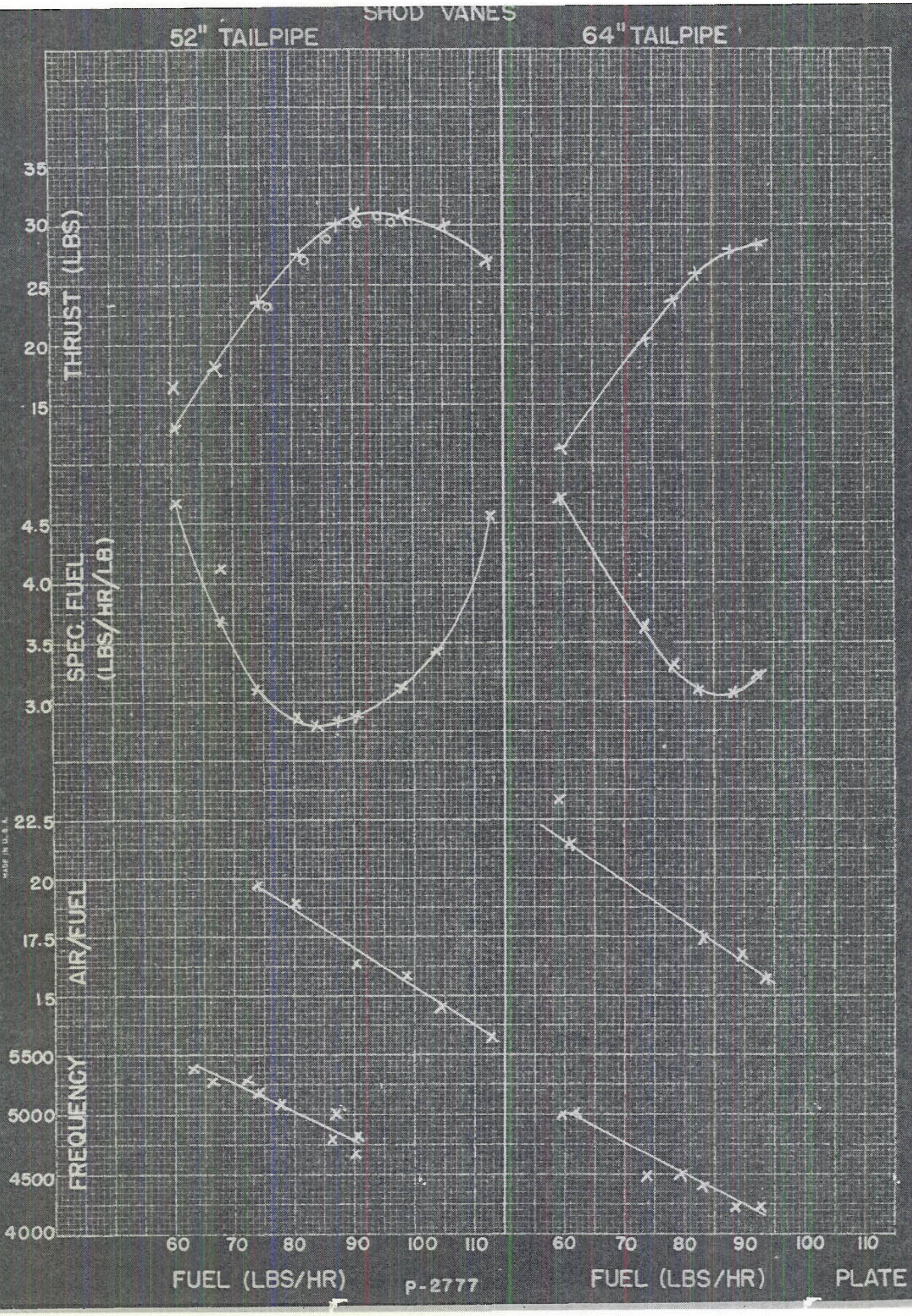

SHOD VANES
40" TAILPIPE
46" TAILPIPE
THRUST (LBS)
35
30
25
20
15
SPEC. FUEL (LBS/HR/LB)
4.0
3.5
3.0
2.5
AIR/FUEL
22.5
20
17.5
15
FREQUENCY (CPM)
6500
6000
5500
5000
60
70
80
90
100
110
FUEL (LBS/HR)
60
70
80
90
100
110
FUEL (LBS/HR)
P-2777

PLATE 13



P-2777

PLATE 14

KEUFFEL & ESSER CO., N. Y. NO. 359-11
10 × 10 to the ½ inch, 5th lines accented.
Engraving, 7 × 10 in.
MADE IN U.S.A.

LAMINATED VANES

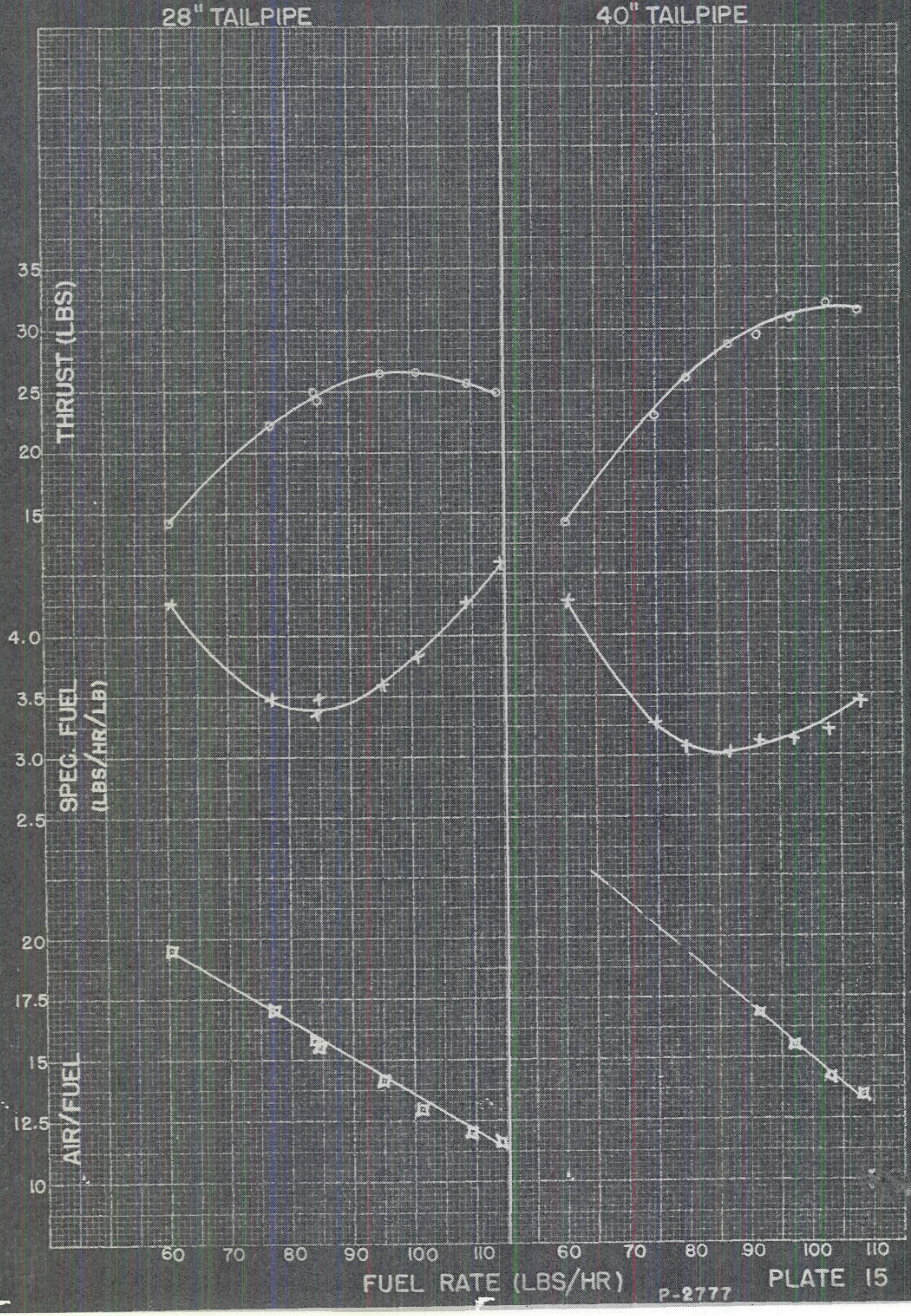
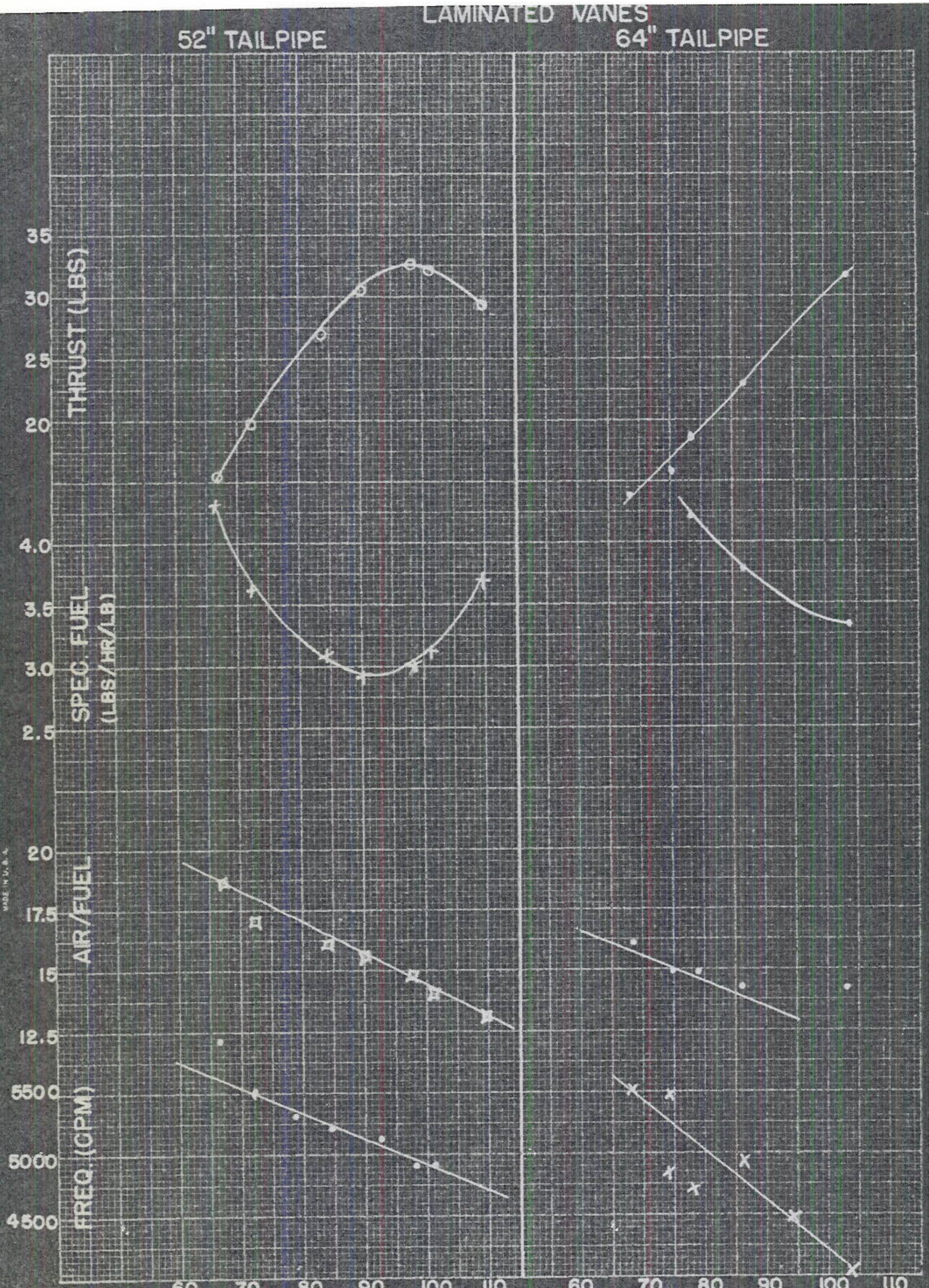


PLATE 15

P-2777

KEUFFEL & ESSER CO., N. Y. NO. 359-11
10 X 10 to the ½ inch, 5th lines accented.
Engraving, 7 X 10 in.
MADE IN U.S.A.



P-2777

PLATE 16

7 $\frac{1}{2}$" CHAMBER
SHOD VANES

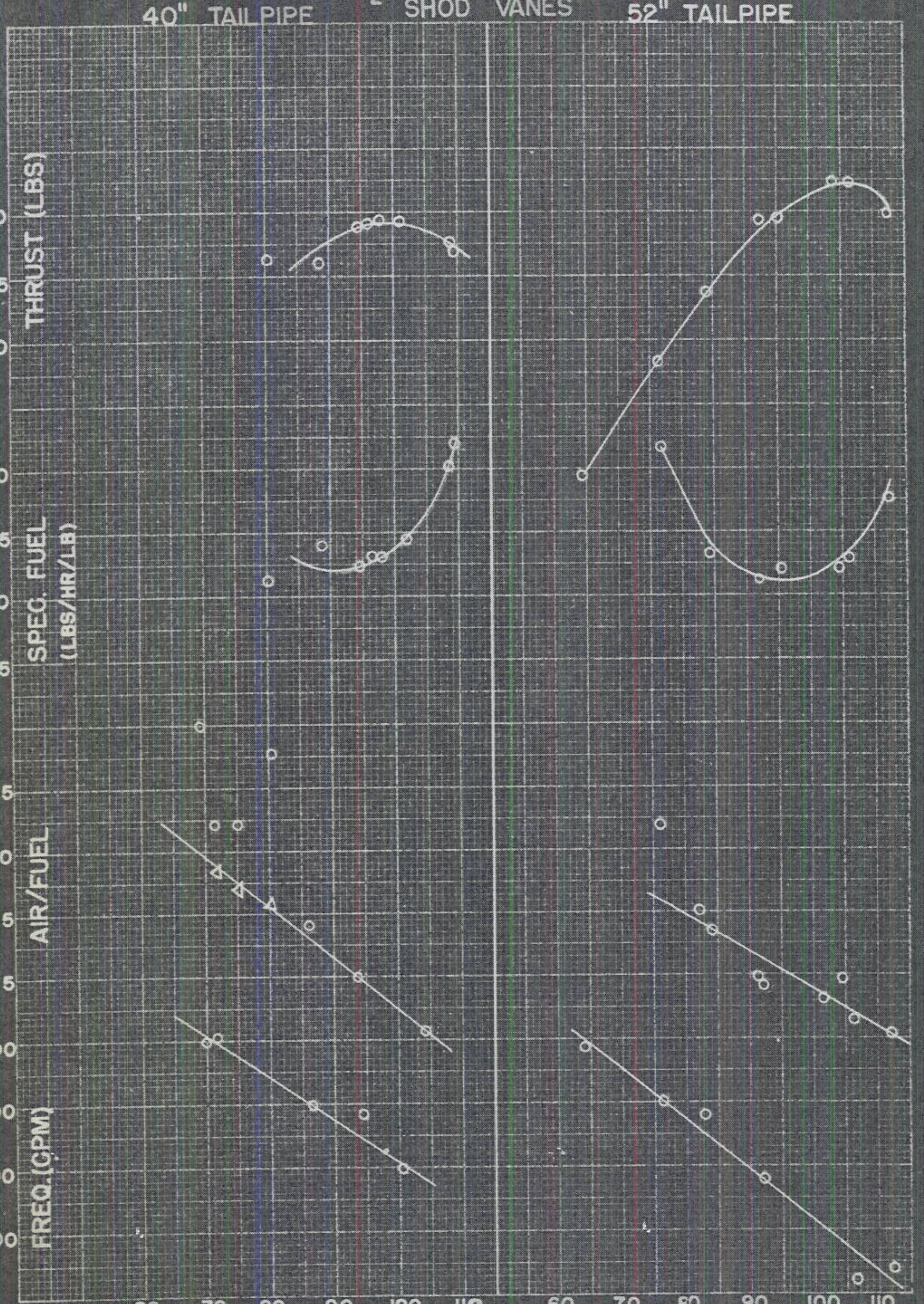
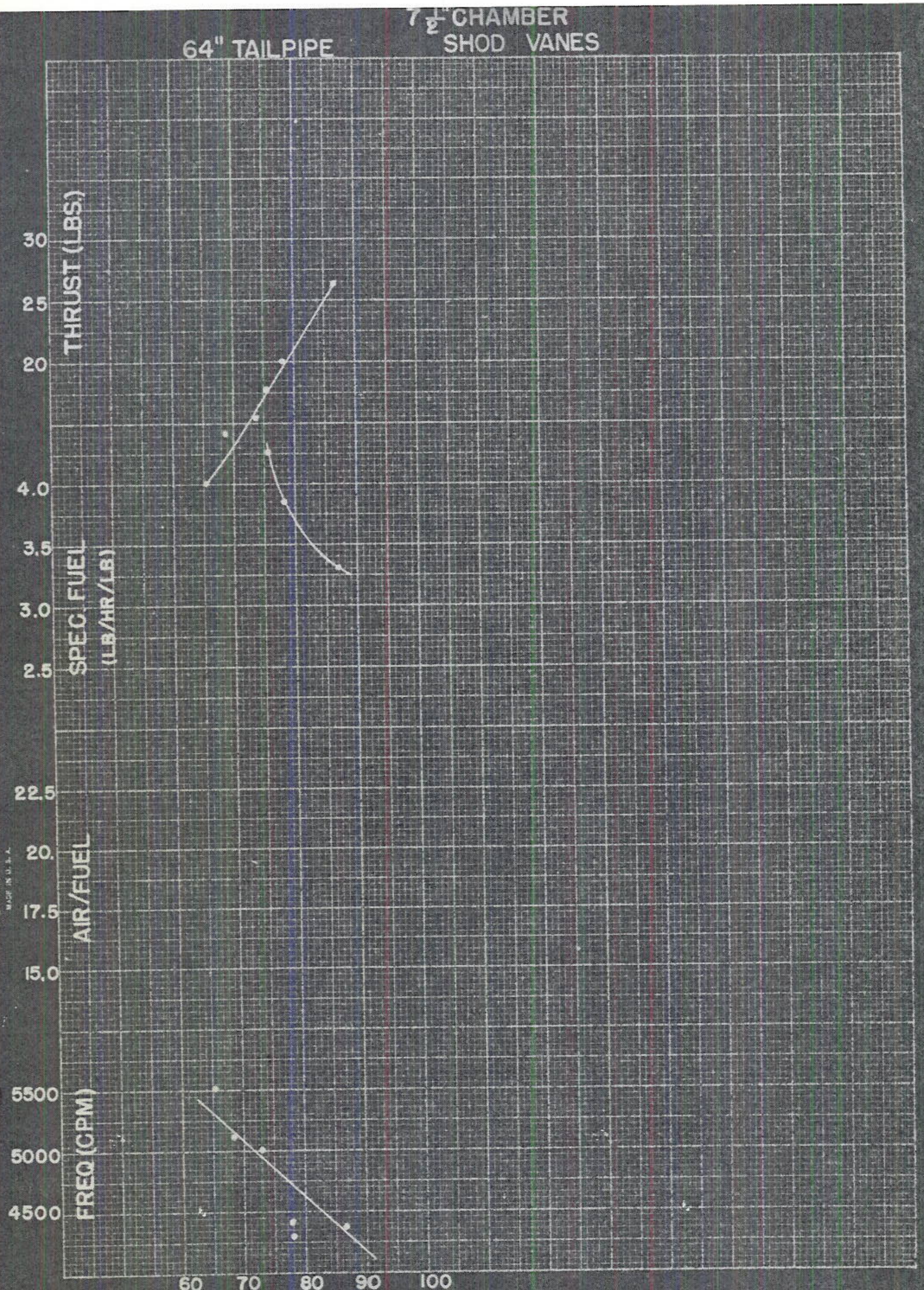
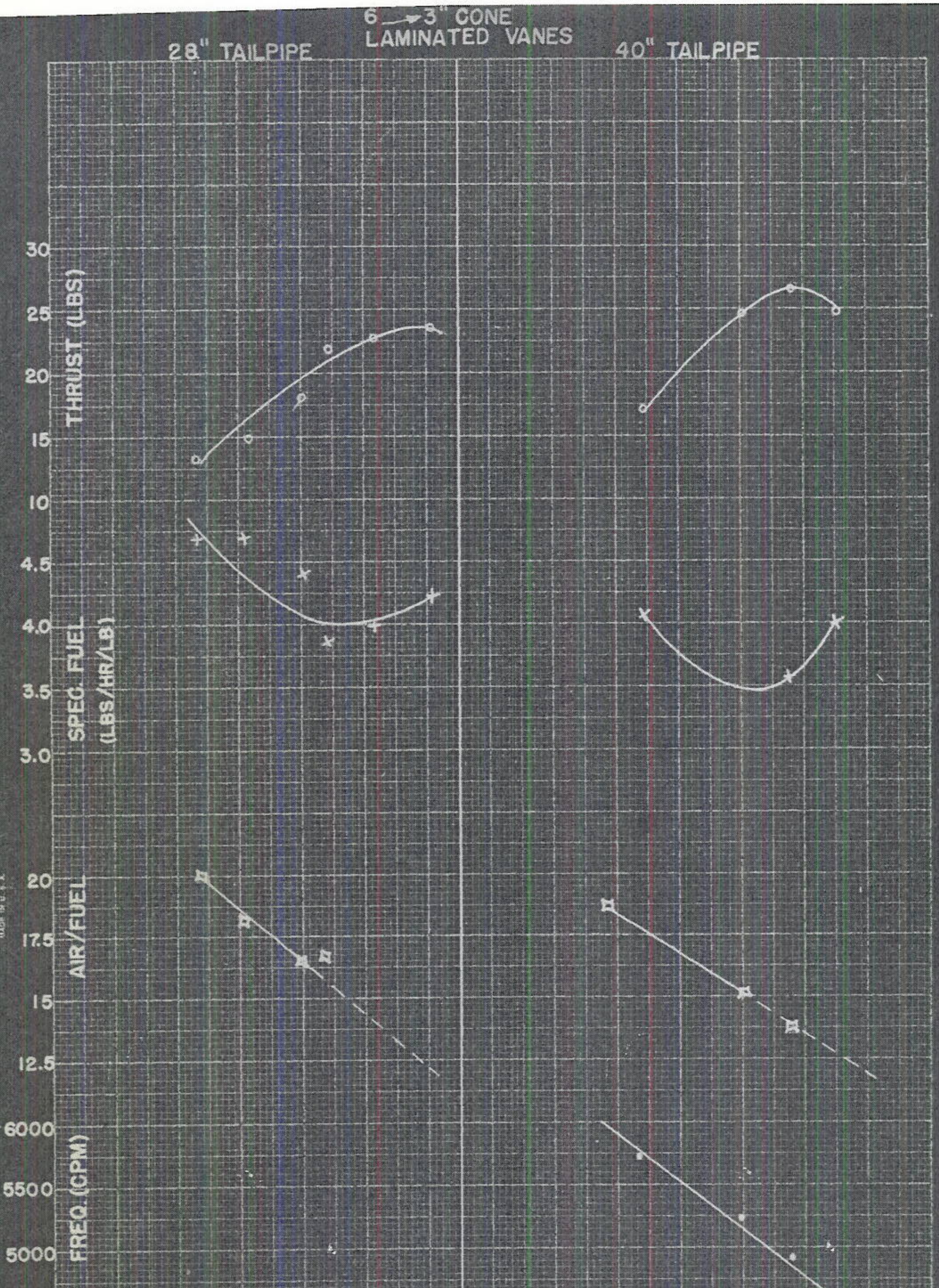


PLATE 17



KEUFFEL & ESSER CO., N. Y. NO. 359-11
10 X 10 to the ½ inch, 5th lines accented.
Engraving, 7 X 10 in.
MADE IN U.S.A.

PLATE 18



P-2777

PLATE 19

12.6 SQ.IN. THROAT
40 IN. TAILPIPE

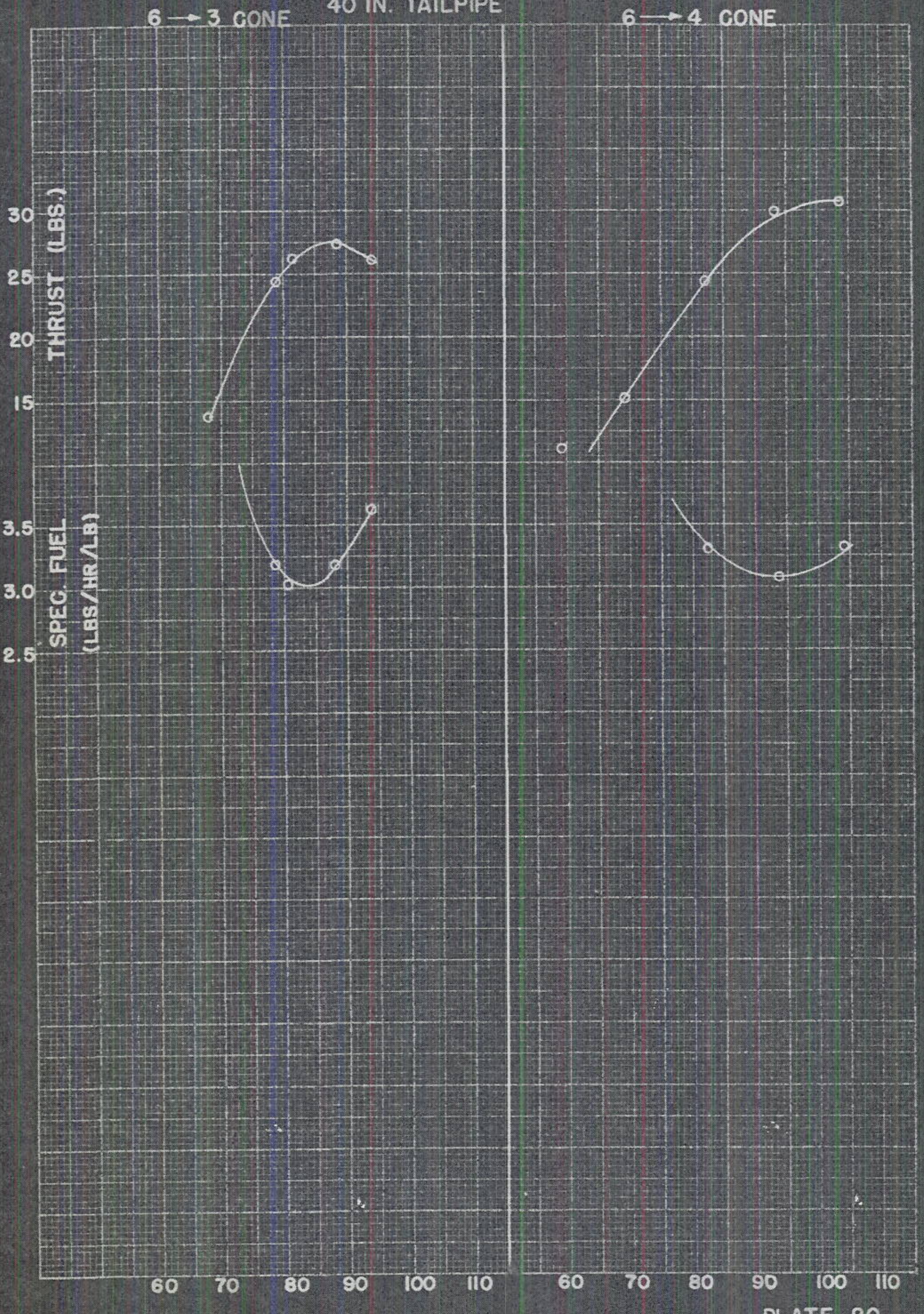


PLATE 20

KEUFFEL & ESSER CO., N. Y. NO. 359-11
10 × 10 to the ½ inch, 5th lines accented.
Engraving, 7 × 10 in.
MADE IN U.S.A.