DECLASSIFIED

COPY NO. [redacted]

NAVAL RESEARCH LABORATORY REPORT

DECLASSIFIED by NRL Contract
Declassification
Date: 12 DEC 2012
Reviewer: H. Do, P. HANNA
Declassification authority: NAVY DECLASS GUIDE/NAVY DECLASS MANUAL, ODE 2012, 02 SERIES

August 1947

FOURTH PARTIAL REPORT ON GAS PULSATOR (Pulse Jet)

By
D. W. Baker, G. C. Milek, and C. D. Porter

Report No. 0-3064

[redacted]

DECLASSIFIED

FR-3064

DECLASSIFIED: By authority of:
5000A January 1958
Entered by: E. Bliss Code 2027
DISTRIBUTION STATEMENT A APPLIES
Further distribution authorized by
UNLIMITED only.

DECLASSIFIED

NAVY DEPARTMENT
OFFICE OF NAVAL RESEARCH
NAVAL RESEARCH LABORATORY
WASHINGTON 20, D. C.

[redacted]

COPY NO. 25

Navy Department - Office of Naval Research

DECLASSIFIED

NAVAL RESEARCH LABORATORY
Washington, D. C.

* * *

PHYSICS DIVISION

THERMODYNAMICS SECTION

August 1947

FOURTH PARTIAL REPORT ON GAS PULSATOR (Pulse Jet)

By D. W. Baker, G. C. Milak, and C. D. Porter

Report O-3064

[redacted]

* * *

Approved by:
L. F. Campbell, Acting Head
Thermodynamics Section

Dr. W. H. Sanders
Acting Superintendent
Physics Division

Commodore Henry A. Schade, USN
Director
Naval Research Laboratory

Preliminary Pages .... a-g
Numbered Pages 65
Figures 87
Distribution List .... h-j

DECLASSIFIED

A255

DECLASSIFIED

ABSTRACT

This is a partial report on the investigation of a standard 13-inch pulse jet engine and various modifications. The variable parameters were the combustion chamber size and shape, tailpipe length and diameter, and the number of vanes in the head assembly. In addition to the standard pulse jet, twenty-four different combustion chambers were designed and tested with six, eight, and ten-inch diameter tailpipes of several lengths. All tests were static, i.e., without relative air speed. The fuel was 62-octane, unleaded gasoline. A maximum thrust of 270 pounds was measured for both Modifications U and V with a 104-vane grid assembly and a tailpipe 10" by 144". The minimum specific fuel values obtained from these modifications were 2.73 and 2.60, respectively. A minimum value of specific fuel of 2.47 was obtained with Modification T, and a minimum of specific fuel of 2.48 was obtained with Modification Q both with a 72-vane grid assembly and a 10" by 144" tailpipe. A maximum value of 4.77 pounds of thrust per square inch of internal tailpipe area was obtained on Modification I with a 72-vane grid assembly and a 6" by 144" tailpipe. The design and peak performance of each modification are discussed. Experimental trends of general design parameters are studied with respect to four performance coefficients, namely: specific fuel, pounds thrust per unit maximum cross-sectional area, pounds thrust per unit of tube surface area, and pounds thrust per unit tailpipe cross-sectional area. Supplementary investigations include multiple ignition points, auxiliary fuel jets, powdered fuels, inertia supercharging, and external fuel spray or injection systems.

DECLASSIFIED

DECLASSIFIED

TABLE OF CONTENTS

Paragraph No.		Page No.
	ABSTRACT	-b-
I.	INTRODUCTION	1
	1. Authorization	1
	2. Previous Development	1
	3. Purpose	1
II.	NOMENCLATURE AND SYMBOLS	2
III.	TEST METHODS	3
	6. Thrust Stands	3
	7. Fuel Systems	3
	8. Pulse-Jet Efficiency and Output	3
	11. Frequency Measurements	4
	12. Pressure Measurements	4
	13. Noise	4
IV.	GENERALIZED DESCRIPTION AND DESIGN - HEAD ASSEMBLIES	5
V.	GENERALIZED DESCRIPTION AND DESIGN - COMBUSTION CHAMBERS	7
VI.	EXPERIMENTAL RESULTS	11
	28. Performance Curves	11
	33. Operational Stability	11
	34. Standard Pulse Jet	12
	35. Standard Pulse Jet 7-Inch-Diameter Tailpipe 54 Inches Long	12
	36. Standard Pulse Jet 7-Inch-Diameter Tailpipe 88 Inches Long	12
	37. Standard Pulse Jet 7-Inch-Diameter Tailpipe 117 Inches Long	13
	38. Standard Pulse Jet 7-Inch-Diameter Tailpipe 132 Inches Long	14
	39. Standard Pulse Jet 8-Inch-Diameter Tailpipe 88 Inches Long	14
	40. Standard Pulse Jet Summary of 7- and 8-Inch-Diameter Tailpipe	15
	41. Straight-Tube Experiment	15
	42. Design and Performance - Modification A	16
	44. Design and Performance - Modification B	16
	46. Design and Performance - Modification C	17
	47. Design and Performance - Modification D	17
	48. Design and Performance - Modification E	18
	50. Design and Performance - Modification F	19
	52. Design and Performance - Modification G	19
	54. Design and Performance - Modification H	20
	56. Design and Performance - Modification I	21
	58. Design and Performance - Modification J	21
	60. Design and Performance - Modification K	21

DECLASSIFIED

DECLASSIFIED

TABLE OF CONTENTS (Continued)

62. Design and Performance - Modification L . . . 22
64. Design and Performance - Modification M . . . 22
65. Design and Performance - Modification N . . . 23
67. Design and Performance - Modification O . . . 23
68. Design and Performance - Modification P . . . 23
71. Design and Performance - Modification Q . . . 24
75. Design and Performance - Modification R . . . 25
76. Design and Performance - Modification S . . . 25
77. Design and Performance - Modification T . . . 25
79. Design and Performance - Modification U . . . 26
81. Design and Performance - Modification V . . . 26
83. Design and Performance - Modification W . . . 27
84. Design and Performance - Modification X . . . 27
86. Design and Performance - Modification Y . . . 27
87. Summary - Similar Combustion Chambers - Modifications A, J, K, and L 27
88. Summary - Similar Combustion Chambers - Modifications E, F, and I 28
89. Summary - Similar Combustion Chambers - Modifications D and T 29
90. Summary - Similar Combustion Chambers - Modifications B, C, G, H, U, and Y 29
92. Summary - Similar Combustion Chambers - Modifications M, P, Q, R, and V 30
93. Comparison of Reversed Combustion Chambers - Modifications D and E 31
94. Comparison of Reversed Combustion Chambers - Modifications K and M 31
95. Summary of Nonoperating Combustion Chambers - Modifications N, O, and S 32

VII. PEAK PERFORMANCE 32
101. Six-Inch Tailpipe 33
103. Eight-Inch Tailpipe 34
105. Ten-Inch Tailpipe 34
106. Specific Fuel Comparison Tables 35

VIII. PERFORMANCE COEFFICIENTS AND TRENDS 40
109. Coefficients of Specific Fuel 40
110. Coefficients of Thrust per Unit Maximum Cross-Sectional Area of Tube 40
112. Coefficients of Thrust per Unit of Tube Surface 42
114. Coefficients of Thrust per Unit of Tailpipe Cross Section 45
116. Dimensionless Ratios 45
119. Trends in Regard to Maximum Thrust per Maximum Cross Section 47
120. Trends in Regard to Maximum Thrust per Unit of Surface Area of Tube 49
121. Trends in Regard to Maximum Thrust per Unit Cross-Sectional Area of Tailpipe Section . . 49
122. Overall Performance Comparison 49
124. Effect of Enlarger - Reducer Angles on Efficiency 51

DECLASSIFIED

DECLASSIFIED

TABLE OF CONTENTS (Continued)

IX. SUPPLEMENTARY EXPERIMENTATION 53
127. Extended Heating Surface Test 53
128. Auxiliary Jets in Tailpipe 53
129. Auxiliary Fuel Jets in the Combustion Chamber . 53
130. External Fuel Spray 54
131. External Fuel Spray, Experimental Procedure for Modification U 54
132. External Fuel Spray, Experimental Procedure for Modification X 55
134. Vane Development 56
135. Powdered Fuels 57
138. Pulverized Anthracite and Bituminous Coal . . 57
139. Powdered Magnesium 58
141. Powdered Aluminum 59
143. Inertia Supercharging 59

X. VALIDITY AND RELIABILITY OF RESULTS 60
152. Comparison of Spiral-Weld and Smooth Tailpipes . 62

XI. CONCLUSIONS 62

XII. RECOMMENDATIONS 63

APPENDIX No. I 64
1. General Information on the Pulse Jet 64

ACKNOWLEDGEMENTS 64

REFERENCE LIST 65

DECLASSIFIED

DECLASSIFIED

LIST OF TABLES

Table No.		Page No.
1.	Combustion Chamber Design - Modification A through X	9
2.	Combustion Chamber Design - Modification A through X	10
3.	Summary of Data for Standard Pulse Jet, 7" x 54" Tailpipe	12
4.	Summary of Data for Standard Pulse Jet, 7" x 88" Tailpipe	13
5.	Summary of Data for Standard Pulse Jet, 7" x 117" Tailpipe	13
6.	Summary of Data for Standard Pulse Jet, 7" x 132" Tailpipe	14
7.	Summary of Data for Standard Pulse Jet, 8" x 88" Tailpipe	15
8.	Operational Frequency Ranges for Various Tailpipe Lengths at Maximum Thrust	33
9.	Operational Frequency Ranges for Various Tailpipe Lengths at Minimum Specific Fuel	34
10.	Distribution of Specific Fuel Values, 10-Inch Tailpipes	35
11.	Specific Fuel Comparison Tables	36
12.	Specific Fuel Comparison Tables	37
13.	Specific Fuel Comparison Tables	38
14.	Specific Fuel Comparison Tables	39
15.	Comparison Chart - Minimum Specific Fuel	41
16.	Comparison Chart - Thrust per Maximum Cross Section	43
17.	Comparison Chart - Thrust per Surface Area of Tube	44
18.	Comparison Chart - Thrust per Tailpipe Cross Section	46
19.	Dimensionless Ratios	48
20.	Overall Comparison Rating	50
21.	Effect of Enlarger and Reducer Angles on Efficiency	52
22.	Data Taken During External Fuel Experiments	55
23.	Data Taken During Runs with Powdered Aluminum	58
24.	Comparison of Data for Identical Engines	61

DECLASSIFIED

DECLASSIFIED

LIST OF FIGURES

	Fig. No.
Pulse Jet Engine	1
Notations used in Report	1a
Thrust and Control Stands (Front View)	2
Thrust and Control Stands (Rear View)	3
Control Stand (Front View)	4
Head No. 1, 2, and 3	5
Head No. 4, 5, and 6	6
Head No. 7, 8, and 9	7
Position of Jets in Side-Entry Fuel Block	8
Head No. 7 with Adjustable Shutter	9
Head No. 9 with Adjustable Shutter	10-11
Design and Performance Curves - Modification A	12-13
Design and Performance Curves - Modification A and B	14
Design and Performance Curves - Modification B	15-17
Design and Performance Curves - Modification C	18-22
Design and Performance Curves - Modification D	23-27
Design and Performance Curves - Modification E	28-32
Design and Performance Curves - Modification F	33-37
Design and Performance Curves - Modification G	38-41
Design and Performance Curves - Modification H	42-46
Design and Performance Curves - Modification I	47
Design and Performance Curves - Modification J	48-49
Design and Performance Curves - Modification K	50
Design and Performance Curves - Modification L	51-52
Design and Performance Curves - Modification M	53-55
Design and Performance Curves - Modification P	56
Design and Performance Curves - Modification Q	57-63
Design and Performance Curves - Modification R	64
Design and Performance Curves - Modification T	65-66
Design and Performance Curves - Modification U and V	67
Design and Performance Curves - Modification X	68
Design and Performance Curves - Standard Pulse Jet	69-74
Night-Firing Run Showing Tailpipe Flame Characteristics	75
Straight Tube Experiment	76
Peak-Performance Graphs	77-80
Design of Inoperative Combustion Chambers	81
Similar Combustion Chambers	82
Extended Heating-Surface Test	83
Auxiliary Jet in Tailpipe	84
Auxiliary Jets in Combustion Chamber	85
External Fuel Spray	86
Performance Curves for Spiral-Weld and Smooth Tailpipe	87

DECLASSIFIED

[redacted]

DECLASSIFIED

I. INTRODUCTION *

1. Authorization. This work was authorized by BuShips Project Order No. 422/45 dated January 3, 1945, by BuShips Project Order No. 390/46 dated 1 July 1945, and by BuAero Project Order No. 249/46 dated 25 August 1945.

2. Previous Development. Refs. (5), (6) and (7) describe experimental work on a standard 13-inch pulse jet engine. A large portion of the initial research was devoted to increasing the vane life for the engine. This resulted in a "sandwich" vane of plastic-impregnated glass cloth between spring steel. This laminated vane (or valve) consisted of 0.008-inch spring steel vane on the impact side, a 0.006 spring steel vane on the combustion side, and a layer of ethyl-cellulose-coated glass cloth between the two steel vanes. The glass cloth served two purposes: (a) to cushion the impact of the vanes on each other and (b) to insulate the striking (impact) vane from the heat of combustion. Ref. (7) describes experimental research of the instantaneous pressure in the combustion chamber and includes a discussion of test methods, pressure measuring equipment, calibration techniques, and recording equipment as well as oscillographic records for various test conditions. From these records it was shown that both the magnitude and the shape of the pressure wave depend upon the fuel rate and the air:fuel ratio. The maximum pressure magnitude recorded during continuous running had a range of -4 psig to 16 psig, or a peak-to-peak value of 20 psi. The frequency of operation was found to vary inversely as the fuel rate.

3. Purpose. The purpose of the research is: (a) to investigate the performance and operation of the pulse jet and (b) to improve the output and efficiency of the engine. This report reviews experiments performed by varying certain design parameters with the hope of improving output and efficiency. The parameters were: (a) size and shape of the combustion chamber, (b) length and diameter of the tailpipe, and (c) the number of vanes in the grid assembly. This investigation of the effect of tube shape upon performance was begun experimentally on 29 August 1946. It is interesting to compare theoretical investigations of tube form outlined in Ref. (3) with the results summarized in this report.

4. As a part of this program, pressure measurements are being continued in order to study the propagation of the pressure wave along the axial length of the tube as recommended in Ref. (7). These pressure measurements will be the subject of a forthcoming report.

* For the benefit of those readers who are not familiar with the operation of the pulse jet, additional information may be found in Appendix I.

DECLASSIFIED

DECLASSIFIED

II. NOMENCLATURE AND SYMBOLS

5. As illustrated in Figs. 1, and 1A all pulse jet engines investigated in this report may be considered as made up of three components: the head assembly, the combustion chamber assembly, and the tail assembly. The following symbols have been adopted for use in this report:

A_h - area of the exit end of the head, square inches.

A_m - maximum cross-sectional area of engine perpendicular to longitudinal axis, square inches.

A_o - inlet area of the combustion chamber, square inches.

A_s - surface area of the tube, or engine tube, not including area of the head, square inches.

A_t - cross-sectional area of the tailpipe, square inches.

A_v - total effective vane area, product of N and C_v, square inches.

C_v - effective intake cross-sectional area per vane taken as 0.40 in this research, square inches.

D_t - inside diameter of the tailpipe, inches.

L_c - length of the combustion chamber inches.

L_e - overall length of the engine, sum of L_h, L_c, and L_t, inches.

L_h - length of the head, inches.

L_t - length of the tailpipe, inches.

N - number of vanes in any grid assembly.

V_c - internal volume of any combustion chamber, cubic inches.

V_e - internal volume of engine, sum V_h, V_c, and V_t, cubic inches.

V_h - internal volume of any head, cubic inches.

V_t - internal volume of the tail, cubic inches.

α - angle between the lateral surfaces of the enlarger and the axis of the tube, degrees.

β - angle between the lateral surfaces of the reducer and the axis of the tube, degrees.

DECLASSIFIED

DECLASSIFIED

III. TEST METHODS

6. Thrust Stands. Figs. 2 and 3, show the control panel and two thrust stands. Both of these thrust stands are similar in principle of operation and type of scale used. The pulse jets are suspended by airplane cables from rolling trolleys which move freely along monorails (I-beams). The average thrust is measured by converting the horizontal force into a vertical force by means of pulleys. The vertical force is "weighed" by a scale mounted on top of the thrust stand. Airplane cable and ball-bearing pulleys on each stand are used to transmit the thrust from the engine to the scales with a minimum of friction. The scales are of spring type with damper and a capacity of 600 pounds. Dead weights are used to calibrate the scales during engine operation.

7. Fuel Systems. A close-up view of the fuel system may be seen in Fig. 4. The fuel is 62-octane unleaded gasoline which is controlled in a pressurized fuel tank suspended from a spring scale similar to that used for thrust measurements. Regulation of air pressure supplied to the fuel tank controls the rate of fuel flow, which is measured by a variable-area-orifice rotameter. Calibration under running conditions is performed by weighing the fuel before and after a timed run with the engine operating at constant fuel rate. The rotameter, manufactured by the Fischer and Porter Co., Hatboro, Pa., has a range of 100 to 750 pounds per hour. The system also contains a filter and manually operated valve for an on-off control.

8. Pulse-Jet Efficiency and Output. In jet propulsion research, it is common practice to rate the output of a unit in terms of THRUST rather than of BRAKE or INDICATED HORSEPOWER. Likewise, efficiency is usually expressed in terms of SPECIFIC FUEL RATE. This is the ratio of the fuel rate in pounds per hour to the thrust in pounds. Another term used to denote efficiency is SPECIFIC THRUST, expressed as the ratio of the thrust in pounds to the fuel rate in pounds per second. It can be seen that specific thrust is the inverse of specific fuel, expressed in different units. The terms thrust and specific fuel have been used throughout this report. It should be noted that a low specific fuel corresponds to a high efficiency.

9. THERMAL EFFICIENCY of the pulse jet engine could be calculated from measurements of fuel rate, thrust, and the jet velocity. However, not only is jet velocity difficult to measure but there is also the more practical consideration that OVERALL EFFICIENCY is the product of the thermal efficiency and the PROPULSION EFFICIENCY. The latter is connected with the propulsive horsepower, which varies with the flight velocity. Furthermore, for flight applications, thermal efficiency is a sufficient basis of comparison only for fuels having the same heat value. Hence, the thermal efficiency has less practical significance for comparing missiles than does specific fuel.

10. The methods of rating jet propulsion power plants, described on page 24 of Ref. (1), are useful in direct determination of the weight of fuel which must be carried in order to fly a given missile a given time with a given engine. The initial weight of the fuel is

DECLASSIFIED

DECLASSIFIED

equal to the product of the specific fuel, the thrust, and the desired duration of flight. Since gross load is equal to the combined weight of fuel plus payload, lowered specific fuel permits greatly increased payloads. For instance, consider a missile which will carry a gross load of 1000 pounds. Suppose that, with an engine having a specific of 3.00, the missile must carry 800 pounds of fuel in order to achieve the necessary range. Then the missile can carry a payload of only 200 pounds. If an engine having a specific of 2.50 is substituted, the missile will require mush less fuel. In particular, the total fuel will be in the ratio of the specifics, or 2.5/3.0. Hence, only 667 pounds of fuel are required. The increased efficiency permits a payload of 333 pounds, or an increase of 66 percent over the original payload. This example clearly illustrates the importance of the quantity, specific fuel.

11. Frequency Measurements. All frequency measurements were taken with a reed vibrometer (Westinghouse Type JC). A comparison of vibrometer data with the calculated frequency from oscillograph records has indicated a deviation of less than 2%. Also, a check against synchronous motors of known frequency showed a maximum deviation of approximately 1.5%. Previous investigations of frequency were reported in Refs. (5), (6), and (7).

12. Pressure Measurements. Ref. (7) describes initial investigations of instantaneous pressure in the pulse jet. Variation in magnitude and shape of the pressure wave in the combustion chamber was correlated with the number of vanes and with the fuel rate. Although no further results are reported here, this investigation is being continued and extended to include the propagation of pressure along the pulse jet and variations between different modifications. Analysis of pressure-time records has resulted in some interesting additions to the theoretical considerations of pulse jets and has provided independent bases for the calculations of thrust, air intake volume, temperature, and gas velocities. Reports covering this field are now being prepared.

13. Noise. An important factor in jet-propulsion research is the noise produced by jet engines and the effect of this noise upon personnel. The vibrations carried by ordinary acoustic paths, as well as those traveling through the earth, have a most annoying impact upon the ears and body; the results of prolonged exposure are both physical and mental fatigue. This effect has been found to be especially noticeable when working with pulse jets which have low frequencies of operation. For instance, during the development of long-life valves, continuous tests of an hour or more were common. The resulting body fatigue and attenuation of hearing were appreciable. Therefore, methods of relieving this annoyance were sought. In general, four methods of reducing noise have been suggested. They are cotton, ear wardens, head phones, and remote control. The first three relieve the ears; the latter relieves the entire body. Cotton is simple and effective. Ear wardens are more effective but require time for application, removal, and care. Head phones are effective and simple. The particular type used had rubberized ear pieces and all electrical parts had been removed. A remote

DECLASSIFIED

DECLASSIFIED

control system would be most effective but is rather complex and time consuming. Hence, although a remote control system is planned, it has not yet been constructed. Instead, the experimenters generally work near the engine protected only by modified head phones.

IV. GENERALIZED DESCRIPTION AND DESIGN - HEAD ASSEMBLIES

14. As indicated in Figs. 5, 6, and 7, the head assembly consists of the grid assembly, the fuel injection system, and the adaptor. The adaptor, the connection between the grid assembly and the combustion chamber, may be in one piece or as an assembly of several components such as frame, cooler, fuel injection block, and expanders. The fuel injection system may be integral either with the grid assembly or with the adaptor. The grid assemblies used throughout this investigation were composed of alternate grid bars and vane bars. The grid bars have eight spaces, four on each side, for vanes. Each vane space has five milled air passages whose total cross-sectional area, C_V, perpendicular to the direction of airflow is 0.40 square inches. The effective vane area, A_V, is the product of the number of vanes, N, by the cross-sectional area, C_V.

$$A_V = N \cdot C_V = 0.40 \cdot N$$

15. The term vane is used to designate the particular type of valve used in this research. It is the same type as that used in the original V-1, and is known as the Eichelberg or flapper vane. The primary purpose of the vanes in the grid assembly is to control the intake air to the combustion chamber. Ref. (6) describes the development of the laminated sandwich assembly or vane which operates successfully for over six hours. Each vane consists of 0.008" spring steel on the impact side and 0.006" spring steel on the flame side, with a layer of plastic impregnated glass cloth between the two. This assembly has been designated as the "8F6" vane, or vane assembly, and was used throughout most of the experimentation described in this report.

16. The method of fuel injection has considerable effect upon the pulse jet engine performance. The fuel jets may be one of several types, such as single stream, multiple stream, conical whirling-spray, or stream-impact spray. Fuel injection may be with a constant or intermittent flow. In this research, jets producing a conical spray having an included angle of approximately 60° were used with continuous injection under pressures ranging from 15 psig to 75 psig. In the case of the expanded grids the fuel jets were placed in pairs projecting at an angle of 48° from the adaptor surfaces which were parallel to the tube axis (see Fig. 8). In some cases, fuel jets were mounted perpendicular to the face of the grid in fuel blocks. Also, preliminary tests were conducted in which all fuel was sprayed externally toward the grid assembly. This method of fuel feed is called external fuel spray or external fuel.

DECLASSIFIED

DECLASSIFIED

17. Originally, in this research, head assemblies were developed to protect the vanes from heating. A venturi placed between the vanes and the combustion chamber partially protects the vanes from heat loading and also provides better mixing of the air. Also, as the research progressed it was desired to investigate pulse jets of different capacities. Therefore, various head assemblies were developed to fill both of these needs. Figs. 5, 6, and 7 show the construction details of Heads No. 1 through No. 9. The first eight heads incorporate a water jacket which is placed next to the head plate. Cooling water is run through the jacket continuously to conduct heat away from the head. This heat would ordinarily pass on to the head assembly and increase the temperature of the grid blocks and vanes. Heads No. 1 through No. 8 are held together by four stud bolts in the head plate. All parts of the head assemblies are constructed so as to fit on these four bolts, thus forming standardized units which can be quickly assembled and disassembled.

18. In addition to the water jacket, Head No. 1 contains a grid block assembly consisting of 40 vanes, one fuel block, and one blank grid block. The latter is merely a spacer. Two fuel jets are mounted on the inside surface of the fuel block. The fuel line from the control panel is connected to either end of the block. Head No. 2 is identical to Head No. 1 except that it has 48 vanes instead of 40. This is accomplished by substituting a standard grid block for the blank one. The fuel block and jets remain the same.

19. Heads Nos. 3, 4, and 5 are similar to each other except for the number of active vanes in the grid assembly. Head No. 3 has 56 vanes and two blank grid blocks; Head No. 4, has 64 vanes and one blank grid block; and Head No. 5 has 72 vanes and no blank grid block. The water jacket is located as in Heads Nos. 1 and 2. A 0.75-inch spacer is inserted between the water jacket and the side-entry fuel block. The object of the spacer is to provide clearance for thefuel jets located in the side-entry fuel block. Four jets are used in this fuel block, two in each side. Each pair of jets is set at an angle of 48 degrees pointing downstream from the incoming airstream. The grid assembly containing 56, 64, or 72 vanes is placed next to the side-entry fuel block, completing the assembly.

20. Heads Nos. 6 and 7 contain 80 and 88 vanes respectively. The 80-vane grid assembly contains one blank grid block and the 88-vane grid assembly none. Otherwise, Heads Nos. 6 and 7 are identical. The water jacket, 0.75-invh spacer, side-entry fuel block and grid assembly are the same as those used for Heads Nos. 3, 4, and 5. However, an adaptor section is placed between the side-entry fuel block and the grid assembly - the purpose being to adapt the grid assembly to the fuel block and also to provide a short rectangular venturi for the incoming air. This was done by the top and bottom surfaces at an angle to the tube axis. Constructional details may be noted in Figs. 6 and 7. Figs. 8 and 9 are photographs showing Head No. 7. Fig. 9 shows the actual installation, including an adjustable shutter assembly on the front of the grid assembly. The purpose of this shutter assembly is to adjust

DECLASSIFIED

DECLASSIFIED

the air-to-fuel ratio when starting the engine, i.e., the shutter can be compared to a choke in a reciprocating engine. In order to start an engine having a large number of vanes, it is necessary to close the shutter until only 72 vanes are exposed. After the pulse jet is running, the shutter is opened to expose the desired number of vanes.

21. As indicated in Figs. 69 through 74 showing the Standard-Pulse-Jet performance curves, the only head assembly used was Head No. 7. In these tests, the shutter was used for starting purposes and also for adjusting the number of exposed vanes. Tests were run for different numbers of exposed vanes, from 48 to 88.

22. Fig. 7 shows the details of Head No. 8. This head uses the water jacket, 0.75 inch spacer block, and the side-entry fuel block as in Heads No. 3 and 8. An additional adaptor-spacer is placed between the side-entry-fuel block and the grid assembly. The latter contains 104 vanes.

23. Head No. 9 was fabricated as a complete unit. Although provisions were made for four side-entry-fuel jets, it was found that better results could be obtained by feeding the fuel through two fuel blocks, using a total of four jets, located in the grid assembly. The latter method apparently provided better mixing of the air and fuel. Figs. 7, 10, and 11 show the setup as used in the tests and recorded in this report.

V. GENERALIZED DESCRIPTION AND DESIGN OF COMBUSTION CHAMBERS

24. Fig. 1, illustrates the nomenclature assigned to the various types of combustion chambers. The various types of head assemblies have been discussed in paragraphs 14 to 23, and illustrated in Figs. 5, 6, and 7. Each head has a minimum area, A_h, through which the mixture of air and fuel pass to the combustion chamber. In general, the latter is a symmetrical chamber of circular cross section whose maximum area, A_m, is greater than A_h. Hence an enlarging section is necessary with lateral surfaces making an angle α with the tube axis. In the special case where the enlarger is simply a flat plate, the conical section has degenerated to a plane and the angle α is 90°. In some designs, the enlargement is made in two steps, the first having an angle α_1 and the second having a different angle α_2. In general, the enlargement may be made in any number of steps. In some cases the enlarging section is followed by a straight section whose area is A_m.

25. All modifications discussed in this report have tailpipes of uniform circular cross section, A_t, which is less than A_m. Therefore, some type of reducing section is necessary. The reducing sections consist of combinations of conical sections where the lateral sides make an angle β with the axis. If the reduction is made abruptly by means of a flat plate, the conical reducer is a plane and the angle β is 90°. Although designs involving more than one angle of reduction were not investigated, they could be tested in a manner simi-

DECLASSIFIED

DECLASSIFIED

lar to that for the angles of enlargement as indicated above. The only tailpipe parameters varied in this research were the tailpipe cross-sectional area, A_t, and the tailpipe length, L_t, and the corresponding tailpipe volume, V_t, equal to the product of A_t and L_t.

26. The standard engine tubes were constructed of 0.125-inch hot-rolled steel arc-welded at the seams. The straight section of the combustion chamber was 20 inches long and had an inside diameter of 13 inches. The reducer section was a truncated cone, 30 inches long for the 7-inch-diameter tailpipe and 25 inches long for the 8-inch-diameter tailpipe. The combustion chamber used with the 7-inch tailpipe had a total volume of 5110 cubic inches, and the combustion chamber used with the 8-inch tailpipe had a total volume of 4880 cubic inches. These figures do not include volume of the head assembly used. Figs. 69 through 74 show the engine dimensions and performance curves.

27. Combustion-Chamber Modifications A through X, were fabricated from Taylor Forge steel-flanged fittings and spiral-welded pipe. Nine sizes of Taylor Forge steel-flanged fittings were used. These particular fittings were conical sections which were combined to form the different combustion-chamber modifications. Spiral-welded pipe was used for the various tailpipes. Each section had flanges welded on both ends. The advantage of using the fittings and spiral-welded pipe are several: first, the spiral pipe has a high strength-to-weight ratio; second, the flanges make for ease of fabrication and increase the strength of the sections; and third, the fittings and spiral pipe were available and could be made up to suit the needs of the research. This meant a saving in time and also permitted tests on a wide variety of shapes. Tables 1 and 2 show pertinent details of each combustion-chamber modification including volume, V_c, tailpipe diameter, D_t, and length L_t, dimensions of conical sections used and reference figure numbers for performance charts of each modification.

DECLASSIFIED

DECLASSIFIED

TABLE 1

MODIFICATIONS A to X

COMBUSTION CHAMBER DESIGN

Modification	V_c Volume Cubic In.	Combustion Chamber Sections Diameters In.	Length In.	D_t Tailpipe Diameter	L_t Tailpipe Length In.	Performance Charts
A	1114	12 to 8	14	8	108, 120, 141	12, 13, 14
B	3114	8 to 14	16	8	96, 120, 132	14, 15, 16, 17
		14 to 8	16			
C	4240	8 to 16	18	8	96, 108, 120	18, 19, 20
		16 to 8	18		132, 141	21, 22
D	6024	8 to 12	14	8	96, 108, 120	23, 24, 25
		12 to 16	18		132, 141	26, 27
		16 to 8	18			
E	6024	8 to 16	18	8	108, 120, 132	29, 30, 31
		16 to 12	18		144, 96	28, 32
		12 to 8	14			
F	6694	12 to 16	18	8	96, 108, 120	33, 34, 35
		16 to 12	18		132, 144	36, 37
		12 to 8	14			
G	4910	12 to 16	18	8	96, 108, 120	38, 39, 40
		16 to 8	18		132	41
H	2883	8 to 14	16	6	96, 108, 120	42, 43, 44
		14 to 8	16		132, 144	45, 46
I	3998	8 to 14	16	6	144	47
		14 to 10	16			
		10 to 6	12			
J	2120	16 to 8	18	8	96, 108, 120	48, 49

DECLASSIFIED

DECLASSIFIED

TABLE 2

Modification	V_c Volume Cubic In.	Combustion Chamber Sections Diameter In.	Length In.	D_t Tailpipe Diameter	L_t Tailpipe Length In.	Performance Charts
K	1557	14 to 8	16	8	120	50
L	1832	14 to 10	16	6	108, 144	51, 52
		10 to 6	12			
M	1557	8 to 14	16	8	120	55
"	"	"	"	6	96, 144	53,54
N	3487	8 to 8	12	6		Unsatisfactory
		8 to 14	16			Operation
		14 to 6	16			
O	2671	12 to 8	14	8		Unsatisfactory
		8 to 14	16			Operation
P	2120	8 to 16	18	8	120	56
Q	3904	8 to 12	14	8	96, 108, 120	57, 58, 59
		12 to 16	18		132, 144	60, 61
Q	3904	8 to 12	14	10	108, 144	62, 63
		12 to 16	18			
R	2790	12 to 16	18	8	120	64
S	2161	8 to 8	12	6		Unsatisfactory
		8 to 14	16			Operation
T	6336	8 to 12	14	10	108, 144	65, 66
		12 to 16	18			
		16 to 10	18			
U	5222	12 to 16	18	10	144	67
		16 to 10	18			
V	6406	12 to 16	18	10	144	67
		16 to 16	18			
X	6048	16 to 16	18	10	144	68
		16 to 10	18			

DECLASSIFIED

DECLASSIFIED

VI. EXPERIMENTAL RESULTS

28. Performance Curves. The performance curves show the output and efficiency of each pulse jet engine under static conditions for a range of fuel flow. Thrust in pounds denotes power output. Specific fuel in pounds of fuel per hour per pound of thrust denotes relative efficiency. The lowest value of specific fuel represents most efficient operation for any given pulse jet. In general, minimum specific fuel and maximum thrust do not occur at the same fuel rate. This is similar to the operation of most internal combustion engines.

29. Performance curves are included for the standard pulse jet and for the various combustion-chamber modifications. Since the immediate goal was to find the optimum operating conditions for a given combustion chamber, each type of combustion chamber, including the standard pulse jet, was run using various lengths of tailpipe. In addition, several different heads were used with each length of tailpipe.

30. Performance curves for standard pulse jets are found in Figs. 69 through 74. Performance curves for modified combustion chambers are found in Figs. 12 through 68. Each set of performance curves also has an accompanying drawing of the corresponding engine. These sketches give the inside dimensions, in inches, of the pulse jet and also illustrate the type and number of welded pipe sections. The scale is 25:1.

31. An adjustable shutter controlled the number of active vanes on Head No. 7 in the standard pulse jet tests. This was the only head used in the tests of standard pulse jet. Different heads, each adapted to a certain number of vanes, were used on the modified combustion chambers. The heads used with each combustion chamber are indicated on each figure. The details of each head are given in Figs. 5, 6, and 7.

32. The performance curves are grouped in the following order: (1) standard pulse jet and (2) modified combustion chambers. The latter are further grouped alphabetically according to (1) combustion chamber type or shape and (2) tailpipe length.

33. Operational Stability. An interesting characteristic of certain unstable modifications is the sudden change in thrust, frequency, and sound at some fuel rate which is not particularly "rich". Immediately after this "crack-over", engine operation is characterized by sharp, explosive pulses instead of the ordinary rythmic roar; by an absence of flame and smoke from the tailpipe, thus indicating more complete combustion; and by the necessity of increased fuel pressure in order to maintain fuel flow. This distinct change in operating characteristics of crack-over is noted just as clearly when going from high to low fuel rates as when going from low to high fuel rates. In general, only a slight increase in fuel results in an appreciable increase in thrust. Hence, there is a sudden change in the slope of the thrust-to-fuel-flow curve as illustrated in Fig. 37 and discussed in paragraph 51. For some modifications, operation above the crack-over point is stable; for others, it is unstable. There is no definite explanation of this phenomenon at the present

DECLASSIFIED

DECLASSIFIED

time although it has been suggested that acoustical resonance may be the cause. This study has indicated that, for a given per cent variation in fuel rate, stable operation is generally accompanied by less change in frequency than is unstable operation.

34. Standard Pulse Jet. All test runs of the Standard Pulse Jet were made using Head No. 7 with the shutter attachment. Figs. 7 and 9 give the design details. The engine was started with the shutter set to expose 48 active vanes. After starting, the shutter was opened to expose 56, 64, 72, 80, or 88 vanes for each successive run. Vanes were replaced as necessary between runs. Fig. 75 illustrates the test stand setup and the jet-flame characteristics during operation.

35. Standard Pulse Jet, 7-Inch-Diameter Tailpipe 54 Inches Long. This tailpipe length produces a maximum thrust of 145 pounds and a minimum specific fuel of 3.77. Both of those values were obtained with the shutter opened to 80 active vanes. As can be noted from the following table, the general trend was for a higher maximum thrust as the number of active vanes was increased. Likewise, the minimum specific fuel decreased as the number of active vanes was increased. This tailpipe is characterized by very flat performance curves as illustrated by Fig. 74. Appreciable burning appeared beyond the end of the tailpipe while running. This might explain the high specific fuel of the 54-inch tailpipe as compared with the 88-, 117-, and 132-inch lengths. It will be seen that the thrust is much lower for the 54-inch length than any of these other three tailpipes.

Table 3

Summary of Data For Standard Pulse Jet.
Tailpipe: 7" Diameter, 54" Length.

No. Vanes	Maximum Thrust	Minimum Specific Fuel
48	87	4.31
56	105	4.27
64	120	4.26
72	135	4.13
80	145	4.77

36. Standard Pulse Jet, 7-Inch-Diameter Tailpipe 88 Inches Long. The 88-inch tailpipe gave the best overall performance of all the various lengths of 7-inch diameter tailpipes tested with the Standard Combustion Chamber. The combination produced a maximum thrust of 195 pounds and a minimum specific fuel of 2.96. From an examination of the following table and the performance curves (Fig. 72), it can be seen that the grid assemblies with 80 or 88 active vanes give approximately the same

DECLASSIFIED

DECLASSIFIED

results. This pulse jet was characterized by rather steady combustion with little or no burning taking place beyond the end of the tailpipe. These data are summarized in the following table:

Table 4

Summary of Data For Standard Pulse Jet.
Tailpipe: 7" Diameter, 88" Length.

No. Vanes	Maximum Thrust	Minimum Specific Fuel
48	128	3.60
56	145	3.37
64	164	3.09
72	188	3.16
80	193	2.96
88	195	2.97

37. Standard Pulse Jet, 7-Inch-Diameter Tailpipe 117 Inches Long. The 117-inch tailpipe followed the same general trend noticed on other tailpipe lengths. The greatest number of active vanes tended to give the largest thrust and the lowest specific fuel. The maximum thrust of 188 pounds was not as great as that obtained with the 88-inch tailpipe. The data would indicate that the 117-inch tailpipe may be a little more efficient. However, the difference in specific fuel for the 88- and 117-inch tailpipes is on the order of 1 per cent. Therefore, the accuracy of the experimental data would hardly permit designating which tailpipe is the more efficient. The performance curves can be seen in Fig. 70. It will be noted that again the grid assemblies with both 80 and 88 active vanes gave practically the same results.

Table 5

Summary of Data For Standard Pulse Jet.
Tailpipe: 7" Diameter, 117" Length.

No. Vanes	Maximum Thrust	Minimum Specific Fuel
48	110	3.60
56	128	3.37
64	162	3.19
72	176	3.15
80	185	2.92
88	188	2.94

DECLASSIFIED
CONFIDENTIAL

DECLASSIFIED

38. Standard Pulse Jet, 7-Inch-Diameter Tailpipe, 132 Inches Long. Fig. 73 shows the performance curves for this 132-inch tailpipe. The curves are of the same size and shape for the 72- and 80-vane grid assemblies. The 80-vane grid, however, gave the better output. The 88-vane grid assembly was not tested with this tailpipe length. This tailpipe is characterized by rather flat performance curves. The maximum output of 178 pounds thrust was slightly below the corresponding values of the 117- and 88-inch tailpipes. The specific fuel value of 2.89 for the 80-vane grid assembly is the lowest obtained with the 7-inch-diameter tailpipe. This tailpipe definitely followed the trend of the greatest number of active vanes giving the largest thrust and lowest specific fuel rates.

Table 6

Summary of Data For Standard Pulse Jet.
Tailpipe: 7" Diameter, 132" Length.

No. Vanes	Maximum Thrust	Minimum Specific Fuel
48	136	3.17
56	150	3.16
64	163	3.11
72	170	2.91
80	178	2.89

39. Standard Pulse Jet, 8-Inch-Diameter 88 Inches Long. The eight-inch-diameter tailpipe gave slightly more encouraging results as far as output and efficiency were concerned. A maximum thrust of 213 pounds and a minimum specific fuel of 2.75 were obtained with the 88-vane grid assembly. Both of these values were better than the corresponding data, 195 pounds thrust and 2.97 specific fuel obtained with the 7-inch tailpipe. The performance curves of Fig. 71 show a maximum fuel rate of about 650 pounds per hour for maximum thrust for the 8-inch tailpipe with the 88-vane grid assembly. For the 7-inch tailpipe, 88 inches long, with an 88-vane grid assembly, maximum thrust was obtained at a fuel rate of 610 pounds per hour. Assuming that the air-fuel ratio was the same at both points of maximum thrust, it can be seen that the 8-inch tailpipe is capable of handling more products of combustion, and hence can produce more thrust. Although this is true doubling the cross-sectional area of the tailpipe did not double the thrust. In explaining this, other factors including design of combustion chamber, size of fuel jets, size of grid assembly, etc., would have to be considered. The thrust was, however, increased from 195 pounds to 213 pounds, an increase of more than 9 per cent. The increase in tailpipe area was 30.7 per cent.

DECLASSIFIED

DECLASSIFIED

Table 7.

Summary of Data For Standard Pulse Jet.
Tailpipe: 8" Diameter 88" Length

No. Vanes	Maximum Thrust	Minimum Specific Fuel
48	140	3.29
56	156	3.37
64	180	3.07
72	192	2.85
80	202	2.85
88	213	2.75

40. Summary of 7- and 8-Inch-Diameter Tailpipes. For the combinations tested the following trends were noted:

(a) All tailpipes showed increased maximum thrust as the number of active vanes was increased.

(b) All tailpipes showed increased efficiency (decreased specific fuel) as the number of active vanes was increased.

(c) As far as thrust was concerned, the optimum length of 7-inch tailpipe was 88 inches.

(d) As far as efficiency was concerned, the optimum length of the 7-inch-diameter tailpipe was 132 inches.

(e) As is to be expected, the 8-inch tailpipe gave more thrust than did the 7-inch tailpipe.

41. Straight-Tube Experiment. As the first step in an investigation of the effect of changes in design parameters of pulse jets, a straight tube was built and tested. Recorded and calculated data, performance curves, and engine dimensions are given in Fig. 76. These data cover the best results obtained from the straight tube experiments, which, in general, were characterized by very unstable combustion. In fact, the engine would not operate until an orifice plate with an inside diameter of 5 inches was inserted between the head assembly and the tube. The orifice plate acted as a flame retainer as well as a degenerate venturi. The frequency of operation was about 3250 cpm, which would be high for a combustion chamber with an 8" by 141" tailpipe. However, the lack of a combustion chamber logically explains the increase in frequency. Also, high specific fuel and low thrusts were produced. The advantage of the straight tube would be its small cross-sectional area if the thrust per unit area could be approximately that for the tailpipe of the standard pulse jet. Therefore, for a given output the maximum cross-sectional area would be low and would produce less parasitic drag. To date, a

DECLASSIFIED

DECLASSIFIED

maximum value of 5.07 pounds thrust per square inch of tailpipe area has been obtained from a 7-inch standard pulse jet. The straight tube gave about 0.75 pounds thrust per square inch.

42. Design and Performance - Modification A. The necessity of an orifice plate used in the straight-tube experiment showed that some sort of a combustion chamber was desirable for stable, continuous, and efficient operation. It was however, desirable to keep the cross-sectional area of the engine at a minimum. Therefore, Modification A consisted of a conical section, 12" to 8" whose volume was 1114 cubic inches. This section was connected as a reducer as shown in Figs. 12, 13, and 14, with head assemblies bolted to the larger diameter. Tests were performed with 8-inch tailpipes of lengths of 108", 120", and 141 inches. Head No. 1 with 40 vanes and Head No. 2 with 48 vanes were used with the 108" tailpipe; Head No. 5 with 72 vanes was used with 120" tailpipe and 141" tailpipe; Head No. 6 with 80 vanes was used with the 141" tailpipe.

43. Peak performance graphs for Modification A may be found on Fig. 78; performance curves in Figs. 12, 13, and 14, and specific fuel comparisons on Table 11. Although the operation of this modification was more stable than that of a straight tube, the thrusts obtained were low and the specific fuel high. It might be interesting to note that the maximum thrust obtained with the short tailpipe length, 108", was 84 pounds and that the minimum specific fuel was 3.26 with a 40-vane grid assembly. However, with the increase of 8 vanes, using 48 vanes on Head No. 2, the maximum thrust was only 64 pounds and the minimum specific fuel 5.21. On the contrary with the tailpipe of longer length, 141", the same increase in vanes gave an increase in thrust and a decrease in specific fuel. For both the longest and shortest tailpipes, the best performing units gave curves of similar shape. The curves were especially interesting because, at maximum fuel rate, the thrust curves had an increasing slope instead of the decreasing slope in performance curves. At this maximum fuel rate the engine stopped spontaneously on each of the runs which showed this characteristic. This spontaneous cut-off was apparently caused by something other than an over-rich mixture. The tests with this modification effectively demonstrated the critical nature of the number of vanes. In particular, changing from 40 to 48 vanes not only affected the shape of the performance curves but also resulted in decreased thrust for the same fuel rate. Hence, although Modification A was an operable engine with reasonable efficiency, the maximum thrust seemed too low to warrent further investigation.

44. Design and Performance - Modification B. In order to investigate a still larger combustion chamber without a radical departure from a straight tube, Modification B was designed. This chamber consisted of two 8" to 14" cones 16" in length connected with their large diameters together as indicated in Figs. 14, 15, 16, and 17. Tests were performed with 8-inch tailpipes of 96", 120", 132", and 141" lengths. Head No. 5 with 72 vanes was used on all of these tailpipe lengths. Head No. 7 with 88 vanes was used on all but the 141" tailpipe length. This number of vanes was considered to be beyond the optimum operation

DECLASSIFIED

DECLASSIFIED

point for this length. Performance curves are also given in Figs. 14, 15, 16, and 17.

45. All of these curves are similar in shape and may be called normal in that they show that the thrust rose slowly to a maximum and then fell off as the mixture became too rich. Similarly, the specific fuel dropped to a minimum and then rose as the most efficient point of operation was passed. This modification gave quite uniform results for the various tailpipe lengths and number of vanes used in these tests. For the longest tailpipes with Modification B, 72 vanes gave the greatest thrust. The 96" tailpipe with 88 vanes gave a maximum thrust of 195. pounds and the 120" tailpipe with 72 vanes gave the minimum specific of 2.75. Modification B was still more stable in operation than Modification A, and produced more thrust with better efficiencies. It was assumed that the added volume of this combustion chamber improved the operation of Modification B over Modification A.

46. Design and Performance - Modification C. Because of the apparent improvement in operation caused by the slight increase in combustion-chamber volume in Modification B, it was decided to try a still greater volume. Modification C consisted of two 8" to 16" cones, each 18" long, mounted with the large diameters bolted together. Tests were performed with 8-inch tailpipes of lengths of 96", 108", 120", 132", and 141". Head No. 5 with 72 vanes and Head No. 7 with 88 vanes were used on all tailpipe lengths. Head No. 2 with 48 vanes was used on all tailpipes with the exception of the 96" lengths. Performance curves and design details are given in Figs. 18, 19, 20, 21, and 22. The best specific value was 2.84, obtained on the 132" tailpipe with a 72-vane grid assembly. A maximum thrust of 196 pounds produced by Modification C, was with a 132" tailpipe and an 88-vane grid assembly. For all tailpipe lengths, the 88-vane grid assembly produced the greatest thrust, although there was little difference in thrust between the 88- and the 72-vane grid assemblies, nor between the various tailpipe lengths. The 48-vane grid assembly produced lower thrusts - between 85 and 104 pounds - with less efficiency. This was assumed to indicate that with 48 vanes Modification C was undervaned. Very little difference was noticed between Modification B and Modification C. Therefore, it was decided to investigate still other configurations.

47. Design and Performance - Modification D. Modification D was designed with a larger volume and longer combustion chamber than Modification C. This chamber consisted of three conical sections; 8" to 12", 14" long; 12" to 16", 18" long; and 16" to 8", 18" long. Tests were performed on 8-inch diameter tailpipes of 96", 108", 120", 132", and 141" lengths. Head No. 5 with 72 vanes and Head No. 7 with 88 vanes were used on all tailpipe lengths. Head No. 2 with 48 vanes was used on the 120" tailpipe only. Design details and performance curves may be found in Figs. 23, 24, 25, 26, and 27. The best value of specific fuel obtained with this modification was 2.79 and the maximum thrust was 190 pounds. Both of these values were obtained with the 141" tailpipe and 88-vane grid assembly on Head No. 7. The same maximum thrust was also produced by the 132" tailpipe and the same grid assembly but with a higher specific, i.e., lower efficiency. For the tests performed, the general trend of decreased specific fuel rates with the longer tailpipe lengths was ob-

DECLASSIFIED

DECLASSIFIED

served. This modification also showed best efficiencies with the larger number of vanes in the grid assemblies. For the various combinations of tailpipe lengths and vane assemblies, the thrust curves as well as the efficiency curves are of similar shape. In most of the tests, the minimum specific occurred at a fuel rate of approximately 500 pounds per hour. Stability of engine operation was indicated by the fact that these different combinations of tailpipe lengths and vane assemblies could be operated over a wide range of fuel rates. This configuration was further characterized by the fact that the minimum specific occurred at a fuel rate which was somewhat lower than that corresponding to maximum thrust. These facts are graphically indicated on the performance curves. Stability is also indicated by the slight change in frequency with rather large changes in fuel rates as shown in Fig. 78. This figure also indicates that Modification D operated at the lowest frequency range - 1660 to 2200 cpm, - of the configurations investigated. Finally, it was concluded that this configuration showed little advantage over previous modifications with smaller combustion chamber volumes.

48. Design and Performance - Modification E. Following the investigation of Modification D, it was decided to reverse that combustion chamber in order to investigate the effect of the angles of the cones which made up the combustion chamber. Therefore, Modification E had the same combustion chamber volume and length as Modification D, but different orientation. This chamber consists of three conical sections; 8" to 16", 18" long; 16" to 12", 18" long; and 12" to 8", 14" long. Tests were performed on 8-inch-diameter tailpipes of 96", 108", 120", 132", and 144" lengths. Head No. 5 with 72 vanes and Head No. 7 with 88 vanes were used with all tailpipe lengths. Head No. 2 with 48 vanes was used on 108" and 120" tailpipe lengths. Head No. 8 with 104 vanes was used on the 132" and 144" tailpipes. Design details and performance curves may be found in Figs. 28, 29, 30, 31, and 32.

49. The best specific obtained with this modification was 2.65 and the maximum thrust was 206 pounds. The 132" tailpipe with 88 vanes gave the best specific fuel value. The 144" tailpipe with 104 vanes gave the maximum thrust. For the various combinations of tailpipe lengths and vane assemblies which were tried, the longer tailpipe lengths gave better efficiencies. However, in comparison with Modification D, it was found possible to over-vane the engine. This is especially illustrated in Fig. 31, where, with a 132" tailpipe the increase from 88 to 104 vanes produced a decrease in thrust and efficiency. Unfortunately, comparable data were not secured with Modification D. The possibility of over-vaning has been indicated with other configurations. As with Modification D, this configuration could also be operated over a wide range of fuel rate. Most of the combinations produced curves of similar shapes. The 48-vane grid was the exception because of the large volume of the combustion chamber compared with the small effective vane area. Here again, the minimum specific occurred at a fuel rate of approximately 500 pounds per hour. Also, the minimum specific occurred at a fuel rate which was lower than the fuel rate for maximum thrust. The effect of reversing the combustion chamber was particularly noticeable in the frequency of engine operation. For the same volumetric conditions, Modification E had higher frequencies, and greater frequency

DECLASSIFIED

DECLASSIFIED

ranges, but less stable operating characteristics. This is graphically illustrated in Figs. 78 and 79. It was interesting to observe the effect of reversing the combustion chamber, particularly since this modification produced slightly higher thrust and better efficiency than modifications previously tried.

50. Design and Performance - Modification F. In order to investigate a combustion chamber similar to Modification E but with a slightly larger volume, it was decided to test Modification F. This modification consisted of three conical sections: one 12" to 16", 18" long; one 16" to 12", 18" long; and one 12" to 8", 14" long. Tests were performed on 8-inch-diameter tailpipes of 96", 108", 120", 132",and 144" lengths. Head No. 2, 48 vanes, was used on the 108" tailpipe; Head No. 5, 72 vanes, and Head No. 7, 88 vanes, were used on all the tailpipe lengths tested; Head No. 8, 104 vanes, was used on 132" and 144" tailpipe lengths; and Head No. 9, 104 vanes, was used on the 132" tailpipe length only. Design details and performance curves may be found in Figs. 33, 34, 35, 36, and 37.

51. The minimum specific fuel obtained was 3.10 with Head No. 8, 104 vanes on 144" tailpipe. A maximum thrust of 204 pounds was obtained with Head No. 9, 104 vanes on 132" tailpipe. The thrust obtained from the 72-vane grid assembly varied from 150 to 175 pounds. The shorter tailpipes gave the least amount of thrust. In general, this trend was similar to the 88- and 104-vane grid assemblies. The dotted lines on the performance curves of Fig. 37, 144" tailpipe, indicate irregular or "crack-over" operation. Reference is made to paragraph 33. At the lower fuel rates, this combination was characterized by very low thrusts and high specifics. This "crack-over" transition occurred between fuel rates of 450 and 550 pounds per hour, depending upon the length tailpipe used. It is not known what actually caused this kind of operation but possibly the combination of the long tailpipe with the largest volume combustion chamber tested upset the combustion at fuel rates between 450 and 550 pounds per hour. At fuel rates above this range of irregular operation, the engine had operational characteristics similar to those of the 132" tailpipe length.

52. Design and Performance - Modification G. Since considerable testing had been done on the long combustion chambers D, E, and F, it was desired to investigate a shorter combustion chamber without reducing the volume too much. Therefore, Modification G consisted of two conical sections: one 12" to 16", 18" long and one 16" to 8", 18" long. Tests were performed on 8-inch-diameter tailpipes of 96", 108", 120", and 132" lengths. Head No. 5 with 72 vanes and Head No. 7 with 88 vanes were used on all tailpipe lengths. Head No. 2 with 48 vanes was used on 108" and 120" tailpipes only. Design details and performance curves may be found in Figs. 38, 39, 40, and 41.

53. The minimum specific fuel obtained was 2.92 with a 72-vane grid assembly on 132" tailpipe. A maximum thrust of 193 pounds was also obtained on the 132" tailpipe, but with an 88-vane grid assembly. For this particular combustion chamber, the longer tailpipes gave the higher thrusts and lower specifics within the range of tailpipe lengths tested. For all of the combinations of tailpipes and number of vanes which were

DECLASSIFIED

DECLASSIFIED

used with the Modification G combustion chamber, the frequency range of operation was rather wide. The one exception was the case of 88 vanes and 132" tailpipe. This particular combination operated at almost constant frequency for the complete fuel range and produced the maximum thrust and also one of the best specific fuel values. The use of the 48-vane grid resulted in low thrust and poor efficiency. This was taken to indicate that 48 vanes did not permit sufficient air to enter the combustion chamber. In conclusion Modification G was an operable engine with no particular advantages.

54. Design and Performance - Modification H. Next it was decided to study similar combustion chamber configurations with 6-inch-diameter tailpipes. Modification H consisted of two conical sections: one 8" to 14", 16" long and one 14" to 6", 16" long. Tests were performed on 6-inch-diameter tailpipes only. The lengths tested were 96", 108", 120", 132", and 144". Heads No. 1 with 40 vanes, No. 2 with 48 vanes, No. 3 with 56 vanes, and No. 4 with 64 vanes were used on all tailpipe lengths. Design details performance curves may be found in Figs. 42, 43, 44, 45, and 46.

55. The minimum specific fuel rate obtained was 2.97 and the maximum thrust was 123 pounds. Both of these values were obtained on a 144" tailpipe with a 56-vane grid assembly. The average thrust increase from the 96" tailpipe to the 144" tailpipe was 19.4 per cent for all grid assemblies. The average specific fuel decrease from the 96" tailpipe to the 144" tailpipe was 15.2 per cent. In general, for any given number of vanes, maximum thrust and minimum specific fuel were produced with the longest tailpipe length. For any given tailpipe length, a variation in the number of vanes tended to shift the performance curves. In general, for the tests made on Modification H, an increase in vanes resulted not only in increased thrust but also in best operation at a higher fuel rate. In other words, for any given tailpipe length, the points of maximum efficiency occurred at higher fuel rates for increased number of vanes. For any given tailpipe length, the best operating point did not necessarily occur with the largest number of vanes. It can be noted that the 56-vane grid assemblies showed the best operating characteristics on the majority of the tailpipe lengths tested with the modification. This set of runs clearly illustrates that it is possible to over-vane a given configuration as well as to under-vane. This configuration illustrates difficulties caused by the presence of the several variables encountered in pulse-jet research. For instance, two parameters not completely investigated are the fuel distribution and the venturi design. Figs. 6 and 7 give the design details of the heads used with this modification. Heads No. 1 and No. 2 had the same fuel distribution system but different numbers of vanes. The same thing is true of Heads No. 3 and No. 4. However, there is a definite break in the performance characteristics of Heads Nos. 3 and 4. The difference in fuel distribution systems may explain the fact that in some cases the relationship between maximum thrust and the number of vanes is not regular. In conclusion, Modification H was an operable engine and the results were particularly useful in illustrating the effect of the different parameters.

[redacted]

DECLASSIFIED

DECLASSIFIED

56. Design and Performance - Modification I. Next it was decided to investigate a configuration similar to Modification E but suitable for use on a 6-inch tailpipe. Modification I consisted of three conical sections: one 8" to 14", 16" long; one 14" to 10", 16" long; and one 10" to 6", 12" long. Tests were performed on the 6-inch diameter, 144" length tailpipe only since this was found to be the most efficient tailpipe for Modification H. Head No. 2 with 48 vanes and Head No. 5 with 72 vanes were used in this test. Design details and performance curves may be found on Fig. 47.

57. This modification produced the greatest thrust of any of the configurations using the 6-inch tailpipe. The maximum thrust obtained was 135 pounds and the minimum specific was 3.12. Both of these values were obtained on Head No. 5 with 72 vanes. It is interesting to note that this thrust of 135 pounds corresponds to a value of 692 pounds per square foot of tailpipe cross-sectional area and is the highest obtained to date in this research. While the total thrust and the thrust per unit cross-sectional area of tailpipe were high for this engine, the efficiency was poor. For this reason, investigations were confined to the 144" tailpipes which had previously been found to be, in general, the most efficient length.

58. Design and Performance - Modification J. Since most of the investigation had been carried out on the larger combustion chambers, it was desired to obtain more data on the smaller volume combustion chambers similar in shape to Modification A. Modification J consisted of one conical section, 16" to 8", 18" in length. Tests were performed on 8-inch tailpipes with lengths of 96", 108", and 120". Head No. 1 with 40 vanes was run on all the tailpipe lengths and Head No. 2 with 48 vanes was run on the 108" tailpipe only. Design and performance curves may be found on Figs. 48, and 49.

59. A maximum thrust of 108 pounds was obtained on the 108" tailpipe with Head No. 2 and 48 vanes. The minimum specific was 3.33 and was produced on the 120" tailpipe with Head No. 1 and 40 vanes. The general characteristics of this modification were short operating fuel ranges and relatively high frequencies. In Fig. 48, it is interesting to note the performance curves of the long and short tailpipes. In both curves, small changes in fuel rate produced a large change in thrust. The engine choked spontaneously with further increases in fuel. Had the engine continued operating at higher fuel rates with the continuation of the curves as such, more desirable performance characteristics might have been obtained. Since output and efficiency were only fair, tests were discontinued.

60. Design and Performance - Modification K. In order to investigate a combustion chamber with a similar shape as Modifications A and J, but with an intermediate volume, Modification K was tested. Modification K consisted of one conical section, 14" to 8", 16" in length. Tests were performed on an 8-inch tailpipe, 120" in length. Heads No. 1 and No. 2 with 40 and 48 vanes, respectively, were tested on this engine tube. Design details and performance curves may be found in Fig. 50.

DECLASSIFIED

DECLASSIFIED

61. A maximum thrust of 100 pounds was obtained on Head No. 2 with 48 vanes, and the minimum specific of 3.32 was obtained on Head No. 1 with 40 vanes. It was found that the operating characteristics were similar to Modification J, as illustrated by Fig. 50. High frequencies of operation, low thrusts, and high specifics were observed. Increased number of vanes in the grid assembly did increase the thrust, but decreased the efficiency.

62. Design and Performance - Modification L. In order to investigate further combustion chambers of similar shape as Modifications A, J, and K, but with a different tailpipe diameter, Modification L was tested. Modification L consisted of two conical sections, one 14" to 10", 16" long and one section 10" to 6", 12" long. Tests were performed on 6-inch tailpipe 108" and 144" in length. Heads No. 1 and No. 2, with 40 and 48 vanes respectively, were used on both tailpipe lengths. Head No. 3 with 56 vanes was used on the 144" tailpipe only. Design details and performance curves may be found in Figs. 51 and 52.

63. A maximum thrust of 104 pounds and a minimum specific of 3.54 was produced with 56 vanes and the 144" tailpipe. The performance curves were normal in all respects, except that the specific fuel rates were high. Each run was characterized by unstable combustion as indicated by the large operating frequency ranges. The average variation in frequency from high to low fuel rates was approximately 475 cycles per minute. The engine exhibited a marked tendency to "surge" which could not be removed by the insertion of check valves in the fuel line.

64. Design and Performance - Modification M. Modification M was the first attempt to deviate from the use of converging tapered sections between the combustion chamber and the tailpipe. Modification M is the reverse of Modification K, and consisted of one conical section 8" to 14", 16" long. Different size adaptor plates bolted to the large diameter of the combustion chamber made it possible to test either 6 or 8-inch tailpipes. Initial discussion will concern the 8-inch-diameter tailpipe. Head No. 2 with 48 vanes and Head No. 4 with 64 vanes were run with a 120" tailpipe only. Maximum thrust obtained from Modification M with the 8-inch tailpipe and 64 vanes was 145 pounds. With 48 vanes this modification produced a minimum specific of 2.94 with this same tailpipe. Design details and performance curves may be found in Fig. 55. The 6-inch-diameter tailpipe was tested with 96" and 144" lengths. Head No. 1, 40 vanes, and Head No. 4, 64 vanes, were tested on both tailpipe lengths. Head No. 2, 48 vanes, was tested on the 96" tailpipe only. Design details and performance curves may be found on Figs. 53 and 54. Maximum thrust of 112 pounds was produced by the engine with a 144" tailpipe and 64 vanes. The minimum specific of 3.04 was obtained from the 144" tailpipe and 64 vanes. The minimum specific of 3.04 was obtained from the 144" tailpipe with 40 vanes. For the 96" tailpipe, the points of maximum efficiency occurred at increasing fuel rate with increased number of vanes. In this particular case the best efficiency was obtained with the smaller number of vanes. A comparison of the 96" tailpipe and the 144" tailpipe with 64 vanes shows that the longer tailpipe gave slightly higher thrust and better efficiency.

DECLASSIFIED

DECLASSIFIED

65. Design and Performance - Modification N. Modification N was designed with a straight section on the front part of the combustion chamber. It was hoped that this section would provide an added venturi and a more homogeneous mixture of fuel and air. It was also thought that this section would produce a delayed ignition, which could be varied by the length of straight section. Therefore, this modification consisted of a straight section, 8-inch diameter, by 12" length and two conical sections, one 8" to 14" and one 14" to 6", both 16" in length. A 6-inch-diameter tailpipe 96" in length with Head No. 3, 56 vanes, was used for this test. Fig. 81 shows the design. Owing to the difficulties experienced in starting and the highly irregular running characteristics while the engine was in operation, no performance curves were drawn.

66. Modification N ran erratically with a very low thrust of 30 to 35 pounds at a fuel rate of 225 pounds per hour. The engine seemed to be trying to resonate simultaneously on two entirely different frequencies. This was apparently caused by the additional straight section on the front of the combustion chamber.

67. Design and Performance - Modification O. It was thought that the presence of a venturi in the center of the combustion chamber would produce additional turbulence and improve performance characteristics. This venturi was formed by using two conical sections, one 12" to 8" and one 8" to 14", bolted together at the small diameters. A 6-inch-diameter tailpipe, 120" in length, with Head No. 4, 64 vanes, was used for this test. Fig. 81 shows the design. This modification was operated at a fuel rate between 380 and 430 pounds per hour and produced such an irregular thrust that no scale reading was possible. Therefore, no performance curves were drawn.

68. Design and Performance - Modification P. Modification P was tested to investigate further a diverging tapered combustion chamber of larger volume. This combustion chamber is similar in shape and construction to Modification M and consisted of one conical section 8" to 16", 18" long. An 8-inch diameter tailpipe was tested with Head No. 4, 64 vanes, Head No. 5, 72 vanes and Head No. 7, 88 vanes. The only length tailpipe tested was 120". Design details and performance curves may be found in Fig. 56.

69. The 72-vane grid assembly yielded the maximum thrust of 176 pounds and the minimum specific of 2.82. The performance curves illustrate the fact that there is a definite relationship between the number of vanes and the configuration of the tube. It can be seen from the curves that the 72 vanes gave the best results when compared to more or fewer vanes.

70. In comparing Modification M and Modification P utilizing 120" tailpipes, and 64 vane grids, it can be seen that the added volume of Modification P produced slightly higher thrust and greater efficiency. Modification P produced a maximum thrust of 152 pounds and a minimum specific of 2.97 as compared with Modification M which produced 145 pounds of thrust and a specific of 3.29. These tests confirmed the ad-

DECLASSIFIED

DECLASSIFIED

vantages of the reversed-cone-type combustion chamber, with definite increases in thrust and efficiency.

71. Design and Performance - Modification Q. To investigate the advantages of the diverging combustion chamber as carried out in Modifications M and P, it was decided to increase the volume and length without increasing the cross-sectional area. Modified combustion chamber Q consisted of two conical sections 8" to 12", 14" long, and 12" to 16", 18" long. Tests were performed on 8-inch-diameter tailpipes, 96", 108", 120", 132", and 144" in length, and on 10" diameter tailpipes, 108" and 144" in length. Head No. 5, 72 vanes; Head No. 7, 88 vanes; and Head No. 8, 104 vanes were used on all tailpipe lengths. Design details and performance curves may be found in Figs. 57, 58, 59, 60, 61, 62, and 63. Initial discussion will concern the 8-inch tailpipe only.

72. The maximum thrust produced by Modification Q on an 8-inch-diameter tailpipe was 208 pounds and the minimum specific fuel was 2.59. Both of these values were obtained from a 72-vane grid assembly on a tailpipe 144" long. On the shorter tailpipe lengths, (96", 108", and 120") increasing the number of vanes in the grid assembly increased the maximum thrust. This follows trends noted previously in this research. However, on the longer tailpipe lengths- 132" and 144" - complete reversal of this characteristic was experienced; i.e., increasing the number of vanes decreased the maximum thrust and efficiency. This confirms the previous observation that there is an optimum number of vanes for best efficiency, on any given engine tube. Experience with this modification further indicated that best efficiencies are obtained with the longer tailpipes. This modification was characterized by very stable combustion, low operating frequency range, and a comparatively large fuel range. In a majority of cases the trend was for the specific fuel values to drop as the length of the tailpipe was increased.

73. Modified combustion chamber Q, (See Figs. 62 and 63) on a 10-inch diameter tailpipe produced a maximum thrust of 215 pounds. This thrust was obtained on a 144" tailpipe and an 88-vane grid assembly. However, the 72-vane grid assembly proved a better all-around performer. A minimum specific fuel rate of 2.48 and a maximum thrust of 212 pounds was obtained. The operating and performance characteristics of Modification Q were similar to both the 8-inch- and 10-inch-diameter tailpipe. In general the frequency tended to increase with an increase in the number of vanes on any tailpipe length. As indicated previously, an engine operates most efficiently with one particular number of vanes. The 88 vanes produced the two highest thrust values in the case of Modification Q. Attention is called to the particular flatness of the specific fuel curves as illustrated by Fig. 61. Another observed characteristic of this tube was the comparatively small frequency range within which this engine operated. Additional information regarding the characteristics of this modification, obtained by the aid of pressure-time oscillographs, will be reported on soon.

DECLASSIFIED

DECLASSIFIED

74. Modifications M, P, and Q all seem to indicate that a combustion-chamber exit orifice with a low flow coefficient is desirable. Since these three modifications all have an angle β equal to 90° (See Fig. 1), a Borda orifice could be easily installed for a further study of combustion chamber exits having low flow coefficients. This study could be furthered by the use of multiple tailpipes. Definite plans are now being made to investigate the many possibilities opened up by the use of the Modification Q combustion chamber.

75. Design and Performance - Modification R. Modification R was tested in order to try a diverging combustion chamber having an abrupt enlargement from the head assembly somewhat similar to that of Modifications A, F, J, G, and K. Modification R was designed to be similar to Modification Q. However, the first cone was removed with the intention of determining the effect of a smaller combustion chamber on operating characteristics without too much change in combustion chamber contour. This combustion chamber was similar in shape to Modifications M and P, and consisted of one cone 12" to 16", 18" long. An 8-inch-diameter tailpipe 120" in length was tested with Heads No. 5, 72 vanes, and No. 7, 88 vanes. Design details and performance curves may be found in Fig. 64. The 88-vane assembly produced the highest thrust of 164 pounds. The 72-vane combination produced the lowest specific fuel of 2.97. However, there was very little difference in the maximum thrust (164 and 160 pounds) and minimum specific fuel values (3.17 and 2.97) of both engines in comparison to the tremendous difference in frequency range limits. Frequency range for the 72-vane head was 2440 to 2500 cpm; the range for the 88-vane head was 2340 to 2880 cpm. This represents a difference of from 60 to 540 cpm. An analysis of the data shows, however, that both combinations produced maximum thrust at practically the same fuel rate and frequency. This was an exceptional run where the 72-vane head assembly was characterized by much more stable operation than the 88-vane head assembly, as evidenced by the lower frequency range with approximately the same output.

76. Design and Performance - Modification S. In conjunction with Modification N, it was desired to study the effects of a low-flow-coefficient combustion-chamber exit with the added straight section on the front part of the combustion chamber. Therefore, Modification S consisted of a straight section 8" diameter by 12" long and one conical section 8" to 14". A 6-inch tailpipe 96" in length was used with Head No. 2. Fig. 81 shows the design. This modification had easy starting characteristics but would run over only a small fuel range. Consequently no performance curves were drawn.

77. Design and Performance - Modification T. It was desired to test a combustion chamber similar in shape to Modification D, but adaptable to a 10-inch diameter tailpipe. Therefore, Modification T consisted of three conical sections, one 8" to 12", 14" long; one 12" to 16", 18" long; and one 16" to 10", 18" long. As mentioned above, tests were performed on a 10-inch diameter tailpipe of lengths of 108" and 144". Head No. 5, 72 vanes; Head No. 7, 88 vanes; and Head No. 8, 104 vanes, were tested on both tailpipe lengths. Design details and performance curves may be found in Figs. 65 and 66.

DECLASSIFIED

DECLASSIFIED

78. A maximum thrust of 220 pounds was produced by Head No. 8, 104 vanes, on the 144" tailpipe. A minimum specific of 2.47 was produced on the 144" tailpipe but with Head No. 5, 72 vanes. This value of specific is the lowest obtained in this research on all engines using internal fuel injection. Modification T was characterized by stable combustion as indicated by the short range of frequency operation and the flat efficiency curves. This modification was exceptionally stable over a wide range of fuel flow, since for variations in fuel of 225 pounds per hour the frequency did not change more than 200 cpm. These results with a 10-inch tailpipe confirm those found with Modification D with an 8-inch tailpipe. A further comparison may be found in paragraph 89.

79. Design and Performance - Modification U. In order to continue the comparison of the effect of similar combustion chambers over a wide variety of tailpipe diameters, Modification U was designed and tested. This combustion chamber was similar in shape to Modification G except for the use of the 10-inch diameter tailpipe. The combustion chamber consisted of two conical sections, one 12" to 16" and one 16" to 10", both 18" long. Head No. 9, 104 vanes was used with the 144" tailpipe for this test. Design details and the performance curves may be found in Fig. 67.

80. Maximum thrust for this modification was 270 pounds and the minimum specific was 2.73. The range of fuel flow was limited to 20 pounds per hour in order not to exceed the maximum rate indicated by the rotameter. Over this narrow range the specific fuel was practically constant. However, the frequency varied about 150 cpm over this same range. This confirmed the audible indication that this modification was rather unstable in operation as discussed in paragraph 33. The small section of the thrust curve might be extrapolated to indicate some slight increase in thrust at higher fuel rates. Further research on this modification was discontinued because of the limitation imposed by the rotameters available at that time.

81. Design and Performance - Modification V. In order to investigate further 10-inch-diameter tailpipes, Modification V was constructed from a conical section 12" to 16", 18" long, and a straight section 16" in diameter, 18" long. This combustion chamber provided still more volume than Modification U and provided an orifice having a low flow coefficient somewhat similar to that used in Modification Q between the combustion chamber and the tailpipe. Head No. 9, 104 vanes, was used with a 10-inch-diameter tailpipe, 144" long. Design details and performance curves may be found in Fig. 67.

82. Maximum thrust for this modification was 270 pounds and the minimum specific was 2.60. The fuel range was relatively long, especially as compared with Modification U, being more than 180 pounds per hour. Here again however, the modification was not run to its maximum fuel rate but only to the maximum value measurable with the rotameter. Operation was stable as indicated by audible sounds and narrow frequency range (See paragraph 33). The frequency range was only 200 cpm. The curve of specific-fuel rate was particularly interesting be-

DECLASSIFIED

DECLASSIFIED

cause it is unusually flat for the upper 75% of the fuel range. For all thrusts over 225 pounds, the specific fuel was less than 2.7. Hence, the maximum thrust was secured at a specific of 2.7 which is not greatly different from the best obtained with this modification. This modification further confirmed the advantages resulting from the low-flow-coefficient orifice.

83. Design and Performance - Modification W. As a further investigation of the low-flow-coefficient orifice, Modification W was designed with a straight combustion chamber 16" in diameter and 36" long. Head No. 9 with 104 vanes was used with a 10-inch diameter tailpipe 144" long. Design details and performance curves will not be found in this report since this modification did not operate satisfactorily.

84. Design and Performance - Modification X. It was next decided to try a standard-shaped combustion chamber constructed from the Taylor Forge fittings and using a 10-inch tailpipe. Therefore, Modification X was constructed from a straight section 16" in diameter, 18" long, and a reducing conical section 16" to 10", 18" long. Head No. 9, with adjustable shutter closed to 72 vanes, and Head No. 9, 104 vanes, were used with a tailpipe 144" long. Design details and performance curves may be found in Fig. 68.

85. A maximum thrust of 255 pounds and a minimum specific of 2.52 were produced with 104 vanes. The fuel range for this combination (590-720) was 130 pounds per hour, the variation in frequency was 50 cpm, and the best efficiency occurred at a low fuel rate. However, the fuel range of operation was made at specifics all below 2.90. This modification produced less thrust per unit area of tailpipe than did the modification of similar shape but smaller tailpipe size.

86. Design and Performance - Modification Y. It was next decided to investigate the possibilities of operating a pulse jet with a 12-inch diameter tailpipe. Therefore, Modification Y was constructed from two conical sections; one 12" to 16", 18" long, and the other 16" to 12", 18" long. Head No. 9, 104 vanes, with fuel jets mounted from the side of the venturi at an angle of 135° with the axis of the air flow, was used with a 12-inch diameter tailpipe, 144" long. Design details and performance curves are not included in this report since this modification did not operate satisfactorily. This unsatisfactory operation was attributed to poor distribution of fuel. Investigations were discontinued because the maximum fuel rate indicated by the rotameter was too low for complete study of this large tube.

87. Summary - Similar Combustion Chambers Modifications A, J, K, and L. Although Modifications A, J, K, and L were composed of similarly shaped combustion chambers and exhibited a few common operating characteristics, there was little similarity in shape of the performance curves. The performance curves and design details may be found in Figs. 12, 13, and 14; 48 and 49; 50, 51, and 52 respectively. As illustrated by Fig. 82, all of the combustion chambers used reducer sections only. In general, this group of combustion chambers was charac-

DECLASSIFIED

DECLASSIFIED

terized by unstable operation in the higher fuel range, by high frequency of operation, by low thrust, and by high specific fuel over the entire fuel range. At the point of spontaneous cut-off, the thrust was still rising with increased fuel rate. In the lower fuel ranges all modifications ran smoothly but produced low thrust. As the fuel rate was increased on each test, thrust increased rapidly as the "crack-over" point was approached. As indicated in paragraph 33, the term crack-over point designates a changed mode of burning characterized by a rapid increase in thrust for a small increase in fuel rate. In these modifications, operation at or above the crack-over point was unstable and resulted in "surging" or an alternation between operation below crack-over and a operation above crack-over. A possible explanation is that during the short periods of crack-over, the combustion-chamber pressure increased to a value which retarded fuel flow. This momentary decrease in the fuel flow caused the engine to return to a few cycles of normal operation with lower combustion-chamber pressures. Then, the lower combustion chamber pressures permitted the fuel rate to be re-established at the higher value and the engine continued to alternate between the two modes of operation. A check valve in the fuel line did not eliminate this surging. If, at this point, an attempt was made to force the fuel rate above the critical value, the engine choked and ceased to operate. No indications of conventional choking due to an over-rich fuel mixture (an increase of smoke and flame at the tail, lowered frequency, or softer pulsations) were observed. In particular, Modification A, 108" tailpipe, and 40 vanes illustrated in Fig. 13, shows very unusual performance curves which have large values of slope at the point where the engine ceased to operate. This is in contrast to the normal thrust curve of the conventional pulse jet which exhibits a rather constant value of slope until near the point of maximum thrust, after which the thrust decreases and the tube finally chokes out because of an over-rich fuel-air mixture. Although the minimum specific fuel attained with Modification A was 3.26, it is obvious that if operation could be stabilized at higher fuel rates and the same values of slope maintained, a very low specific fuel could be secured.

88. Summary - Similar Combustion Chambers Modifications E, F, and I. As illustrated in Fig. 82, Modifications E, F, and I were of similar shape and for this reason will be discussed in one group. Each had one enlarger section and one reducer section with the latter approximately twice as long as the former. From the performance curves, it can be seen that maximum thrust on Modifications E and F was obtained with 104-vane grid assemblies. In general, however, the best results were obtained from the 88-vane grid assembly on Modification E, and the best over-all results from the 104-vane grid assembly on Modification F. A 72-vane grid assembly gave the best performance on Modification I. Apparently, there is some relation between the number of vanes and the size of combustion chamber. It would seem logical that the larger combustion chambers would require a larger amount of air-fuel mixture to operate properly. This would, in turn, necessitate a larger grid assembly. Modification E was characterized by more stable operation than Modifications F or I. These modifications produced rather high thrusts but the efficiencies obtained were, in general, poor. The only test runs with resulting specifics of less than 3.0 were obtained on Modification E. This modification produced a specific of 2.65.

DECLASSIFIED

DECLASSIFIED

89. Summary - Similar Combustion Chambers Modifications D and T. Design details and performance curves for Modifications D and T may be found in Figs. 23, 24, 25, 26, and 27; and 65 and 66, respectively. These combustion chambers were of similar shape with an enlarger about twice as long as the reducer. This can be observed in Fig. 82. Both combustion chambers were characterized by stable combustion for the various combinations of tailpipe lengths and grid assemblies. This is evidenced by the fact that all performance curves are comparatively flat with a wide operating fuel range in the vicinity of minimum specific fuel and maximum thrust. Maximum thrust was obtained with the longest tailpipe length tested on each combustion chamber. Modification D produced a maximum thrust of 190 pounds with an 88-vane grid assembly, and Modification T a maximum thrust of 220 pounds with a 104-vane grid assembly. These were the maximum number of vanes used on each combustion chamber. Both combustion chambers gave approximately the same value of thrust per vane at maximum thrust - 2.16 pounds for Modification D, and 2.11 pounds for Modification T. There were some differences in performance characteristics. For Modification D, each tailpipe length showed a maximum thrust with the 88-vane grid assembly. Modification T produced a minimum specific fuel with a 72-vane grid assembly for each tailpipe length. The value of 2.47 specific fuel, obtained with the combination of the 144" tailpipe and 72 vanes on Modification T, is the lowest value found in this investigation with internal fuel injection.

90. Summary - Similar Combustion Chamber Modifications B, C, G, H, U, and Y. As illustrated in Fig. 82 Modifications B, C, G, H, U, and Y are of similar shape. Each has one enlarger and one reducer section connected at the large ends. In each case the enlarger is the same length as the reducer. Despite the similarity in shape, there are differences in the entrance and exit relationships. For this reason, Modifications B, C, H, and Y will be discussed as one group, and Modifications U and G will be discussed as another. Modifications B, C, H, and Y were composed of identical conical sections used ad reducers and enlargers. Modification Y did not operate satisfactorily, probably as a result of inadequate fuel distribution. Investigations on Modification Y were discontinued because the maximum fuel rate which could be indicated by the rotameter was too low for complete study of this large engine. All of the performance curves of Modification B, C, and H had similar shapes with maximum thrust occurring at a fuel rate slightly higher than that for minimum specific. In general, the minimum specific occurred at approximately the middle of the operational fuel range. These modifications were characterized by rather stable operation and could be run with a rich mixture. This is evidenced by the curves, which indicate that the thrust rose and then fell slightly as the fuel rate was further increased, whereas, some of the engines which were less stable in operation - such as Modifications A, J, K, or L - stopped running with a rich mixture.

91. Modifications G and U differed slightly in general contour from Modifications B, C, and H. In the latter, the entrance and exit diameters of the combustion chamber were the same; 8" in the case of Modifications B and C, and 6" in the case of Modification H. On the

DECLASSIFIED

DECLASSIFIED

other hand, Modifications G and Y had different entrance and exit diameters. As indicated by Figs. 38, 39, 40, 41, and 67 the entrance diameter was 12" for both modifications whereas, the exit diameter was 8" in the case of Modification G and 10" on Modification U. This difference in entrance and exit diameters in Modification G and U may have accounted for the slight instability of operation. For Modification G, the shorter tailpipe lengths gave maximum efficiency at fuel rates near the point of maximum thrust. The performance curves show that with the longer tailpipe lengths - 120" and 132" - the points of maximum thrust and maximum efficiency occurred at widely separated points in the fuel range. In addition, these curves more nearly resemble those for Modifications B, C, and H. Modification U was only partially investigated because of the limited capacity of the available rotameter. However, present data seem to show that Modifications G and U gave less stable operation than Modifications B, C, and H.

92. Summary - Similar Combustion Chambers Modifications M, P, Q, R, and V. As can be seen in Fig. 82, the exit from the combustion chambers of Modifications M, P, Q, R, and V have low flow coefficients since they were designed as divergent combustion chambers with $\mathcal{E} = 90^{\circ}$. The performance curves and design details may be found in Figs. 53, 54, 55; 56; 57, 58, 59, 60, 61, 62, 63; 64; and 67 respectively. With the exception of Modification V, all of these combustion chambers use enlarger sections only. In addition, Modification V, which has a straight section, will be discussed in this group because of the low flow coefficient of the exit from the combustion chamber. Combustion chambers of Modifications M, P, and R were shorter than those of either Modification Q or V. The first three modifications were characterized by unstable combustion in contrast with the more stable operation of Modifications Q and V. The performance curves illustrate this fact since they have rather high values of slope, as compared with those for Modification Q. This instability may be due to the shorter length of combustion chamber. Modifications M, P, and R gave maximum efficiency at a higher fuel rate for a greater number of vanes with any given tailpipe length. Likewise, with any given tailpipe length, maximun thrust was produced at a higher fuel rate for each greater number of vanes. These trends seem reasonable, and have been found in other combustion chambers reported by this research, specifically, Modification H. These modifications were further characterized by short operating fuel ranges near the point of maximum efficiency. In contrast to Modifications M, P, and R, Modification Q was characterized by stable operation as indicated by the flat performance curves. In addition, maximum thrust was produced with good efficiency and the range of efficient operation was greater than that for Modifications M, P, and R. Modification Q was also characterized by short frequency range of operation. On the shorter lengths (96", 108", and 120") of 8-inch tailpipe, an increase in the number of vanes in the grid assembly increased the maximum thrust. This follows trends observed for other modifications. On the longer tailpipes (132" and 144") a complete reversal of this characteristic was observed; i.e., an increase in the number of vanes decreased the maximum thrust and the efficiency with either tailpipe length. On the 10-inch tailpipe, with 108" and 144" lengths, maximun thrust was obtained with an 99-vane grid assembly. This confirms the previous ob-

DECLASSIFIED

DECLASSIFIED

servation that there is an optimum number of vanes for any given engine. Also, in Modification M with the 64-vane grid assembly a thrust of 145 pounds was obtained with the 120" tailpipe. Maximum thrusts of 105 and 112 pounds were obtained on the 96" and 141" tailpipe, respectively. This confirms the fact that there is an optimum length of tailpipe for any given combination of combustion chamber and grid assembly.

93. Comparison of Reversed Combustion Chambers. Modifications D and E. Modifications D and E were the same in construction, but were used with different orientation. Only tests made with engines operated under identical conditions will be compared in this section. This will eliminate any differences in grid assemblies or tailpipe lengths. The 141" tailpipe on Modification D will however, be compared with the 144" tailpipe on Modification E. Eleven sets of test runs will be discussed in this comparison for five lengths of tailpipe with either two or three different heads on each length tailpipe. Of these eleven test runs, Modification E produced the greatest thrust on nine runs. Modification D produced the greatest thrust on one, and both modifications produced the same thrust on one. Modification E produced the lowest value of specific fuel on eight of the eleven test runs. Modification E operated in higher frequency ranges than did Modification D. This was true in every test, and, although the exact frequency range of each engine was not determined, each test included the points of maximum efficiency and maximum thrust. From the foregoing statements, it can be seen that Modification E gave the best overall performance. The reversal of the combustion chamber in Modification D (to form Modification E) produced, in general, greater thrust, better efficiency, and higher frequency of operation.

94. Comparison of Reversed Combustion Chambers Modifications K and M. As far as construction is concerned, Modifications K and M were the same. The difference was in the orientation of the two combustion chambers. Modification K used the conical section as a reducer and Modification M used the conical section as an enlarger. In the comparison of Modifications K and M, only the 120" tailpipe with Head No. 2, 48 vanes, will be discussed since this was the only combination of tailpipe length and head assembly tested with both combustion chambers. Modification M gave about 6% more maximum thrust. The big difference in performance characteristics however, was noted in the minimum specific fuel values. Modification M produced a minimum specific of 2.94 as compared with 3.87 for Modification K. This increase of 31.6 percent is, of course, greater than experimental error or control factors can explain. Modification M operated between 2480 and 3180 cpm and Modification K operated between 2980 and 3500 cpm for the corresponding fuel range. Apparently more turbulence was present in Modification M during the entire cycle. This increased turbulence was probably due to the low flow coefficient of the combustion chamber exit. This would facilitate better air and fuel mixing which could give added efficiency of operation. Also the reflection of a shock wave from the adaptor plate in Modification M opposed the flow of the gas from the combustion chamber and momentarily raised the combustion pressure. In conclusion the reversal of the combustion chamber from Modification K to Modification M, increased the efficiency by about 31 percent and the thrust by approximately 6 percent, but decreased the operating frequency approximately 14 percent.

DECLASSIFIED

DECLASSIFIED

95. Summary of Nonoperating Combustion Chambers Modification N, O, and S. As illustrated in Fig. 81 Modifications N, O, and S were tried with the specific idea of protecting the charge from immediate contact with the retained gases. One advantage might be that a greater volume of charge could be inducted into the chamber prior to ignition. Then very rapid burning or detonation would occur in the cylindrical charge which would be compressed by the initial combustion of the advanced portions of the charge in the combustion chamber. Modification O, a combination of Modifications A and M, is illustrated by Fig. 81. This engine ran with an odd pulsating sound, and the thrust scale oscillated so that readings were difficult to obtain. The vibrometer indicated a double frequency of 2100 and 2500 cycles per minute simultaneously. A possible explanation is that ignition occurred for several cycles in one chamber and then for several cycles in the other. The first chamber was similar to that of Modification A, a chamber of relatively high operating frequency. The second chamber was similar to that of Modification M, which had a lower operating frequency. It seems plausible to assume that burning may not have proceeded rapidly, and that the reduced exhaust velocity then produced a lowered intake velocity which allowed the flame to turn back into chamber "A" after one or more cycles. Then the process was repeated. The straight forms, Modifications N and S, operated with the same characteristics of low frequency, low thrust, and considerable smoke and flame at the end of the tailpipe. The ducts on the combustion chambers remained relatively cool throughout the tests. Complete oscillographic analysis is at present reserved for more promising forms.

VII. PEAK PERFORMANCE

96. In order to give a clear picture of the progress of this research on the pulse jet engine, the bar-graph system of illustration has been adopted. This graphic presentation gives all the identifying information for each configuration. It is possible to note simultaneously peak performance expressed by maximum thrust and by minimum specific fuel. In addition, the complete frequency range of operation is indicated.

97. Many important trends of the problem progress are shown graphically. These include the fact that research into various combinations of tailpipe length, tailpipe diameter, combustion chamber, and head assembly gradually resulted in the improvement of the operating characteristics. To the research group the bar-graph served as a filtering device by which the inefficient and low-thrust designs could be easily detected. By the same method, it was also possible to select the engines which were more efficient and those which produced greater output. Hence, this research and development has been guided by graphic representation of results.

98. The peak performance graphs will be discussed in three groups: 6-inch-diameter tailpipe, 8-inch-diameter tailpipe, and 10-inch-diameter tailpipe. However, throughout the rest of this report, the word "diameter" will be dropped, and each will then be referred to as a 6, 8, or 10-inch tailpipe.

DECLASSIFIED

DECLASSIFIED

99. Figs. 77, 78, 79, and 80, illustrate graphically the peak performance of the various modifications in terms of output and efficiency. Peak output is recorded as the maximum thrust in pounds. Best efficiency is expressed as minimum specific fuel in pounds of fuel per hour per pound of thrust.

100. In general, the best efficiency and the maximum output occurred at different fuel rates. The engines used in all tests, the results of which are illustrated here, were of nonstandard configuration. Standard tubes are illustrated by Figs. 69, 70, 71, 72, 73, and 74. A total of twenty combustion chambers, six tailpipe lengths, three tailpipe diameters, and nine head assemblies used in various combinations are reported upon here. These figures also illustrate graphically the frequency range, expressed in cycles per minute, in which each configuration operated; the higher frequencies corresponding to the lower fuel rates.

101. Six-Inch Tailpipe. Fig. 77 depicts the best results obtained from various configurations using 6-inch tailpipes. A total of four combustion chambers, five tailpipe lengths, and five head assemblies were used in various combinations. Figures 42 through 47 and 51 through 54 give the design details and complete performance curves.

102. Modification H gave the best overall performance on the basis of output and relative efficiency. Modification I, produced the highest thrust for any 6-inch tailpipe, a maximum of 135 pounds. For these tests the greatest maximum thrust was obtained by using the largest number of vanes. With one exception, the head assembly with 56 vanes gave the best efficiency and the highest thrust. This exception was Modification I, which produced its peak thrust of 135 pounds and a specific fuel of 3.12 with 72 vanes. Frequency range for all runs producing 100 pounds thrust, or more, was between 1700 and 2600 cycles per minute. In all cases, the higher thrust values were obtained at the lower frequencies. Frequencies at which each modification operated to produce maximum thrust, regardless of the number of vanes are given in Table 8.

Table 8

Frequency Ranges for Maximum Thrust
Six-Inch Tailpipe

Tailpipe Length (Inches)	Frequency Range (CPM)
96	2100 to 2300
108	2100 to 2300
120	2000 to 2100
132	1825 to 2000
144	1825 to 2000

DECLASSIFIED

DECLASSIFIED

Frequencies at which each modification operated to produce minimum specific fuel value regardless of the number of vanes are given in Table 9.

Table 9

Frequency Ranges for Minimum Specific Fuel
Six-Inch Tailpipe

Tailpipe Length (Inches)	Frequency Range (CPM)
96	2100 to 2550
108	2100 to 2550
120	2090 to 2280
132	1950 to 2100
144	1950 to 2100

103. Eight-Inch Tailpipe. Figs. 78, 79, and part of Fig. 80, depict the best results obtained from the various configurations with 8-inch tailpipes. A total of thirteen combustion chambers, six tailpipe lengths, and seven head assemblies were used. Incidentally, two-thirds of all the data reported herewith cover 8-inch tailpipe performance. Figs. 12 through 41, 48 through 50, 55 through 61, and 64, show the design details and complete performance curves.

104. Modification Q was the best performing engine both in power output and in relative efficiency. Figs. 57 through 61, show the complete operating curves. Modification Q gave the highest thrust value of 208 pounds, followed closely by Modifications F and E with 204 pounds and 206 pounds respectively. Modification Q gave the lowest minimum specific fuel value of 2.59. Modification A was the poorest of all performers, never producing over 100 pounds thrust with specific fuel values ranging as high as 9.9. In general, an increase in the number of vanes produced a higher maximum thrust. Head No. 5 with 72 vanes produced the highest thrust and best efficiency in two cases with the Modification Q combustion chamber. As expected, the longest tailpipe produced highest thrust values and lowest frequencies. High thrust values were attained at the lower end of the frequency range. Configurations having comparatively low combustion-chamber-to-tailpipe-volume ratios operated inefficiently in respect to both power output and efficiency.

105. Ten-Inch Tailpipe. Fig. 80 depicts the best results obtained from the various configurations using 10-inch diameter tailpipes. A total of five combustion chambers, two tailpipe lengths, and four head assemblies were used. Fig. 65 through 68 show the design details and complete performance curves. Modification U and Modification V produced the highest thrust values attained in this research. In both cases the thrust was 270 pounds. Modification T and Modification Q produced the two lowest minimum-specific-fuel values of 2.47 and 2.48 respectively.

CONFIDENTIAL

DECLASSIFIED

DECLASSIFIED

All of these values were obtained with a tailpipe 144" in length. As in the case of the 6- and 8-inch tailpipe, the peak thrusts of a 10-inch tailpipe were attained at the lower end of the frequency range. All modifications with a 10-inch tailpipe attained at least one value of specific fuel below 3.00. For most of the modifications having a 10-inch tailpipe, specific fuel values below 3.00 were secured throughout the entire fuel range. The 10-inch tailpipe produced the highest thrust of the pulse jet engines tested. Other than in the Supplementary Experimentation Group, the best efficiency of the pulse jet engines tested was obtained on a 10-inch tailpipe. Because of this improvement in efficiency, a statistical table (Table 10) showing the distribution of the 90 specific fuel values between 2.40 and 3.00 was compiled.

Table 10

Distribution of Specific Fuel Values
Ten-Inch Tailpipe

Specific Fuel	Number of Readings
2.40 to 2.49	5
2.50 to 2.59	9
2.60 to 2.69	16
2.70 to 2.79	18
2.80 to 2.89	28
2.90 to 2.99	14

The fact that thirty values were below 2.70 indicates that the particular modifications tested were comparatively efficient for all variations in length of tailpipe and in number of vanes. In addition, the table shows that these modifications exhibited flat efficiency curves, i.e., are efficient for a wide fuel range.

106. Specific Fuel Comparison Tables. Relative efficiency values of the various engine modifications are shown on Tables 11, 12, 13, and 14 below. Values of specific fuel were calculated after the completion of each run. As stated in paragraph 8, specific fuel is the number of pounds of fuel per hour required to produce one pound of thrust. These readings represent the total number of thrust measurements recorded at the various fuel rates in one particular run. Specific fuel values were divided into two groups, the number of readings below 3.00 and the number of readings above 3.00. This was done in order to show the progressive improvement in relative efficiency with larger diameter of tailpipe.

107. The fuel rate range covers or includes that period of engine operation during which the thrust and fuel rates were observed and recorded. "Minimum" and "Maximum" fuel rates as listed in the tables do not necessarily represent the limits (continued on page 40.)

DECLASSIFIED

DECLASSIFIED

TABLE II

SPECIFIC FUEL COMPARISON TABLE

MODIFICATION NUMBER	TAILPIPE DIAMETER (INCHES)	TAILPIPE LENGTH (INCHES)	NUMBER OF VANES	FUEL RATE POUNDS PER HOUR			SPECIFIC FUEL READINGS LBS. FUEL / HOUR / LB. THRUST			THRUST POUNDS	
				MIN. FUEL RATE	MAX. FUEL RATE	FUEL RATE RANGE	NUMBER OF READINGS BELOW 3.00	NUMBER OF READINGS ABOVE 3.00	TOTAL NUMBER OF READINGS	THRUST READING AT MIN. FUEL RATE	THRUST READING AT MAX. FUEL RATE
I	6	144	72	346	403	57	0	3	3	100	126
H	"	"	56	250	394	144	1	5	6	66	123
H	"	"	64	326	480	154	0	5	5	58	118
H	"	132	64	355	504	149	0	5	5	80	116
H	"	108	64	346	480	134	0	6	6	78	116
H	"	120	64	326	451	125	0	6	6	76	115
H	"	132	40	177	307	130	0	7	7	30	82
H	"	"	56	269	451	182	0	6	6	81	108
M	"	144	64	350	400	50	0	2	2	102	112
H	"	108	56	317	403	86	0	4	4	90	108
-											-
H	6	96	64	355	485	130	0	4	4	70	108
M	"	"	"	312	384	72	0	3	3	84	105
H	"	144	48	192	403	211	0	9	9	40	105
H	"	96	56	269	427	158	0	6	6	60	100
L	"	144	56	278	384	106	0	6	6	50	104
H	"	120	56	269	394	125	0	6	6	68	108
H	"	132	48	182	384	202	0	8	8	28	93
H	"	120	48	177	393	216	0	10	10	27	88
L	"	108	48	202	374	172	0	8	8	42	88
H	"	144	40	177	278	101	0	5	5	38	86
-											-
M	6	96	48	202	355	153	0	7	7	44	80
L	"	144	48	192	365	173	0	8	8	44	85
I	"	"	48	211	346	135	0	4	4	54	88
M	"	144	40	163	250	87	0	5	5	36	82
H	"	108	48	202	384	182	0	7	7	38	80
H	"	120	40	177	307	130	0	6	6	34	80
H	"	96	48	182	350	168	0	8	8	29	77
H	"	96	40	187	264	71	0	4	4	48	76
L	"	108	40	187	302	115	0	6	6	42	76
M	"	96	40	182	269	87	0	5	5	50	75
H	"	108	40	177	289	121	0	6	6	40	74
L	"	144	40	192	298	106	0	5	5	42	71
-											-
A	8	141	72	365	528	163	0	5	5	30	62
A	"	141	80	470	518	48	0	4	4	70	96
A	"	108	40	197	275	78	0	5	5	40	84
A	"	108	48	240	384	144	0	4	4	46	64
A	"	120	72	432	494	62	0	3	3	40	50
B	"	141	72	538	614	76	0	3	3	170	180
B	"	132	72	403	604	201	5	3	8	90	182
B	"	132	88	422	576	154	0	5	5	110	175
B	"	120	72	451	576	125	6	1	7	158	186
B	"	120	88	403	576	173	0	6	6	92	177
B	"	96	72	451	605	154	0	8	8	118	180
B	"	96	88	461	635	174	0	7	7	140	195

DECLASSIFIED

DECLASSIFIED

TABLE 12

SPECIFIC FUEL COMPARISON TABLE

MODIFICATION NUMBER	TAILPIPE DIAMETER (INCHES)	TAILPIPE LENGTH (INCHES)	NUMBER OF VANES	FUEL RATE POUNDS PER HOUR			SPECIFIC FUEL READINGS LBS. FUEL / HOUR / LB. THRUST			THRUST POUNDS	
				MIN. FUEL RATE	MAX. FUEL RATE	FUEL RATE RANGE	NUMBER OF READINGS BELOW 3.00	NUMBER OF READINGS ABOVE 3.00	TOTAL NUMBER OF READINGS	THRUST READING AT MIN. FUEL RATE	THRUST READING AT MAX. FUEL RATE
C	8	96	72	442	624	182	0	6	6	128	145
C	"	96	88	442	662	220	0	7	7	115	170
C	"	108	48	240	389	149	0	5	5	62	100
C	"	108	72	398	653	255	0	9	9	88	180
C	"	108	88	413	720	307	0	9	9	104	185
C	"	120	48	269	413	144	0	5	5	50	85
C	"	120	72	427	653	226	3	5	8	134	180
C	"	120	88	403	634	231	0	9	9	122	190
C	"	132	48	317	355	38	0	3	3	78	96
C	"	132	72	394	634	240	6	3	9	116	190
C	"	132	88	413	653	240	3	6	9	128	195
C	"	141	48	298	413	115	0	5	5	83	104
C	"	141	72	346	576	230	5	5	10	93	185
C	"	141	88	394	624	230	2	7	9	105	195
-											-
D	8	96	88	442	662	220	0	7	7	115	170
D	"	96	72	442	624	182	0	6	6	128	145
D	"	108	88	422	672	250	0	6	6	108	180
D	"	108	72	394	624	230	0	8	8	52	160
D	"	120	48	278	374	96	0	4	4	48	68
D	"	120	72	413	595	182	2	4	6	140	160
D	"	120	88	422	643	221	0	7	7	132	172
D	"	132	88	418	677	259	3	6	9	135	190
D	"	132	72	403	595	192	1	4	5	135	155
D	"	141	72	422	672	250	1	7	8	144	165
D	"	141	88	451	672	221	4	4	8	162	188
-											-
E	8	144	72	389	557	168	1	6	7	126	162
E	"	144	88	432	605	173	2	5	7	150	199
E	"	144	104	432	624	192	7	1	8	170	204
E	"	96	72	394	653	259	0	8	8	68	165
E	"	96	88	432	576	144	0	5	5	125	170
E	"	120	88	413	672	259	1	7	8	130	180
E	"	120	72	355	624	269	0	9	9	47	160
E	"	120	48	264	418	154	0	5	5	63	83
E	"	132	72	384	586	202	1	6	7	116	170
E	"	132	88	413	691	278	6	4	10	150	204
E	"	132	104	538	710	172	0	4	4	115	180
E	"	108	48	240	341	101	0	4	4	56	88
E	"	108	72	394	624	230	0	7	7	74	170
E	"	108	88	413	701	288	0	8	8	122	187
-											-
F	8	96	72	413	576	163	0	6	6	84	150
F	"	96	88	451	614	163	0	6	6	100	172
F	"	120	72	480	586	106	0	4	4	136	145
F	"	120	88	461	614	153	0	5	5	130	178

DECLASSIFIED

DECLASSIFIED

TABLE 13

SPECIFIC FUEL COMPARISON TABLE

MODIFICATION NUMBER	TAILPIPE DIAMETER (INCHES)	TAILPIPE LENGTH (INCHES)	NUMBER OF VANES	FUEL RATE POUNDS PER HOUR			SPECIFIC FUEL READINGS LBS. FUEL / HOUR / LB. THRUST			THRUST POUNDS	
				MIN. FUEL RATE	MAX. FUEL RATE	FUEL RATE RANGE	NUMBER OF READINGS BELOW 3.00	NUMBER OF READINGS ABOVE 3.00	TOTAL NUMBER OF READINGS	THRUST READING AT MIN. FUEL RATE	THRUST READING AT MAX. FUEL RATE
E	8	132	72	418	557	139	0	5	5	120	171
E	"	132	88	432	634	202	2	7	9	110	204
E	"	132	104	528	643	115	0	5	5	140	206
F	"	108	48	259	346	87	0	4	4	63	94
F	"	108	72	432	605	173	0	7	7	80	158
F	"	108	88	432	634	202	0	6	6	82	172
I											-
G	8	96	88	424	605	181	0	7	7	100	175
G	"	96	72	432	576	144	0	6	6	94	172
G	"	108	48	240	379	139	0	6	6	44	100
G	"	108	72	442	610	168	0	6	6	93	170
G	"	108	88	422	643	221	0	7	7	100	190
G	"	120	48	264	384	120	0	4	4	30	82
G	"	120	72	398	605	207	0	8	8	70	165
G	"	120	88	422	624	202	0	8	8	123	173
G	"	132	72	403	586	183	3	3	6	70	186
G	"	132	88	432	624	192	1	5	6	139	193
I											-
J	8	96	40	192	259	67	0	4	4	44	73
J	"	108	40	202	336	134	0	6	6	53	87
J	"	108	48	245	422	177	0	8	8	56	108
J	"	120	40	202	250	48	0	4	4	47	74
K	"	120	40	182	250	68	0	4	4	47	75
K	"	120	48	201	389	188	0	10	10	48	100
M	"	120	48	192	384	192	1	8	9	42	103
M	"	120	64	355	490	135	0	5	5	92	145
P	"	120	64	360	480	120	2	3	5	112	152
P	"	120	72	360	514	154	3	2	5	87	176
P	"	120	88	403	528	125	1	5	6	118	172
I											-
Q	8	96	88	494	624	130	0	6	6	153	180
Q	"	96	104	480	662	182	0	7	7	157	188
Q	"	108	72	398	672	274	4	7	11	105	180
Q	"	108	88	442	643	201	0	8	8	135	193
Q	"	108	104	432	682	250	5	4	9	150	195
Q	"	120	72	384	576	192	1	5	6	104	158
Q	"	120	88	365	614	249	6	4	10	110	180
Q	"	120	104	442	610	168	4	2	6	154	194
Q	"	132	72	413	605	192	1	8	9	155	190
Q	"	132	88	437	614	177	5	2	7	158	191
Q	"	132	104	422	629	207	5	5	10	140	188
Q	"	144	72	384	653	269	11	3	14	126	208
Q	"	144	104	432	624	192	0	7	7	144	177
R	"	144	88	432	576	144	8	0	8	154	197
R	"	120	72	379	557	178	1	5	6	100	158
R	"	120	88	365	614	249	0	8	8	76	160

DECLASSIFIED

DECLASSIFIED

TABLE 14

SPECIFIC FUEL COMPARISON TABLE

MODIFICATION NUMBER	TAILPIPE DIAMETER (INCHES)	TAILPIPE LENGTH (INCHES)	NUMBER OF VANES	FUEL RATE POUNDS PER HOUR			SPECIFIC FUEL READINGS LBS. FUEL / HOUR / LB. THRUST			THRUST POUNDS	
				MIN. FUEL RATE	MAX. FUEL RATE	FUEL RATE RANGE	NUMBER OF READINGS BELOW 3.00	NUMBER OF READINGS ABOVE 3.00	TOTAL NUMBER OF READINGS	THRUST READINGS AT MIN. FUEL RATE	THRUST READING AT MAX. FUEL RATE
Q	10	144	72	408	557	149	8	0	8	150	212
Q	"	144	88	422	634	212	9	0	9	152	215
Q	"	144	104	461	624	163	3	2	5	156	192
Q	"	108	72	408	624	216	4	4	8	110	196
Q	"	108	88	461	605	144	6	1	7	152	206
Q	"	108	104	422	677	255	5	4	9	150	195
T	10	108	72	432	614	182	5	2	7	158	195
T	"	108	88	422	624	202	7	1	8	120	210
T	"	108	104	442	672	230	5	4	9	158	198
T	"	144	72	379	576	197	10	0	10	144	203
T	"	144	88	422	672	250	8	1	9	156	215
T	"	144	104	432	701	269	4	5	9	154	220
U	"	144	104	720	739	19	3	0	3	260	270
V	10	144	104	538	720	182	7	1	8	155	270
X	"	144	72	509	586	77	1	3	4	165	180
X	"	144	104	590	720	130	5	0	5	225	255

DECLASSIFIED

DECLASSIFIED

(paragraph 107 continued from page 35)

of engine operation. In some cases the thrust reading was irregular at lower fuel rates. It was therefore necessary to increase the fuel flow until a stable thrust reading of plus or minus 3 pounds could be made. This fuel rate was recorded as the minimum fuel rate.

108. The maximum fuel rate represents the condition of maximum thrust so that further increase in fuel flow produced a decrease in thrust. It should therefore be noted that the maximum thrusts as illustrated in the bar graphs Figs. 77, 78, 79, and 80 do not correspond to the thrust readings at maximum fuel rates as listed in preceding Tables 11, 12, 13, and 14 on pages 36, 37, 38, and 39 respectively.

VIII. PERFORMANCE COEFFICIENTS AND TRENDS

109. Coefficients of Specific Fuel. The use of specific fuel as a coefficient of performance has already been discussed in paragraphs 8, 9, and 10. The comparative ratings of the various combustion chambers are set forth in Table 15 below on page 41. Modification Q, with twenty-one runs in various combinations, appears eleven times within the list of the best twenty-four. Modification T, which appeared in various combinations six times, appears on the list five times. Modification X, in two combinations, appears once. Modification V, in one combination, appears once. Modification E, tested in eight combinations, appears twice. Modification U, tried in five combinations, appears once. Modification D, tried in ten combinations, appears once. Modification B, tried in ten combinations, appears once. There are twenty-four tube combinations whose specific fuel consumption is 2.85 or under. If the results of external fuel experiments are included, there are four combinations with specific fuel values between 2.35 and 2.52. It is interesting to compare these results with Table 1, Ref. (2), which summarizes performance of a number of pulse jets. The best specific listed in this table is 3.00. Therefore, the present NRL research has resulted in a decided increase in pulse jet efficiency.

110. Coefficient of Thrust per Unit Maximum Cross-Sectional of Tube. The coefficient of thrust per unit maximum section is obtained by dividing the maximum thrust by the area of the maximum cross section perpendicular to the axis of the tube. The unit of the coefficient is pounds of thrust per square foot. The coefficient of thrust per unit maximum cross section at minimum specific fuel, i.e., at best efficiency, is another important factor of engine performance. It is desirable that the fuel rate for maximum thrust coincide with the fuel rate for best efficiency. It is important to note that the statically determined value of the coefficient of thrust per maximum cross-sectional area is not necessarily a valid basis for the prediction of flight characteristics. This coefficient indicates qualitatively the velocity possibilities of a given engine only if the gross thrust is a uniform function of velocity irrespective of the tube parameters. Since this is generally not the case, it is suggested that this particular coefficient is hardly a just method of rating pulse (continued on page 42)

DECLASSIFIED

DECLASSIFIED

TABLE 15

COMPARISON CHART

ORDER OF MINIMUM SPECIFIC FUEL

ORDER NO.	SPECIFIC FUEL POUNDS FUEL PER HOUR PER POUND THRUST	COMBUSTION CHAMBER TYPE	NUMBER OF VANES	TAILPIPE DIMENSIONS (inches)	
				DIAMETER	LENGTH
1.	2.47	Mod T	72	10	144
2.	2.48	Mod Q	72	10	144
3.	2.52	Mod X	104	10	144
4.	2.58	Mod T	88	10	144
5.	2.59	Mod Q	72	8	144
6.	2.60	Mod V	104	10	144
7.	2.63	Mod Q	72	8	132
8.	2.65	Mod E	88	8	132
9.	2.67	Mod Q	88	10	144
10.	2.69	Mod Q	88	8	144
11.	2.73	Mod U	104	10	144
12.	2.73	Mod T	72	10	108
13.	2.74	Mod Q	88	8	132
14.	2.74	Mod E	88	8	141
15.	2.75	Mod B	72	8	120
16.	2.75	Mod Q	88	10	108
17.	2.79	Mod D	88	8	141
18.	2.80	Mod Q	104	8	108
19.	2.80	Mod T	104	10	144
20.	2.82	Mod P	72	8	120
21.	2.82	Mod Q	72	10	108
22.	2.82	Mod T	88	10	108
23.	2.83	Mod Q	104	10	108
24.	2.85	Mod Q	104	8	120
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
61.	3.07	STANDARD TUBE SPIRAL WELD TAILPIPE	88	8	88

DECLASSIFIED

DECLASSIFIED

(paragraph 110 continued from page 40)

jet engines. In addition, it should be noted that this coefficient has been used to charge pulse jet engines with the aerodynamic drag which they would produce although customarily other aircraft engines are not so charged. Therefore, for present applications greater emphasis should be placed upon securing better efficiency even at a sacrifice of thrust per maximum cross-sectional area.

111. The standard combustion chamber with the spiral-weld tailpipe (N.B., the smooth standard model was not compared) heads the list on Table 16 below (page 43) with 201.5 pounds of thrust per square foot of cross-sectional area at a specific fuel of 3.34. Modifications U, V, and X (all 10-inch tailpipe modifications) gave 194 to 183 pounds of thrust per square foot of maximum cross section, at much lower specific fuel rates. The values were 2.67 to 3.00. Hence, an increase of 0.67 pounds of fuel per pound of thrust per hour produced only 7.5 pounds additional thrust per square foot of maximum diameter in the less efficient standard chamber. Six runs of Modification B appear next in line. There are five runs of Modification T listed (orders 12 to 25). When these are compared to the three runs of Modification Q with the 10-inch tailpipe, they show higher specific fuel at maximum thrust. Modification Q gave 152 pounds per square foot at 2.62 while Modification T gave 157 pounds per square foot at a specific of 3.22 and 151 pounds per square foot at a specific of 2.98. Other modifications appearing on the listing are F and E which failed to give desirable specifics at high outputs.

112. Coefficient of Thrust per Unit of Tube Surface. The coefficient of thrust per unit area of tube surface is very important from a weight standpoint. This coefficient is obtained by dividing the maximum thrust by the total surface area of the tube. The units are pounds per square foot. The total tube weight will be the product of the surface area by the weight per square foot. Suppose that an engine tube produces a thrust of 7 pounds per square foot of surface and that the engine thrust is directed vertically. If it can be constructed from material weighing one pound per square foot, there will be about six pounds per square foot of useful lift. The gross load must include fuel, head assembly, and control system as well as payload. Therefore, this coefficient is of great importance if the pulse jet engine is to be used in aircraft or flying missiles.

113. The listing of the top twenty-five combinations on Table 17 below (page 44) shows that Modification B heads the list with 7.81 pounds per square foot of surface and also appears four times out of the seven combinations which were tried. Modification B, with 72 vanes and an 8" by 120" tailpipe, gives good performance - 6.47 pounds of thrust per square foot at 2.75 minimum specific fuel. Modification Q appears next with a thrust of 7.03 pounds per square foot of surface but in one of its less efficient forms. Modification Q appears eight times out of fifteen tested combinations with the 8-inch tailpipe. Modification Q with 104 vanes and an 8" by 108" tailpipe produced a maximum coefficient of 6.88 and 5.95 pounds, at a specific of 2.80. A form of Modification Q with a desirable specific fuel was that with 72 vanes, (continued on page 45)

CONFIDENTIAL
DECLASSIFIED

DECLASSIFIED

TABLE 16

COMPARISON CHART OF THRUST PER MAXIMUM CROSS SECTION

ORDER NO.	MAX. THRUST PER MAX. SECTION LB./SQ.FT.	SPECIFIC FUEL AT MAX. THRUST LB./LB./HR.	THRUST SP. MIN. PER MAX. SECTION LB./SQ. FT.	SPECIFIC FUEL MINIMUM LB./LB./HR.	COMBUSTION CHAMBER TYPE	VANE NO.	TAIL DIMENSIONS (INCHES) DIAMETER	TAIL DIMENSIONS (INCHES) LENGTH
1.	201.5	3.34	193.2	3.07	Std. (S.W.) *	88	8	88
2.	194.0	2.67	172.0	2.60	Mod V	104	10	144
3.	194.0	2.73	191.3	2.73	Mod U	104	10	144
4.	184.8	8.5	184.8	8.5	Mod A	72	8	141
5.	182.7	3.00	172.0	2.52	Mod X	104	10	144
6.	179.5	3.29	165.5	3.15	Mod B	88	8	96
7.	174.0	2.84	166.5	2.75	Mod B	72	8	120
8.	171.0	3.04	171.0	3.04	Mod B	72	8	96
9.	170.2	2.95	159.0	2.88	Mod B	72	8	132
10.	166.0	3.25	149.0	3.21	Mod B	88	8	120
11.	165.0	3.16	165.0	3.16	Mod B	72	8	141
12.	157.7	3.22	110.0	2.80	Mod T	104	10	144
13.	154.0	3.12	139.5	2.58	Mod T	88	10	144
14.	154.0	2.94	136.0	2.67	Mod Q	88	10	144
15.	154.0	3.28	147.4	3.12	Mod F	100	8	132
16.	151.9	2.62	147.0	2.48	Mod Q	72	10	144
17.	151.0	2.98	132.0	2.80	Mod T	88	10	108
18.	150.0	3.00	132.5	2.59	Mod Q	72	8	144
19.	148.0	2.93	136.0	2.75	Mod Q	88	10	108
20.	146.2	3.15	122.0	2.65	Mod E	88	8	132
21.	146.2	3.06	138.0	2.94	Mod F	88	8	132
22.	145,0	2.83	119.5	2.47	Mod T	72	10	144
23.	142.5	3.59	120.0	2.74	Mod E	88	8	141
24.	142.0	2.93	121.0	2.69	Mod Q	88	8	144
25.	142.0	3.25	113.0	2.79	Mod T	104	10	108

* Standard Tube with Spiral Weld Tailpipe.

26. or 19b.	147.5	2.82	121.8	2.82	Mod E	104	8	144

#26 [redacted] Computed after original charts were prepared.

DECLASSIFIED

DECLASSIFIED

COMPARISON CHART

ORDER OF THRUST per SURFACE AREA OF TUBE

ORDER NO.	MAXIMUM THRUST PER SURFACE AREA *	SPECIFIC FUEL AT MAXIMUM THRUST LB/LB/HR	THRUST AT MIN. SP. FUEL SURFACE AR. LB/SQ. FT.	MINIMUM SPECIFIC FUEL	COMBUSTION CHAMBER TYPE	NUMBER OF VANES	TAILPIPE DIMENSIONS (inches)	
							DIA.	LENGTH
1.	7.81	3.29	7.20	3.15	Mod B	88	8	96
2.	7.45	3.04	7.45	3.04	Mod B	72	8	96
3.	7.03	3.52	6.50	3.08	Mod Q	104	8	96
4.	6.88	3.28	5.95	2.79	Mod Q	104	8	108
5.	6.88	3.37	5.68	3.07	Mod C	88	8	96
6.	6.78	3.34	6.43	3.07	STD. (SW) **	88	8	88
7.	6.77	3.33	5.88	3.03	Mod Q	88	8	108
8.	6.73	3.47	5.72	3.23	Mod Q	88	8	96
9.	6.67	3.54	5.89	3.15	Mod C	88	8	108
10.	6.60	3.44	6.48	2.89	Mod Q	72	8	108
11.	6.56	3.38	6.18	3.00	Mod C	72	8	108
12.	6.56	2.97	6.33	2.80	Mod P	72	8	120
13.	6.50	3.38	5.71	3.16	Mod G	88	8	108
14.	6.47	2.84	6.27	2.75	Mod B	72	8	120
15.	6.45	3.45	6.42	3.36	Mod G	88	8	96
16.	6.42	2.74	6.35	2.73	Mod U	104	10	144
17.	6.40	3.07	6.15	2.98	Mod P	88	8	120
18.	6.34	3.14	5.55	2.85	Mod Q	104	8	120
19.	6.34	3.35	5.75	3.33	Mod G	72	8	96
20.	6.28	3.37	5.50	3.26	Mod Q	72	8	96
21.	6.26	3.20	5.48	3.00	Mod C	88	8	120
22.	6.24	2.93	5.76	2.75	Mod Q	104	10	108
23.	6.20	3.00	5.31	2.59	Mod Q	72	8	144
24.	6.15	3.25	5.57	3.21	Mod B	88	8	120
25.	6.14	2.66	5.45	2.60	Mod W	104	10	144

* --- LB/SQ.FT.

** --- STANDARD TUBE WITH SPIRAL WELD TAILPIPE.

DECLASSIFIED

(paragraph 113 continued from page 42)

DECLASSIFIED

and an 8" by 144" tailpipe, which produced a thrust of 6.2 pounds per square foot of surface and a thrust of 5.31 pounds per square foot at a specific fuel of 2.59. Perhaps one of the best combinations was Modification U with a coefficient of 6.42 pounds thrust per square foot of surface at a specific fuel of 2.74. Modification P also is a good performer with a maximum of 6.56 pounds per square foot and 6.33 pounds per square foot at a specific fuel of 2.80.

114. Coefficient of Thrust per Unit of Tail Cross Section. The coefficient of thrust per unit of tail cross section is obtained by dividing the maximum thrust by the inside area of the tailpipe. Units are pounds per square foot. As in the preceding coefficients, a value may also be computed at minimum specific fuel. The result is equal to, or, more generally, less than the value computed at maximum thrust. Although this coefficient is unimportant at air speeds which are low compared to jet velocity, it gives a qualitative picture of tailpipe loading. Furthermore, this coefficient indicates whether a particular modification approaches the maximum obtained thrust (692.0) for a given tailpipe. Static thrust is a function of the weight of expelled products, the average jet velocity, the weight of air drawn into the tailpipe, and the average velocity of tailpipe inflow. If density changes are neglected, the average jet velocity may be shown to vary as the square root of the coefficient of thrust per unit of tailpipe area.

115. Table 18 on page 46 indicates that of the twenty-seven 6-inch-tailpipe combinations tested, ten appear on the list of the twenty-six best combinations of all sizes rated on the basis of maximum thrust per cross-sectional tailpipe area. On the other hand, no 6-inch combinations appear on any of the other lists of best performance. Modification I, a large combustion chamber with a 6" by 144" tailpipe, heads the list with 692 pounds of thrust per square foot of tailpipe. Modification H appears eight times out of the twenty combinations tested. Modification F appears next, followed by Modification Q. The latter is characterized by a good value of specific fuel. Out of fifteen combinations of Modification Q tested, six appear on this list. Modification E also gave high thrust per square foot of tailpipe section at a low specific.

116. Dimensionless Ratios. Table 19 on page 48 lists four dimensionless ratios of mechanical sizes. These are:

(1) V_t/V_c, the volume of the tail divided by the volume of the chamber.

(2) A_o/A_h, the area of chamber entry divided by the area of the head orifice.

(3) A_t/A_v, the area of the tailpipe section divided by the effective vane area.

(4) A_m/A_t, the area of the maximum tube section divided by the area of the tailpipe section.

(continued on page 47)

DECLASSIFIED

DECLASSIFIED

TABLE 18

COMPARISON CHART

ORDER OF THRUST per TAIL CROSS SECTION

CHART--C_{tt} -- Coefficient of Thrust (lb.) per unit cross section of tail (sq. ft.)

ORDER NO.	C_{tt} at MAXIMUM THRUST (lb./sq.ft)	SPECIFIC FUEL at MAXIMUM THRUST (lb/lb/hr)	C_{tt} at SPECIFIC MINIMUM (lb/ sq ft)	SPECIFIC FUEL MINIMUM (lb/lb/hr)	COMBUSTION CHAMBER TYPE	VANE NO,	TAIL DIMENTIONS (inches)	
							DIAMETER	LENGTH
1.	692.0	3.55	642.0	3.12	Mod I	72	6	144
2.	627.0	3.39	591.0	3.02	Mod H	56	6	144
3.	615.0	3.28	591.0	3.12	Mod F	100	8	132
4.	612.0	3.60	612.0	3.60	Mod H	64	6	144
5.	606.0	4.23	591.0	3.64	Mod H	64	6	132
6.	596.0	3.00	530.0	2.59	Mod Q	72	8	144
7.	590.0	4.09	581.0	3.87	Mod H	64	6	108
8.	585.0	3.15	487.0	2.65	Mod E	88	8	132
9.	585.0	3.06	553.0	2.94	Mod F	88	8	132
10.	585.0	3.92	551.0	3.81	Mod H	64	6	120
11.	581.0	3.95	535.0	3.11	Mod H	56	6	132
12.	570.0	3.04	481.0	2.74	Mod E	88	8	141
13.	570.0	3,43	520.0	3.28	Mod M	64	6	144
14.	565.0	2.92	521.0	2.69	Mod Q	88	8	144
15.	562.0	3.28	470.0	2.80	Mod Q	104	8	108
16.	562.0	3.18	516.0	2.95	Mod C	88	8	132
17.	558.0	3.61	496.0	2.96	Mod C	88	8	141
18.	556.0	2.84	470.0	2.63	Mod Q	72	8	132
19.	556.0	3.14	487.0	2.85	Mod Q	104	8	120
20.	553.0	3.33	481.0	3.02	Mod Q	88	8	108
21.	550.0	3.29	507.0	3.15	Mod B	88	8	96
22.	550.0	3.20	481.0	3.00	Mod C	88	8	120
23.	550.0	3.51	520.0	3.38	Mod H	56	6	108
24.	550.0	4.48	540.0	4.20	Mod H	64	6	96
25.	548.0	3.11	484.0	2.84	Mod C	72	8	132
26. or 7b.	590.0	2.82	487.0	2.82	Mod E	104	8	144

26 Computed after original charts were made.

DECLASSIFIED

(paragraph 116 continued from page 45)

DECLASSIFIED

These values have been computed for each engine combination on each of the four lists of performance coefficients. Each block of values of five was averaged to indicate internal trends and an overall average was secured for each dimensionless ratio and for each coefficient.

117. With one exception, the lowest specific was secured when the ratio of tailpipe-to-chamber-volume was about two. The exception was Modification Q with a 10-inch tailpipe. The size and angle ϕ of reflecting surface at the junction of the tailpipe and chamber seem to have an important influence on the most desirable volume ratio.

118. With the exception of Head No. 9, which had a different fuel jet arrangement, the best specifics were obtained on modifications where the ratio of A_o/A_h was as small as possible with head and reducer combinations tried. Some improvement might result if A_o/A_h were similar in shape and of equal area. This could be achieved by a design in which there would be no abrupt change in section area but only a smooth streamline from the rectangular throat to the circular conical section of the enlarger. The exceptions, Modifications U, V, and X, all had large chamber and tailpipe volumes and showed increased efficiency in spite of the large value of A_o/A_h. This might be attributed to other variables such as adaptor design, location of fuel injection, overall size, and number of vanes. The average value of A_t/A_v for the five modifications with lowest specific was 2.26 or well above the average of any grouping of five with higher specific fuel. The top four with respect to specific fuel all had A_m/A_t equal to 2.56, which means that for best specific fuel under static conditions the area of the tailpipe must be large with respect to the maximum diameter. This is similar to the effect of the relation A_t/A_v, which indicated that some of the best performing tubes with respect to specific fuel were ones in which the area of the tailpipe was large with respect to the effective vane area.

119. Trends in Regard to Maximum Thrust per Maximum Cross Section. Table 19 indicated that the five top combinations in the list averaged according to thrust per maximum section had large values of V_t/V_c which gradually decreased in average group magnitude. This means, in general, that a slim chamber of small volume with respect to the large-diameter tailpipe is desirable from a standpoint of thrust per maximum cross-sectional area. The same top five also has a significantly large ratio of A_o/A_h. This indicated that the standard tube with head orifice opening suddenly into maximum diameter of chamber is desirable for a high value of thrust per maximum section. The average of the first five in the group and the overall average of the listed combinations show that A_t/A_v is smaller with respect to low specific fuel than in the case of top performance. This indicates that it is desirable to have more vanes per tailpipe section. As might be suspected from the fact that low cross-sectional area is very important, the ratio A_m/A_t is lower for the average of the top five tubes of thrust per maximum cross section than any other sequence.

DECLASSIFIED

DECLASSIFIED

Table 19

Dimensionless Ratios

Reference Table	Coefficient & Order Number	V_t/V_c	A_o/A_h	A_t/A_v	A_m/A_t
15	(Specific Fuel)				
	1-5 Average	2.04	1.82	2.26	2.85
	6-10 Average	1.86	1.48	1.74	3.42
	11-15 Average	1.66	1.48	1.84	3.29
	16-20 Average	1.87	1.30	1.70	3.42
	21-25 Average	1.84	1.30	2.01	2.92
	Average	1.85	1.48	1.91	3.18
16	(Maximum Thrust per A_m)				
	1-5 Average	2.59	2.96	1.77	2.51
	6-10 Average	2.02	1.30	1.62	3.06
	11-15 Average	1.95	1.48	1.87	2.95
	16-20 Average	1.96	1.30	2.07	3.14
	21-25 Average	1.43	1.62	1.78	3.46
	Average	1.95	1.72	1.82	3.02
17	(Maximum Thrust per Square Foot of Tube Surface)				
	1-5 Average	1.40	1.30	1.40	3.62
	6-10 Average	1.24	1.72	1.49	3.72
	11-15 Average	1.63	1.94	1.62	3.81
	16-20 Average	1.75	1.81	1.60	3.71
	21-25 Average	1.85	1.48	1.68	3.25
	Average	1.57	1.65	1.56	3.61
18	(Maximum Thrust per A_t)				
	1-5 Average	1.21	1.48	1.14	5.15
	6-10 Average	1.24	1.68	1.36	4.57
	11-15 Average	1.67	1.30	1.29	4.57
	16-20 Average	1.57	1.30	1.45	4.00
	21-25 Average	1.31	1.30	1.39	4.39
	Average	1.40	1.39	1.33	4.54

DECLASSIFIED

DECLASSIFIED

120. Trends in Regard to Maximum Thrust per Unit of Surface Area of Tube. Table 19 illustrates that for the best coefficient of maximum thrust per unit of surface area, the values of V_t/V_c are small compared to the same ratio for previously discussed coefficients. This means both shorter and smaller-diameter tailpipes are desirable to reduce the overall surface area of the tube. In most tube forms, this tendency is contrary to the demands for a good specific and high thrust per maximum section, but in Modification B the best specific is achieved with a comparatively short tailpipe; hence, Modification B produces a high thrust per unit of surface area. In the group of the top five performing tubes with respect to this coefficient, it is noted that A_o/A_h is at the minimum value possible with components at hand. The average value of A_o/A_h is slightly greater than is the case of minimum specific. The ratio A_t/A_v is much smaller and increases slowly with groups of increasing coefficient. This means that more vanes per square foot of tailpipe area are necessary to achieve high thrust per surface area. The ratio A_m/A_t is significantly higher for the average of the top five and in overall average value than in the preceding lists.

121. Trends in Regard to Maximum Thrust per Unit Cross-Sectional Area of Tailpipe Section. Since the cross-sectional area of the tailpipe is of paramount importance in this particular ratio, maximum values of this coefficient are obtained with tubes of relatively small tailpipe areas, i.e., if all tube parameters except the tailpipe area are held constant it is an experimental fact that variation of thrust is of a lower order than the variation in tailpipe area. Results are as expected and V_t/V_c is less than for any preceding coefficient. The ratio A_o/A_h is slightly higher for the first average group than the similar group in the preceding coefficient of thrust. The overall average is less than in any other grouping. The ratio A_t/A_v is smaller than in the case of any preceding group term for term. The ratio A_m/A_t far exceeds the values in any other lists of coefficients.

122. Overall Performance Comparison. In Table 20 Modification Q was the only combustion chamber appearing on all four coefficient lists. It appears with both a long and a short tailpipe. The former gave the best specific fuel, thrust per maximum area, and thrust per unit of tailpipe cross-sectional area; the latter gave the highest value of thrust per surface area. This modification described in generalized terms has a small angle of 8.1 for α, while β is 90°. Reference is made to paragraphs 92 and 104 showing the superior performance of various models with abrupt reducers.

123. Modification V appears in three of the four lists and shows up exceptionally well. The same pattern is noted as with Modification Q. The α_2 is only 6.3° and β_1 is 90°. One difference is that α_1, is 90° owing to head design. If long, small-angle enlargers always produce a low specific, it would be expected that a head and enlarger of the proper capacity, where A_o/A_h is unity, might still further improve the performance. These ratios also suggest that proper volume of long-tapered chambers may be secured without excessive area by the use of a short length of straight section whose maximum diameter provides a favorable ratio for both maximum thrust per maximum area and low specific fuel.

DECLASSIFIED

DECLASSIFIED

Table 20

Over-all Comparison Rating.

Mod.	No. Vanes	Tailpipe[x] Dimensions	Specific Fuel-15**	T_m/A_m 16**	T_m/A_s 17**	T_m/A_t 18**
Q	72	8 x 144	2.59 (5)*	150 (17)*	6.20 (23)*	596 (6)*
Q	104	8 x 108	2.80 (19)	141 (25)	6.88 (4)	562 (15)
Mods. appearing on 3 Comparison Charts, (Tables 15, 16, 17, or 18.)						
B	72	8 x 120	2.75 (15)	174 (7)	6.47 (14)	533 xx
Q	88	10 x 108	2.75 (16)	148 (19)	6.24 (22)	378 xx
V	104	10 x 144	2.60 (6)	194 (2)	6.13 (25)	495 xx
U	104	10 x 144	2.73 (11)	194 (3)	6.42 (16)	495 xx
E	88	8 x 132	2.65 (8)	146 (20)	5.59 xx	585 (8)
Q	88	8 x 144	2.69 (10)	142 (24)	5.65 xx	565 (14)
E	88	8 x 141	2.74 (14)	142 (23)	5.46 xx	570 (12)
Q	104	8 x 120	2.85 (25)	140 xx	6.34 (18)	556 (19)
B	88	8 x 96	3.15 xx	179 (6)	7.81 (1)	550 (21)
Some Mods. appearing on 2 Comparison Charts, (Tables 15, 16, 17, or 18.)						
T	72	10 x 144	2.47 (1)	145 (22)	4.50 xx	372 xx
Q	72	10 x 144	2.48 (2)	152 (16)	5.06 xx	389 xx
X	104	10 x 144	2.52 (3)	183 (5)	5.82 xx	467 xx
B	72	8 x 96	3.04 xx	171 (8)	7.45 (2)	524 xx
	88	8 x 88	3.07 xx	201 (1)	6.78 (6)	624 xx

* Numbers in parenthesis refer to order number on reference table.

** Reference Table.

x All tailpipes made from spiral-welded pipe; 8 x 144 = 8" diameter by 144" length.

xx Not on list of first twenty-five. (See Reference Table).

(paragraph 123 continued from page 49)

An internal method to permit a large reflecting surface without enlarged section or reduced flow might be desirable. Modification B shows a fair specific at a fair value of thrust per maximum area and a fair value of thrust per surface area of tube. On the basis of specific fuels, two long-enlarger combustion chambers are tied (within experimental error) for top place. Of these, Modification Q achieves higher maximum thrust coefficients at lower specific fuel than Modification T. From this

DECLASSIFIED

DECLASSIFIED

standpoint alone a reducer with β equal to 90° is superior to reducers of small angles. This conclusion is again substantiated when the performance of Modifications V and X are compared. On the first glance, X seems superior with a specific of 2.52 which is third on the list. When the respective specific fuels at maximum thrust are examined it is seen that Modification V achieves higher thrusts coefficients at a specific of 2.67 while Modification X has much lower maximum coefficients at a specific of 3.00. The only difference is that for Modification V, α_2 is 6.3° and β_1 is 90° while for Modification X, α_1 is 90° and β_1, 9.5°. Exhaustive experimentation would probably determine the exact angles of α and β necessary for optimum operation. Another phase of the development would be the design of a tube which would have the optimum of all coefficients. This might involve tailpipe variations from the simple constant-diameter type used as standard in this study.

124. Effect of Enlarger and Reducer Angles on Efficiency. This investigation of design parameters permits a study of pulse-jet operation as affected by the enlarger angle α, and the reducer angle β. (See Fig. 1 and 1A). For easy visualization, modifications have been listed in Table 21, page 52 according to these angles, together with two values of specific fuel. One is the minimum specific fuel (Sp.Min.) obtained with that chamber in its most efficient combination and the other is the specific fuel obtained at maximum thrust (Sp.Max.). The average values for all combustion chambers with the same angle indicates the trends in the effect of these angles upon efficiency. There are some limitations caused by neglecting the effect of other parameters such as A_m/A_t and the tailpipe size. In the case of a reducer used with only one size of tailpipe, it must be remembered that, in general, a 10-inch tailpipe gave the lowest specific fuel; the 8-inch tailpipe, the next lowest specific; and the 6-inch the highest specific. Comparative results are set forth in Figs. 77, 78, 79, and 80.

125. Without exception it has been found that the lowest average specific fuel (2.57) was obtained when α_1 was as small as possible with available cones. The only value of α_2 was also small (6.3°) and the average specific fuel was low (2.73). With the exception of the 6-inch tailpipe models appearing in the second series of combustion chambers, the efficiency decreases as the angle of the enlarger is increased.

126. The lowest average value of specific fuel at maximum thrust was obtained when the angle of β_1 was 90°. The three modifications for which β_1 was 9.5° all utilized 10-inch tailpipes. Because of this, it is expected that average specific fuels for these designs will be low. No reliable internal tendencies are observed in the case of small changes in β_2.

DECLASSIFIED

DECLASSIFIED

Table 21

Effect of Enlarger and Reducer Angles on Efficiency.

$\alpha_1 =$ 8.1°	Mod	D	Q-8'	Q-10'	T				Ave.
	Sp Min	2.74	2.59	2.48	2.47				2.57
	Sp Max	3.03	3.00	2.62	3.22				2.97
$\alpha_1 =$ 10.6°	Mod	B	H	I	M				
	Sp Min	2.75	2.97	3.20	2.94				2.96
	Sp Max	2.84	3.28	3.55	3.29				3.24
$\alpha_1 =$ 12.5°	Mod	C	E	P					
	Sp Min	2.84	2.65	2.82					2.77
	Sp Max	3.37	3.15	2.97					3.16
$\alpha_1 =$ 90.0°	Mod	A	F	G	J	K			
	Sp Min	3.26	2.94	2.92	3.33	3.32			3.01
	Sp Max	8.50	3.28	2.94	3.38	3.32			3.61
$\alpha_1 =$ 90.0°	Mod	L	R	U	V	X			
	Sp Min	3.54	2.97	2.73	2.60	2.52			
	Sp Max	3.69	3.18	2.73	2.67	3.00			
$\alpha_2 =$ 6.3°	Mod	D	F	G	Q-10'	R	T	U	V	
	Sp Min	2.74	2.94	2.92	2.48	2.97	2.47	2.73	2.60	2.73
	Sp Max	3.03	3.28	2.94	2.62	3.18	3.22	2.73	2.67	2.96
$\beta_1 =$ 7.1°	Mod	I	L							
	Sp Min	3.20	3.54							3.37
	Sp Max	3.55	3.69							3.62
$\beta_1 =$ 8.1°	Mod	A	E	F						
	Sp Min	3.26	2.65	2.94						2.95
	Sp Max	8.50	3.15	3.28						4.97
$\beta_1 =$ 9.5°	Mod	T	U	X						
	Sp Min	2.47	2.73	2.52						2.67
	Sp Max	3.22	2.73	3.00						2.98
$\beta_1 =$ 10.6°	Mod	B	K							
	Sp Min	2.75	3.32							3.03
	Sp Max	2.84	3.32							3.08
$\beta_1 =$ 12.5°	Mod	C	D	G	J					
	Sp Min	2.84	2.79	2.92	3.33					2.97
	Sp Max	3.37	3.03	2.94	3.38					3.18
$\beta_1 =$ 14.0°	Mod	H								
	Sp Min	2.97								2.97
	Sp Max	3.28								3.28
$\beta_1 =$ 90.0°	Mod	M	P	Q-8'	Q-10'	R	V			
	Sp Min	2.94	2.82	2.59	2.48	2.97	2.60			2.73
	Sp Max	3.29	2.97	3.00	2.62	3.18	2.67			2.95

DECLASSIFIED

DECLASSIFIED

IX. SUPPLEMENTARY EXPERIMENTATION

127. Extended Heating Surface Test. Pulse-jet operation is generally somewhat erratic and characterized by "hunting". In order to determine if this irregularity might be caused by variations in ignition, investigations were made of multiple-point ignition. This could be done either by a large number of spark plugs or by hot spots. The latter was easily accomplished by installing small steel rods inside the combustion chamber where they would be heated to incandescence by combustion. This additional heating surface might also have a regenerative effect which would raise the average temperature of the gases. This particular type of multiple ignition also produced additional turbulence. Some improvement in operating characteristics might result from such turbulence. Hence, this particular study was made with two different types of variations in combustion chamber design, extended heating surface and increased turbulence. The extended heating surface was supplied by one hundred and sixteen steel bolts 2-3/8 inches long and 1/4 inch in diameter inserted in the straight section of standard tube combustion chamber and spaced in ten rows. Approximately 215 square inches of additional internal surface area was thus supplied. The area of the chamber before the bolt addition was approximately 1750 square inches. Fig. 83 shows the bolt arrangement and method of attachment. Several runs were made with various fuel rates. After several minutes of running, the bolts, seen through the valve openings while the engine was in operation, were white hot. Instrumentation at the time was not set up as a result, a frequency change, if any, was not measured. However, no change in thrust occurred and no audible change in running characteristics was detected. Results to date have shown no obvious improvement in operating characteristics by the use of multiple ignition points supplied in this manner.

128. Auxiliary Jets in Tailpipe. Because of the influx of air through the tailpipe during a portion of the cycle, an attempt was made to utilize this air in order to secure additional thrust directly or by compression of the primary charge. It was hoped that the incoming air entering through the tailpipe would combine with the fuel injected by means of an auxiliary fuel jet. Then the products of combustion might expand through the tailpipe to the combustion chamber, compressing the air-fuel mixture entering the front of the pulse jet through the grid assembly. Additional compression in the combustion chamber would then result in higher combustion pressure and temperature. This, in turn, would result in higher thrust. Fig. 84 shows the design details for experimentation with an auxiliary jet in the tailpipe. The jet was located 7 inches from the end of the tailpipe with the exit end of the fuel jet set flush with the interior surface. A standard engine with combustion Head No. 2 and a 48-vane grid assembly was used for the test. Several tests were made but no change in thrust or frequency was observed. Additional burning occurred beyond the tailpipe but there was no audible change in running characteristics. Therefore, this method of increasing output and efficiency was unsatisfactory.

129. Auxiliary Fuel Jets in the Combustion Chamber. Experimental investigations were carried out with auxiliary jets in the combustion chamber. Fig. 69 shows the performance curves and engine di-

DECLASSIFIED

mensions for the pulse jet used for this purpose. The engine was a standard type with Head No. 7 and the shutter attachment. A more detailed drawing of the assembly may be found in Fig. 85. The original idea was to improve fuel distribution by means of auxiliary fuel jets. Two methods of testing were used: (1) the main fuel flow was held at a constant rate while additional fuel was supplied through the auxiliary jets at different rates and (2) the auxiliary fuel flow was held at a constant rate while additional fuel was supplied through the main jets at different rates. In Fig. 69, the dotted lines represent the fuel range covered when the auxiliary jets were used. The engine was started on main jets for all runs. After starting, the auxiliary fuel was turned on and either held at a constant rate or adjusted to a number of different rates according to (1) or (2). The results were not encouraging, since operation was characterized by erratic running and by high fuel consumption. Specific fuel values varied from 4.5 to 6.0. It has been suggested that the auxiliary fuel had insufficient time to mix thoroughly with the incoming air before burning. This would indicate that fuel should be supplied near vanes or even externally as discussed in paragraph 130.

130. External Fuel Spray. Of the various supplementary experiments, the investigation of external fuel spray was one of the most promising. Such a system provides a method of supplying additional and premixed fuel, and at the same time acts as a cooling system for the valves. The intermittent flow of fuel through the valve openings is of particular advantage. Internal steady flow tends to build up layers of fuel next to the valves during the explosive cycle. These layers do not burn readily because of insufficient air. On the other hand, external fuel spray is premixed thoroughly with air before entering the combustion chamber. The experimental setup is illustrated in Fig. 86, and data taken during experiments on Table 22, page 55.

131. External Fuel Spray, Experimental Procedure for Modification U. The engine was started using internal fuel with a 116-vane grid opened to 80 vanes by means of an adjustable shutter. As the number of effective vanes was increased, additional fuel was supplied to maintain smooth operation by keeping an optimum air-fuel ratio. With 116 active vanes the internal fuel flow was adjusted to a rate of 600 pounds per hour. Thrust at this fuel rate was 125 pounds. After two minutes of operation, the external fuel valve was opened permitting part of the total fuel from the main source to flow through the external fuel jets. The total (combined) fuel rate remained at 600 pounds per hour. Operation was rough. Thrust was 135 pounds. This was an increase of 10 pounds over the value with internal fuel. After one minute of operation at the combined fuel rate, the internal fuel supply was cut off. Immediately the frequency dropped 300 cycles per minute (from 2250 to 1950 cpm); and the thrust increased 37 pounds. Because of the smaller fuel jets, the external fuel rate was 432 pounds per hour. Successive thrust readings were recorded as the external fuel was increased. At 461 pounds per hour the thrust was 180 pounds, and for successive fuel rates of 480, 499 and 504 pounds per hour the thrust readings were 190, 197 and 200 pounds. When the external fuel was increased to a rate of 520 pounds per hour, another distinct change was noticed in running

DECLASSIFIED

DECLASSIFIED

characteristics. The frequency increased 300 cycles per minute, or from 2100 to 2400 cpm, while the thrust dropped to 140 pounds. No additional increase or decrease in thrust values were observed as the external fuel was raised to a rate of 600 pounds per hour. The engine was stopped at this point. As a check for repeatability, the above procedure was repeated twice. Identical results were obtained each time.

Table 22

Data Taken During External Fuel Experiments

Mod. Tested and Data	Fuel Rate, (Pounds per Hour)			Thrust (Pounds)	Specific Fuel	Freq. (CPM)
	Internal Flow	Combined Flow	External Flow			
Mod. U	600	-	-	125	4.80	2250
Tailpipe:	-	600	-	135	4.08	2250
10" Dia.	-	-	432	172	2.51	1950
144" Long	-	-	461	180	2.51	2000
	-	-	480	190	2.53	2000
116 Vanes	-	-	499	197	2.53	2100
	-	-	504	200	2.53	2100
	-	-	520	140	3.72	2400
	-	-	600	140	4.29	2400
Mod. X	-	620	-	120	5.17	-
Tailpipe:	-	-	432	110	3.92	2100
10" Dia.	-	-	520	110	4.72	2100
144" Long	-	-	432	110	3.92	2100
	-	-	422	112	3.76	2080
116 Vanes	-	-	403	165	2.44	2020
	-	-	398	169	2.35	2000
	-	-	389	163	2.39	2000
	-	-	384	162	2.37	1980
	-	-	374	158	2.37	1950
	-	-	370	155	2.39	1900

132. External Fuel Spray, Experimental Procedure for Modification X. Unlike Modification U, Modification X was started with both the external and internal fuel. Starting was easily accomplished. Careful watch was made on the external fuel since there was some danger of ignition outside of the combustion chamber by the initial explosion. However, there was no external burning. This was probably due partly to new tight-fitting vanes as well as to the fact that the blower was directed into the intake air stream of the head assembly. The engine operated rather smoothly at a combined fuel rate of 620 pounds per hour.

DECLASSIFIED

DECLASSIFIED

Thrust was 120 pounds. After two minutes of operation the internal fuel was cut off, leaving 432 pounds of fuel an hour flowing through the external fuel jets. Thrust at this fuel rate was 110 pounds, a 10-pound drop accompanying a 188 pounds an hour drop in fuel flow. Unlike Modification U, Modification X gave only a slight audible change in operating characteristics. The frequency was 2100 cpm. Thrust and frequency data were taken from this point for various rates of fuel flow. As the external fuel flow was increased, no thrust increase was observed nor was there any noticeable change in operating characteristics. Operation was stable for the entire fuel range up to 520 pounds per hour. Thrust remained at 110 pounds and frequency at 2100 cycles per minute. The fuel control operator began to decrease the fuel supply gradually. At a fuel rate of 422 pounds per hour a slight decrease of frequency of about 20 cycles per minute was observed with an increase in thrust of 2 pounds. At an external fuel rate of 403 pounds per hour, the engine suddenly began to operate on a slightly lower frequency, dropping from 2080 cycles per minute to 2020 cycles per minute. This was accompanied by a thrust increase of 53 pounds, i.e., from 112 pounds to 165 pounds. As in the case of Modification U, the procedure was repeated several times. In each case the results were identical. Of particular interest was the formation of frost patterns on those portions of the grid assembly upon which the spray impinged from the external fuel jets. This seemed to indicate an appreciable cooling effect produced by this type of fuel injection.

133. Because of the unexpected behavior of the engine during tests a complete evaluation of external fuel injection is difficult, especially since only two runs were made, each with a different modification. Each run was of short duration, approximately 5 to 7 minutes. In each case the engine was stopped when a sudden back flash ignited the incoming fuel thus presenting a hazard to the operators. Subsequent examination in both cases revealed that slightly damaged vanes permitted flame leakage, which in turn ignited the incoming fuel. Further tests were discontinued until a protective hopper could be designed and constructed in order to protect personnel fully against injury.

134. Vane Development. The laminated vane assembly or vane used throughout most of the experimentation has been described in paragraph 2. As the research progressed, materials other than spring steel and plastic-impregnated glass cloth were tried. Experimentation revealed that 0.006" beryllium copper could be used successfully as the sandwich material. Silicon-resin-coated glass-cloth and 0.006" spring steel were both tried with less success. "Inconel" was tried for the outer members of the vane assembly with no notable improvement over spring steel. Although the vane-life testing program has been limited, vane development is still being studied. Sandwich materials similar to flak cloth and special finishes will be investigated. Quantitative results will be secured in order to compare accurately various materials and vane assemblies.

DECLASSIFIED

DECLASSIFIED

135. Powdered Fuels. The study of various pulse jet modifications has indicated that each can utilize only a limited amount of air. Therefore, a fuel giving a greater total heat release per pound of air than is possible with gasoline, might increase pulse-jet combustion temperatures and pressures, and hence increase thrust. This effect might be heightened by the use of two fuels having different ignition points.

136. An attempt was made to utilize fuels with different heat content. Powdered coal was tried first, in the hope of producing a double ignition. The gasoline would ignite first, compressing the air possibly to the point where the powdered coal would detonate. This would result in a greater heat release over a larger portion of the cycle and should increase the thrust of the engine. According to Ref. (4), aluminum releases 3500 BTU per pound of air burned, and magnesium releases 3700 BTU per pound of air, assuming the reaction goes to completion. In contrast, gasoline releases approximately 1300 BTU per pound of air. The advantage of using one of the powdered metallic fuels would be in the increased heat release during the combustion process. As mentioned above, this would increase the combustion temperatures and pressures, and, in turn, the thrust.

137. Four powdered fuels, bituminous coal, anthracite coal, magnesium, and aluminum, were tried. Two one-quart, fiber-type containers were used as the dispensers. The cover of each container was perforated with a series of holes so as to produce a salt-shaker type dispenser. Both containers were strapped together and then fixed to the end of a six-foot pole for safety in case ignition or explosion should occur outside the combustion chamber. The operator of the powdered-fuel dispenser held the containers about four inches from the head assembly. At this distance it was reasonable to assume that there was no blocking to interfere with the air intake of the pulse jet. The containers were tilted at 45° to the axis of the engine so as to permit gravity feed. The intake air stream then carried the powdered fuel into the combustion chamber. Because of the crude technique it was not possible to determine an accurate rate of flow. The engine was started with gasoline supplied internally. After several minutes of operation powdered fuel was added. Thrust readings were taken before, during, and after each addition of powdered fuel. Each run was repeated several times to check repeatability of results. A standard tube was used only for coal additions. Modification Q was used for all four powdered fuel additives.

138. Pulverized Anthracite and Bituminous Coal. Since the behavior of the anthracite and bituminous additives were somewhat similar, this discussion covers both of the tests. Samples of anthracite and bituminous were pulverized by using a laboratory mortar and pestle. The finished samples ran approximately 50 or 75-mesh particle size plus a very small percentage of fine floats. Several runs were slow in burning as evidenced by considerable flame and numerous hot particles emitted from the end of the tailpipe. Thrust readings remained constant throughout each addition. No measurable frequency changes were observed and no audible change in running characteristics was detected on either type of engine.

DECLASSIFIED

DECLASSIFIED

139. Powdered Magnesium. Similarly, the powdered magnesium produced no change in running characteristics. However, when the engine was dismantled, flaked magnesium was scraped from the inner wall of the combustion chamber. Although the magnesium had been introduced at a fairly slow rate, no indication of burning was evident from the flakes. These flakes were later ignited by torch flame and burned brilliantly. Modification Q was used in these tests with Head No. 5 and an 8" by 144" tailpipe.

140. During the introduction of powdered magnesium it was observed that small luminous lines appeared in front of the grid during the "blow-back" period. Even with new vanes, some "blow-back" occurred because of vane inertia and imperfect sealing. Since these lines were sufficiently brilliant to be observed with the naked eye in sunlight, it is believed that the particles would attain sufficient brilliancy for high speed photographs through transparent windows in the tube. By this method, it might be possible to determine the velocity of gas motion during a portion of the combustion cycle. By control of particle size it might even be possible to achieve measurable results over the entire cycle in downstream portions of the tube. This technique is suggested as one possible method of attaining data upon gas velocity.

Table 23

Data Taken During Runs With Powdered Aluminum

Test Number	Gasoline Fuel Rate (Lbs/Hr)	Thrust Before Powdered Aluminum Addition (Lbs)	Thrust During Powdered Aluminum Addition (Lbs)	Thrust Increase (Lbs)	Time of Powdered Fuel Addition (Secs)
Test #1	432	154	174	20	6
	432	154	173	19	6
	432	153	170	21	6
	432	154	174	20	6
	432	152	174	22	6
Test #2	528	166	182	16	6
	528	165	180	15	6
	528	163	184	21	6
	528	163	184	21	6
	528	163	182	19	6
Test #3	403	128	158	30	6
	403	127	160	33	6
	403	128	158	30	6
	403	127	156	29	6
	403	127	157	30	6

DECLASSIFIED

DECLASSIFIED

141. Powdered Aluminum. Three experimental runs were made with powdered aluminum. Each run consisted of five separate additions of powdered aluminum. All runs were made with Modification Q with Head No. 5 and an 8" by 144" tailpipe. An increase in thrust resulted when the powdered aluminum was introduced into the intake airstream. Table 23 above shows the results of these three experimental runs. After the engine was dismantled, a caked deposit of aluminum and aluminum oxide was scraped from the inner wall of the combustion chamber. A partial examination of this caked material revealed an aluminum oxide content of approximately 20%. This is indicative that partial burning took place in the combustion chamber.

142. Because of the limited experimentation, it is difficult to draw definite conclusions regarding the respective merits of powdered fuels in the pulse jet. Although only aluminum produced an increase in thrust, changes in conditions might permit use of other powdered fuels. Since both the coal and the magnesium were coarse in comparison to the aluminum, micro-pulverization of the solids would be desirable. In addition, head assembly and combustion chamber design are critical factors. Preheating of the powdered fuel before injection could also be investigated. In any case, further research into this problem is warrented by the fact that a thrust increase was obtained by the addition of powdered aluminum. An accurate metering system now in the design stage will permit qualitative research.

143. Inertia Supercharging. Some experimentation was carried out along the lines of the Wibu system of engine supercharging. This system involves a tuned length of intake pipe which increases the amount of air intake per cycle by using the inertia intake charge. It was suggested that engine resonance might be controlled by a light-weight pipe forward of the vanes and working in atmospheric air. It was recognized that resonance might be erratic due to unchanging atmospheric conditions in the forward resonance chamber as compared with varying resonance conditions in the combustion chamber. The latter results from temperature variations.

144. A light-weight section of pipe was attached to the head of the pulse jet. A slide permitted variations in the resonance length from 100" to 140". This length was calculated to be within the resonance range of the engine on the assumption that the driving impulse was a simple series of suctions at a fundamental frequency of operation. It was soon discovered that appreciable "blow-back" occurred during the first part of the explosion cycle. This gave a virtual driving frequency much higher than the fundamental, and caused destructive interference. As a result all attempts to run at these lengths were unsuccessful.

145. It was next decided to enclose the head in a cowl and to add increments of pipe until some length produced constructive resonance at the driving frequency. Because of its stability, Modification M with a 6" by 144" tailpipe was chosen for this series of experiments. A conical section 16" x 8", 18" in axial length, was used as a cowl with the large diameter attached to the plate at the head end of the combustion chamber. The head assembly extended about 4" into the cowl. Smooth

DECLASSIFIED

DECLASSIFIED

running could be obtained with the cowl plus a 6" length of 8" pipe. When, however, a 12" length was suddenly added, the engine immediately stopped. On the other hand, an orifice plate about 4.5" in diameter at the face of the 6" length of induction pipe did not stop operation. It was concluded that the additional length stopped the pulse jet because of destructive resonance rather than throttling. A conical section 16" x 8", 18" in axial length, was used as a cowl with the large diameter attached to the plate at the head end of the combustion chamber.

146. To study the effect of the cowling upon efficiency, comparative runs were made with and without the cowling for 40 and 48 vanes, respectively. Modification M, with 40 vanes and a 6" by 144" tailpipe, but without the cowling had produced a thrust of 84 pounds with a minimum specific of 3.14. This may be compared to a minimum specific fuel of 3.03 at a thrust of 73 pounds with the cowl. With the same setup, except for a 48-vane grid, a minimum specific fuel of 3.81 was obtained without the cowl at 83 pounds thrust compared to a minimum specific of 3.63 at 82 pounds thrust with the added cowl. Still better efficiency may be possible by the proper design of entry diffuser and entry duct. Experiments with external fuel feed indicate that efficiency would be further increased by fuel injection at the entry throat. The exact shape and dimensions of cowl and induction section for optimum efficiency will require considerable research. Other research workers have shown that efficiency may be improved under high velocity conditions by proper cowling design.

X. VALIDITY AND RELIABILITY OF RESULTS

147. In any experiment, it is important to know whether or not the instruments are accurately measuring the quantities involved in the test. The accuracy of the instruments and the correctness of the test methods control the validity of experimental results. In order to obtain valid results in these experiments, it was necessary to make sure the measurements of thrust, fuel rate, and frequency were as accurate as possible. The methods of performing these measurements are described in paragraphs 6, 7, and 11. Dead weights were used to calibrate the scales during engine operation. This gave a dynamic calibration. The friction in the system was minimized by the use of ball-bearing pulleys. The vibrations caused by the engine pulsations tended to overcome undesired frictional effects. Calibration of the fuel rotameter was performed periodically by weighing the fuel used during a timed run with the engine operating at a constant fuel rate. The vibrometer used for frequency measurements was checked against synchronous motors of known frequency and showed a maximum deviation of approximately 1.5 per cent.

148. Factors pertaining to reliability and repeatability of test runs are based upon the construction and condition of the engine. The most important factors controlling the engine setup are condition of vanes, shape of engine tube and smoothness of inside surfaces, condition of fuel jets and fuel lines, and condition of the gaskets between the various sections of the engine. Although little trouble was experienced with vanes, a constant check was maintained on the grid

DECLASSIFIED

DECLASSIFIED

assemblies to make sure all vanes were in good condition and that leakage was at a minimum. Initial test runs resulted in excessive warping and distortion - particularly in the tailpipe - caused by the heat of combustion. A spray system of cooling the combustion chamber and tailpipe was incorporated to minimize distortion. Fuel jets were periodically inspected for spray characteristics. Leaks in the fuel system were prevented by the use of compression fittings. The gaskets between the engine tube sections were inspected before each run and leaky or blown gaskets were replaced. Table 24 compares data taken with supposedly identical engines at different times.

Table 24

Comparison of Data - Identical Engines

Description of Test Run	Date of Test Run	Maximum Thrust	Minimum Specific Fuel
Modification C 8x132 Tailpipe 88 vanes, Hd.#7	2 June 1947	196	2.79
	3 October 1946	196	2.95
Modification C 8x132 Tailpipe 72 vanes, Hd.#5	2 June 1947	187	2.81
	3 October 1946	191	2.84
Modification F 8x132 Tailpipe 88 vanes, Hd.#7	1 October 1946	204	2.94
	12 June 1947	195	3.22
Modification F 8x132 Tailpipe 72 vanes, Hd.#5	1 October 1946	171	3.17
	10 June 1947	174	3.26

149. From Table 24, it can be seen that re-assembly of the engine, using new parts such as vanes, spray jets, combustion chamber and tailpipe sections, or changes in test stand or instruments do not greatly affect the ability of an engine to duplicate a performance. The largest variation in maximum thrust readings was about 3.7%.

150. It was observed that ambient air temperature had an effect upon engine efficiency as indicated by the specific fuel consumption. It was also observed that the static position of the vanes and the type of vane sandwich material had considerable influence on the maximum thrust obtained and upon the specific fuel consumption. These factors were not closely controlled; hence variations in them may account for small variations in similar runs conducted at different periods. Maxi-

DECLASSIFIED

DECLASSIFIED

mum variation of minimum specific fuel consumption was 8.7% in the case of Modification F, 88-vane and 8" by 132" tailpipe. Average variation in specific fuel consumption between similar runs at different periods was only 4.4%.

151. Other factors which probably affect repeatability of engine operation to a lesser degree are relative humidity, wind velocity and direction, and the disposition of the steam from the cooling water. No data were taken on relative humidity, or wind velocities. A centrifugal blower was used to force steam generated by the cooling water away from the grid assembly. This blower had no effect on thrust measurement since the force from it was merely sufficient to keep the grid clear of steam. Tests were not run on very windy days, particularly when the wind direction was opposite to that of the blower. The tests reported herewith were run between May and January and were not made on rainy or exceptionally cold days. While no attempt was made to control operating conditions other than those pertaining to the engine setup, it is felt that by operating on dry days, under average conditions of temperature and humidity, the accuracy of the data is within a maximum experimental error of 10%.

152. Comparison of Spiral-Weld and Smooth Tailpipes. A few special runs were made in order to determine the effect of the spiral-welded pipe. Fig. 87 shows the resulting curves of thrust and of specific fuel versus fuel rate. Two runs were made with a standard combustion chamber having a smooth, 8-inch-diameter tailpipe and two runs were made with an identical combustion chamber having a Taylor Forge spiral-welded tailpipe of the same length and diameter. Both runs with the smooth tailpipe produced higher maximum thrust and gave lower specific fuel than either of the two runs with the spiral-welded tailpipe. Since comparative data is not yet available for the entire series of modified chambers with both smooth and spiral-weld tailpipes, the accuracy of a correction factor on the basis of one chamber might be questionable. Moreover, these curves imply a qualitative improvement in performance with smooth tailpipes. This is probably due to less frictional loss than in the case of the spiral-weld. Since all observations relating to the various modifications were obtained using spiral-welded tailpipes, it is believed that specific fuels and maximum thrusts obtained are conservative.

XI. CONCLUSIONS

153. This experimental investigation has indicated that pulse jet performance is greatly affected by the mechanical design of the engine and, in particular, by the size and shape of the combustion chamber, the diameter and length of the tailpipe, the design of the head assembly, and the number of vanes in the grid assembly. For any given combustion chamber there seems to be an optimum number of vanes and an optimum length of tailpipe. These investigations also indicate the relative advantages of a number of different combustion chamber designs. Some particular combinations of parameters have produced minimum specific fuel values of 2.5 and less. It has been possible to operate practically any

DECLASSIFIED

DECLASSIFIED

design of combustion chamber but little prediction of relative merits could be made from information currently available in the literature. Hence it seems imperative that additional experimental work and interpretative analysis be carried out in order to afford a more adequate basis for rational design, and for prediction of characteristics.

XII. RECOMMENDATIONS

154. Experimentation should be continued in order to further study the pulse jet operation and performance. This group expects to continue research along the following lines:

1. Experimentation to increase thrust per unit cross-sectional area.
2. Experimentation to increase efficiency as indicated by lower values of specific fuel.
3. Investigation of the propagation of pressure waves in various modifications.
4. Study of fuels - powdered, multiple, and high energy types.
5. Temperature measurements of gases.
6. Gas analysis of combustion products.
7. Investigation of fuel distribution systems.
8. Investigation of flame velocities.
9. Investigation of gas velocities.
10. Investigation of multiple tube combinations.
    a. Tubes connected structurally and operated close to each other.
    b. Tubes with common components, (i.e., cowling, ducting, combustion chambers or exhaust nozzles).
    c. Tubes with interconnecting ducts.
11. Study of valve design in order to improve life and operating characteristics.

155. Other experimentation which this group does not have facilities to perform but which should be carried out in order to determine the full potentialities of the pulse jet are:

1. Investigation of the effect of ram air and of high air speed. This would include diffusers, ducting, and augmentation.
2. Determination of the relationship between static operation and flight operation.

CONFIDENTIAL
DECLASSIFIED

DECLASSIFIED

APPENDIX - I

1. General Information on The Pulse Jet. The pulse jet engine, also known as the intermittent jet or the Aëropulse, operates on an adapted Lenoir cycle utilizing oxygen from the atmosphere and a petroleum fuel. The engine operates with practically no compression, except for that obtained from the ram air when traveling at high speeds. It derives its propulsive force from conversion of the heat energy in the fuel into kinetic energy of hot gases by means of a combustion process starting at approximately atmospheric pressure.

2. This engine, unlike the gas turbine, has a definite cycle of operation. Air is induced into the combustion chamber through the vane-grid assembly in the front (see Fig. 1 and 1A) by the partial vacuum formed by the exhaust of the preceding cycle in leaving the tailpipe. The new charge of air mixes with the fuel which is sprayed continously into the combustion chamber through atomization jets. This air-fuel mixture is ignited by any residual hot burned gases or over-rich slow burning mixture which may be left over from the preceding cycle. This combustion process, however, is not yet completely understood. The ignited air-fuel mixture then burns very rapidly, raising the pressure in the combustion chamber to 15 or 20 psig. This increased pressure closes the vanes at the intake (grid assembly) and the gas is forced to expand through the tailpipe, being discharged at high speed. The high-speed discharge of the hot gases through the tail or exhaust pipe forms a partial vacuum in the combustion chamber, opening up the vanes (intake valves) and thus inducing air for the next cycle. The process of mixing, burning, and expansion are then repeated.

3. In starting the engine, it is necessary to use an air blast through the front of the vanes in order to get the initial air and fuel mixed. Also, a spark plug is used to ignite the initial cycles. After the engine begins to resonate, the spark is not necessary and may be turned off.

4. The frequency of operation varies from 30 to 250 cycles per second depending mainly upon the dimensions of the engine. Other factors affecting operating frequency are the fuel rate and the number of vanes in the grid assembly. It is desirable for the engine to operate at as high a frequency as possible because this makes for smoother operation. Also, a very rapid pressure rise (detonation) is desirable because this enables the mixture to rise to a higher pressure giving a greater average thrust, (or thrust). There is a definite correlation between maximum pressure and average thrust.

ACKNOWLEDGEMENTS.

This investigation of pulse jets has been directed by L. F. Campbell. Experimentation was performed at the Chesapeake Bay Annex of the Naval Research Laboratory. Experimental operation has been supervised by G. C. Milak with the assistance of D. W. Baker and C. D. Porter. Instrumentation has been the responsibility of T. O. Meyer. This report has been prepared by D. W. Baker, G. C. Milak, and C. D. Porter, with the assistance of H. H. Loose and the general supervision of T. O. Meyer.

CONFIDENTIAL
DECLASSIFIED

DECLASSIFIED

REFERENCE LIST.

Reference (1). Jet Propulsion, a reference text prepared by the staffs of the Guggenheim Aeronautical Laboratory and the Jet Propulsion Laboratory, Galcit, California Institute of Technology, for the Air Technical Service Command. 1946.

Reference (2). A Summary of Design Performance Characteristics and Possible Future Improvements of the Pulse Jet Engine, by H. E. Carlson; Hughes Aircraft Company, Culver City, California. November 12, 1946.

Reference (3). Gas-Dynamic Investigations of the Pulse-Jet Tube Parts I and II; by F. Shultz-Grunow; Technical High School, Aachen, Germany. NACA Technical Memo., No. 1131, Washington, February 1947.

Reference (4). Combustion of Solid Fuels for Ram Jets, Bureau of Mines Progress Report #3, Project NAer 00597.

Reference (5). NRL Report O-2650 of 24 September 1945.

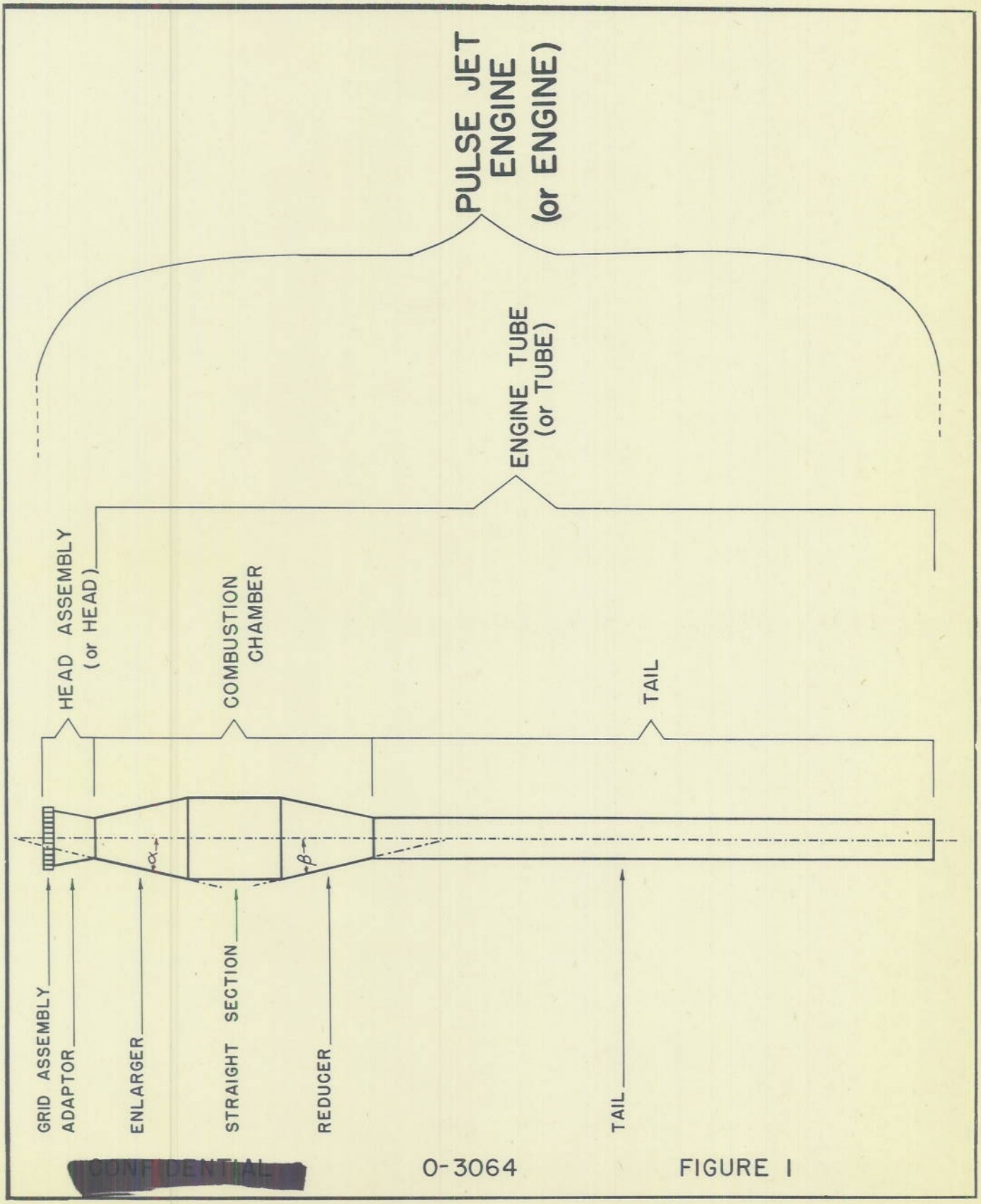
Reference (6). NRL Report O-2730 of 2 January 1946.

Reference (7). NRL Report O-2859 of 14 October 1946.

Original Data recorded in NRL log books Nos. 5453, 6082, and 6712.

CONFIDENTIAL SSIFIED

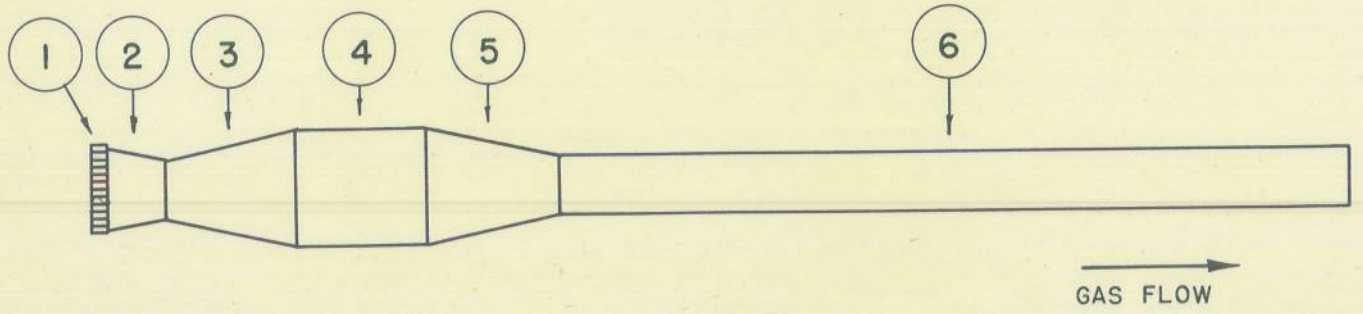
DECLASSIFIED



[redacted] 0-3064 FIGURE 1

DECLASSIFIED

CONFIDENTIAL



1. = GRID ASSEMBLY
2. = ADAPTOR
} SEE FIGURES # 5, 6 & 7.

1 & 2. = ASSEMBLY (or HEAD)

3. = ENLARGER

4. = STRAIGHT SECTION

5. = REDUCER

3, 4 & 5. = COMBUSTION CHAMBER

6. = TAIL

3, 4, 5 & 6. = ENGINE TUBE (or TUBE)

1, 2, 3, 4, 5 & 6. = **PULSE JET ENGINE (or ENGINE)**

0-3064

ADAPTOR NUMBER	1.	2.	3.	4.	5.	6.	7.	8.	9.
ADAPTOR VOLUME	77.6 IN^3	77.6 IN^3	195.2 IN^3	195.2 IN^3	195.2 IN^3	311.35 IN^3	311.35 IN^3	323.8 IN^3	462.8 IN^3

FIGURE 1A

NOTATIONS USED IN REPORT

DECLASSIFIED

DECLASSIFIED

DECLASSIFIED



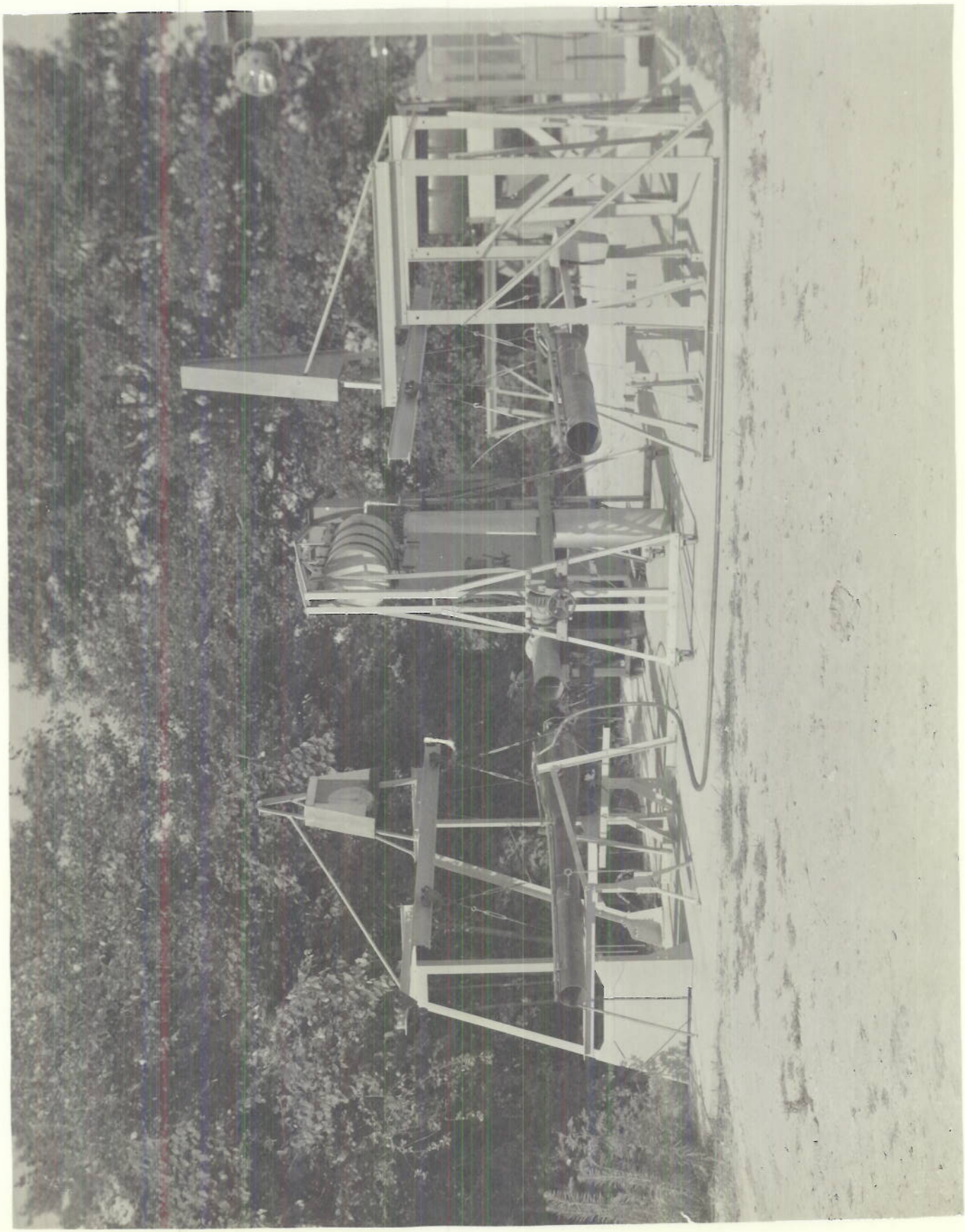
DECLASSIFIED

CONFIDENTIAL

FIG. 2

THRUST AND CONTROL STANDS (FRONT VIEW)

DECLASSIFIED



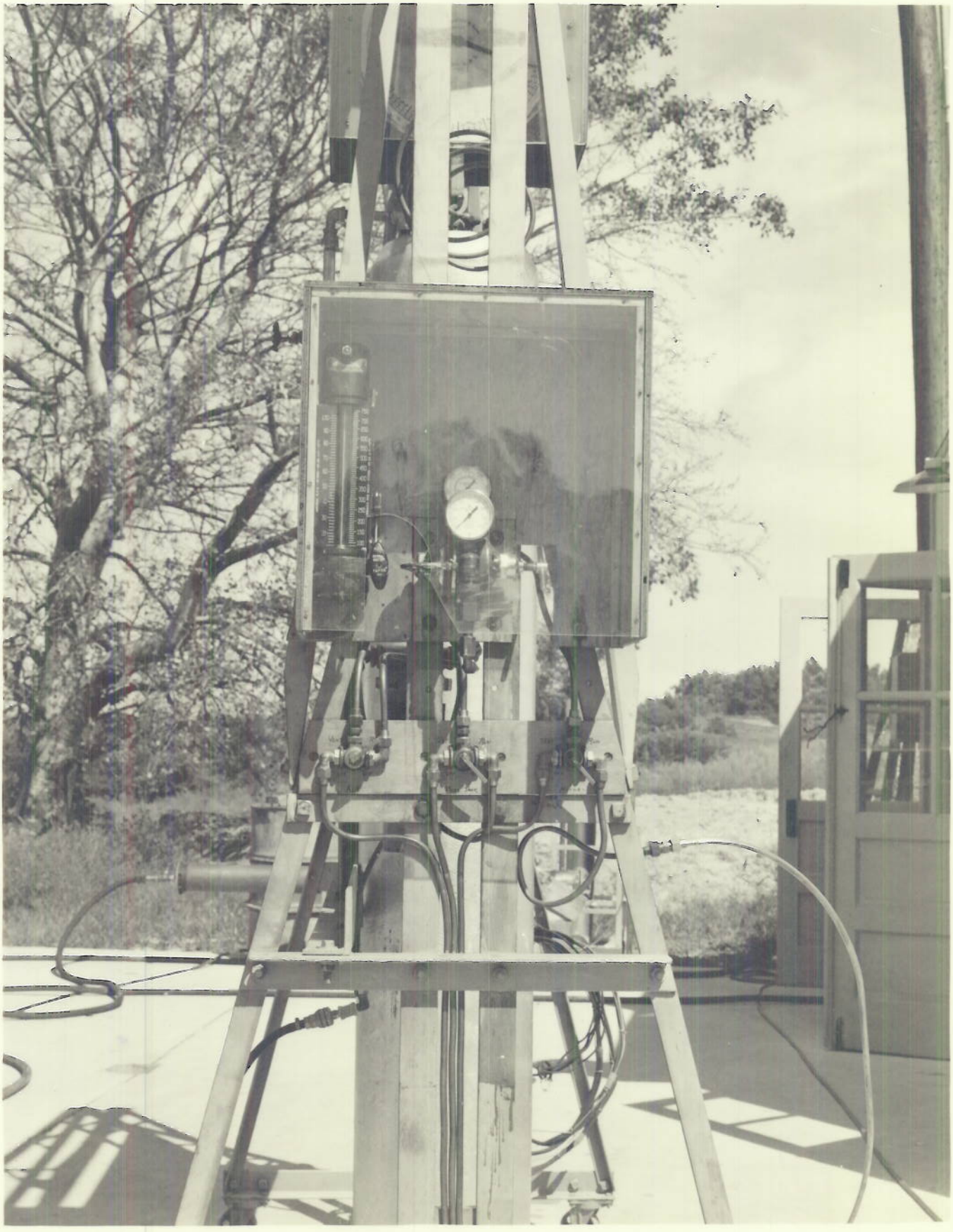
DECLASSIFIED

[redacted]

FIG. 3

THRUST AND CONTROL STANDS (REAR VIEW)

DECLASSIFIED



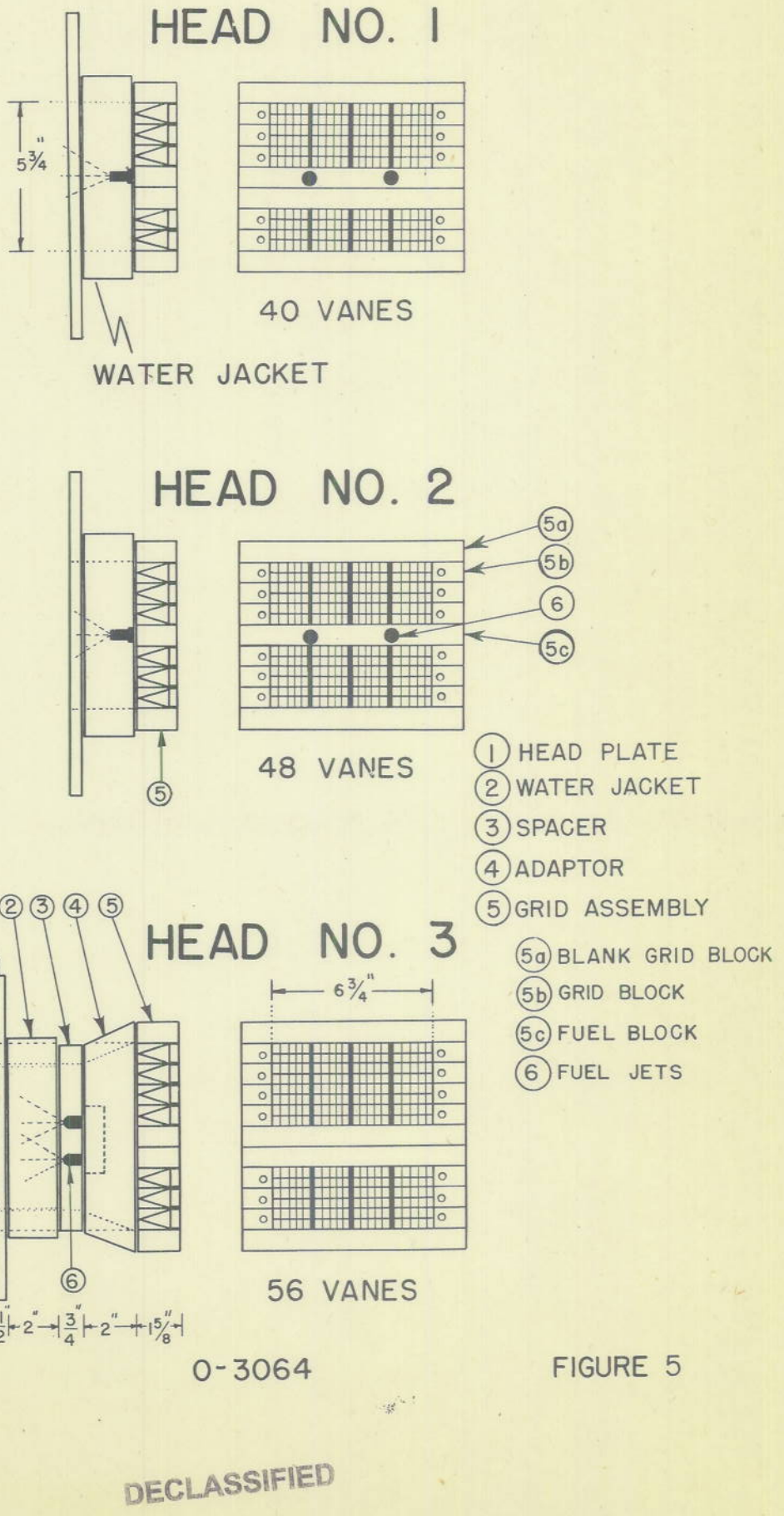
DECLASSIFIED

[redacted]

CONTROL STAND (FRONT VIEW)

FIG. 4

DECLASSIFIED



CONFIDENTIAL

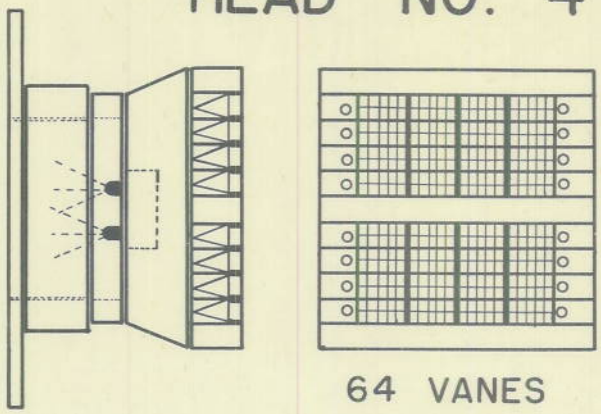
0-3064

FIGURE 5

DECLASSIFIED

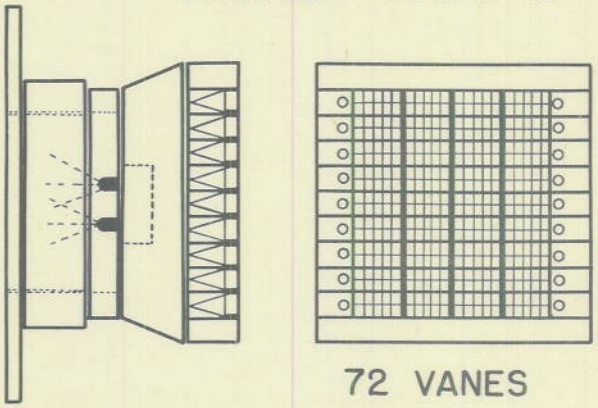
DECLASSIFIED

HEAD NO. 4



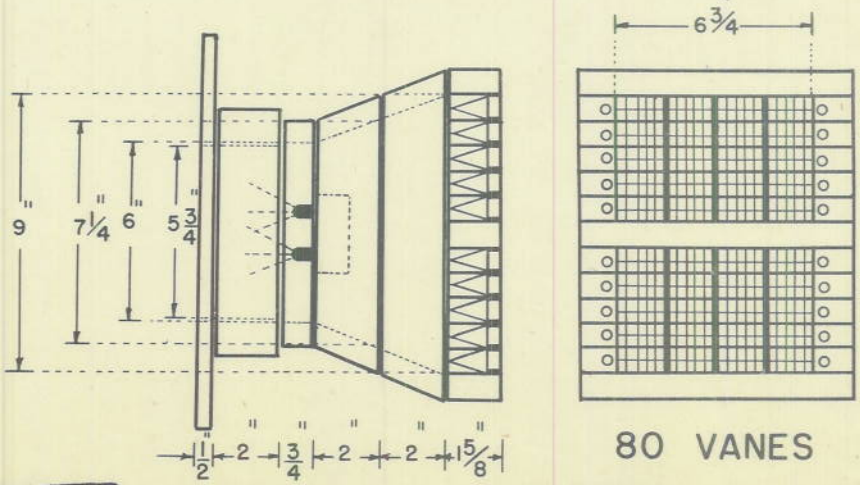
64 VANES

HEAD NO. 5



72 VANES

HEAD NO. 6



80 VANES

CONFIDENTIAL

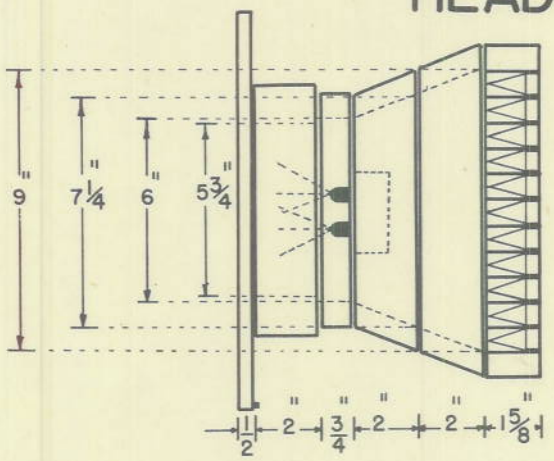
0-3064

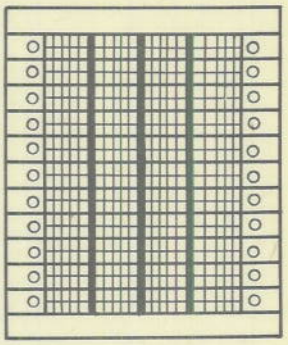
FIGURE 6

DECLASSIFIED

DECLASSIFIED

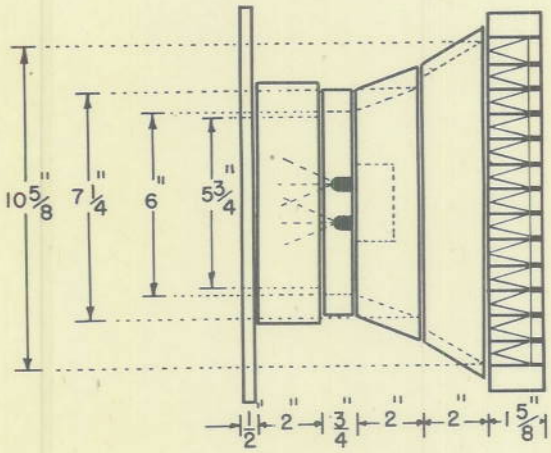
HEAD NO. 7

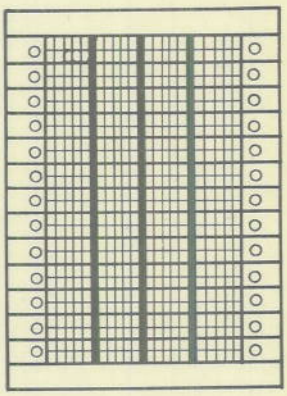




88 VANES

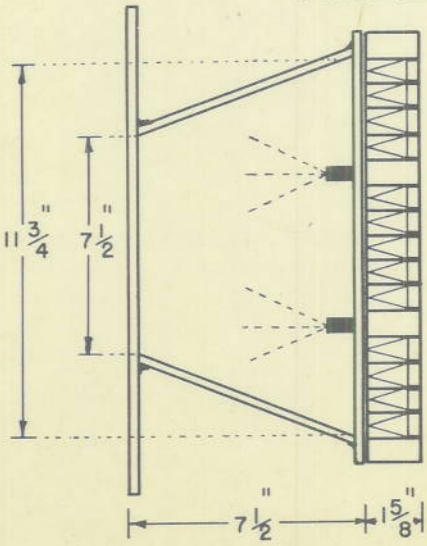
HEAD NO. 8

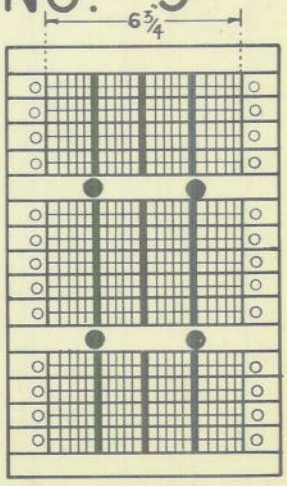




104 VANES

HEAD NO. 9





104 VANES

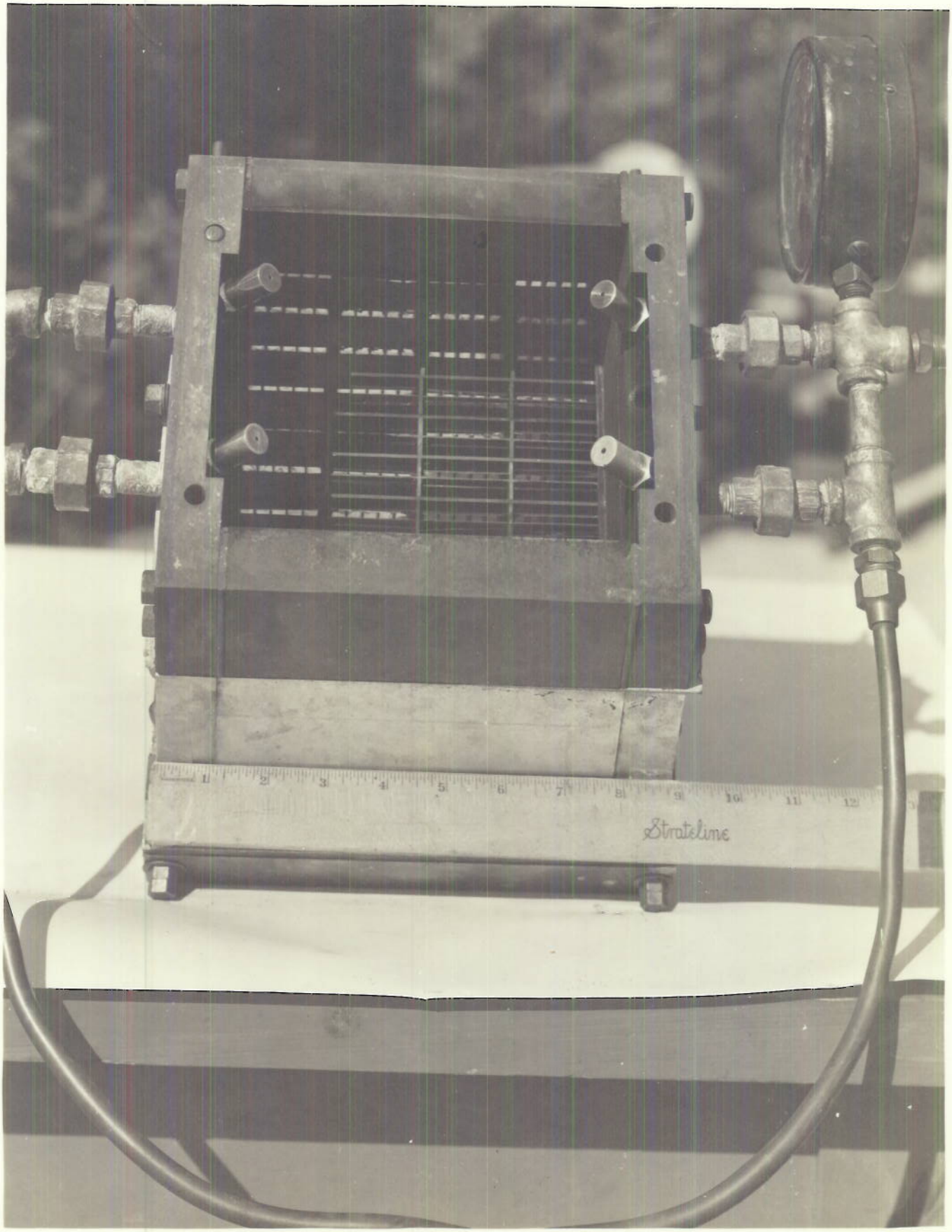
CONFIDENTIAL

0-3064

FIGURE 7

DECLASSIFIED

DECLASSIFIED



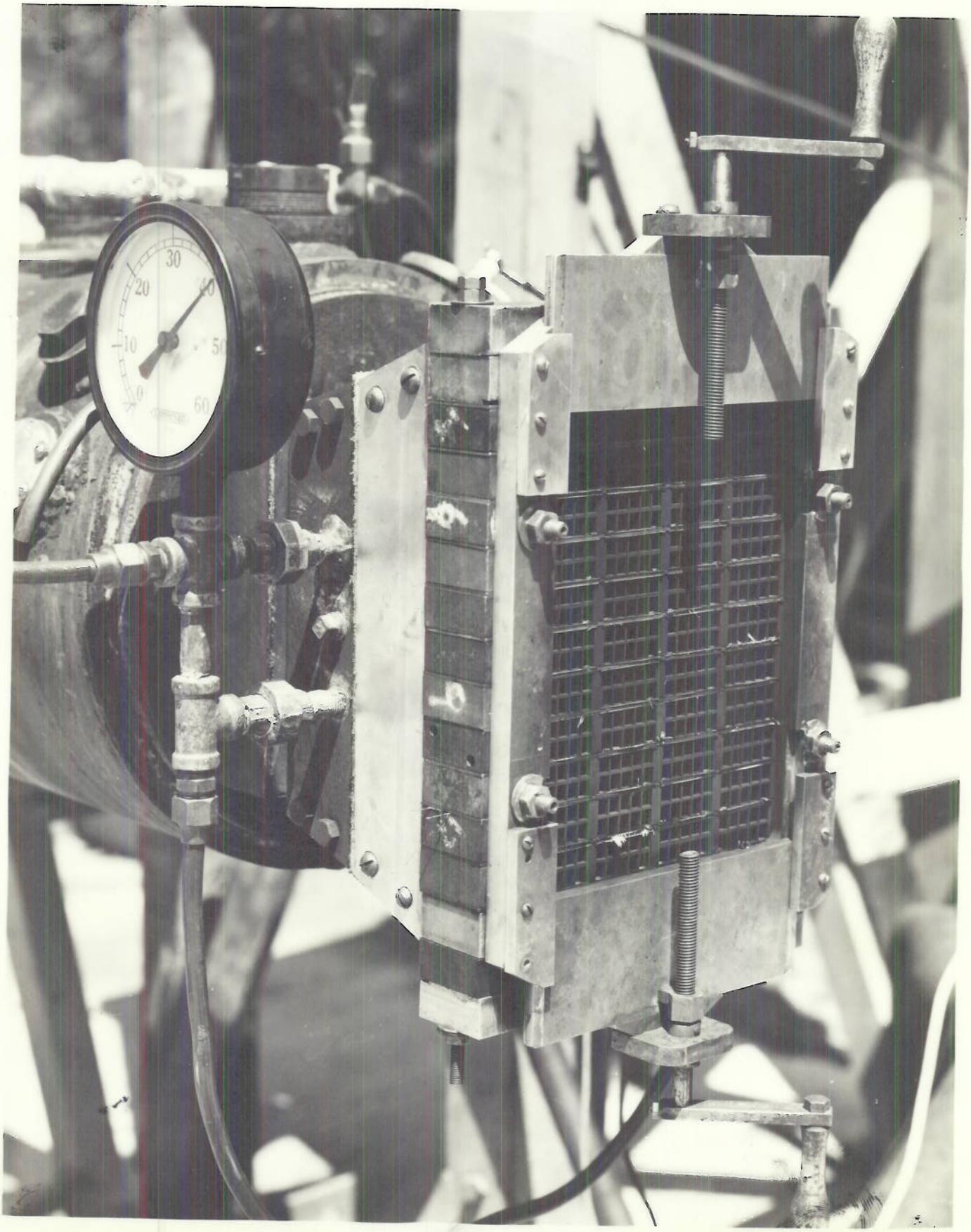
DECLASSIFIED

CONFIDENTIAL

POSITION OF JETS INSIDE - ENTRY FUEL BLOCK

FIG. 8

DECLASSIFIED



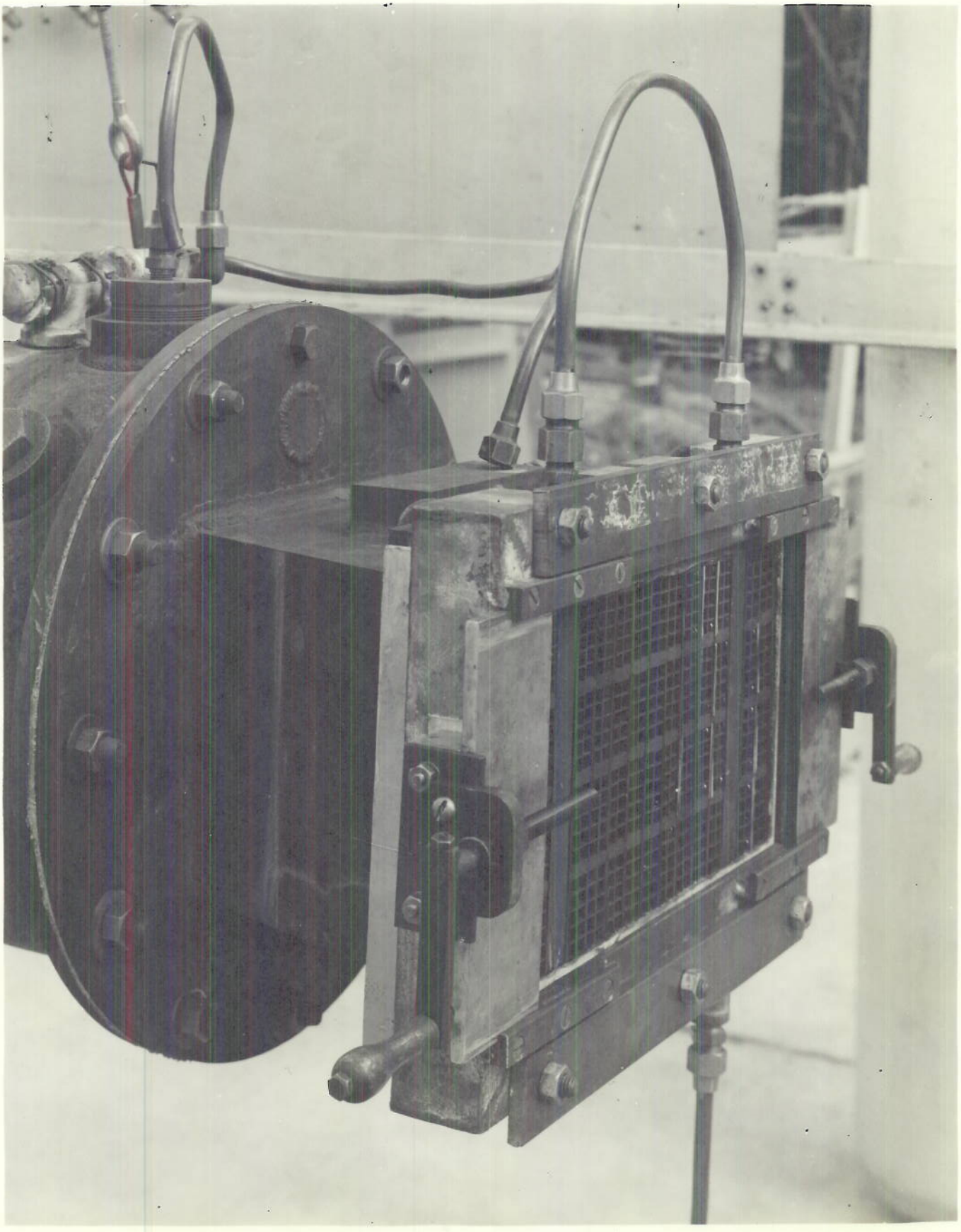
DECLASSIFIED

CONFIDENTIAL

HEAD NO. 7, WITH ADJUSTABLE SHUTTER

FIG. 9

DECLASSIFIED



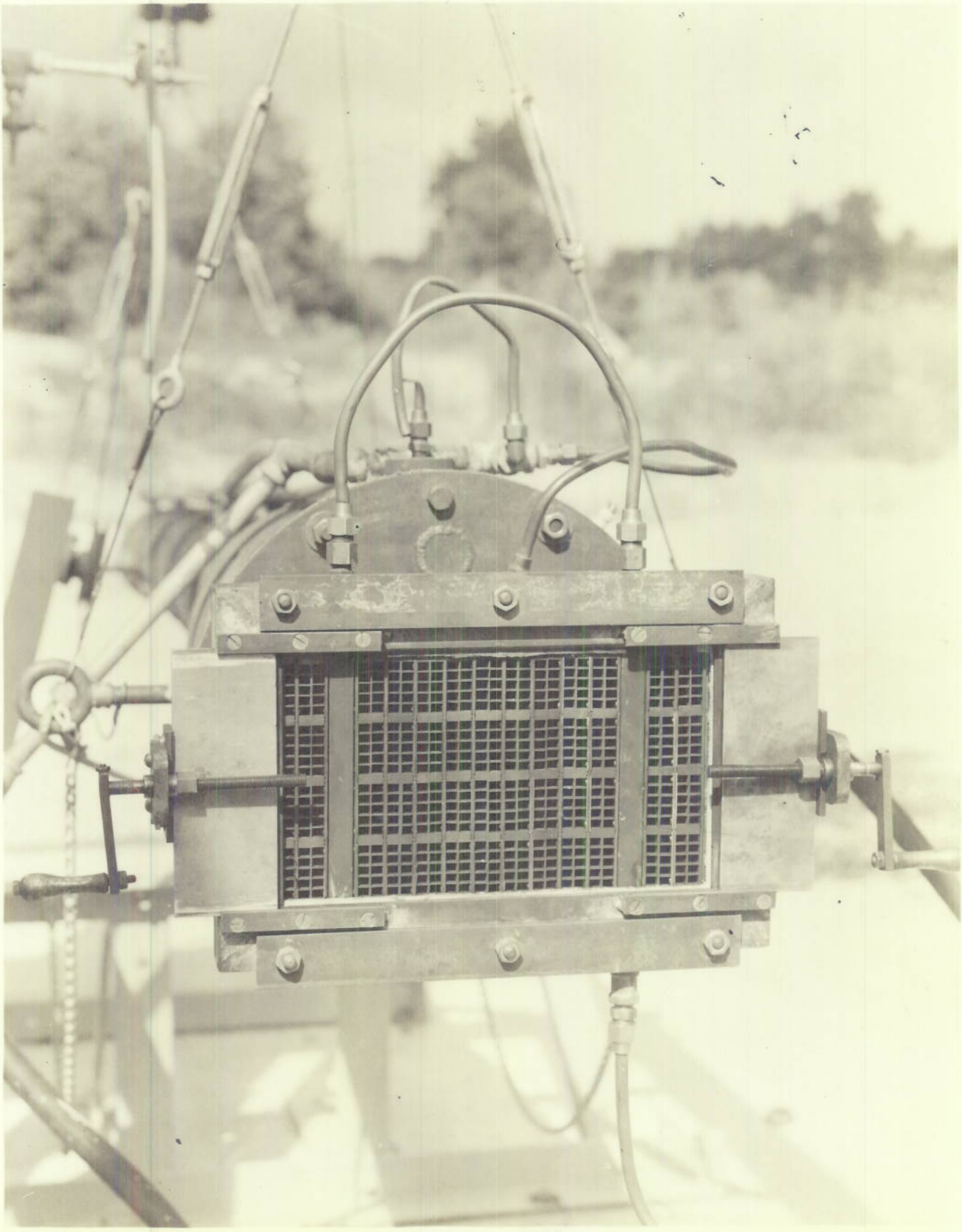
DECLASSIFIED

CONFIDENTIAL

HEAD NO. 9 WITH ADJUSTABLE SHUTTER

FIG. 10

DECLASSIFIED



DECLASSIFIED

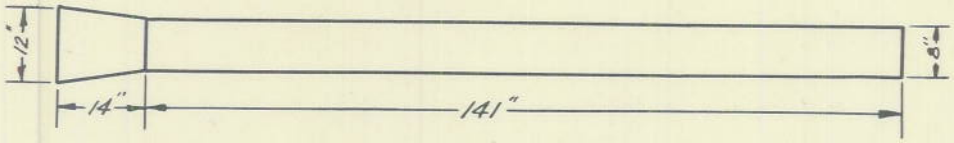
CONFIDENTIAL

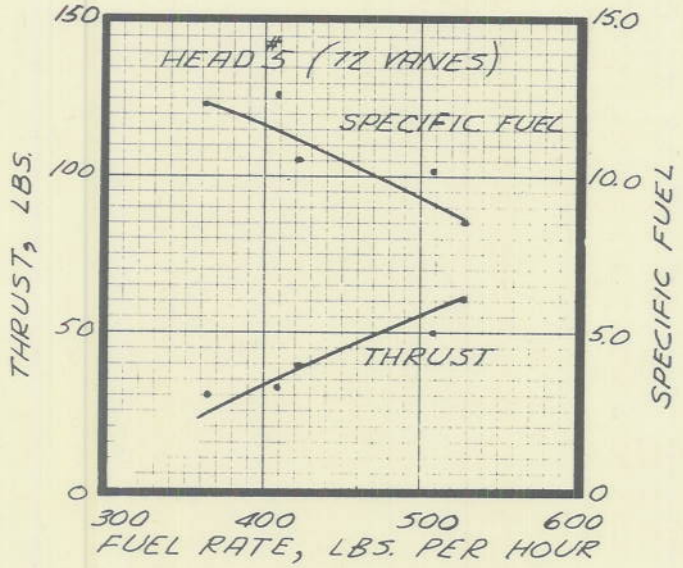
HEAD NO. 9 WITH ADJUSTABLE SHUTTER, (FRONT VIEW)

FIG. 11

DECLASSIFIED

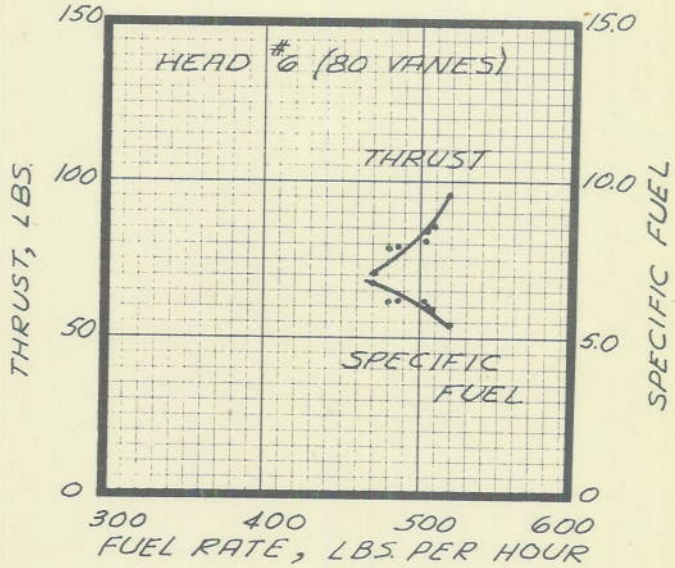
MODIFICATION "A"





MAX. THRUST = 62
MIN. SPECIFIC FUEL = 8.5
FREQ. RANGE = 2880-2900

MAX. THRUST = 96
MIN. SPECIFIC FUEL = 5.40
FREQ = 2900 @ 480-500 #/FUEL



[redacted]

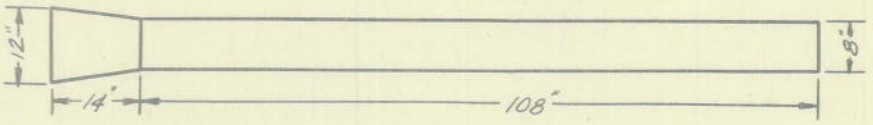
0-3064

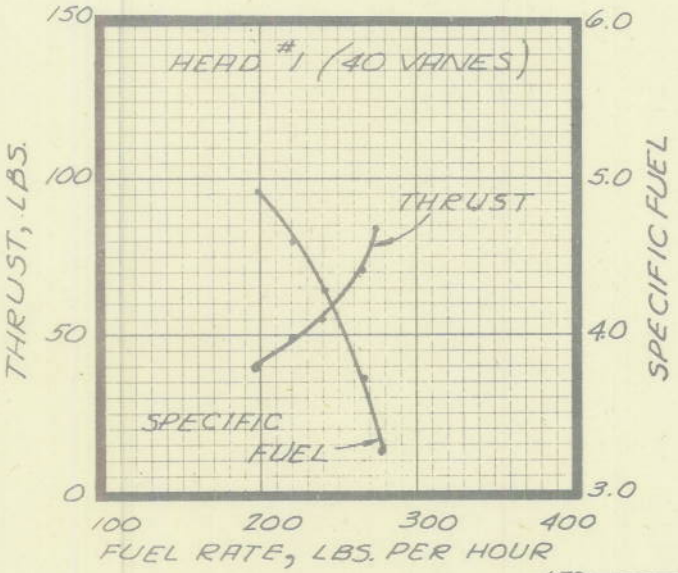
FIGURE 12

DECLASSIFIED

DECLASSIFIED

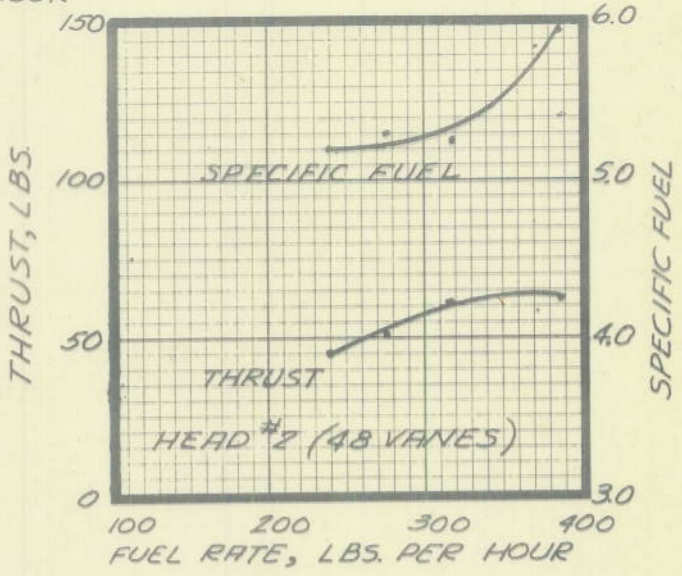
MODIFICATION "A"





MAX. THRUST = 84
MIN. SPECIFIC FUEL = 3.26
FREQ. RANGE = 3450-3800

MAX. THRUST = 64
MIN. SPECIFIC FUEL = 5.21
FREQ. RANGE = 3550-3750



[redacted]

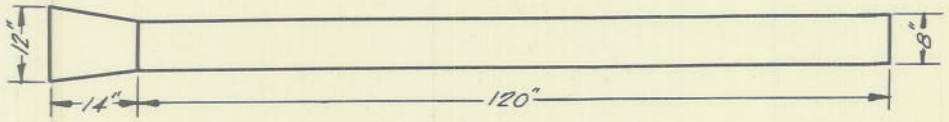
0-3064

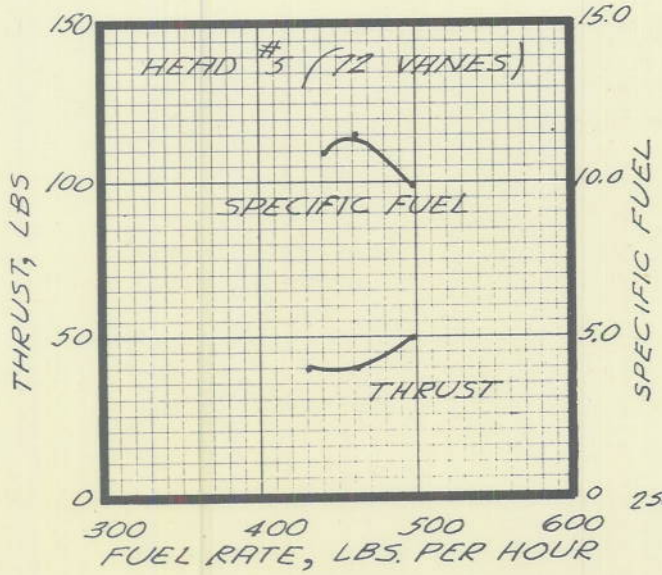
FIGURE 13

DECLASSIFIED

DECLASSIFIED

MODIFICATION "A"

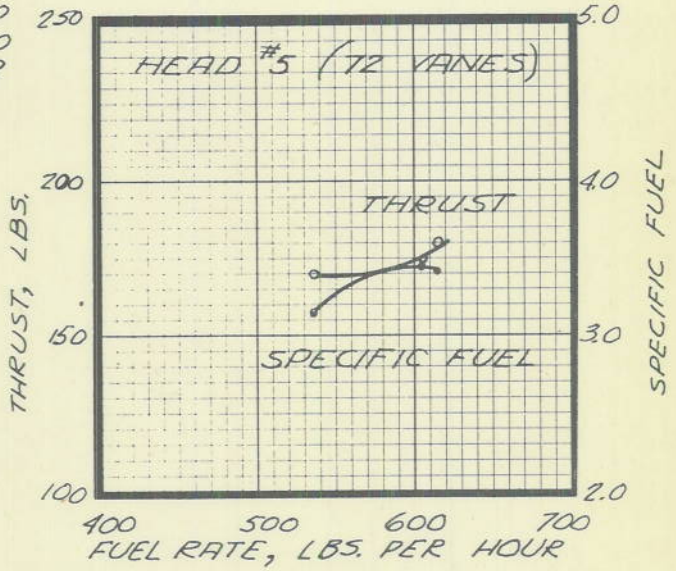


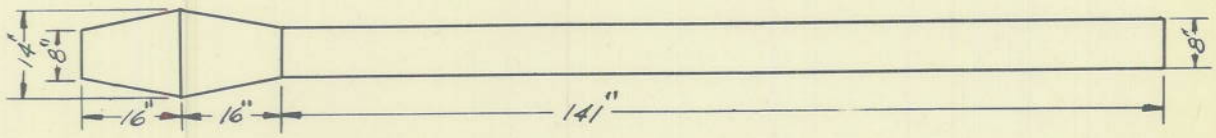


MAX. THRUST = 50
MIN. SPECIFIC FUEL = 9.9
FREQ. RANGE = 3300-3350

MAX. THRUST = 180
MIN. SPECIFIC FUEL = 3.16
FREQ. RANGE = 1900-2200

MODIFICATION "B"





CONFIDENTIAL

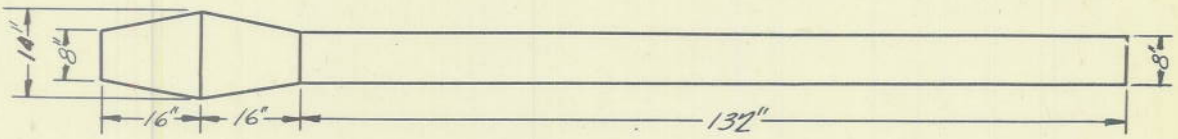
O-3064

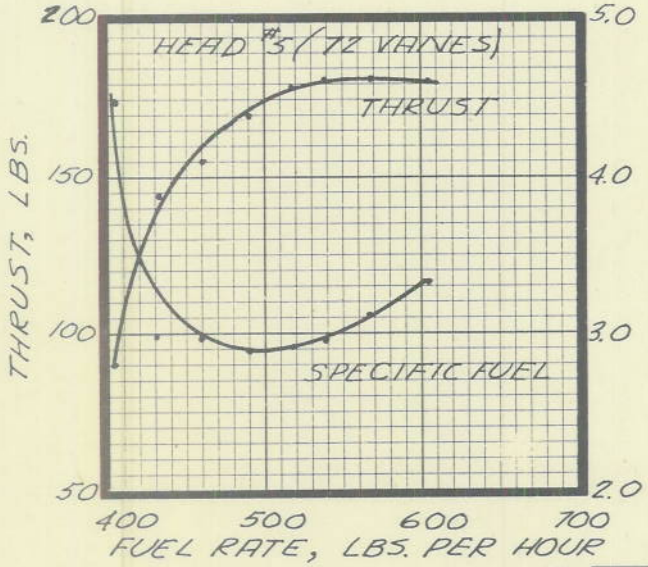
FIGURE 14

DECLASSIFIED

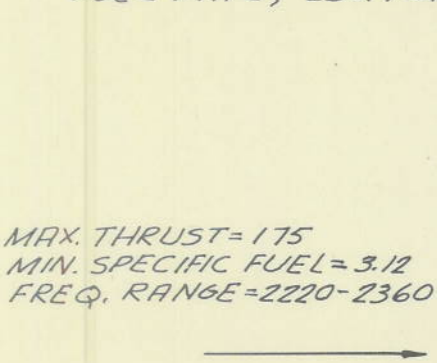
DECLASSIFIED

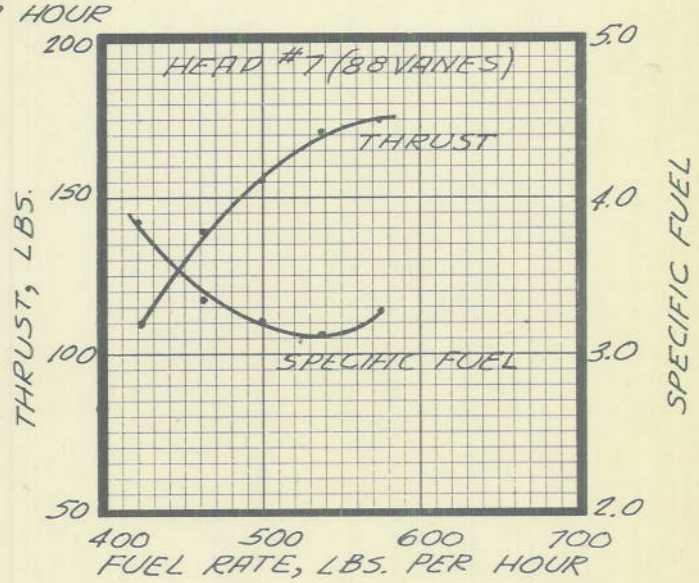
MODIFICATION "B"





MAX. THRUST = 182
MIN. SPECIFIC FUEL = 2.88
FREQ. RANGE = 2060-2400





MAX. THRUST = 175
MIN. SPECIFIC FUEL = 3.12
FREQ. RANGE = 2220-2360

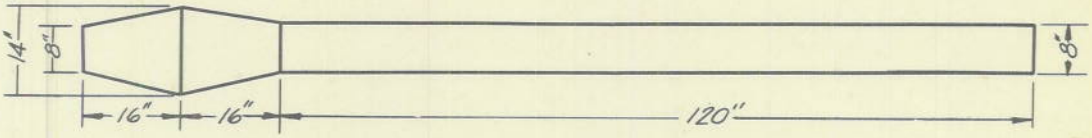
CONFIDENTIAL

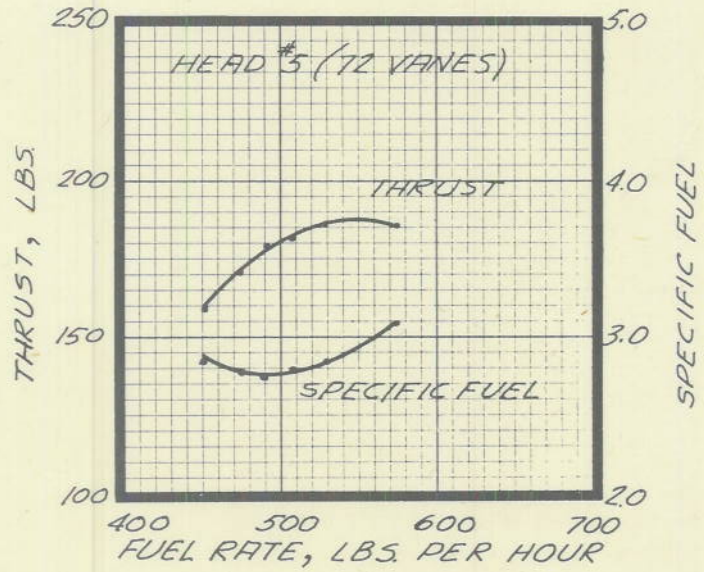
FIGURE 15

DECLASSIFIED

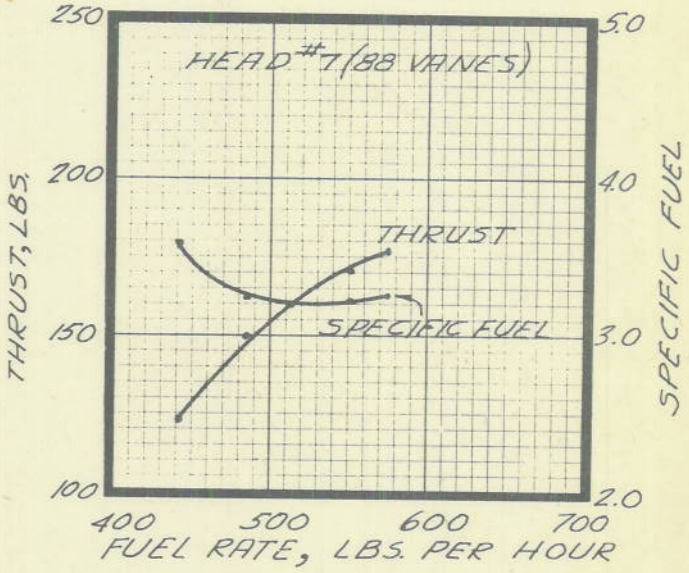
DECLASSIFIED

MODIFICATION "B"





MAX. THRUST = 186
MIN. SPECIFIC FUEL = 2.75
FREQ. RANGE = 2200-2300



MAX. THRUST = 177
MIN. SPECIFIC FUEL = 321
FREQ. RANGE = 2320-2500

CONFIDENTIAL

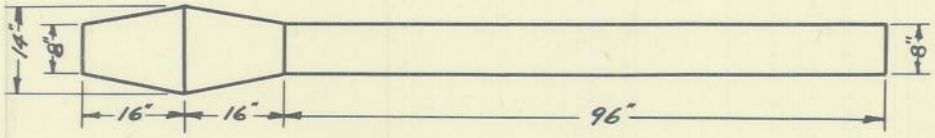
O-3064

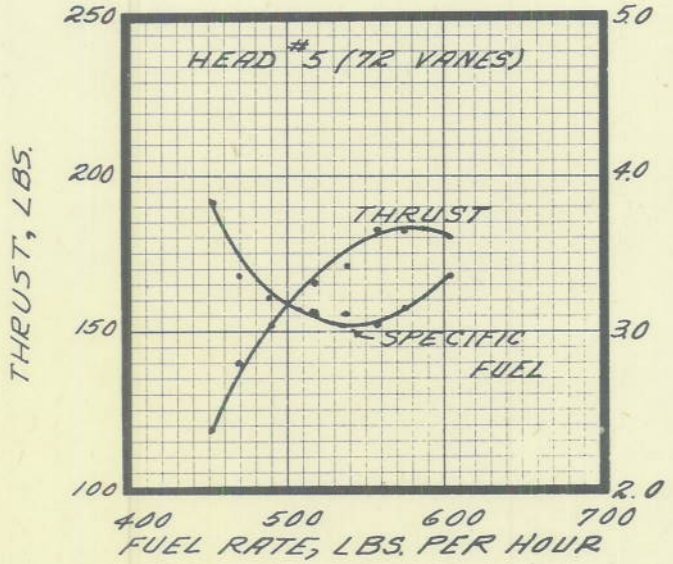
FIGURE 16

DECLASSIFIED

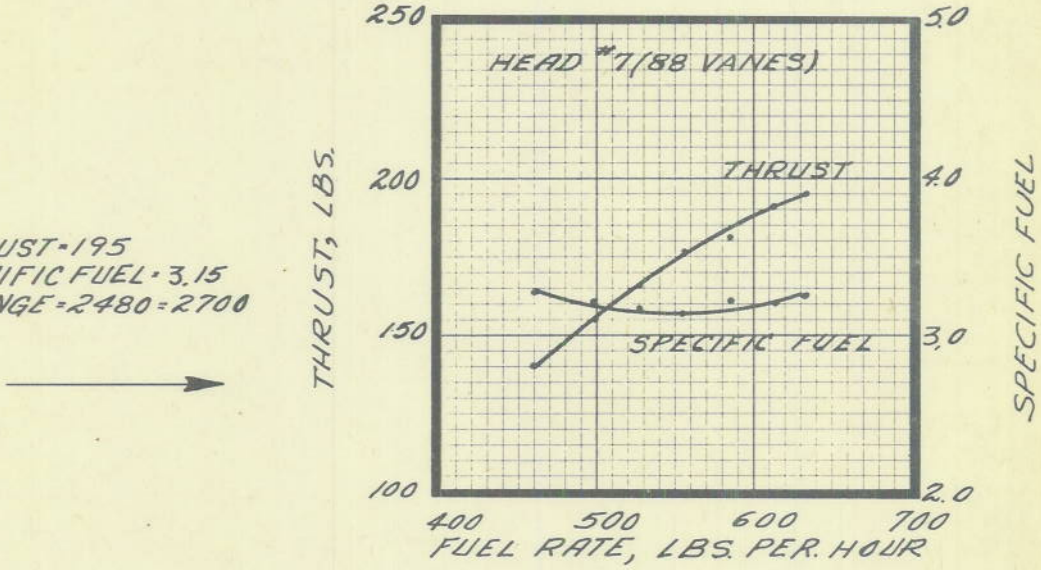
DECLASSIFIED

MODIFICATION "B"





MAX. THRUST = 183
MIN. SPECIFIC FUEL = 3.04
FREQ. RANGE = 2490-2650



MAX. THRUST = 195
MIN. SPECIFIC FUEL = 3.15
FREQ. RANGE = 2480 = 2700

CONFIDENTIAL

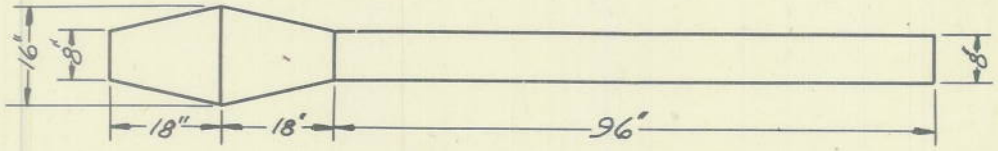
O-3064

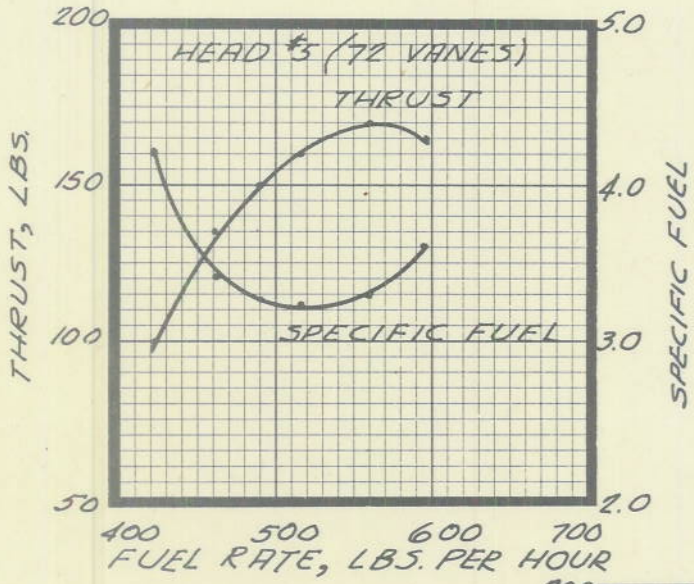
FIGURE 17

DECLASSIFIED

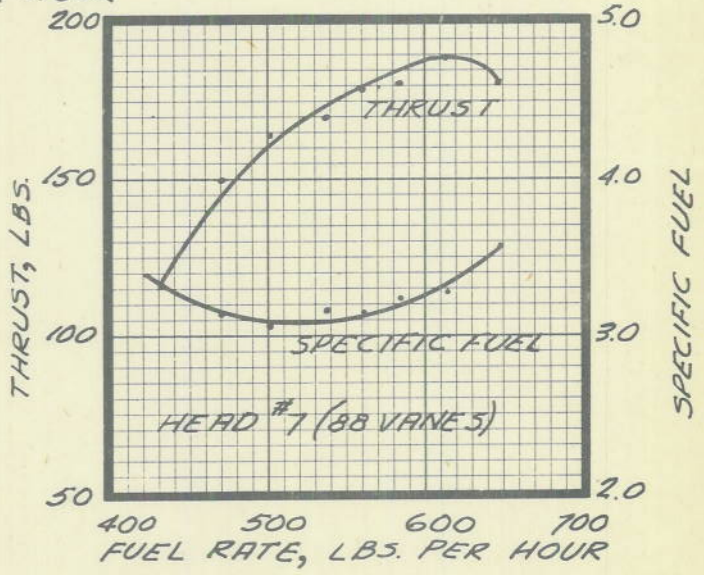
DECLASSIFIED

MODIFICATION "C"





MAX. THRUST = 170
MIN. SPECIFIC FUEL = 3.24
FREQ. RANGE = 2300-2660



MAX. THRUST = 188
MIN. SPECIFIC FUEL = 3.07
FREQ. RANGE = 2310-2480

CONFIDENTIAL

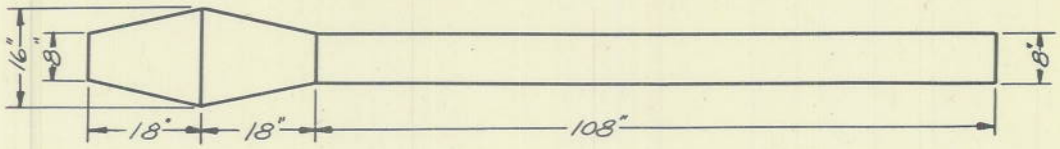
O-3064

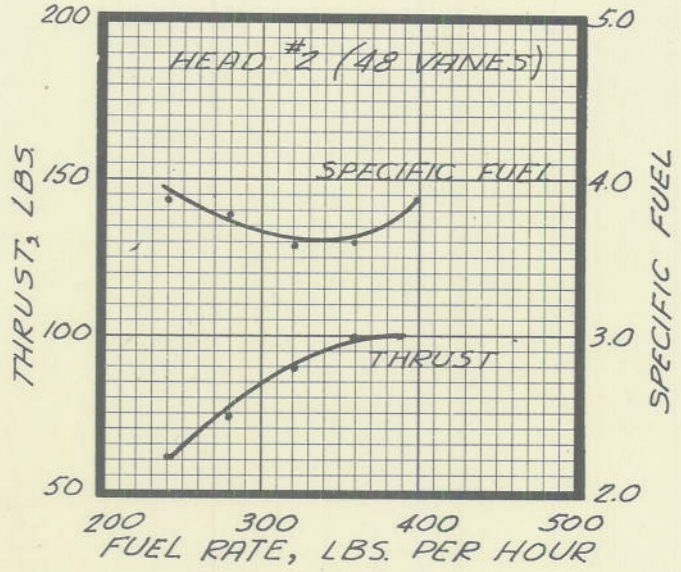
FIGURE 18

DECLASSIFIED

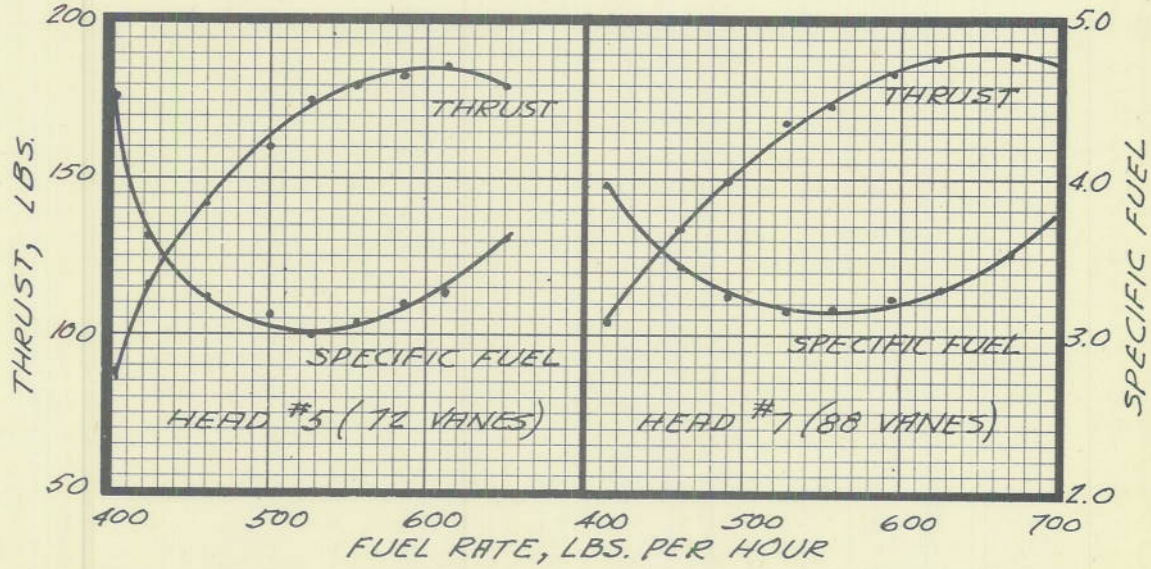
DECLASSIFIED

MODIFICATION "C"





MAX. THRUST = 100
MIN. SPECIFIC FUEL = 3.58
FREQ. RANGE = 2100-2400



MAX. THRUST = 187
MIN. SPECIFIC FUEL = 3.00
FREQ. RANGE = 2160-2500

MAX. THRUST = 190
MIN. SPECIFIC FUEL = 3.15
FREQ. RANGE = 2250-2420

CONFIDENTIAL

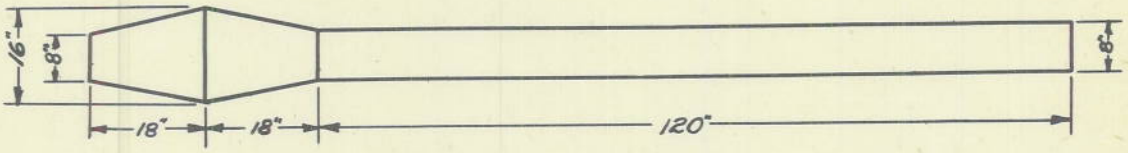
0-3064

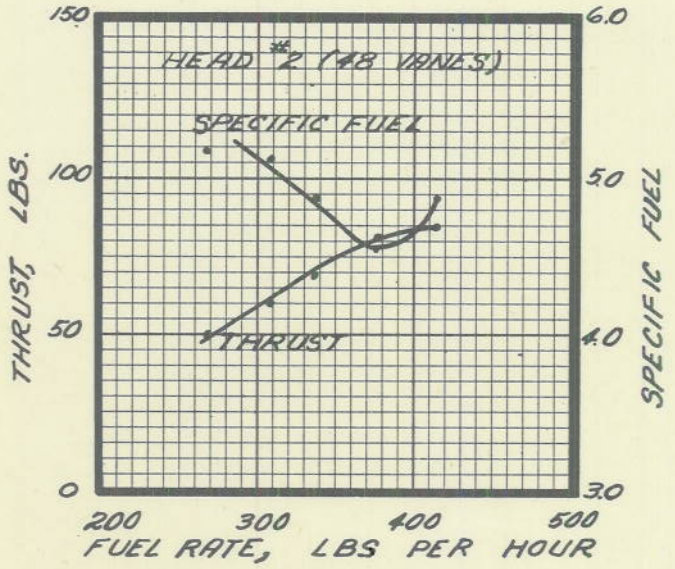
FIGURE 19

DECLASSIFIED

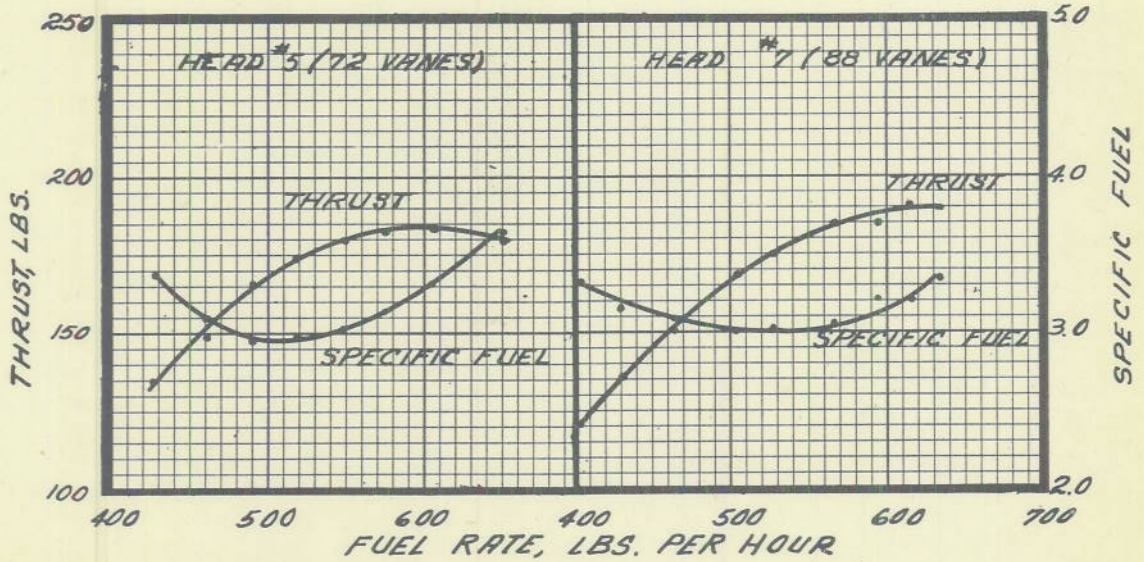
DECLASSIFIED

MODIFICATION "C"





MAX. THRUST = 85
MIN. SPECIFIC FUEL = 4.57
FREQ. RANGE = 2110-2300



MAX. THRUST = 183
MIN. SPECIFIC FUEL = 2.96
FREQ. RANGE = 2020-2280

MAX. THRUST = 192
MIN. SPECIFIC FUEL = 3.00
FREQ. RANGE = 2110-2310

CONFIDENTIAL

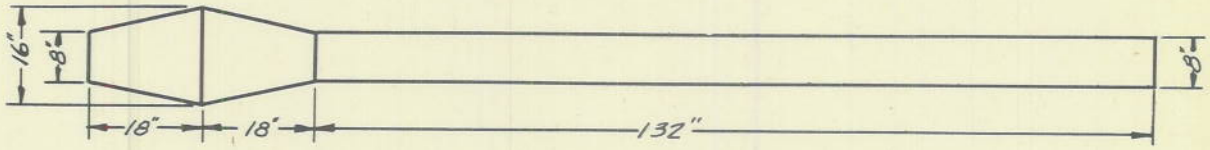
0-3064

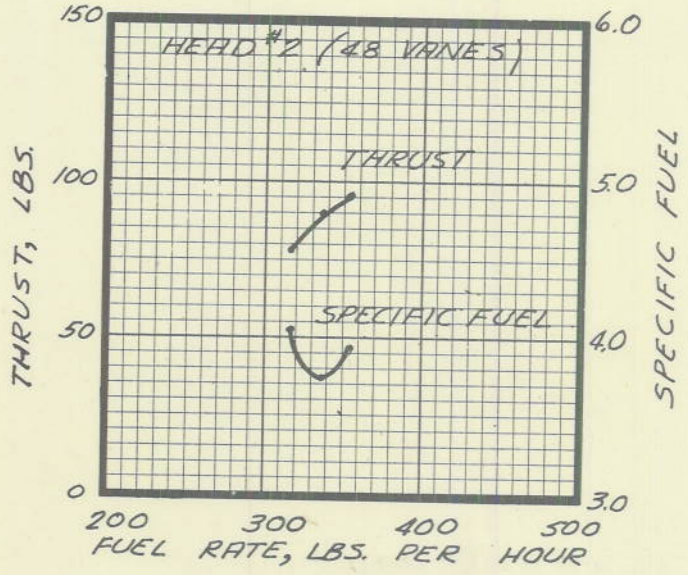
FIGURE 20

DECLASSIFIED

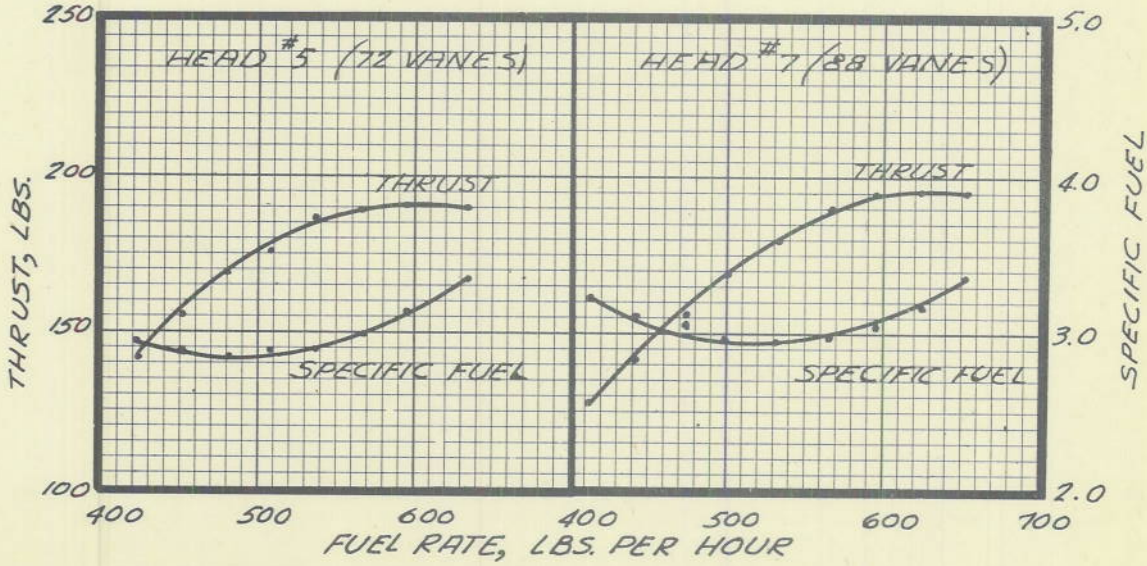
DECLASSIFIED

MODIFICATION "C"





MAX. THRUST = 96
MIN. SPECIFIC FUEL = 3.74
FREQ. RANGE = 1980-2050



MAX. THRUST = 191
MIN. SPECIFIC FUEL = 2.84
FREQ. RANGE = 1920-2220

MAX. THRUST = 196
MIN. SPECIFIC FUEL = 2.95
FREQ. RANGE = 1990-2250

CONFIDENTIAL

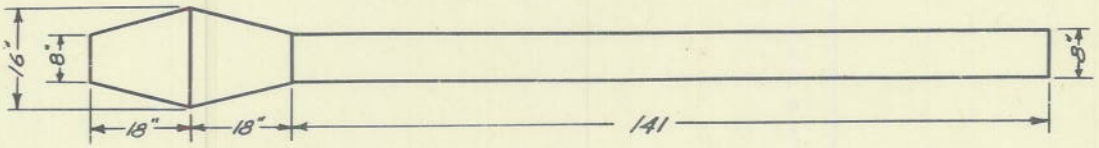
0-3064

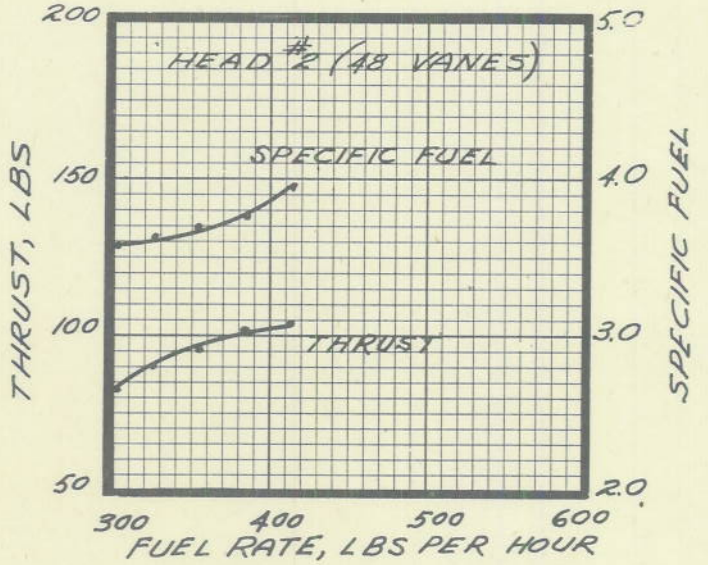
FIGURE 21

DECLASSIFIED

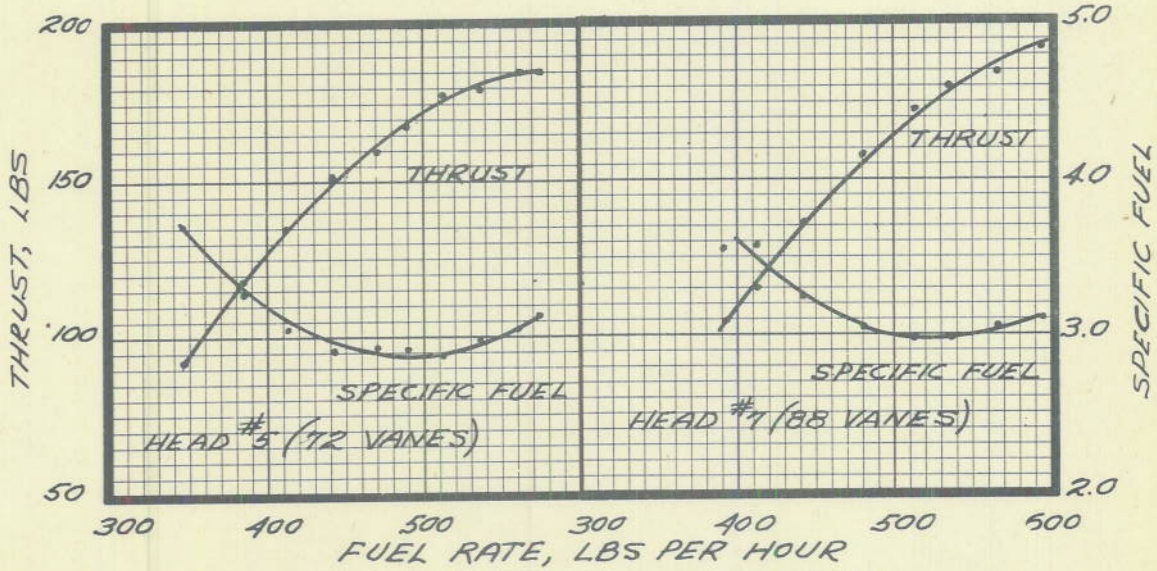
DECLASSIFIED

MODIFICATION "C"





MAX THRUST = 104
MIN SPECIFIC FUEL = 3.57
FREQ. = 1960 @ 300 LBS FUEL



MAX. THRUST = 185
MIN. SPECIFIC FUEL = 2.89
FREQ RANGE = 1900 - 2100

MAX THRUST = 195
MIN SPECIFIC FUEL = 2.97
FREQ = 1925 @ 595 LBS FUEL

CONFIDENTIAL

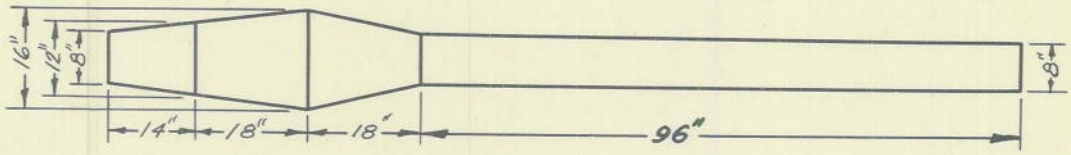
O-3064

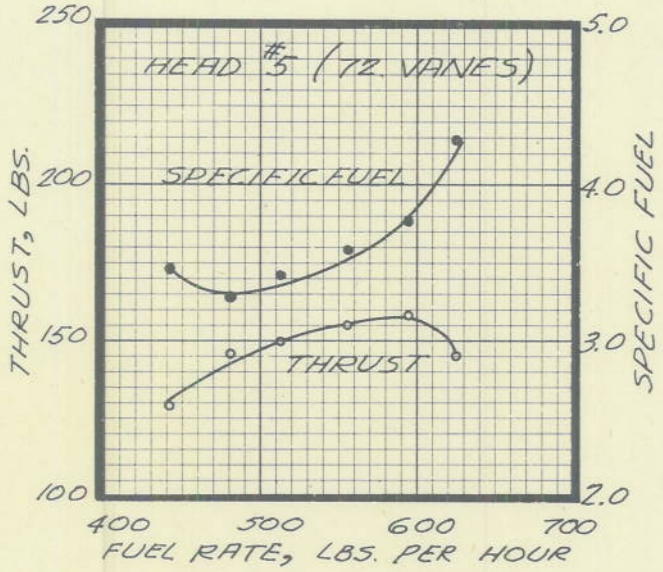
FIGURE 22

DECLASSIFIED

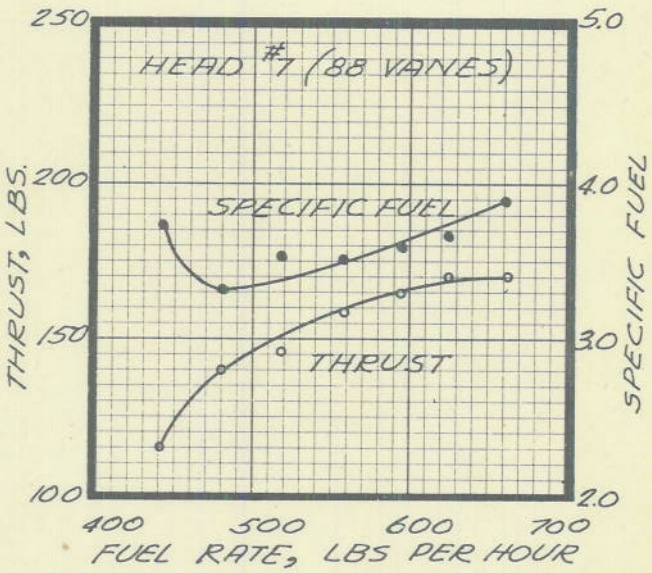
DECLASSIFIED

MODIFICATION "D"





MAX. THRUST = 157
MIN SPECIFIC FUEL = 3.29
FREQ. RANGE = 1780-2000



MAX. THRUST = 170
MIN. SPECIFIC FUEL = 3.32
FREQ RANGE = 1800-2125

CONFIDENTIAL

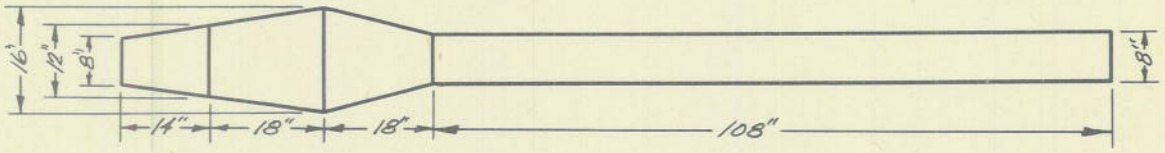
0-3064

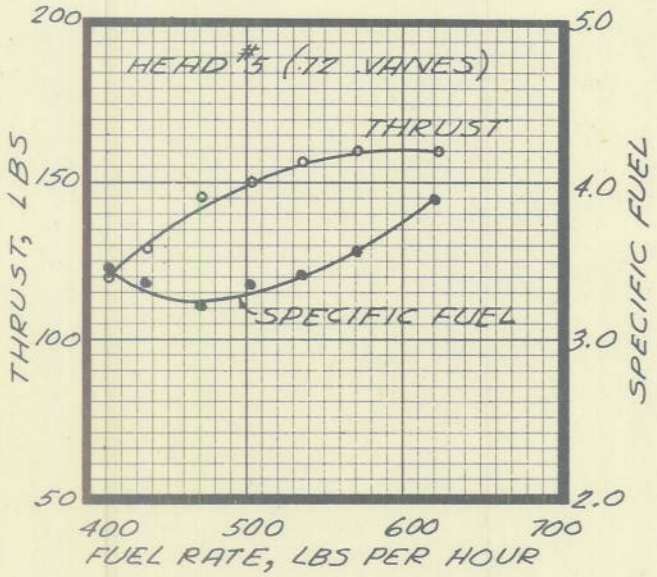
FIGURE 23

DECLASSIFIED

DECLASSIFIED

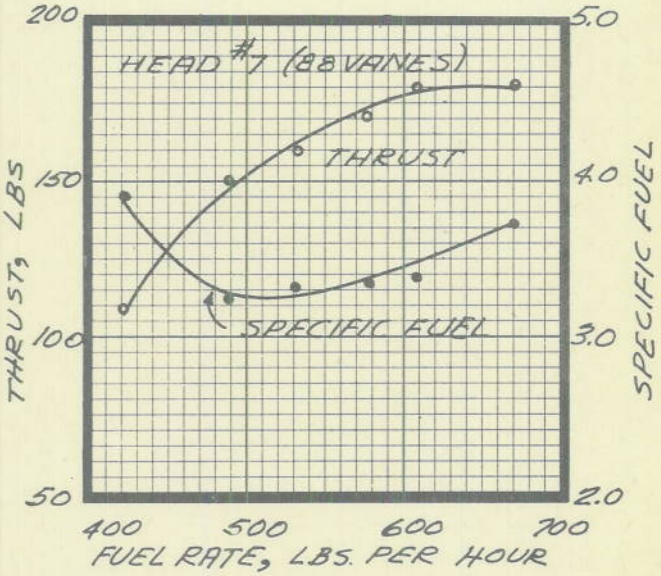
MODIFICATION "D"





MAX. THRUST = 160
MIN. SPECIFIC FUEL = 3.22
FREQ. RANGE = 1750 - 2200

MAX. THRUST = 180
MIN. SPECIFIC FUEL = 3.26
FREQ RANGE = 1810 - 2090



CONFIDENTIAL

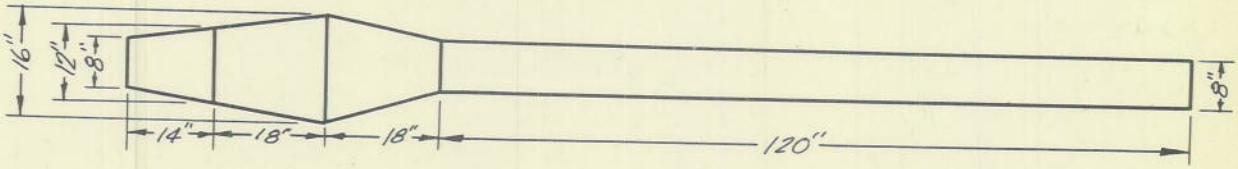
0-3064

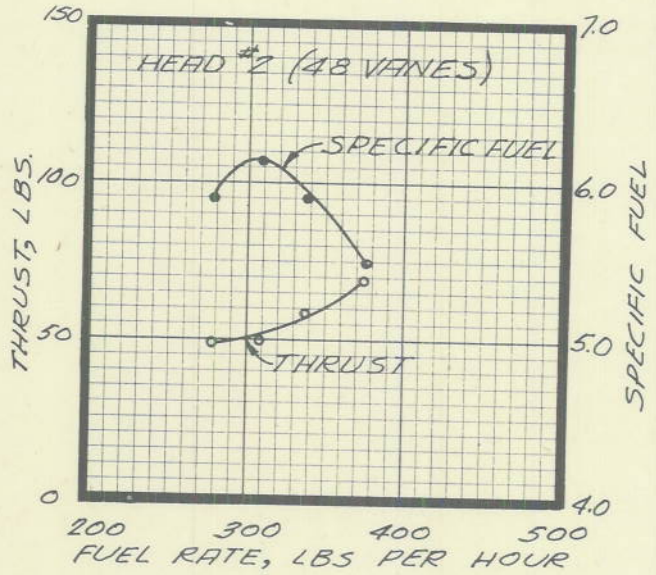
FIGURE 24

DECLASSIFIED

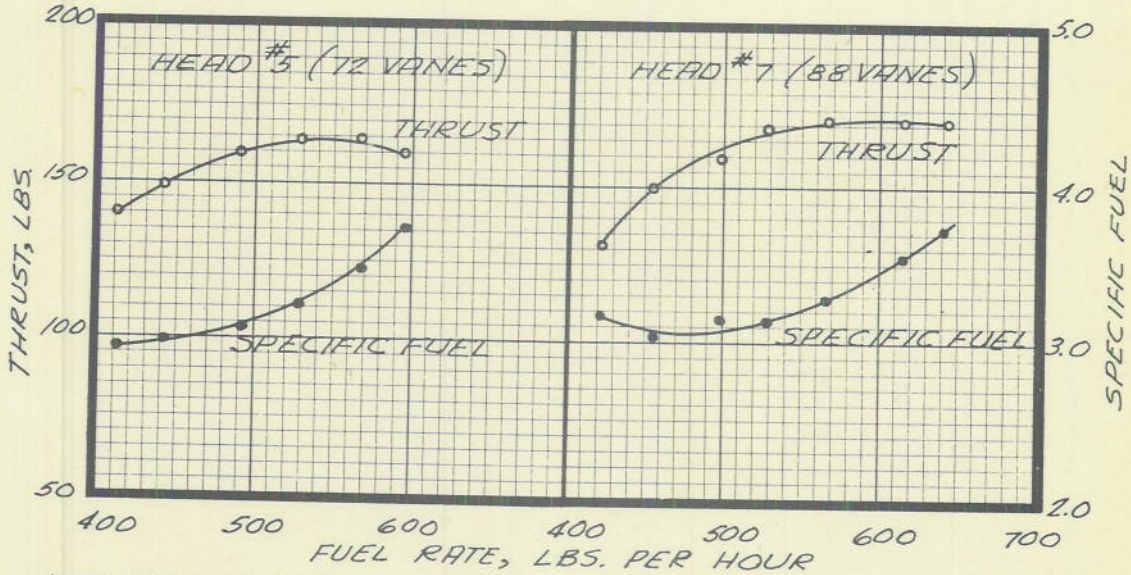
DECLASSIFIED

MODIFICATION "D"





MAX. THRUST = 68
MIN. SPECIFIC FUEL = 5.50
FREQ. RANGE = 1750 - 1900



MAX THRUST = 164
MIN. SPECIFIC FUEL = 2.95
FREQ. RANGE = 1640 - 1800

MAX. THRUST = 172
MIN. SPECIFIC FUEL = 3.04
FREQ. RANGE = 1680 - 1850

CONFIDENTIAL

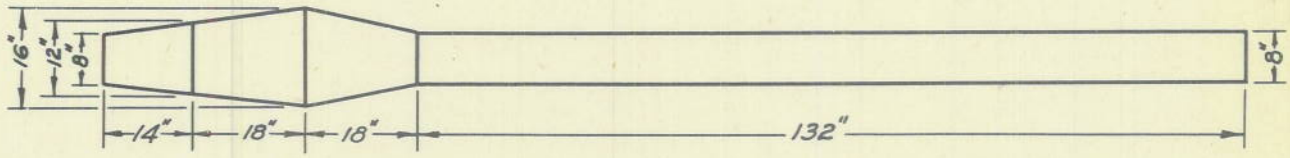
0-3064

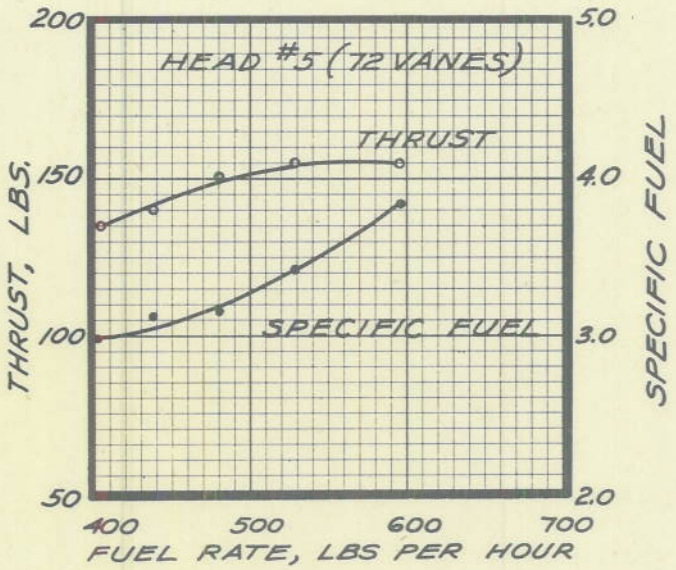
FIGURE 25

DECLASSIFIED

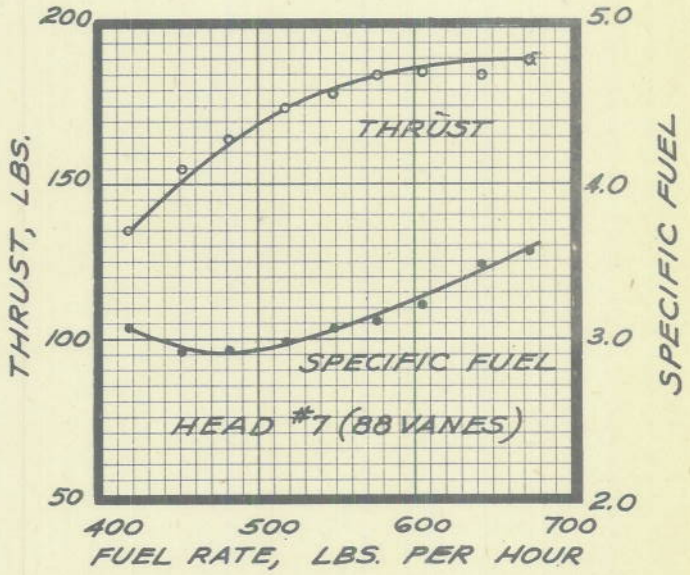
DECLASSIFIED

MODIFICATION "D"





MAX. THRUST = 155
MIN. SPECIFIC FUEL = 2.99
FREQ. RANGE = 1650-1750



MAX. THRUST = 190
MIN. SPECIFIC FUEL = 2.91
FREQ. RANGE = 1670-1850

CONFIDENTIAL

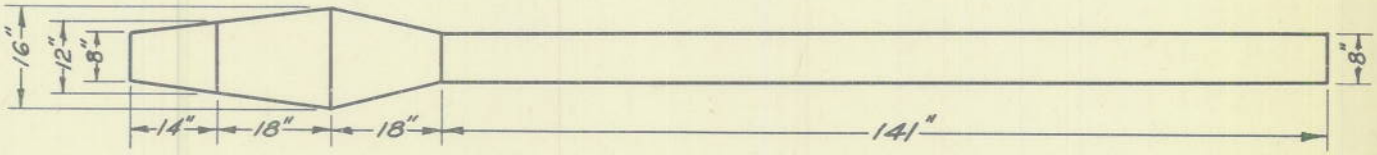
0-3064

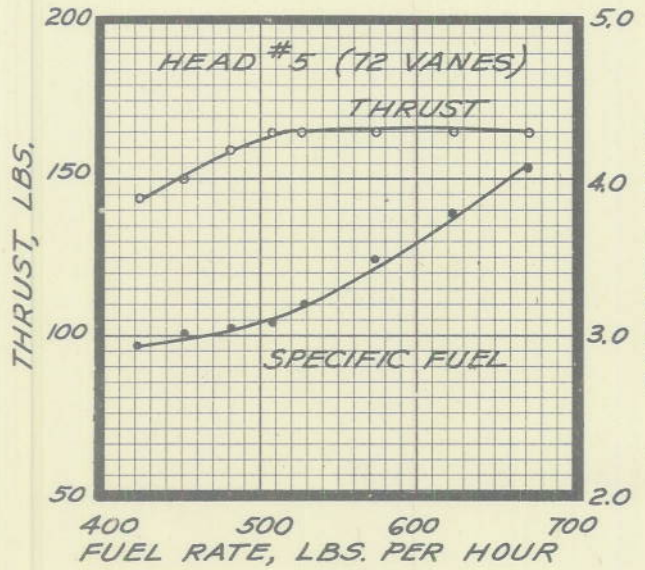
FIGURE 26

DECLASSIFIED

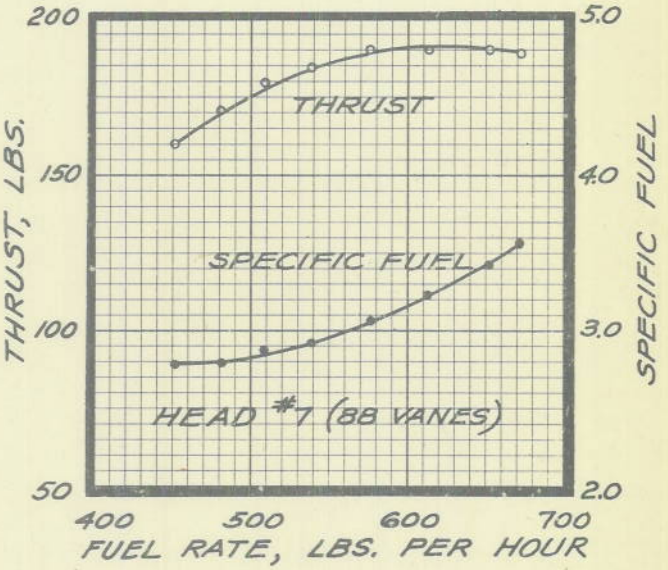
DECLASSIFIED

MODIFICATION "D"





MAX. THRUST = 165
MIN. SPECIFIC FUEL = 2.93
FREQ. RANGE = 1675 - 1770



MAX. THRUST = 190
MIN. SPECIFIC FUEL = 2.79
FREQ. RANGE = 1660 - 1760

CONFIDENTIAL

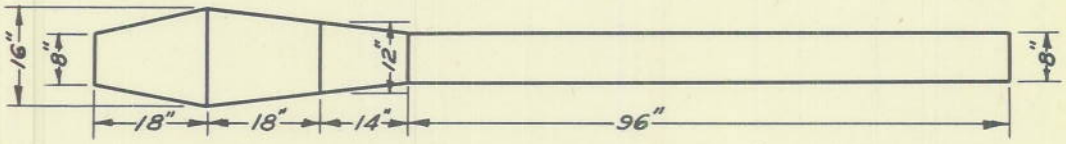
0-3064

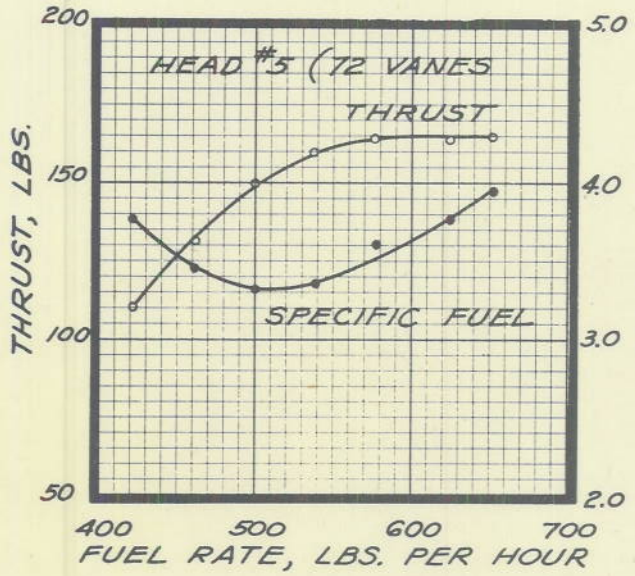
FIGURE 27

DECLASSIFIED

DECLASSIFIED

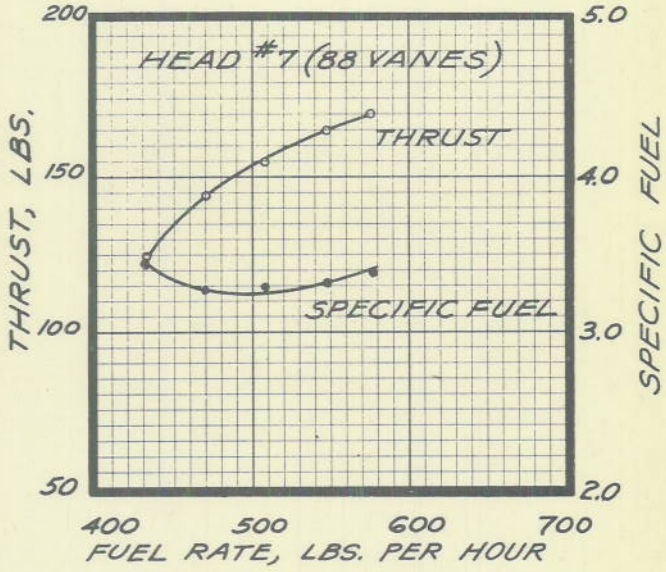
MODIFICATION "E"





MAX. THRUST = 165
MIN. SPECIFIC FUEL = 3.33
FREQ. RANGE = 1925-2250

MAX. THRUST = 170
MIN. SPECIFIC FUEL = 3.27
FREQ. RANGE = 2150-2300



CONFIDENTIAL

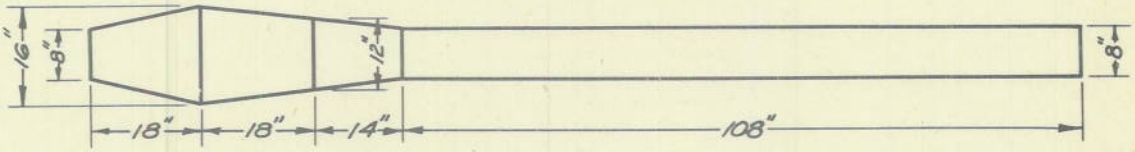
0-3064

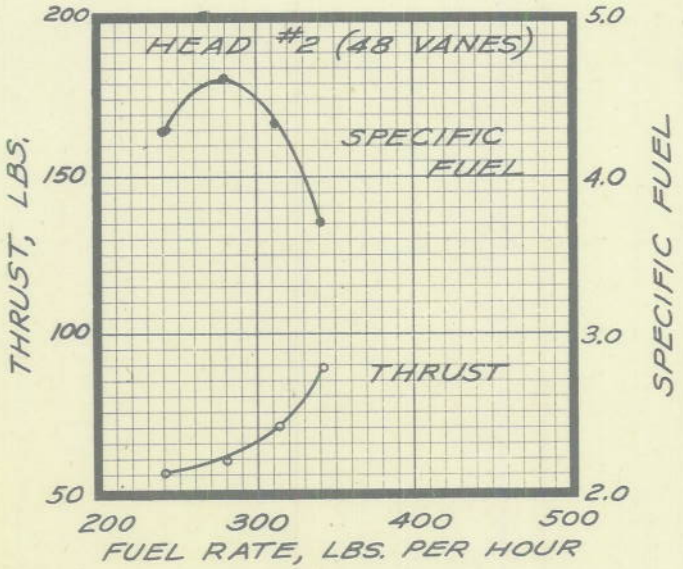
FIGURE 28

DECLASSIFIED

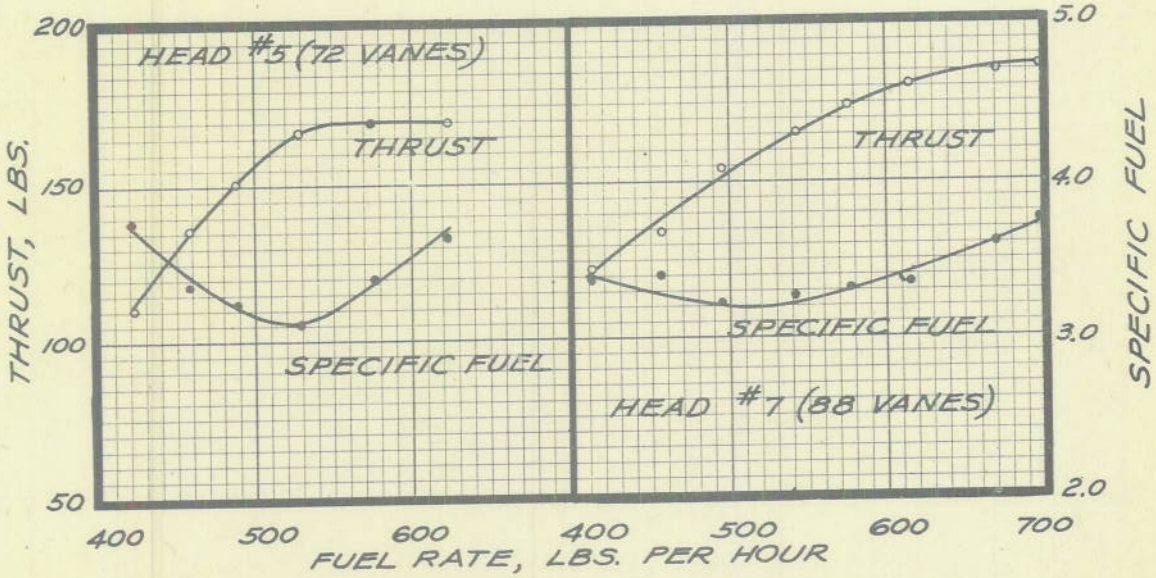
DECLASSIFIED

MODIFICATION "E"





MAX. THRUST = 88
MIN. SPECIFIC FUEL = 3.86
FREQ. RANGE = 2000 – 2200



MAX. THRUST = 170
MIN. SPECIFIC FUEL = 3.16
FREQ. RANGE = 1900 – 2120

MAX. THRUST = 187
MIN. SPECIFIC FUEL = 3.21
FREQ. RANGE = 1950 – 2150

CONFIDENTIAL

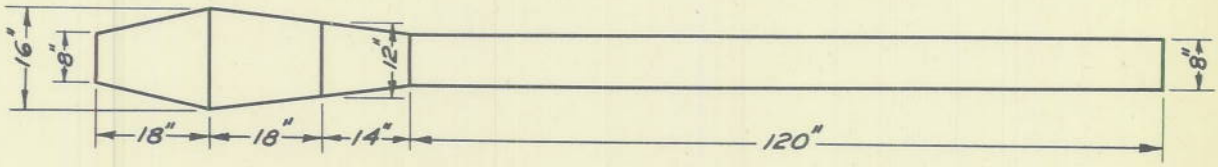
0-3064

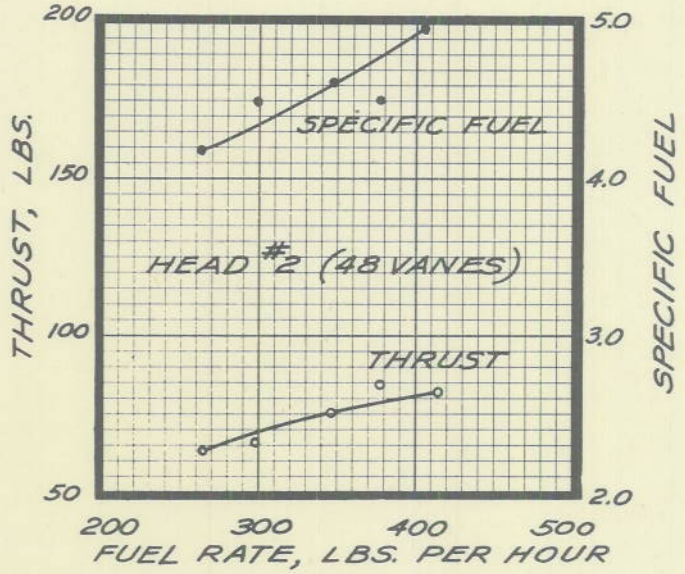
FIGURE 29

DECLASSIFIED

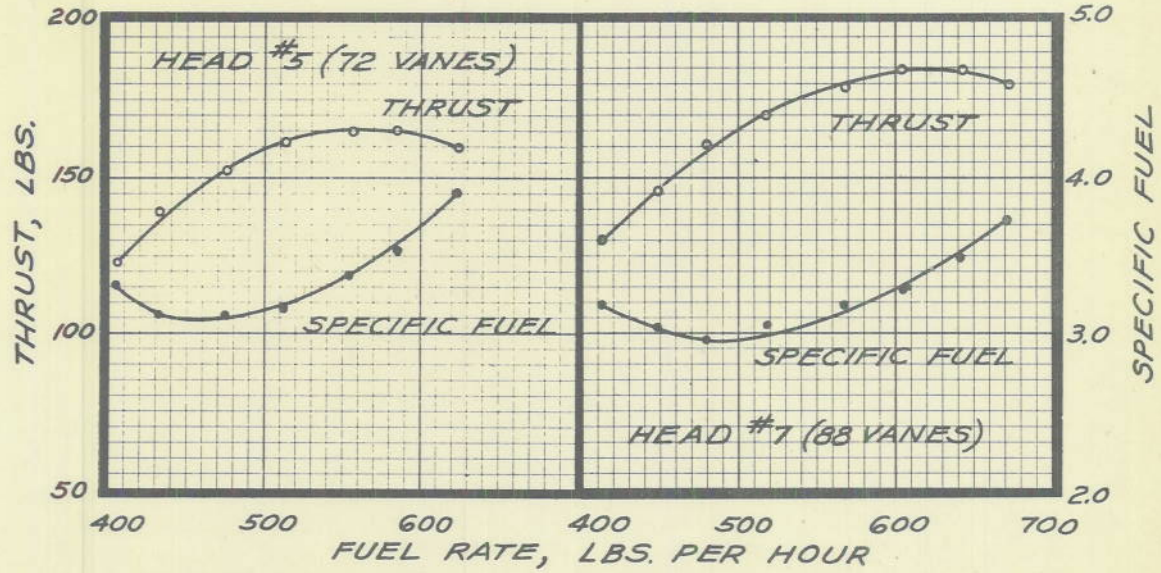
DECLASSIFIED

MODIFICATION "E"





MAX. THRUST = 84
MIN. SPECIFIC FUEL = 4.19
FREQ. RANGE = 1810 – 2090



MAX. THRUST = 165
MIN. SPECIFIC FUEL = 3.11
FREQ. RANGE = 1840-2000

MAX. THRUST = 184
MIN. SPECIFIC FUEL = 2.96
FREQ. RANGE = 1810-2000

CONFIDENTIAL

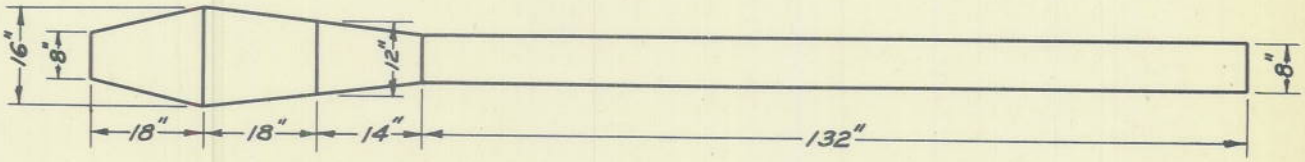
0-3064

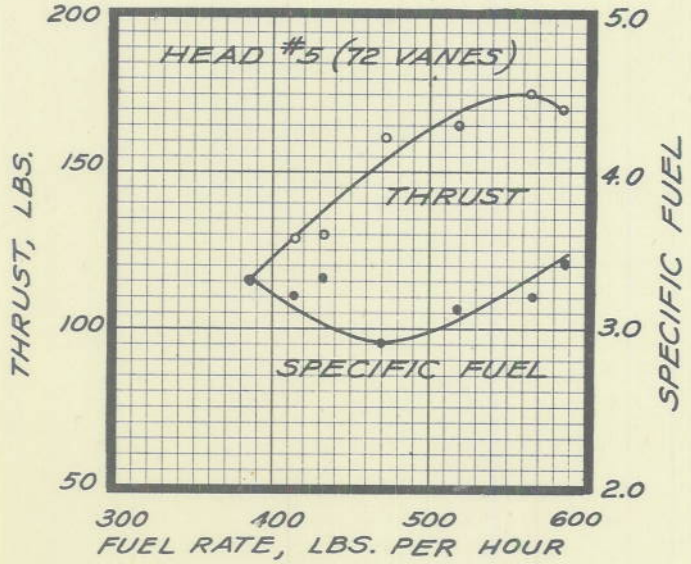
FIGURE 30

DECLASSIFIED

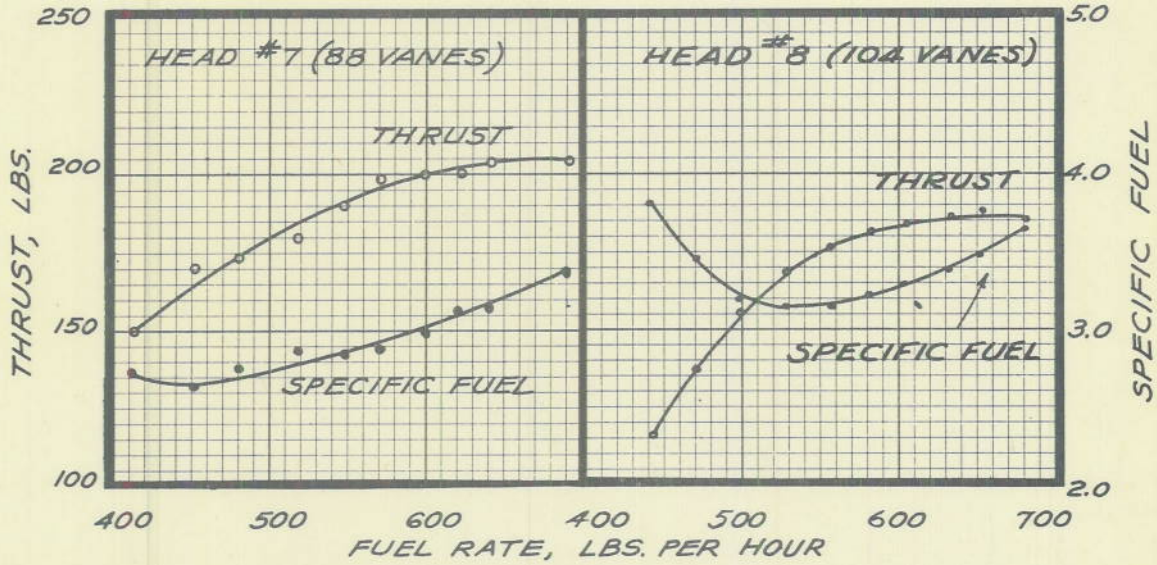
DECLASSIFIED

MODIFICATION "E"





MAX. THRUST = 176
MIN. SPECIFIC FUEL = 2.90
FREQ. RANGE = 1850 - 1920



MAX. THRUST = 204
MIN. SPECIFIC FUEL = 2.65
FREQ. RANGE = 1800 - 1950

MAX. THRUST = 188
MIN. SPECIFIC FUEL = 3.14
FREQ. RANGE = 1890 - 2200

CONFIDENTIAL

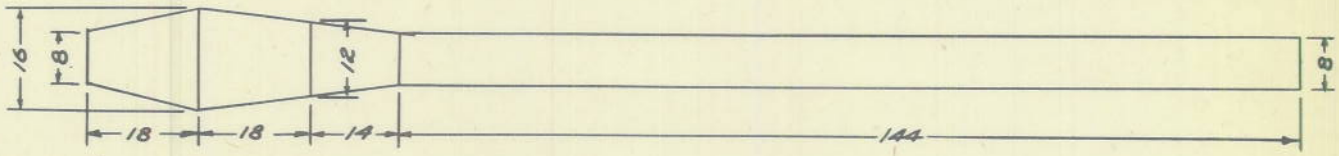
0-3064

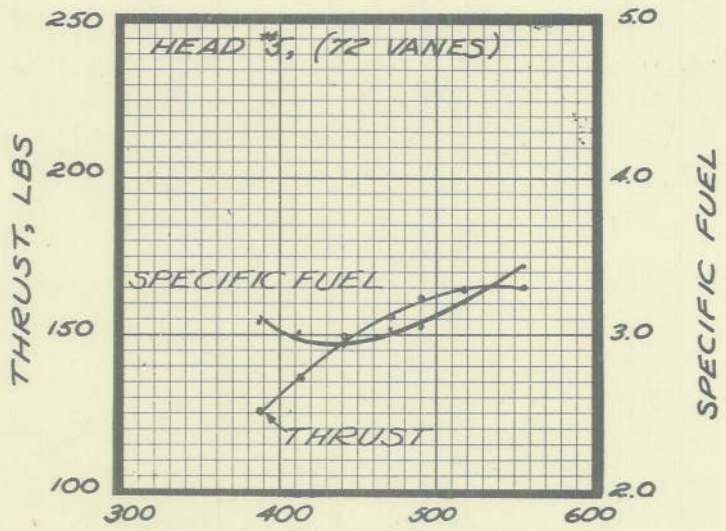
FIGURE 31

DECLASSIFIED

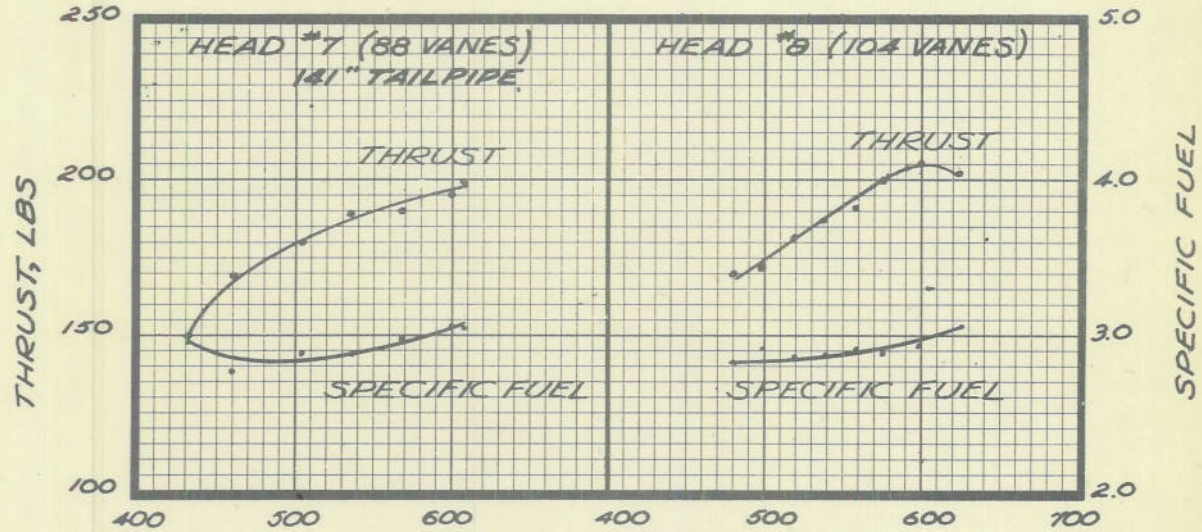
DECLASSIFIED

MODIFICATION "E"





MAX THRUST = 162
MIN SPECIFIC FUEL = 2.94
FREQ. RANGE = 1680 - 1890



MAX. THRUST = 199
MIN. SPECIFIC FUEL = 2.74
FREQ. RANGE = 1780 - 1875

MAX. THRUST = 206
MIN. SPECIFIC FUEL = 2.82
FREQ. RANGE = 1780 - 1910

CONFIDENTIAL

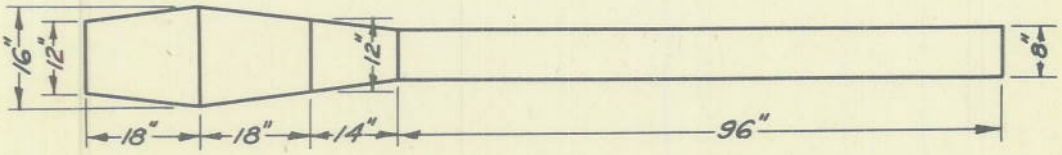
0-3064

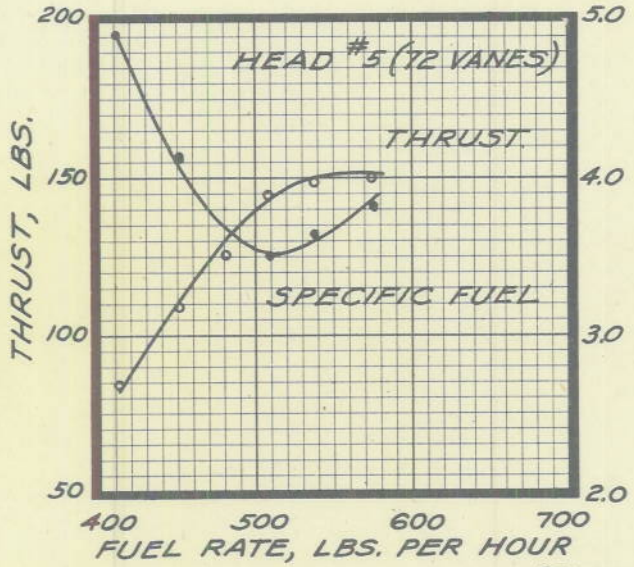
FIGURE 32

DECLASSIFIED

DECLASSIFIED

MODIFICATION "F"



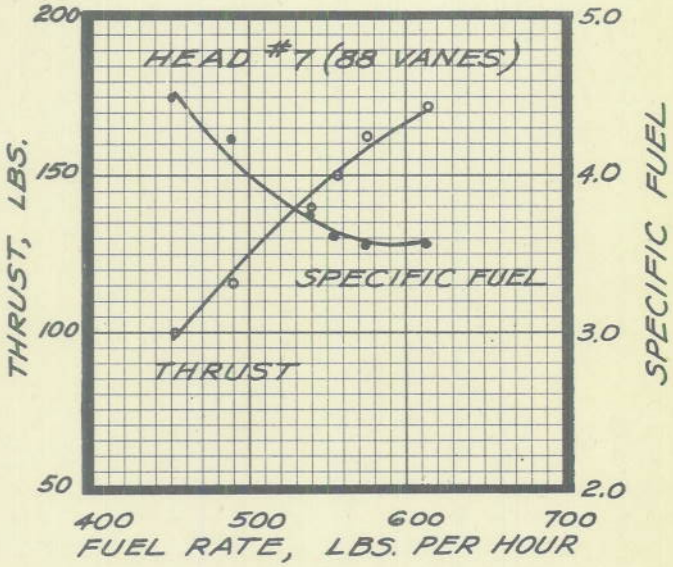


MAX. THRUST = 150
MIN. SPECIFIC FUEL = 3.51
FREQ. RANGE = 2030-2250

←

MAX. THRUST = 172
MIN. SPECIFIC FUEL = 3.56
FREQ. RANGE = 2000-2300

→



CONFIDENTIAL

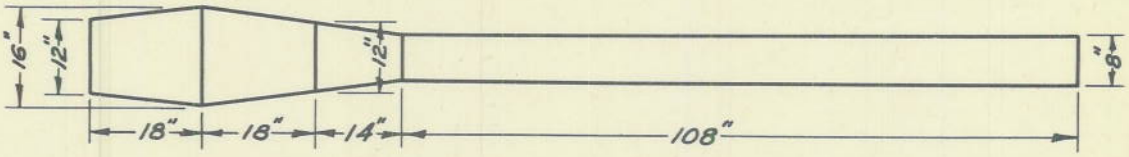
0-3064

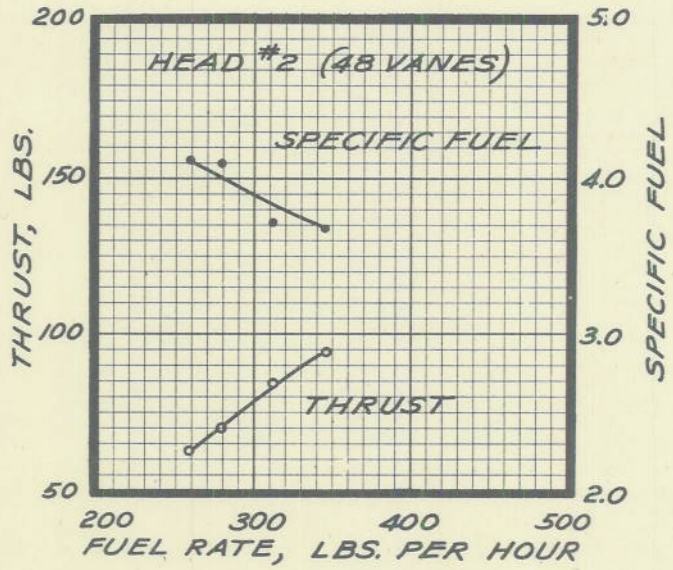
FIGURE 33

DECLASSIFIED

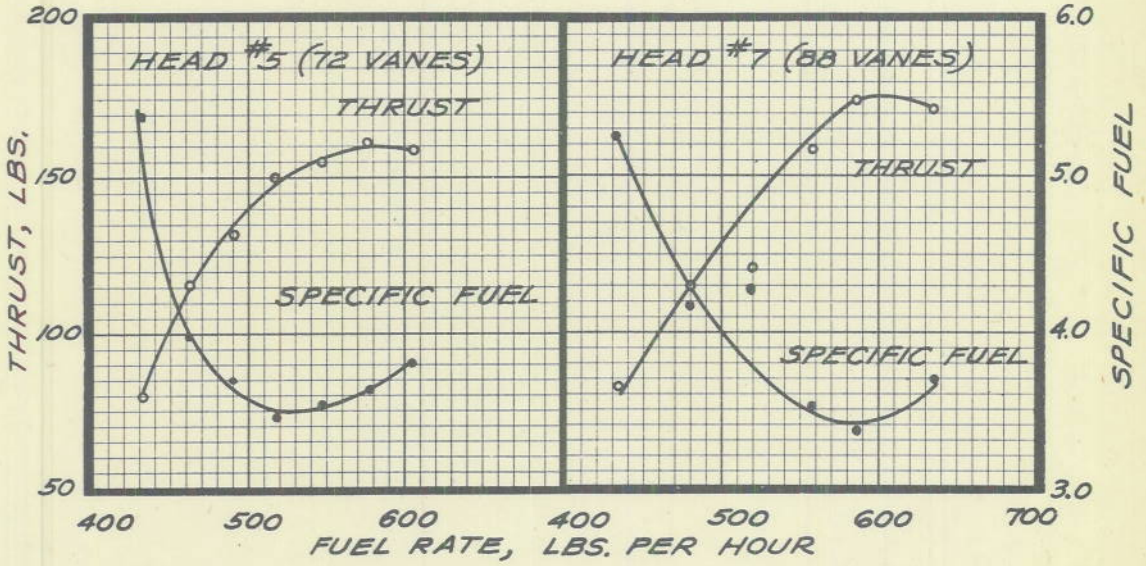
DECLASSIFIED

MODIFICATION "F"





MAX. THRUST = 94
MIN. SPECIFIC FUEL = 3.67
FREQ. RANGE = 2050-2250



MAX. THRUST = 162
MIN. SPECIFIC FUEL = 3.45
FREQ. RANGE = 1850-2080

MAX. THRUST = 174
MIN. SPECIFIC FUEL = 3.36
FREQ. RANGE = 1900-2150

CONFIDENTIAL

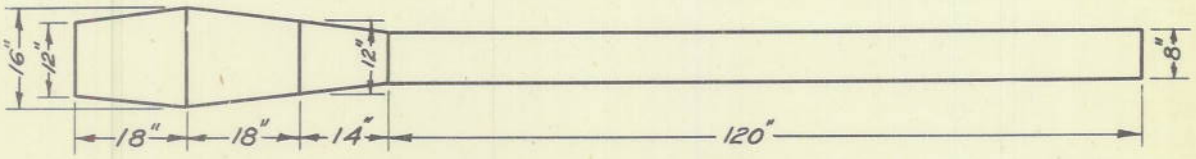
0-3064

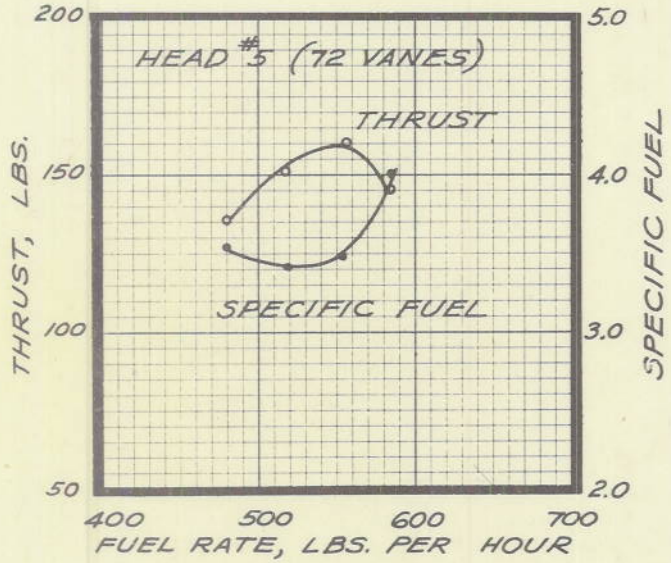
FIGURE 34

DECLASSIFIED

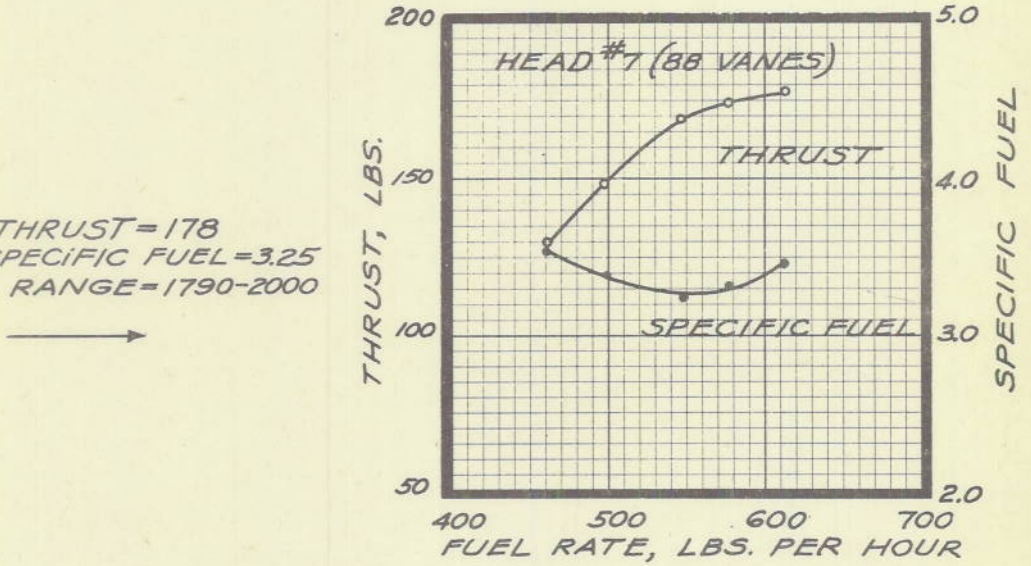
DECLASSIFIED

MODIFICATION "F"





MAX. THRUST = 160
MIN. SPECIFIC FUEL = 3.41
FREQ. RANGE = 1720-1900



MAX. THRUST = 178
MIN. SPECIFIC FUEL = 3.25
FREQ. RANGE = 1790-2000

CONFIDENTIAL

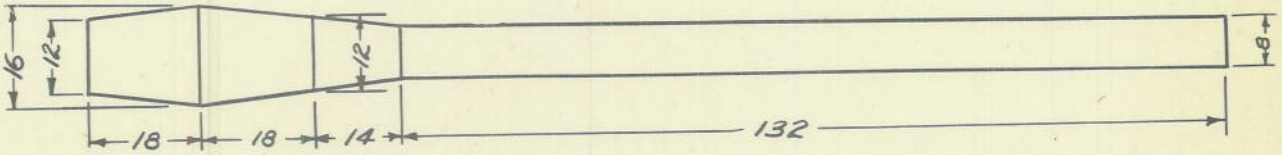
0-3064

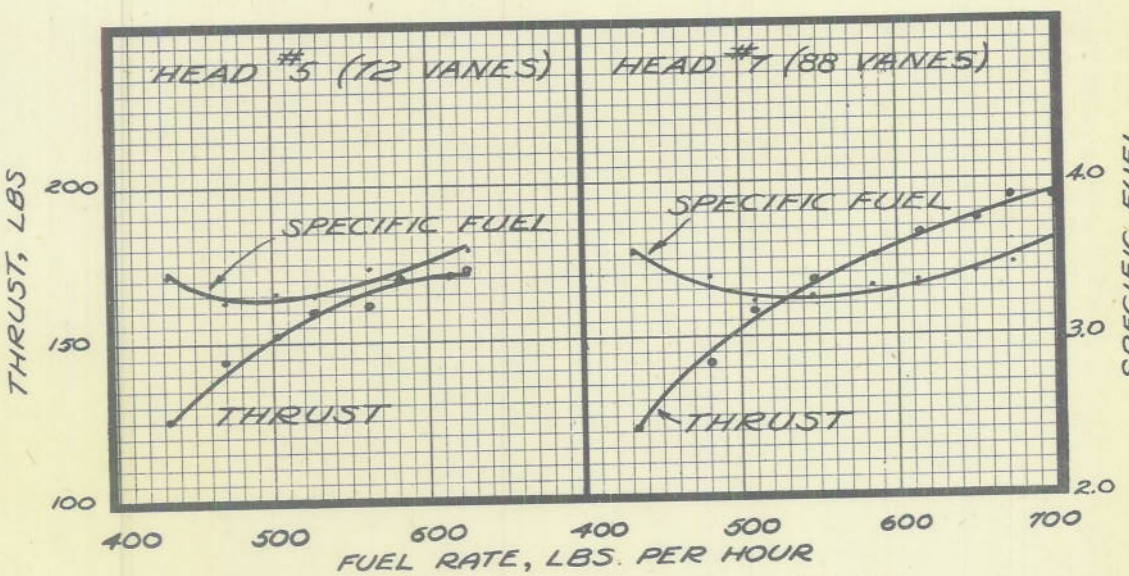
FIGURE 35

DECLASSIFIED

DECLASSIFIED

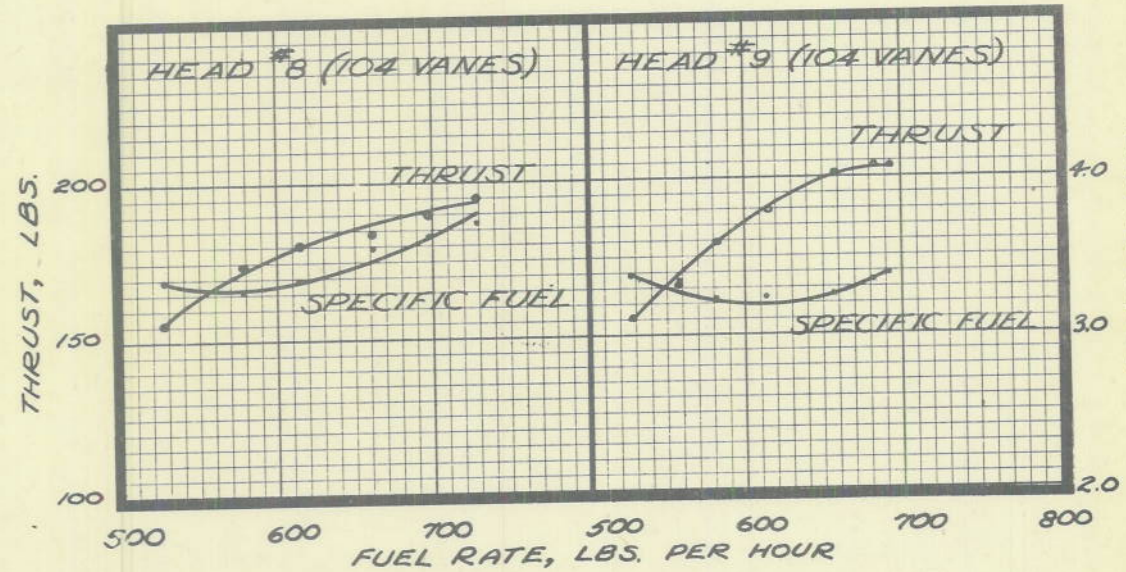
MODIFICATION "F"





MAX THRUST = 174
MIN SPECIFIC FUEL = 3.26
FREQ RANGE = 1910-2140

MAX THRUST = 195
MIN SPECIFIC FUEL = 3.22
FREQ RANGE = 1890-2110



MAX. THRUST = 195
MIN SPECIFIC FUEL = 3.31
FREQ RANGE = 1900-2200

MAX THRUST = 204
MIN SPECIFIC FUEL = 3.23
FREQ. RANGE = 1850-2140

CONFIDENTIAL

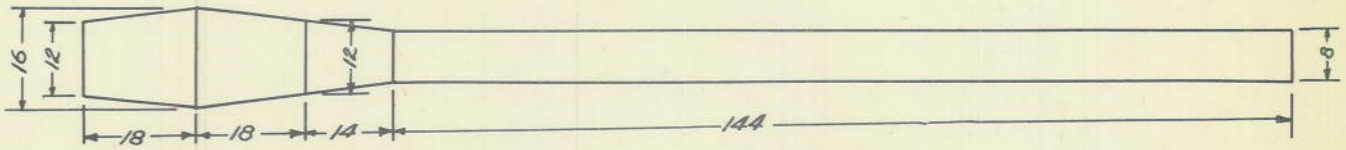
0-3064

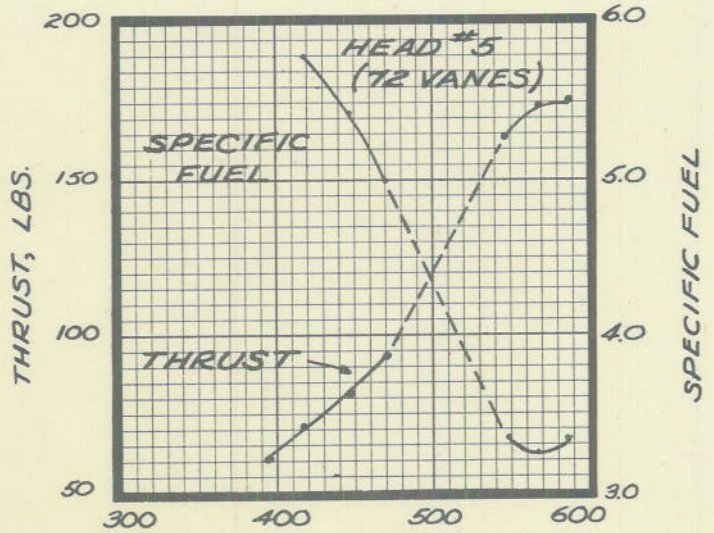
FIGURE 36

DECLASSIFIED

DECLASSIFIED

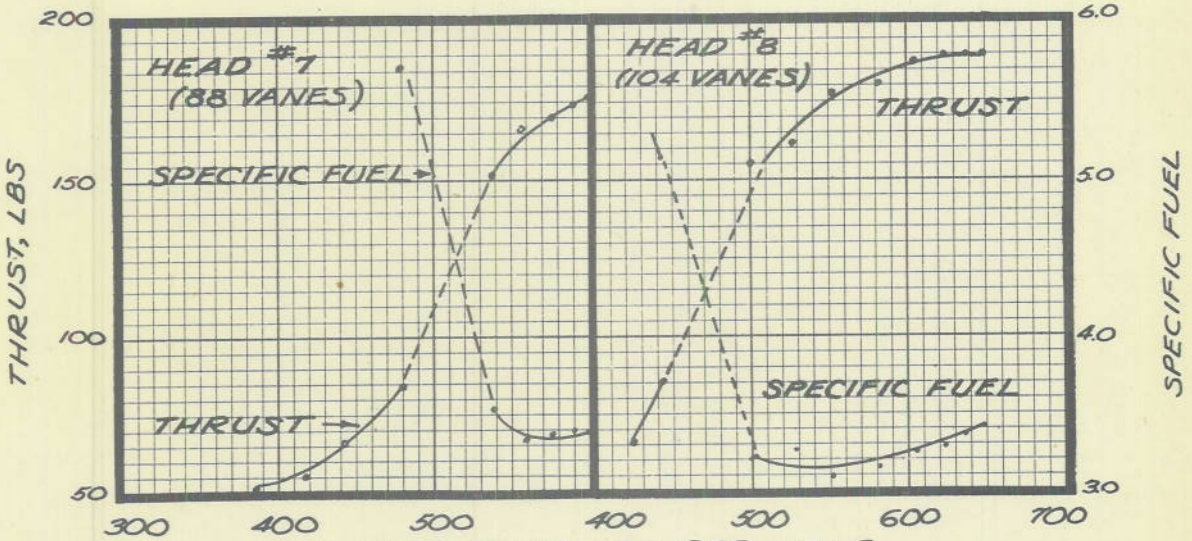
MODIFICATION "F"





FUEL RATE, LBS PER HOUR
MAX. THRUST = 176
MIN. SPECIFIC FUEL = 3.26
FREQ. RANGE = 1700-2100

NOTE: DOTTED LINES INDICATE UNSTABLE COMBUSTION.



FUEL RATE, LBS. PER HOUR

MAX. THRUST = 177
MIN. SPECIFIC FUEL = 3.34
FREQ. RANGE = 1650-2100

MAX. THRUST = 190
MIN SPECIFIC FUEL = 3.10
FREQ. RANGE = 1760-2200

CONFIDENTIAL

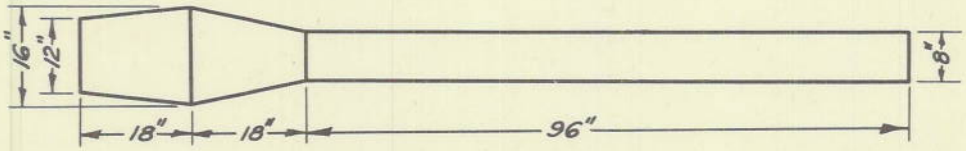
0-3064

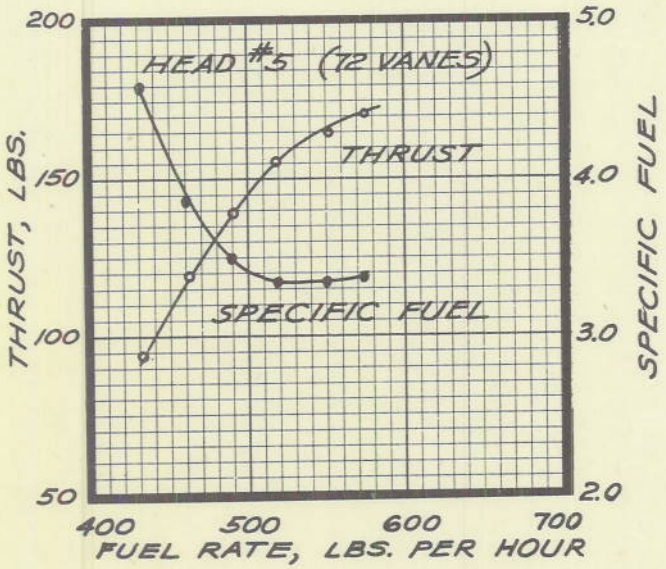
FIGURE 37

DECLASSIFIED

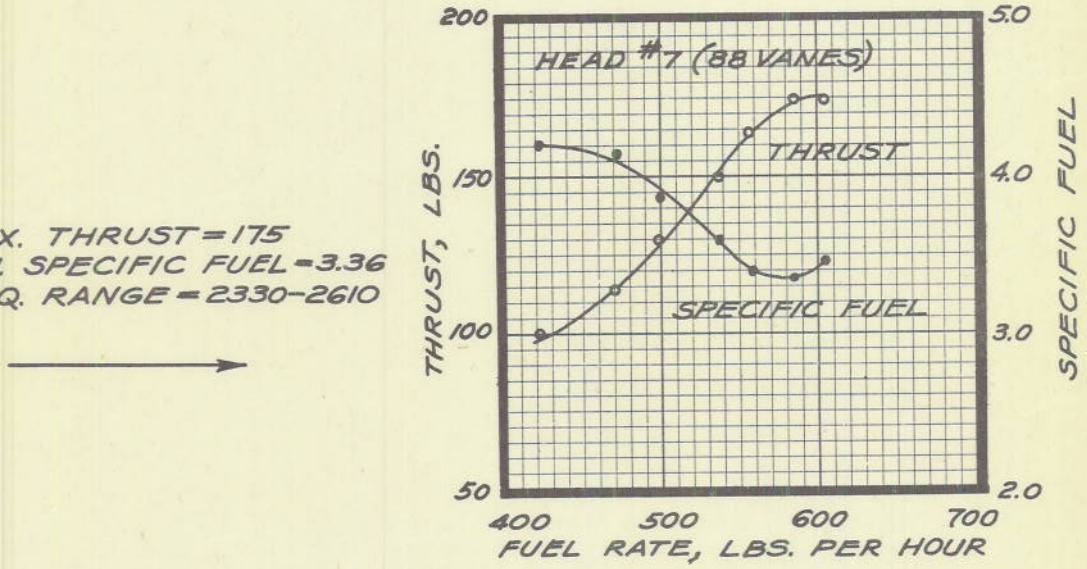
DECLASSIFIED

MODIFICATION "G"





MAX THRUST = 172
MIN. SPECIFIC FUEL = 3.33
FREQ. RANGE = 2280-2500



MAX. THRUST = 175
MIN. SPECIFIC FUEL = 3.36
FREQ. RANGE = 2330-2610

CONFIDENTIAL

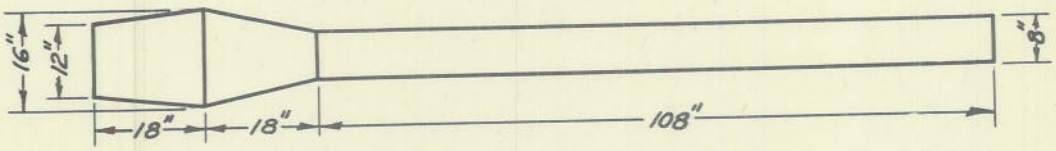
0-3064

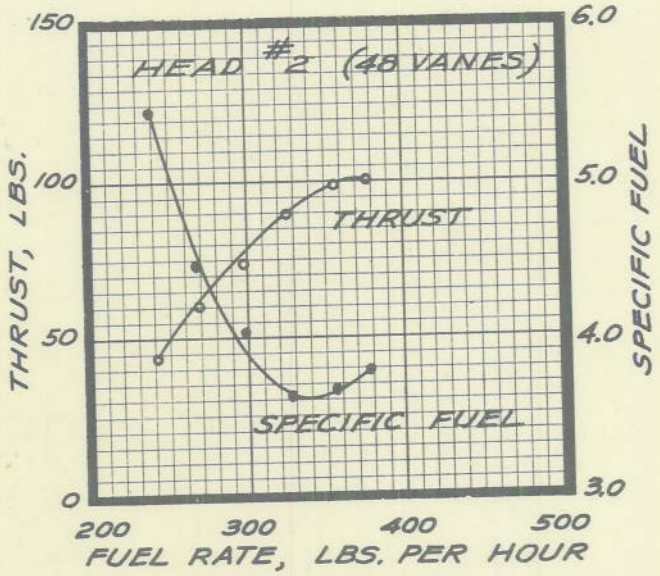
FIGURE 38

DECLASSIFIED

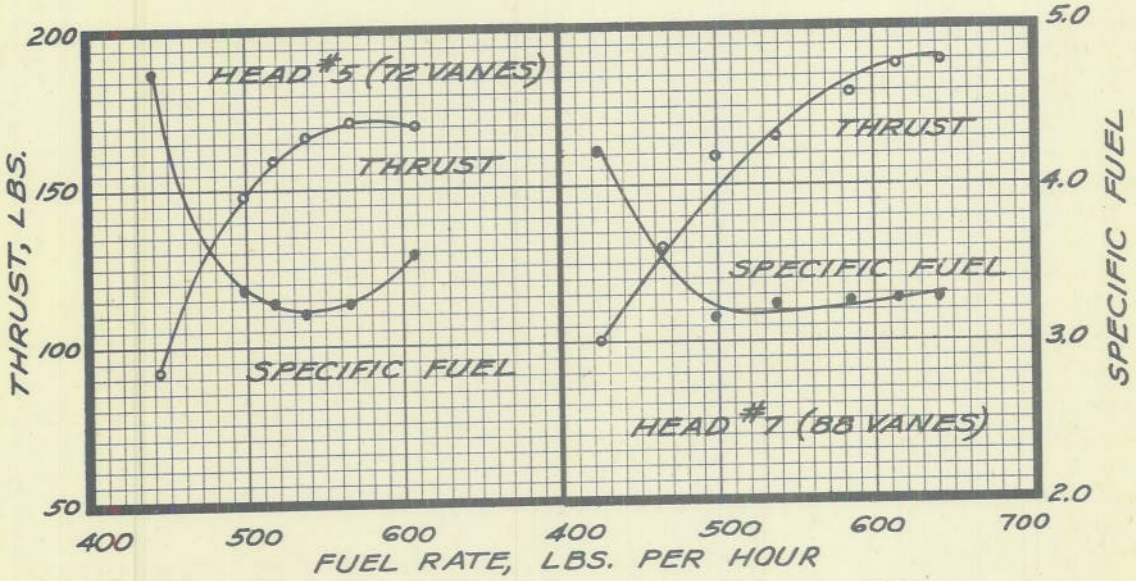
DECLASSIFIED

MODIFICATION "G"





MAX. THRUST = 100
MIN. SPECIFIC FUEL = 3.62
FREQ. RANGE = 2220–2600



MAX. THRUST = 173
MIN. SPECIFIC FUEL = 3.22
FREQ. RANGE = 2080-2390

MAX. THRUST = 190
MIN. SPECIFIC FUEL = 3.16
FREQ. RANGE = 2170–2420

CONFIDENTIAL

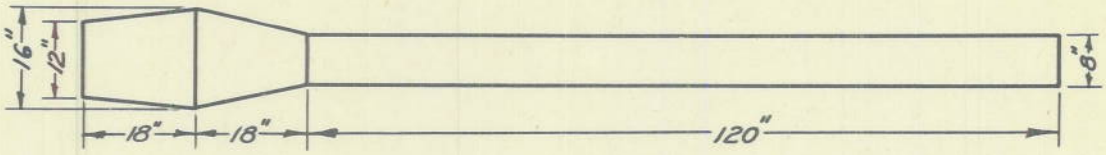
0-3064

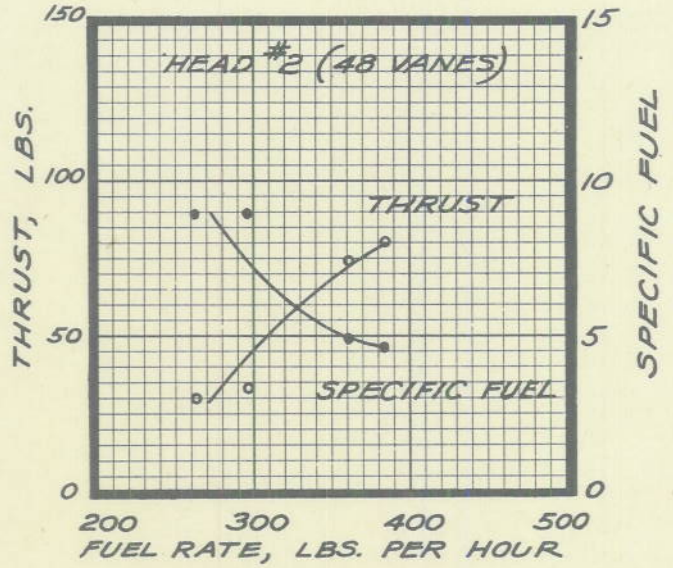
FIGURE 39

DECLASSIFIED

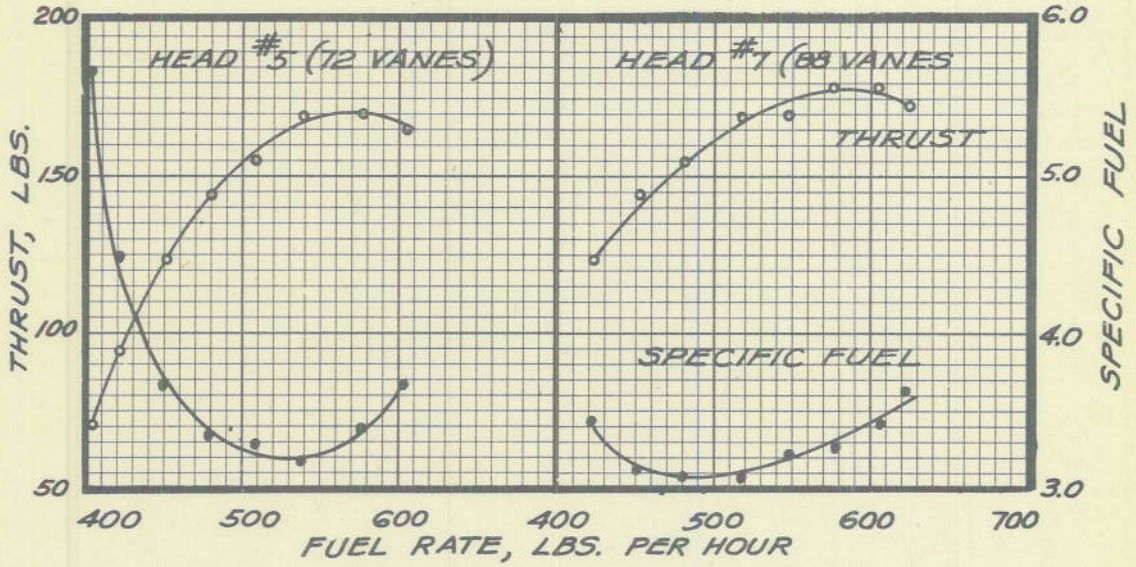
DECLASSIFIED

MODIFICATION "G"





MAX. THRUST = 82
MIN. SPECIFIC FUEL = 4.68
FREQ. RANGE = 2150-2550



MAX. THRUST = 170
MIN. SPECIFIC FUEL = 3.19
FREQ. RANGE = 2000-2300

MAX. THRUST = 178
MIN. SPECIFIC FUEL = 3.08
FREQ. RANGE = 1980-2240

CONFIDENTIAL

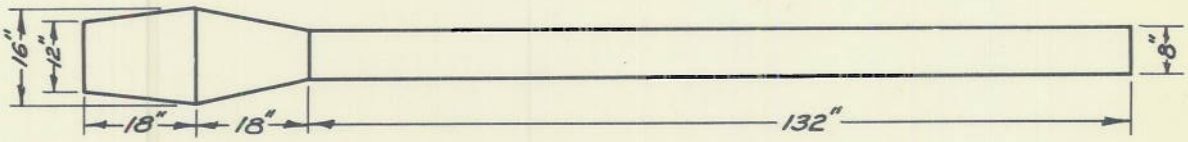
0-3064

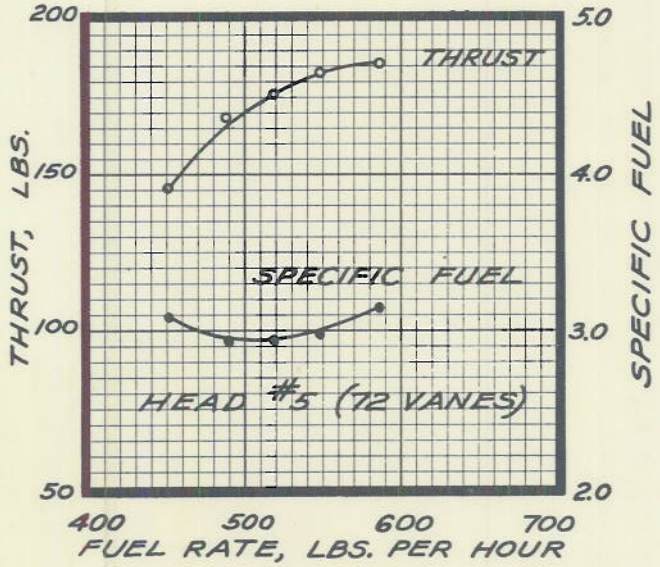
FIGURE 40

DECLASSIFIED

DECLASSIFIED

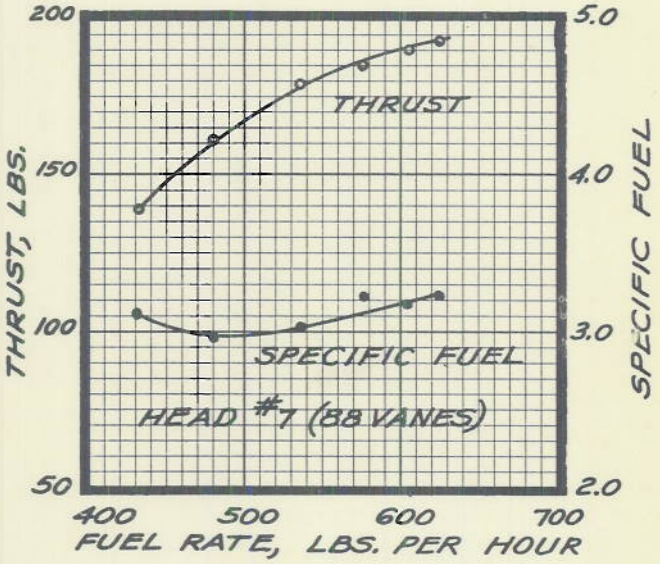
MODIFICATION "G"





MAX. THRUST = 186
MIN. SPECIFIC FUEL = 2.92
FREQ. RANGE = 1900–2100

MAX. THRUST = 193
MIN. SPECIFIC FUEL = 2.96
FREQ. RANGE = 1900–2000



CONFIDENTIAL

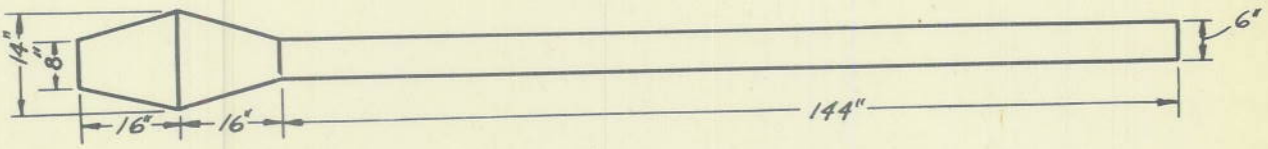
0-3064

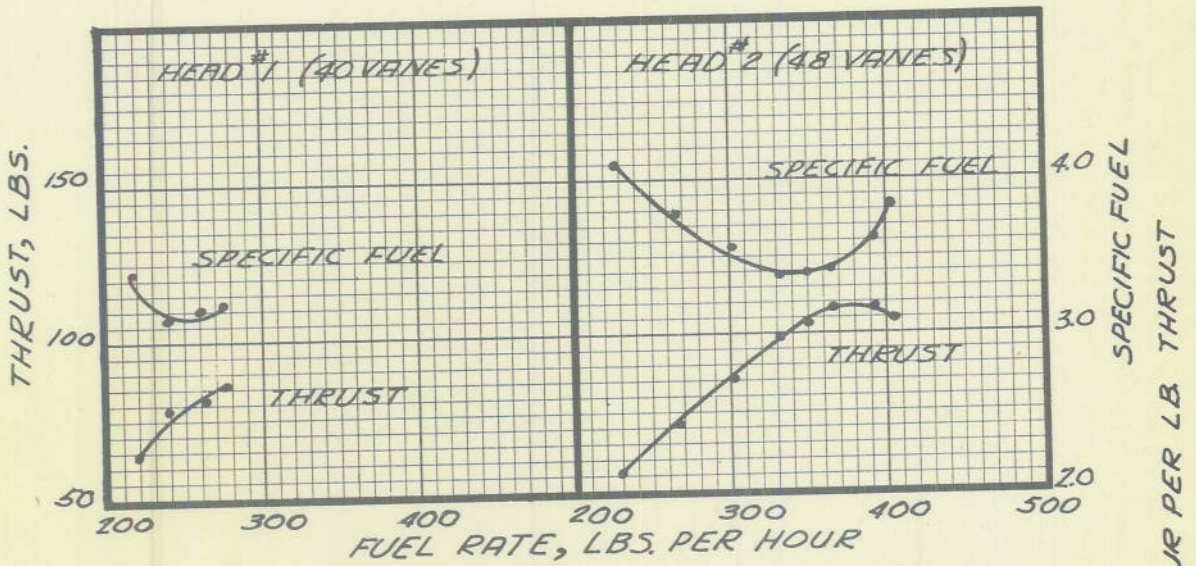
FIGURE 41

DECLASSIFIED

DECLASSIFIED

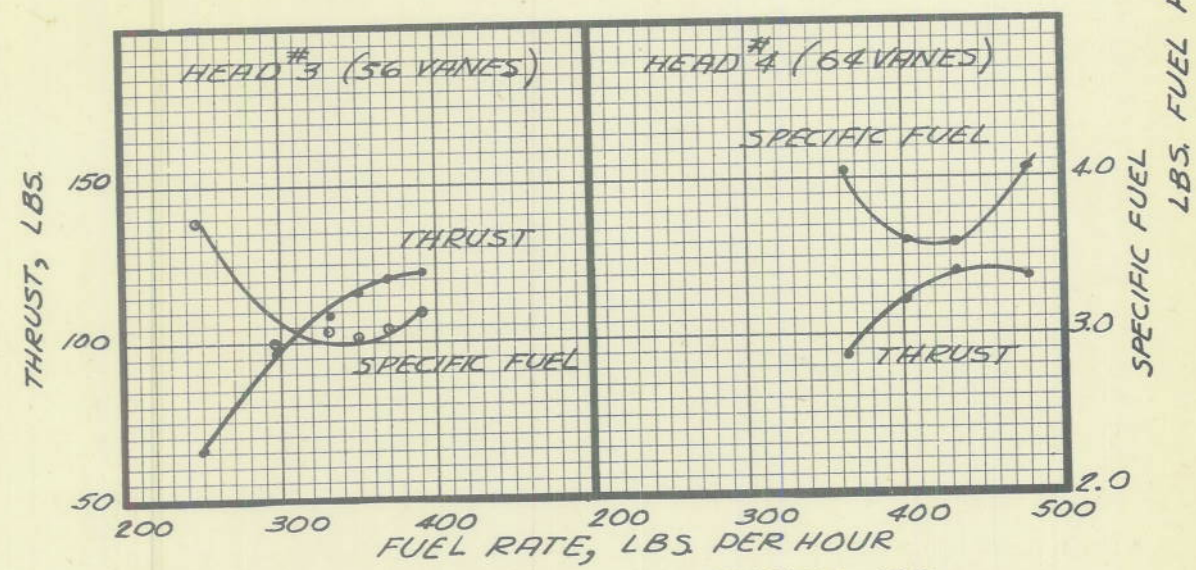
MODIFICATION H





MAX. THRUST = 86
MIN. SPECIFIC = 3.16
FREQ. RANGE = 1850-2350

MAX. THRUST = 108
MIN. SPECIFIC = 3.38
FREQ. RANGE = 1850-2400



MAX. THRUST = 123
MIN. SPECIFIC FUEL = 2.97
FREQ. RANGE = 1800-2200

MAX. THRUST = 120
MIN. SPECIFIC FUEL = 3.60
FREQ. RANGE = 1860-2300

CONFIDENTIAL

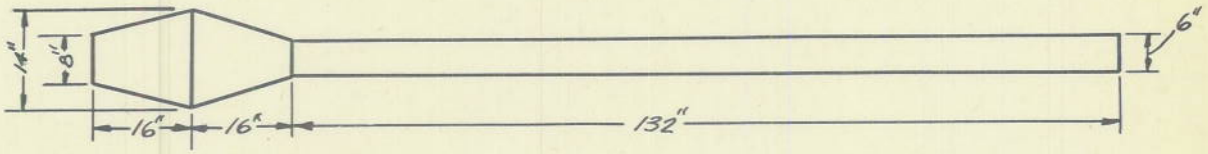
O-3064

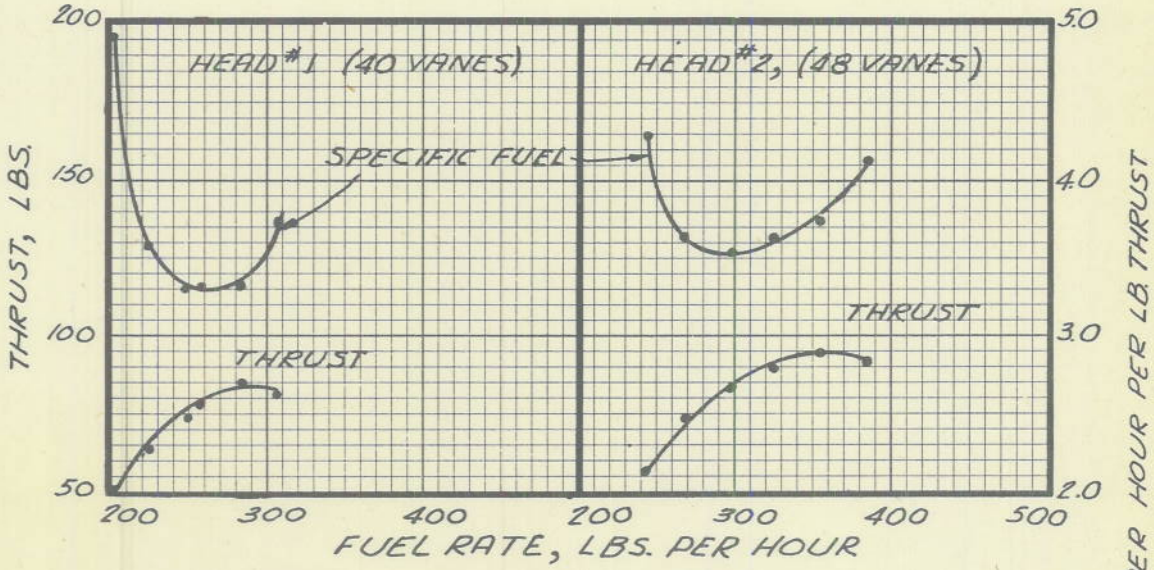
FIGURE 42

DECLASSIFIED

DECLASSIFIED

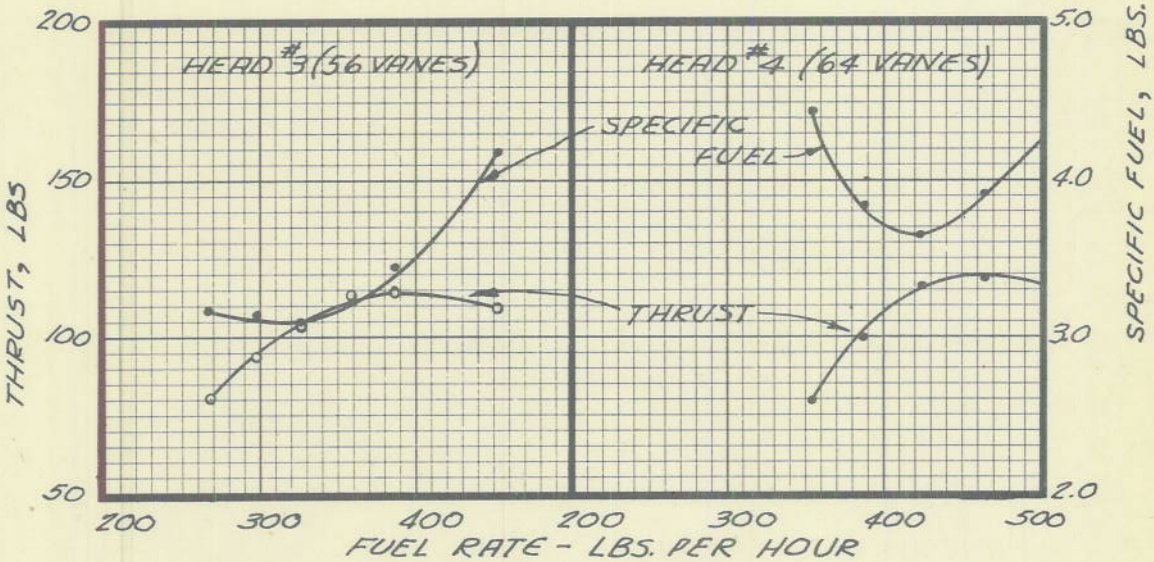
MODIFICATION H





MAX. THRUST = 85
MIN. SPECIFIC FUEL = 3.30
FREQ. RANGE = 1825-2510

MAX. THRUST = 95
MIN SPECIFIC FUEL = 3.54
FREQ. RANGE = 1900-2600



MAX. THRUST = 114
MIN. SPECIFIC FUEL = 3.11
FREQ. RANGE = 1750-2175

MAX. THRUST = 119
MIN. SPECIFIC FUEL = 3.64
FREQ. RANGE = 1850-2260

CONFIDENTIAL

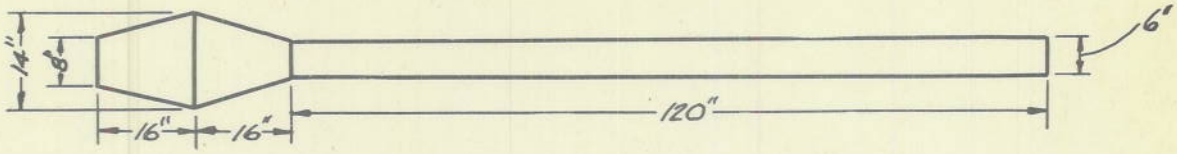
0-3064

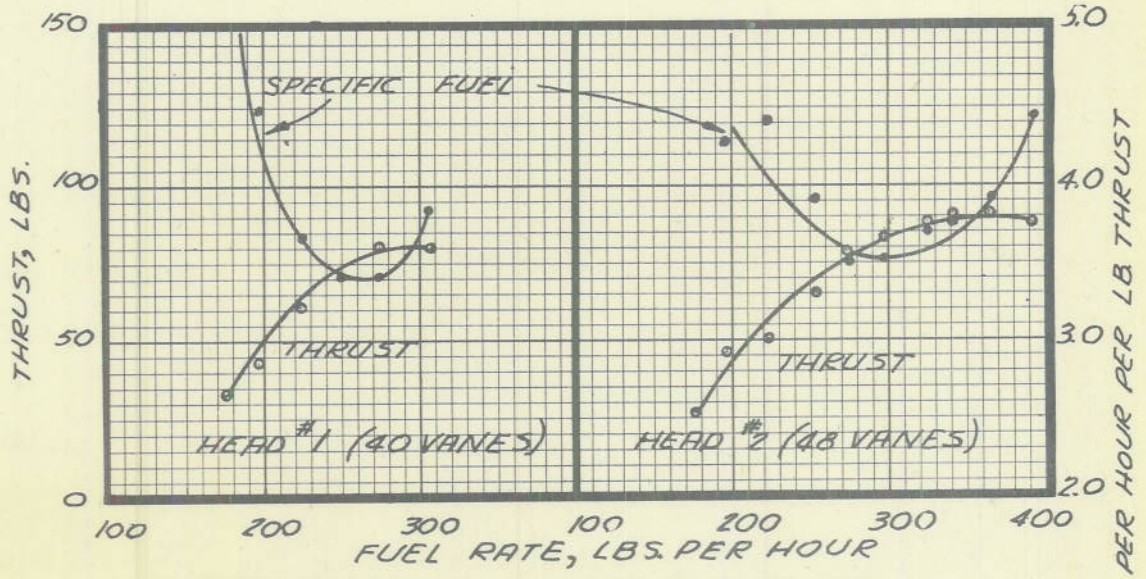
FIGURE 43

DECLASSIFIED

DECLASSIFIED

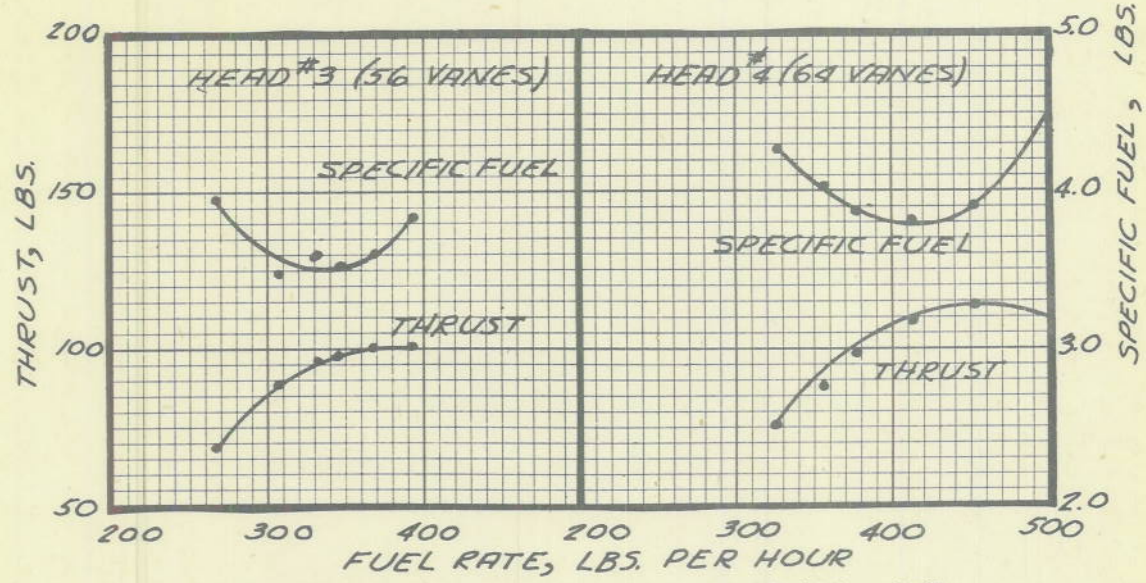
MODIFICATION H





MAX. THRUST = 80
MIN. SPECIFIC FUEL = 3.41
FREQ. RANGE = 2020-2620

MAX. THRUST = 92
MIN. SPECIFIC FUEL = 3.50
FREQ. RANGE = 2070-2660



MAX. THRUST = 102
MIN. SPECIFIC FUEL = 3.49
FREQ. RANGE = 1950-2200

MAX. THRUST = 115
MIN. SPECIFIC FUEL = 3.81
FREQ. RANGE = 2090-2360

CONFIDENTIAL

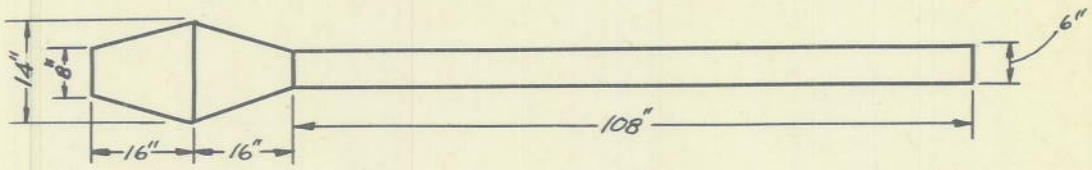
O-3064

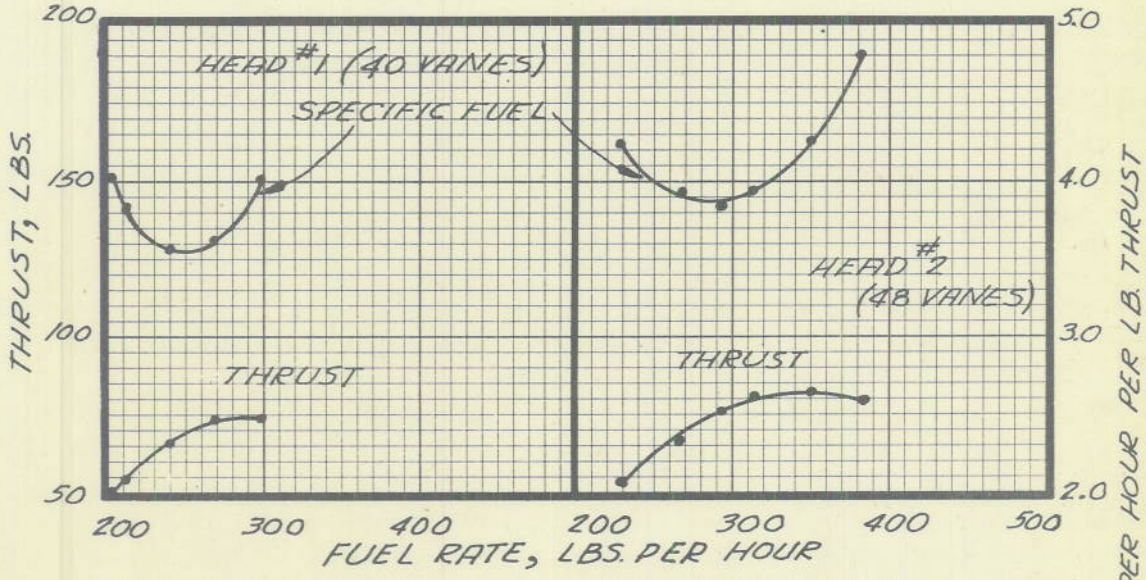
FIGURE 44

DECLASSIFIED

DECLASSIFIED

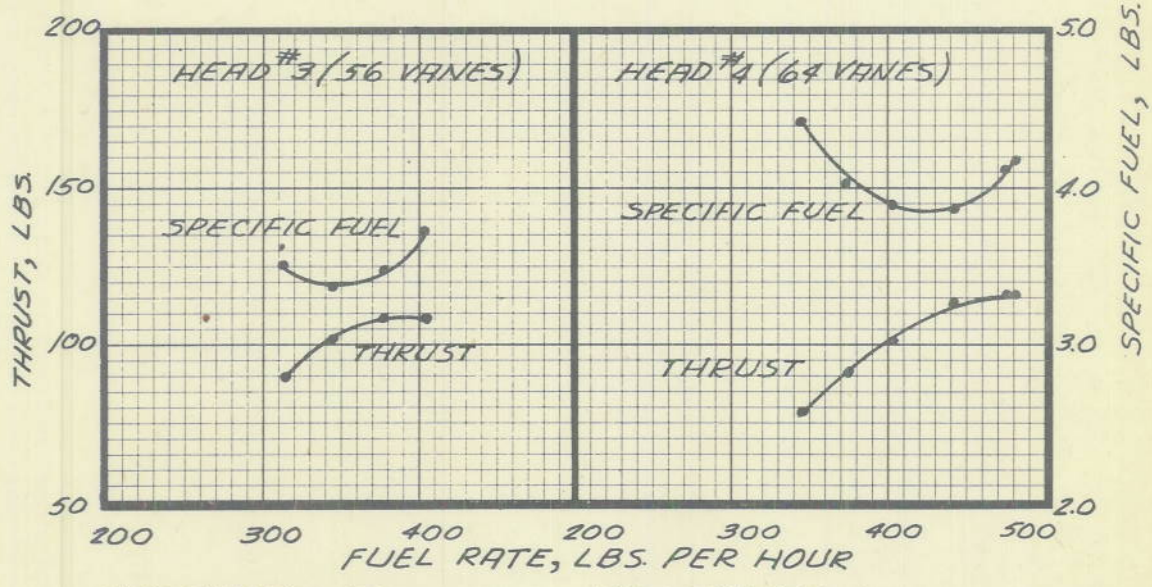
MODIFICATION H





MAX. THRUST = 74
MIN. SPECIFIC FUEL = 3.59
FREQ. RANGE = 2000-2500

MAX. THRUST = 82
MIN. SPECIFIC FUEL = 3.85
FREQ. RANGE = 2100 - 2580



MAX. THRUST = 109
MIN. SPECIFIC FUEL = 3.38
FREQ. RANGE = 2000-2280

MAX. THRUST = 116
MIN. SPECIFIC FUEL = 3.87
FREQ. RANGE = 2100-2450

CONFIDENTIAL

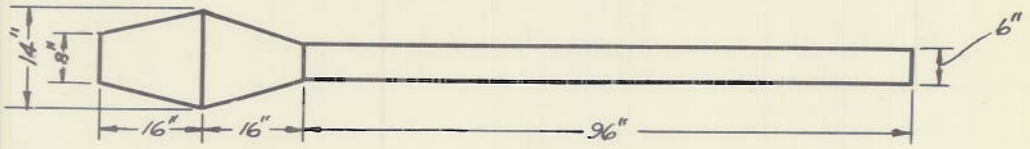
O-3064

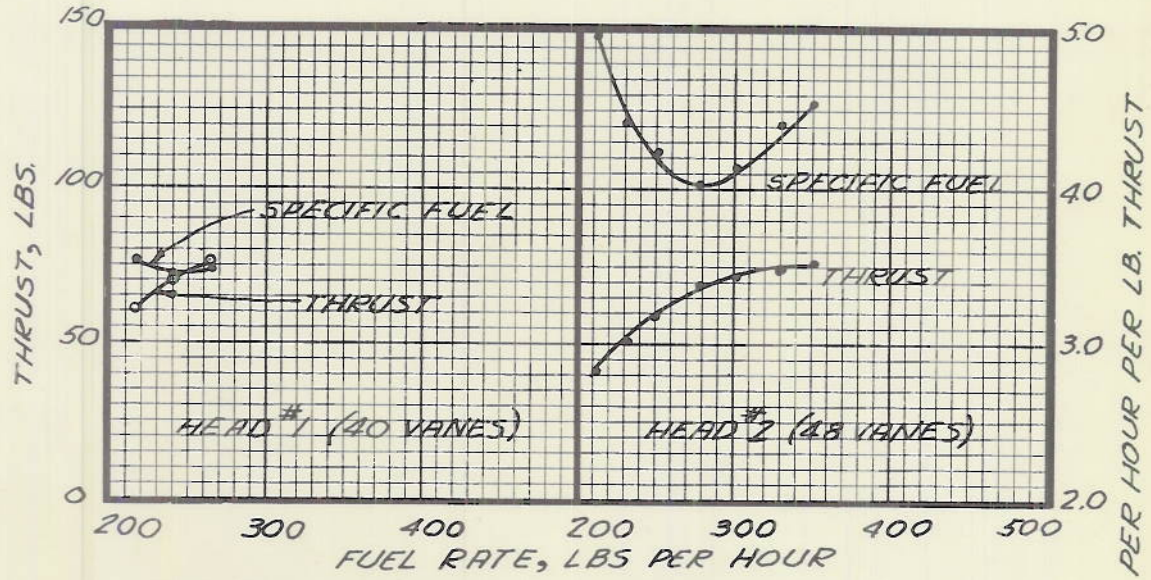
FIGURE 45

DECLASSIFIED

DECLASSIFIED

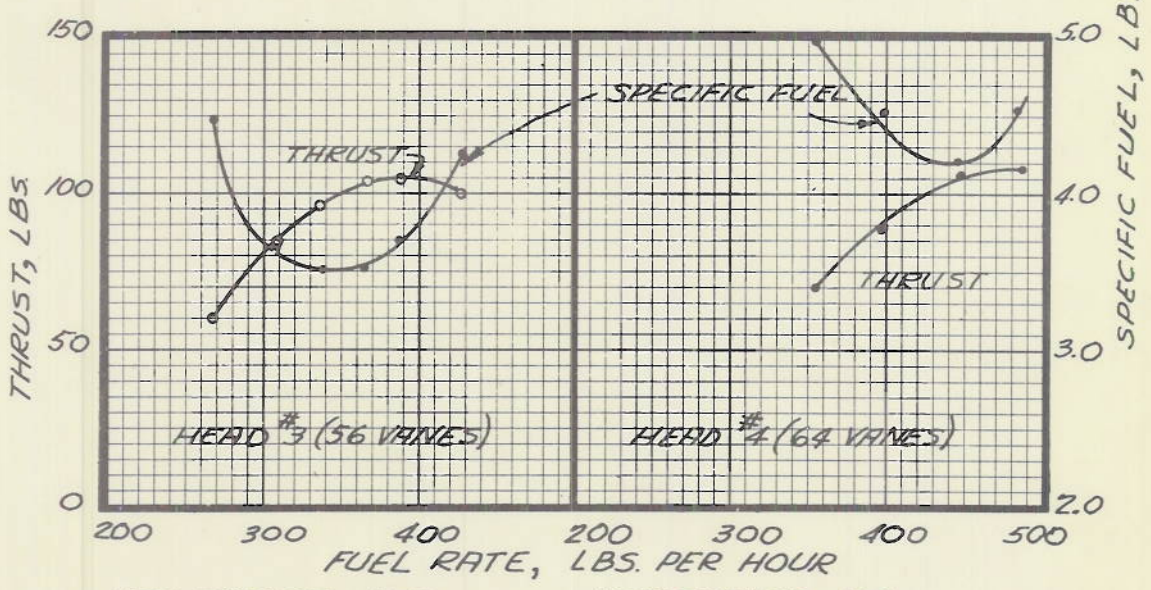
MODIFICATION H





MAX. THRUST = 76
MIN. SPECIFIC FUEL = 3.43
FREQ. RANGE = 2260-2660

MAX. THRUST = 77
MIN. SPECIFIC FUEL = 4.03
FREQ RANGE = 2300-2830



MAX. THRUST = 105
MIN. SPECIFIC FUEL = 3.50
FREQ. RANGE = 2100-2600

MAX. THRUST = 108
MIN. SPECIFIC FUEL = 4.20
FREQ. RANGE = 2200-2550

CONFIDENTIAL

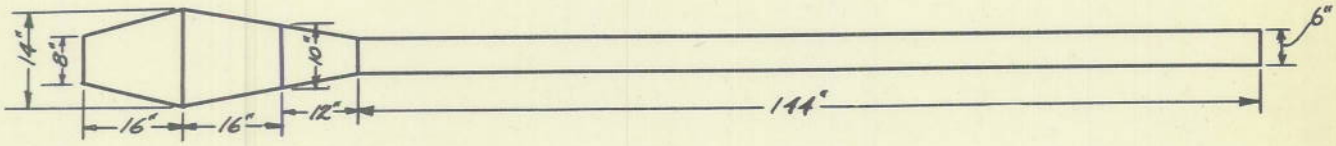
0-3064

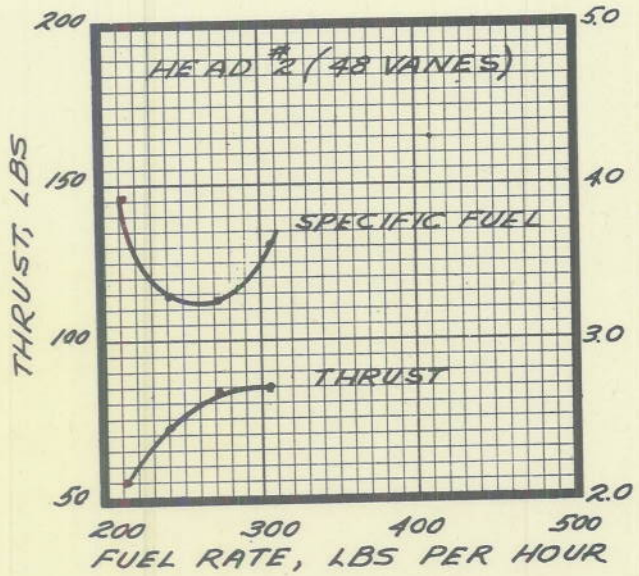
FIGURE 46

DECLASSIFIED

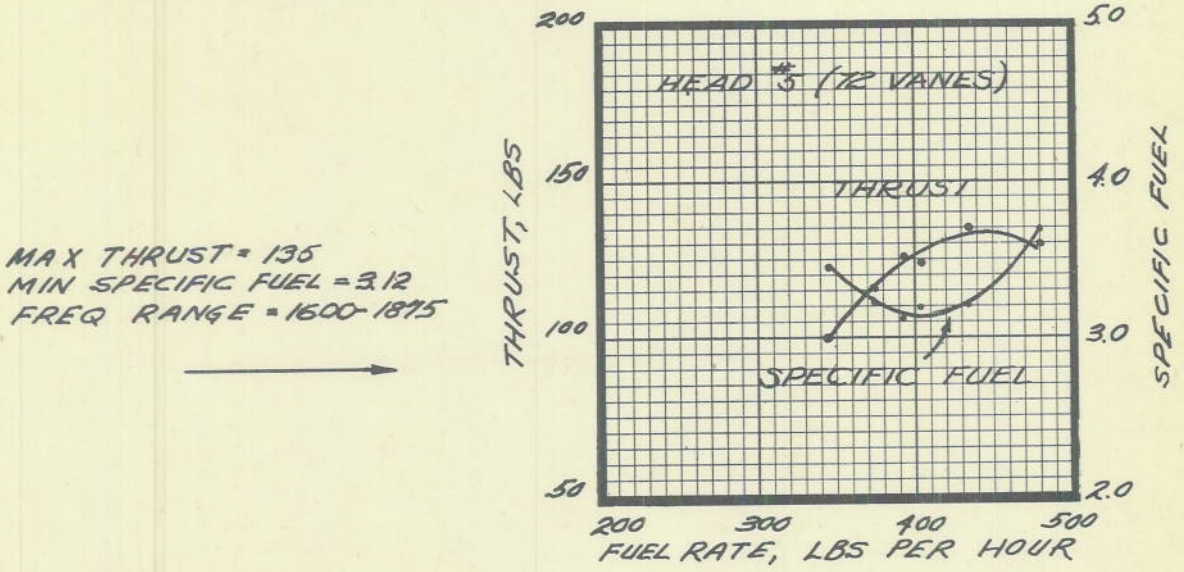
DECLASSIFIED

MODIFICATION "I"





MAX THRUST = 85
MIN SPECIFIC FUEL = 3.26
FREQ RANGE = 1725-1875



MAX THRUST = 135
MIN SPECIFIC FUEL = 3.12
FREQ RANGE = 1600-1875

CONFIDENTIAL

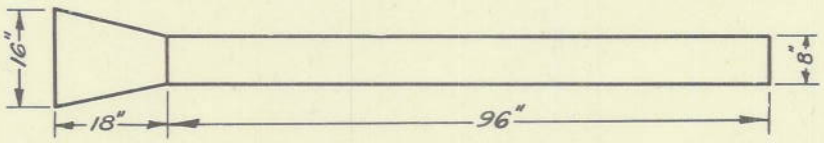
O-3064

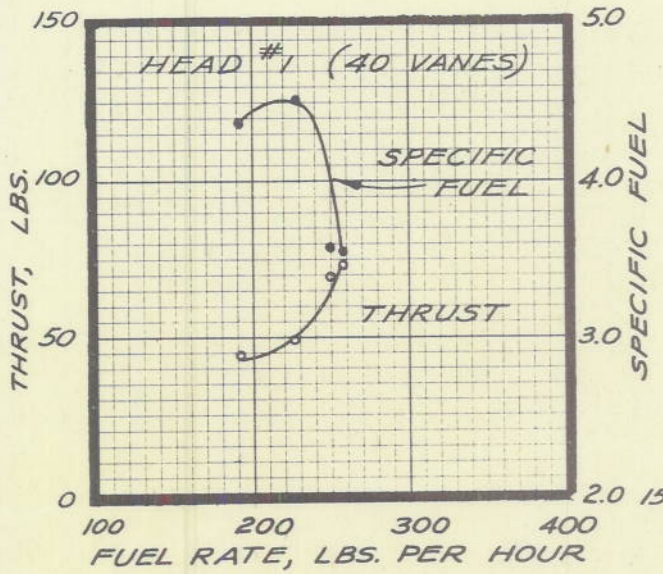
FIGURE 47

DECLASSIFIED

DECLASSIFIED

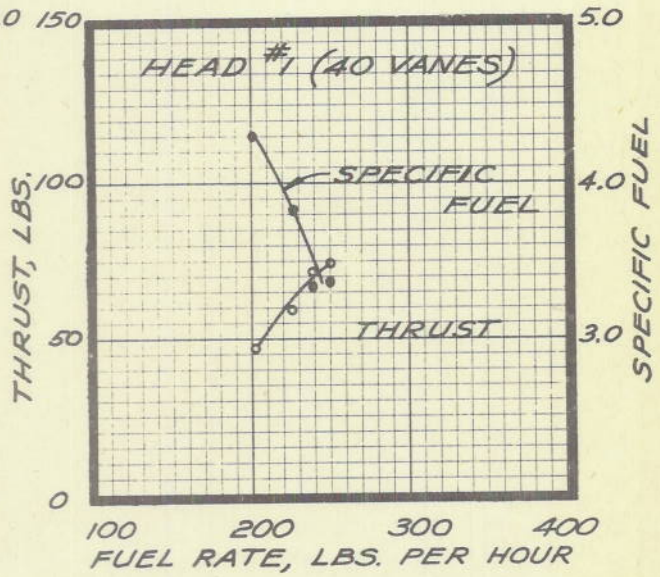
MODIFICATION "J"



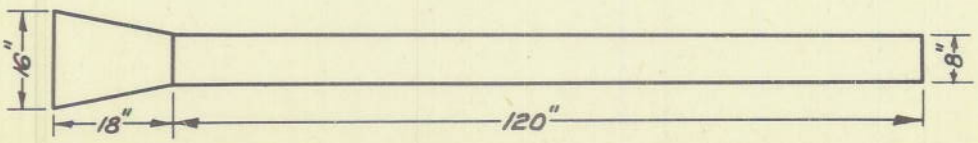


MAX. THRUST = 73
MIN. SPECIFIC FUEL = 3.55
FREQ. RANGE = 3700 - 4000

MAX. THRUST = 74
MIN. SPECIFIC FUEL = 3.33
FREQ. RANGE = 3000 - 3400



MODIFICATION "J"



CONFIDENTIAL

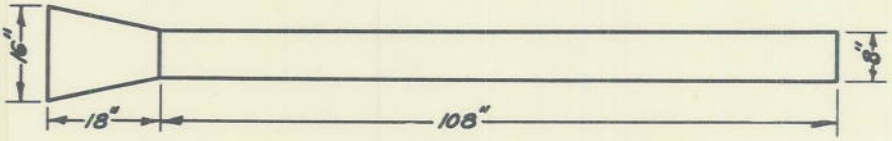
0-3064

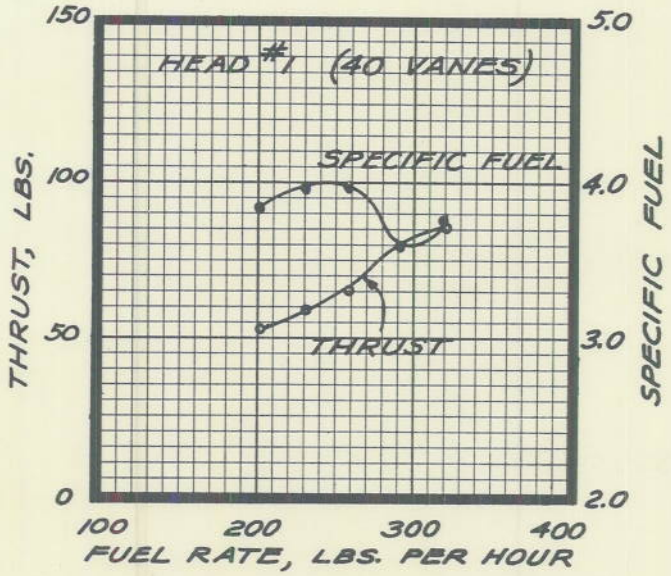
FIGURE 48

DECLASSIFIED

DECLASSIFIED

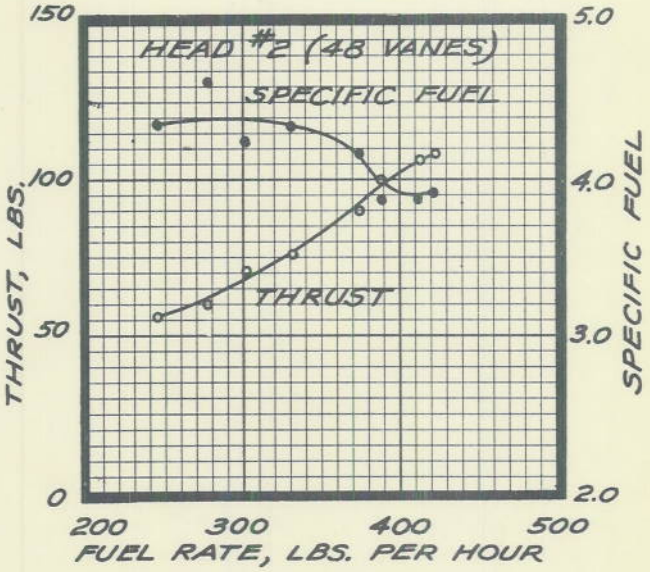
MODIFICATION "J"





MAX. THRUST = 86
MIN. SPECIFIC FUEL = 3.60
FREQ. RANGE = 2750–3250

MAX. THRUST = 108
MIN. SPECIFIC FUEL 3.88
FREQ. RANGE = 2800–3250



CONFIDENTIAL

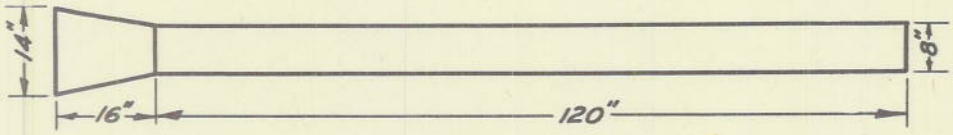
0-3064

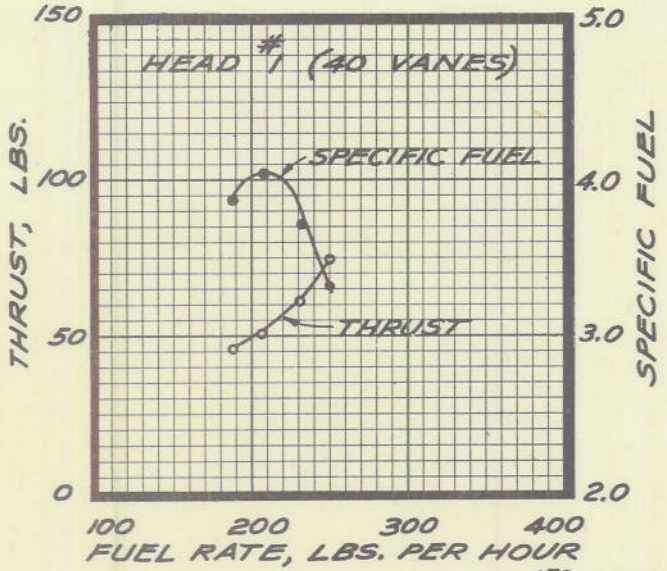
FIGURE 49

DECLASSIFIED

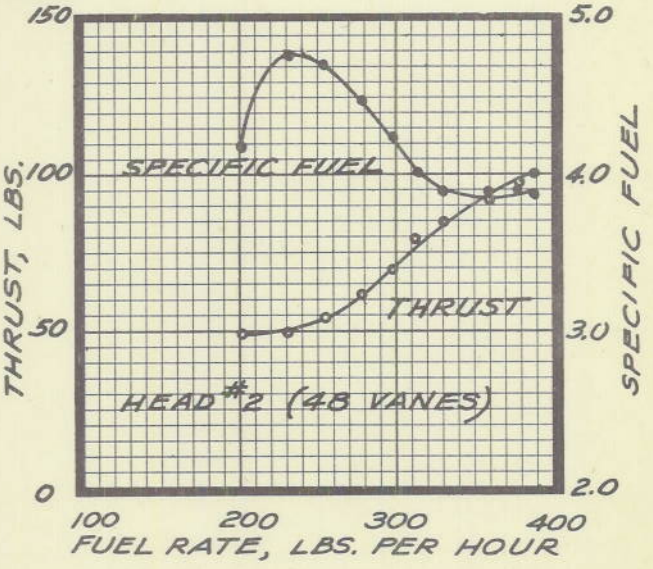
DECLASSIFIED

MODIFICATION "K"





MAX. THRUST = 75
MIN. SPECIFIC FUEL = 3.32
FREQ. RANGE = 3000–3250



MAX. THRUST = 100
MIN. SPECIFIC FUEL = 3.87
FREQ. RANGE = 2950–3500

CONFIDENTIAL

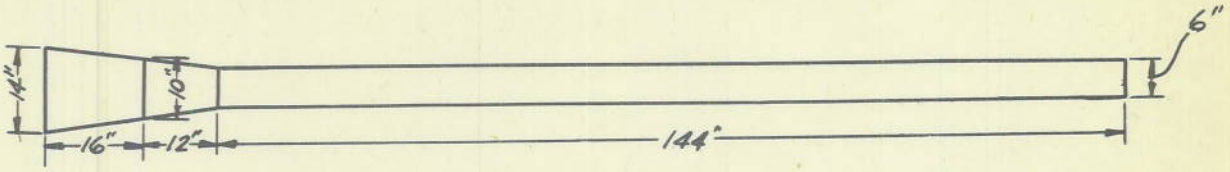
0-3064

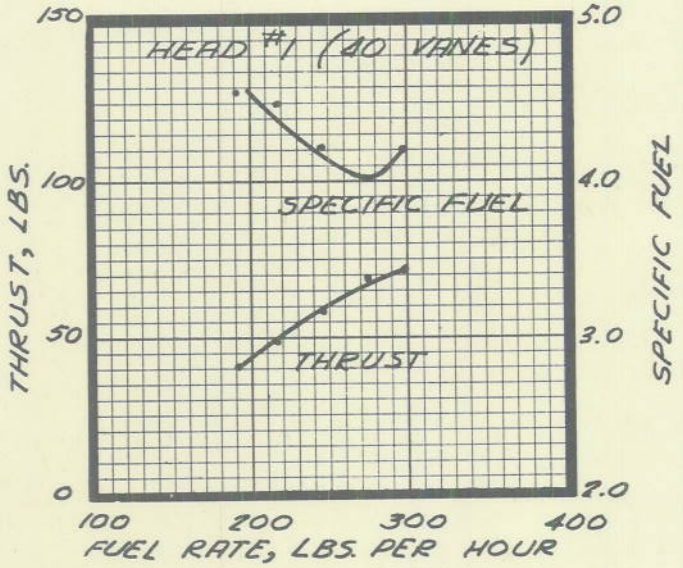
FIGURE 50

DECLASSIFIED

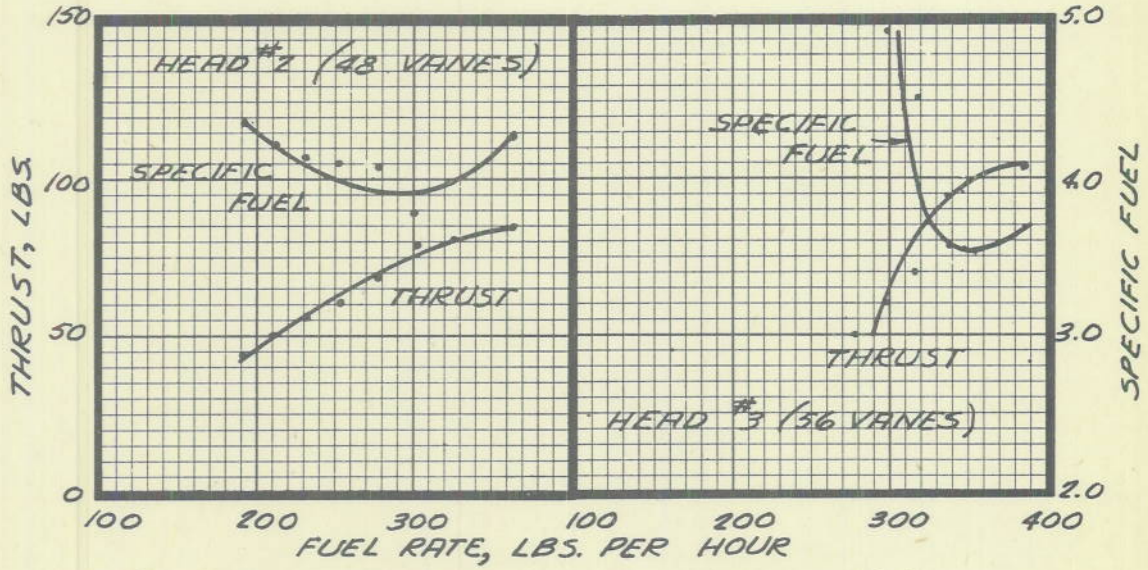
DECLASSIFIED

MODIFICATION "L"





MAX. THRUST = 71
MIN. SPECIFIC FUEL = 4.02
FREQ. RANGE = 2190-2600



MAX. THRUST = 85
MIN SPECIFIC FUEL = 3.78
FREQ. RANGE = 2350-2830

MAX. THRUST = 104
MIN. SPECIFIC FUEL = 3.54
FREQ. RANGE = 2000-2400

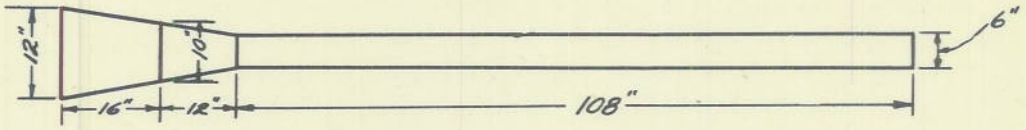
CONFIDENTIAL

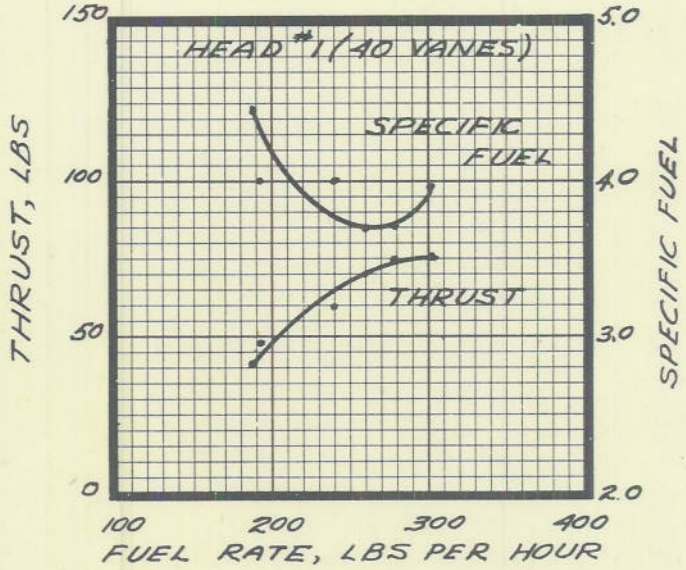
0-3064

FIGURE 51

DECLASSIFIED

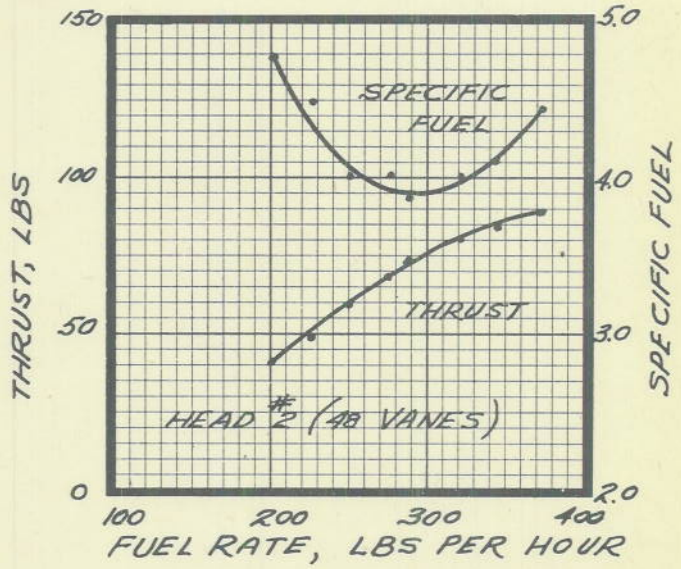
MODIFICATION "L"





MAX THRUST = 76
MIN SPECIFIC FUEL = 3.70
FREQ RANGE = 2550-3000

MAX THRUST = 88
MIN SPECIFIC FUEL = 3.89
FREQ. RANGE = 2520-3075



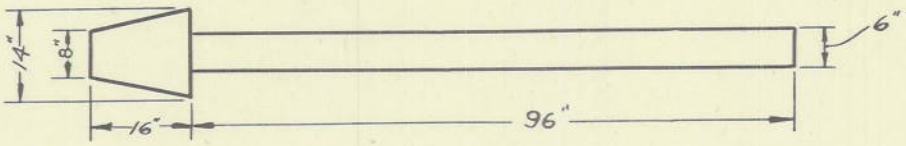
CONFIDENTIAL

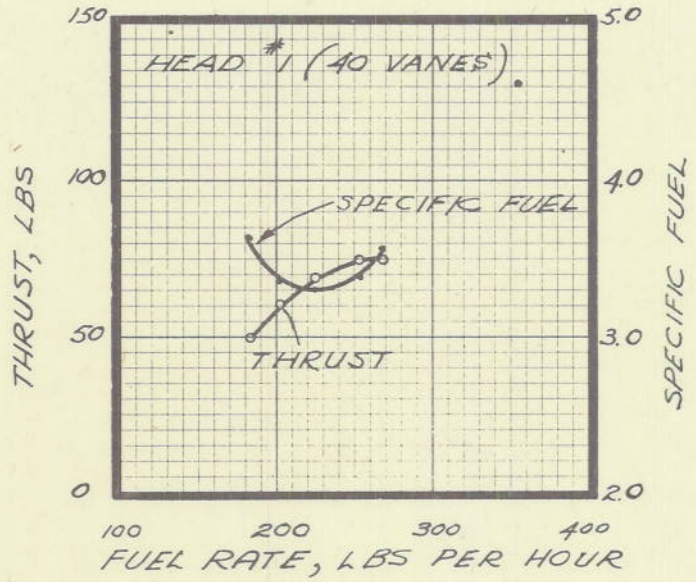
0-3064

FIGURE 52

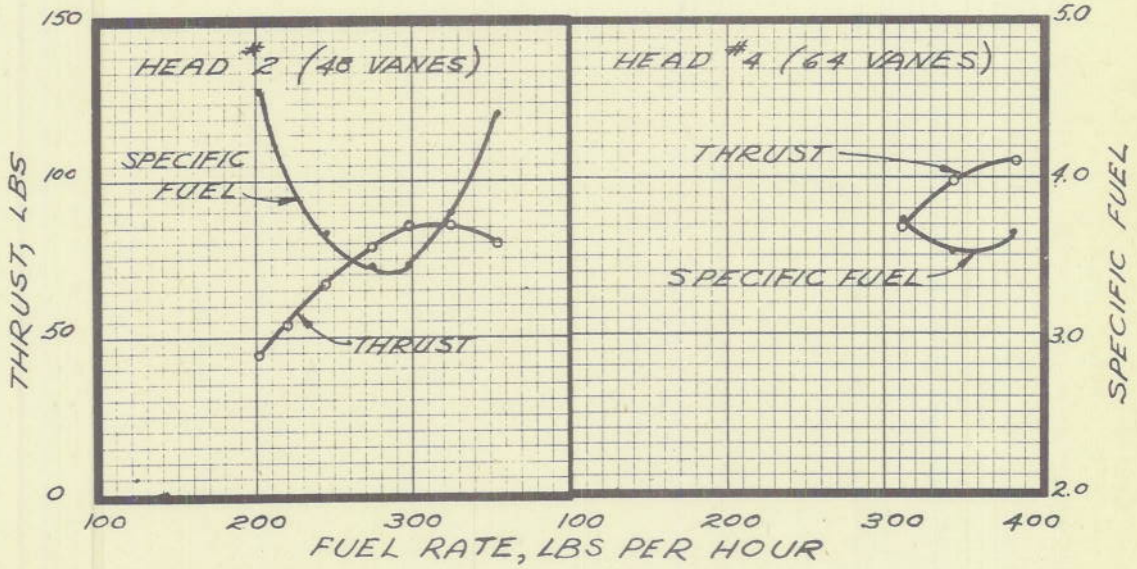
DECLASSIFIED

MODIFICATION "M"





MAX. THRUST = 75
MIN SPECIFIC FUEL = 3.31
FREQ. RANGE = 2900-3325



MAX THRUST = 86
MIN SPECIFIC FUEL = 3.46
FREQ RANGE = 2700-3350

MAX THRUST = 105
MIN SPECIFIC FUEL = 3.53
FREQ RANGE = 2900-3000

CONFIDENTIAL

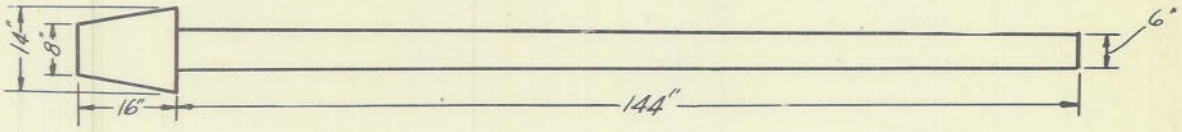
O-3064

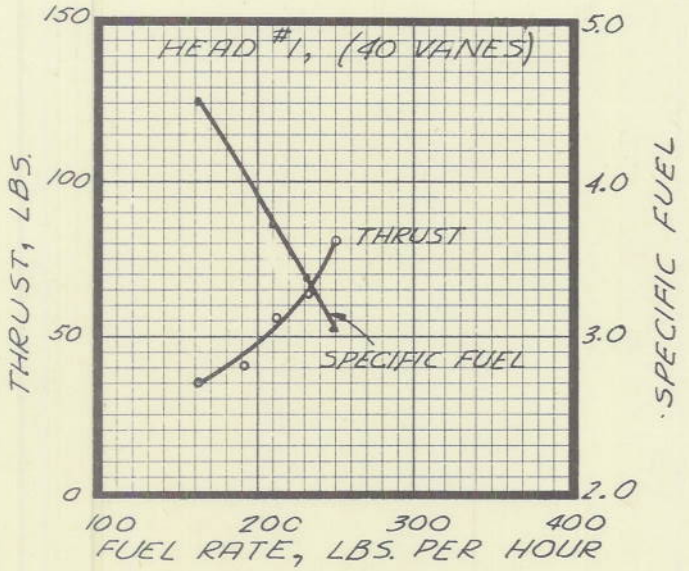
FIGURE 53

DECLASSIFIED

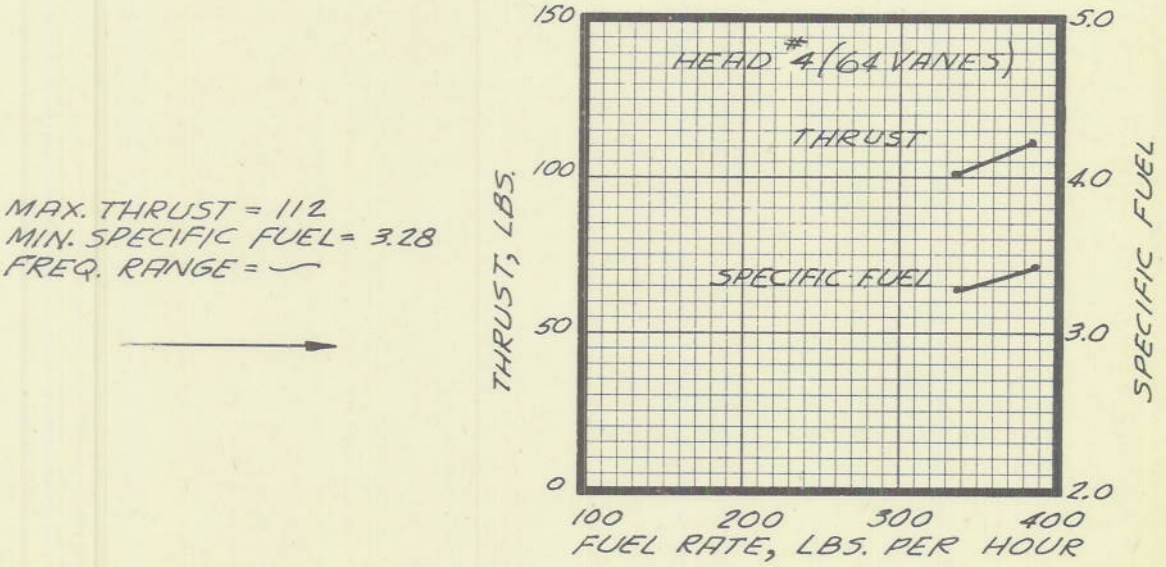
DECLASSIFIED

MODIFICATION "M"





MAX. THRUST = 82
MIN. SPECIFIC FUEL = 3.04
FREQ. RANGE = ⌣



MAX. THRUST = 112
MIN. SPECIFIC FUEL = 3.28
FREQ. RANGE = ⌣

CONFIDENTIAL

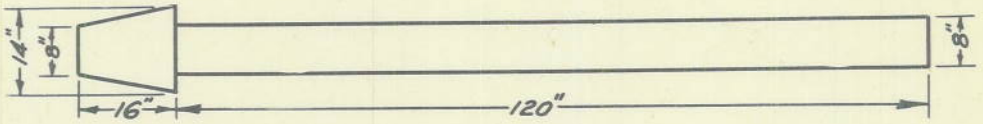
O-3064

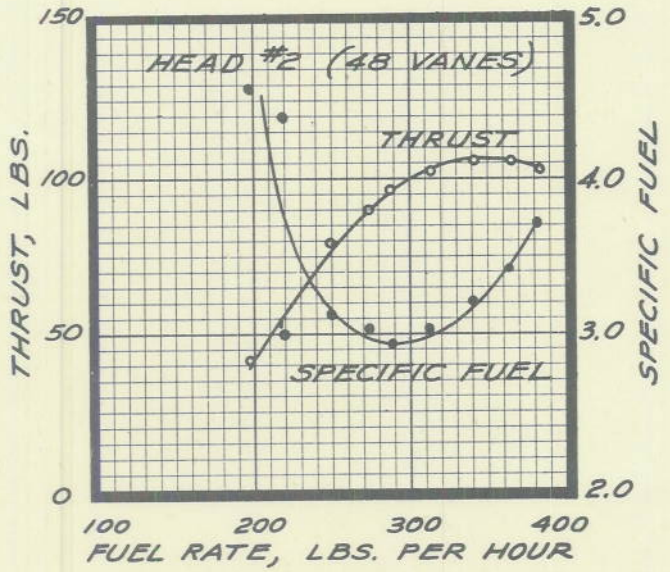
FIGURE 54

DECLASSIFIED

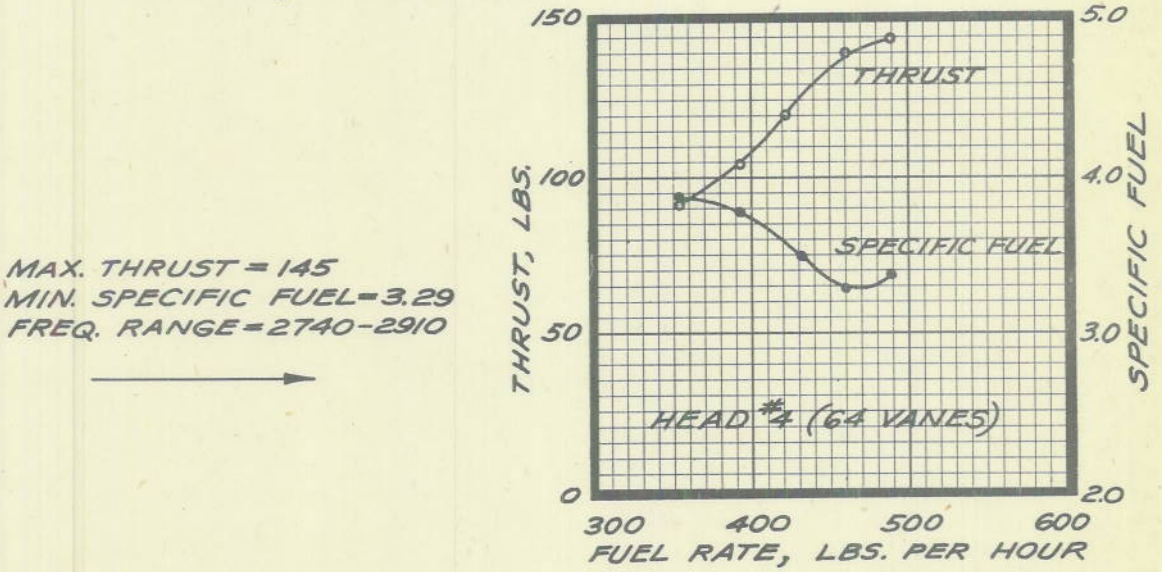
DECLASSIFIED

MODIFICATION "M"





MAX. THRUST = 106
MIN. SPECIFIC FUEL = 2.94
FREQ. RANGE = 2480-3180



MAX. THRUST = 145
MIN. SPECIFIC FUEL = 3.29
FREQ. RANGE = 2740-2910

CONFIDENTIAL

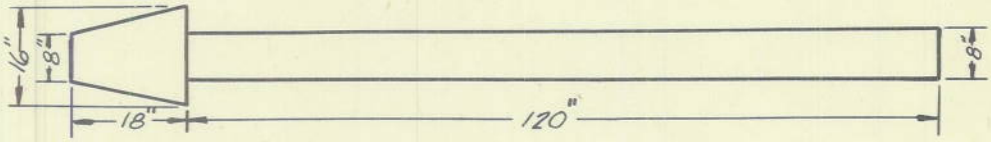
0-3064

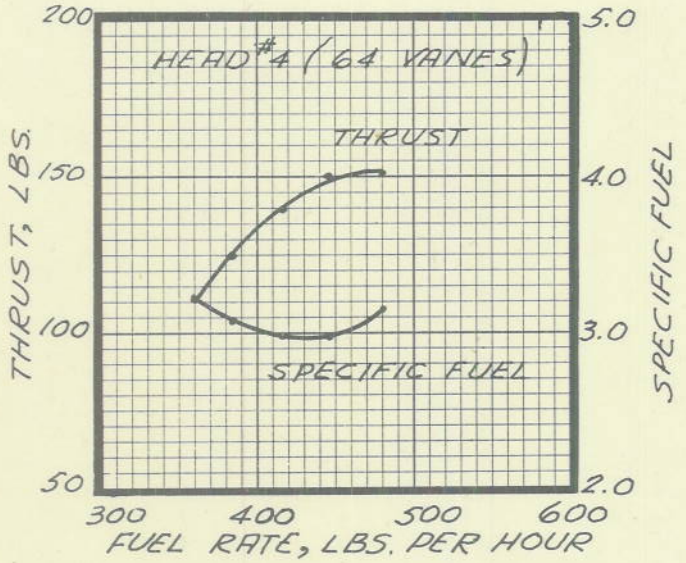
FIGURE 55

DECLASSIFIED

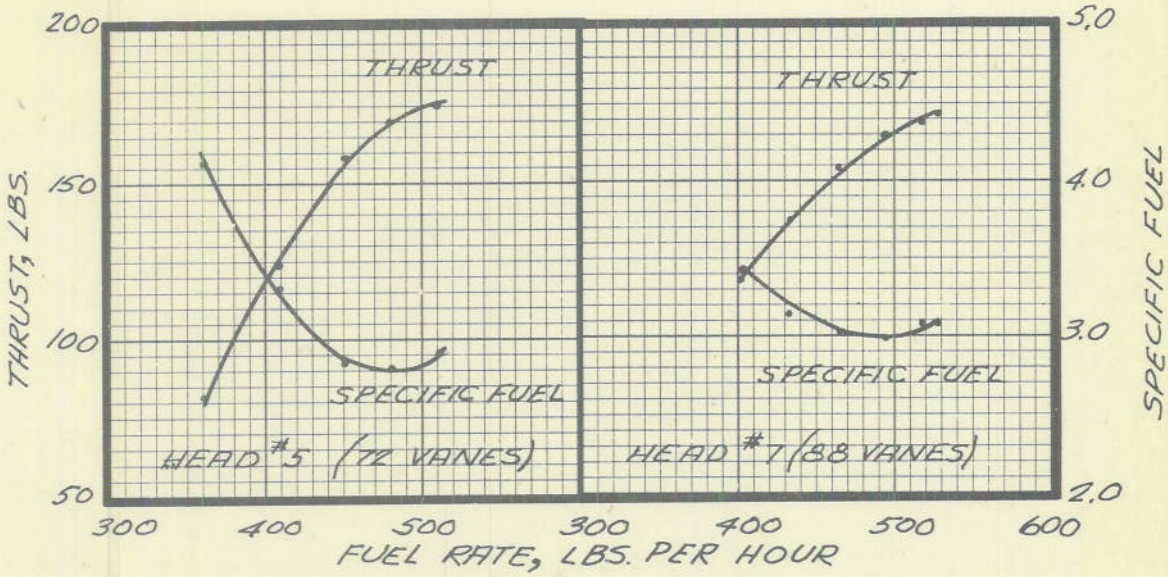
DECLASSIFIED

MODIFICATION "P"





MAX. THRUST = 152
MIN. SPECIFIC FUEL = 2.97
FREQ. RANGE = 2400-2700



MAX. THRUST = 176
MIN. SPECIFIC FUEL = 2.82
FREQ. RANGE = 2450-2850

MAX. THRUST = 172
MIN. SPECIFIC FUEL = 2.98
FREQ. RANGE = 2480-2800

CONFIDENTIAL

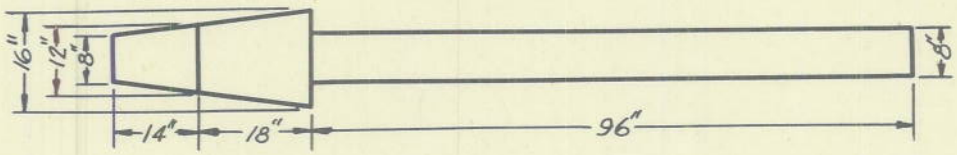
0-3064

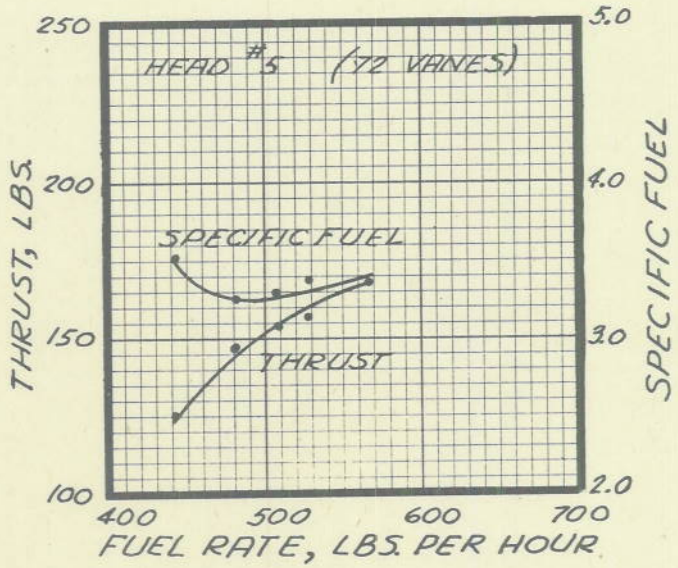
FIGURE 56

DECLASSIFIED

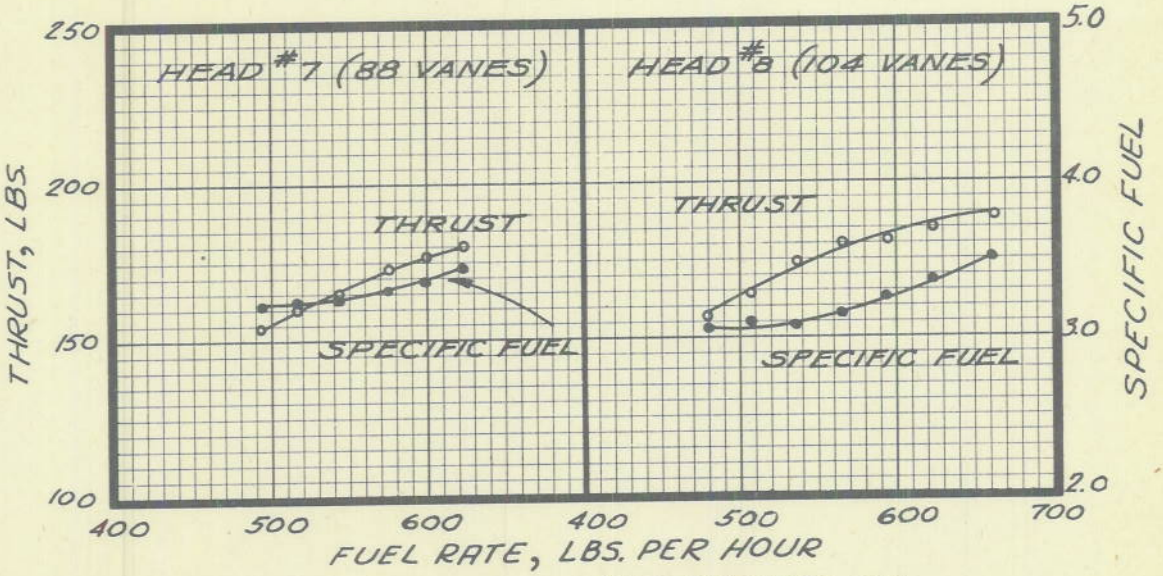
DECLASSIFIED

MODIFICATION Q





MAX. THRUST = 168
MIN. SPECIFIC FUEL = 3.26
FREQ. RANGE = 2280-2450



MAX. THRUST = 180
MIN. SPECIFIC FUEL = 3.23
FREQ. RANGE = 2210-2390

MAX. THRUST = 188
MIN. SPECIFIC FUEL = 3.06
FREQ. RANGE = 2350-2500

CONFIDENTIAL

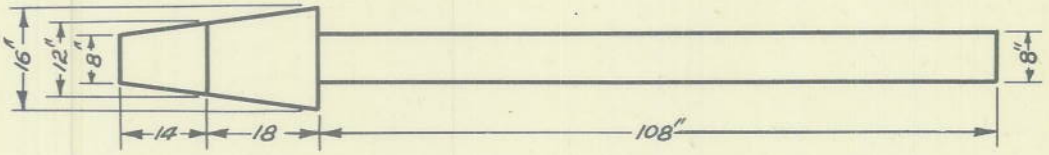
O-3064

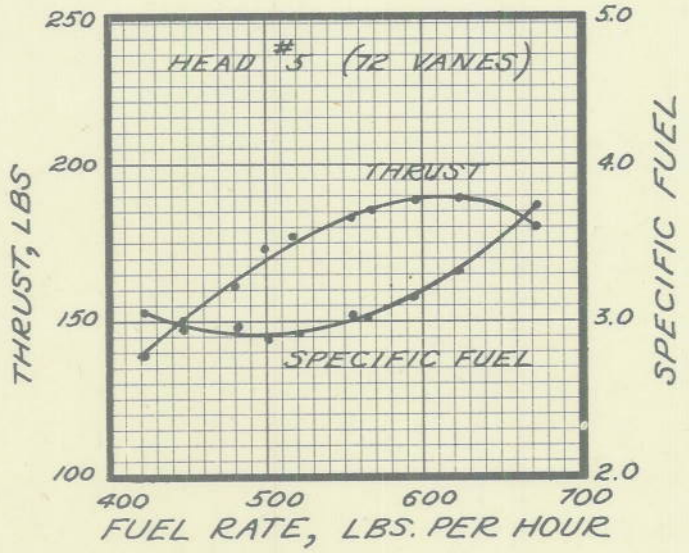
FIGURE 57

DECLASSIFIED

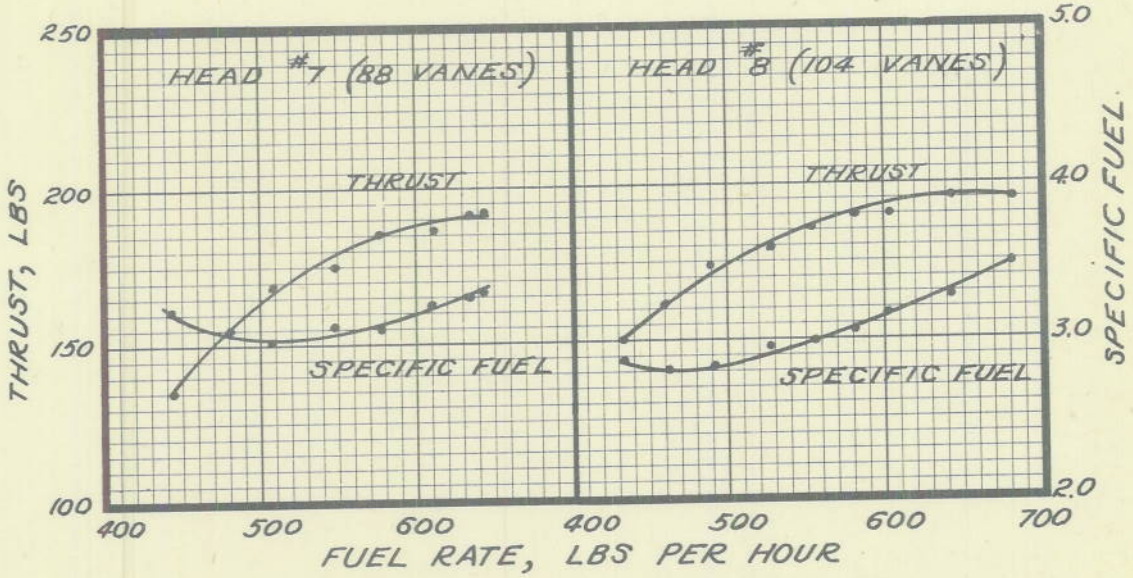
DECLASSIFIED

MODIFICATION Q





MAX. THRUST = 188
MIN. SPECIFIC FUEL = 2.89
FREQ. RANGE = 2110 - 2400



MAX. THRUST = 193
MIN. SPECIFIC FUEL = 3.02
FREQ RANGE = 2130-2310

MAX. THRUST = 196
MIN. SPECIFIC FUEL = 2.80
FREQ RANGE = 2280-2400

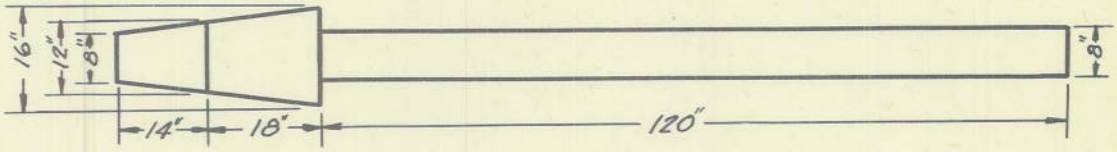
CONFIDENTIAL

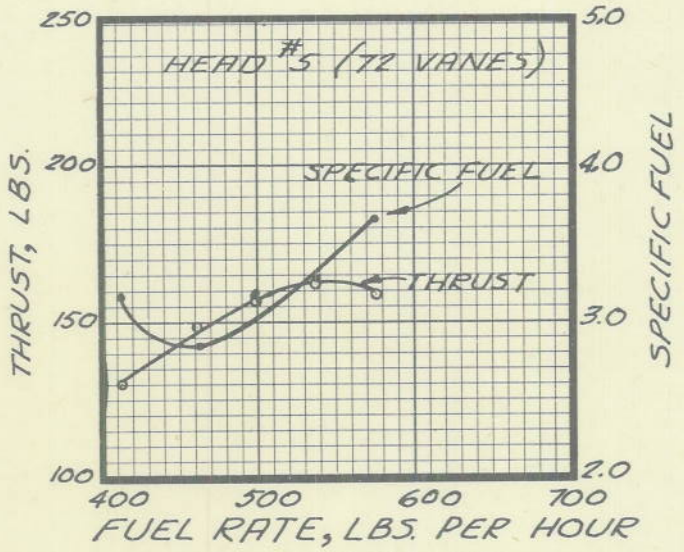
FIGURE 58

DECLASSIFIED

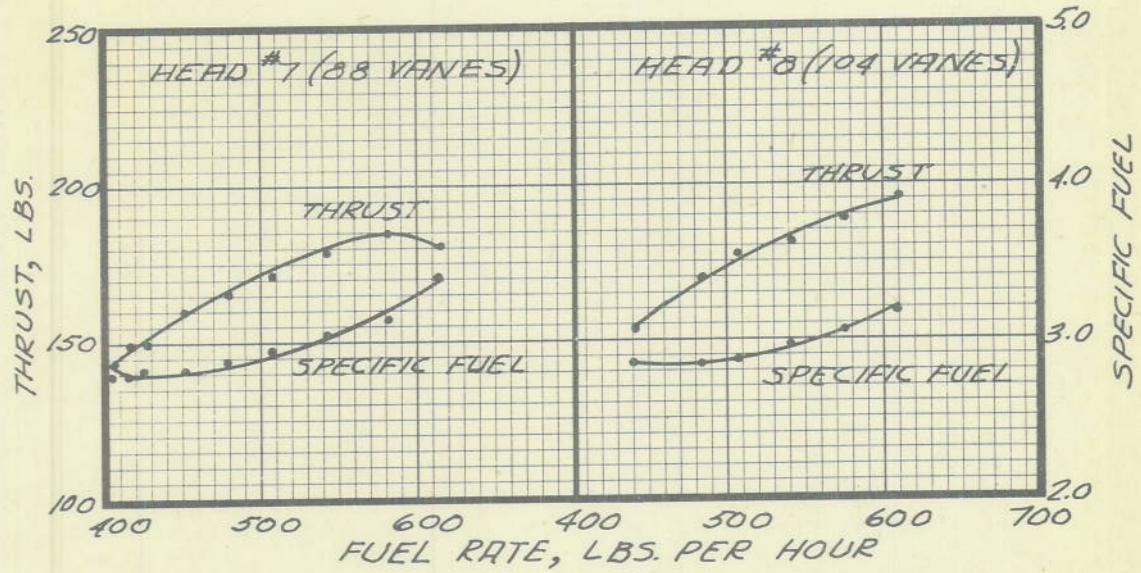
DECLASSIFIED

MODIFICATION Q





MAX. THRUST = 163
MIN. SPECIFIC FUEL = 2.86
FREQ. RANGE = 2000-2230



MAX. THRUST = 185
MIN. SPECIFIC FUEL = 2.78
FREQ RANGE = 2090-2300

MAX. THRUST = 194
MIN. SPECIFIC FUEL = 2.85
FREQ. RANGE = 2260-2400

[redacted]

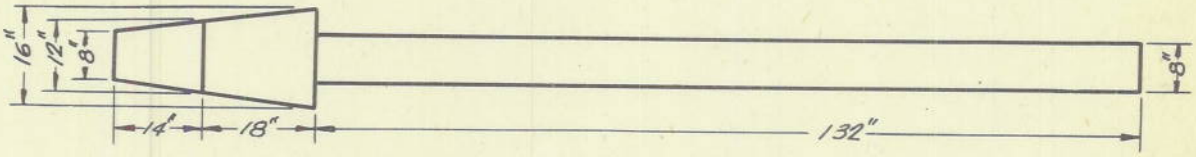
0-3064

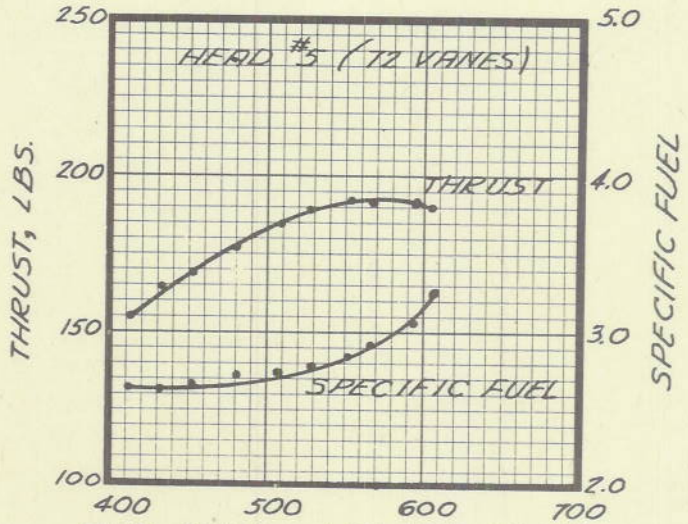
FIGURE 59

DECLASSIFIED

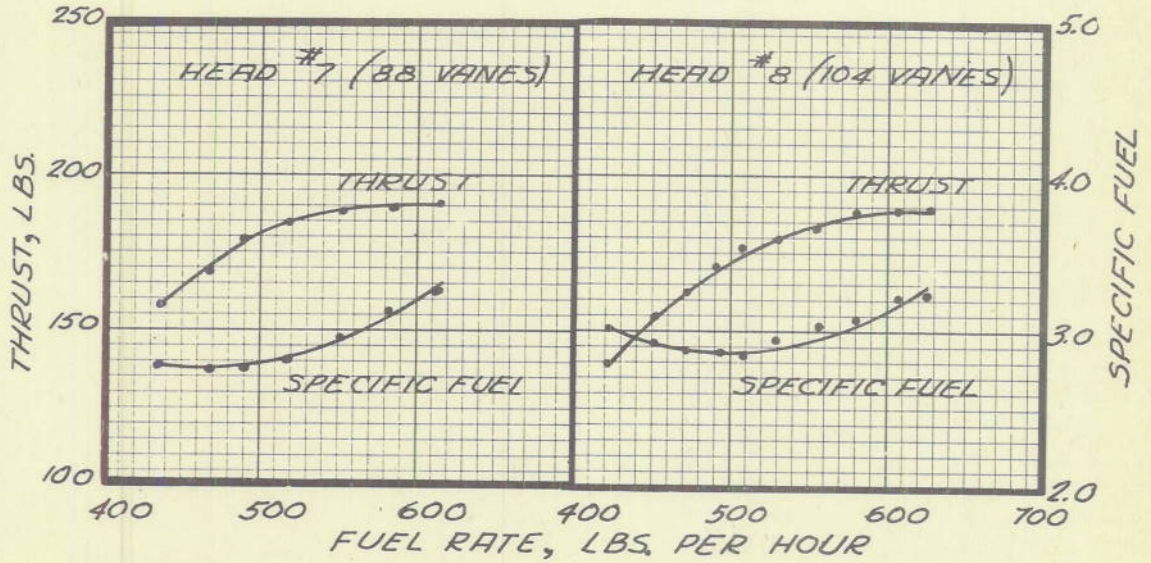
DECLASSIFIED

MODIFICATION Q





MAX. THRUST = 194
MIN. SPECIFIC FUEL = 2.63
FREQ. RANGE = 1910-2110



MAX. THRUST = 191
MIN. SPECIFIC FUEL = 2.74
FREQ RANGE = 1950-2060

MAX. THRUST = 188
MIN. SPECIFIC FUEL = 2.86
FREQ. RANGE = 2100-2260

CONFIDENTIAL

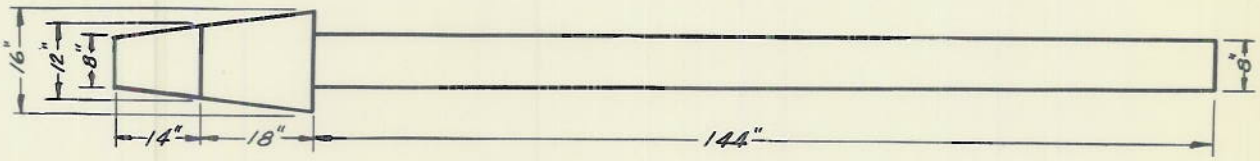
O-3064

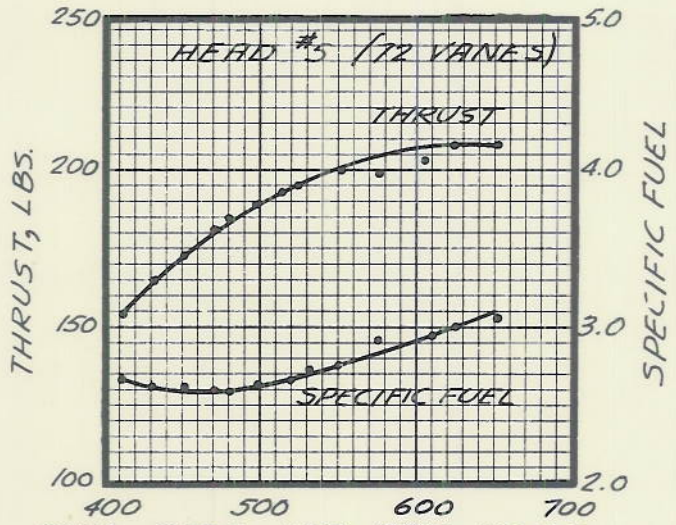
FIGURE 60

DECLASSIFIED

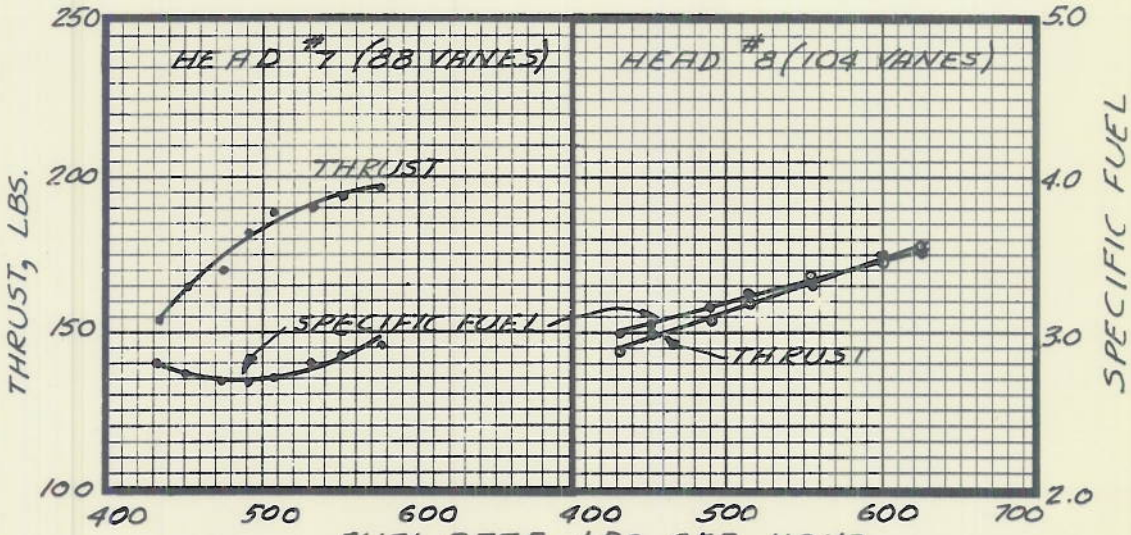
DECLASSIFIED

MODIFICATION Q





MAX. THRUST = 208
MIN. SPECIFIC FUEL = 2.59
FREQ. RANGE = 1800-2070



MAX. THRUST = 197
MIN. SPECIFIC FUEL = 2.69
FREQ. RANGE = 1950-2020

MAX. THRUST = 177
MIN. SPECIFIC FUEL = 3.0
FREQ. RANGE = 2060-2250

CONFIDENTIAL

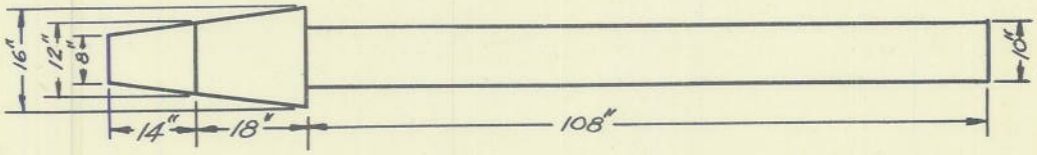
0-3064

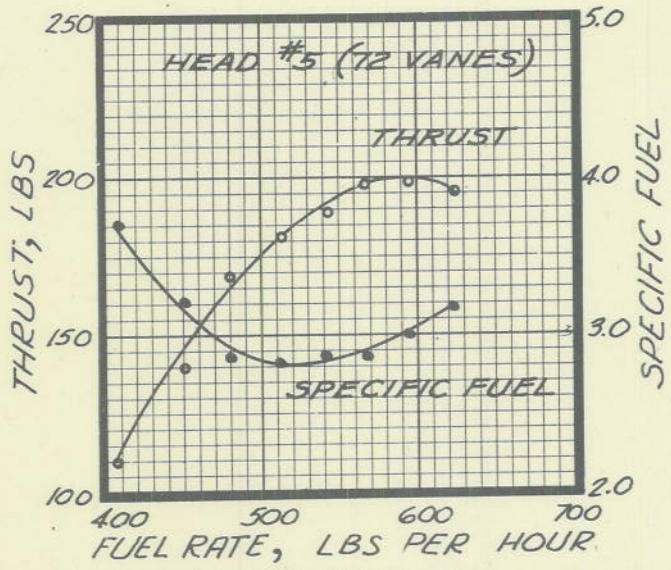
FIGURE 61

DECLASSIFIED

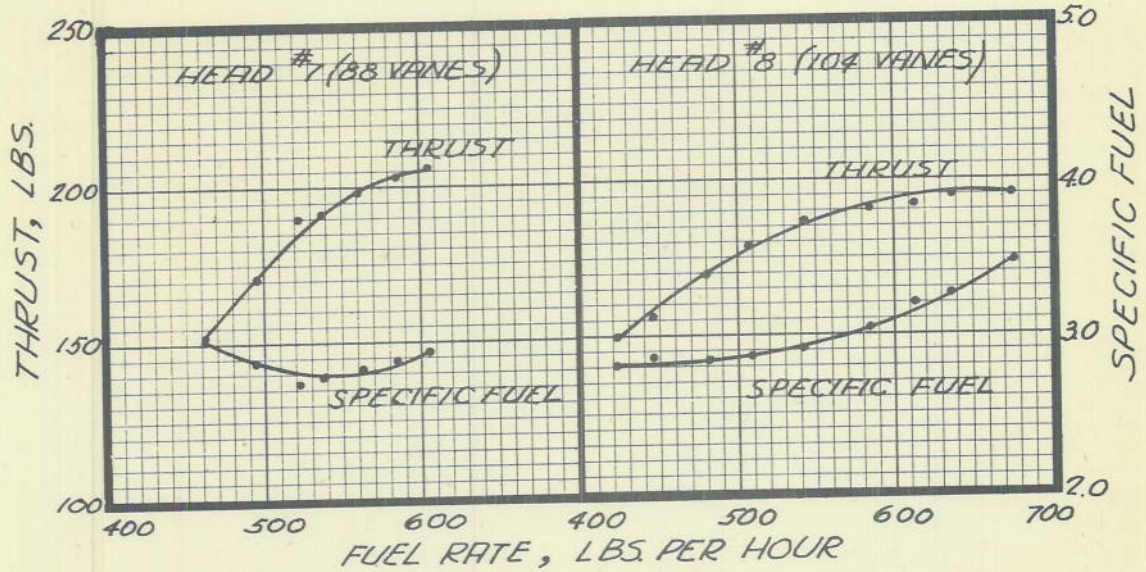
DECLASSIFIED

MODIFICATION Q





MAX. THRUST = 198
MIN. SPECIFIC FUEL = 2.82
FREQ. RANGE = 2350-2600



MAX. THRUST = 206
MIN. SPECIFIC FUEL = 2.75
FREQ. RANGE = 2470-2600

MAX. THRUST = 195
MIN. SPECIFIC FUEL = 2.81
FREQ. RANGE = 2490-2620

CONFIDENTIAL

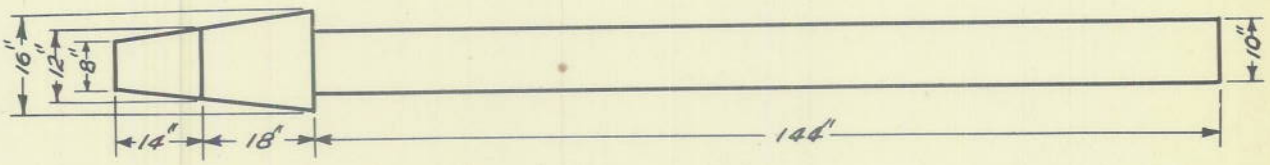
0-3064

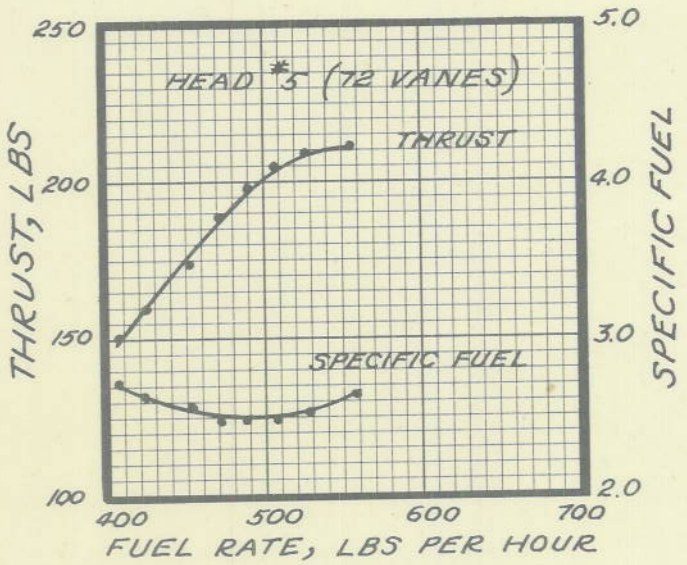
FIGURE 62

DECLASSIFIED

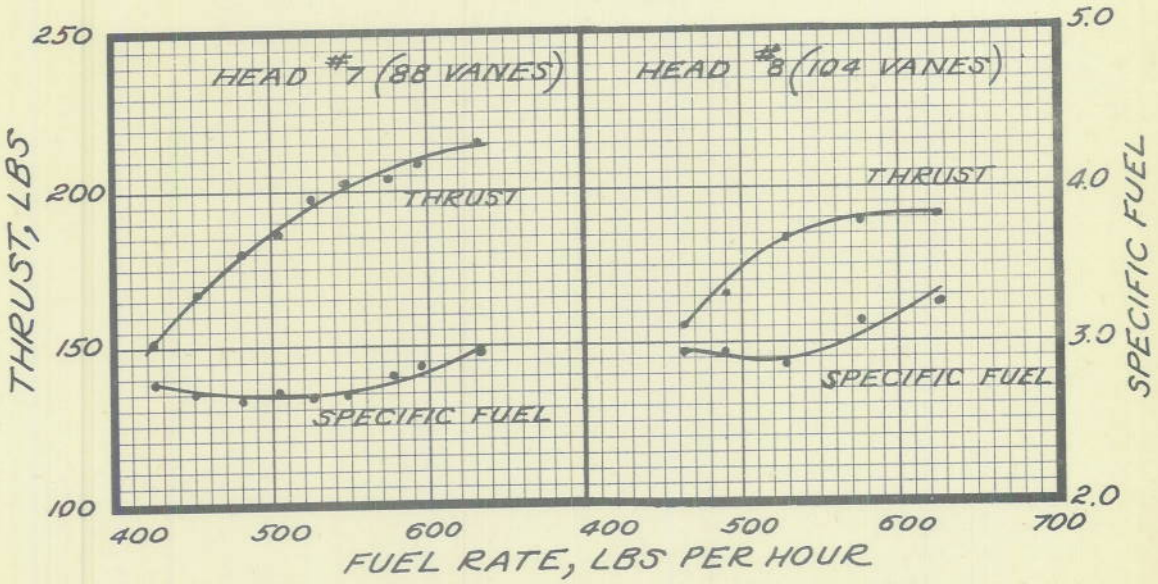
DECLASSIFIED

MODIFICATION Q





MAX. THRUST = 212
MIN. SPECIFIC FUEL = 2.48
FREQ RANGE = 2070-2150



MAX. THRUST = 215
MIN. SPECIFIC FUEL = 2.67
FREQ. RANGE = 2020-2120

MAX. THRUST = 192
MIN. SPECIFIC FUEL = 2.87
FREQ. RANGE = 2140-2290

O-3064

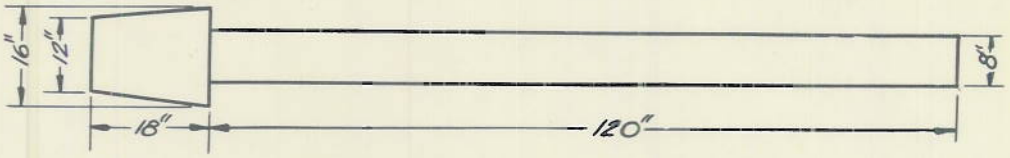
FIGURE 63

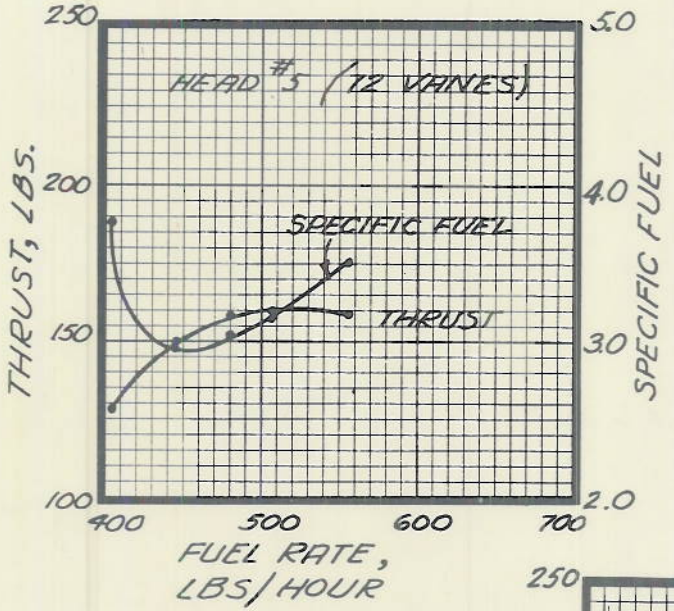
CONFIDENTIAL

DECLASSIFIED

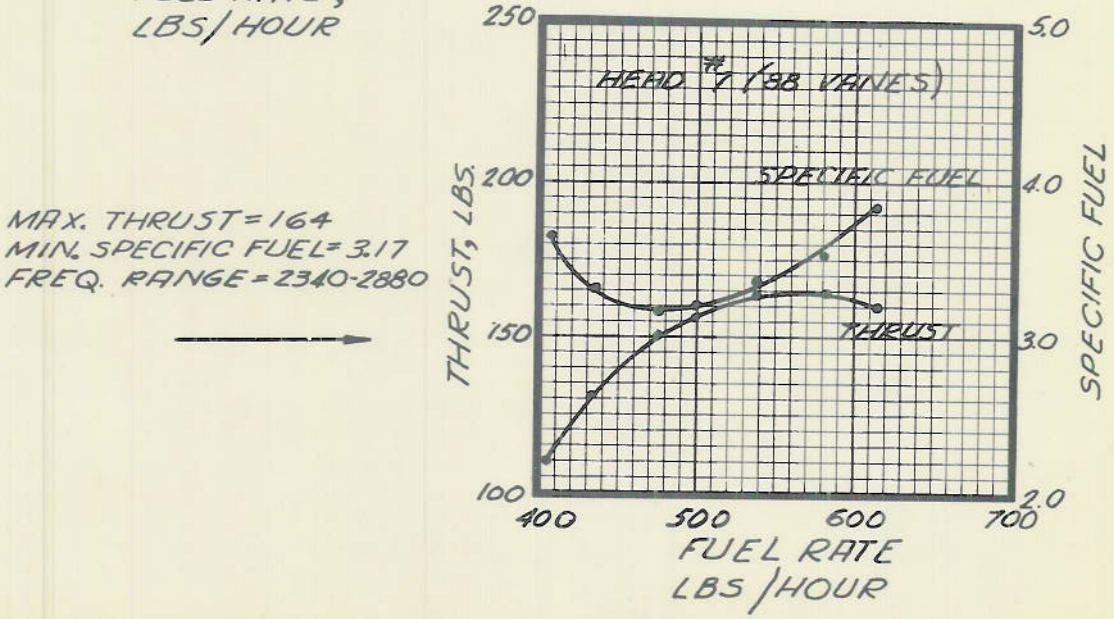
DECLASSIFIED

MODIFICATION R





MAX. THRUST = 160
MIN. SPECIFIC FUEL = 2.97
FREQ. RANGE = 2440-2500



MAX. THRUST = 164
MIN. SPECIFIC FUEL = 3.17
FREQ. RANGE = 2340-2880

CONFIDENTIAL

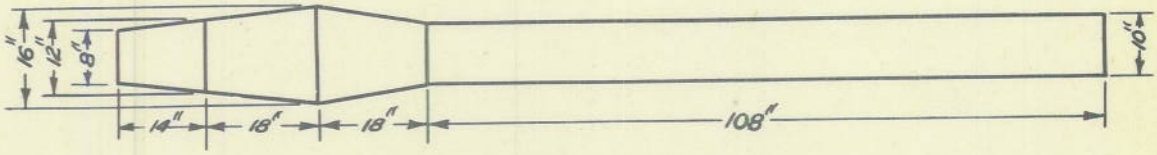
O-3064

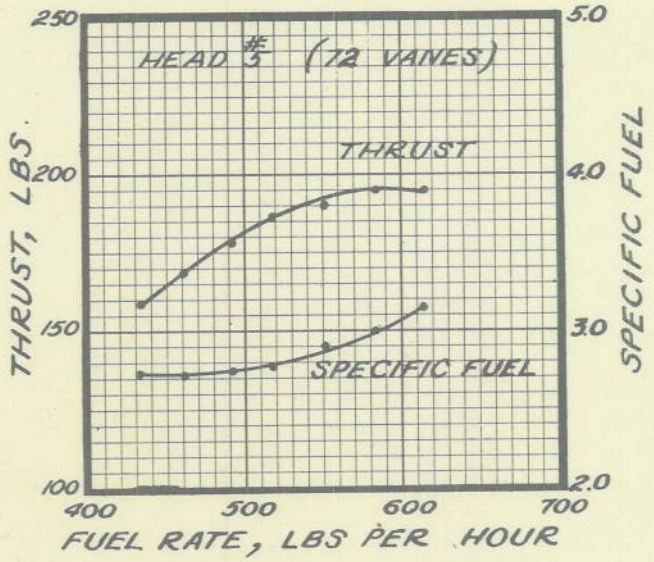
FIGURE 64

DECLASSIFIED

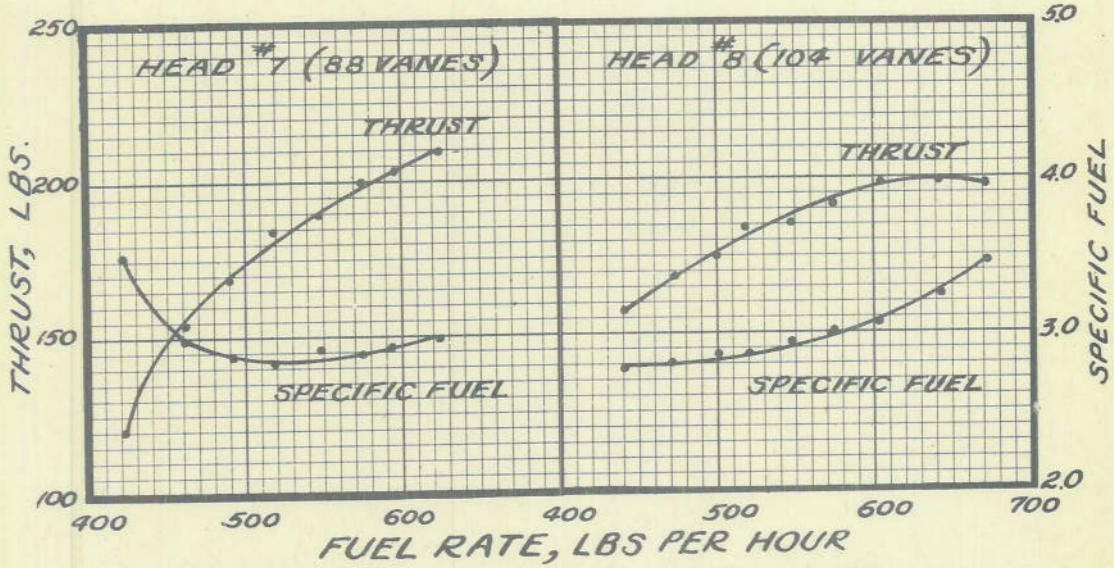
DECLASSIFIED

MODIFICATION T





MAX. THRUST = 195
MIN. SPECIFIC FUEL = 2.72
FREQ. RANGE = 2050-2210



MAX. THRUST = 210
MIN. SPECIFIC FUEL = 2.82
FREQ. RANGE = 2100-2290

MAX. THRUST = 198
MIN. SPECIFIC FUEL = 2.79
FREQ. RANGE = 2230-2300

CONFIDENTIAL

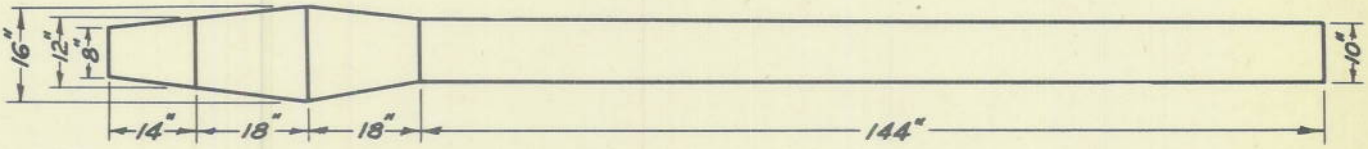
0-3064

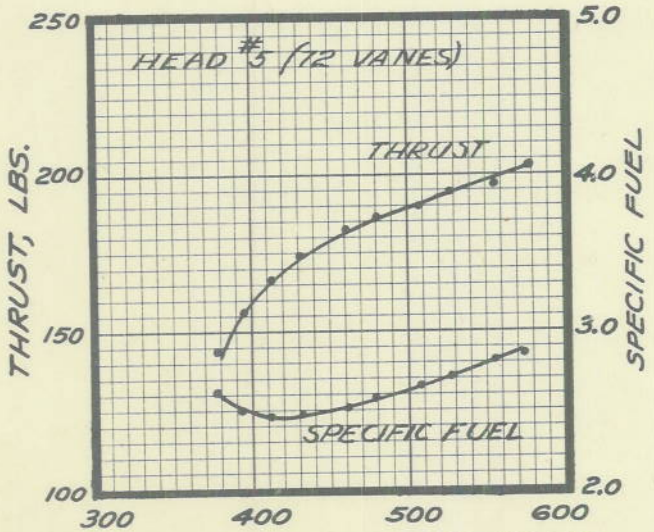
FIGURE 65

DECLASSIFIED

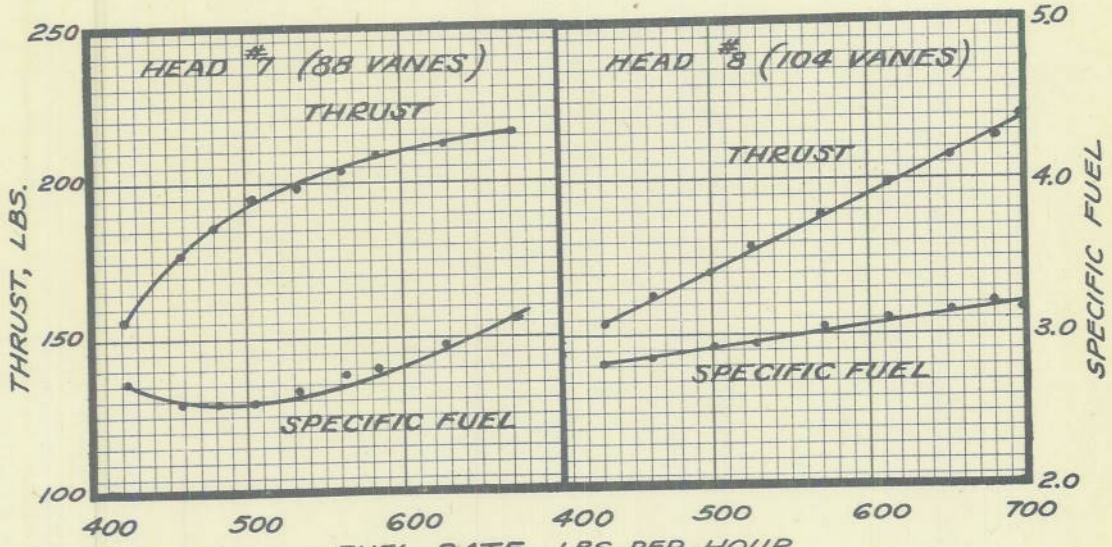
DECLASSIFIED

MODIFICATION "T"





FUEL RATE, LBS. PER HOUR
MAX. THRUST=203
MIN. SPECIFIC FUEL=2.47
FREQ. RANGE=1750-1900



FUEL RATE, LBS. PER HOUR

MAX. THRUST=215
MIN. SPECIFIC FUEL=2.58
FREQ. RANGE=1770-1960

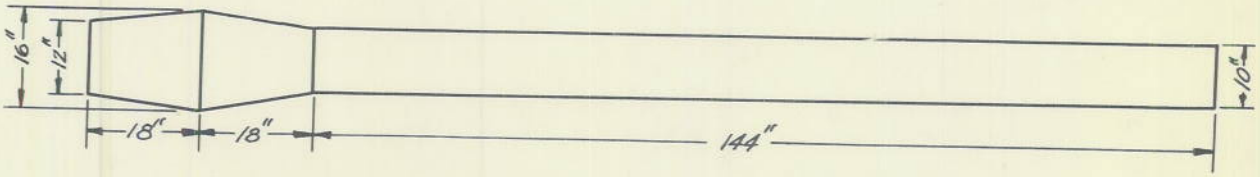
MAX. THRUST=220
MIN. SPECIFIC FUEL=2.80
FREQ. RANGE=1830-2010

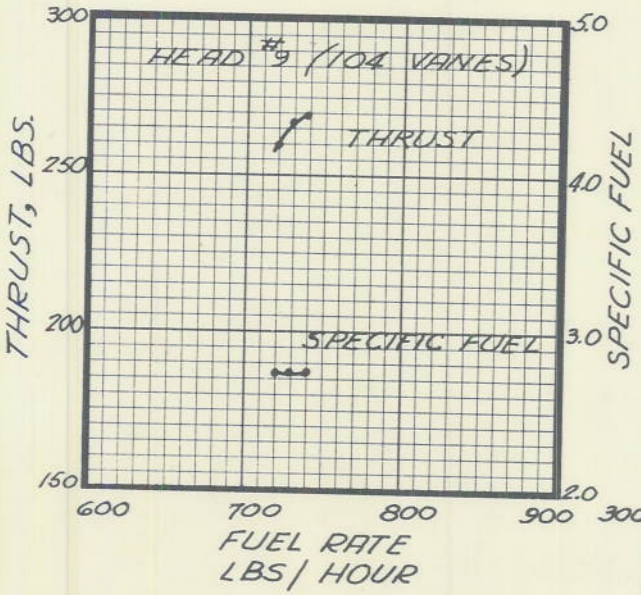
[redacted] 0-3064 FIGURE 66

DECLASSIFIED

DECLASSIFIED

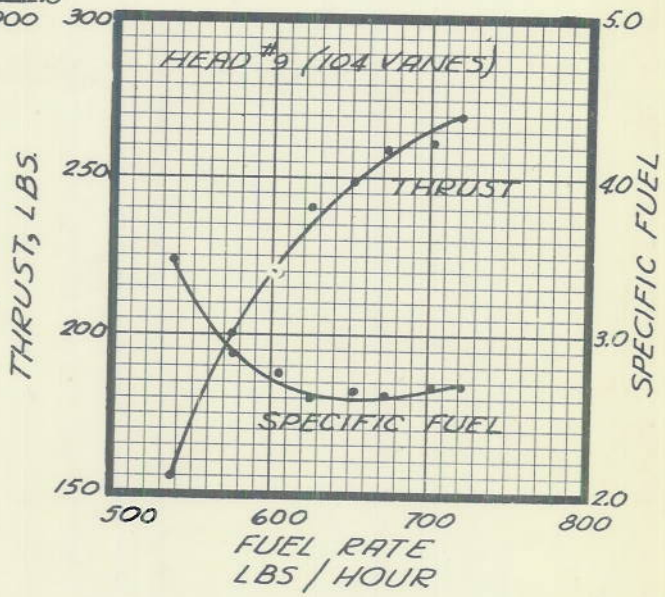
MODIFICATION U



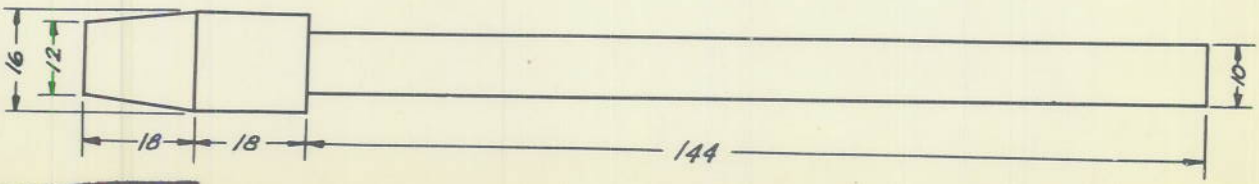


MAX. THRUST = 270
MIN. SPECIFIC FUEL = 2.73
FREQ RANGE = 2050-2200

MAX. THRUST = 270
MIN. SPECIFIC FUEL = 2.60
FREQ. RANGE = 1900-2120



MODIFICATION V



CONFIDENTIAL

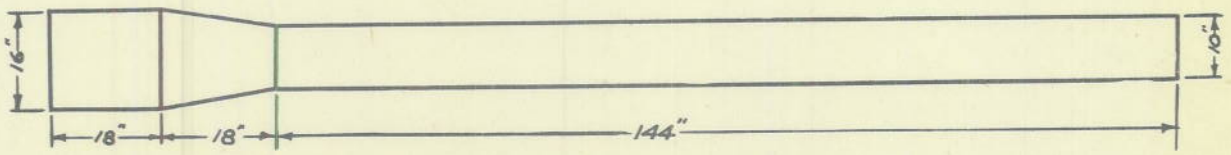
0-3064

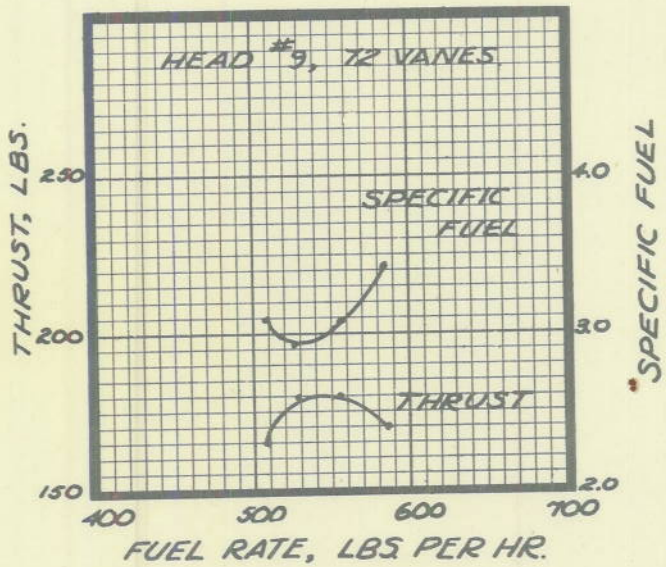
FIGURE 67

DECLASSIFIED

DECLASSIFIED

MODIFICATION "X"





MAX. THRUST = 180
MIN. SPECIFIC FUEL = 2.93
FREQ. RANGE = 1920 - 1950

←

MAX. THRUST = 2.55
MIN. SPECIFIC FUEL = 2.52
FREQ RANGE = 2000-2050

→

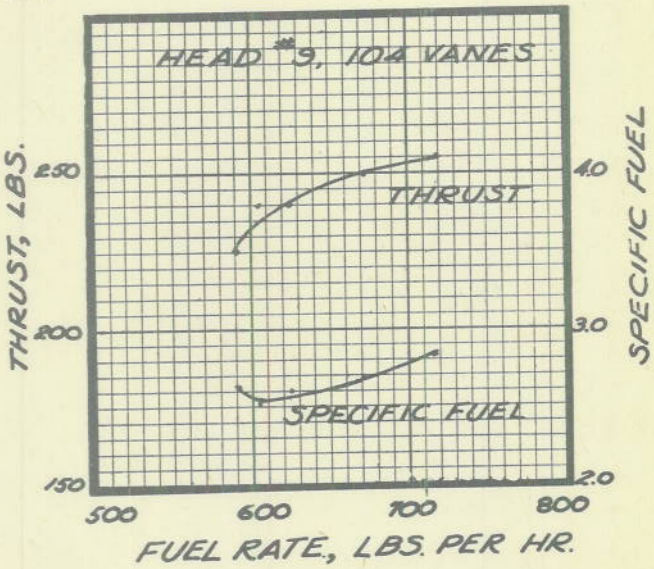


FIGURE 68

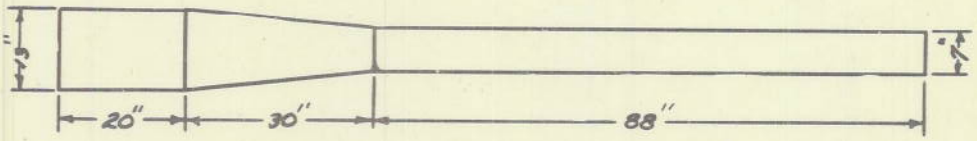
CONFIDENTIAL

DECLASSIFIED

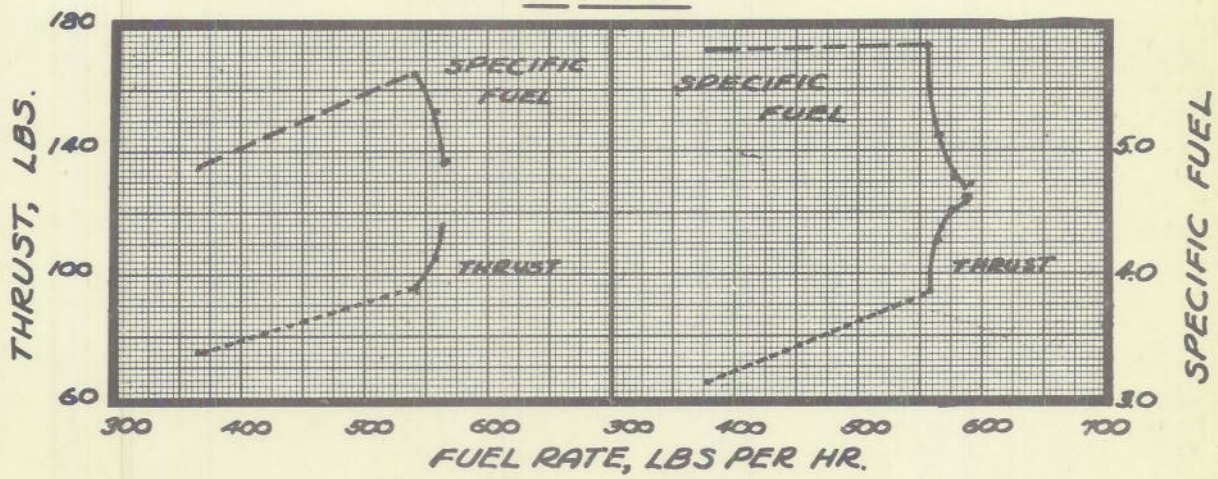
DECLASSIFIED

STANDARD PULSE JET

HEAD #1 WITH SHUTTER



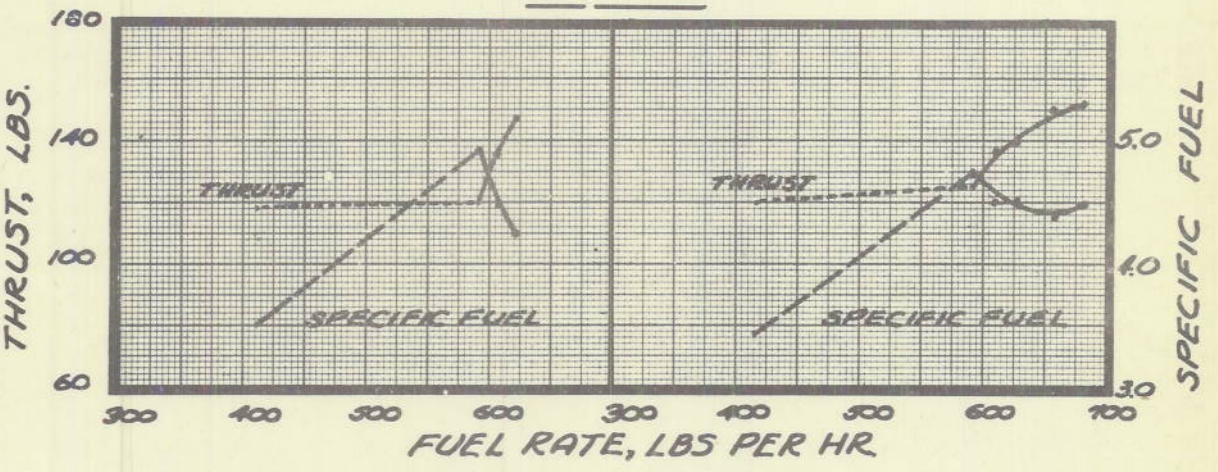
56 VANES



MAIN JET FUEL RATE CONSTANT AT 365 LBS/HR.

AUX. JET FUEL RATE CONSTANT AT 178 LBS/HR.

64 VANES



MAIN JET FUEL RATE CONSTANT AT 413 LBS/HR.

AUX. JET FUEL RATE CONSTANT AT 178 LBS/HR.

NOTE: AUXILIARY JETS LOCATED IN COMBUSTION CHAMBER; SEE FIGURE 85

[redacted]

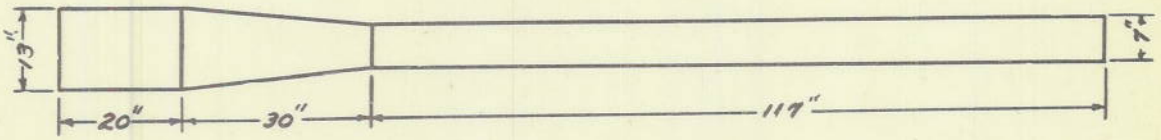
DECLASSIFIED

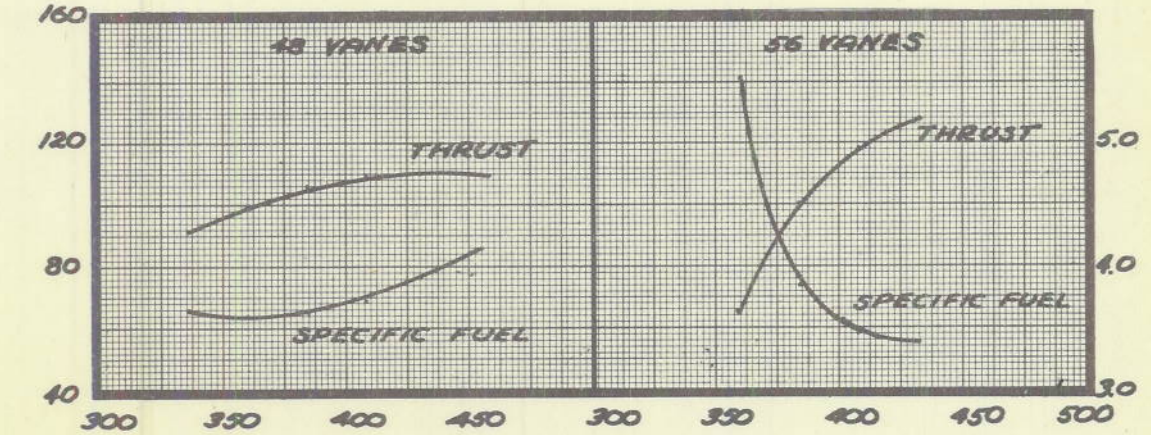
FIGURE 69

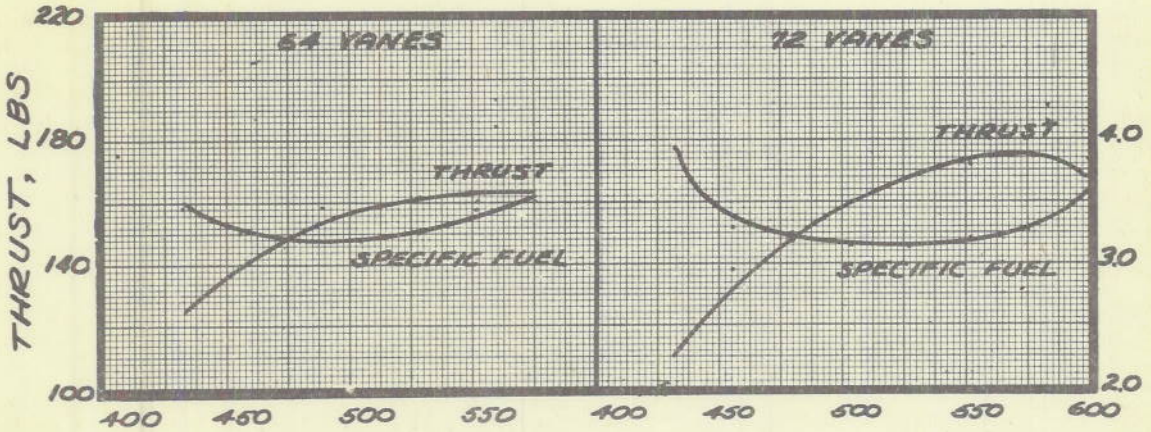
DECLASSIFIED

STANDARD PULSE JET

HEAD #7 WITH SHUTTER

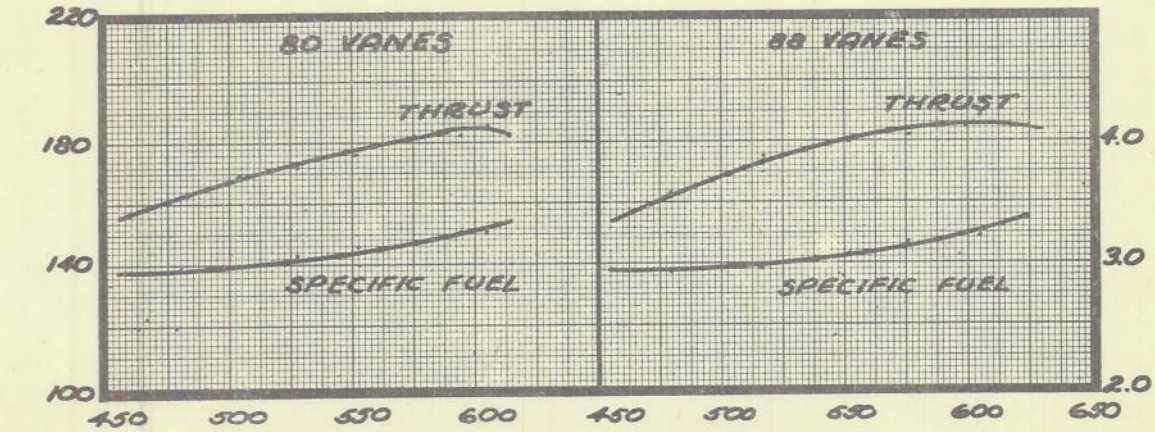






THRUST, LBS

SPECIFIC FUEL



FUEL RATE, LBS PER HOUR

[redacted]

O-3064

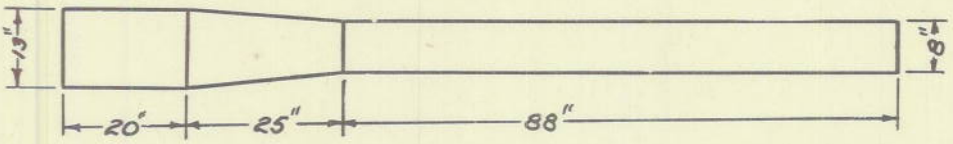
FIGURE 70

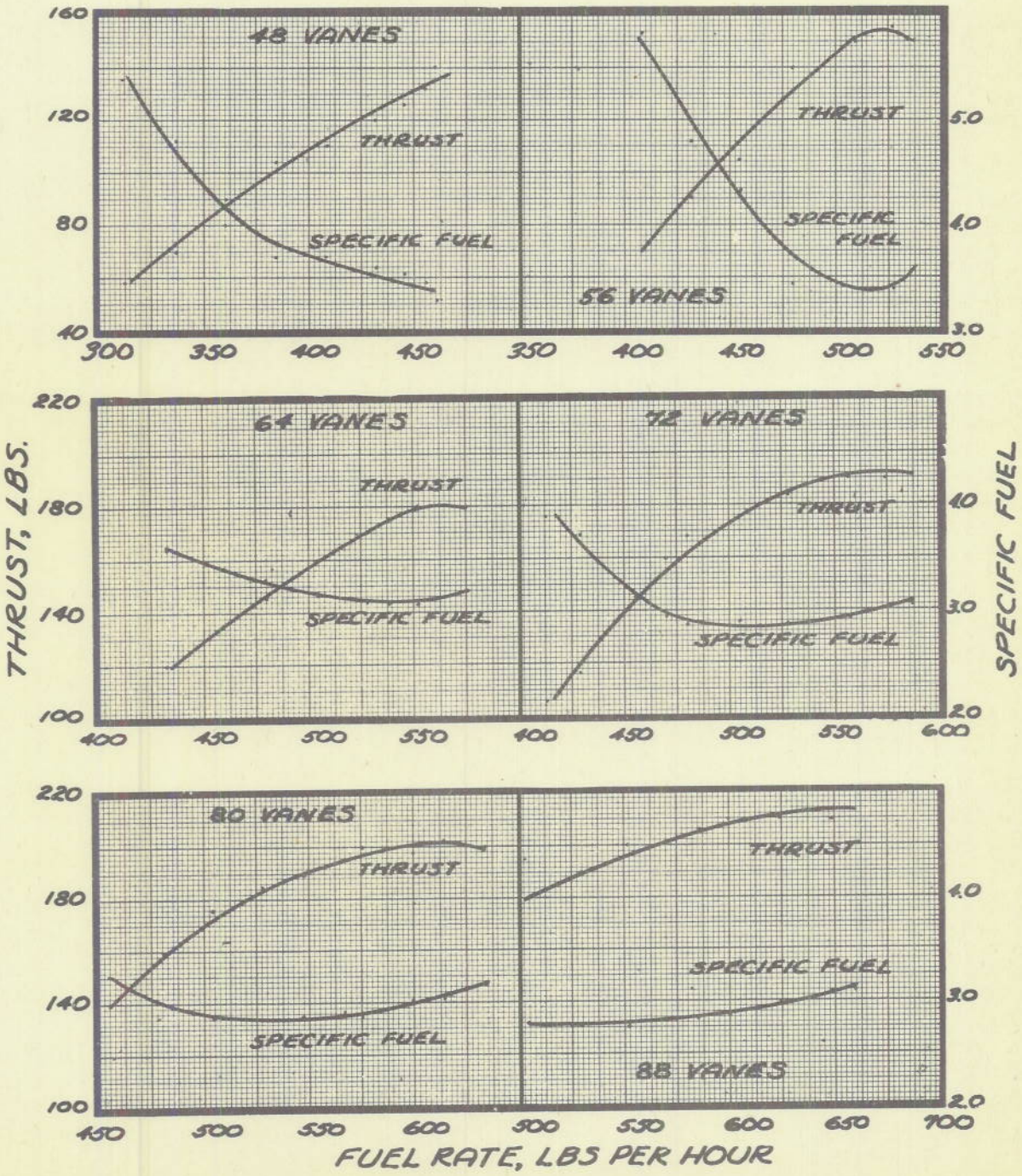
DECLASSIFIED

DECLASSIFIED

STANDARD PULSE JET

HEAD #7 WITH SHUTTER





CONFIDENTIAL

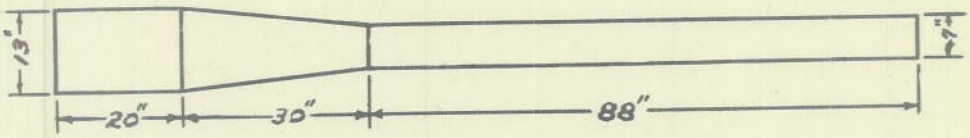
O-3064

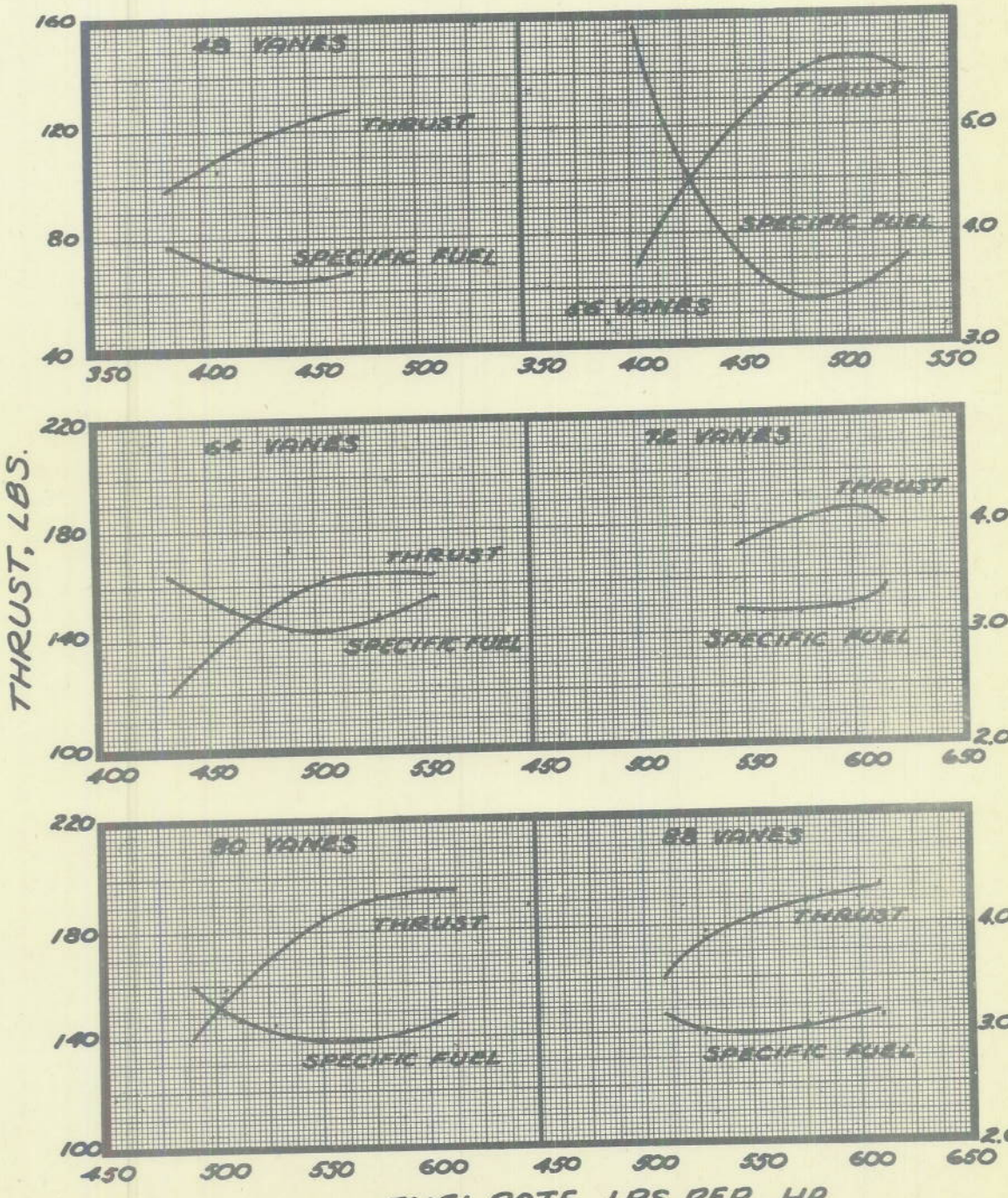
DECLASSIFIED

FIGURE 71

DECLASSIFIED

STANDARD PULSE JET
HEAD #7 WITH SHUTTER





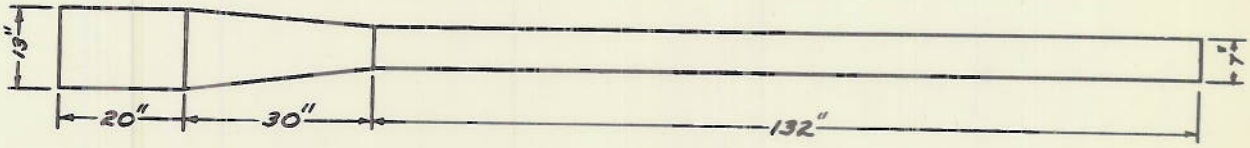
0-3064

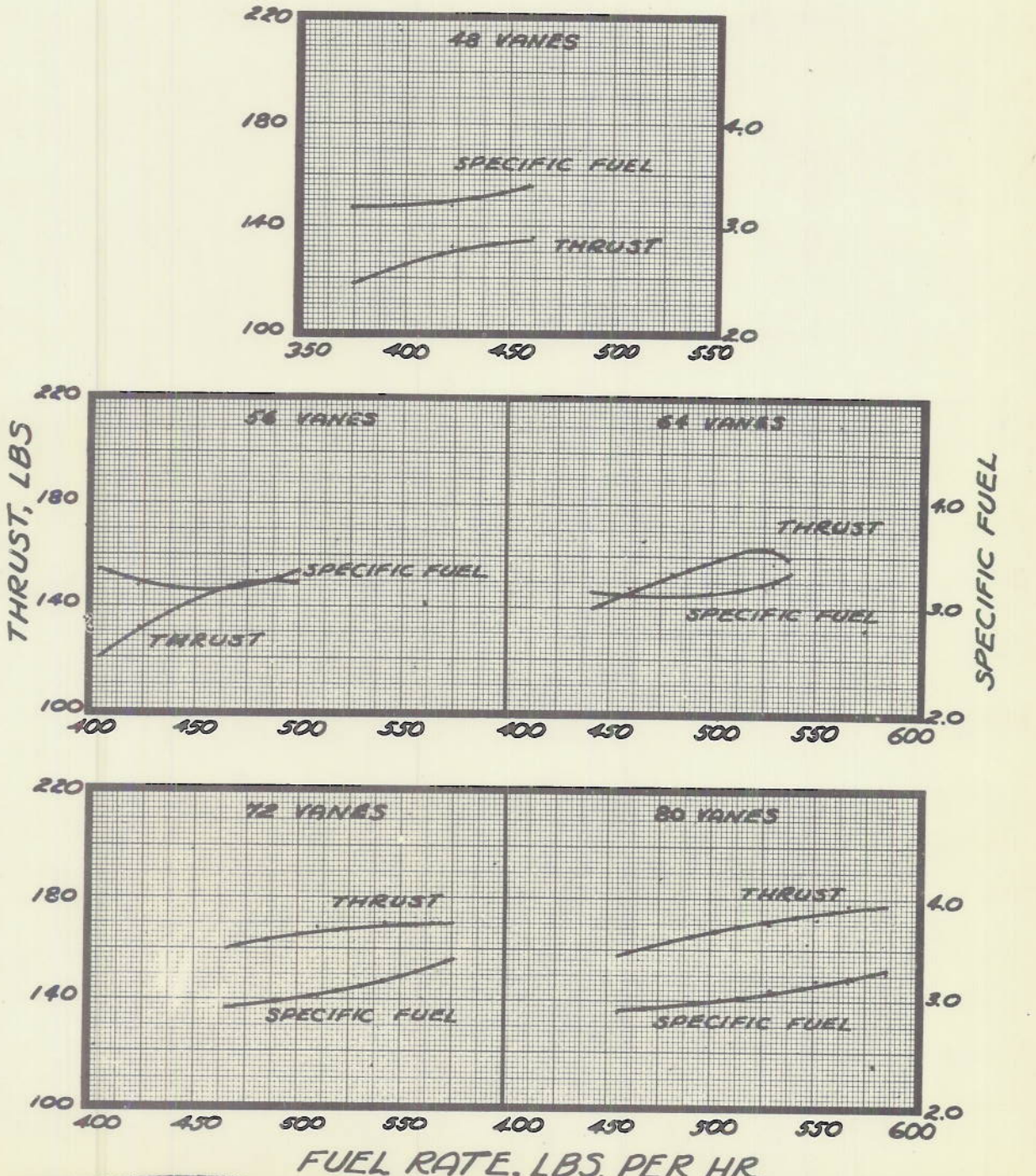
FIGURE 72

DECLASSIFIED

DECLASSIFIED

STANDARD PULSE JET
HEAD #7 WITH SHUTTER





CONFIDENTIAL

O-3064

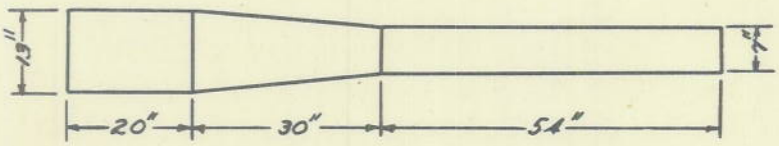
FIGURE 73

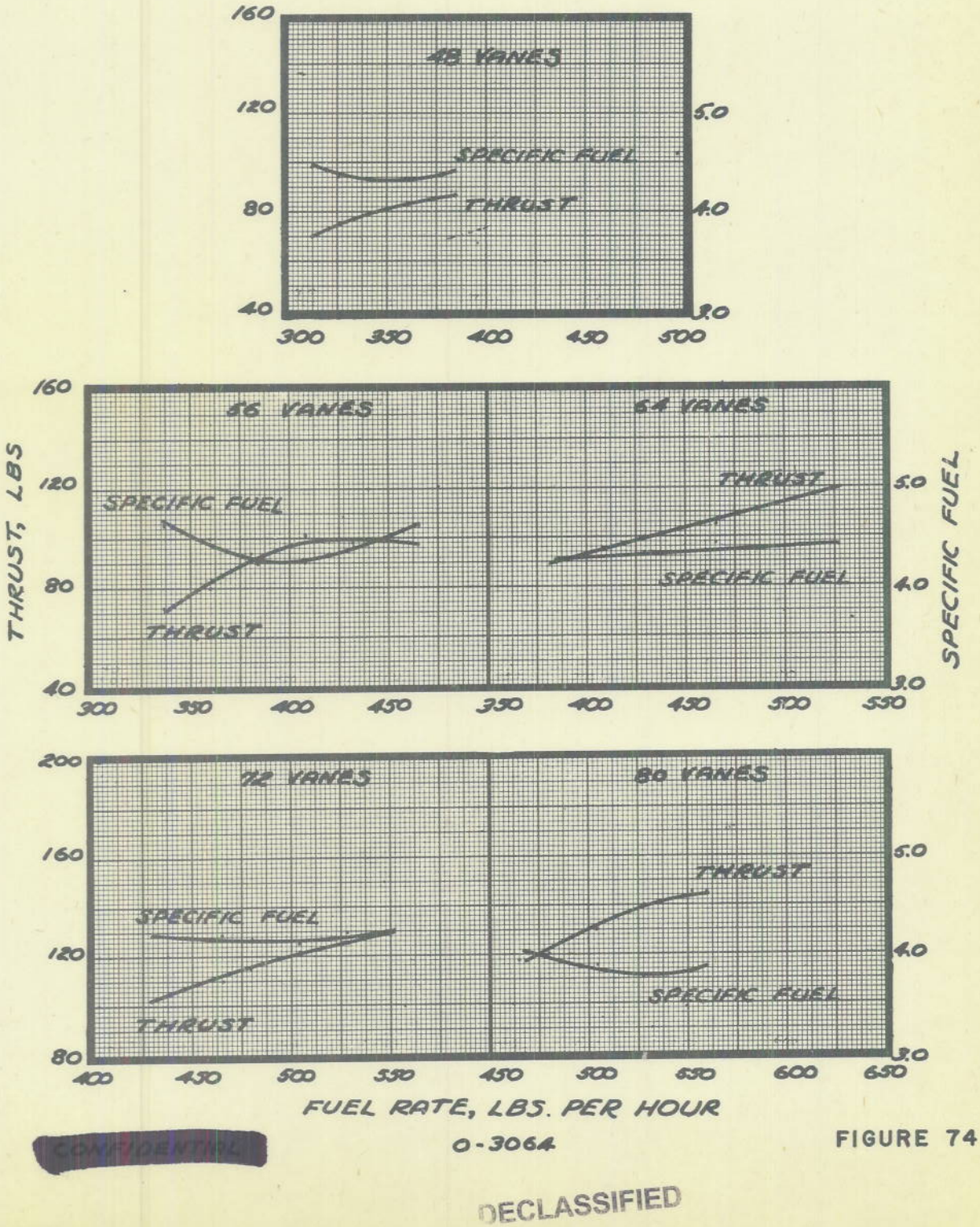
DECLASSIFIED

DECLASSIFIED

STANDARD PULSE JET

HEAD #7 WITH SHUTTER





0-3064

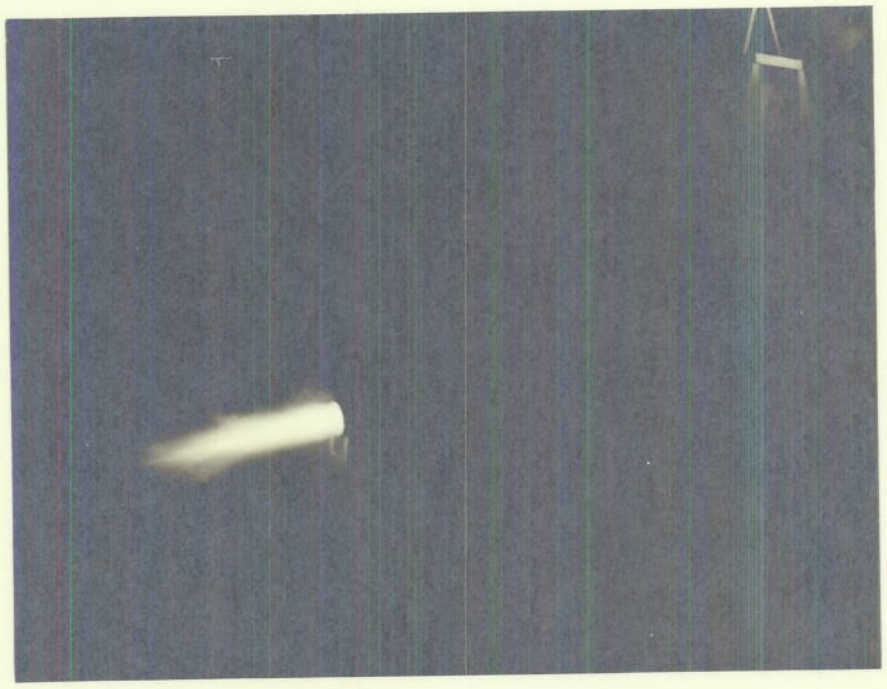
FIGURE 74

CONFIDENTIAL

DECLASSIFIED

DECLASSIFIED





NIGHT FIRING, RUN SHOWING TAILPIPE FLAME CHARACTERISTICS

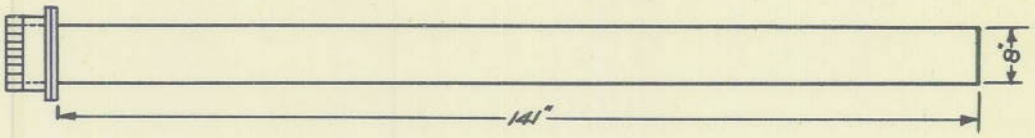
DECLASSIFIED

CONFIDENTIAL

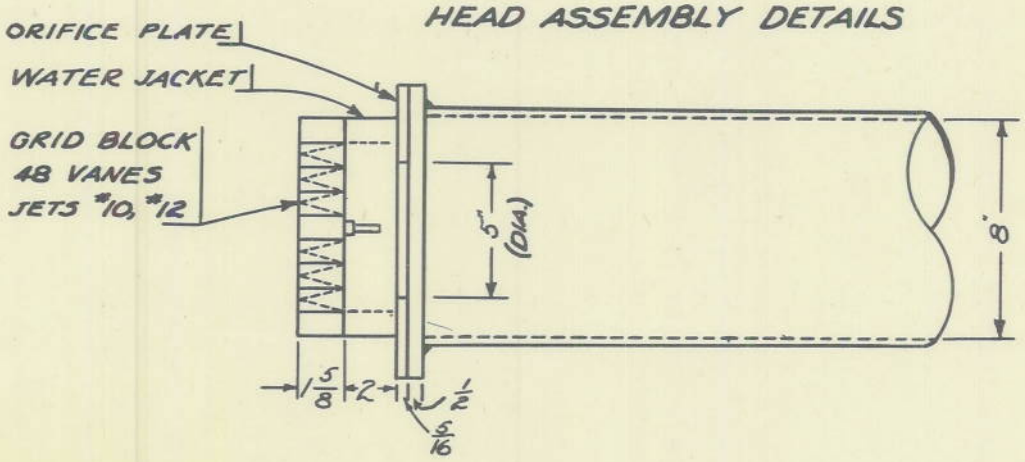
FIG. 75

DECLASSIFIED

STRAIGHT-TUBE EXPERIMENT

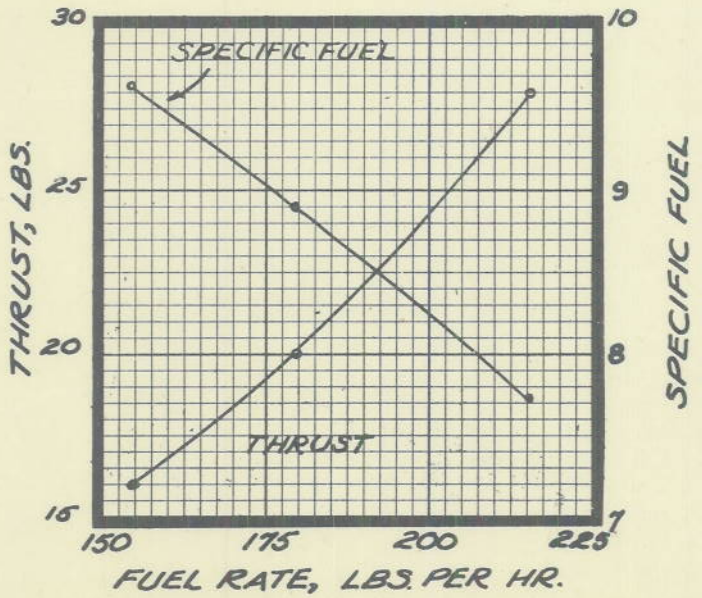


HEAD ASSEMBLY DETAILS



DATA

FUEL #/HR.	THRUST LBS.	SPECIFIC FUEL	FREQ CPM
154	16	9.65	3250
178	20	8.90	—
216	28	7.72	3250



CONFIDENTIAL

O-3064

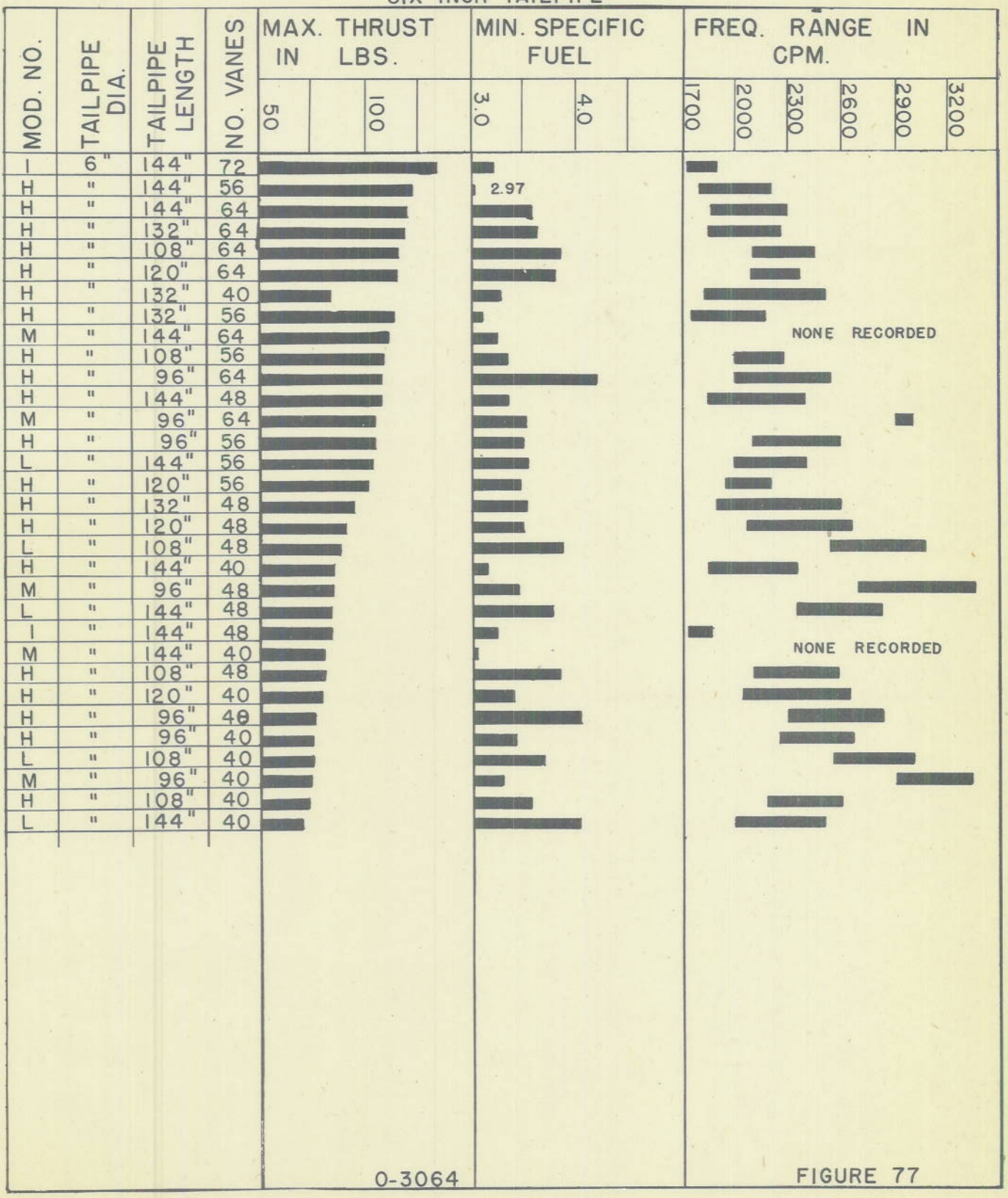
FIGURE 76

DECLASSIFIED

DECLASSIFIED

PEAK PEFORMANCE BAR GRAPH

SIX-INCH TAILPIPE



0-3064

FIGURE 77

DECLASSIFIED

DECLASSIFIED

PEAK PERFORMANCE BAR GRAPH

EIGHT-INCH TAILPIPE

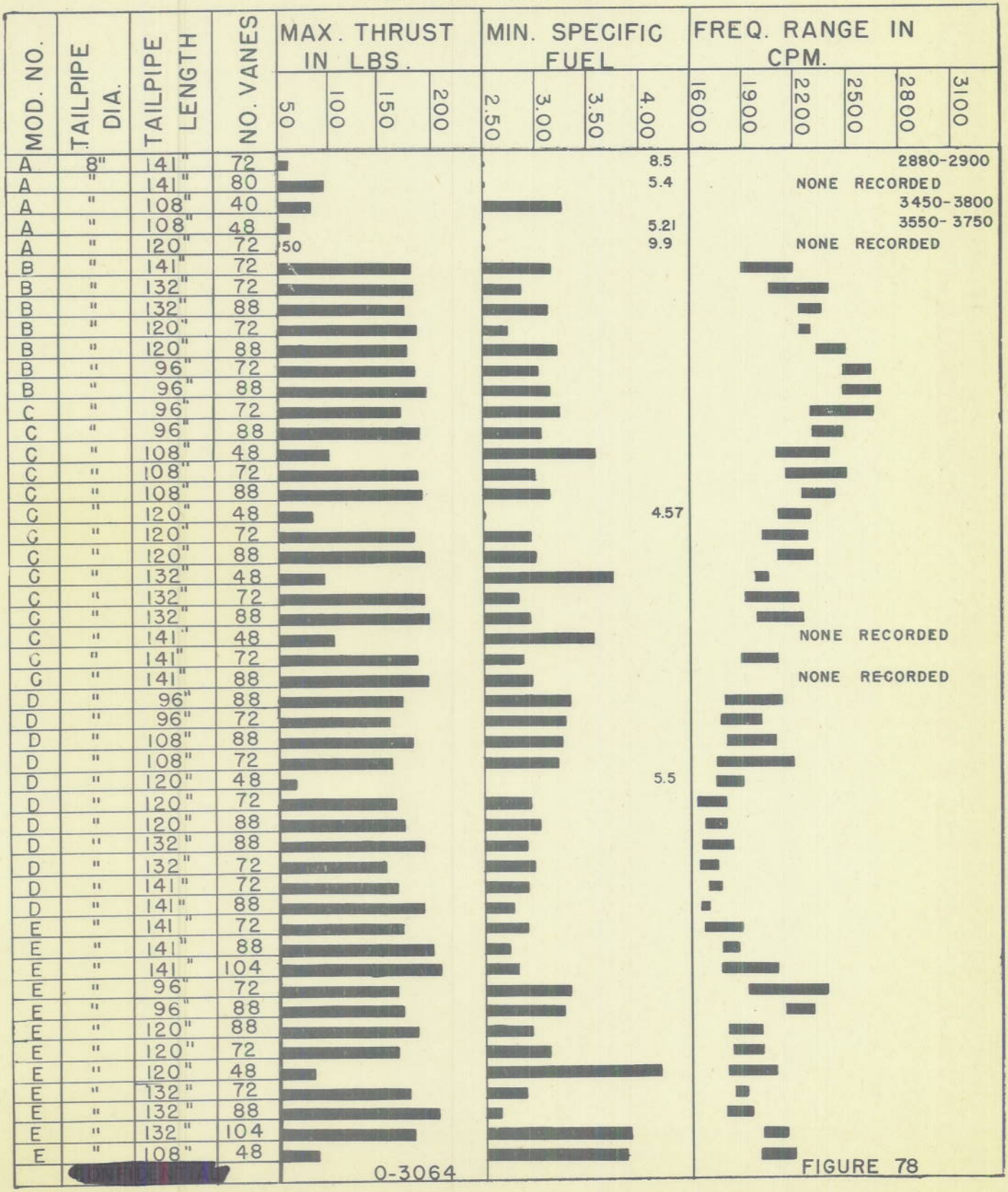


FIGURE 78

DECLASSIFIED

DECLASSIFIED

PEAK PERFORMANCE BAR GRAPH

EIGHT-INCH TAILPIPE

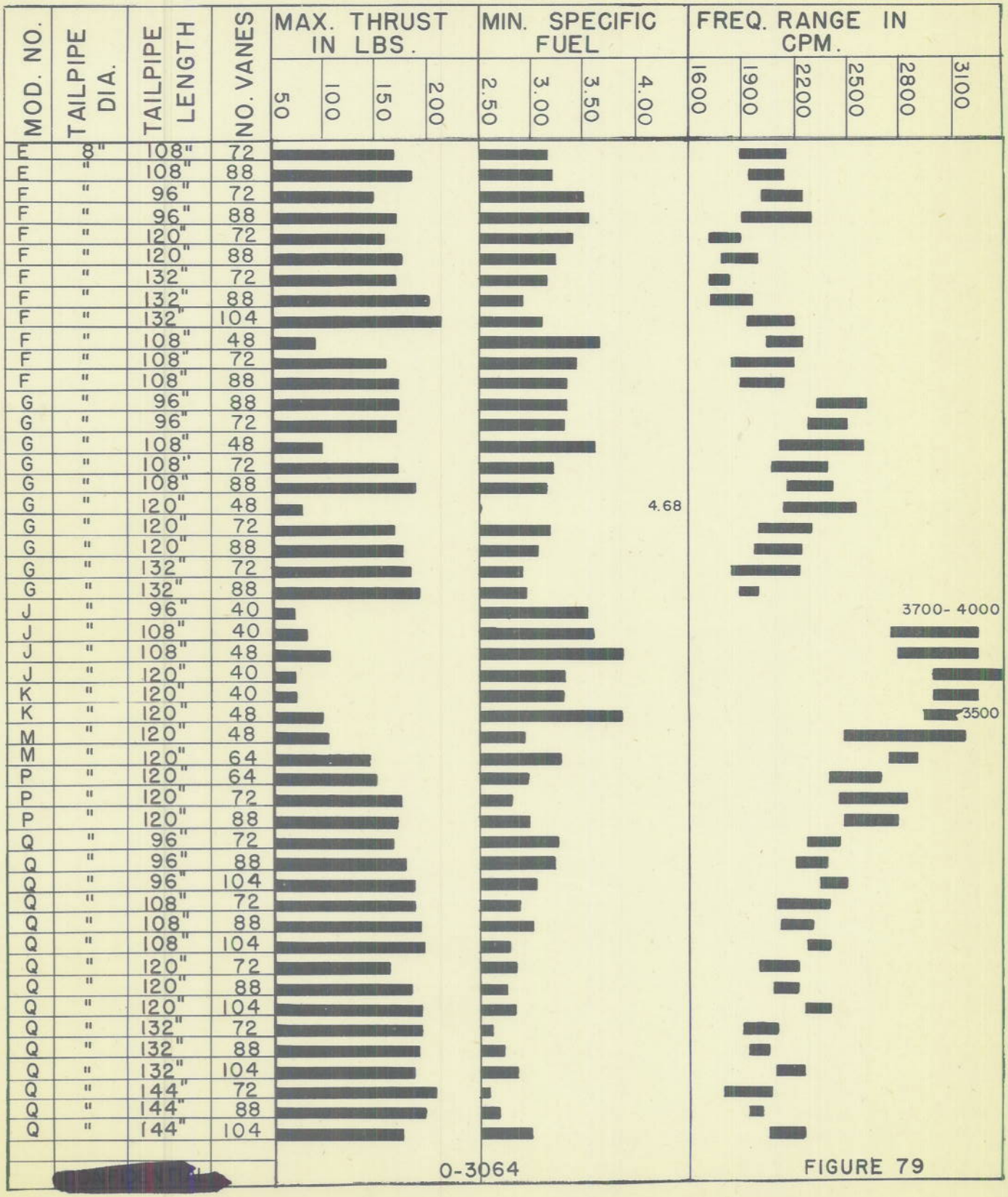


FIGURE 79

DECLASSIFIED

DECLASSIFIED

PEAK PEFORMANCE BAR GRAPH

TEN-INCH TAILPIPE

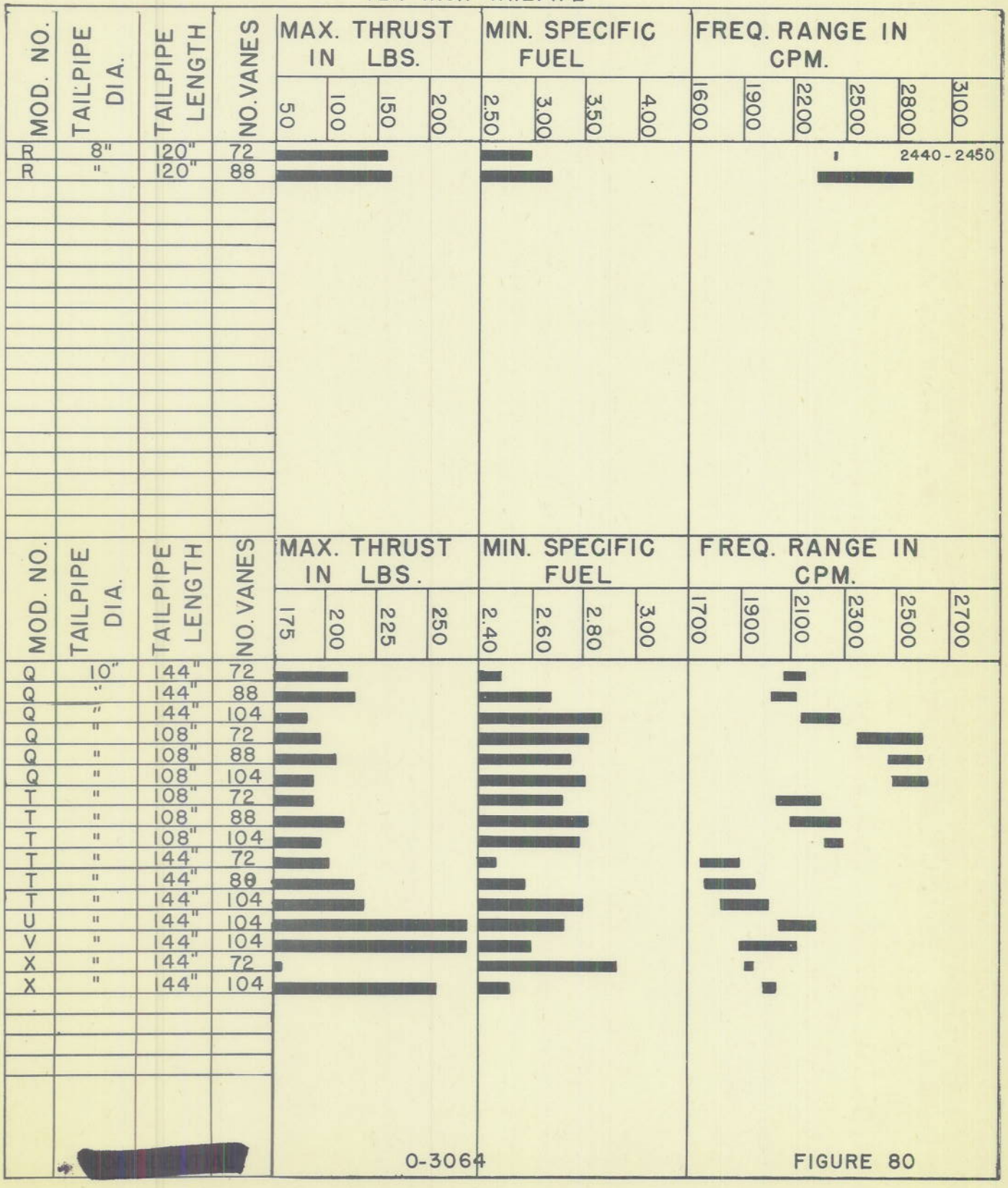
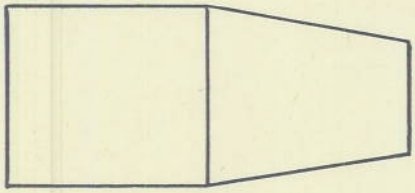


FIGURE 80

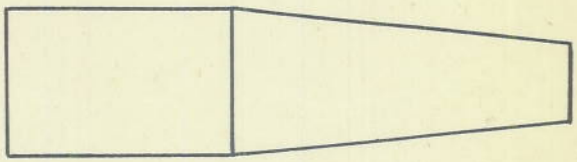
DECLASSIFIED

DECLASSIFIED

MODIFICATION X AND STANDARD COMBUSTION CHAMBER

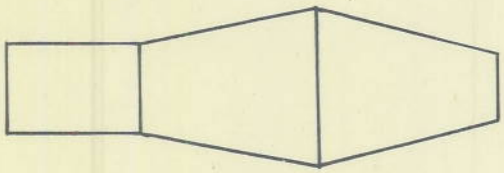


X

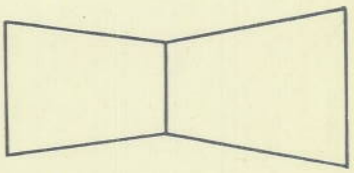


STANDARD

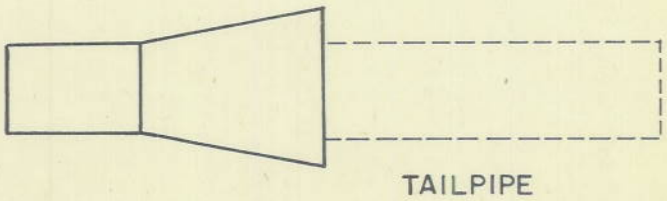
INOPERATIVE COMBUSTION CHAMBERS



N



O



S

SCALE=1:15

CONFIDENTIAL

0-3064

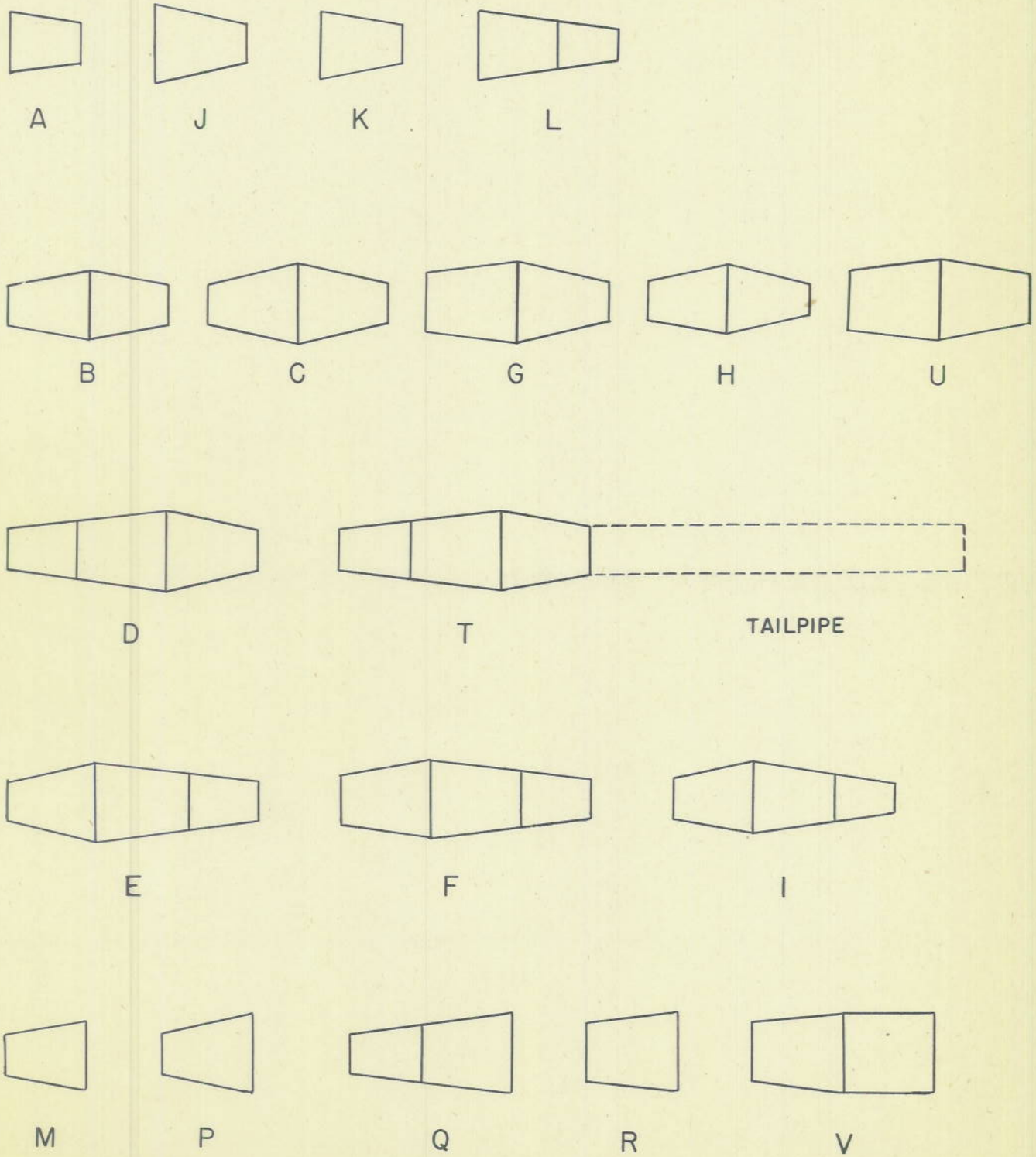
FIGURE 81

DECLASSIFIED

DECLASSIFIED

SIMILAR COMBUSTION CHAMBER

SCALE=1:25



CONFIDENTIAL

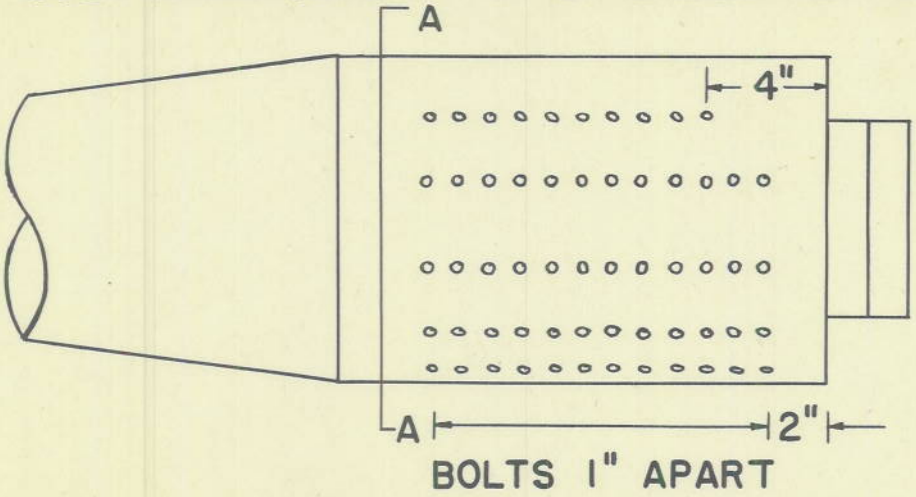
0-3064

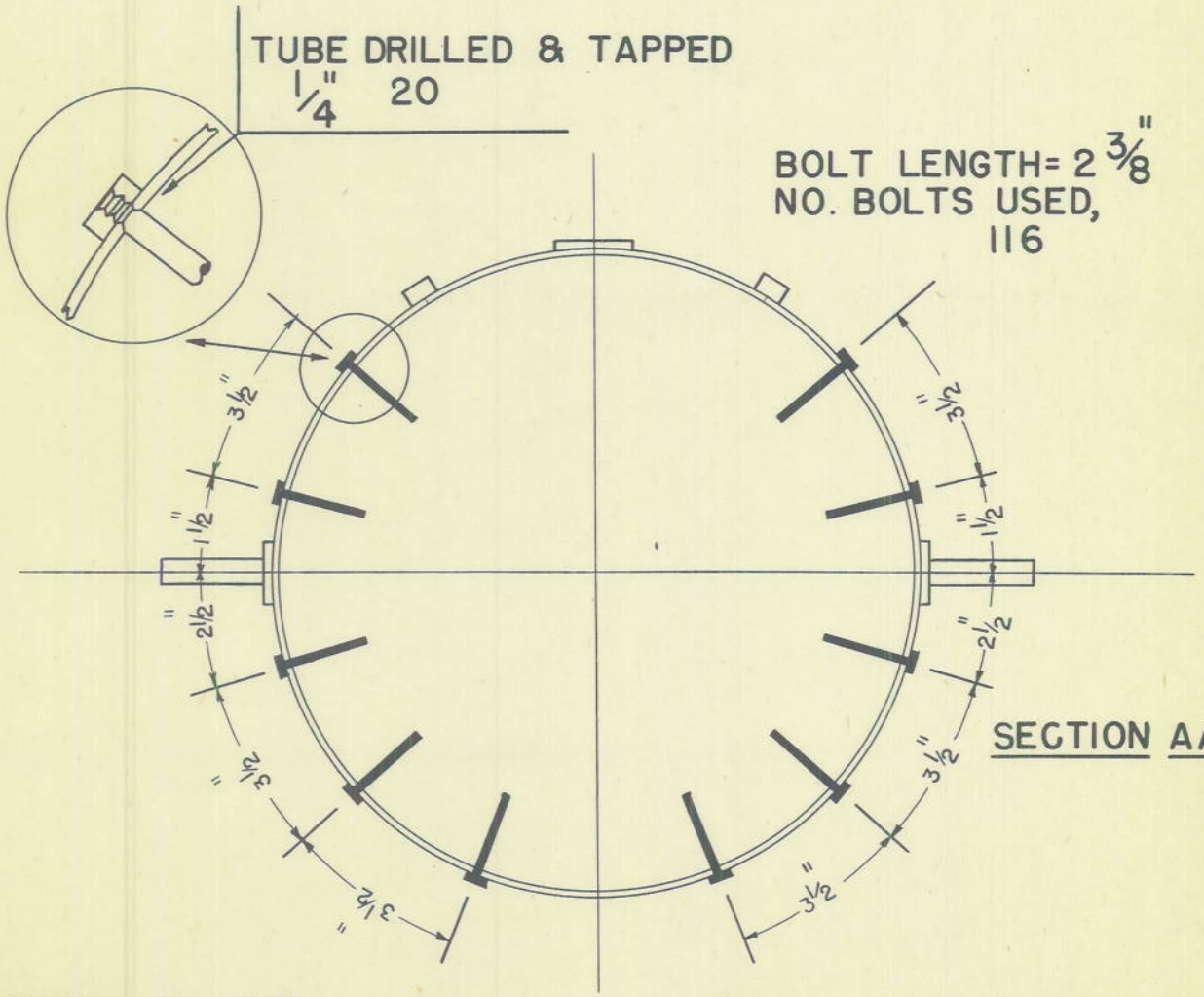
FIGURE 82

DECLASSIFIED

DECLASSIFIED

BOLT ARRANGEMENT FOR EXTENDED-HEATING SURFACE TEST





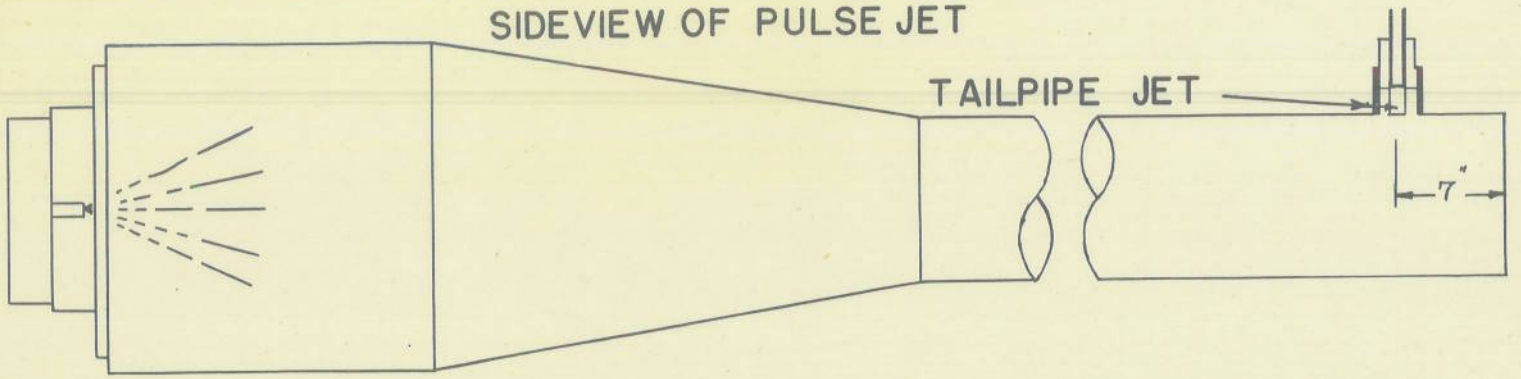
CONFIDENTIAL

0-3064

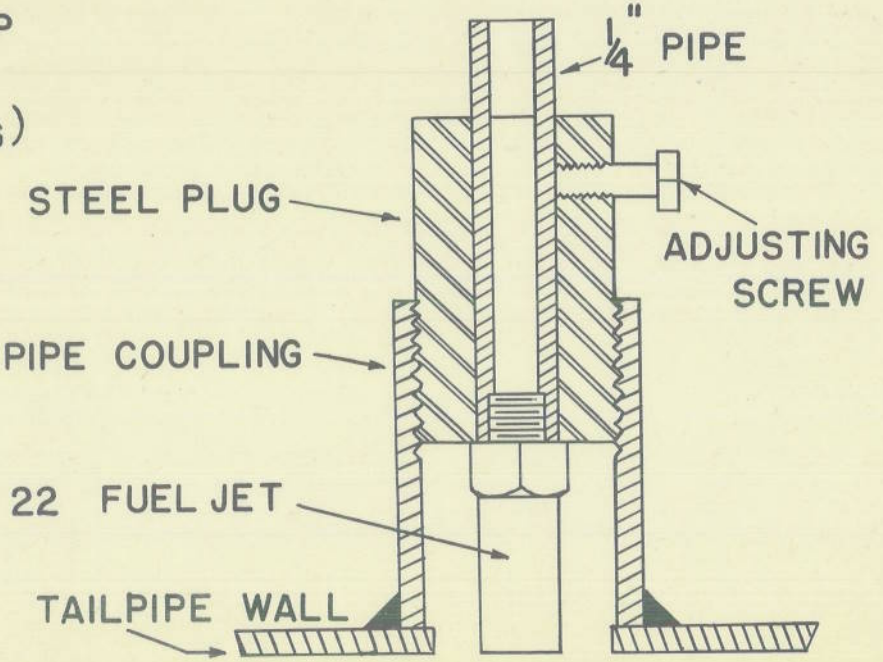
FIGURE 83

DECLASSIFIED

CONFIDENTIAL



STANDARD 48 VANE SETUP
ON STANDARD TUBE
(TAILPIPE: 7" DIA., 88" LONG)

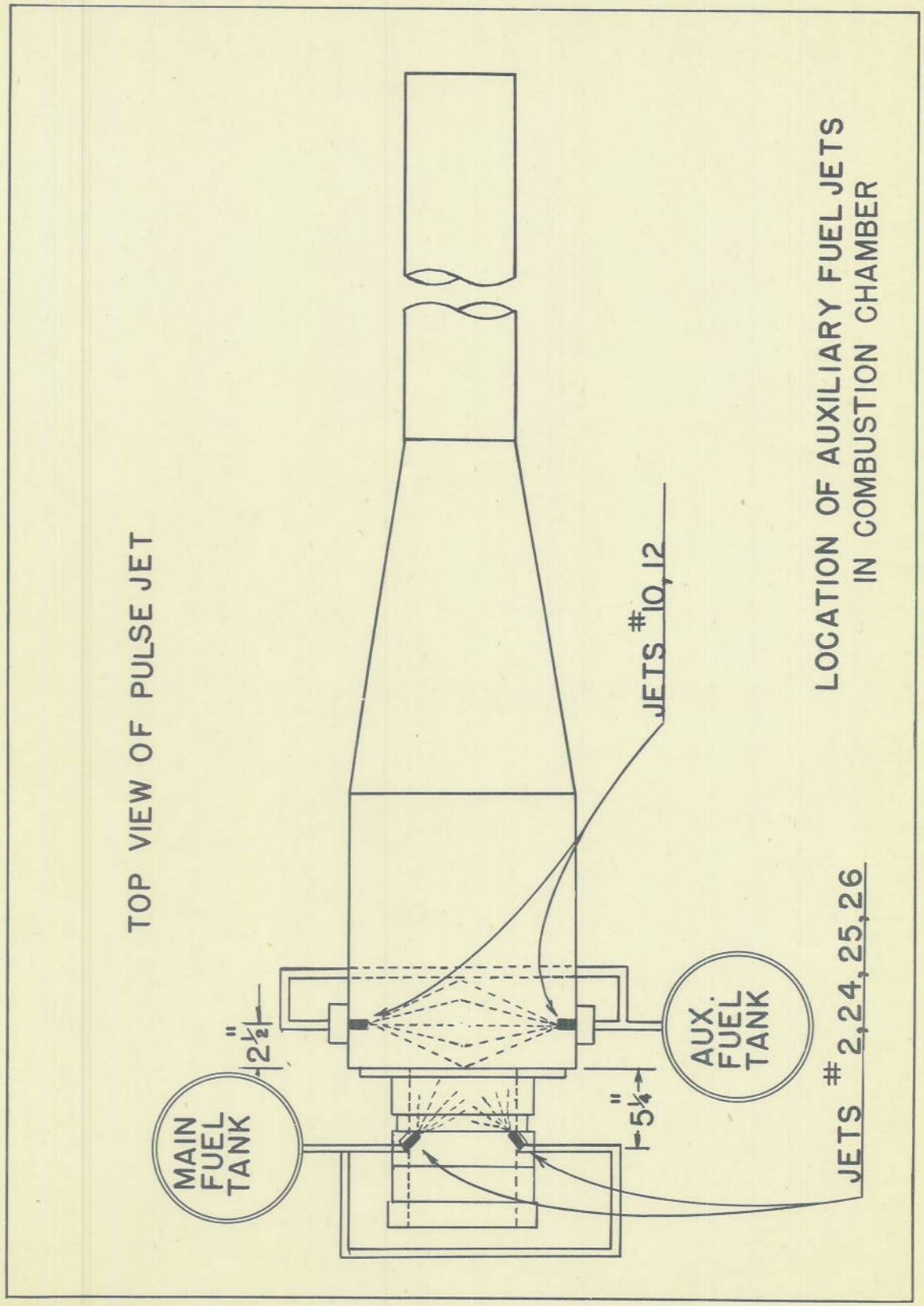


LOCATION AND DETAIL
OF AUXILIARY JET
IN TAILPIPE.

FIGURE 84

0-3064
DECLASSIFIED
DECLASSIFIED

DECLASSIFIED



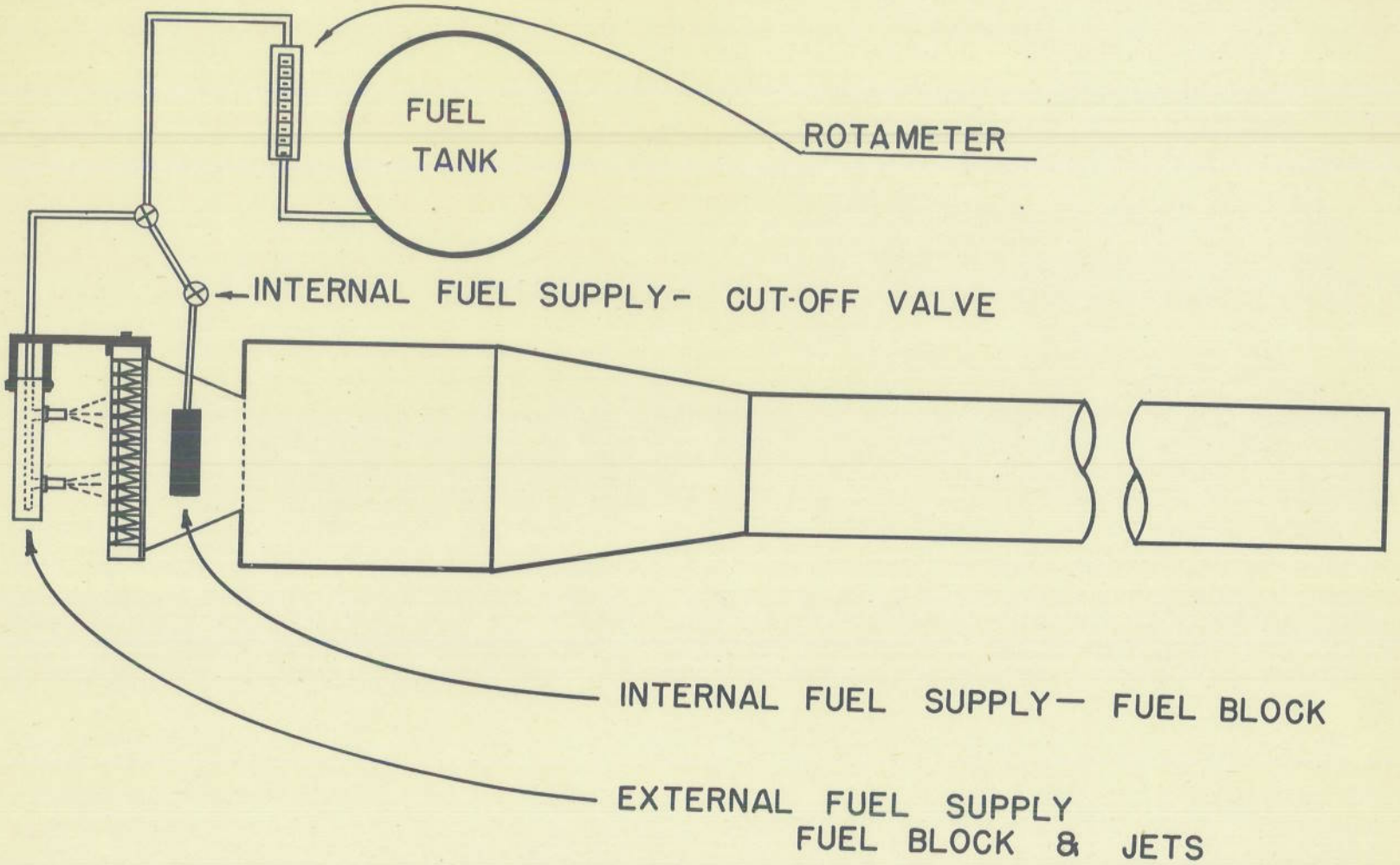
CONFIDENTIAL

0-3064

FIGURE 85

DECLASSIFIED

CONFIDENTIAL



EXTERNAL FUEL

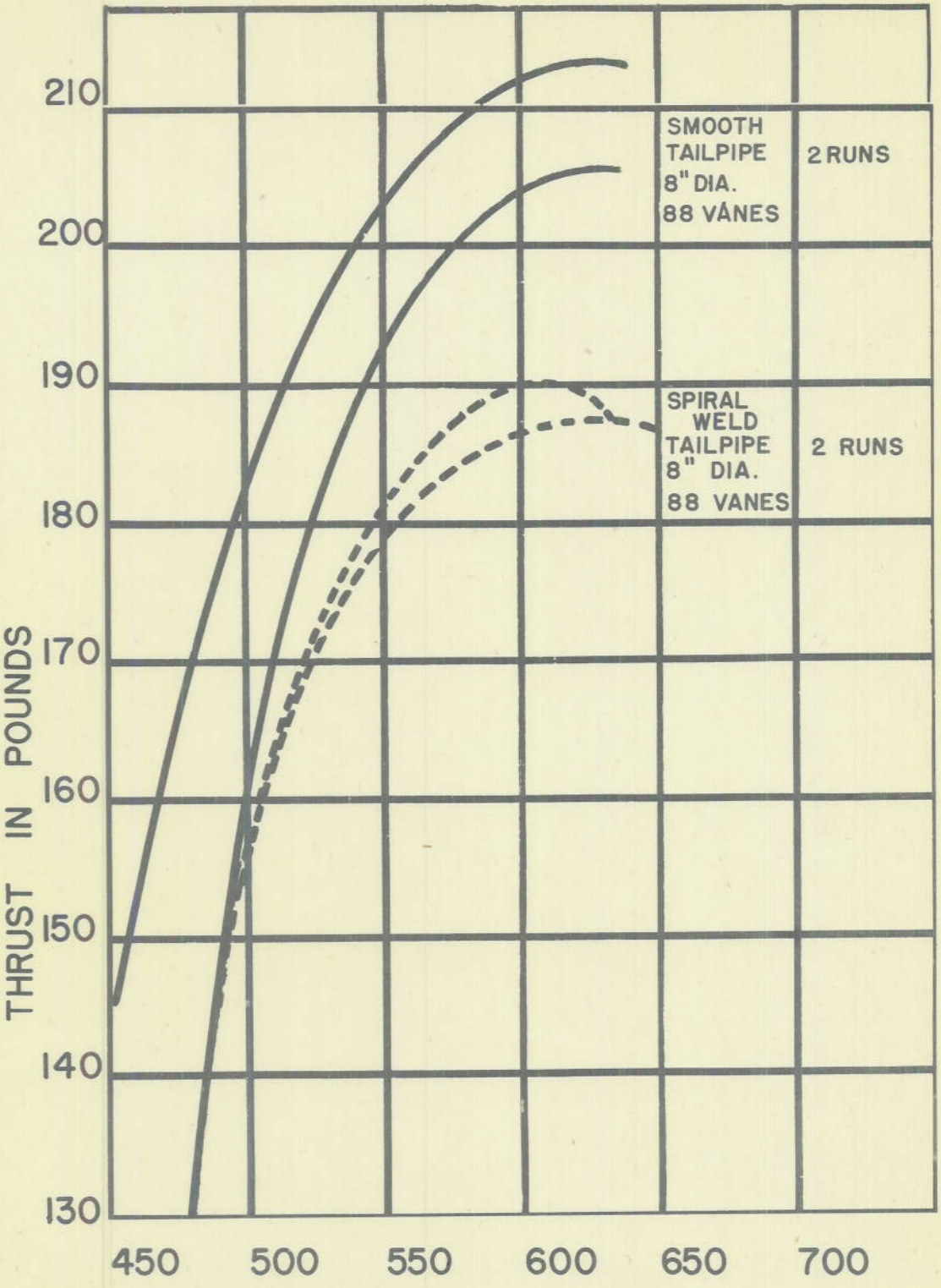
DECLASSIFIED

0-3064

FIGURE 86

DECLASSIFIED

DECLASSIFIED



PERFORMANCE CURVES
SPIRAL-WELD & SMOOTH TAILPIPE

CONFIDENTIAL

0-3064

FIGURE 87

DECLASSIFIED

DECLASSIFIED

A List

	Copy No.
GMC Committee, RDB, Wash., D. C.	A (1)
CG, AAF, Wash., D. C., Attn: AC/AS-4, DRE-3, Pentagon	" (2-5)
CG, AMC, Wright Field, Dayton, Ohio, Attn: TSEON-2	" (6-30)
CG, Air Univ., Maxwell Field, Ala., Attn: Air Univ. Library	" (31)
BuAer, Wash., D. C., Attn: TD-4	" (32-37)
BuOrd, Wash., D. C., Attn: Re-9	" (38-41)
BuShips, Wash., D. C., Attn: Codes 633, 910A, and 343	" (42-44)
Ch/GMBranch, Technical Command, Army Chem. Center, Md.	" (45)
CG, APG, Md., Attn: Ballistic Res. Lab.	" (46)
CG, Eglin Field, Fla., Attn: First Exp., GM Group	" (47)
CG, AAS, Fort Bliss, Texas	" (48)
CO, Frankford Arsenal, Phila., Attn: Fire Control Design Div.	" (49)
Commander, NAMC, Phila.	" (50)
CO, NADS, Johnsville, Pa.	" (51)
CO, ONR, San Francisco	" (52-53)
CO, SCEL, Bradley Beach, N. J.	" (54-55)
CO, NAMTC, Pt. Mugu, Calif.	" (56)
CO, NOTS, Inyokern, Calif.	" (57)
CO, Alamorgodo Army Air Base, N. M.	" (58)
Dir., DTMB, Wash., 7, D. C., Attn: Aero. Mechanics Div.	" (59)
Dir., NACA, Wash., D. C., Attn: Mr. C. H. Helms	" (60-63)
Dir., NRL, Wash., 20, D. C.	" (64-66)
Dir., Spec. Devices Center, ONR, Sands Point, L. I., Attn: TID	" (67)
First Antiaircraft Artillery, GM Btn., White Sands Proving Ground	" (68)
Head, PG School, U. S. Naval Academy, Annapolis	" (69)
RDB, Attn: Library	" (72)
Off. Ch/Ord, Res. and Dev. Div., Rocket Branch, Pentagon	" (73)
OinC, BOEU, Hydraulics Bldg., Nat'l BuStds., Wash., D. C.	" (74)
OinC, NOL, NavGun, Wash., D. C., Attn: Dr. R. J. Seeger	" (75-76)
OinC, Ord. Res. and Dev. Div. Suboffice (Rocket) Ft. Bliss, Texas	" (77)
CNO, Op-57	" (78)
Watson Labs., AMC, Eatontown, N. J.	" (79)
Watson Labs., AMC, Cambridge Field Station, Mass., Attn: Dr. M. O'Day	" (80)
CG, Army Ground Forces, Ft. Monroe, Va., Attn: Ch/Dev. Sect. GNDEV-9	" (81)
ONR, c/o Lib. of Congress, Tech. Info. Sect., Attn: J. Heald	" (82-84)
Ch/Res. and Eng. Div., Off. Ch. Chem. Corps, Army Chem. Center, Md.	" (85)

CONFIDENTIAL

DECLASSIFIED

DECLASSIFIED

C List

	Copy No.
DCO for APL, JHU, Silver Spring, Md.	C (1-3)
BAR, Buffalo, for BAC, Niagara Falls, Attn: Mr. R. H. Stanley and Mr. Hamlin	" (4)
BTL, Murray Hill, N. J., Attn: W. A. MacNair	" (5)
Bendix Av. Corp., East Teteboro, N. J., Attn: Dr. H. Selvidge	" (6)
Boeing Aircraft Corp., Seattle, Attn: Mr. R. H. Nelson	" (7)
DCO for C-V Air. Corp., LSL, Daingerfield, Texas, Attn: Mr. Arnold	" (8)
BAR, Consolidated-Vultee Air. Corp., San Diego, Attn: Mr. Ables	" (9)
DCO for Cornell Aero. Lab., Buffalo, N. Y., Attn: Mr. W. M. Duke	" (10)
BAR for Curtiss-Wright Corp., Columbus, Attn: Mr. B. Eaton	" (11)
BAR for Douglas Aircraft Co., El Segundo, Calif., Attn: Mr. Heinemann	" (12)
Douglas Air. Co., Santa Monica, Attn: Mr. A. E. Raymond, (Project Rand) and Mr. E. F. Burton	" (13-14)
INSORD for Eastman Kodak Co., Rochester, N. Y., Attn: Dr. Trotter	" (15)
Fairchild Eng. and Air. Corp., NEPA Div., Oak Ridge, Attn: Mr. Kalitinsky	" (16)
RIC-BuAer for Fairchild Eng. and Air. Corp., Farmingdale, Attn: J. A. Slonin	" (17)
CO, NADS for Franklin Inst. Labs., Phila., Attn: Mr. R. H. McClarren	" (18)
Gen. Elec. Co., Schenectady, Project HERMES, Attn: Mr. C. K. Bauer	" (19)
DCO for G. E. Co., Schenectady, Attn: A. L. Ruiz	" (20)
G. E. Co., Av. Div., Schenectady, Attn: Mr. S. A. Schuler, and Mr. P. Class	" (21)
BAR for Glenn L. Martin Co., Balt., Attn: Mr. N. M. Voorhies	" (22)
Glenn L. Martin, Balt., Attn: Mr. W. B. Bergen	" (23)
INSMAT, Chicago for Globe Corp., Joliet, Ill., Attn: Mr. J. A. Weagle	" (24)
BAR for Goodyear Aircraft Corp., Akron, Attn: Dr. Carl Arnstein	" (25)
Goodyear Aircraft, Plant B, Akron, Attn: Mr. A. J. Peterson	" (26)
BAR for Grumman Air. Engr. Corp., Bethpage, L. I., Attn: Mr. Schwendler	" (27)
Hughes Aircraft Co., Culver City, Calif., Attn: Mr. D. H. Evans	" (28)
OinC, Res. and Dev. Serv. Suboffice (Rocket) CIT, Pasadena	" (29-30)
INSMAT for Kellex Corp., New York, N. Y.	" (31)
M. W. Kellogg Co., Jersey City, N. J., Attn: Dr. G. H. Messerly	" (32)
NORTLO for Chairman, MIT, GMC, Project Meteor Office, Cambridge, Attn: Dr. H. G. Stever	" (33-34)
BAR for McDonnell Aircraft Corp., St. Louis, Attn: W. P. Montgomery	" (35)
BAR for NAA, Inc., Los Angeles, Attn: Mr. D. H. Mason	" (36)
Northrop Aircraft Inc., Hawthorne, Calif.	" (37)
DCO for P. U. Phys. Dept., Princeton, N. J., Attn: Mr. Harry Ashworth	" (38)
CO, ONR Branch Office, N. Y. for Princeton U., Attn: Proj. SQUID	" (39-41)
INSMAT for Radio Corp. of America, Camden, N. J., Attn: Mr. T. T. Eaton	" (42)
BAR for Radioplane Corp, Van Nuys, Calif., Attn: Mr. Ferris Smith	" (43)
INSMAT, Boston, for Raytheon Mfgr. Co., Waltham, Attn: Mrs. H. L. Thomas	" (44)
INSMAT, Brooklyn, for Reeves Instrument Corp., N. Y., N. Y.	" (45)
Republic Aviation Corp., Farmingdale, L. I., Attn: Dr. Wm. O'Donnell	" (46)
Ryan Aero. Co., Lindberg Field, San Diego 12, Calif., Attn: Mr. H. A. Sutton	" (47)
INSMAT, Brooklyn, for Sperry Gyroscope Co, Great Neck, L. I.	" (49)
BAR, U. A. Corp., Stratford, for U. A. Corp, Chance Vought Air. Div., Stratford, Conn., Attn: Mr. P. S. Baker	" (50)
BAR, U. A. Corp., E. Hartford, for U. A. Corp., Research Dept., E. Hartford, Attn: Mr. J. G. Lee	" (51)
Univ. of Mich., Aero. Res. Center, Willow Run Airport, Attn: R. F. May and Dr. A. M. Kuethe	" (52)
BAR, Pasadena for USC, Naval Res. Proj., LA, Attn: Dr. R. T. DeVault	" (53)
DCO, Univ. of Texas, Defense Res. Lab., Austin, Attn: Dr. C. P. Boner	" (54)
Lockheed Aircraft Corp., Burbank, Calif., Attn: Mr. H. L. Hibbard	" (56)
Calif. Inst. of Tech., JPL, Pasadena, Attn: Mr. L. G. Dunn	" (57)

CONFIDENTIAL

DECLASSIFIED

DECLASSIFIED

		Copy No.
BAR, Pasadena, for Aerojet Engr. Corp., Azuza, Attn: Mr. K. F. Mundt	DP	(1)
Armour Research Foundation, Chicago, Attn: Mr. W. A. Casler	"	(2)
Arthur D. Little, Inc., Cambridge, Attn: Mr. Helge Holst	"	(3)
Battelle Memorial Institute, Columbus, Attn: Dr. B. D. Thomas	"	(4)
DCO, for Bendix Aviation Corp., N. Hollywood, Attn: R. M. Russell	"	(5)
Bendix Products Div., Bendix Aviation Corp., S. Bend, Ind., Attn: F. C. Mock	"	(6)
CG, AAF, Pentagon, Attn: AC/AS-4, DRE-2E	"	(7)
CG, AMC, Wright Field, Attn: TSEPP-4B(2) TSEPP-4A(1) TSEPP-5C(1) TSORE(1) TSEPP-5A(1)	"	(8-13)
CO, Picatinny Arsenal, Dover, N. J., Attn: Technical Div.	"	(14)
CO, Watertown Arsenal, Watertown, Mass., Attn: Laboratory	"	(15)
BAR for Continental Av. and Engr. Corp., Detroit	"	(16)
Curtiss-Wright Corp., Prop. Div., Caldwell, N. J., Attn: Mr. C. W. Chillson	"	(17)
DCO for Experiment, Inc., Richmond, Va., Attn: Dr. J. W. Mullen, II	"	(18)
BAR, Bethpage, L. I., for Fairchild Air. and Eng. Co., Farmingdale, N. Y.	"	(19)
BAR for Gen. Motors Corp., Allison Div., Indianapolis, Attn: Ronald Hazen	"	(20)
G. M. Giannini and Co., Inc., Pasadena	"	(21)
INSMAT, New York for Hercules Powder Co., Port Ewen, N. Y.	"	(22)
BAR, Pasadena, for Marquardt Aircraft Co., Venice, Attn: Dr. R. E. Marquardt	"	(23)
Menasco Mfg. Co., Burbank, Calif., Attn: Robert R. Miller	"	(24)
INSMAT, N.Y. for N. Y. U., Applied Math. Center, N. Y., Attn: Dr. R. Courant	"	(25)
Office of Ch. of Ord., Ord. Res. and Dev. Div., Rocket Br., Pentagon	"	(26)
INSMAT, N. Y. for Polytechnic Inst., of Brooklyn, Attn: Mr. R. P. Harrington	"	(27)
INSMAT, Chicago for Purdue Univ., Attn: Mr. G. S. Meikel	"	(28)
BARR, Dover, for Reaction Motors, Inc., Dover, N. J.	"	(29)
Rensselaer Polytechnic Inst. Troy, Attn: Inst. of Naval Science	"	(30)
Solar Aircraft Co., San Diego, Attn: Dr. M. A. Williamson	"	(31)
INSMAT, N. J. for Standard Oil Co., Esso Lab., Elizabeth, N. J., Attn: W. J. Sweeney	"	(32)
DCO, Charlottesville, for U. of Va., Physics Dept., Attn: Dr. J. W. Beams	"	(33)
INSMAT, Chicago, for U. of Wisconsin, Attn: Dr. J. O. Hirschfelder	"	(34)
BARR, Westinghouse for Westinghouse Electric Co., Essington, Pa.	"	(35)
BAR, Woodridge, for Wright Aeronautical Corp., Woodridge, N. J.	"	(36)
Supt., Shipbuilding, USN, Quincy, for Bethlehem Steel Corp., Shipbuilding Div., Quincy, Attn: Mr. B. Fox	"	(37)
Ohio State University, Columbus, Attn: Dr. H. L. Johnson	"	(38)
DCO, APL, JHU, for Rocket Propellant Agency, APL, JHU, Attn: Dr. S. Githens	"	(39)

CONFIDENTIAL

DECLASSIFIED