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E: ROTARY WING TIP-MOUNTED PULSE-JET ENGINE STRUCTURAL, NOISE REDUCTION, VALVE PHASING AND ELECTRICAL ANALOGY INVESTIGATIONS

INTERIM ENGINEERING REPORT

DEL NO. **COPY NO.** 5

American helicopter co. inc.

MANHATTAN BEACH, CALIF. • MESA, ARIZONA

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ENGINEERING REPORT

SECURITY INFORMATION

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INTERIM ENGINEERING REPORT

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NOTE: This Report Contains Proprietary Information

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1. SUMMARY

This interim report describes the pulse-jet engine development work which has been accomplished under Supplement No. 4 of U. S. Air Force Contract No. AF 33(600)-5860 during the six-month period from 15 July 1952 (start of program) to 15 January 1953.

This program consists of the following major phases:

(a) Structural development
(b) Noise Control development
(c) Inlet valve phasing investigations
(d) Development of an electrical analogy of the pulse-jet engine.

The objective of the work under these phases is to advanced develop of rotary wing tip-mounted pulse-jet engines and components having increased performance and life, and decreased weight and noise.

Maximum emphasis under the structural development phase has been given to work on the shell of the engines. In addition, a limited amount of work has also been accomplished toward improving the fuel injector, venturi and engine mount, As a result of this work, the following overall improvements have been made:

CHARACTERISTIC	ORIGINAL ENGINES	CURRENT ENGINES
Design Speed	375 ft/sec	425 ft/sec
Design Acceleration Loading	325 "g"	444 "g"
Life @ Design Speed	35 hours	over 41 hours
Maximum Speed Limitation	425 Ft/sec	over 500 ft/sec
Maximum Acceleration Loading	420 "g"	over 575 "g"
Lbs. Thrust /lb. Weight	1.45	2.23

These improvements have been made without the usual compromises and resulting adverse effects on engine performance.

In addition, the maintenance characteristics have been improved by decreasing the number and increasing the life expectancy of the gaskets, and improving the accessability of the fuel injector components.

The results of a limited fuel injector whirl test investigation indicate that an improvement in engine fuel consumption characteristics may be expected with further development work.

An analysis of the performance potential of the ducted pulse-jet type of power plant has indicated that it may produce as much as 25-percent greater thrust than the "plain" pulse-jet at 550 ft/sec tip speed. The ducted engines also appear to have advantages in structural characteristics. A ducted pulse-jet engine configuration was therefore designed. A study of the detail design revealed that the cost of developing such a power plant would be beyond the limitations of the present contract. Therefore, this work is being continued under another contract.

It has been found that a significant reduction in pulse-jet engine fundamental frequency sound level is achieved by the acoustic coupling of two engines whose tailpipes are located in close proximity. A considerable amount of work has been concerned with exhaust shrouds intended to enhance this acoustic coupling as well as to provide a structure for containing sound and absorption material to be used to attenuate the sound level of frequencies above the fundamental. After a series of static tests of many different configurations, the design requirements were determined for exhaust shrouds which do not adversely affect engine static performance.

Preliminary tests of opposed engine configurations has yielded significant results with respect to further reducing the sound level of the fundamental frequency. Favorable effects on the engine operating characteristics were also noted.

Attempts to utilize acoustically coupled 1/4 wave ducts on the inlets of the engines in order to reduce the inlet noise level have been unsuccessful. Such ducts caused the valved engines to cease to operate.

The engine inlet valve-pressure cycle phasing program has consisted of the investigation, selection and development of suitable instrumentation for determining inlet valve frequency, damping and instantaneous position, and engine cyclic pressures.

As a result of a study of the engine pressure pick-up requirements, including a survey of other investigators experience in the field of transient pressure measruements, it was decided to use a capacitance type of pressure pick-up in conjunction with a suitably designed high impedance probe.

An unsuccessful attempt was made to use commercial vibration equipment to determine inlet valve natural frequency and damping characteristics. Alternate methods of determining these characteristics are being considered.

A crystal pick-up was used to make initial checks of instantaneous inlet valve position; however, this technique was not satisfactory. Subsequently, one of the inlet valves of the valve assembly was electrically insulated from the others and used in an open-close switch circuit. This circuit is highly satisfactory within its limitations, ie., it does not provide quantitative data regarding position except at the instant of opening and closing.

Initial investigations have been made to determine the possibility of using strain gages to determine valve position. Valve temperatures were determined to be sufficiently low (145°F) to permit the use of such instrumentation.

It was originally intended to use a galvanometer recording oscillograph to record engine pressure valve position; however, further consideration and tests of the primary instrumentation revealed that a dual beam cathode ray oscilloscope equipped with a "Polaroid-Land Camera" was most desirable because: data may be instantaneously observed and recorded, the output of the pressure pick-ups may be observed directly without the use of amplifiers, and the cost is significantly less. This equipment has been procured.

The use of an electrical analogy is believed to be a new approach to pulse-jet engine analysis which it is hoped may provide important lacking fundamental information and aid in realizing the fuel potential of the pulse-jet engine. The work accomplished during the first six months on this phase of the program has been:

(a) The development of basic circuitry which has demonstrated the analogous behavior of electrical circuitry (with simplifications) and pulse-jet engine.

(b) A relaxation oscillator to simulate combustion phenomena and to provide for repetitive operation of the analogy has been developed.

(c) After extensive analytical and imperical investigations, and artificial electrical line which simulates the acoustic resonant characteristics of the engine tube was developed.

(d) The resonant modes of an actual engine tube were determined in order to provide data for correlation with the characteristics of the above artificial line of the electrical analogy.

The following major items of work are planned to be accomplished in the immediate future:

(1) Subject the improved engine to a 50 hour flight rating test.

(2) Determine the optimum material gages and types which may be used in the engine shell.

(3) Whirl test an elliptical engine.

(4) Determine the noise reduction effectiveness of dual engine configurations with exhaust shrouds which incorporate sound absorption material.

(5) Develop the strain gage method of determining valve position.

(6) Measure valve position and engine pressures simultaneously to determine their phase relationship.

(7) Develop electrical circuitry to simulate actual pulse-jet engine inlet valves.

2. INTRODUCTION

This interim engineering report is submitted in accordance with Item 2c of Exhibit "D" of Supplement No. 4 to U. S. Air Forces Contract No. AF 33(600)-5860. Detailed information concerning the work accomplished in the development of improved tip-mounted pulse-jet engine components for rotary wing application during the period of from 15 July 1952, to 15 January 1953, is presented herein. This development work is being accomplished in accordance with Items 1a, 1b, 1c and 1g of Exhibit "D" of the above mentioned Supplement.

The quarterly progress reports which are being submitted (References 1 and 2) are intended to summarize the work being accomplished under the subject contract. These quarterly reports provide overall and general information. This interim report is intended to provide more detailed engineering information on the work being accomplished to supplement that provided in the quarterly reports.

This report describes the work accomplished in the structural development (Item 1a), noise control (Item 1b), inlet valve phasing (Item 1c) and electrical analogy (Item 1g) investigations under Supplement No. 4 during the six month period since work was initiated, 15 July 1952, through 15 January 1953. Since certain of the analytical work, particularly under the electrical analogy development program, is highly specialized, certain of these analyses are not presented in the body of the report. They are, however, presented in the Appendices such that complete information is made available. In addition to the work already accomplished, an outline of the work intended to be accomplished in the immediate future is also presented herein.

It should be noted that the power control work under Items 1d, 1e and 1f of the Supplement is described in separate reports (Ref. 3).

Structural development of the engine components and all engine development testing is being accomplished by the Power Plant Division at the Mesa Arizona facility. Instrumentation, electrical analogy and noise control development is being accomplished jointly by the Power Plant Division, Test and Instrumentation Section of the Manhattan Beach, California facility and the Western Electro-Acoustic Laboratory consultant.

3. D I S C U S S I O N

The objectives of the work described herein are to develop pulse-jet engines and components having increased engine performance and life, and decreased engine weight and noise.

The work under the structural development phase is an extension of that accomplished earlier in accordance with Exhibit "A" of the subject contract. The development work aimed at decreasing engine noise is a continuation of that initiated under Contract No. AF 33(038)-6099. The other two phases of this program, inlet valve phasing investigations and electrical analogy development, represent relatively new approaches aimed at improving pulse-jet engine performance.

3.1 STRUCTURAL DEVELOPMENT

The work under this phase (Item 1a of Exhibit "D" of the subject contract) of the component development program involves the investigation of means of further decreasing the weight of pulse-jet engine components for rotary wing aircraft under high speed (600 ft/sec) conditions.

3.1.1 Work Accomplished

Prior to the initiation of detail design and development testing of improved engine components under the present program, a comparison of the weights of the various components of the AJ-6.75, AJ-7.5, AJ-9.4 and AJ-10.0 conical engines previously developed (Photographs of these engines are presented in Figures 1, 2, 3 and 4, respectively) was made. This comparison is presented in Table I.

The first nine items of Table I are combined to make up the engine shell, and it is apparent that this component accounts for the greatest percentage of the total engine weight.

In addition to contributing the greatest percentage of weight to the engine assembly, the engine shell has been the limiting component insofar as engine life and high speed performance are concerned. Specifically, engine shell life at the start of this program was approximately 35 hours at 325 "g's", with 420 "g's" limit ultimate load; whereas, inlet valve life was in excess of 60 hours. Moreover, the high speed performance, determined by means of the Special Test Stand and shown in Figure 5, indicated that it would be advantageous to operate the existing configurations at higher design speeds if the engine shell could be developed to withstand the higher centrifugal loads.

For the foregoing reasons, it was decided that maximum emphasis should be given to attempts to increase the strength and decrease the weight of the shell of the engines in this structural development phase of the program. The potential merits of the ducted type of pulse-jet power plant and considerations of structural and functional improvement of other components of the engines have also been investigated during the period covered by this report. The following paragraphs present the results of these investigations.

3.1.1.1 Engine Shell Development

Temperature data obtained as part of the previous development programs (References 4 and 5) showed that an engine shell exposed to free-stream air flow conditions cooled considerably better (and was therefore stronger) than the existing double shell conical engines cooled by means of ram scoops; further, these ram air scoops (See Figures 1, 2 and 4) had compromised the performance of the engines, by increasing the cold drag coefficient of the engine from approximately 0.25 to 0.35, more than was believed necessary. It was therefore decided to investigate engine shell configurations which would permit free-stream air cooling.

The initial engine shell configuration designed with the foregoing objective in mind was that shown in Figure 6. This, 6.75" diameter, engine incorporated a cantilever "I" beam structural member welded to the engine mounting straps and extending rearward. This "I" beam was attached to the aft end of the tailpipe by a band which would allow the tailpipe to expand and contract. The "I" beam replaced the outer shell which is used in the conical engines to support the tailpipe, and it permitted the engine shell to be exposed to free-stream air flow conditions. This configuration weighed 30% less than previous designs.

The "I" beam braced engine was inititally whirl tested on the Special Test Stand at "g" loads up to 250 with no indications of structural failures. The engine was then whirl tested at speeds up to 350 ft/sec on the 13.5 ft. radius whirl arm on the Portable Test Stand (270 "g"). The "I" beam and tailpipe of the engine shell were in good condition after these tests; however, the combustion chamber developed a buckle as shown in Figure 7. This failure is attributed to the fact that an abnormally large amount of lead weight was added to the forward end of the engine in order to balance it about the centerline of the mounting straps. This resulted in abnormally high stresses being developed in the combustion chamber under whirling conditions. Although the results of these preliminary tests of the "I" beam braced engine were encouraging, particularly from the standpoint of potential weight reduction, further work with this configuration was postponed because of faborable results obtained from other types of engine shell modifications described below.

Soon after work with the "I" beam braced engine was initiated, a review of past engine shell development work, described in Reference 6, indicated that certain of the single shell, "modified conical", engine configurations tested statically in the earlier programs had desirable weight distribution and cooling characteristics. It was, therefore, decided to evaluate similar configurations under whirling conditions.

"Preliminary design" of the modified conical engine configuration consisted of the application of data from Reference 6 to the design and static testing of the several geometries shown in Figure 8 in order to develop one which produced approximately the same static thrust with approximately the same overall length as the best of the previous conical engines. The results of these static tests are presented in Figure 9.

Based upon the results of the static test investigations, the configurations shown in Figures 10 and 11, were fabricated and whirl tested. The net thrust performance of these engines, at various tip speeds, is presented in Figure 12. These data show that the high speed performance of all configurations was inferior to that of the previously developed AJ-6.75 conical engines which produce from 30 to 35 lb. net thrust at 375 ft/sec.

Although the foregoing modified conical engine shell configurations were unsatisfactory from the standpoint of thrust performance, they were simple, economical to fabricate, weighed less than 75% as much as the previous conical engines and were believed potentially able to withstand higher "g" loads than previous engines. In addition, the cold drag of the modified conical engines compared favorably with that of the conical engines. In view of these favorable considerations, it was decided to determine the effect of lengthening the transition section of a "conventional" engine in increments approaching the above described modified conical engine configurations.

The initial engine shell configuration tested in this transition length investigation is shown in Figures 13A and 14. The high speed performance of the geometry is presented in Figure 15.

The three engine shell geometries shown in Figures 13 B, 13 C and 13 D, were then subjected to whirl test evaluation and the performance data obtained are presented in Figures 16, 17 and 18, respectively.

Cross-plots of the foregoing data are presented in Figures 19 and 20. These figures show that as transition length increases, with constant combustion chamber and constant overall shell length, engine performance decreases; however, the difference in performance at the highest speeds is small. As pointed out by Figure 20, not only did the transition length vary in this investigation, but so did the tail-pipe length. In fact, the characteristics of the cross-plot data indicate that tailpipe length may be the more significant parameter.

The results from the modified conical engine shell investigations, which preceeded the transition length investigations, had indicated that an exhaust augmentor having a 14° included angle provided performance which was superior to one having a 24° included angle; therefore the configurations shown in Figure 21 A and 21 B were subjected to whirl test evaluation and the results are presented in Figures 22 and 23.

A comparison of the data presented in these figures with those in Figure 14 (engines identical except for augmenter configuration) shows that the "standard" 24° included angle augmenter provides better performance characteristics than the 14° augmenters (at lease with this particular tube geometry).

It should be noted that the absolute level of performance of the foregoing (modified conical and variable transition length) 6.75" diameter engines is not necessarily representative of their eventual performance since interference drag, peculiar to the installation on the test stand (shown in Figure 24), is believed to have detracted from engine performance. This condition should not however, invalidate the data with respect to relative performance.

Subsequent to the evaluation of the effects of transition length on engine performance on the 30 ft. radius whirl arm of the Special Test Stand, it was decided to evaluate the structural characteristics of one of these modified conical engine shells. Engine No. 169 (Figure 13C) was selected since the efficiency of this shell as a uniformly loaded beam was increased by approximately 25% over the "reference" configuration(Figure 13 A) with only 10% loss in peak net thrust. This engine (Figure 13C) was whirled on the 13.5 ft. radius whirl arm on the Portable Whirl Test Stand for 4 hours at 375 ft/sec and 400 ft/sec. (310 and 360 "g's"). Performance data obtained during these tests are presented in Figure 25. It was then whirled at 430 ft/sec. (380 "g's") for 10 minutes at maximum power. The engine shell was in excellent condition after these tests.

The results of the foregoing tests not only indicated the good structural potential of the modified conical type of engine shell, but they also revealed that 430 ft/sec tip speed was the maximum obtainable with the existing Portable Test Stand driving engine due to the high drag of the whirl arm; as a result, it was not possible to determine the structural limitations of the modified conical engine shell configurations. Three possible solutions to this test stand power limitation were considered. They were:

(a) Installation of a higher power dynamometer driving engine with suitable gearing.

(b) Decrease the drag of the test whirl arm.

(c) Increase the size of the pulse-jet engine to provide additional thrust to decrease the amount of driving engine power required.

It was deemed most expedient and economical to provide additional and improved fairing to the whirl arm to reduce its drag and to apply the previous results to a slightly larger engine in order to attain the higher speeds desired. The latter(larger engine) would also provide a more severe engine tube structural condition since the larger engine would have a somewhat greater absolute overall length. Accordingly, the whirl arm was refaired, as shown in Figure 26, and the results from the above investigations were applied to the design of a 7.5" maximum diameter engine. The resulting shell configuration is indicated in Figure 27A. This engine shell was fabricated from .050" thick Haynes Alloy No. 25. An improved integral fuel injector valve attach section, described in Section 3.1.1.5 of this report, was used on this engine tube. This engine was whirl tested on the 13.5 ft. radius whirl arm and the resulting thrust performance data are presented in Figure 28.

The AJ-7.5 conical engines previously built have produced as much as 42 lbs. peak net thrust at 375 ft/sec. Since the drag of the modified conical engine of Figure 27A was less than the AJ-7.5 engines, it was believed that the modified conical engine should produce approximately 40 lbs. of thrust at 375 ft/sec. It was suspected that the cooling air shroud of the original AJ-7.5 engines effectively increased the tailpipe area; it was, therefore, decided to check the performance of the modified conical engine shell configurations shown in Figures 27B and 27C. The performance of these configurations is shown in Figures 29 and 30, respectively.

As suspected, the increase in tailpipe diameter resulted in an increase in peak thrust performance of the modified conical engine, but the throttling characteristics and specific fuel consumption were adversely affected. Therefore, the third, intermediate diameter, tailpipe configuration shown in Figure 27D was fabricated (from .044" Haynes Alloy No.25) and whirl tested. The results, shown in Figure 31, indicated that this shell configuration was the optimum of those tested in this investigation. This engine accumulated approximately four (4) hours operating time at tip speeds ranging from 375 to 500 ft/sec. on the 13.5 ft. radius whirl arm. A total of 20 minutes operation at maximum power at 500 ft/sec. (570 "g's") was completed with no signs of engine failure (500 ft/sec is the structural design limit of the 13.5 ft. radius whirl arm).

Since the results of the high speed structural checks of the modified conical engine were very encouraging, it was decided to subject the engine to an endurance test; therefore, a new engine shell having the geometry shown in Figure 27D was fabricated from .044" Haynes Alloy No. 25 and fitted with a "piano hinge" type mounting strap (See Section 3.1.1.4 of this report). This engine was designated the "AJ-7.5-1 Modified Conical Engine" and it weighed 17.5 pounds. The results of pre-endurance test performance checks of this AJ-7.5-1 engine are presented in Figure 32.

After the performance checks were completed, the engine and whirl arm were installed on the Endurance Test Stand as shown in Figure 33. After approximately four hours of endurance testing at maximum engine power, at 430 ft/sec, the venturi cracked at the weld between it and the combustion chamber forward bulkhead. It was decided that the failure was due mainly to high temperatures and a new venturi was fabricated using Haynes Alloy No. 25 instead of the Type 321 Stainless Steel originally used.

The rebuilt engine was then whirl-tested for 41 hours at 435 ft/sec. (440 "g's") at maximum pulse-jet engine power. A fatigue failure of the test stand whirl arm fitting resulted in the engine being thrown from the whirl arm and the resulting impact damage to the engine is shown in Figure 34.

The engine had been inspected just prior to this failure and it was in excellent condition. Since the engine shell design is based upon 1,000 hr. stress-rupture data, it is believed very possible that the shell life may be several hundred hours. Based upon past experience, it is believed that the inlet valves can be expected to last at least 200 hours.

In view of the significant improvements in the "Model AJ-7.5-1 Modified Conical Engine" over the previous designs, preparations are being made to subject this Model to an Air Force witnessed Flight Rating Test, Reference 7, so that it may be made available for flight test evaluation.

3.1.1.2 Fabrication of Tapered Sheet

Analysis of the structural properties of the engine shell indicate that its loading condition represents a cantilever beam with approximate uniform loading. It is obvious that a considerable reduction of weight for a given strength can be obtained if the aft sections of the engine shell could be fabricated with decreasing thickness as the distance from the support strap increases. The benefits from tapering the thickness of the tube shell are twofold, (a) the "dead weight" loads resulting from the action of centrifugal force on the elements of the tube decreases with increasing distance from the support strap, and (b) the cross-sectional moment of inertia is decreased roughly, in proportion to the applied loads.

The funds allocated for the investigation of structural improvement of the engine do not permit an extensive investigation of the several possible methods of producing a tapered sheet of a high temperature steel alloy. However, it was decided worthwhile to make a "one shot" attempt to fabricate a tapered sheet for use in an engine shell.

The procedure attempted to adhesively bond a sheet of constant thickness material to a heavy backing plate and then to grind the sheet to obtain a tapered thickness. This technique was attempted, but proved unsuccessful because the heat generated during the grinding operation was sufficient to cause the adhesive bond to fail. Although further attempts to fabricate the tapered thickness engine shell will not be made under the present contract, it is believed that the use of recent high temperature adhesives for bonding the sheet to the plate and/or adequate cooling of the sheet during the grinding operation could result in satisfactory fabrication of tapered sheets.

3.1.1.3 Elliptical Engine Investigation

An analysis, made as a part of the work under the previous statement of work, of the factors affecting the engine tube strength has shown that an elliptical cross-section would provide a noteworthy increase in engine shell bending strength. A complete evaluation of elliptical engines is beyond the scope of the present contract. However, preliminary design layouts showed that the valves from an existing 7.5" diameter engine could be installed in the slightly rectangular 6.75" diameter engine valve box casting and such a combination used in at least one elliptical engine configuration. It was, therefore, decided to design, fabricate and test one elliptical engine configuration in an attempt to determine the potential advantages and/or problems associated with elliptical cross-section engines.

The inlet cowl, valve box and fuel injector-venturi section for this engine have been completed and are shown in Figures 35 and 36. Final design and fabrication of the elliptical shell is being delayed pending completion of other tests which will provide further design data to be applied to the design of this engine shell.

3.1.1.4 Engine Mount Development

The design and development of a suitable engine attachment method and engine mount has been closely associated with the development of the modified conical engine shell.

Initially, the "boiler plate" weldment indicated in Figure 24 was used for an engine mount and the engine was attached by four bolts through the simple strap on the engine as indicated in Figure 14.

Some refinement of the engine mount was accomplished by utilizing the streamlined aluminum engine mount shown in Figure 37. Both this and the boiler plate design were interim configurations used to expediate the engine shell development testing.

A hinge type engine attach fitting was designed to facilitate rapid engine changes. This engine attachment member is formed from .062" thick annealed Inconel "X" as an integral part of the strap around the engine. Figure 38 shows one of these fittings after having been subjected to a static load of 24,000 lbs which is 2.96 times the design load.

A refined engine mount was designed for use in the above mentioned Flight Rating Test. Prior to fabricating this part, a mock-up of it was made from balsa wood and installed on an engine as shown in Figure 39. The results of whirl tests of the engine with the mock-up engine mount revealed that its drag was only one to two pounds at 400 to 500 ft/sec tip speed.

An actual part was then fabricated from heat treated 4140 Steel with sheet metal hinge type tabs at the engine attachment points. This part is shown in Figure 40. The combination of the refined engine mount and engine attach fitting is shown in Figure 41.

3.1.1.5 Fuel Injector - Venturi Section Development

The forward section of the engines previously developed consisted of several separate parts as shown in Figure 42. This arrangement provided a degree of flexibility which was desirable in order to facilitate the incorporation of improved components; however, development and flight test experience revealed the following two weaknesses in this arrangement:

1) The gaskets are located in a hot area of the assembly and frequently burned out, causing blow-by and a decrease in engine thrust and valve life.

2) The studs used to attach the valve box to the engine shell are welded in the forward bulkhead of the combustion chamber. As a result they become relatively hot and, since they are under tension, gradually elongate and eventually fail.

The shortcomings of the original fuel injector-venturi section led to the design, fabrication and testing of two alternate configurations. The first of these, shown in Figure 43, had the fuel injector, air starting ring and venturi welded to the engine shell, therefore they became an integral part of it. Engine performance with this configuration is presented in Figure 44. By comparing these data with those of Figure 15 (engines identical except for the subject section) it is seen that the performance with the redesigned parts was inferior to the original design.

The second alternate fuel injector-venturi section, shown in Figure 45, was a compromise design which incorporated part of the features of the original design and part of those of the first alternate. The performance of this second alternate configuration is presented in Figure 46. A comparison of these data with those in Figure 16 indicates that the performance of the second alternate configuration was inferior to that of the original design.

Both of the foregoing alternate fuel injector-venturi section designs eliminated the problems encountered with the original design; however the adverse effect of the design changes upon engine performance was difficult to explain since every effort was made to retain the same internal configuration in the alternate design as had been used in the original configuration. It was therefore decided to re-check the performance of the first alternate fuel injector-venturi section design, Figure 43, on a 7.5" diameter engine, (The above tests were with 6.75" diameter engines). The results of this check revealed no difference in engine performance attributable to the new design. This improved configuration has therefore been incorporated in the Model AJ-7.5-1 Modified Conical Engine. (The reason for the adverse affect of this alternate fuel injector-venturi section design on 6.75" diameter engine performance is at present unexplained).

It was necessary to use a special wrench in order to remove the fuel nozzle used in the improved forward section. Since this is one of the few parts of the engine which requires inspection, it was deemed advisable to redesign the fuel nozzle assembly such that it could be more readily removed. Therefore, the configuration shown in Figure 47 was designed and used in the modified conical engines. This nozzle can be disassembled for inspection, replacement and/or cleaning using only a screw driver.

Figure 47 also shows the concentric tubular slip-joint design used where the fuel and starting air lines pass through the venturi wall. This design eliminated fatigue failures which occasionally occured with earlier designs wherein the fuel and air tubes were welded directly to the venturi wall.

A limited amount of additional work with the fuel injection system was initiated with the following objectives in mind:

1) To decrease the weight per unit of thrust by increasing the net thrust of the basic pulse-jet engine.

2) To increase the efficiency of the pulse-jet engine (ie., reduce the specific fuel consumption).

This work was performed with a "standard" 6.75-inch diameter engine, and with two basic types of fuel nozzles. The first was a commercial, "Benjamin" solid cone fuel nozzle rated at 20 gallons per hour. The second was an AHCo. designed, miniature, hollow cone, fuel nozzle. Four of these nozzles were set in a rectangular fuel manifold. The nozzles were so designed that the output of the "four injector fuel manifold" was the same as the Benjamin, solid-cone, 20 G.P.H. nozzle with the same supply pressure. The purpose of the "four-injector fuel manifold" was to improve the distribution and atomization of the fuel.

A direct comparison of the two types of fuel injection is difficult because there are several other "head end" components which affect the distributions, atomization, and burning of the fuel. The area and shape of venturi throat, the venturi length, the size and location of the fuel baffle relative to the fuel nozzle, and venturi throat are all parameters which affect the combustion process. These effects are inter-related, and therefore difficult to evaluate separately.

In the "standard" or "reference" head-end configuration the fuel spray impinges on the baffle as shown in sketch A of Figure 48. The four corner system was assembled as shown in sketch B. This system would not operate properly without the fuel baffle at the throat. The best multiple spray configuration developed in this limited program and the "standard" configurations were whirl tested at speeds up to 450 ft/sec. The results of these tests are shown in Figures 49, 50 and 51.

These data show that, although the peak net thrust of the "standard" fuel injector assembly is higher than the multiple spray configuration, the specific fuel consumption is best with the multiple spray arrangement. It is believed that the reason for the improvement in fuel consumption characteristics is attributable to improved fuel and air mixing.

No further work with the fuel injector is planned under the present contract since this, structural development, phase is mainly aimed at engine weight reduction. However, the foregoing results indicate that future programs should include further fuel injector investigations aimed at reducing the specific fuel consumption and increasing peak thrust at high speeds.

3.1.1.6 Inlet Valve Development

It has been found that the blue clock spring steel inlet valves are susceptable to damage from exposure to residual fires which occur if an improper starting technique is used. They also rust if stored without a protective coating. It was therefore decided to attempt to substitute full-hard stainless steel for the blue clock spring steel in the inlet valves. Engine performance with a set of stainless steel valves is compared with the performance with spring steel ones in Figure 52. These data indicate that the stainless steel valves have an adverse affect upon engine performance.

It was believed desirable to attempt to decrease the time required for valve box assembly removal since this part is removed for inspection of the downstream side of the valves and to gain access to the fuel injector. Therefore a modified fuel injector-venturi section and valve box were designed to utilize a "Marman" "V" clamp for attaching the valve box to the engine in place of the six (6) bolts presently used. These components have been released for fabrication.

It might be noted that the valve box for the previously mentioned elliptical engine, Figure 35, contains only 6 valve units as compared with the 9 required in the equivalent circular cross-section engine valve box.

3.1.1.7 Ducted Engine Investigation

In accordance with the statement of work contained in Exhibit "D" of the subject contract, the major effort in the structural investigations is to be directed toward "plain pulse-jet engines". However, the statement of work provides for preliminary investigation of ducted pulse-jet engines.

A review and study of the analysis described in References 8 and 9 was made, and as a result, it was concluded that the ducted type of power plant may be expected to produce as much as 25% greater thrust, at 550 ft/sec, than the unducted pulse-jet engine. In addition, the structural characteristics of this type of engine appear superior to those of an unducted engine because there is provided an opportunity to incorporate auxiliary structure to support the basic pulse-jet engines without having to place such structure in the free stream. This structure is located in the secondary air duct and, because of the lower air velocity therein, this results in a reduced external drag as compared with that which would otherwise be obtained in an unducted configuration.

In view of the performance and structural potential of the ducted type of power plant, it was decided to design and fabricate such an engine for whirl test evaluation.

It was originally intended to test a single ducted pulse-jet engine; however, the results from testing under the noise control phase of the present contract indicated that the design of the duct might be more critical than initially realized because of the potential adverse acoustic coupling characteristics of the engines together with the duct if not properly matched. This same program, however, also indicated that the acoustic coupling characteristics of the duct might be minimized if a dual pulse-jet engine configuration was used. Therefore, a dual ducted engine configuration was designed utilizing, insofar as possible, the components previously developed for the 6.75" diameter engine in the two basic pulse-jets in the assembly.

Upon completion of the detail design of the dual ducted engine, it was immediately apparent that the cost of fabricating and developing this type of power plant could easily require all of the funds allocated to the structural development phase of the present contract. In view of this and the fact that this type of power plant has been recommended to power the Project MX-1660 rotor system, it was decided to fabricate and test the initial configuration and to continue its development under the project (Contract No. AF 33(600)-15613).

Assembled and exploded views of the initial configuration are presented in Figures 53 and 54.

3.1.2 Work To Be Accomplished

The following work is intended to be accomplished under the structural development program in the more immediate future:

(a) The Model AJ-7.5-1 Modified Conical Engine will be subjected to a Preliminary Flight Rating Test.

(b) Further engine shell configurations will be tested to determine the optimum material types and minimum material thickness which may be used.

(c) Engine configurations having longer tailpipes will be whirl tested.

(d) The elliptical engine will be completed and whirl tested.

(e) The "Marman Clamp" quick change valve box retention design will be fabricated and tested.

3.2 NOISE CONTROL INVESTIGATIONS

The work under this phase (Item 1b of Exhibit "D" of the subject contract) involves the evaluation of various pulse-jet engine noise reduction devices under static and whirling conditions to determine their effect on the noise emitted by the engines, and on engine thrust and fuel consumption.

3.2.1 Work Accomplished

The approach to noise control of pulse-jet engines under this program has been directed by two basic strategies. The first is the attenuation of the higher frequency components of the noise spectrum (250 cps and up) which is to be accomplished by a sound absorption technique using the sound absorption properties of high temperature fiberglass or certain of the new ceramic fibers (Reference 10). Attempts to attenuate the engine fundamental frequency component of the noise spectrum have been concentrated on cancellation techniques by acoustic coupling of two engines. This is accomplished by various configurations of two engines in which the respective resonant systems operate 180° out of phase. Thus it is possible to partially rectify both the flow through the system and also the pressure pulsations which are emitted by the configuration.

The noise reduction problem entails both the noise emitted from the engine exhaust and inlet. Although the exhaust noise overshadows the inlet noise of the basic engine, the inlet noise may become the predominant problem if the exhaust noise is greatly decreased. Therefore, although major emphasis has been placed on the exhaust noise in this program to date, possible means to reduce inlet noise have been considered and several configurations have been tried.

Since pulse-jet engines depend on a resonant system for their operation, extreme care must be exercised in noise control techniques to prevent the engine performance from being decreased when the noise control device is added. Secondary or auxiliary resonant systems which are set up in the system may enhance or deter the primary system.

3.2.1.1 Exhaust Noise Control

It has been demonstrated (Reference 11) that under certain conditions, two identical pulse-jet engines operating side-by-side statically will tend to resonate 180° out of phase. This coupling is due to a mutual interference of the pressure pulsations of the two engines. Thus, when a pressure pulse is emitted from one tailpipe a return pressure wave is transmitted to and propagates upstream in the second tailpipe. This is coincident with the rarefaction wave which is propagated upstream in the first tailpipe, hence the system is conducive to 180° phasing. Figure 55 presents a photograph of this configuration with a diagrammatic sketch depicting the acoustic coupling. This phenomonem attenuates the fundamental frequency component of the noise spectrum as shown in Figure 56. Performance of this configuration is compared with a single engine in Figure 57.

With this preliminary knowledge of dual pulse-jet engine coupling characteristics, a program was outlined whereby more pronounced coupling could be attained by addition of certain appendages to the configuration. These appendages also provide a structure for mounting acoustic liners. All configurations in this program were additions to, or modifications of a "standard" AHCo. AJ-6.75 pulse-jet engine.

A configuration in which the exhausts from two pulse-jet engines are directed into a common tailpipe is shown in Figure 58. This configuration was tested with two exhaust duct lengths and the data is presented in Figure 59. The reduced performance of this configuration as compared with the standard single pulse-jet engine shown in Figure 59, is attributed to several factors. First, the bend in the tailpipe of the pulse-jet engine could be expected to retard the resonant cycle. Since this bend is in a region of high particle velocity, losses in total pressure would decidedly hinder engine operation. Another factor which prevents this configuration from attaining the potential performance of the basic pulse-jet resonant system is the exhaust shroud so restricting the oscillating flow that the reflected wave is not strong engough to support strong resonance.

Since instrumentation was not available at the time this engine was tested, it could not be ascertained for sure whether or not the two engines were operating in phase or out of phase. Audible observations indicated that the frequency was reduced slightly as compared with the basic engine. This lowered frequency probably can be attributed to the increased length of the engine. Since the static performance of this configuration was poor and since there was little, if any, audible noise reduction, this configuration was abandoned.

The next series of exhaust appendages tested consisted of plenum chambers into which the exhausts from two side-by-side pulse-jet engines were exhausted. Two exhaust plenum shapes, one circular and the other oval, have been tried. These configurations are shown in Figures 60 and 61. The oval chamber was fabricated in order to compare qualitatively its performance with the circular chamber. This comparison indicates little difference in the operation of the two. Quantitative data for the circular plenum chamber configuration is shown in the following table:

Engines Running	Fuel Flow PPH	Static Thrust Pounds	Mean Comb. Pressure (In, Hg.)
#1	130	20	4.00
#1 & 2	200	21	1.95
"	240	27	2.30
"	260	33	2.90
"	280	32	2.70
"	320	33	2.55
"	360	33	2.85

The phasing characteristics of this configuration could not be definitely ascertained due to lack of instrumentation, although it sounded like the two engines were resonating in phase (0^{o} phase angle) rather than out of phase (180^{o} phase angle). Very little, if any, reduction could be detected.

An exhaust nozzle was added to the exhaust plenum as shown in Figure 60. With a nozzle exit diameter of 7.30" the engine produced performance shown in the following table:

Engines Running	Fuel Flow PPH	Static Thrust Pounds	Comb. Chamber Pressure (In. Hg.)
#1	130	22	1.90
#1 & 2	200	19	1.40
"	240	25	2.25
"	260	28	2.50
"	280	28	1.60
"	300	28	1.30

The engine would not operate with a nozzle exit diameter of less than six inches.

The next series of tests to investigate engine exhaust coupling characteristics consisted of exhausting two side-by-side engines into an open shroud as shown in Figure 62. The first test consisted of determining the phase relationship of the two engines. This was accomplished by a technique utilizing a dual beam oscilloscope to simultaneously record the open-close position of valves in the respective engines. Two adjacent reeds in the valve box were used as a switch. Thus, when the valves are closed, the circuit is complete, and when the valves are open, the circuit is incomplete. This circuit is shown in Figure 63, with a photograph of the oscilloscope trace. The "valve closed" position is shown by a horizontal line and the "valve open" position by a curved discharge line. This curved line is due to a capacitance effect in the system as differentiated from an expected square wave. Using this technique it was shown that the two engines were 180^{o} out of phase. An earlier technique tried was to attempt to record the outputs of two inductive microphones located adjacent to the respective tailpipes on a dual beam oscilloscope. The outputs of the microphones in this intense field was so distorted that the phasing could not be determined.

Performance characteristics of this shrouded configuration are shown in Figure 64. It is seen that in order for a shroud not to decrease engine performanace, it should be open at both ends.

It was reasoned that one factor which may be a deterrent to the operation of two side-by-side engines resonating 180° out of phase, is that if the exhausts are close enough to exhibit positive coupling due to pressure influences, the effect of the gas inertia may tend to hinder operation. If two engines are resonating 180° out of phase, one engine must be inducting air into the tailpipe (back-flow process) at the same instant that the other engine is discharging a charge of gases; thus, if these velocity fields come in contact they will be opposing each other and the process may be hindered. A series of tests were initiated in order to investigate this effect. The first configuration consisted of mounting two engines tailpipe to tailpipe as shown in Figure 65. Thus, both the pressure coupling and the inertia coupling would be conductive to "out of phase" operation and the configuration would resonate as a half wave resonator closed at both ends. The cycle history of this configuration is shown in Figure 66.

This configuration was first tested with a subtended angle of 180° . The engines started easily and operation was very stable. The valves in both engines were destroyed after about one minute of running time. The noise level was high with a characteristic high pitch. The fundamental frequency was apparently highly attenuated and the harmonics were the predominant components of the spectrum. In order to further investigate this phenomon without the destruction of the valves, the subtended angle was decreased and the spacing between the tailpipes was varied. Quantitative data for this series of tests are shown in Figure. 67.

In order to utilize this strong tailpipe to tailpipe coupling, the momentum of the gases must be deflected 90° in order that the thrust will be directed in the direction of motion. A possible means of doing this is to direct the exhausts into a phenum chamber and then expanding the gases through a nozzle. Such a configuration is shown in Figure 68. This engine started easily and ran smoothly. The engines coupled and exhibited the characteristic high pitch. The fundamental frequency was highly attenuated and the harmonics were predominant. The data recorded during the test follow:

Engines Running	Fuel Flow (Lbs. Per Hr.)	Static Thrust Pounds	Comb. Chamber Pressure (In.Hg.)
# 1 & 2	240	20	3.25
"	260	20	3.25
"	280	22	3.75

The engine got extremely hot during this run. The valves were severly damaged and the tailpipe protrubences into the shroud were melted off.

3.2.1.2 Front End Noise Control

A possible means of attenuating front end noise is to acoustically couple two engines at the inlet, as shown in Figure 69A.

A single engine was fitted with a quarter wave acoutic duct as shown in Figure 69A. Since the quarter wave length of the fundamental frequency (150 cps) was calculated to be 23 inches ($l = c/4f$) the tube was fabricated to be variable from 18" to 28" in order to bracket the calculated length. It was impossible to start the single engine when the tube length was 23 inches. The tube was extended to 28 inches and the engine started easily. Decreasing the tube length slowly caused the thrust to drop off noticeably and finally caused the engine to stop. The variation of thrust with tube length is shown in the following table:

Tube Length (Inches)	Static Thrust (Pounds)	Fuel Flow (pounds per hour)
28	31	130
27	30	"
26	30	"
25	29	"
24	27	"
23	Engine cut-out	"
22	Wouldn't start	"
21	"	"
20	"	"
19	"	"
18	24	"

It is reasoned that the cause of inoperation at or near the 1/4 wave length is due to the resonance characteristics of an air column with a variable impendance boundary at one end, which would be the case with the valve box. The valve box acts as a closed boundary (high impendance) when the valves are closed and as an open-end boundary (low impendance) when they are open. Thus, the impedance of the valve box is dependent upon the position of the valves and hence; if a resonant (or more aptly termed a synchronous) system is to be established, it must be one which will conform to the varying conditions at the valve box. With an open end tube of 1/4 wave length such a resonant system is not established as can be seen by investigation of the cycle history diagram shown in figure 69A. This diagram indicates that the pressure and rarefaction waves hitting the upstream and downstream sides of the valve box are timed so as to nullify the valve action. This prevents the engine from inducing sufficient air for operation.

In order to investigate the feasibility of this theory, three more configurations were investigated. These include a 1/4 wave length tube with a closed end (Figures 69B),a 1/2 wave length tube with an open end (Figure 69C), and a 1/4 wave length tube with an open end but with the valves removed (Figure 69D).

The 1/4 wave length closed end tube shown in Figure 69B had breather holes near the valve end to allow the induction of air. These holes also served as a means of maintaining a low impedance at this end at all times. The anticipated cycle history of this configuration is shown in Figure 65B, and it is seen that the pressure and rarefaction waves hitting the valve box, are phased so as not to interfere with engine operation. This configuration produced 35 pounds of thrust at 130 lbs/hr fuel flow which is comparable to the basic engine.

The open end 1/2 wave length tube shown in Figure 69C produced 35 pounds of thrust at 130 lbs/hr fuel flow. The anticipated cycle history of this configuration is shown in Figure 69C, and it too indicates that the phasing of the pressure and rarefaction waves would not hinder valve action.

It was then decided to fabricate a configuration consisting of an open end 1/4 wave length inlet tube with the reed valves removed as shown in Figure 69D, to further study this wave action influence on engine performance. This configuration corresponds to the valveless pulse-jet which has received some recent attention. This engine resonated very well although its measured static thrust was low (about 10 pounds). It was impossible to maintain resonance in the absence of ram air.

Since these tests substantiated the theory that the valves act as a boundary of varying impedence, it was reasoned that if two engines were placed side-by-side inducting air through a common inlet, the conditions would be favorable for 180° out of phase acoustic coupling of the two engines. This engine, shown in Figure 70, was built to investigate this reasoning. The static performance of this engine is shown in the following table:

Fuel Flow (Lbs per Hour)	Static Thrust (pounds)
170 Lean out	
180	49
200	57
220	63
240	69
260	76
280	76
300	75
320	74
340	74
360	One engine riches out

This engine has good operating stability and the two adjacent units were 180° out of phase. The flow through the inlet was essentially steady, indicating that the alternating component was highly attenuated. There was a slight reduction in audible noise level, although no quantitative measurements were made.

This configuration also holds the possibility of reducing the aerodynamic drag at high speeds. If the inlet velocity ratio can be held constant instead of fluctuating violently as it does with a single pulse-jet engine, it may be possible to reduce the drage by designing the cowl for this non-fluctuating inlet velocity ratio. The cowl of this configuration was designed to have an inlet velocity ratio of 0.70 at 400 ft/sec.

3.2.2 Work To Be Accomplished

Work to be accomplished during the more immediate future will consist of further investigations of noise reduction configurations in which sound absorption liners will be placed in the exhaust shrouds to attenuate the higher frequency components of the noise spectrum. Quantitative noise measurements will be made in order to check the effectiveness of this technique. These tests will be made on configurations in which the fundamental frequency is attenuated and which have not decreased engine performance to any great extent.

Static and whirl tests will be conducted on the dual common-cowl engine and noise measurements made under both conditions.

3.3 INLET VALVE PHASING INVESTIGATIONS

The object of this phase of the program is first to determine the relationship between pulse-jet engine inlet valve position and pressure within the engine and then to investigate the effects of variations in valve natural frequency and damping characteristics on engine performance.

It should be noted that the valve position, and engine pressure cycle data to be obtained under this phase will be of considerable value in the electrical analogy investigation.

3.3.1 Work Accomplished

3.3.1.1 Valve Position Instrumentation

Four Methods of determing instantaneous valve position have been considered to-date, and the techniques are being evaluated in order to arrive at a method which will give the truest picture of valve motion.

The first technique tried consisted of utilizing a Rochelle salt crystal pick-up of the type used for phonograph pick-ups. The needle of the pick-up was replaced with a wire probe and the other end of the probe was placed at various positions on the valve. This installation is shown in Figure 71. The pick-up output was fed directly into an oscilloscope. Figure 72 presents various probe installation sketches, and trace photographs of each. Figure 72A and 72B, both indicate a tendency for the probe not to follow the valve. Figure 72C, is an installation in which the probe is positively attached. This trace probably most closely depicts valve motions. The high frequency "buzz" noticed in this trace is probably due to seconday vibrations set up in the support truss.

The second technique tried was to utilize two adjacent valves as switches. The technique is illustrated in Figure 73. This method shows only "open" or "closed" positions; however, this is an important factor to be able to determine. It is also a technique which can be used in conjunction with other methods.

An oscilloscope trace obtained by using this method is shown in Figure 74. The straight horizontal line indicates the "closed" valve position, and the curved decay line indicates the "open" portion of the cycle. This curved decay line, as opposed to the expected square wave, is probably caused by a capacitive phenomenon in the circuit.

A third technique being investigated involves mounting strain gages on one of the reed valves near the base. Thus, the strain in the valve at this point would be proportional to the relative valve tip position. The strain gage bridge output voltage is recorded on a cathode ray oscilloscope. This proposed circuit is shown in Figure 75.

As a preliminary test to determine the feasibility of using this technique, temperature measurements were made on and in the vicinity of the valves to determine whether or not the valves remained cool enough to allow strain gages to be used. Thermocouples were installed and the average temperature of the valves was found to be 145° F. The average temperature in the air stream directly behind the valve bank was found to be 242° F.

3.3.1.2 Valve Frequency and Damping Instrumentation

After a review of possible methods of determing the frequency and damping characteristics of pulse-jet engine inlet valves, it was decided to evaluate the Model C31 vibration equipment manufactured by the MB Manufacturing Company of New Haven, Connecticut. Several typical inlet valves were therefore forwarded to that company for checking. Two major difficulties were encountered:

1. The valves are non-linear. That is, the natural frequency is dependent upon amplitude. This also means that damping varies with amplitude. It is therefore necessary to maintain a constant vibration amplitude in determing even the relative frequency and damping of the valves. The MB Company found it difficult to maintain a constant amplitude with the Model C31 equipment.

2. An attempt was made to use the signal generator on the Model C31 equipment to determine reed damping; however, the signal generator "sees" force not only due to damping but due to inertia also. It is next to impossible to separate these forces.

Further valve natural frequency and damping measurements will be accomplished by use of either the strain gage or photoconductive cell techniques. The valves will be excited by an abrupt impact or "twang" method and the strain gage or photo cell output will be recorded on an oscilloscope, natural frequency and the damping logrithmic decrement curve can then be determined by direct measurement.

3.3.1.3 Engine Pressure Measuring Instrumentation

A survey of available literature pertaining to the work accomplished by other organizations in the measurement of pulse-jet engine pressures were made. The more recent progress in the measurement of transient phenomena in the rocket motor field was also reviewed. The most complete report on the latter subject is given in Reference 12.

As a result of this survey, the pick-ups selected were those made by the Rutishauser Corporation of Pasadena, California. These capacitance type pressure pickups use a carrier frequency of 12.5 megacycles and have a 50 psi maximum pressure limit. Two important requirements of these pressure cells are:

1. They must be linear, and sensitivity must remain constant.

2. The pressure pick-up system must be capable of both static and dynamic calibration since steady state and alternating pressures are to be measured.

Temperature effects constitute the major factor in varying the linearity and sensitivity of the pressure pickups. Therefore, special high impedance probes are being fabricated which will permit locating the pressure pickups sufficiently far from the high temperatures of the engine, so that the linearity and sensitivity of the pickups will not be altered. The impedance of the probes will be such that the true pressure conditions that exist within the engine will not be disturbed. The design of the probes follows closely the work described in Reference 13.

3.3.1.4 Recording Instrumentation

It was originally anticipated that a galvanometer recording oscillograph would be used for recording engine pressure and valve position data. However, the experience gained during the testing described above indicated that a dual beam cathode ray oscilloscope and a "polaroid-Land Camera" would be a superior instrument for recording engine pressure and valve position data for the following reasons:

(a) Data may be instantaneously observed and recorded with the oscilloscope; record processing is required with a recording oscillograph.

(b) The majority of investigations require observation of two signals simultaneously. The dual beam oscilloscope is ideal for this application.

(c) The output of the pressure pick-ups may be observed directly on a high input impedance device such as an oscilloscope, whereas a recording galvanometer oscillograph requires match amplifiers and/or cathode follower equipment.

(d) The cost of the dual beam oscilloscope and polaroid-land camera is significantly less than the cost of the oscillograph with galvanometers.

This equipment was therefore procured.

3.3.2 Work To be Accomplished

A fourth technique for measuring instantaneous valve position is being considered and consists of the use of a photoconductive cell such as a lead sulfide unit. This cell is sensitive to changes in light intensity, and by placing it in front of the valve box the circuit output should give a good indication of valve opening. This technique is scheduled for early evaluation.

After the valve position technique has been developed the instantaneous pressure cell instrumentation described above will be installed in an engine and valve position vs. engine instantaneous pressure will be studied utilizing the dual beam oscilloscope equipped with a "Polaroid Land Camera" for viewing and recording the data.

3.4 ELECTRICAL ANALOGY DEVELOPMENT

The purpose of the work under this phase (Item 1g of Exhibit "D" of the subject contract) is to develop an electrical circuitry analogous to the various components and operating characteristics of the pulse-jet engine. Such a device will facilitate rapid and economical analysis and prediction of the effects of various parameters on engine performance.

It is believed that the work under this phase is a new approach to pulse-jet engine analysis which may provide important lacking fundamental information and aid in realizing the full potential of the pulse-jet power plant.

3.4.1 Work Accomplished

3.4.1.1 Simplified Engine Analogy

The initial phase of this program involved the development of a simplified pulse-jet electrical analogy; with particular emphasis being placed upon investigating the effect of valve opening upon the response of a resonant system.

The basic pulse-jet tube is shown in Figure 76 in very simplified form. For the most basic approach, the combustion process is idealized as a pulsing pressure generator at the valve end of the tube. It is assumed that the positive pressure pulses close the valves, permitting the burning gases to be expelled only from the open end of the tube, and that the negative pressures open the valves to admit a fresh mixture.

It is known from noise analysis that the pulse-jet engine is a resonant system which is capable of response in many modes. The discrete frequency spectrum is a series of harmonics. The lowest or fundamental mode of this resonant system could be duplicated by a simple Helmholtz resonator, although it is known that a pulse-jet tube approaching this form will not operate. Nevertheless, the duplication of this fundamental mode respresents a simple starting point for circuit analysis, since it is known that the behavior of any electrical line can be simulated at one characteristic frequency by the single pi-section. Therefore, the simplest analogous circuit which can represent the behavior of the valves in the resonant tube is shown in Figure 77. The correspondence of elements is explained as follows:

The lowest mode of the pulse-jet tube can be represented as the oscillation of the mass M of gas in the tailpipe upon the complaint cavity V. The volume V represents a storage tank which alternately stores and expells the excess mass of gas taking part in the oscillation.

Likewise, in the circuit of Figure 77, the capacitance C represents a storage tank for oscillating electric charge. The inertia-like behavior of the current is furnished by the inductance L which has the property of opposing the change in movement of charge or current in the circuit.

When the valves are closed, no gas can pass through the closed end of the cavity V. Likewise, it is necessary to drive the electrical circuit in such a manner that the oscillatory current remains in the capacitance and does not flow appreciably in the generator. This is accomplished by driving the resonant circuit from an oscillator E_o through a high value of resistance R_s. In this way, the response of the circuit, as measured by the voltage E_1, for example, is decoupled from the oscillator so that although E_o is held constant, E_1 can undergo large changes as dictated by the demands of the circuit.

The characteristics of the electrical circuit are described by measuring the voltage E_1, the alternating current flow in the L, C circuit and the direct current flow in the circuit. These quantities are found to vary considerable as the circuit is fed by the oscillator at various frequencies near the resonant frequency of the system.

The electrical quantities correspond to the acoustical or gas movement quantities in the following manner:

The oscillating pressure in the combustion chamber P_1 is represented by E_1. P_1 will be found to vary considerably in response to a fixed oscillating gas current with which the tube may be excited.

The alternating gas velocity which evidences the gas oscillation in the tailpipe is represented by i_{ac} in the electrical circuit. The passage of the steady flow as the fresh air is admitted by the valves, burned with fuel and exhausted from the tailpipe is represented by i_{dc}. Although the oscillatory and steady gas flow simultaneously, it is convenient to consider an alternating flow superimposed upon the steady flow, and measure these quantities separately, since their behavior is quite distinct.

The behavior of the resonant tube and the resonant circuit without the complication of valves is represented in Figure 78 by the curves marked $R = \infty$. If the valves are closed during all of the cycle, no steady gas flow can occur. Likewise, no direct current flows in the electrical circuit. The response of the system reaches a peak at the resonant frequency where both the oscillating pressure P_1 (or voltage E_1) and the oscillating velocity V_{ac} (or current i_{ac}) are maximum. In the graph, both these quantities are expressed in terms of decibels where

$$DB = 20 \log 10 \frac{E_1}{e_o} \text{ or } \frac{(i_{ac})}{(i_o)}$$

where e_o is an arbitrary reference voltage = one microvolt and i_o is an arbitrary reference current. Actual point values are given in terms of voltage or current for reference. A change of 6 decibels represents a change in response by a factor of two.

The action of the valves in the pulse-jet can be represented in the analogous circuit by an electrical diode which, like the valves, has the property of passing current in only one direction. The analogous action is as follows: In the engine, when the pressure becomes positive due to the explosion, or the return of a condensation wave, the valves close, permitting an accumulation of gas pressure within the chamber. Likewise, when the voltage across the condenser C becomes positive, current will not flow through the diode, a charge accumulates on the condenser and the voltage across it builds up. On the other hand, when the pressure in the chamber drops below outside pressure by virtue of the expulsion of gas through the tailpipe, then the valves open, preventing further decrease in chamber pressure by admitting fresh gas. Likewise, when the electrical voltage across C goes negative, the diode draws current, preventing further increase of negative voltage across C by supplying the current as a shunt path.

The extreme of this condition is presented in Figure 78 by the curves marked R= O. Almost all semblance of resonant behavior has disappeared. The small remaining maximum in the circuit voltage E_1 has moved down to about 500 cps. A large DC flow is accomplished, the peak value occuring at 600 cps.

This example represents an extreme condition for the pulse-jet engine, namely that the open valves should be equivalent to complete removal of the end of the chamber. This is by no means the case, since the maximum opening of the valves represents only a partial area of opening and considerable resistance to flow of air must still be presented. Such a condition may be represented in the analogous circuit by the inclusion of the resistance R. This element has the effect of limiting the flow of current when the diode passes current. Changing the value R is equivalent to changing the percentage opening of the end of the combustion chamber.

It is well known that this factor has a controlling influence on the performance of pulse-jet engines. It is found that the valves must not open too large an area. The reason for this observation is quite well illustrated in the behavior of the electrical circuit. As the resistance R is increased, the circuit again shows a resonant behavior both in the voltage E_1 and in the alternating current i_{ac}. In other words, there is a frequency at which it preferes to operate. This is equivalent in the engine to saying that there is a preferred mode of operation, a frequency at which the essential resonant wave system can be established. For too large an open area, the waves are highly damped and re-ignition or valve action is no longer possible.

The wave shapes for E_1 and i_{ac} are shown for various values of R in Figure 79.

It should be stressed that the correlation of these factors is shown so far only qualitatively. That is, there is nothing yet to indicate by the electrical circuit the degree of resonance which is essential to pulse-jet operation. However, the essential analogous behavior of the circuit elements is clearly demonstrated.

3.4.1.2 Analogy of the Combustion Process

The next step in the analogy program was the investigation of electronic circuitry to approximate the combustion phenomena in the actual engine. In the following discussions of the combustion process it should be noted that some of the statements may be speculative, since it is generally agreed that many details of the combustion process require clarification.

The combustion process itself does not add a significant amount of new material (charge, mass) to the system. The material which is expelled with each exhaust impulse consists of burned gasses which have the same mass as the intake of fresh air mixed with fuel. It is generally supposed that the fuel to air weight ratio varies in the range from 1/14 to 1/30; therefore, in the elctrical analogy, we propose that the fresh charge can be represented by the electrical current passing through the simulated valves. All theoretical work so far has ignored the weight of fuel. However, this weight is to be included in the weight of fresh charge.

The energy causing the propulsive impulse results from the addition of heat energy by the combustion process. It is important in considering the approximation which is achieved in an analogous electrical system, to realize the distinction between impulsive energy furnished by the injection of new material as contrasted with the energy injected in the form of heat. The process in an actual engine is assumed to be a sudden increase in the temperature of the gas in the fresh charge. The resulting increase in pressure in this charge causes the expulsion of gases.

Note that it is assumed that heat energy can be furnished only by the volume of fresh charge. From this region, the pressure must spread to other regions. Hence, any volume in the combustion chamber which is not filled with new charge must be compressed by the new charge and may therefore represent a diminution of available pressure energy.

The analog of pressure in a chamber is the voltage developed across an element in the electrical circuit. The anlog of a volume such as the combustion chamber is an electrical capacitance. Therefore, a pressure increase in the combustion chamber is represented by an increase in the voltage across a condenser. Now, it is physically impossible for the voltage across a condenser to be increased without the addition of electrical charge. Herein we are faced with a limitation in the electrical system: the electrical system simulates fairly accurately the behavior of the acoustic jet, that is, a cold system. The increase in pressure (voltage) occurs only with the displacement of material (electrical charge); that is, the movement of the piston. (To be strictly correct, we should recognize that the movement of the piston constitutes a change in the volume of the cavity, the analog of which would be a change in the electrical capacitance under conditions of constant electrical charge. At present, it is not considered feasible to produce this distinction in the physical system.) It is clear that we do not have in the electrical system the third dimension corresponding to temperature change.

In the case of combustion, the three dimensions are volume, pressure and temperature change due to the addition of heat. In the cold system (or in the electrical system), the two dimensions are volume (capacity) and pressure (voltage). It is candidly recognized that in an acoustical system, a change in temperature inevitably accompanies a sufficiently rapid change in pressure; however, this temperature change is adiabatic; that is, it does not represent a change in internal energy.

Upon the initiation of burning within the combustion mixture, the pressure rises at a finite rate determined by many little-understood aspects of the combustion phenomenon. Similarly, we must arrange that the voltage across the appropriate elements in the electrical circuit must rise at a finite and controllable rate. It is recognized by the most recent theortical work that this <u>rate</u> of combustion is perhaps one of the most controlling factors in the efficiency of the pulse-jet engine; therefore, a control respresenting the rate of combustion should be provided in the analogy.

Most investigators recognize that at least three factors control the moment of ignition: (a) The arrival at the region of fresh charge of positive pressure pulse returned from the end of the tailpipe; (b) Contact of the fresh charge with the residue of hot gases remaining from the previous explosion; (c) Contact of the fresh charge with the hot walls of the combustion chamber. It is not presumed that all of these factors can be represented individually in the electrical analog; what is important is that there is apparently a critical factor which we shall call an "ignition function" which must be simulated.

The magnitude of the pressure rise due to combustion is dependent upon the amount of fresh air taken in and upon the amount of fuel burned. Both of these factors must be simulated.

When the explosion occurs, the resulting current of gas can move in three possible directions: (a) to increase the pressure in the residual volume of the combustion chamber; (b) to force the exhaust of gas from the tailpipe; (c) to force gas past any leakage in the valves.

The nature of the required electrical source may be clarified by considering the combustion chamber alone. Assume a closed chamber with a partition dividing it in half. In one half is explosive mixture; in the other half is burned gas. Let the explosion occur, raising the pressure in one side to a value P_1 and temperautre T_1. Now remove the partition and let the gases mix. The pressure and temperature will both be reduced to the new values P_2 and T_2. In the analogous circuit, these two volumes should be represented by separate capacitors in parallel. If an electrical charge is introduced on one capacitor only, the resulting increase in voltage will be determined by the sharing of this charge with the other capacitor.

The simplest form of the electrical circuit which will begin to reproduce these phenomena is shown in Figure 80. The combustion chamber volume is represented by C_1 and C_2. A charge is placed on C_1 by the low impedance generator represented by E_o. Upon the introduction of this charge, the resulting voltage which will be produced across these two condensers, is represented by E_1. The distribution of this charge from C_1 to C_2 is one of the three paths indicated above.

Another of these paths is represented by the inductance L. The electrical charge will surge from the capacitor through this inductance.

The valves are represented by the diode D which has a certain reverse leakage conductance, but in general will not pass current until the voltage E_1 becomes negative. The degree of reverse conductance can be artifically controlled by the value of resistance R_1. The value of forward conduction through the diode, which represents the induction of fresh air into the engine, may be artifically controlled by the value of resistance R_2.

It is clear that the relative value of C_1 and C_2 should be made to change automatically corresponding to changes in the amount of "inhaled" air. The value of C_1 plus C_2 is constant, representing the total volume of the chamber. The value of E_o should be controlled by the total charge passing in a forward direction through the diode. Since automatic control of the proportion of C_1 and C_2 is not practical, the diagram is simplified by the equivalence shown in Figure 81. For the values given in circuit A, there are equivalent values in B.

Several alternate circuits which have been considered, are shown in Figure 82, where circuit B is the simplified equivalent of Figure 80, and circuit A is the equivalent of the circuit used in the simplified analogy described above in Section 4.1.1.

Let a positive pulse be applied from the generator. Now suppose that the chamber is closed; that is, looking into the tailpipe from the combustion chamber the tailpipe is blocked. This means that the inductance L is removed from the circuit. Circuit A behaves properly; that is, the resulting voltage across C will be greater than if some charge were allowed to surge through L.

Circuit B is correct for the same reason.

Circuit C is not correct because when L is removed the circuit of the generator is no longer complete and no voltage can be developed across C.

Circuit D is not correct because the injected voltage does not appear across C due to the high impedance of the diode.

Now suppose that the volume of the combustion chamber is reduced to a very small value; that is, we open circuit C. We again apply a positive pulse from the generator. Circuit A is correct since the voltage E_1 is increased and the current through L increases since the path into the combustion chamber has been eliminated.

Circuit B is not correct in the limit of zero value for C unless the value of E_0 is adjusted in conformity with the discussion of Figure 81. Circuit C is not correct because, although a voltage E_1 is developed, no current can flow so long as the diode is non-conducting by virtue of the positive pulse. Circuit D is not correct for the same reason.

It is clear that either circuit A or circuit B can be made to produce the desired result. However, the limitations of circuit A should now be clarified.

If the impedance represented by Z is a resistance, then when a positive pulse is applied from E_0 the voltage E_1 will be developed only slowly depending on the charging time of C through Z. If the impedance Z is a capacity, we have exactly the equivalent of Figure 80, and the voltage E_1 develops instantaneously.

There is a major remaining difficulty with the circuit of Figure 80 or circuit B of Figure 82. Another condition which the electrical circuit must satisfy, if it is to simulate the pulse-jet behavior, is that once a charge is applied to C with a sudden increase in voltage E_1 the following decrease in E_1 should be determined solely by the circuit parameters as the charge surges from C through L. In particular, the subsequent behavior of the voltage should not in any way be influenced by subsequent change in the voltage E_0.

The circuit behaves properly; that is, if E_0 suddenly increases and then remains at a constant value. This behavior is satisfactory as long as only a single pulse is considered. However, it is desired to restore

E_o in preparation for the next positive pulse. This is not possible with this configuration. Therefore, circuit A is considered in conjuction with another possibility. Suppose the impedance Z is a diode biased by a battery as shown in Figure 83. Now let E_o be a pulse which rises to a value which exceeds the bias and after a short interval returns to zero value. During the period that E_o is greater than the bias, a charge will flow into the condenser C, and as soon as E_o returns to a value less than the bias, the diode can no longer conduct and the return path for the charge is blocked. Thereafter, the voltage E_1 can decrease only as the charge surges from C through the inductance L. The equivalence of these two circuits; that is, Figure 83 and Figure 80, has been proven experimentally by transient excitation of the form shown in the figures. The results are shown in Figure 84. In both cases, the resulting oscillograph traces are identical. The circuit of Figure 83 is therefore chosen only because it is capable of repetitive operation.

The circuit already reproduces even some of the secondary phenomena which are observed in the pulse-jet engine. The decrease in frequency accompanying an increase in fuel flow has been noted in noise analysis (Reference 14). The results now verify a non-linear behavior with increased excitation of the electrical circuit. Referring to Figure 84 the wave forms for transient excitation have been plotted from the oscilloscope screen. Trace A shows the excitation of the resonant circuit by a pulse when the value of R in series with the diode is zero and the excitation is low. A damped wave results. (Incidentally, if the excitation is low, and R has some greater value the damping is much less and the oscillation persists longer.) As the excitation level increases the duration of the first negative oscillation is observed to increase until, for a high level pulse, the negative cycle has greatly lengthened and changed form as in B. In this case the change in period is the order of three times and illustrates the principle admirably.

The current drawn through the diode, corresponding to the induction of fresh air through the valves, is shown in curve C, corresponding to the voltage trace B. Trace D should be compared with B and shows the effect of increasing the resistance in series with the diode at a high excitation level. To increase R corresponds with a decrease in the area of opening of the valves, not a change in time of opening. This result, i.e. an increased strength of resonance and decrease in period, agrees well with the earlier results for steady state excitation.

Another limitation of the analogy should be explained. The behavior shown in the traces of Figure 84 is clearly indicative of a non-linear circuit. It is well to understand the reason for this non-linear behavior by which the response of the system varies with excitation level.

The diode is presumably the only non-linear element in the circuit. This element passes current in only one direction just as the valves pass gas current in only one direction. In the electrical circuit all non-linear behavior must be attributed to the diode properties.

Many other aspects of non -linear behavior are to be expected in the engines. Even in a cold system such as the "Acoustic Jet" the achievement of thrust is attributed to the non-linear behavior of a jet. This behavior is reported in Reference 15. However, these factors are believed to be of secondary interest as compared with the major problems which are the interaction of waves with valves, the influence of valve tuning and impedance, the effect of engine chamber shapes, and the coupling of engines. After the major properties of the pulse-jet engine have been duplicated in a system using essentially linear elements, the problem of devising non-linear elements to reproduce any essential characteristics will be undertaken.

Having determined the proper method for driving the circuit and verified the essential behavior by transient excitation, the next step was the design and development of suitable electronics to provide continuous excitation, and control over the various factors which influence pulse-jet performance. The required circuit is shown in Figure 85 together with a diagram showing the time history of events which are expected at various points in the circuit. In explanation it may be said that the circuit is basically similar to the simple relaxation oscillator. The biased cathode follower is used to prevent the formation of negative pulses and to control the total charge delivered to the circuit which simulates the rate of fuel flow. The RC delay in the grid, P_1 to G_2, is used to simulate ignition time delay and burning time. The "artificial line" (described in the subsequent section of this report) and other elements comprising the engine analog furnish the time lag connecting plate and grid, P_2 to G_1. An adjustable negative bias at G_1, which must be overcome by the positive pulse reflected by the electrical line, furnishes the critical "ignition function".

3.4.1.3 Development of an Artificial Line

All data which has been presented so far has used a simple resonant circuit to simulate the acoustical resonant properties of the pulse-jet engine. This procedure was satisfactory as a first approximatation only for the following reasons: The simple circuit exhibits only the first of the many resonant modes of an actual engine; when excited by a positive pulse it does respond by returning first a negative and then a positive wave; however, the returned waves which result from the shock excitation of only one resonant mode are sinusoidal in form and not sharp pulses. It is known that an actual engine made in the form of a simple resonator (Helmholtz resonator), for which the simple series LC circuit would be a proper representation, will not operate (this is probably because of the inability of the circuit to return a sharp positive pressure pulse so as to cause re-ignition). It is also known that the acoustical tube, consisting of the combustion chamber, transition section, and tailpipe, behaves approximately like a quarter wave pipe. Such a pipe produces a series of resonant modes whose relative frequencies are determined by the length of the tube and the impedance in which the ends of the tube are terminated. In the case of the quarter wave tube, one end is terminated in a rigid boundary and the other end is open to the atmosphere. Such a resonant tube has a series of modes whose resonant frequencies are in the ratios of odd integers, that is, the frequency ratios should be 1, 3, 5, 7, 9. etc. Departures from this simple series are to be expected depending upon the change in cross section area which may exist along the length of the pipe.

Therefore, the next objective was to design and develop an "electrical line" which with proper terminations will permit resonances to be established with frequency ratios related by odd integers for simulation of the acoustic characteristics of the engine tube.

Such an electric line can be approximated by a series of meshes consisting of series inductance with shunt capacitance and can be represented at any one frequency by a simple T or pi section of an appropriate resonant frequency. For this particular application, a pi section with capacitative input to simulate the combustion chamber is required. Such an artificial line, shown in Figure 86, corresponds to a low pass filter with cut-off frequency given by $f = \frac{1}{\pi\sqrt{2LC}}$ where L is the value of the inductance in each of the shunt arms. The characteristic impedance is given by $R = \sqrt{\frac{L}{2C}}$. To duplicate the total line behavior, an infinite number of such identical pi sections is required. A line so composed and terminated in its characteristic impedance is capable of passing all frequencies below its cut-off frequency without any reflections.

To achieve the reflections characteristic of a resonant condition, it is necessary to mismatch the terminations by impedances other than its characteristic impedance. The acoustic line is terminated at one end in a low impedance which is represented by the open end of the tube and by a high impedance at the other end as represented by the closed valves. Likewise, its electrical counterpart must have corresponding terminations to produce the same wave behavior. This calls for a high input impedance and a short-circuited output impedance for the electric line. The short circuited termination will produce the 180 degree phase reversal as produced in the acoustic line. Likewise, the in-phase reflection at the high impedance end of the acoustic line is duplicated by the in-phase reflection at the high input impedance of the electric lines.

Obviously the line cannot be made infinite but must consist of a finite number of sections. Therefore, initial experimentation was conducted with lines comprised of identical sections to determine the degree of deviation from the required odd harmonic relationship when a reasonable number of sections was used. Each section was comprised of a .530 henry series inductance and .1 microfarad condenser in each of the shunt arms. The input resistance was .1 megohm; the output was short-circuited. The cut-off frequency was measured to be 1100 c.p.s. The experimental technique consisted of driving the circuit with an audio-oscillator and noting the resonant frequencies as indicated by the voltage readings at the input of the network. Results of tests with 1, 2, 3, and 4 sections showing the frequencies obtained and the frequency ratios are tabulated below:

Number of Sections	Frequency	Frequency Ratios
1	700	1
2	380, 930	1, 2.45
3	255, 700, 970	1, 2.75, 3.8
4	195, 560, 850, 1,000	1, 2.88, 4.36, 5.13

As can be seen from the data above, there is a one to one correspondence between the number of sections in the network and the number of modes produced. Furthermore, the frequency ratios of these modes are seen to approach an odd harmonic series with increasing number of sections, the fundamental frequency decreasing with added sections. Since the cut-off frequency remains constant, the fundamental frequency then has to decrease as sections are added in order to accomodate the entire series below the cut-off point. Stated another way: If the line is designed for a given fundamental frequency, the cut-off frequency will have to be extended as more sections are added and the number of harmonics in the series is increased.

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The results shown above substantiate the theory that in the limit the line can be represented by an infinite number of sections. It is apparent, however, that far more sections than is practical could be required with this method to bring the frequency ratios to an acceptable degree of harmonic relationship.

The alternative procedure then was to vary the values of the parameters comprising the sections, taking care not to distort the line to the extent that prominent intermediate reflections would be set up due to mismatch in the line. Changes were limited to the condensers only, maintaining the value of .530 henrys for the inductances. A total of 31 tests were made. A clearly defined trend which might serve as a basis for development of a theory predicting values for the elements was not obvious. It was ascertained however, that lines consisting of smoothly tapering values decreasing from the input end were found to produce more favorable frequency ratios than those tapering in the opposite direction. Several satisfactory configurations were obtained which complied within 2 percent of an integral odd harmonic series. The final four mesh circuit with values of the parameters and frequency ratios is shown in Figure 87. The steady state behavior of an acoustic line was thus apprximated for a limited frequency range by means of an electrical artificial line.

On the basis of the foregoing studies, it was decided to proceed with the development of an artificial line consisting of ten meshes. It was believed that this number of modes would permit sufficiently realistic representation of the acoustic line (engine tube).

The classical values for such a 10 element artificial line are shown in Figure 88. The pi sections are identical. With these values the series of resonant modes does not have the desired harmonic frequency ratios. Therefore, it was necessary to attempt to adjust the elements to produce a harmonic series to reproduce the behavior of a closed tube.

A considerable amount of time was spent in this approach, and altogether over 130 different configurations were tried but none produced the desired harmonic modes.

The empirical approach to the development of the artificial line was used initially for two reasons:

(1) It was believed that the analytical approach would involve an extremely large amount of mathematical effort.

(2) It was expected that the experience gained in the emperical approach would make it possible to make adjustments to a given situation relatively quickly.

A different approach was therefore taken. The reason for the insistance on harmonic modes, that is uniform phase velocity, was the requirement of faithful pulse transmission; that is, an electrical system having wave transmission characteristics which would simulate the pulse transmission of the acoustic tube closed at one end and open at the other. The characteristic of such a tube, as used in the pulse-jet engine, is that when a positive pressure pulse is created at the closed end, the pressure wave travels down the tube to the open end, reflects as a negative wave at the open end , and returns as a negative pressure pulse again to the close end. Successive positive and negative pulses are thereafter returned. A similar behavior is expected from the electrical line in terms of the voltage pulses which travel along it and are alternately reflected from the open circuited and short-circuited ends of the network.

Therefore, it was decided to concentrate on the pulse transmission characteristics of the networks.

Pulses of voltage can be applied to the network at the open-circuited end by the method shown in Figure 89. An electronic generator is used which produces extremely sharp pulses of voltage. These pulses are applied through a biased diode. The diode passes current, that is, it is a low impedance, only when the pulse of voltage exceeds the bias voltage. When the pulse voltage again drops below the bias voltage the diode becomes a high impedance. Hence the circuit passes current only for a very brief interval of time, applying a charge to the network, and then becomes an open circuit termination while the network continues to respond in the manner dictated by such a termination. The shape of the voltage pulse is shown in Figure 90 by a sharp vertical pulse. In the figures which follow it will be apparent that the time length of this pulse is an extremely short interval as compared with the duraction of response of the network. The phenomenon is made repetitive, so that it can be displayed on an oscilloscope screen, by pulsing the network intermittently, at a rate of about one-sixth of the fundamental frequency of the network.

The simplest approximation to a pulse-jet tube was shown in Section 3.4.1.1. This is a simple parallel resonant circuit which when suddenly charged and then permitted to discharge without further influence of the charging circuit, furnishes a damped train of sine-waves. Insofar as such a train of waves represents successive positive and negative voltages (pressures) it simulates the tube. Actually this wave represents only the fundamental frequency of a pulse, that is one component of the many modes which sharp pulse transmission requires.

The next approximation to pulse transmission is furnished by a three section line which was developed experimentally and is shown in

Figure 91. This network has mode frequencies which are in quite precise harmonic relationship. The response of this network to pulses is shown in Figure 92. It will be observed that the retuning negative and positive pulses are much narrower than the sine-wave traces. But the limited number of modes (three) are evident in the residual oscillations in the intervals between pulses.

The next stage of the development continued the work on the ten -section line, but now with accent on pulse transmission characteristics. The performance of the classical 10 section line when excited by a pulse using the circuit of Figure 89, is shown in Figure 93. Any semblance of returning pulses is difficult to find. However, part of the confusion is due to the fact that the effect of one pulse has not decayed completely when the next pulse arrives. Therefore it is desirable to add a small amount of external damping at the input of the network. This is done using a resistor and diode in series as in Figure 94. This type of damping, incidentally, is a mild form of the type which the valves cause in the engine, that is it damps primarily the negative waves. The effect on pulse transmission is shown in Figure 95, where it is clear that the effect of one pulse is finished when the next arrives. Still there is no semblance of good pulses returning.

The next stage of improvement results when the value of the first condenser is increased considerably. The best value was found experimentally. When the pulses are applied the result is as shown in Figure 96, and it is clear that discrete positive and negative pulses are beginning to appear. The damping is still used in this trace.

The next improvement results from the recognition of a characteristic which is common to all transmission networks or amplifiers which have a limited frequency range with a sharp cut-off. Such systems when excited with a pulse show an apparent resonance at the cut-off frequency which is responsible for so-called overshoot, which is a transient oscillation occuring on the tail of each pulse. Such is the nature of this artifical line, because it has a number of modes equal to the number of sections and then no transmission whatever. Such a characteristic follows also from its similarity to a low pass filter, which in fact it is, except that it is not terminated in its characteristic impedance. It has been found for all such systems that the best pulse transmission does not follow from the flattest frequency response, but rather that it is preferable to roll-off the high frequency response and avoid the sharp cut-off. The corresponding effect is obtained in the artificial line by the use of resistors to damp the components which result in overshoot.

The final form of the artificial line is shown in Figure 97A. The optimum values for the resistances shown in this diagram were obtained experimentally. The pulse transmission of this network is shown in Figure 98 which clearly demonstrates a quite adequate pulse reflection characteristic. Undoubtedly, even greater perfection could be achieved using a still larger number of sections in the line. However, the circuit will be used in this form until the need for further impovement becomes evident. One thing that has become clear from the pulse-response approach is that the importance of a great number of sections lies not in the perfect tuning of the higher frequency modes, but rather that a greater number of lower order modes are brought into proper tuning. The trace shown in Figure 98 results when the diode and resistor damping is applied at the input of the network. If this damping is removed so that the circuit is still ringing from one pulse when the next pulse arrives, the result is as shown in Figure 99.

One other characteristic as regards pulse transmission is also of interest. The pulses shown so far have resulted from an extremely short input signal. In the case of excitation for the pulse-jet analogue, the pulse will not be so short, since it is the characteristic of pulse-jet engines in their present state of development that burning continues over the entire expulsion wave. Therefore it was of interest to show the pulse transmission using a much broader input pulse. Such a pulse is produced using the circuit shown in Figure 100. The parallel inductance and condenser are excited by the sharp pulse through a resistance which also controls the damping. The resulting damped sine-wave train is shown in Figure 101. All but the first positive pulse of this damped sine-wave train is practically eliminated by shunting this network with a diode. The remaining broad positive pulse is shown in Figure 102. This broad positive pulse is then applied to the artificial line through the biased diode as in earlier tests. The form of the final pulse which is passed by the biased diode is then shown in Figure 103. The resulting performance of the artificial line is shown in Figure 104. For use in the pulse-jet analogue, it will be necessary to make the length of the exciting positive pulse of variable time-length to correspond with variable burning rates.

The performance of the final form of the ten-section artificial line should also be characterized by its steady-state behavior. For this purpose, the network is driven by a sine-wave oscillator through a large resistor so that the variation of voltage at the input of the network is indicative of the variation in the input impedances of the network. The results are shown in Table II which indicates the frequency of the various resonant modes, their relative amplitudes in decibels, and the frequency deviation for each mode. The frequency deviation is also plotted in Figure 105.

The fact that the final form of the artificial line which produces the most satisfactory performance in terms of pulse response bares only remote resemblance to the classical line, and does not conform with any theory which we have been able to produce may be of some concern. It must be born in mind, however, that there are two major objectives which this artificial line must meet: (1) that when excited by a transient positive pulse, successive, negative, and positive pulses shall be faithfully returned and (2) that it shall be possible to modify this line so as to simulate both the pulse behavior and the steady-state frequency deviation of the resonant modes of a particular form of tapered acoustical tube. Condition (1) is amply demonstrated. Initial experiments on condition (2) have been made which indicate clearly that this will indeed be possible.

3.4.1.4 Measurement of Resonant Modes of a Pulse-Jet Tube

Subsequent to the development of a satisfactory basic artificial line for pulse-jet tube acoustic simulation, it was necessary to determine the actual resonant frequencies for a typical pulse-jet tube so that the constants of the artificial line might be adjusted to match the characteristics of the actual engine.

The experimental procedure was to mount the chamber vertically on a rigid base and to excite the contents by means of an ANB-H1 earphone driven by an audio-oscillator at a constant input voltage. The response of the chamber was detected by means of a 640-AA condenser microphone feeding into a voltmeter. Both the microphone and driver unit were coupled to the chamber contents by means of probe tubes introduced into two opposite walls at the base of the chamber. Resonance was noted when peak voltages were registered on the voltmeter. The close-valve condition was duplicated with a solid base. Six 1" diameter holes were drilled into the base simulated opened-valve condition. The open area represented 25% of the total frontal area of the tube. A photograph of the experimental set-up is shown in Figure 106.

Let us first consider the case where the tube is completely closed at one end. It can be expected that the acoustical line, consisting of combustion chamber, transition section, and tailpipe would behave approximately like a quarter-wave tube. Such a tube is characterized by a constant area cross-section, one end of which is terminated in a rigid boundary and the other end is open to the atmosphere. The resonant frequencies of such a tube are governed by the length and the terminating impedances. Therefore, the quarter-wave tube has a series of modes, the fundamental of which is determined by its length, the harmonics being related in the ratio of odd integers. Our acoustic tube can be likened to the quarter-wave tube in that the terminating impedances are duplicated during closed valve conditions. However, departure of the geometry of the tube from a constant cross-sectional area can be expected to cause deviations from the harmonic relationship as predicted. The fundamental frequency for quarter wave oscillation in the tube was calculated to be 93 cps based on an acoustic velocity of

1120 feet per second. The fundamental as measured was 77 cps. This represents a deviation of 17% from the simple prediction. Applying an end correction of .8 times the radius, as given by Rayleigh, causes the fundamental to be reduced to 89 cps. Apparently, the deviation of the tube from a purely cylindrical shape is responsible for the difference which is noted. Figure 107 is a plot of the frequency deviation of the modes. These results are shown plotted in the form of a ratio $\frac{F_n/F_1}{2n-1}$ vs. n where F_n is the measured frequency for the nth mode, F_1 is the fundamental frequency and n is the mode number. In interpreting these results, it may be advanced that the large input capacitance as represented by the combustion chamber may serve to reduce the fundamental considerably, exerting little influence upon the fifth and higher modes. These results provide a guide in designing an electrical analogue for the pulse-jet tube. The artificial line will have to be modified to duplicate the modes as shown by the acoustical line.

The test with the six 1" diameter holes drilled in the base simulates the open-valve condition. For this case, the terminating impedance at the base is no longer infinite as was the case for the rigid base. With both ends open, the boundary conditions permit half-wave operation, with the higher modes consisting of integral values of the fundamental. Therefore, it can be expected that the fundamental should be twice that measured for the rigid based tube. The data as presented in Table III shows the fundamental to be 143 cps rather than twice 77 cps or 154 cps as indicated in the argument presented above. However, it must be remembered that the base is not completely open which no doubt alters the terminating impedance sufficiently to produce the deviation in the fundamental. Finally it can be seen that the higher modes are not integrally related to each other.

3.4.2 Work To Be Accomplished

The next major phase, to be undertaken in the immediate future, is the development of the electrical analogy components to simulate the mass inertia, stiffness, damping, bi-directional flow, mechanical displacement, velocity, actuating force, and gas velocity through the inlet valves.

4. CONCLUSIONS

The major accomplishements under Supplement No. 4 (Items la, lb, lc and lg) of Contract No. AF 33(600)-5860 during the initial six months of work were:

a) Whirl test evaluation of an "I" beam braced engine which weighed 30 percent less than previous engine configurations.

b) Extensive static and whirl test evaluations of many alternate engine shell configurations. This program has resulted in an engine weighing 32 percent less, and is able to withstand over 35 percent greater "g" loads than the previous engines. This configuration is believed to have a life expectancy of well over 50 hours.

c) An attempt (unsuccessful) was made to fabricate a sheet of high temperature alloy steel having a tapering thickness.

d) An elliptical engine was designed around existing engine components and all components except the engine shell have been fabricated.

e) A refined engine attach method and engine mount were developed in conjunction with the engine shell development tests.

f) An improved fuel injector-venturi section for the engine was developed which has alleviated gasketing problems and improved the accessability of the fuel injector components.

g) The results of a limited fuel injector development program have indicated that noteworthy improvements in fuel consumption may be expected with further, more extensive, development work.

h) Engine performance with inlet valves made from stainless steel was found to be inferior to that with the blue clock spring steel valves.

i) It was found that the ducted type of pulse-jet engine may have better performance and structural characteristics than the "plain" engines; and the detail design of a ducted engine assembly was completed

j) Static tests of several exhaust shroud configurations on dual engines has provided data to facilitate the design of such shrouds, for noise control purposes, which will not adversely affect engine performance.

k) Preliminary tests of opposed engine configurations have yielded significant results with respect to further reducing the sound level of the fundamental frequency. Favorable effects on the engine operating characteristics were also noted.

l) Attempts to reduce the sound level emitted from the forward end of the engine by means of 1/4 wave tuned inlet ducts were unsuccessful since it was found that such ducts caused the valved engines to cease to operate.

m) Capacitance type pressure pick-ups have been selected and procured for the measurement of transient pressures in the pulse-jet engines.

n) Several methods of determining inlet valve position are being investigated. A technique was developed whereby the valves themselves are used as an on-off switch to determine the instant at which the valves open and close. Temperature measurements have shown that valve operating temperatures are low enough (145°F) to permit the use of strain gages on the valves.

o) A dual beam cathode ray oscilloscope equipped with a "Polaroid-Land Camera" has been selected and procured for indicating and recording engine pressure valve position phase relationship.

p) Commercially available vibration equipment was found to be unsatisfactory for use in determining inlet valve natural frequency and damping characteristics.

q) The analogous operation of the pulse-jet engine and electrical circuitry (with simplifications) was established.

r) A relaxation oscillator to simulate combustion phenomena and to provide for repetitive operation of the analogy was developed.

s) An artificial electrical line which simulates the acoustic resonant characteristics of the engine tube was developed.

t) The actual resonant modes of an engine tube were determined to provide data for correlation with the artificial line of the electrical analogy.

5. REFERENCES

Reference 1: AHCo. Report No. 194-A, "Rotary Wing Tip-Mounted Pulse-Jet Engine Structural, Noise Reduction, Valve Phasing and Electrical Analogy Investigations", First Quarterly Progress Report.

Reference 2: AHCo. Report No. 194-B, "Rotary Wing Tip-Mounted Pulse-Jet Engine Structural, Noise Reduction, Valve Phasing and Electrical Analogy Investigations", Second Quarterly Progress Report.

Reference 3: AHCo. Report No. 195-A, "Development of Power Control System Components for Pulse-Jet-Powered Helicopter Rotors", First Quarterly Progress Report

Reference 4: AHCo. Report No. 172-B, "Development of High Performance Rotary Wing Tip-Mounted Pulse-Jet Engine Components", Second Quarterly Progress Report.

Reference 5: AHCO. Report No. 172-E, "Development of High Performance Rotary Wing Tip-Mounted Pulse-Jet Engine Components", Third Quarterly Progress Report.

Reference 6: AHCo Report No. 123-0-1, "Summary of Pulse-Jet Engine Development Under U. S. Air Forces Contract AF 33(038)-6099".

Reference 7: AHCo. Report No. S-194-c, "Specification-Engine, Rotary Wing Tip-Mounted Experimental Pulse-Jet, Preliminary Flight Rating Test For".

Reference 8: Marquardt Aircraft Co, Report No. PP-7, "Theoretical Studies Associated With Pulse-Jet Engine Development".

Reference 9: Project Squid Report, CAL-36, "An Evaluation of Potential Merits of Ducted Pulse-Jets".

Reference 10: AHCo. Report No. 163-K-2, "Acoustical Model Analysis of Pulse-Jet Engine Noise Reduction Configurations".

Reference 11: AHCo. Report No. 163-P, "Development of a Pulse-Jet Powered Helicopter Rotor", Progress Report for June, 1952.

Reference 12: Nav Ord Report No. 1047, "Survey and Evaluation of Sources of Information on Transient Measurements"

Reference 13: Paper presented before the Acoustical Society of America, "Resistive Terminated Probe Microphone", by Dr. R. W. Leonard, Presented in October 1951.

Reference 14: AHCo. Report No. 163-K-1, "Measurements and Analysis of the Physical Characteristics of Pulse-Jet Engine Noise.

Reference 15: Ingard and Lebate, "Journal of the Acoustical Society", March 1950.

TABLE I

SUMMARY OF COMPONENT WEIGHT OF VARIOUS CONICAL ENGINES

COMPONENT	AJ-6.75		AJ-7.50		AJ-9.40		AJ-1C.00	
	Weight (Lbs)	% of Tot. Wt.	Weight (Lbs)	% of Tot. Wt.	Weight (Lbs)	% of Tot. Wt.	Weight (Lbs)	% of Tot. Wt.
(1) Comb. Chamber	2.47*	12.08	3.36	13.23	4.53	13.90	4.88	11.35
(2) Aft Skin	3.50*	17.13	4.36	17.28	7.35	22.77	13.35	30.00
(3) Transition	2.42*	11.85	2.76	11.05	.94	2.89	5.73	13.30
(4) Tailpipe	3.32*	16.22	3.72	15.05	6.60	20.24	6.08	13.00
(5) Tailpipe Supt. Aft	.27*	1.34	.30	1.19	.42	1.28	.38	.88
(6) Tailpipe Supt. Fwd.	—	—	.69	2.74	—	—	—	—
(7) Air Baffle	.67*	3.28	.63	2.52	—	—	.58	1.35
(8) Mount Strap Assy.	2.67*	13.00	3.73	14.90	3.90	11.97	3.73	8.
(9) Air Scoops	.31*	1.53	.08	.32	—	—	.31	.72
(10) Valve Box Body	.89*	4.35	.80*	3.20	—	—	1.81*	4.20
(11) Valves	1.12*	5.48	1.50*	6.00	—	—	2.12*	4.43
(12) Bumpers & Keepers	.19*	.94	.23*	.92	—	—	.45*	1.05
(13) Fuel Air Ring	.63*	3.08	.64*	2.55	1.05	3.21	.81*	1.88
(14) Venturi	.31*	1.52	.31*	1.23	—	—	.56*	1.30
(15) Gaskets	.13*	.64	.12*	.48	.12*	.37	.28*	.65
(16) Cowl	.37*	1.82	.56*	2.14	1.00*	3.07	.87*	2.02
(17) Fwd. Flange Assy.	1.17*	5.74	1.30*	5.20	2.77	8.50	2.45	5.65
(18) Valve Box Assembly (Grid Bar Type)	- - -	—	—	—	3.91*	11.80		—
TOTALS	20.44	100%	25.09	100%	32.59	100%	43.01	100%

* DEONOTES ACTUAL WT.

TABLE II

STEADY STATE CHARACTERISTICS OF THE FINAL LINE

Mode	Frequency	Amplitude	$\frac{F_n/F_1}{(2n-1)}$
1	1030	91.5	1.00
2	3100	85.3	1.00
3	5200	78.2	1.00
4	7250	73.0	1.00
5	9050	69.7	.976
6	10400	68.5	.918
7	11700	68.3	.873
8	12900	67.6	.834
9	13800	66.6	.788
10	14250	66.2	.729

TABLE III

RESONANT FREQUENCIES FOR PULSE JET TUBE

CLOSED AT THE VALVE END			OPEN AT THE VALVE END	
Mode	Frequency	$\frac{F_n/F_1}{(2n-1)}$	Mode	Frequency
1	77	1.00	1	143
2	275	1.19	2	289
3	500	1.30	3	415
4	685	1.27	4	505
5	860	1.25	5	655
6	1030	1.22	6	680
7	1220	1.22	7	800
8	1280	1.11	8	860
9	1330	1.02	9	940
10	1500	1.03	10	1250

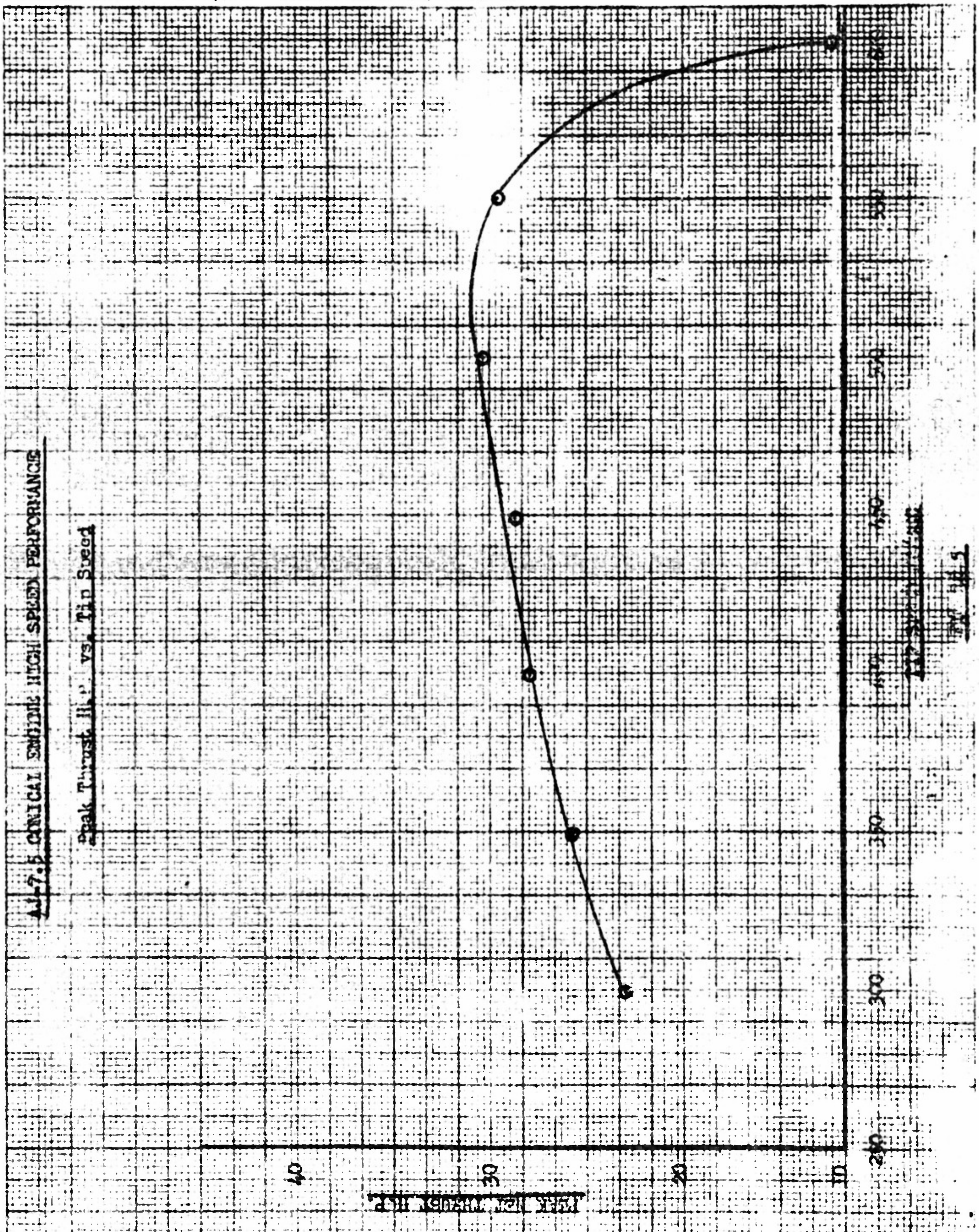

AJ-7.5 CONICAL ENGINE HIGH SPEED PERFORMANCE
Peak Thrust H.P. vs. Tip Speed
PEAK NET THRUST H.P.
10
20
30
40
250
300
350
400
450
500
550
600
TIP SPEED - FT/SEC
FIG 18.5

FIGURE 6
"I" BEAM BRACED ENGINE

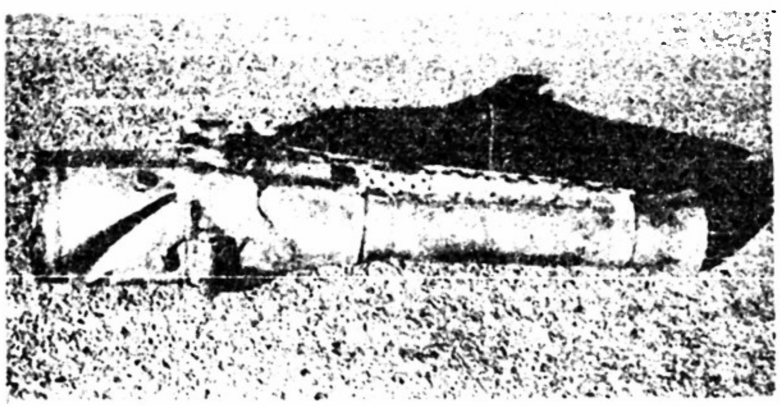


FIGURE 7
"I" BEAM BRACED ENGINE AFTER TESTING

MODIFIED CONICAL ENGINE STATIC TEST CONFIGURATION

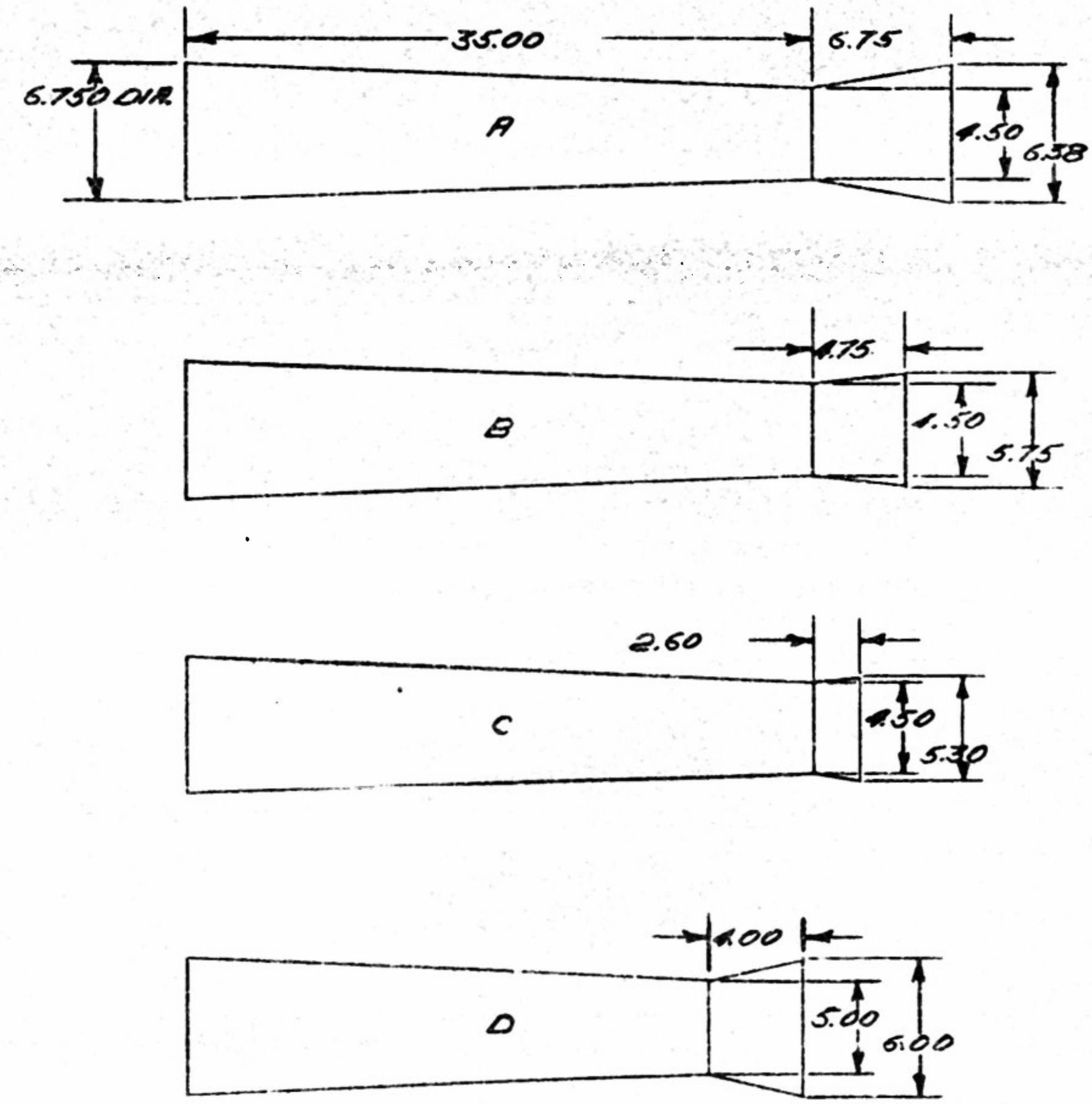


Figure 8

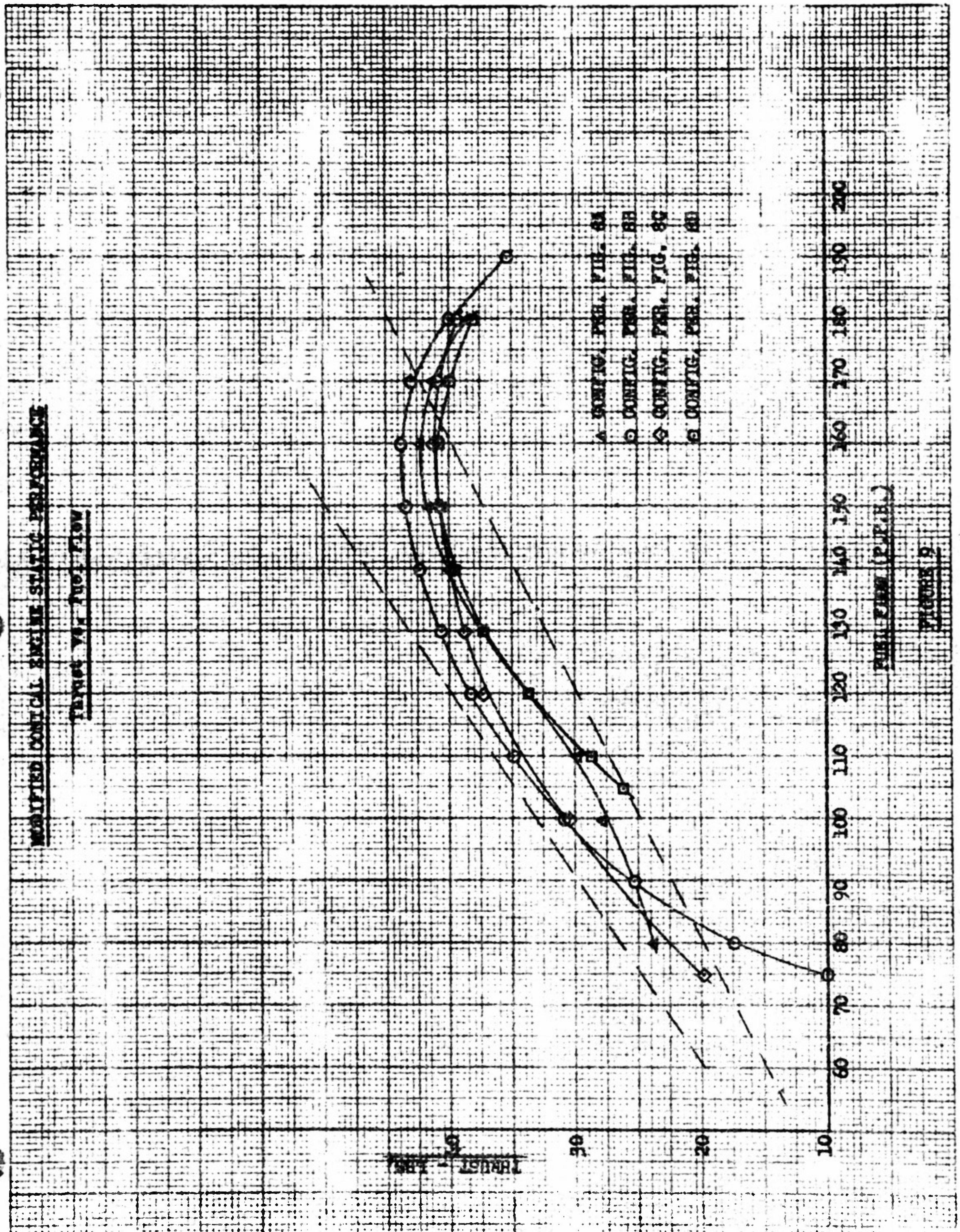

MODIFIED CONICAL ENGINE STATIC PERFORMANCE
Thrust Vs. Fuel Flow
△ CONFIG. PER. FIG. 8A
⊙ CONFIG. PER. FIG. 8B
◇ CONFIG. PER. FIG. 8C
⊡ CONFIG. PER. FIG. 8D
THRUST - LBS.
10
20
30
40
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
FUEL FLOW (P.P.H.)

FIGURE 9

MODIFIED CONICAL ENGINE WHIRL TEST CONFIGURATION

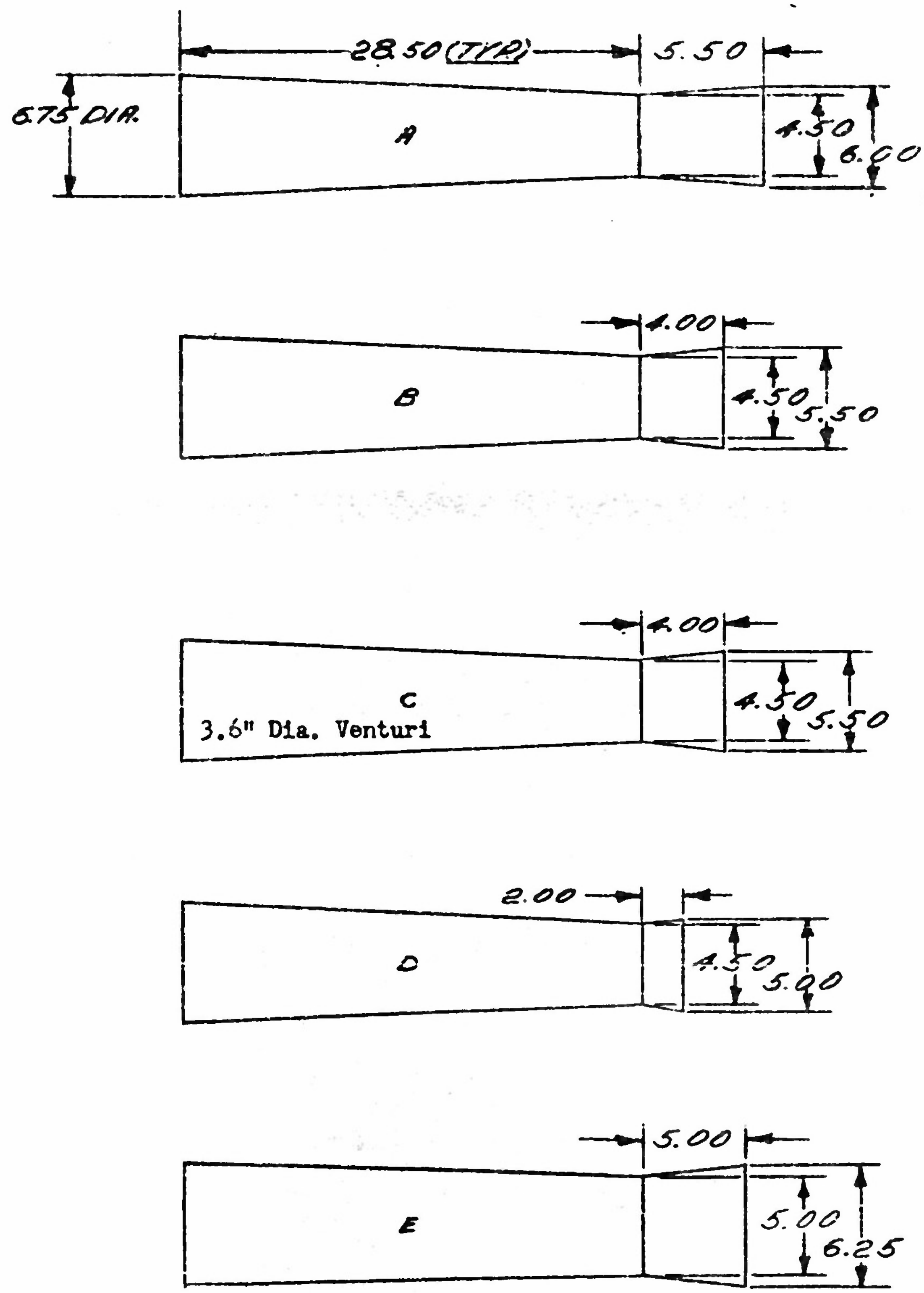


FIGURE 10

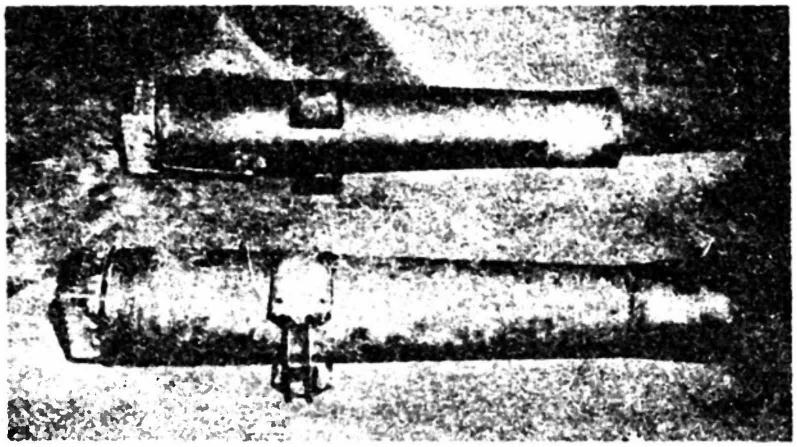


FIGURE 11

TYPICAL MODIFIED CONICAL ENGINES

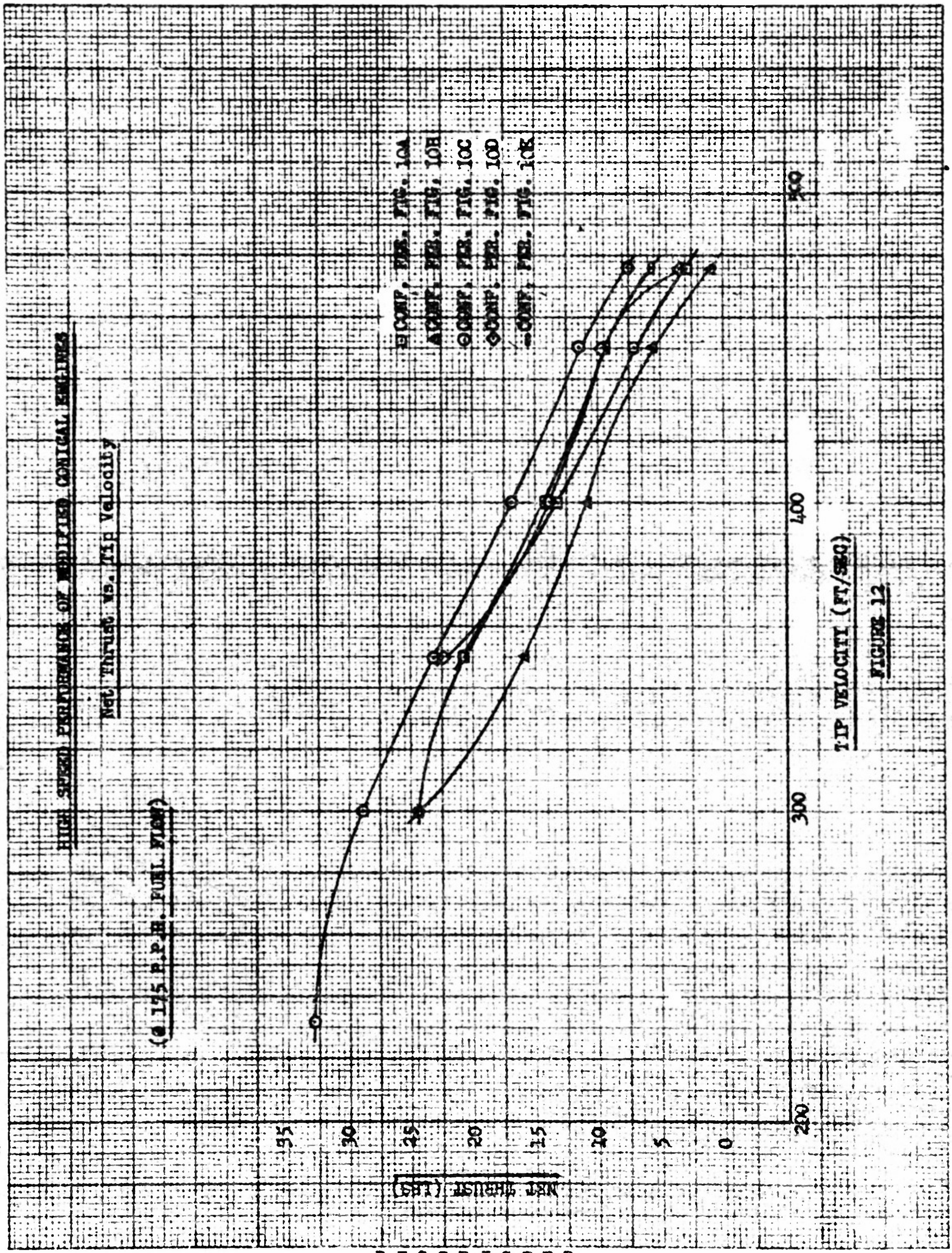

HIGH SPEED PERFORMANCE OF MODIFIED CONICAL ENGINES
Net Thrust vs. Tip Velocity
(@ 125 P.P.H. FUEL FLOW)
COMP. PER. FIG. 10A
COMP. PER. FIG. 10B
COMP. PER. FIG. 10C
COMP. PER. FIG. 10D
COMP. PER. FIG. 10E
NET THRUST (LBS)
35
30
25
20
15
10
5
0
200
300
400
500
TIP VELOCITY (FT/SEC)

FIGURE 12

CONFIGURATIONS TESTED IN TRANSITION INVESTIGATIONS

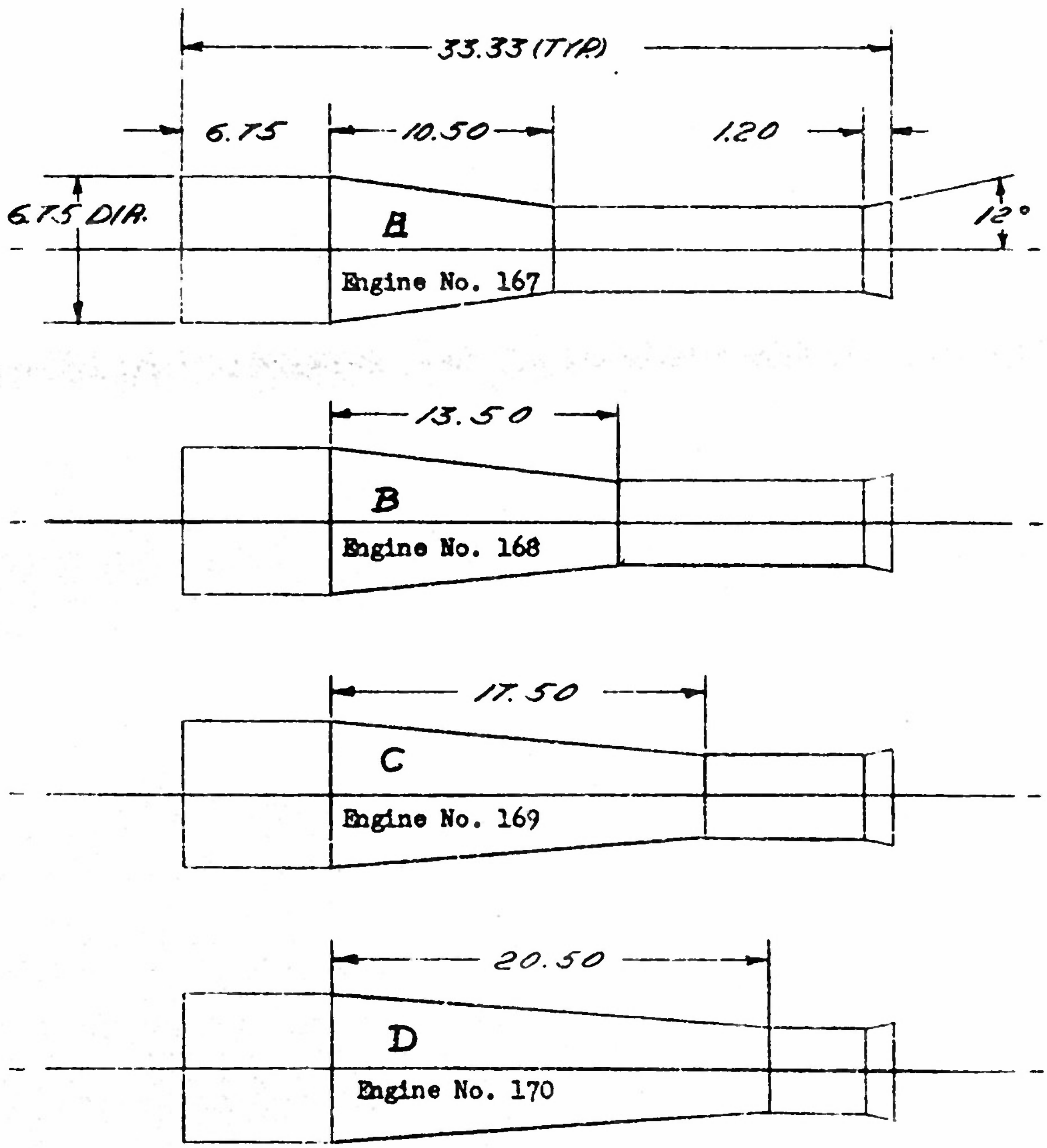


Figure 13

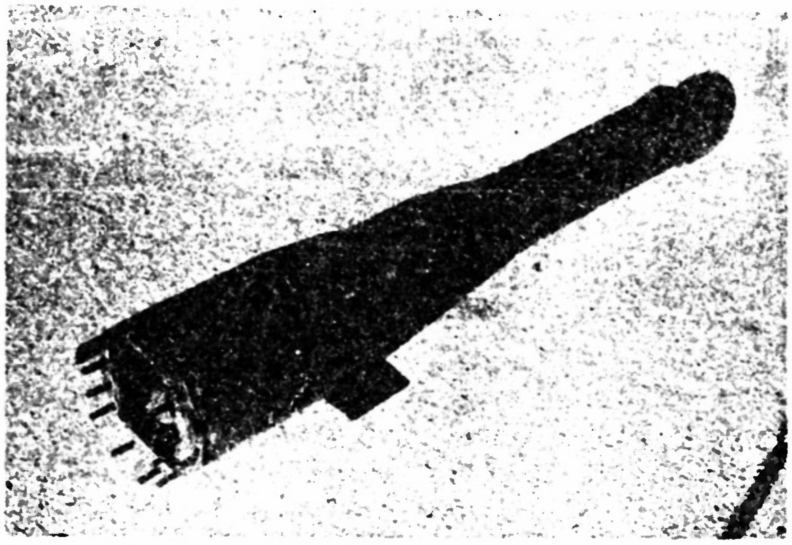


FIGURE 1A

TYPICAL ENGINE TESTED IN TRANSITION INVESTIGATION

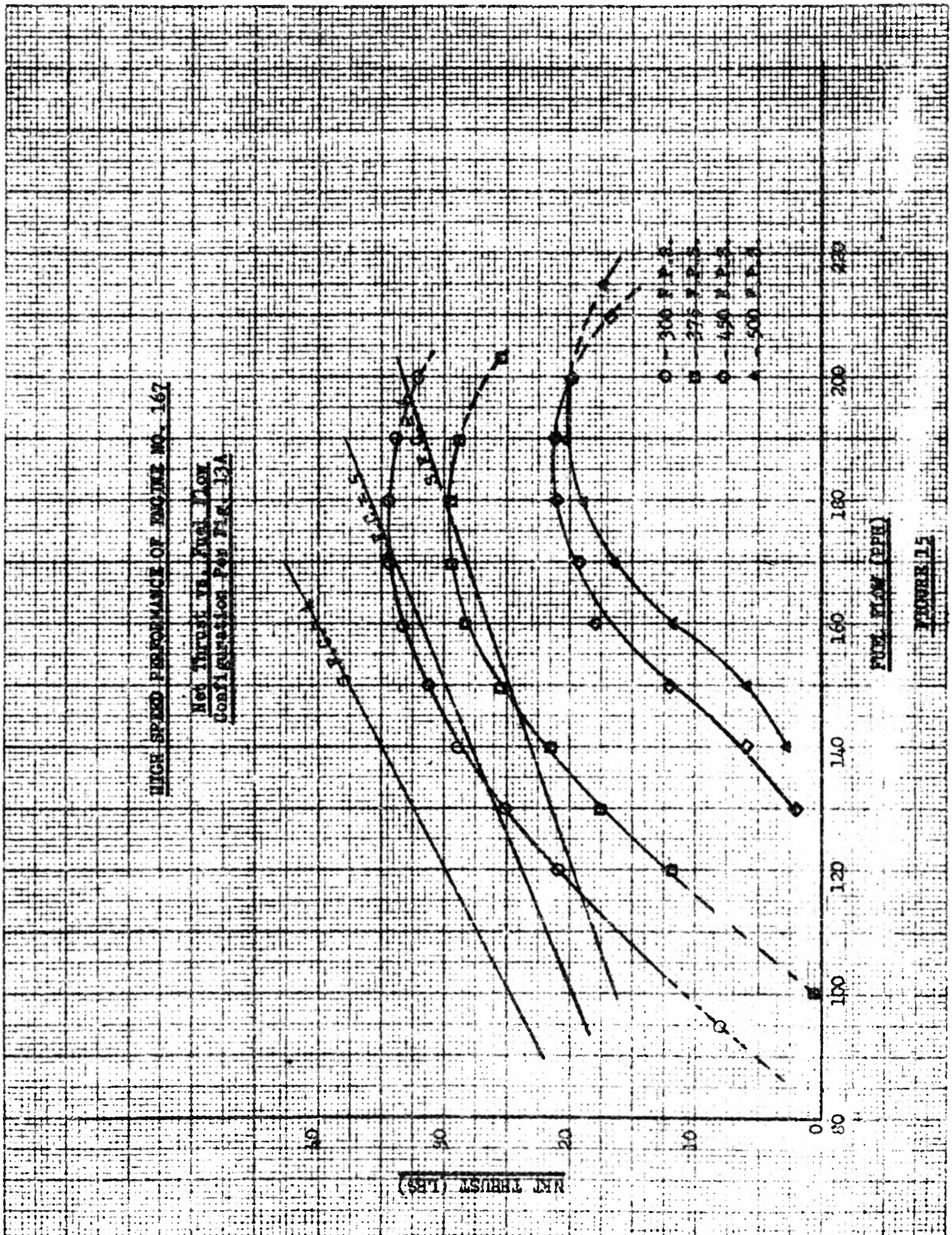
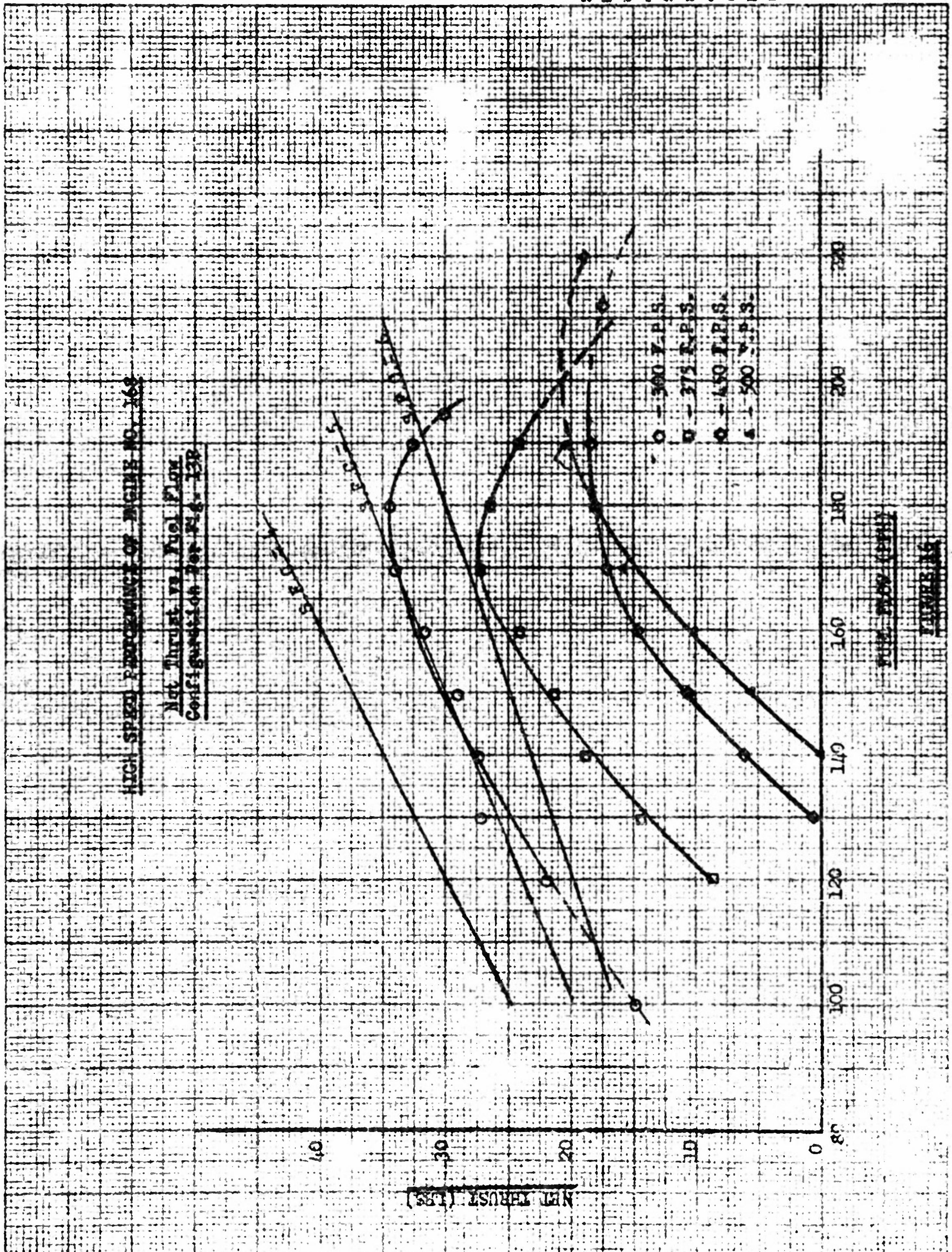

HIGH SPEED PERFORMANCE OF ENGINE NO. 167
Net Thrust vs. Fuel Flow
Configuration Per Fig. 13A
○ – 300 F.P.S.
□ – 375 F.P.S.
◇ – 450 F.P.S.
△ – 500 F.P.S.
NET THRUST (LBS.)
0
10
20
30
40
FUEL FLOW (PPH)
80
100
120
140
160
180
200
220

FIGURE 15


HIGH SPEED PERFORMANCE OF ENGINE NO.
Net Thrust vs. Fuel Flow
Configuration Per Fig. 13B
○ - 300 F.P.S.
□ - 375 F.P.S.
◇ - 450 F.P.S.
△ - 500 F.P.S.
NET THRUST (LBS)
0
10
20
30
40
80
100
120
140
160
180
200
220
FUEL FLOW (PPH)
FIGURE 15

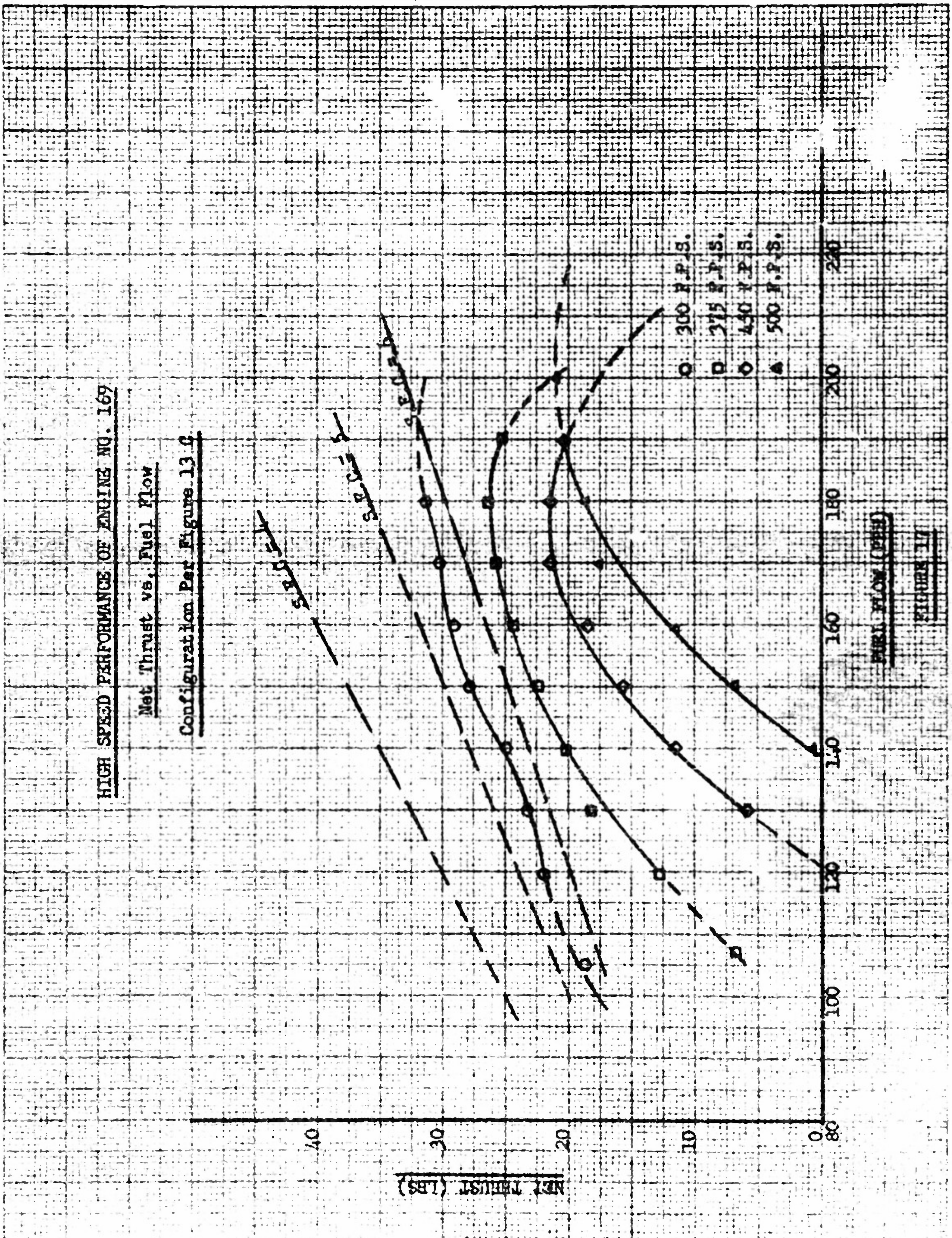
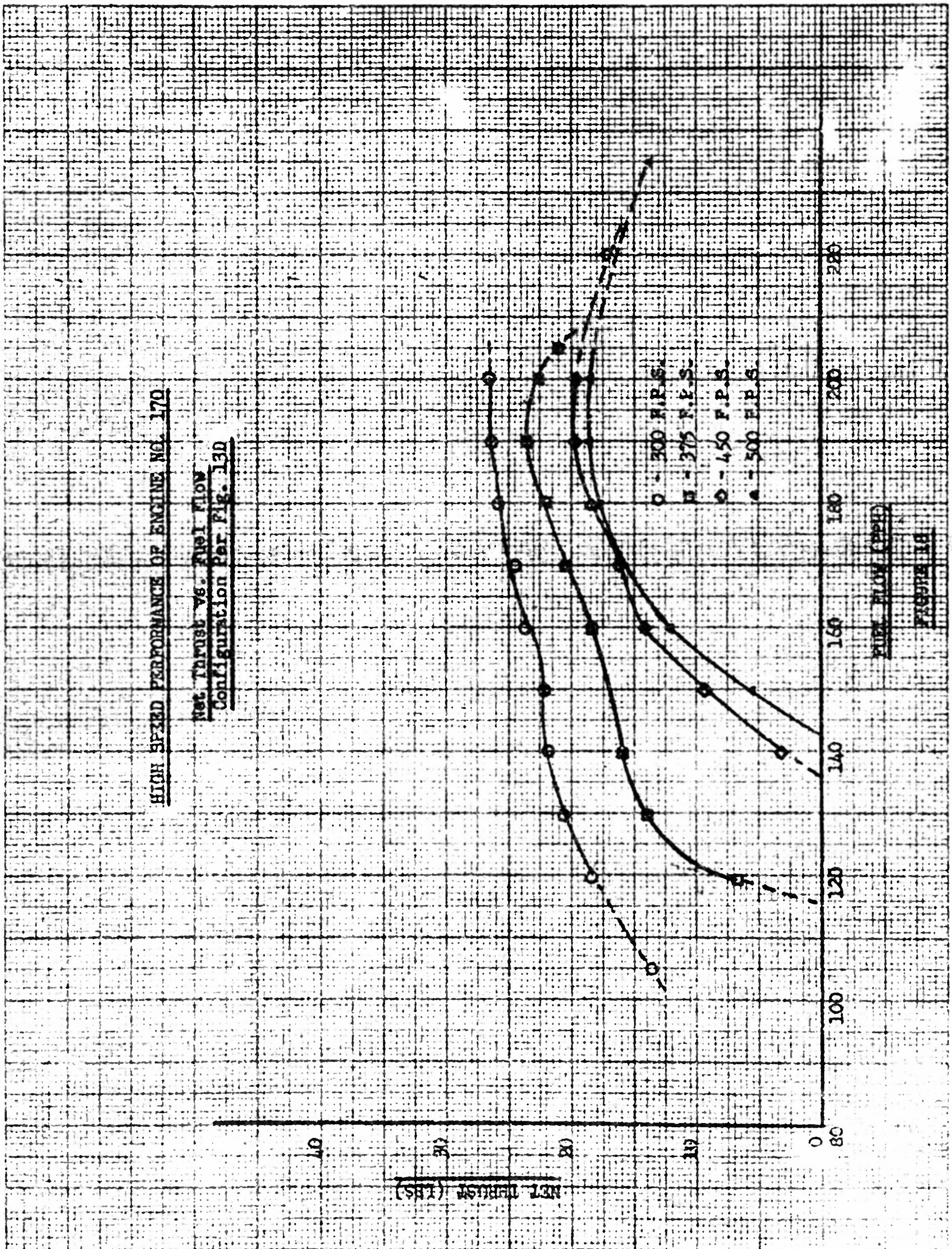

HIGH SPEED PERFORMANCE OF ENGINE NO. 169
Net Thrust vs. Fuel Flow
Configuration Per Figure 13 C
S.F.C.=4
S.F.C.=5
S.F.C.=6
○ 300 R.P.S.
□ 375 R.P.S.
◇ 450 R.P.S.
△ 500 R.P.S.
NET THRUST (LBS)
0
10
20
30
40
80
100
120
140
160
180
200
220
FUEL FLOW (PPH)

FIGURE 17


HIGH SPEED PERFORMANCE OF ENGINE NO. 170
Net Thrust Vs. Fuel Flow
Configuration Per Fig. 13D
○ - 300 F.P.S.
□ - 375 F.P.S.
◇ - 450 F.P.S.
● - 500 F.P.S.
NET THRUST (LBS)
0
10
20
30
40
80
100
120
140
160
180
200
220
FUEL FLOW (PPH)
FIGURE 18

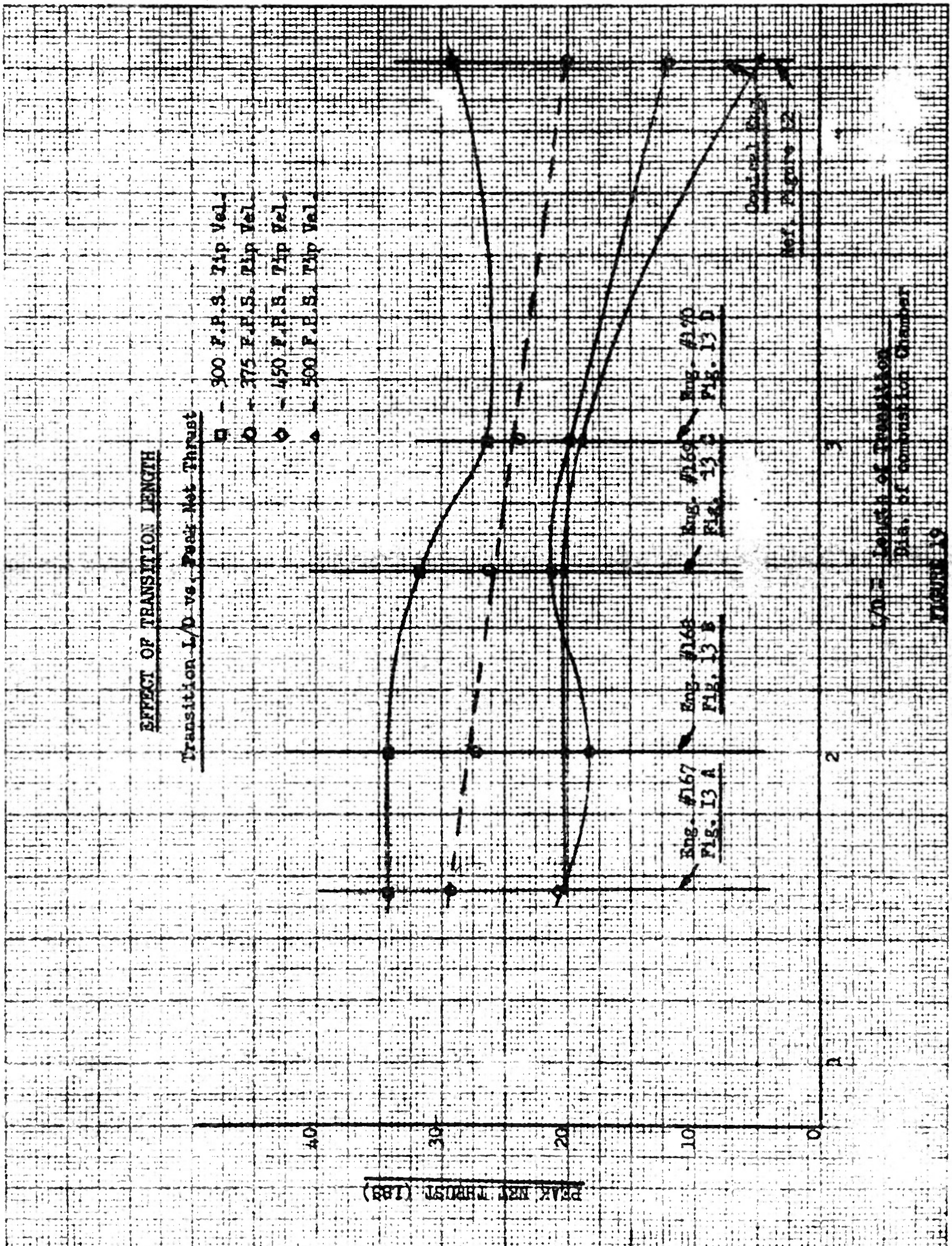

EFFECT OF TRANSITION LENGTH
Transition L/D vs. Peak Net Thrust
□ - 300 F.P.S. Tip Vel
○ - 375 F.P.S. Tip Vel
◇ - 450 F.P.S. Tip Vel
△ - 500 F.P.S. Tip Vel
Eng. #167 Fig. 13 A
Eng. #168 Fig. 13 B
Eng. #169 Fig. 13 C
Eng. #170 Fig. 13 D
Control Eng.
Ref. Figure 12
L/D = Length of Transition / Dia. of Combustion Chamber
PEAK NET THRUST (LBS)
0
10
20
30
40
1
2
3

FIGURE 19

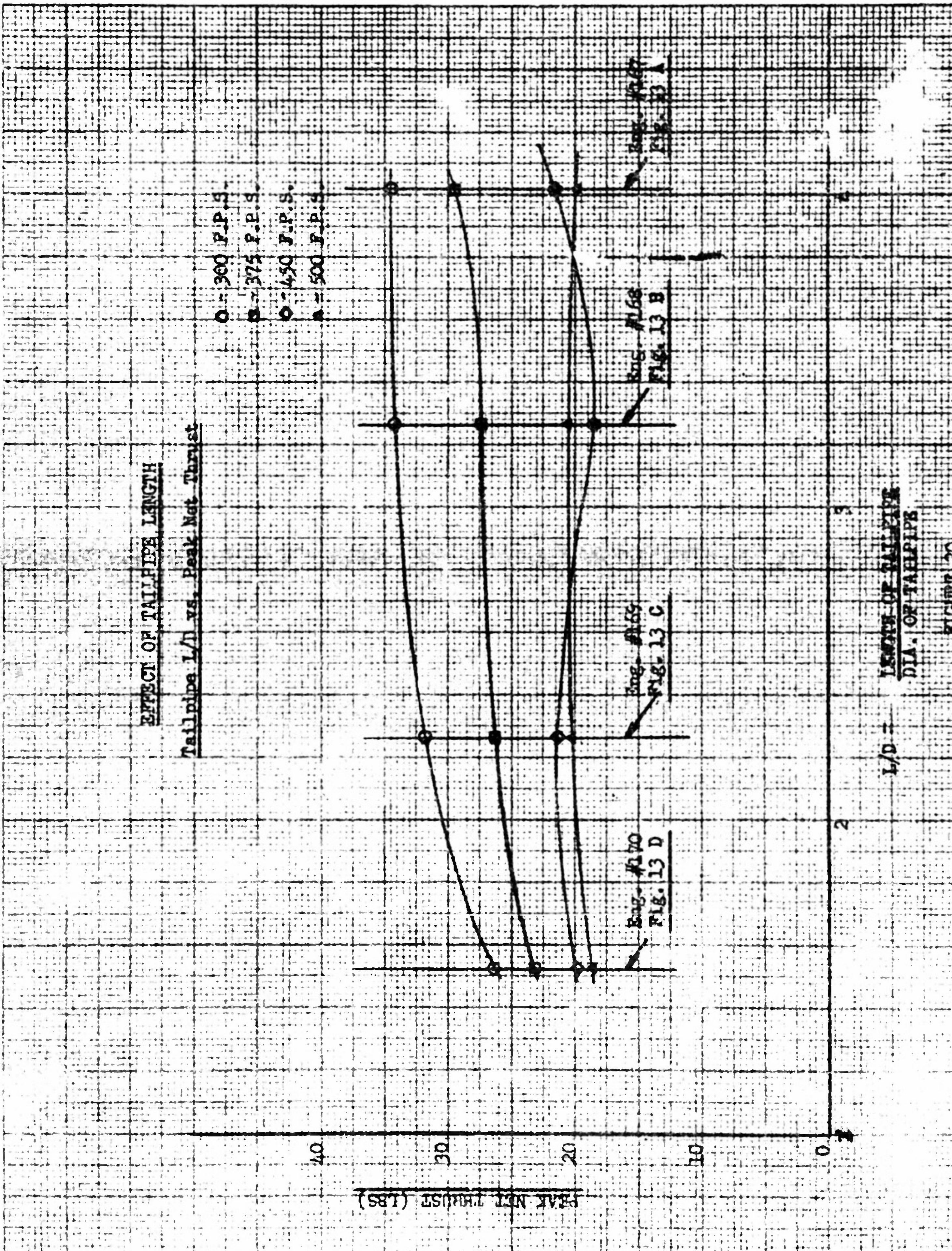

EFFECT OF TAILPIPE LENGTH
Tailpipe L/D vs. Peak Net Thrust
○ - 300 F.P.S.
■ - 375 F.P.S.
◆ - 450 F.P.S.
▲ - 500 F.P.S.
Eng. #167
Fig. 13 A
Eng. #168
Fig. 13 B
Eng. #169
Fig. 13 C
Eng. #170
Fig. 13 D
PEAK NET THRUST (LBS)
0
10
20
30
40
2
3
4
L/D = LENGTH OF TAILPIPE / DIA. OF TAILPIPE

FIGURE 20

EXHAUST AUGMENTER CONFIGURATIONS

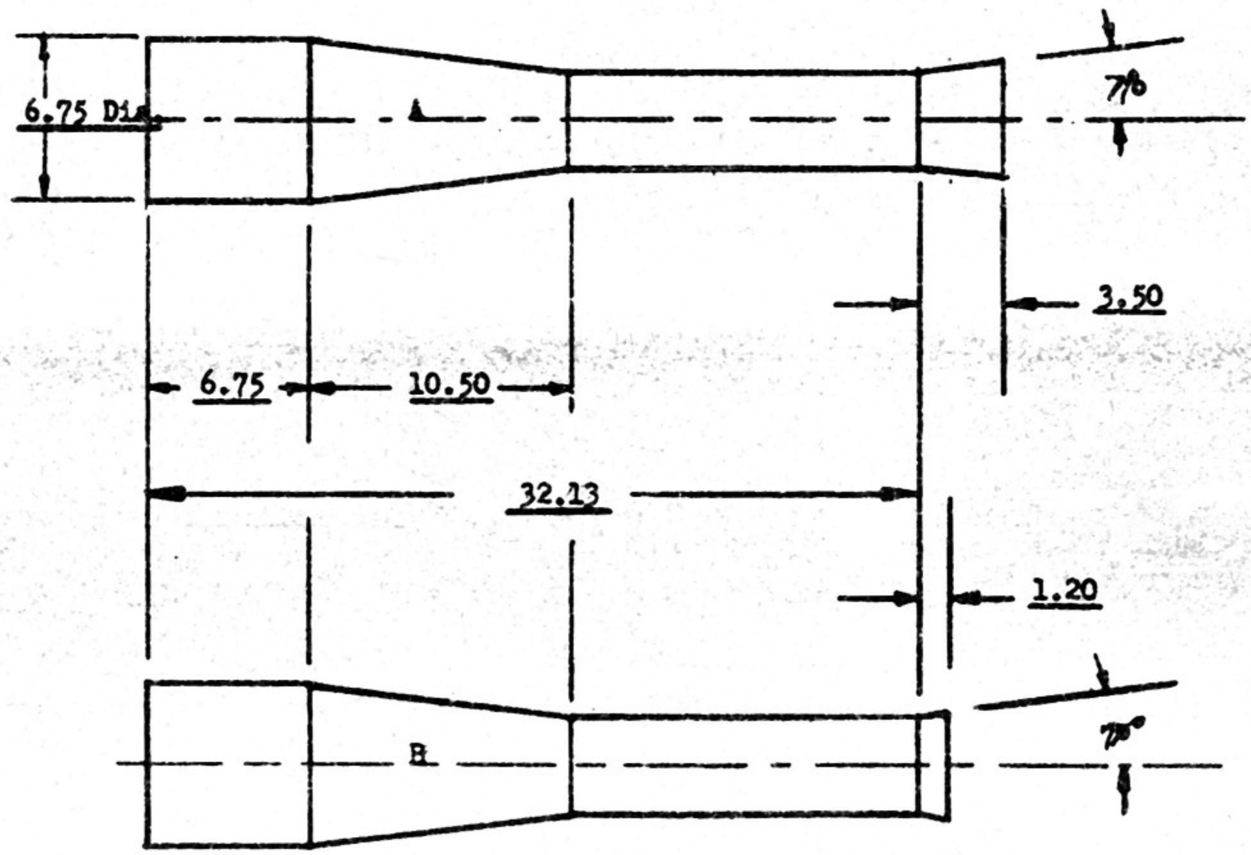


FIGURE 21

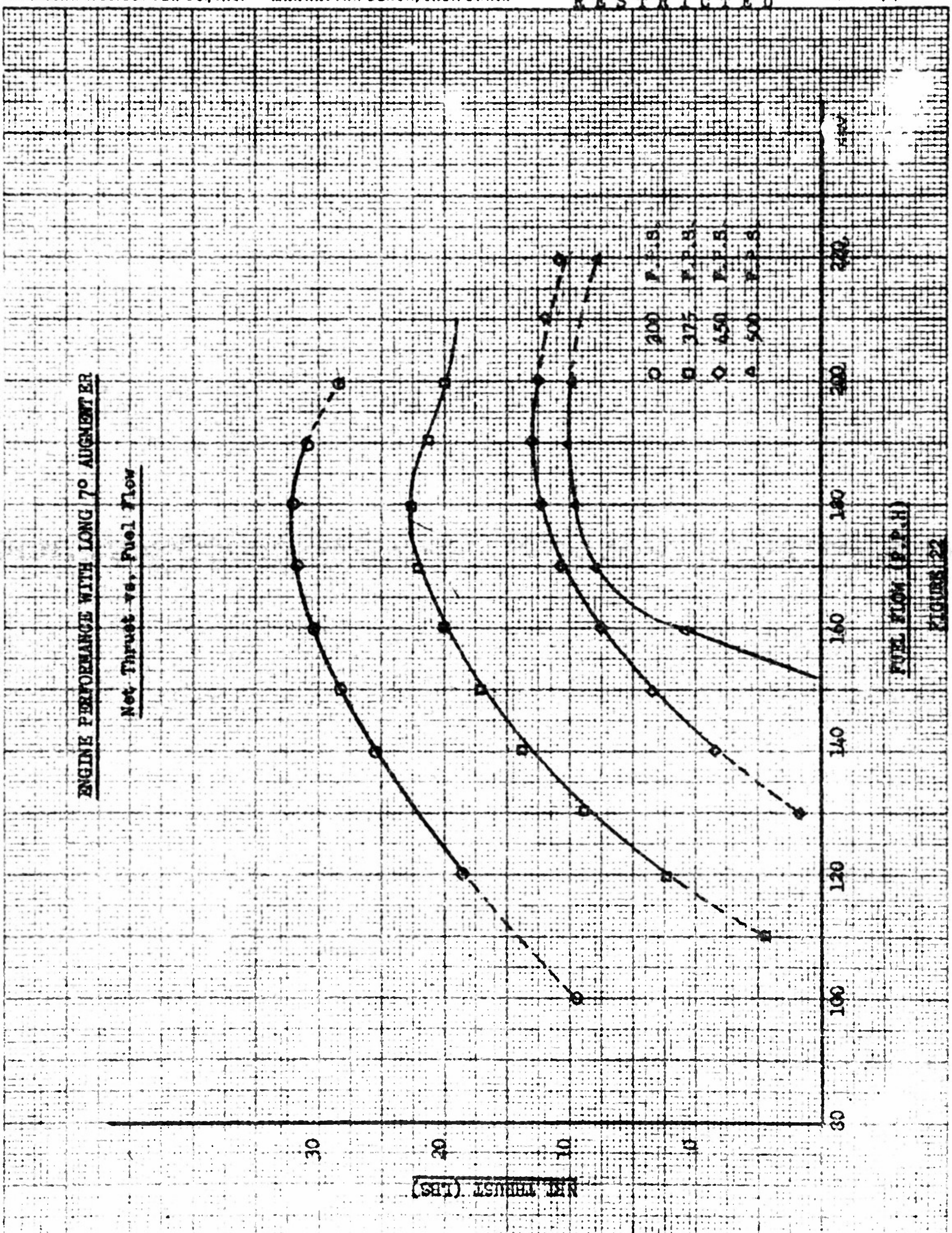

ENGINE PERFORMANCE WITH LONG 7° AUGMENTER
Net Thrust vs. Fuel Flow
○ 300 F.P.S.
□ 375 F.P.S.
◇ 450 F.P.S.
△ 500 F.P.S.
100
120
140
160
180
200
220
FUEL FLOW (P.P.H.)
30
20
10
0
NET THRUST (LBS)

FIGURE 22

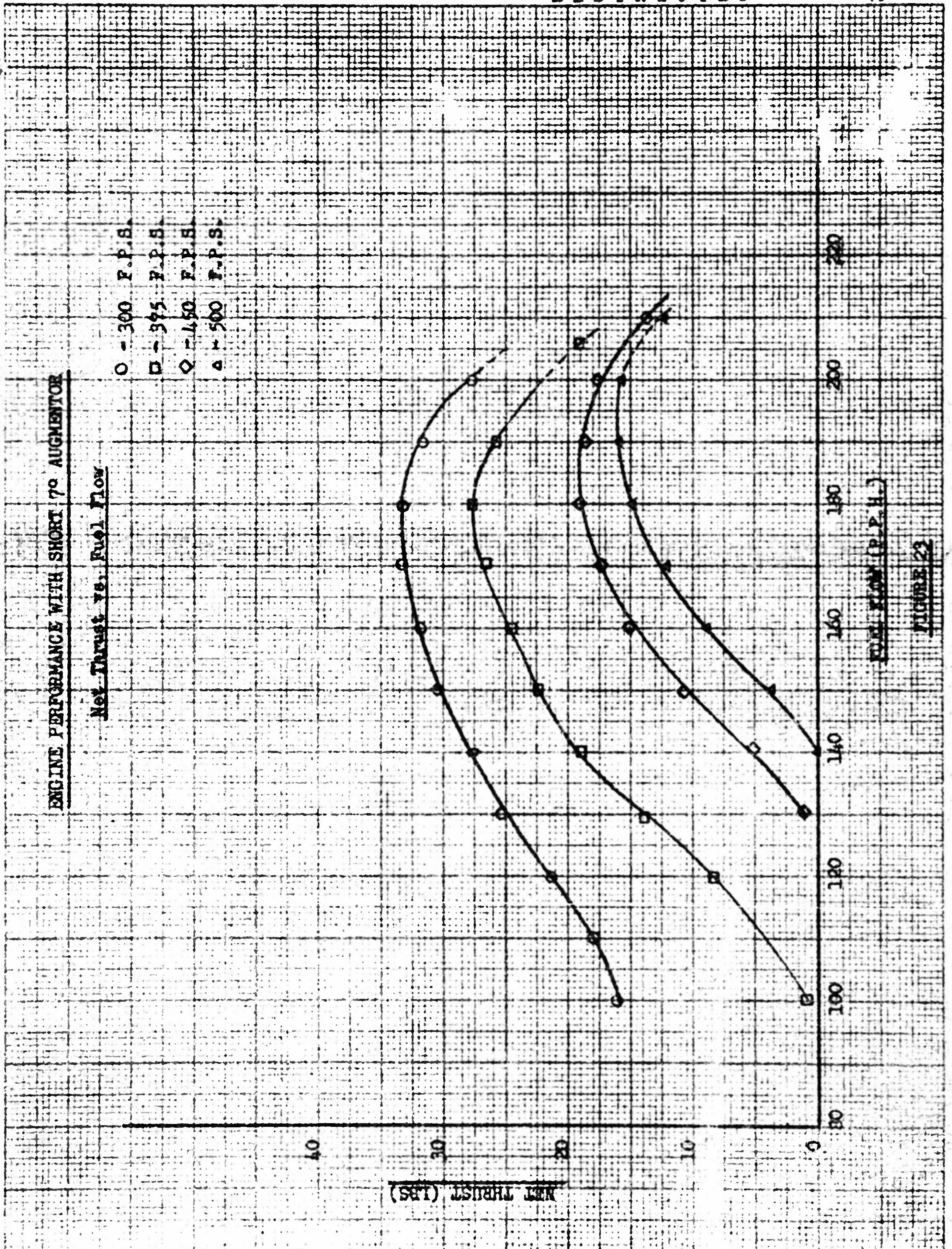

ENGINE PERFORMANCE WITH SHORT 7° AUGMENTOR
Net Thrust vs. Fuel Flow
O - 300 F.P.S.
□ - 395 F.P.S.
◇ - 450 F.P.S.
△ - 500 F.P.S.
NET THRUST (LBS)
0
10
20
30
40
80
100
120
140
160
180
200
220
FUEL FLOW (P.P.H.)

FIGURE 23

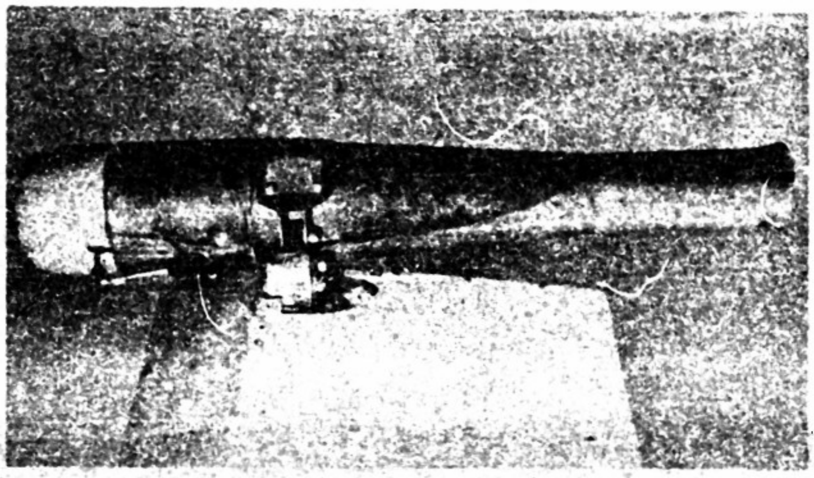
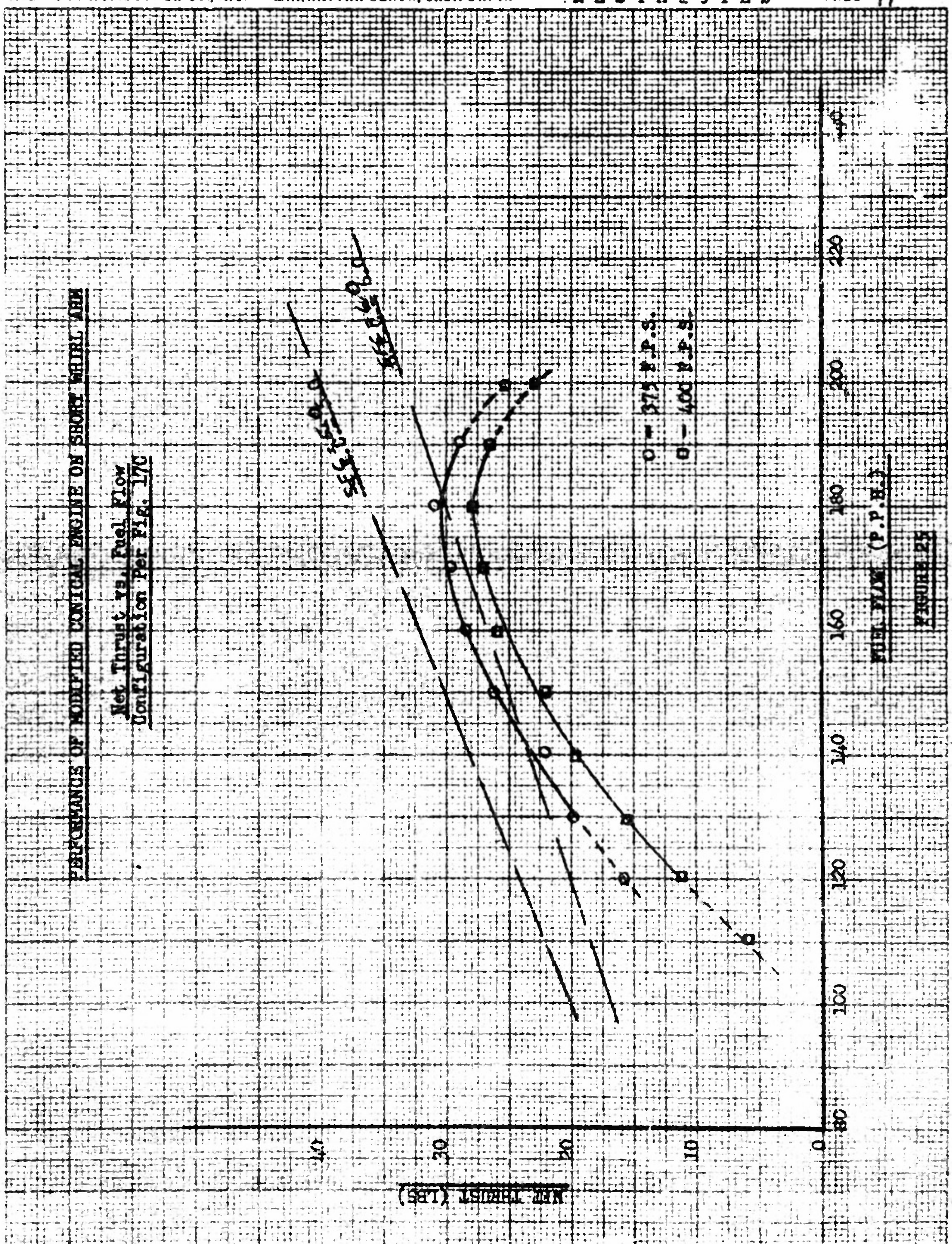


FIGURE 24

6.75" DIA. ENGINE MOUNTED ON TEST STAND


PERFORMANCE OF MODIFIED CONICAL ENGINE ON SHORT WHIRL ARM
Net Thrust vs. Fuel Flow
Configuration Per Fig. 17C
○ — 375 F.P.S.
□ — 400 F.P.S.
NET THRUST (LBS)
0
10
20
30
40
FUEL FLOW (P.P.H.)
80
100
120
140
160
180
200
220
240
FIGURE 25

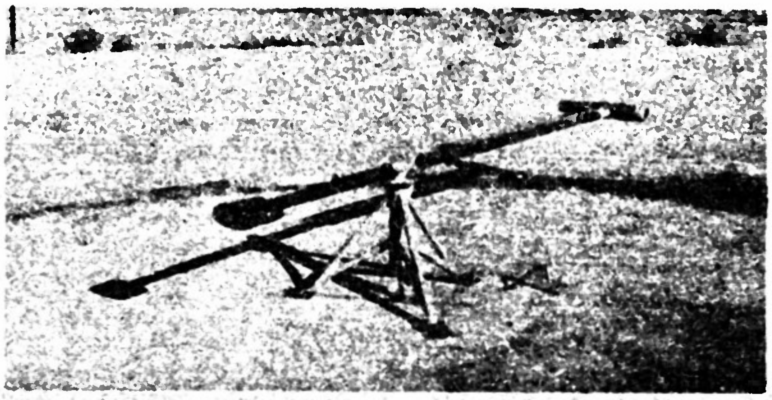


FIGURE 26
13.5 FT. RADIUS WHIRL ARM WITH IMPROVED FAIRING

7.5" MODIFIED CONICAL ENGINE SHELL CONFIGURATION

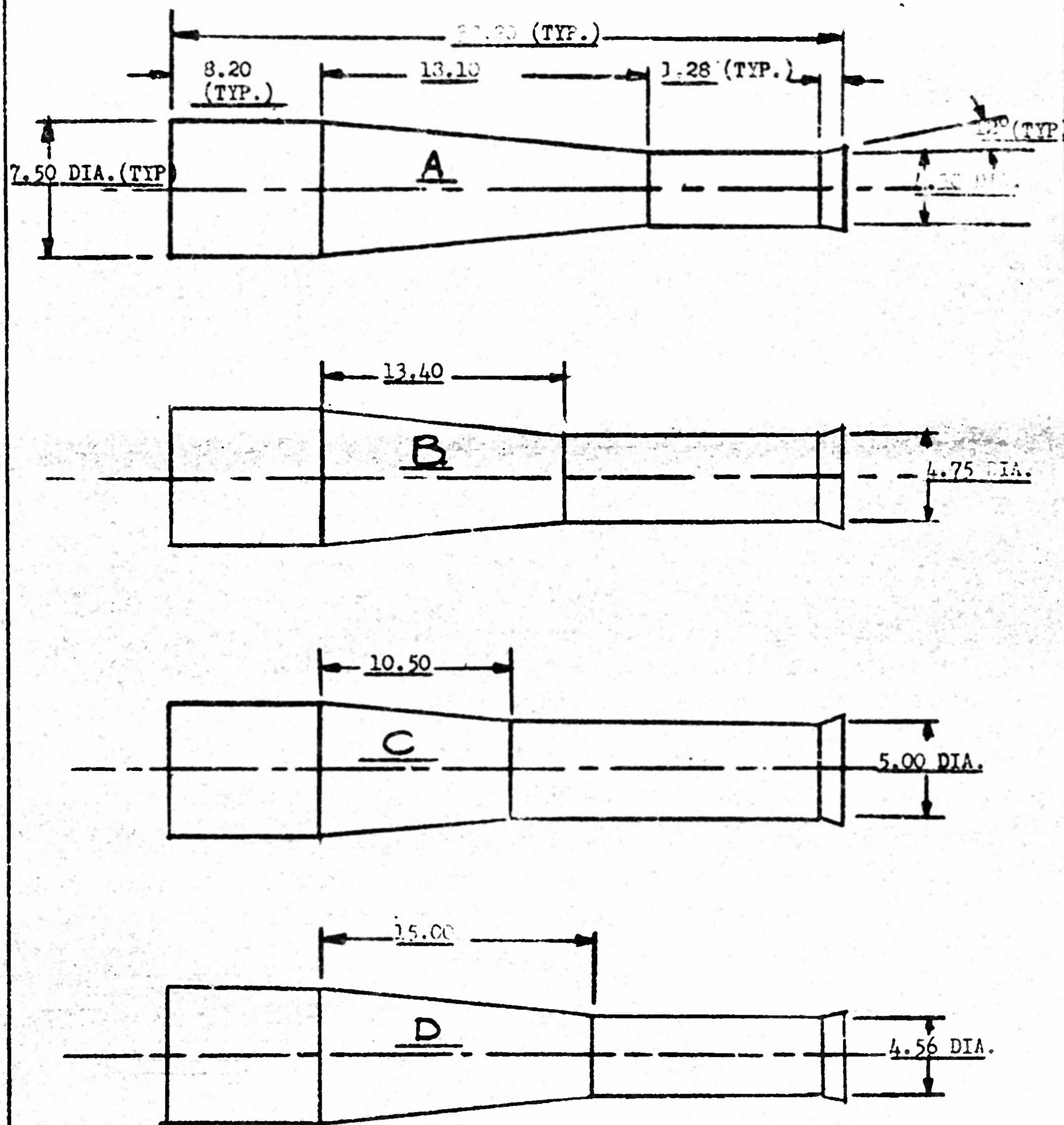


FIGURE 27

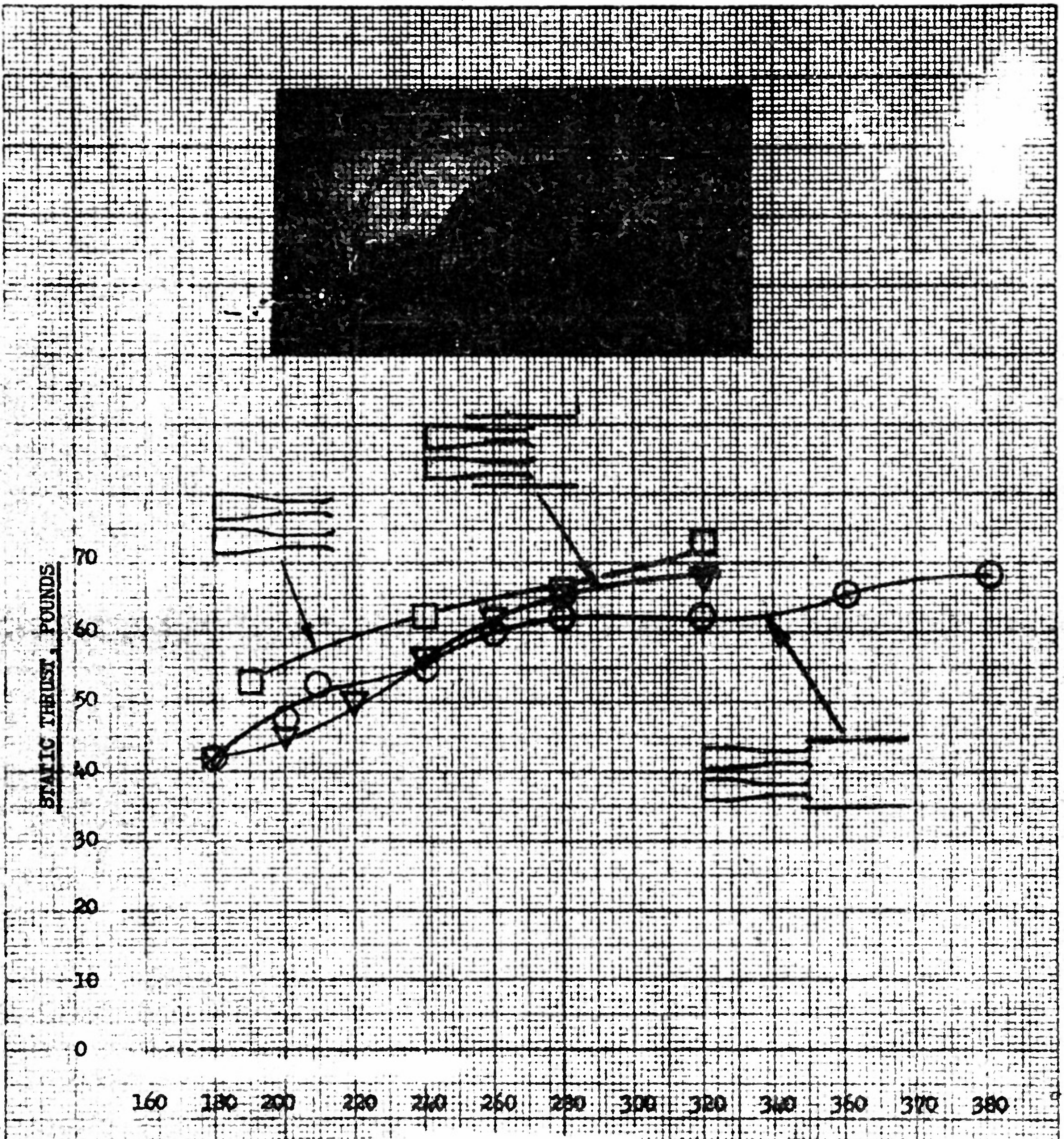


FIGURE [illegible]

TESTS TO DETERMINE EFFECT OF OPEN EXHAUST SHROUD ON DUAL ENGINE PERFORMANCE

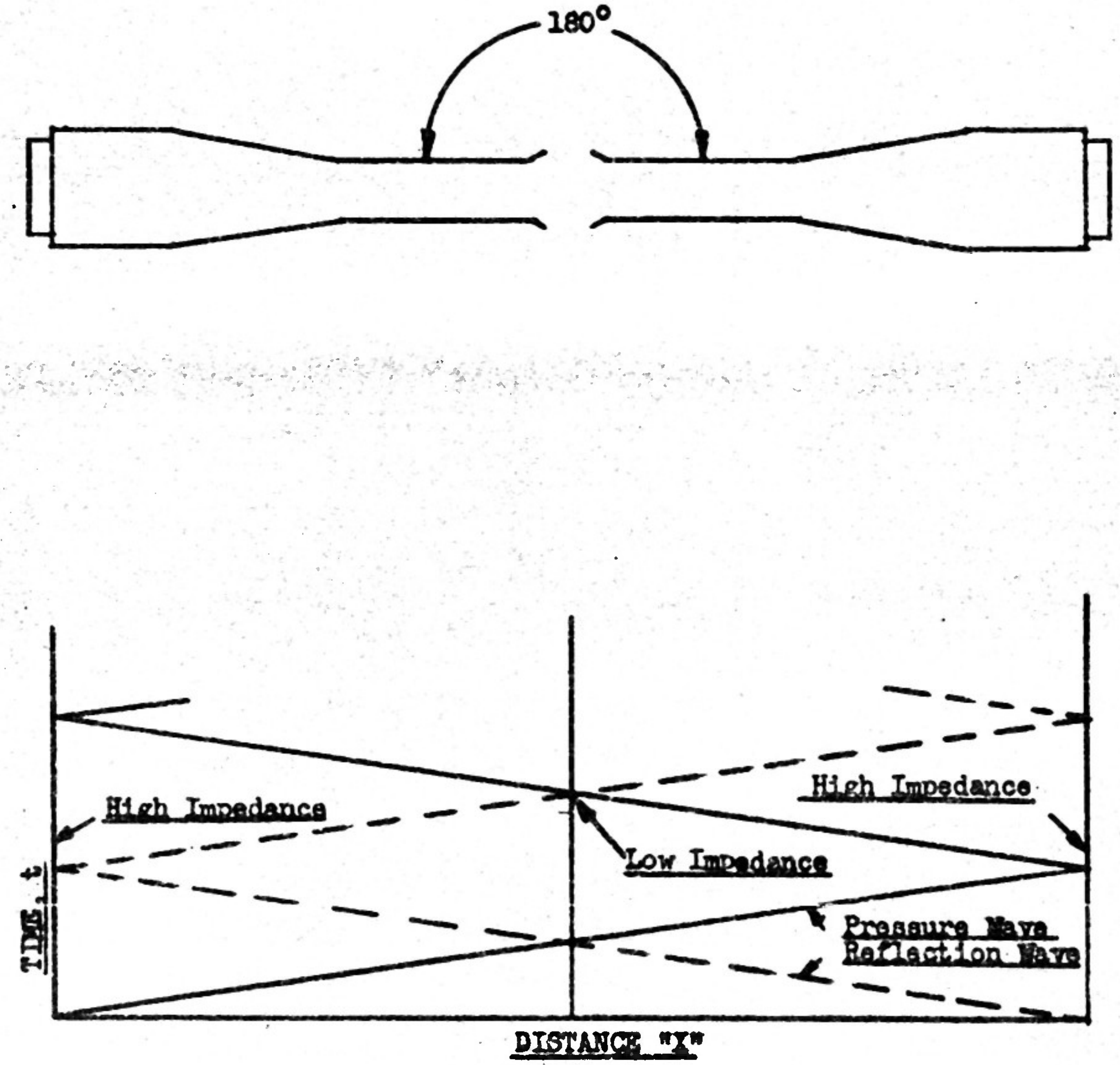


Figure 65

TAILPIPE TO TAILPIPE CONFIGURATION WITH CYCLE HISTORY DIAGRAM

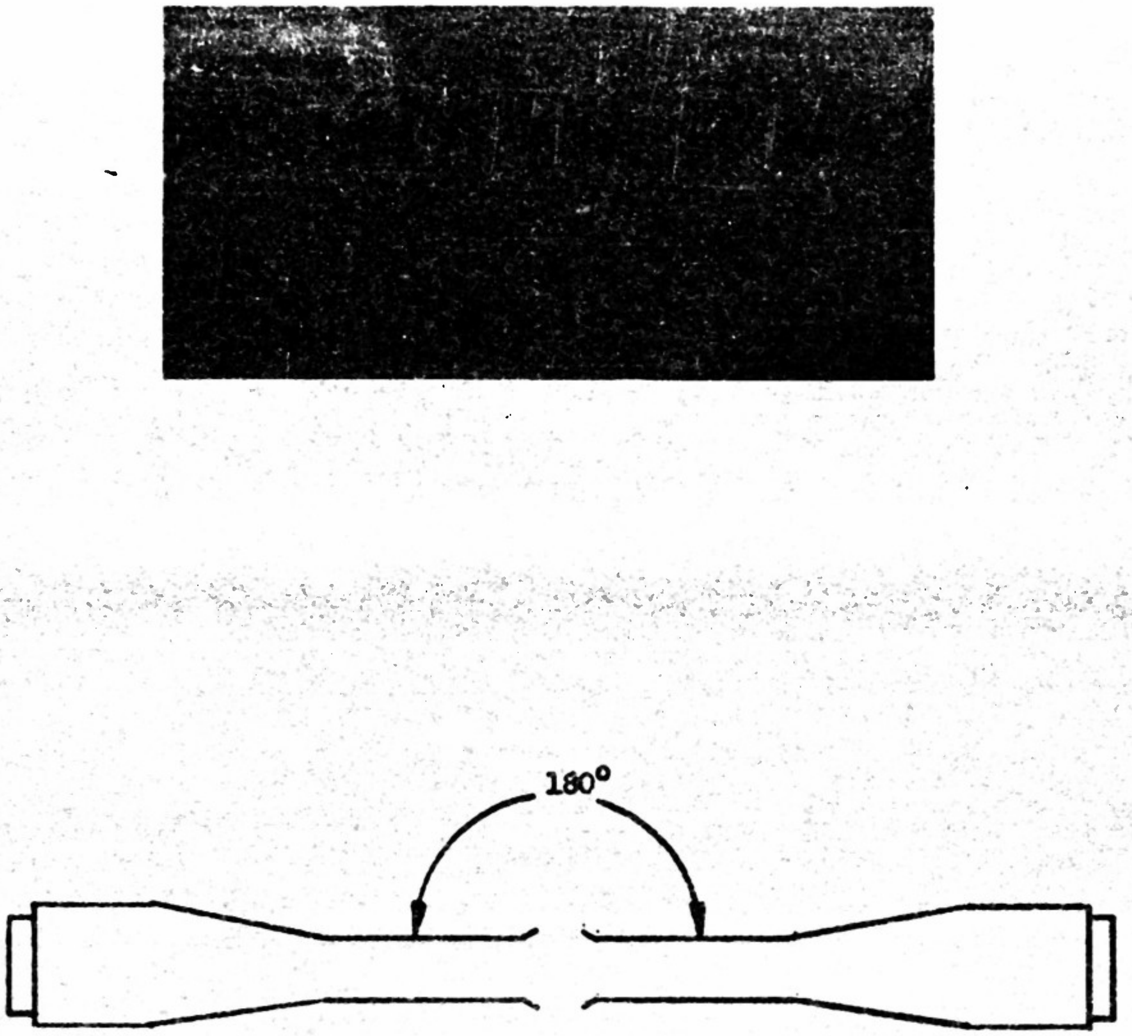
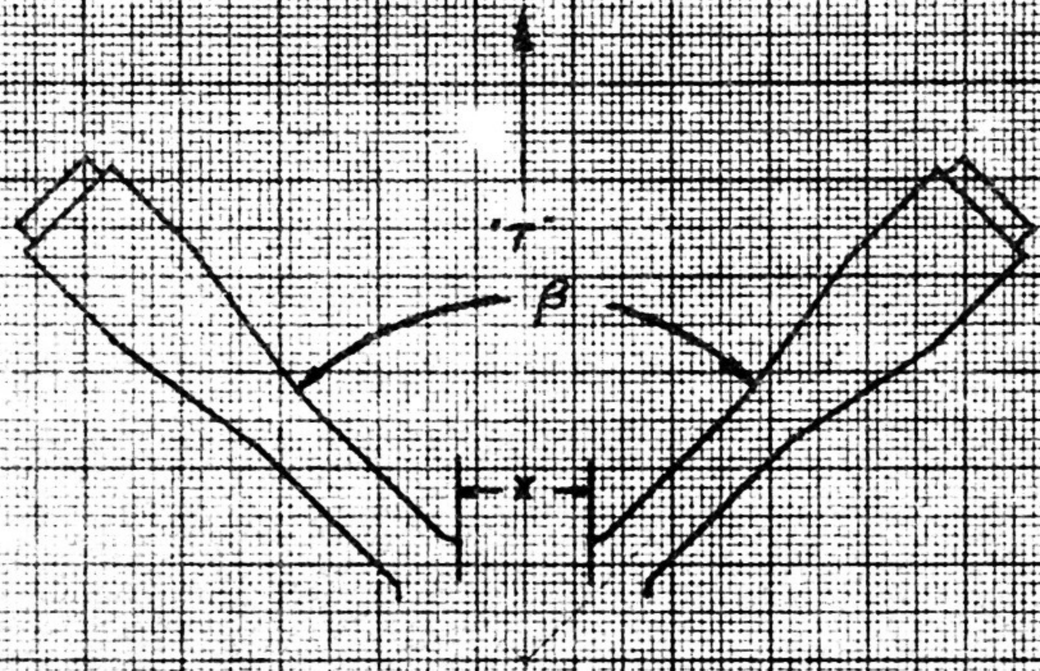


Figure 66

TAILPIPE TO TAILPIPE CONFIGURATION



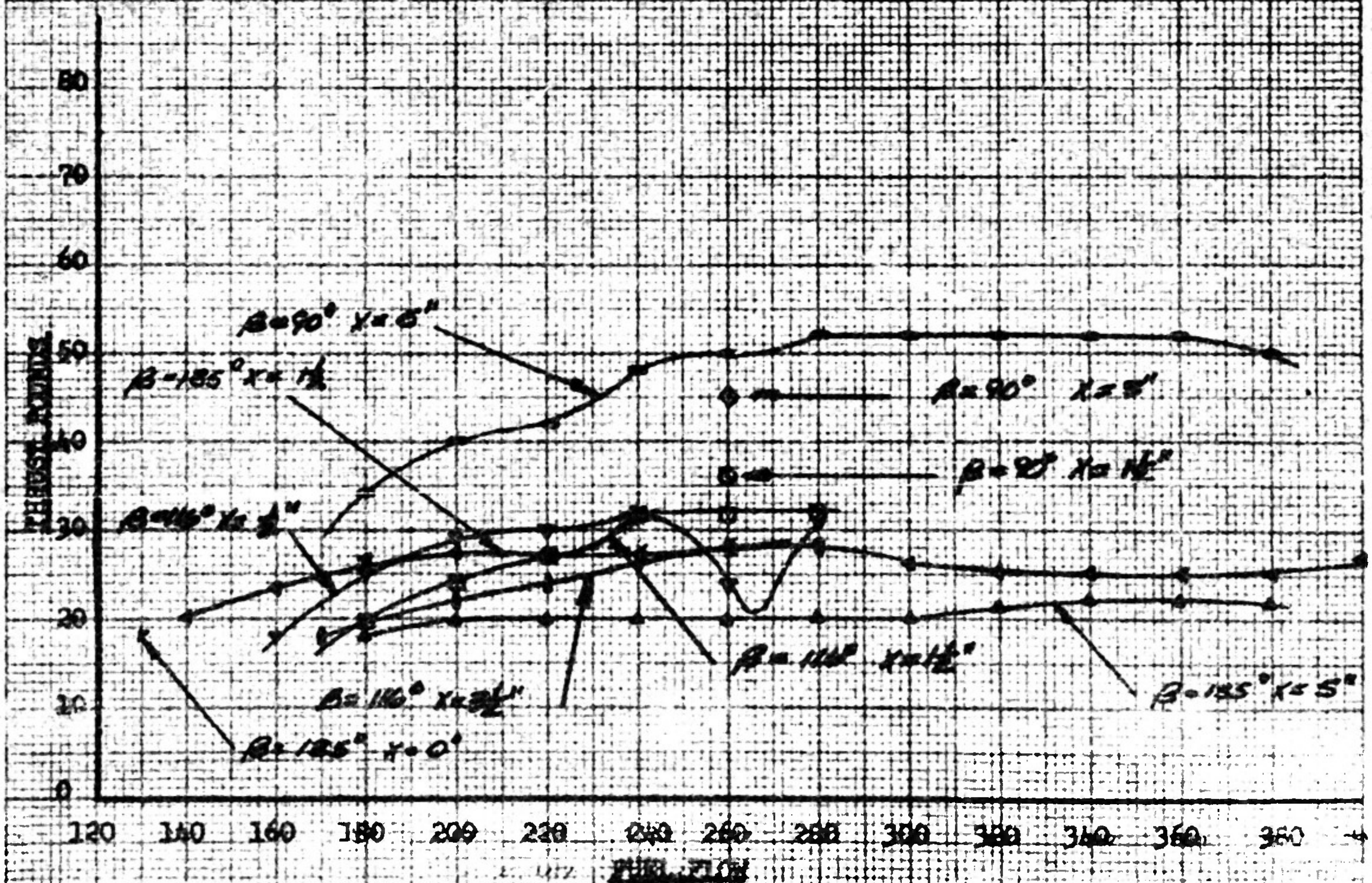
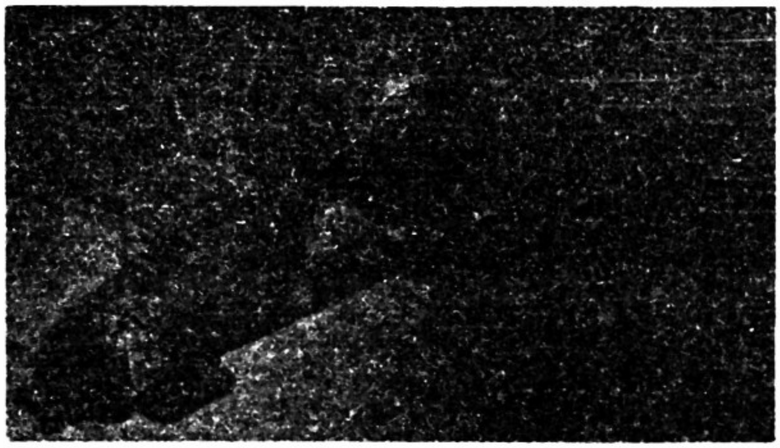


Figure 6[illegible]

STATIC PERFORMANCE CHARACTERISTICS OF TAILPIPE TO TAILPIPE ENGINES



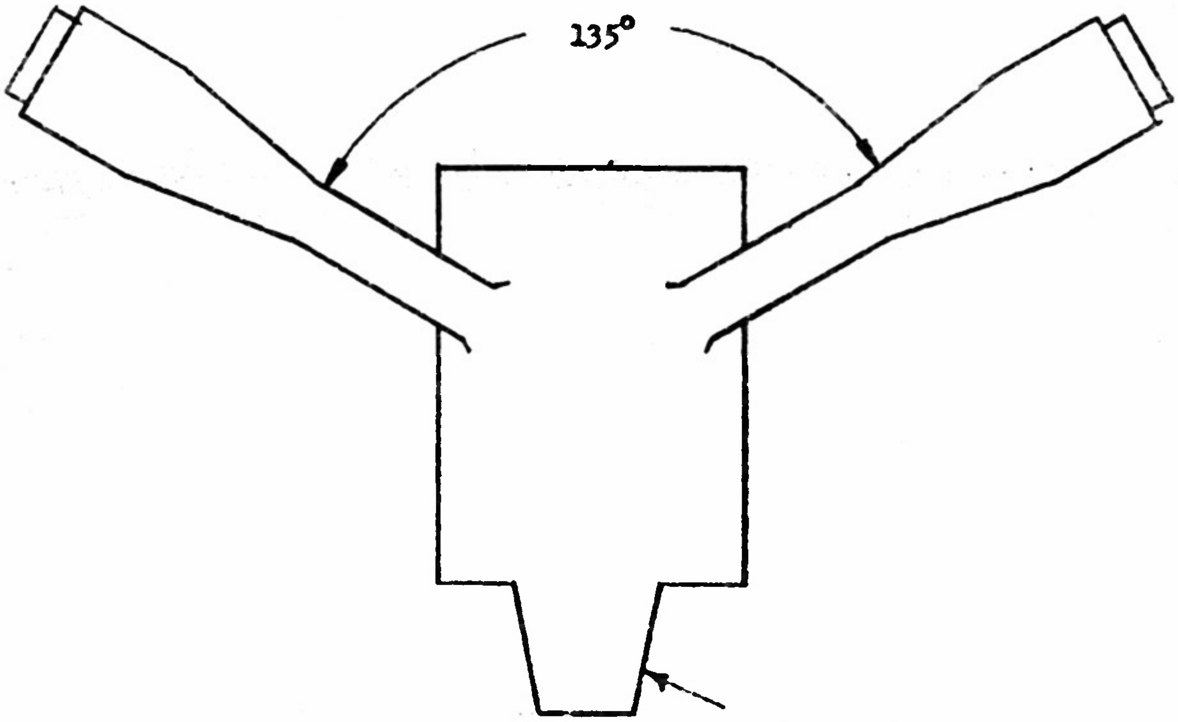
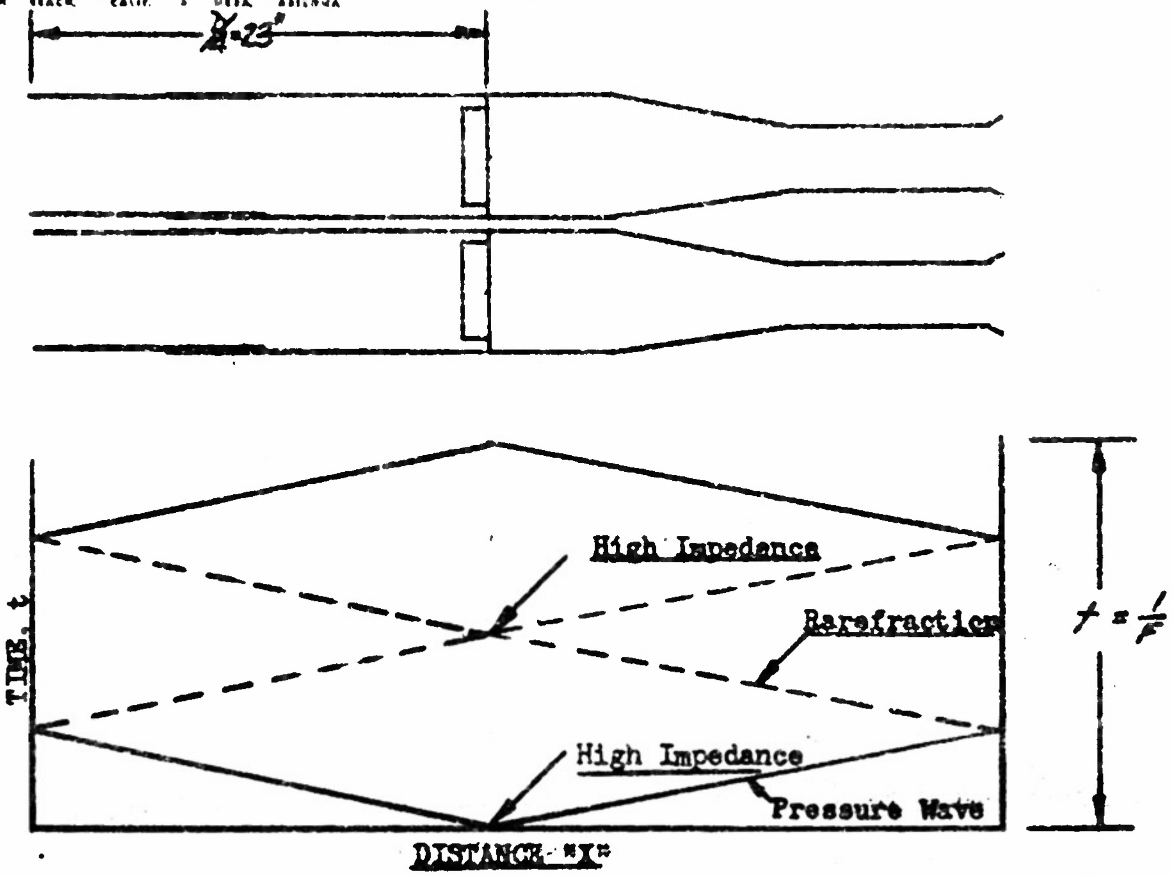
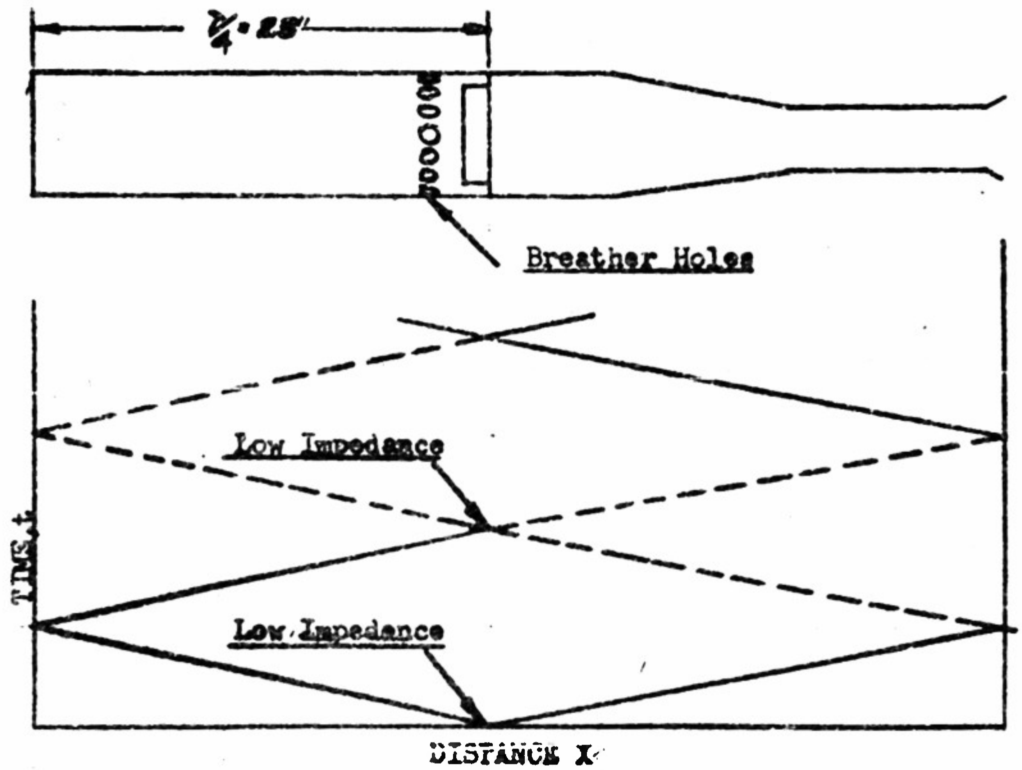


Figure 68

TAILPIPE TO TAILPIPE CONFIGURATION WITH EXHAUST COLLECTOR SHROUD



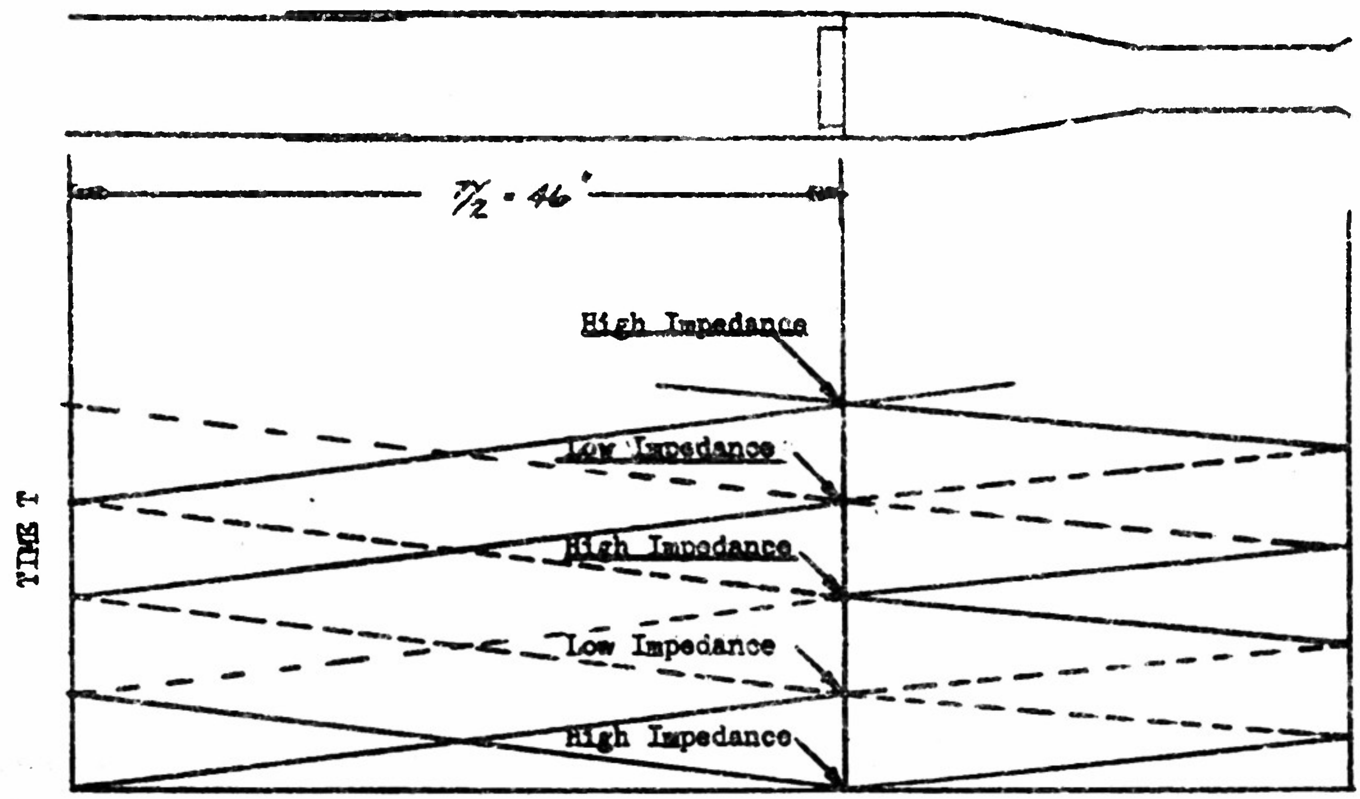
a. Open end quarter wave intake duct



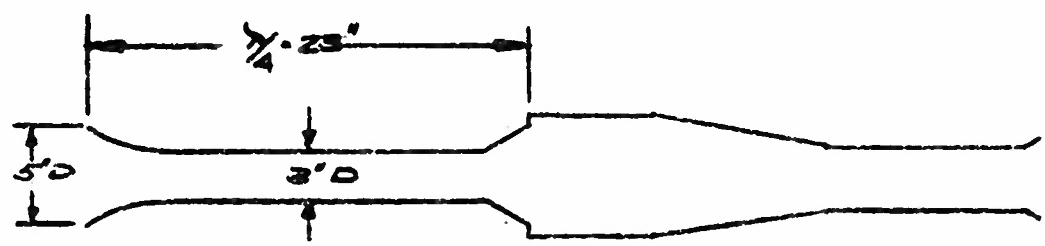
b. Closed end quarter wave intake duct

Figure 69

FRONT END NOISE CONTROL PROGRAM

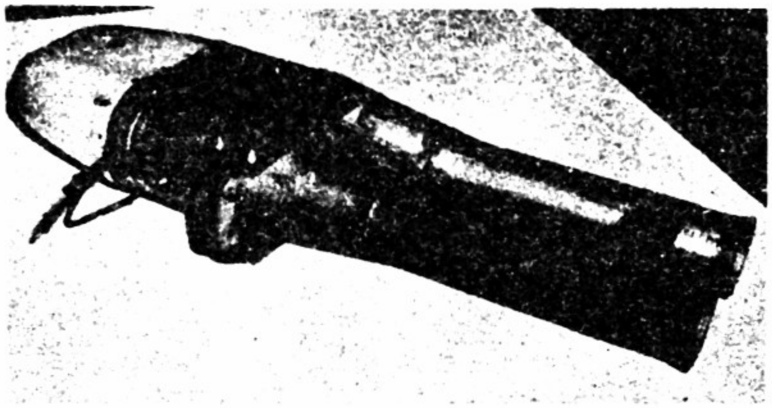


C. Open end half wave intake duct



D. Open end-quarter wave intake duct with valves removed

Figure 69 (Cont'd)



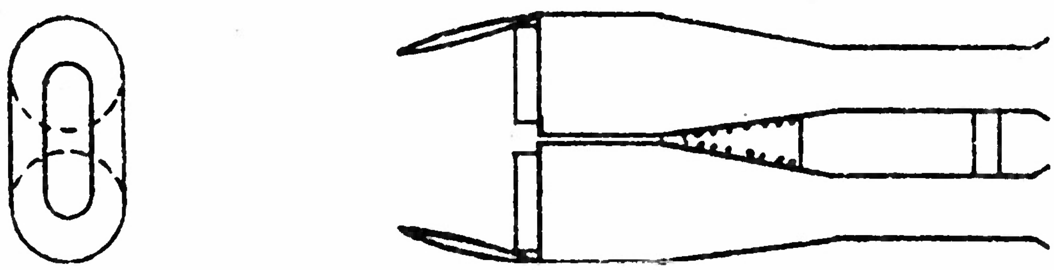


Figure 70

DUAL ENGINES WITH A COMMON INLET COWL

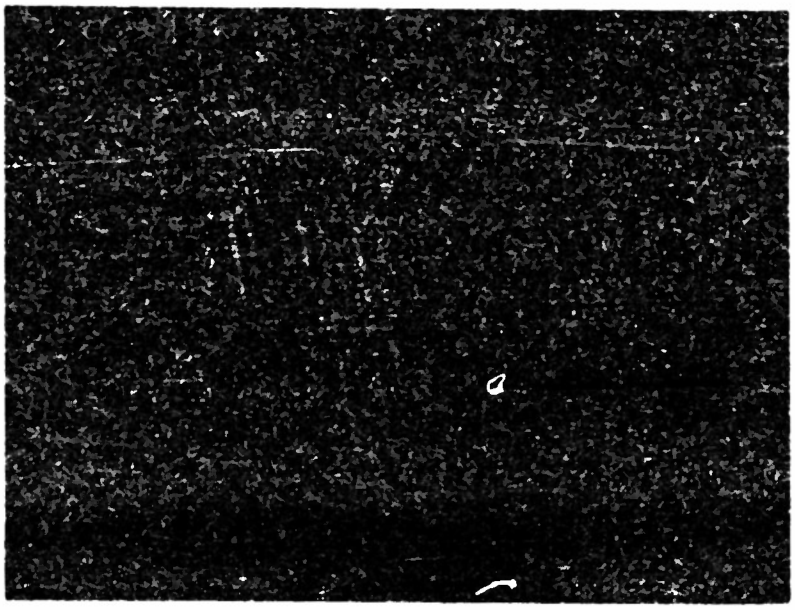


Figure 71

ROCHELLE SALT CRYSTAL PICK-UP INSTALLATION

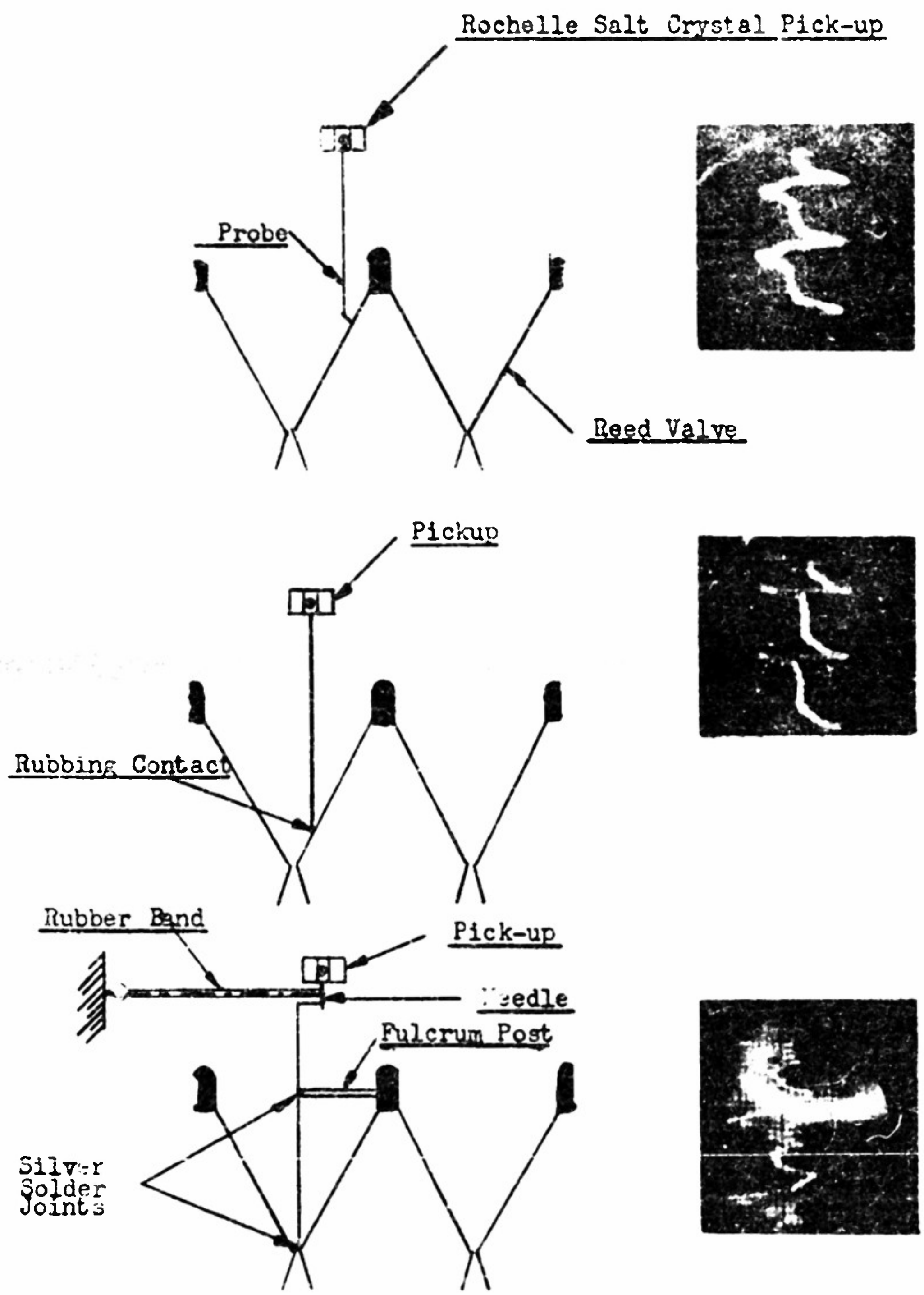


Figure 72

VALVE POSITION INSTRUMENTATION USING A CRYSTAL PICK-UP

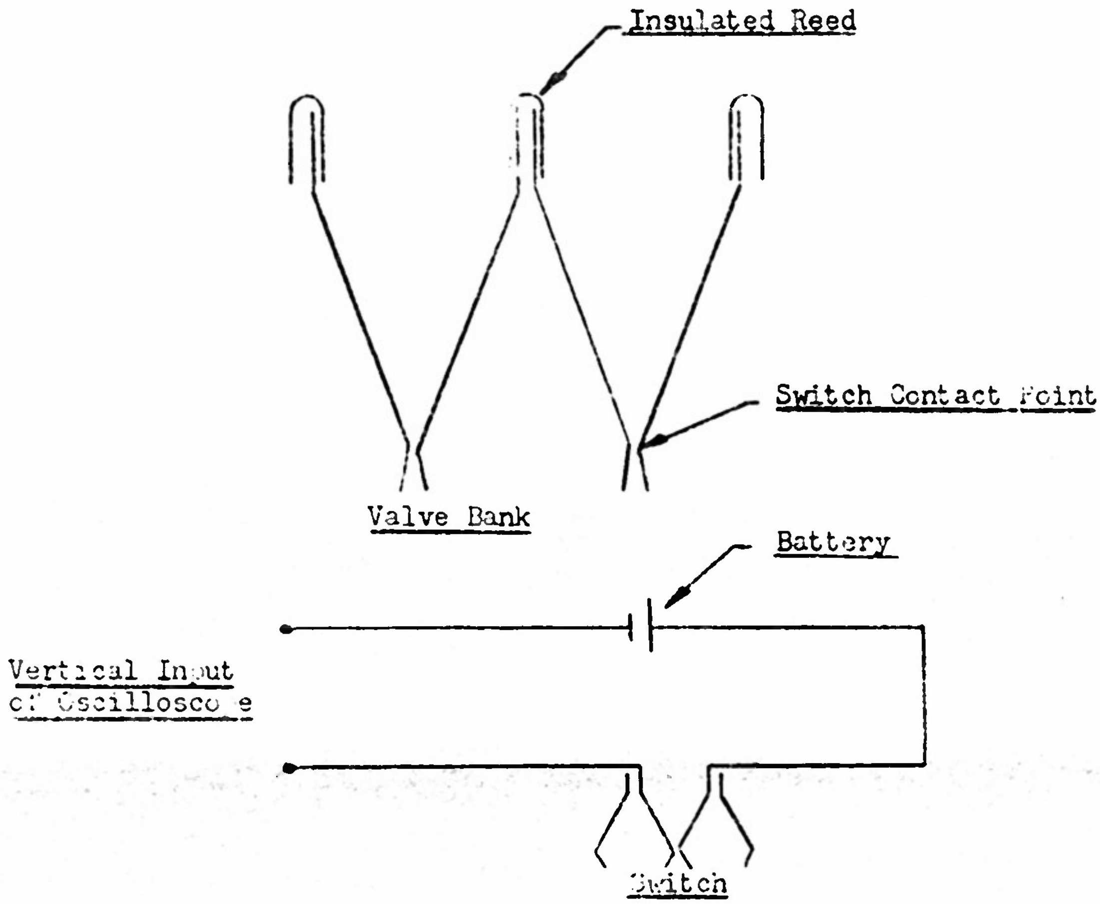


FIGURE 73

VALVE-CONTACT SWITCH VALVE POSITION CIRCUITRY

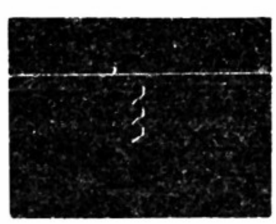


FIGURE 74

PHOTOGRAPH OF VALVE CONTACT SWITCH VALVE POSITION TRACE

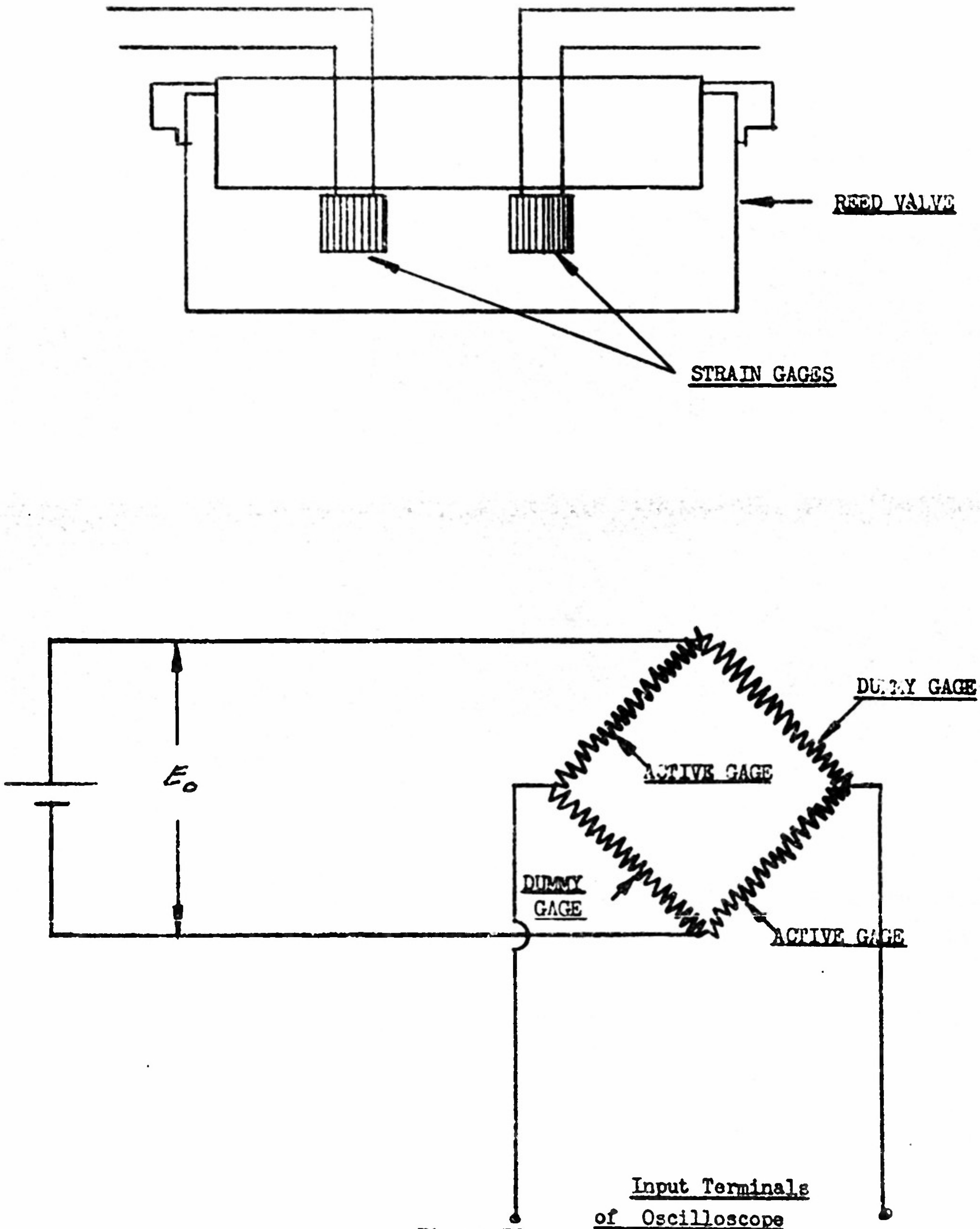
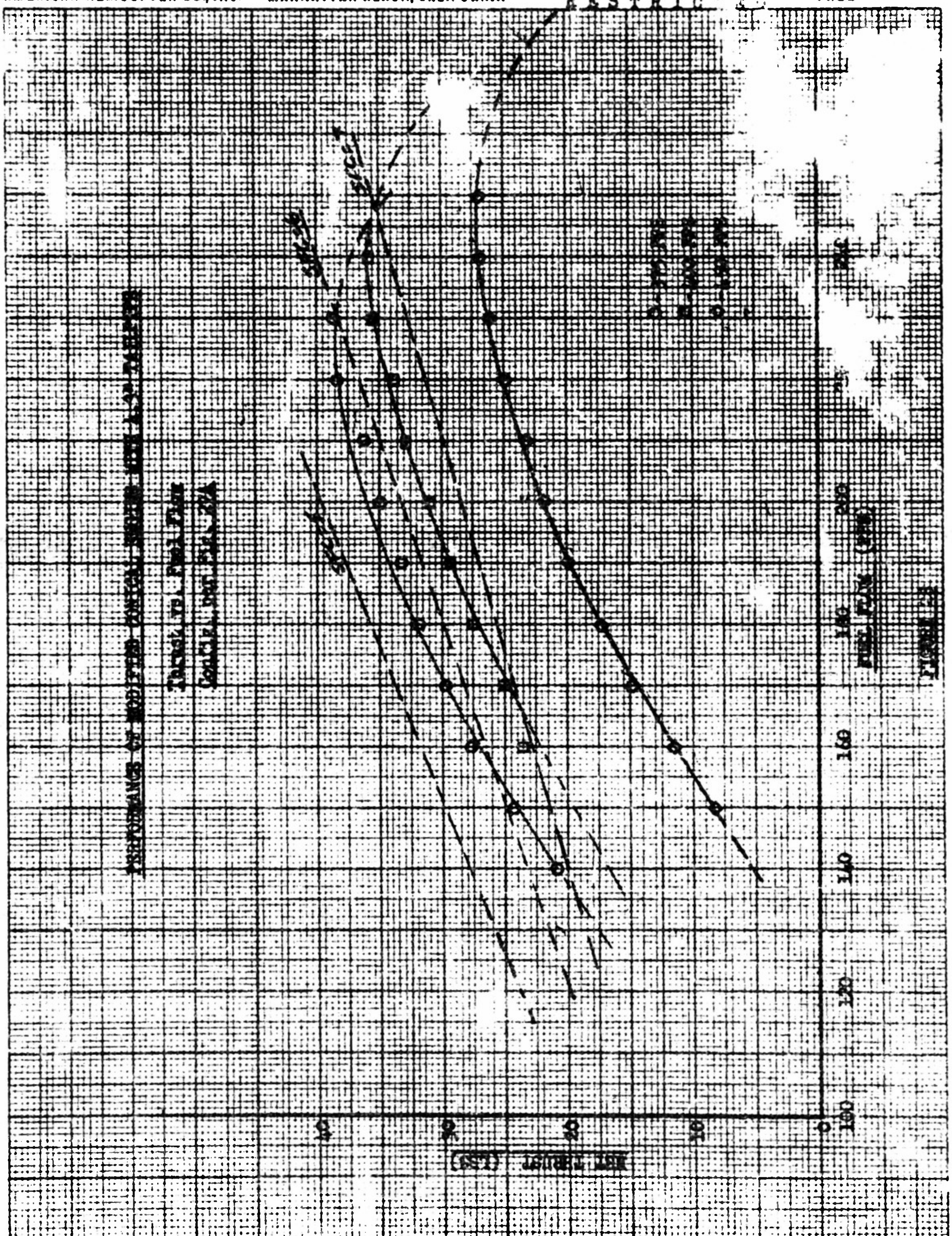


Figure 75

STRAIN GAGE INSTRUMENTATION


Thrust vs. Fuel Flow
NET THRUST (LBS)
FUEL FLOW (PPH)
0
10
20
30
40
100
120
140
160
180
200

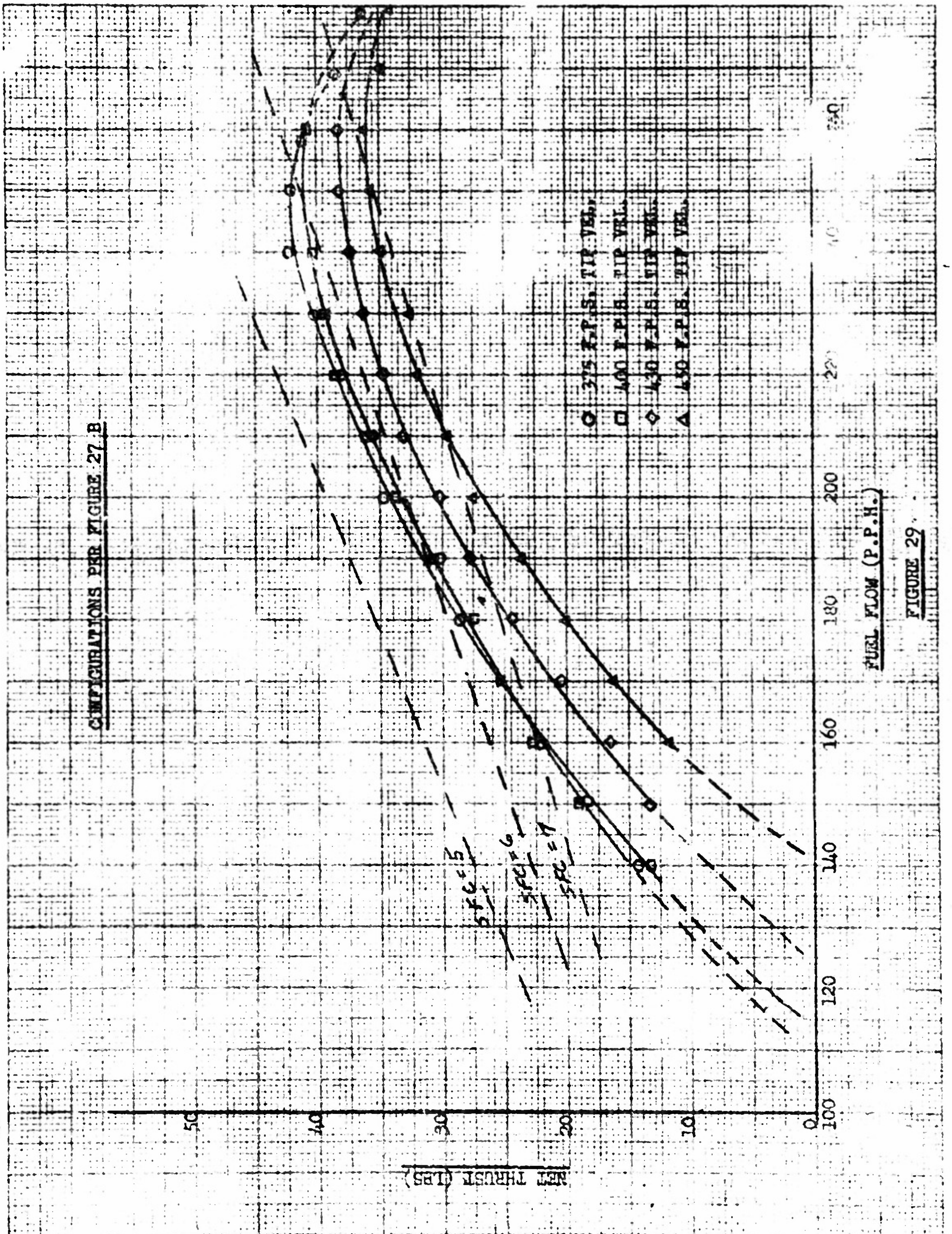
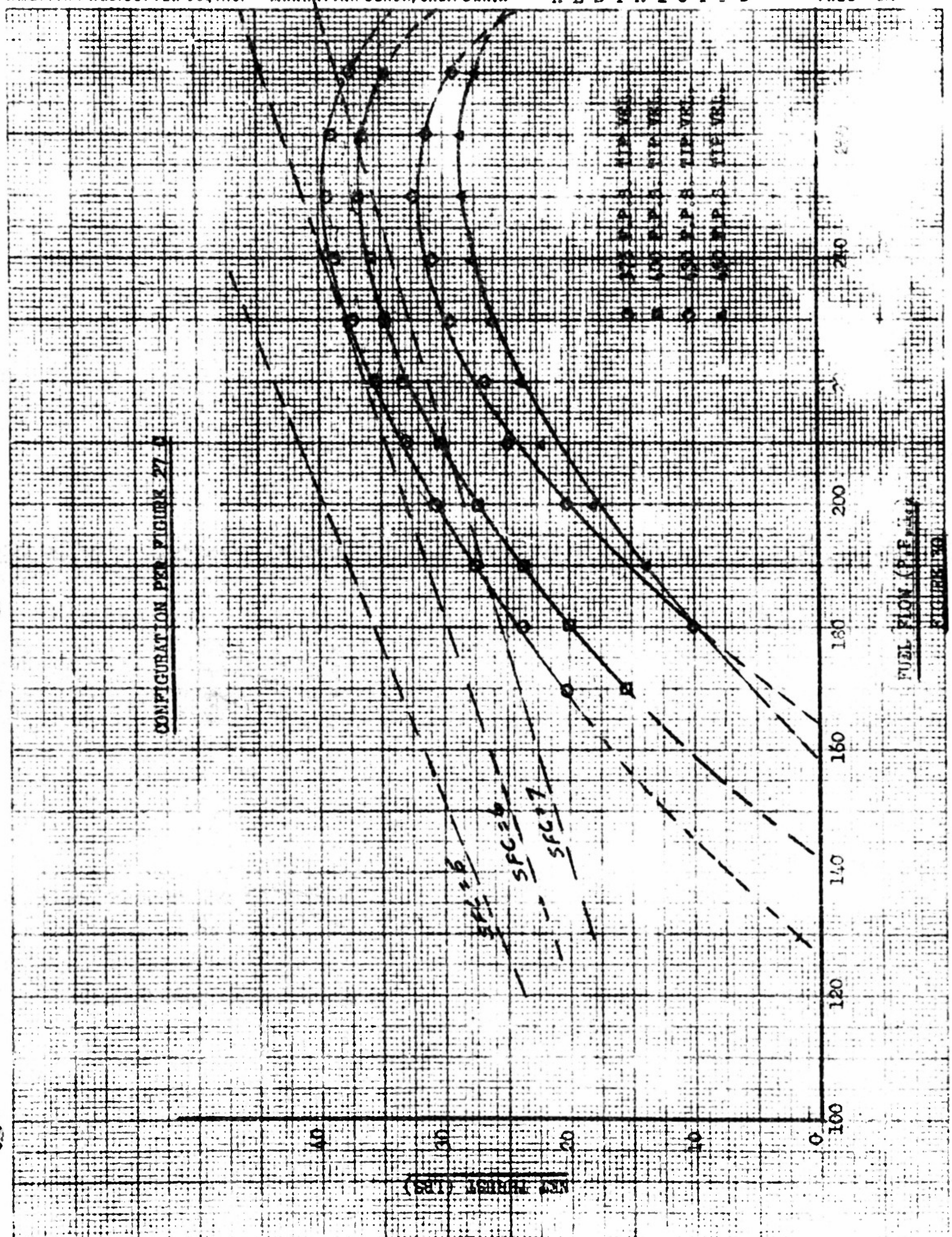

CONFIGURATIONS PER FIGURE 27 B
375 F.P.S. TIP VEL.
400 F.P.S. TIP VEL.
430 F.P.S. TIP VEL.
430 F.P.S. TIP VEL.
SFC = 5
SFC = 6
SFC = 7
NET THRUST (LBS)
0
10
20
30
40
50
FUEL FLOW (P.P.H.)
100
120
140
160
180
200
220

FIGURE 29


CONFIGURATION PER FIGURE 27.0
FUEL FLOW (P.P.H.)
NET THRUST (LBS.)
100
120
140
160
180
200
0
10
20
30
40

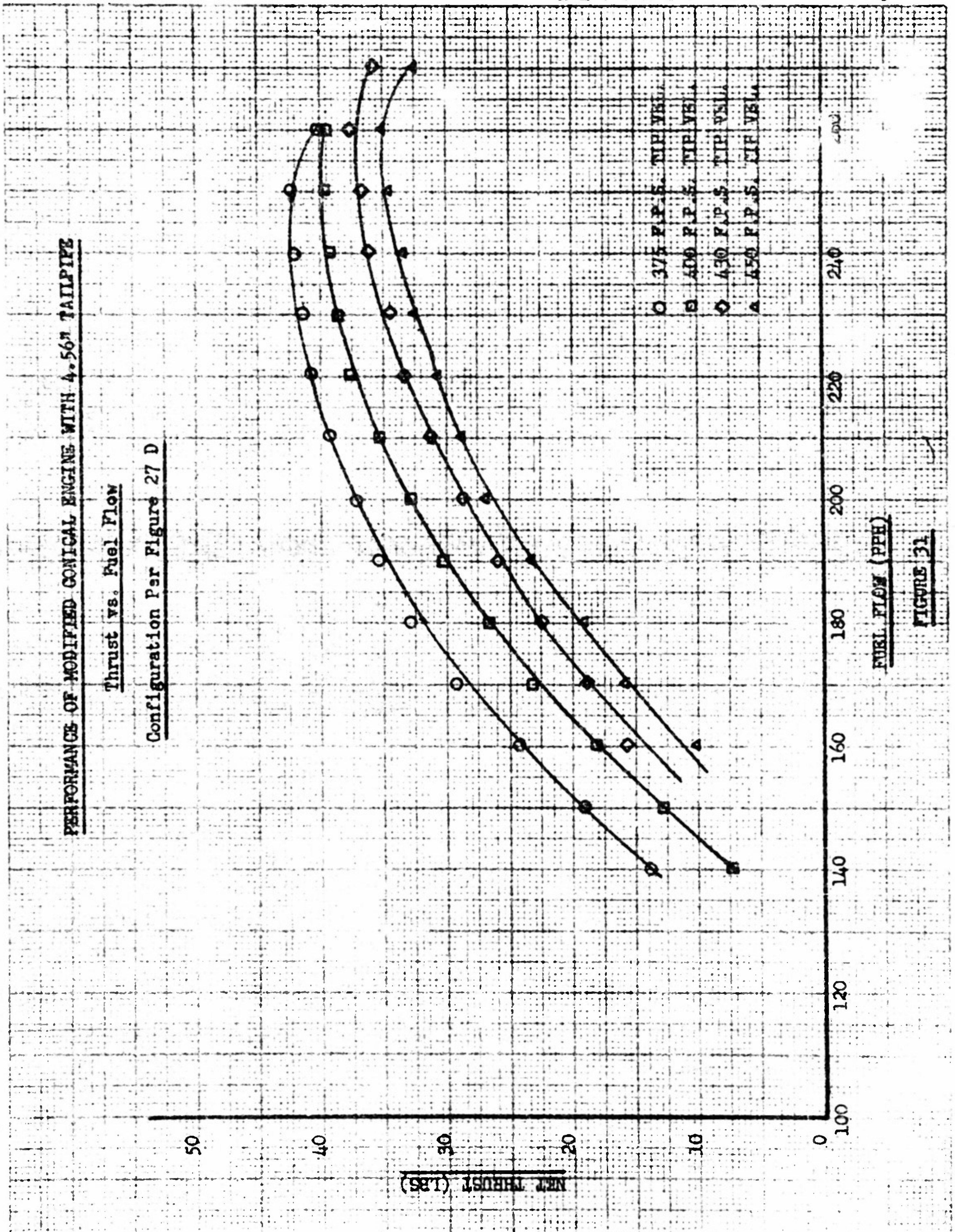

PERFORMANCE OF MODIFIED CONICAL ENGINE WITH 4.56" TAILPIPE
Thrust vs. Fuel Flow
Configuration Per Figure 27 D
375 F.P.S. TIP VEL.
400 F.P.S. TIP VEL.
430 F.P.S. TIP VEL.
450 F.P.S. TIP VEL.
NET THRUST (LBS)
FUEL FLOW (PPH)
0
10
20
30
40
50
100
120
140
160
180
200
220
240

FIGURE 31

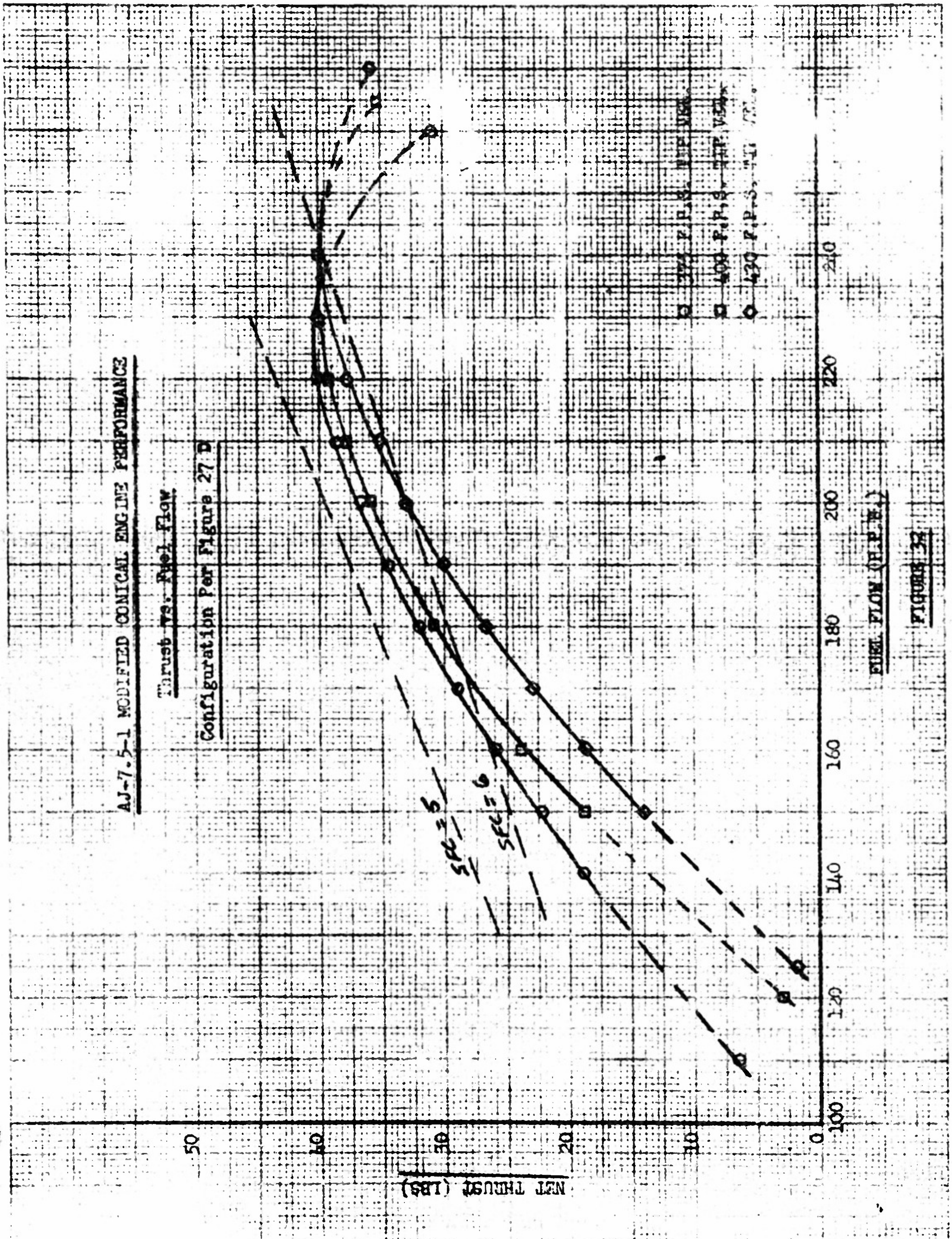

AJ-7.5-1 MODIFIED CONICAL ENGINE PERFORMANCE
Thrust vs. Fuel Flow
Configuration Per Figure 27 D
375 F.P.S. TIP VEL.
400 F.P.S. TIP VEL.
430 F.P.S.
SFC = 5
SFC = 6
NET THRUST (LBS)
50
40
30
20
10
0
100
120
140
160
180
200
220
240
FUEL FLOW (H.P.E.)

FIGURE 32

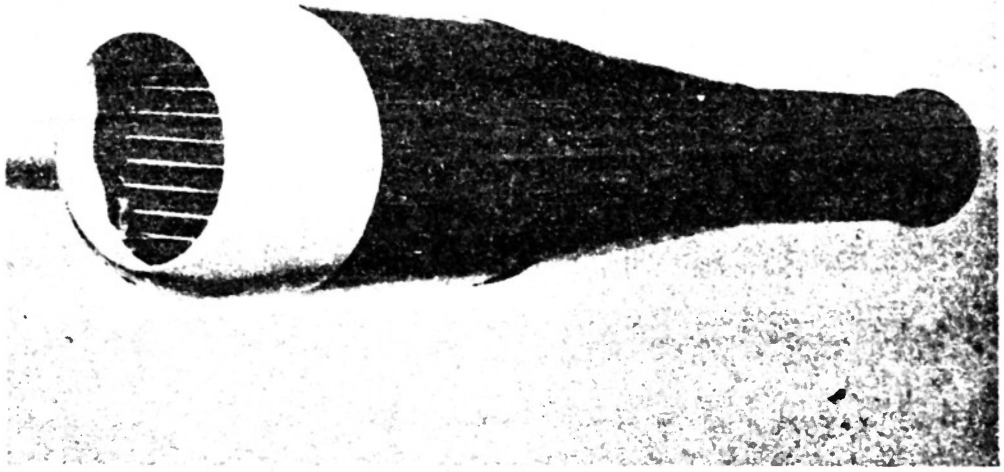


FIGURE 33
AJ-7.5-1 MODIFIED CONICAL ENGINE ON ENDURANCE TEST STAND

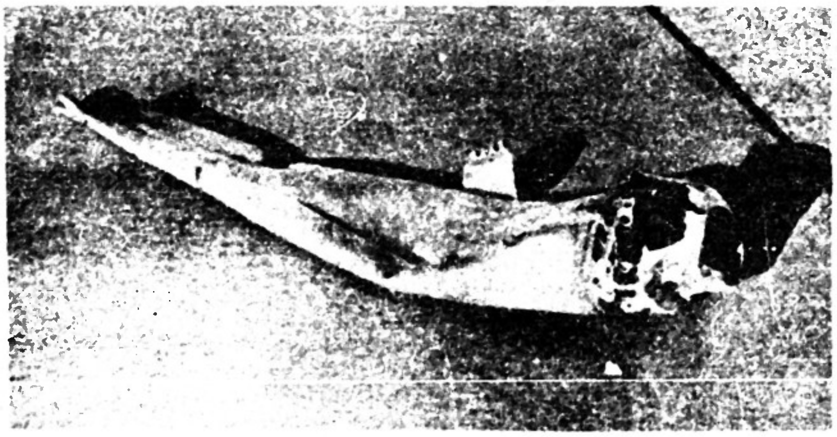


FIGURE 34
AJ-7.5-1 MODIFIED CONICAL ENGINE AFTER BEING THROWN FROM WHIRL ARM

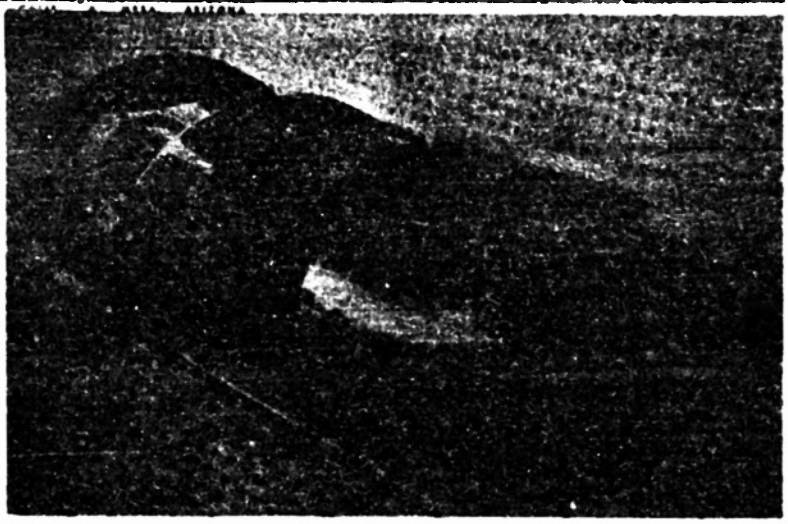


FIGURE 35

ELLIPTICAL ENGINE COMPONENTS, 3/4 FRONT VIEW

FIGURE 36

ELLIPTICAL ENGINE COMPONENTS, 3/4 REAR VIEW

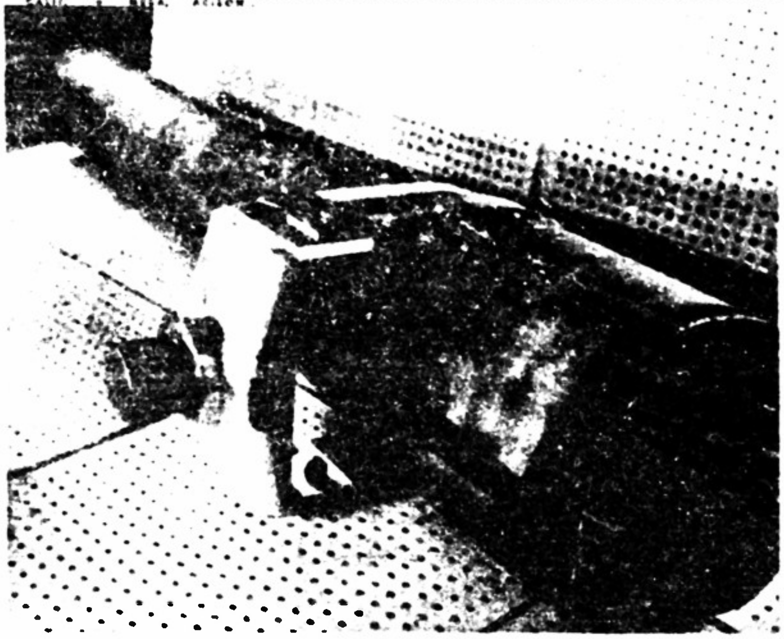


FIGURE 37
ALUMINUM ENGINE MOUNT

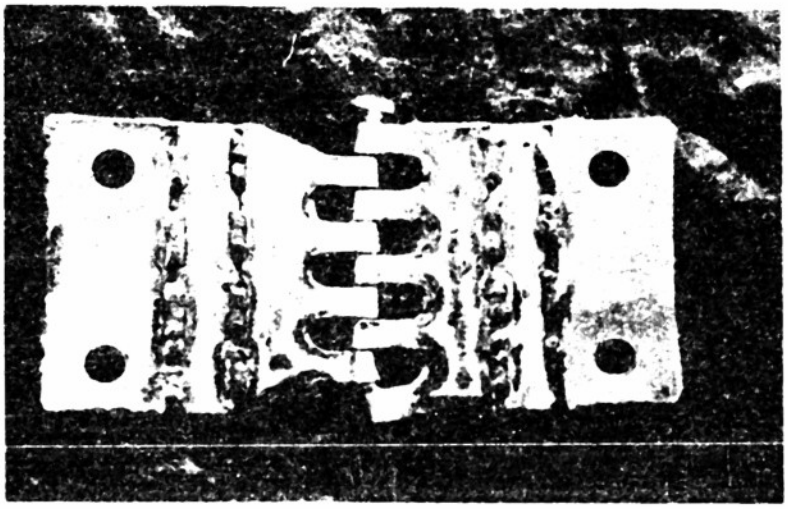


FIGURE 38
HINGE TYPE ENGINE ATTACH FITTING

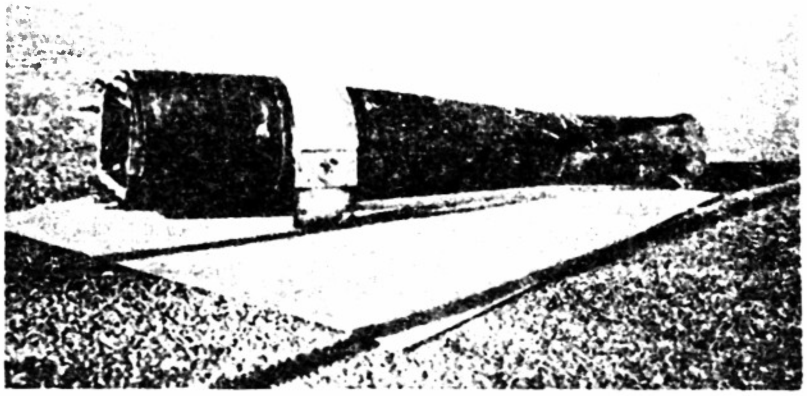


FIGURE 39
MOCK-UP OF REFINED ENGINE MOUNT

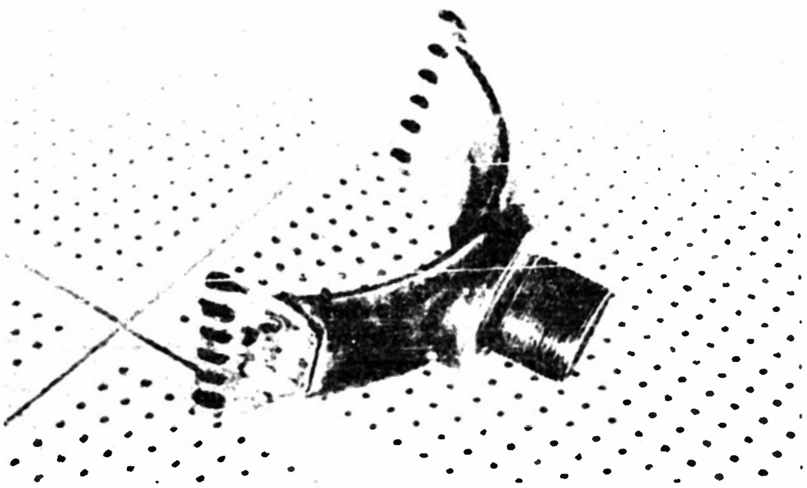


FIGURE 40
REFINED ENGINE MOUNT

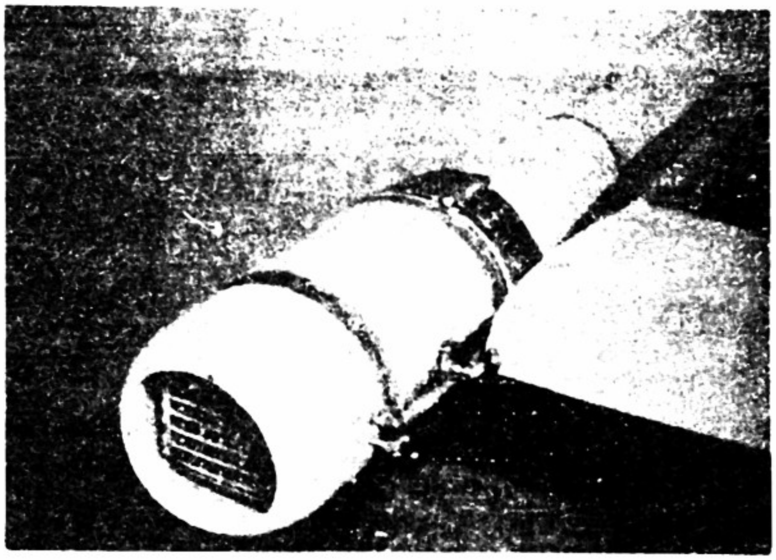


FIGURE 41

MODIFIED CONICAL ENGINE AND REFINED MOUNT

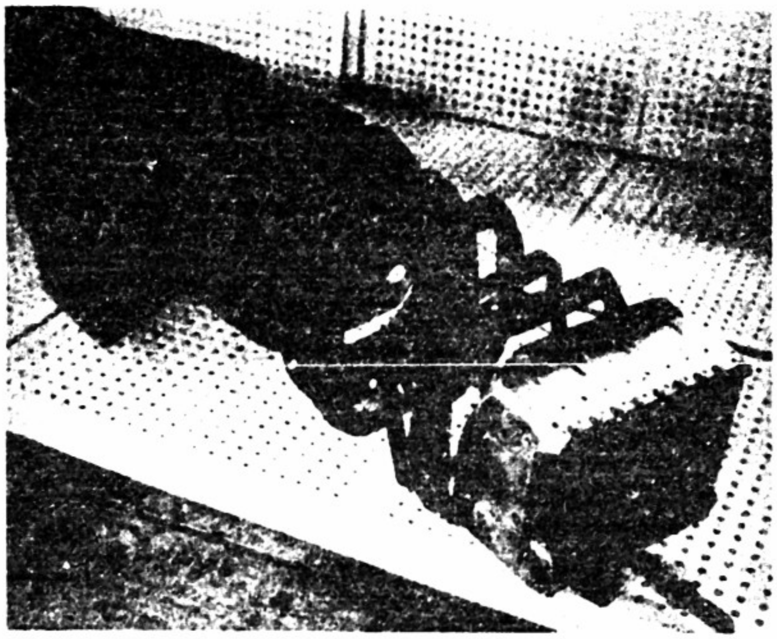


FIGURE 42

ORIGINAL AJ-6.75 ENGINE COMPONENTS

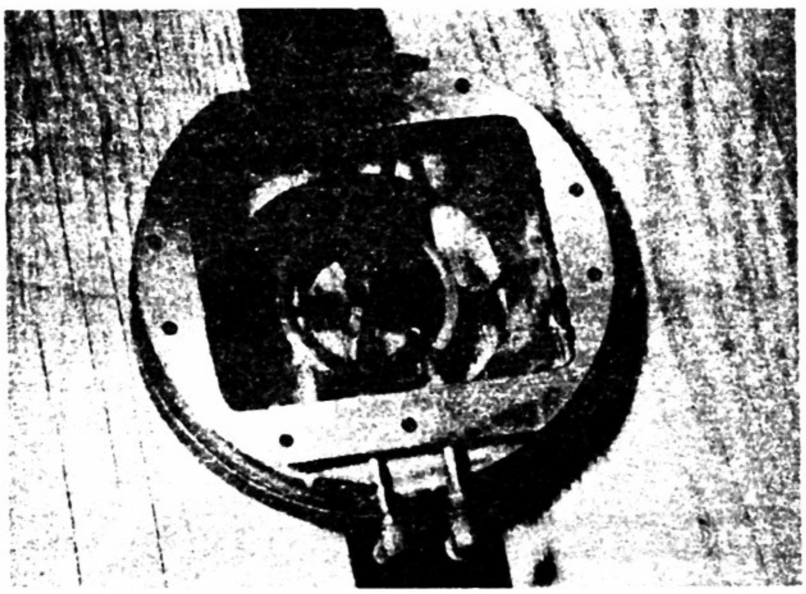


FIGURE 43

FIRST ALTERNATE FUEL INJECTOR VENTURI SECTION

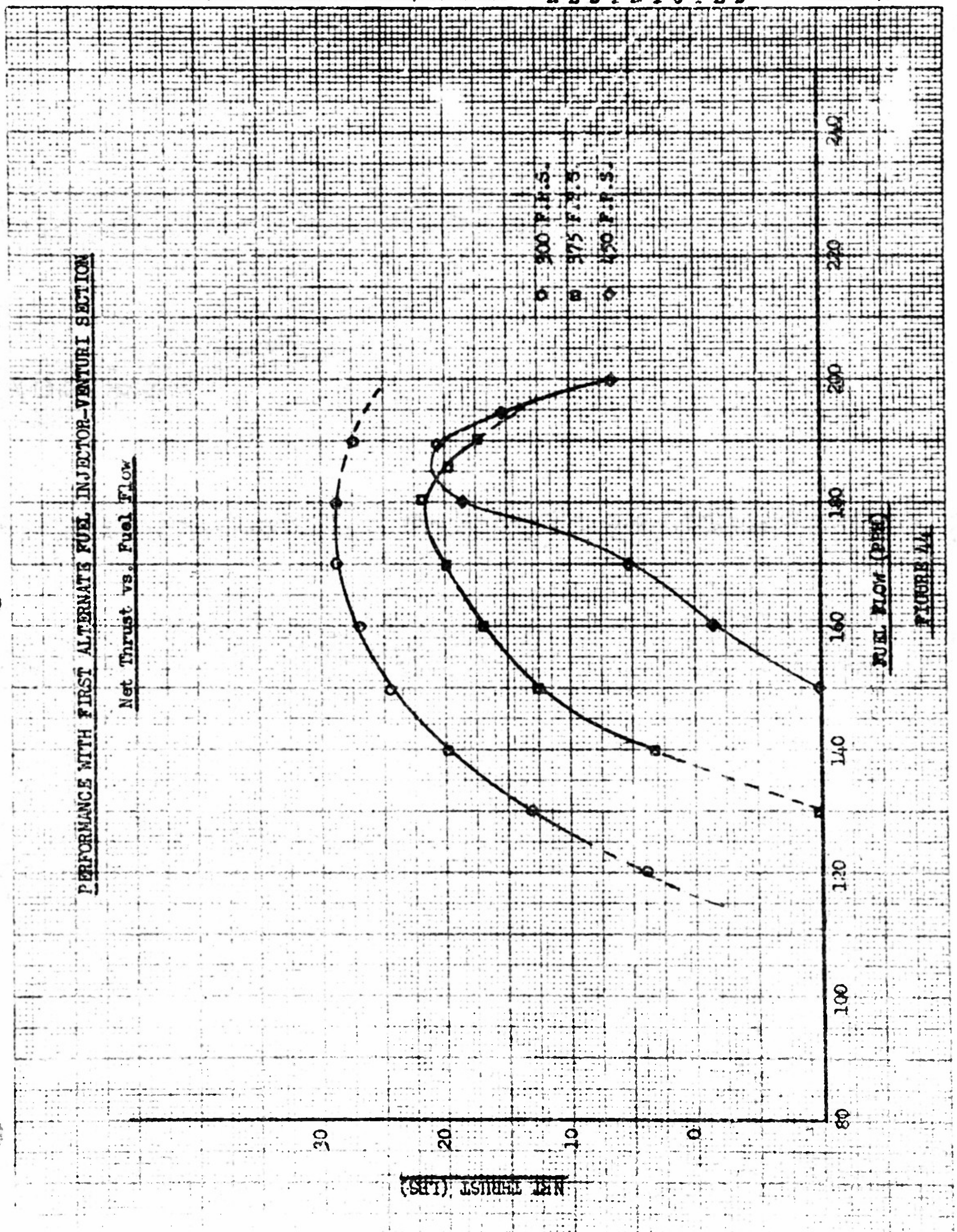

PERFORMANCE WITH FIRST ALTERNATE FUEL INJECTOR-VENTURI SECTION
Net Thrust vs. Fuel Flow
300 F.P.S.
375 F.P.S.
450 F.P.S.
NET THRUST (LBS.)
30
20
10
0
FUEL FLOW (PPH)
80
100
120
140
160
180
200
220
240

FIGURE 44

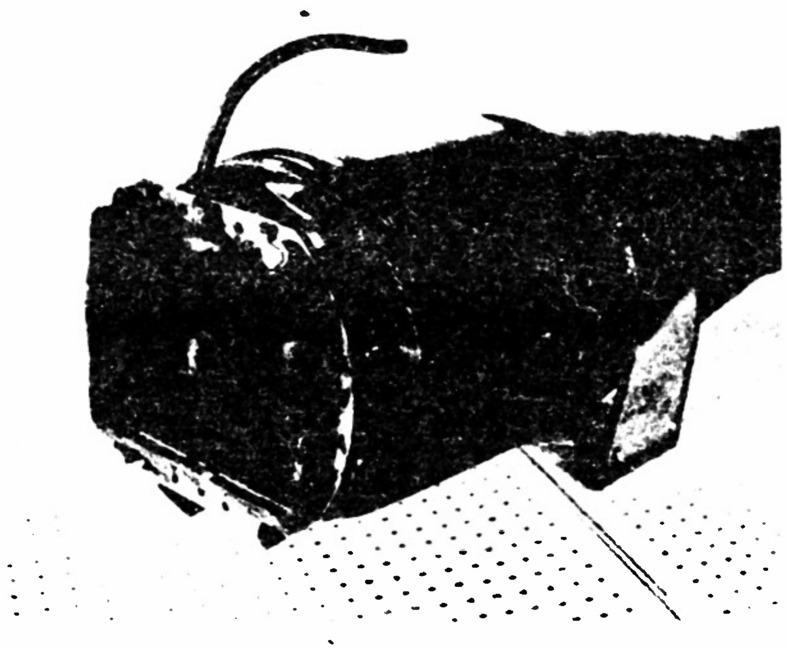


FIGURE 45

SECOND ALTERNATE FUEL INJECTOR-VENTURI SECTION

PERFORMANCE WITH SECOND ALTERNATE FUEL INJECTOR-VENTURI SECTION

Net Thrust vs. Fuel Flow

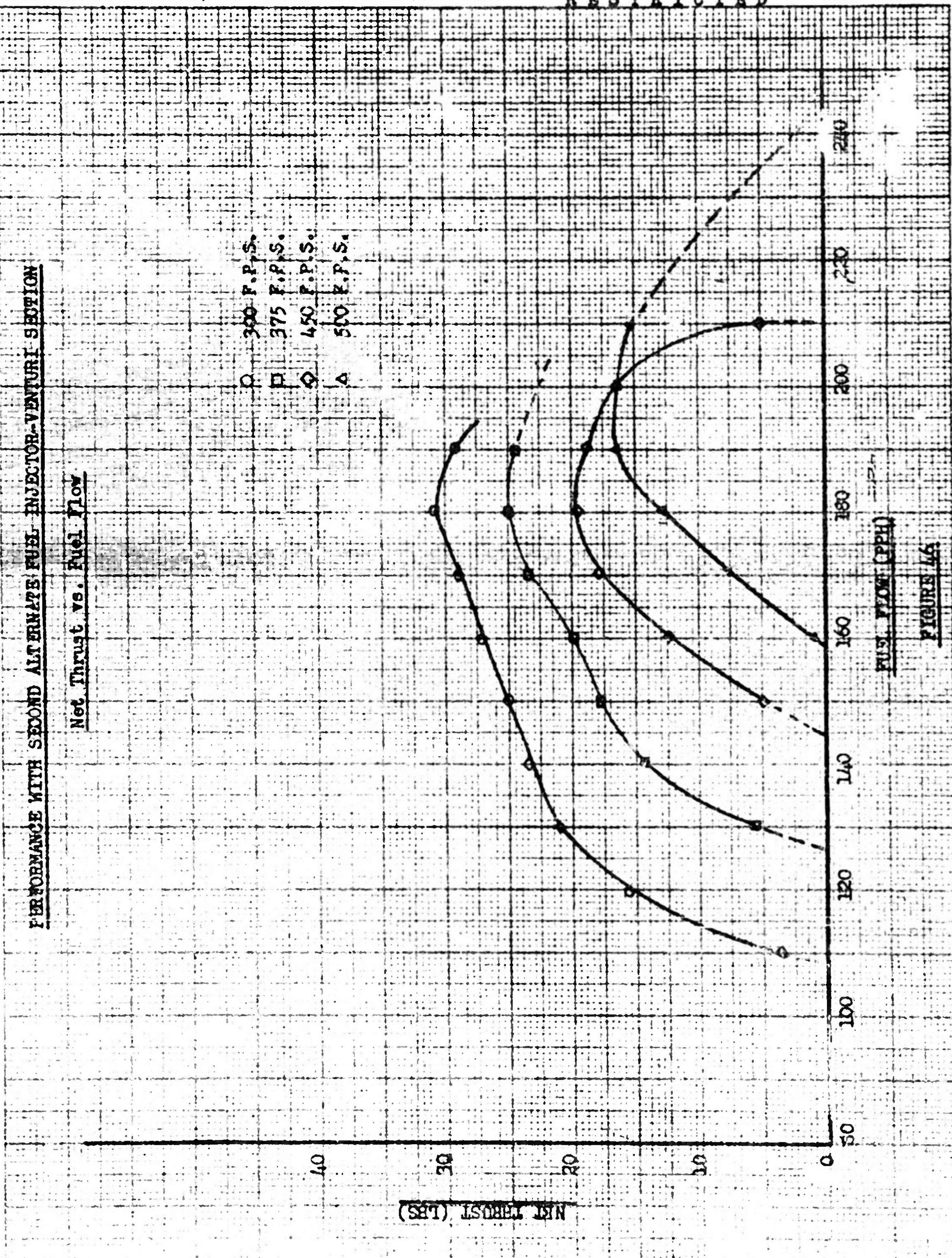


FIGURE 46

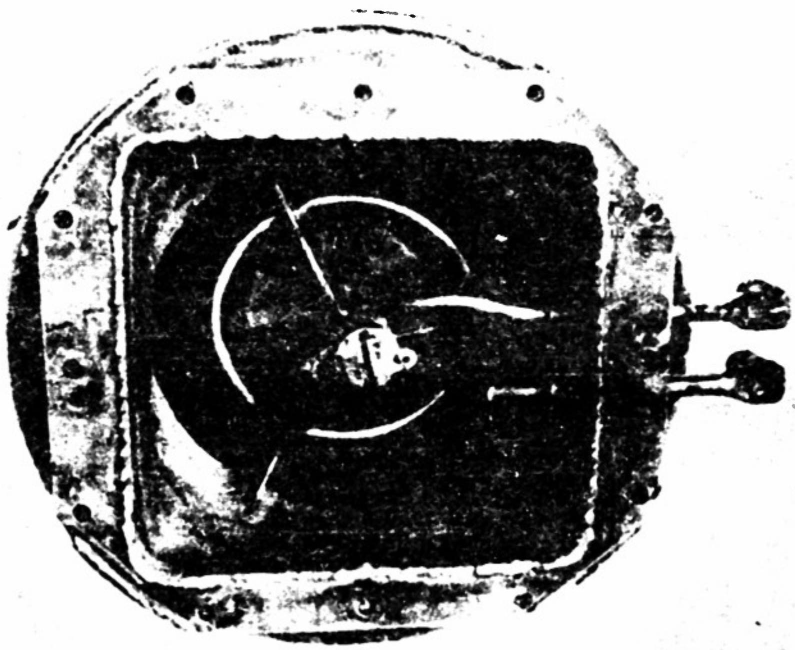
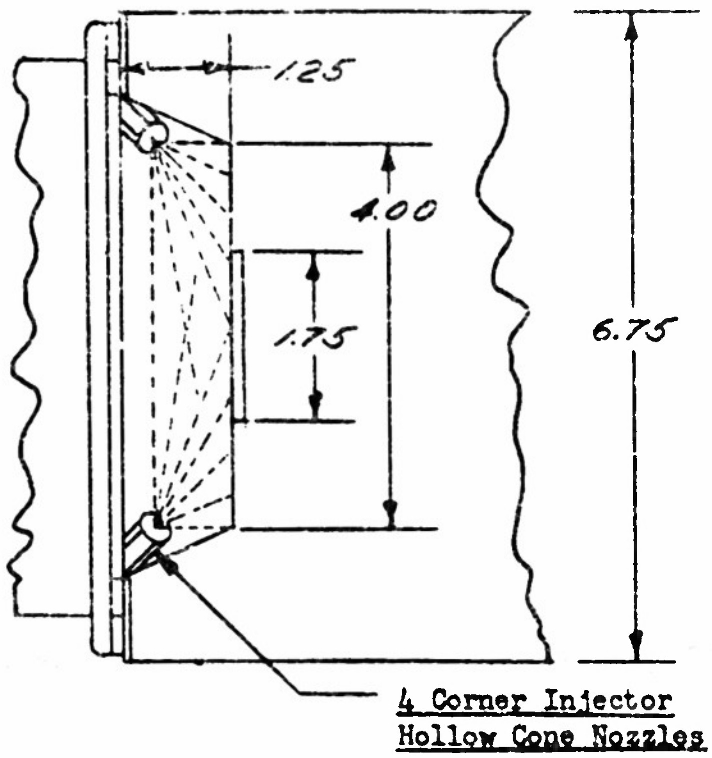


FIGURE 47
IMPROVED FUEL NOZZLE

FUEL INJECTION CONFIGURATION



Sketch B

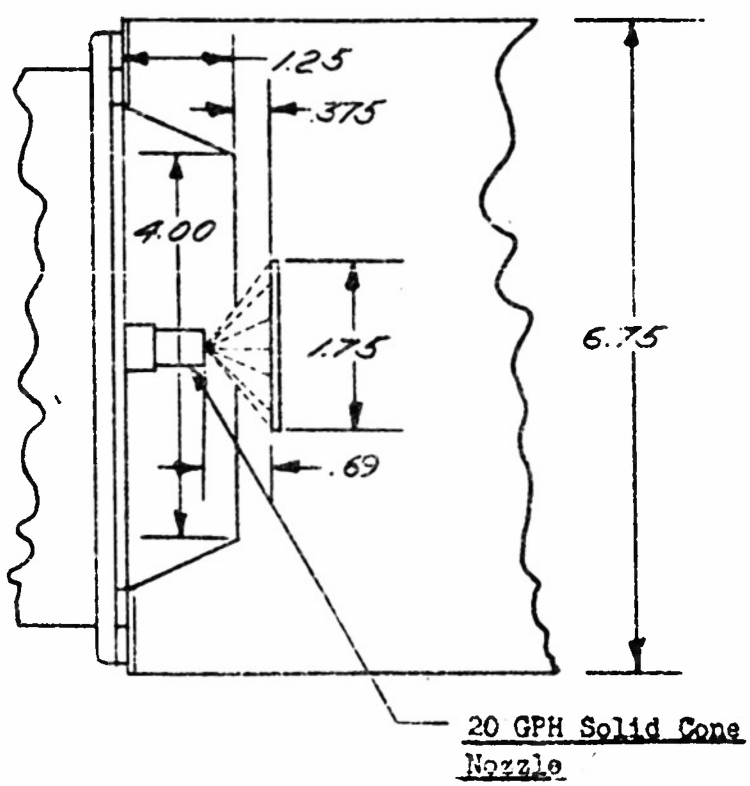


Figure 43

Sketch A

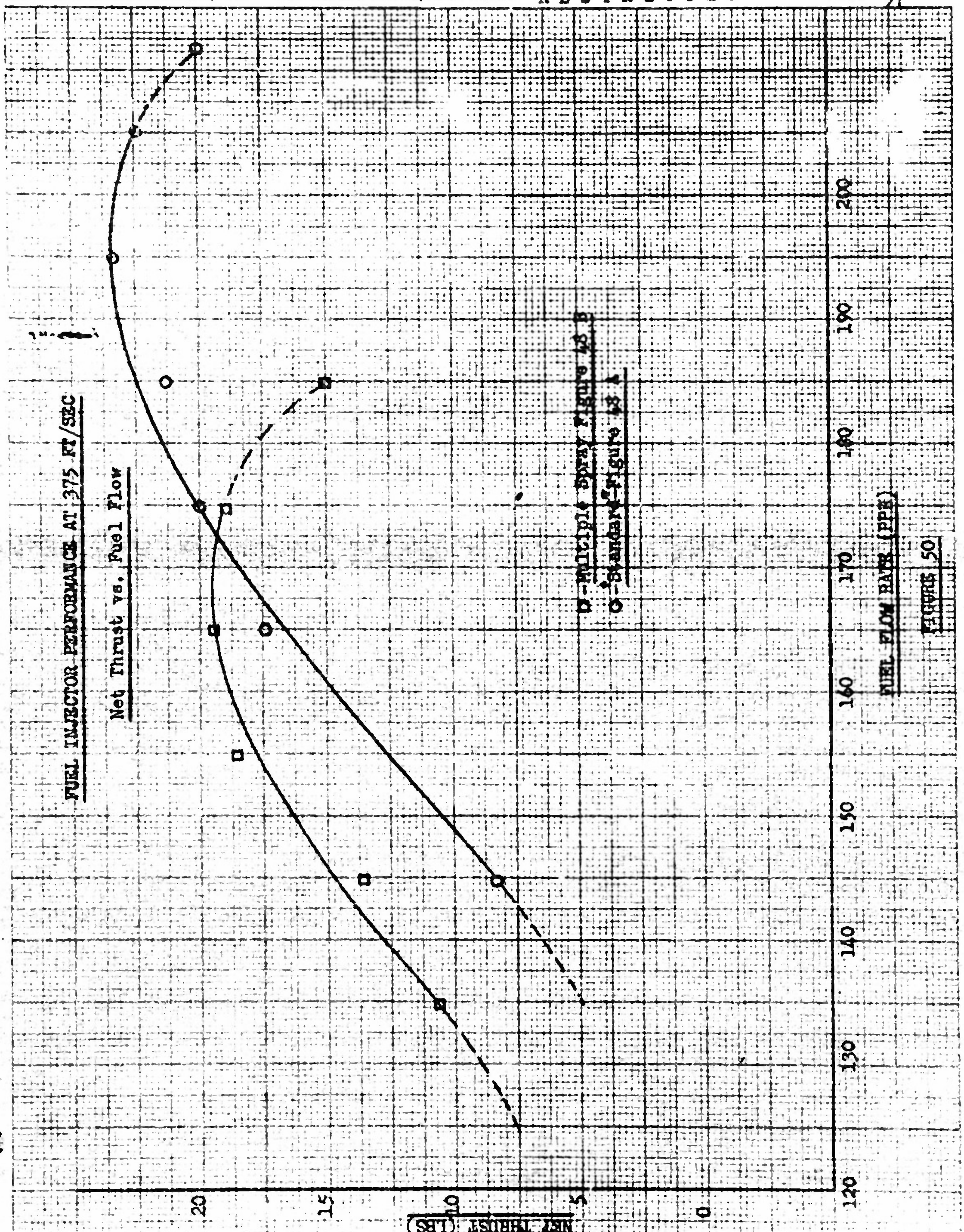

FUEL INJECTOR PERFORMANCE AT 375 FT/SEC
Net Thrust vs. Fuel Flow
□-Multiple Spray Figure 43 B
○-Standard Figure 43 A
NET THRUST (LBS)
0
5
10
15
20
FUEL FLOW RATE (PPH)
120
130
140
150
160
170
180
190
200

FIGURE 50

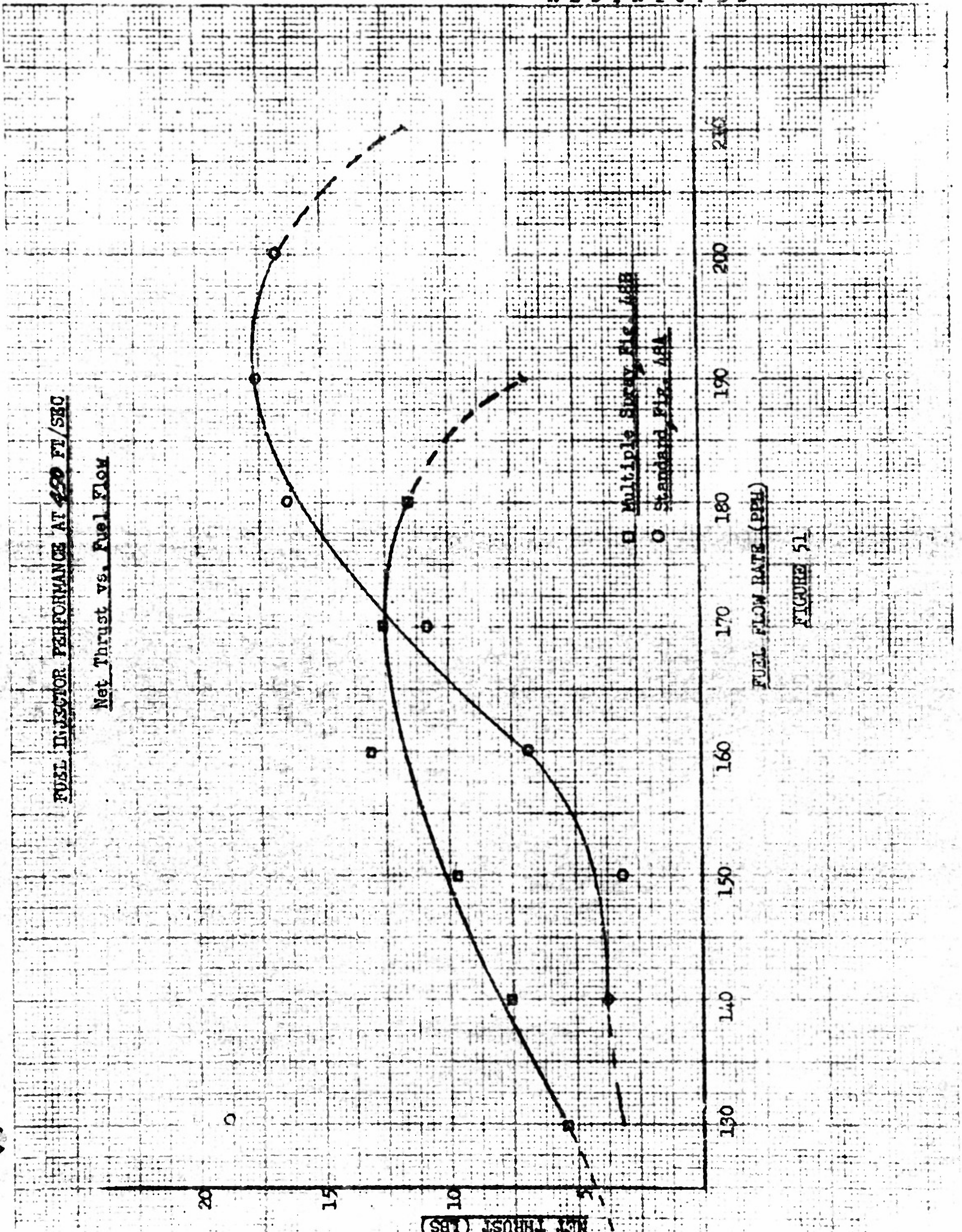
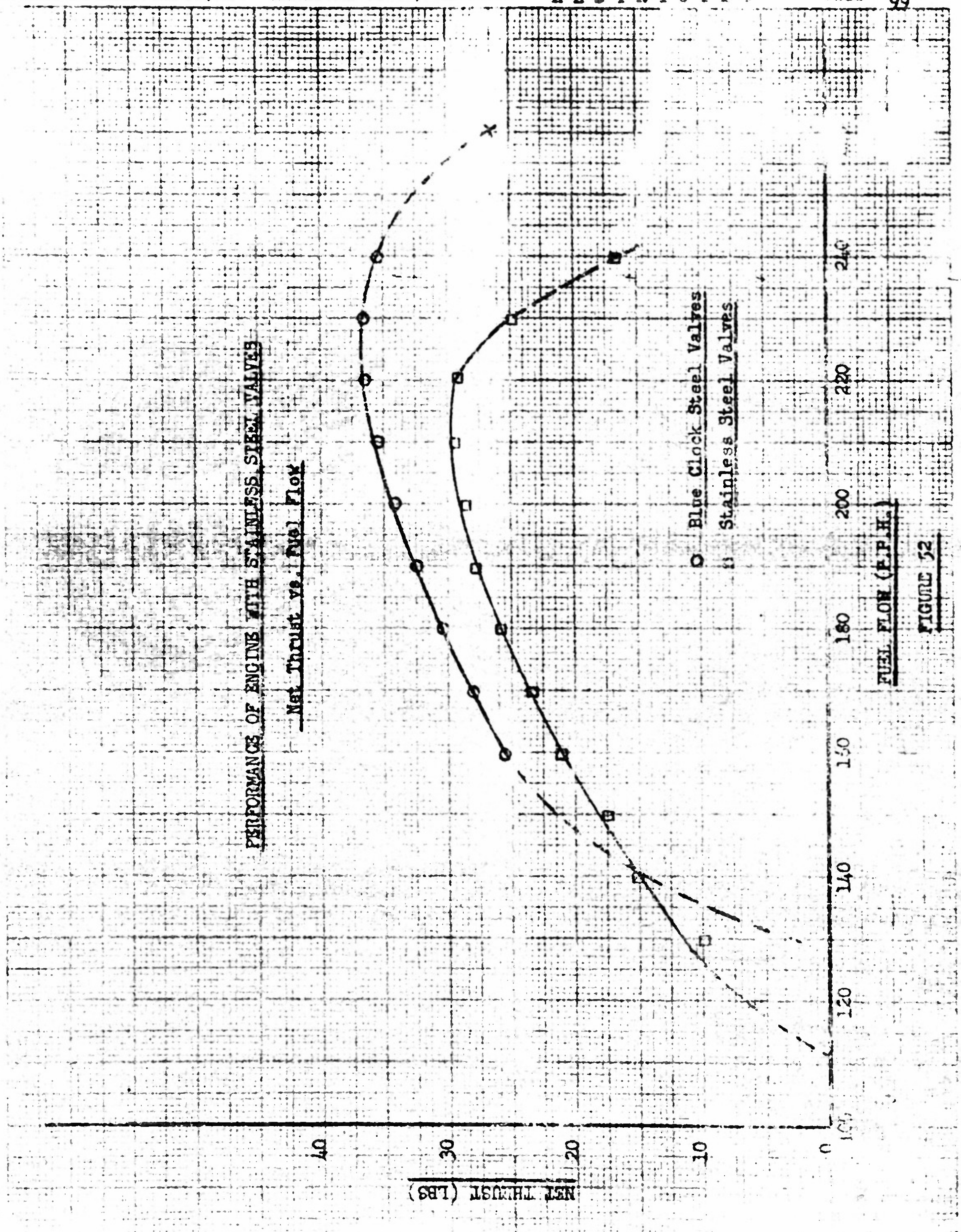

FUEL INJECTOR PERFORMANCE AT FT/SEC
Net Thrust vs. Fuel Flow
□ Multiple Spray Fig. 48B
○ Standard Fig. 48A
FUEL FLOW RATE (PPH)
130
140
150
160
170
180
190
200
210
NET THRUST (LBS)
5
10
15
20

FIGURE 51


PERFORMANCE OF ENGINE WITH STAINLESS STEEL VALVES
Net Thrust vs. Fuel Flow
○ Blue Clock Steel Valves
□ Stainless Steel Valves
NET THRUST (LBS)
0
10
20
30
40
100
120
140
160
180
200
220
240
FUEL FLOW (P.P.H.)
FIGURE 32

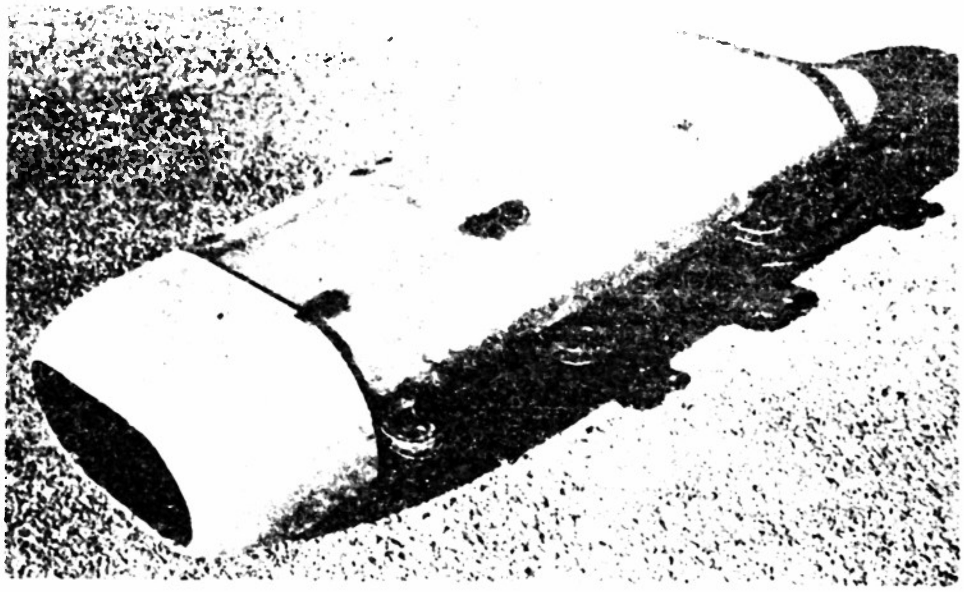


FIGURE 53

DUAL DUCTED ENGINE ASSEMBLY

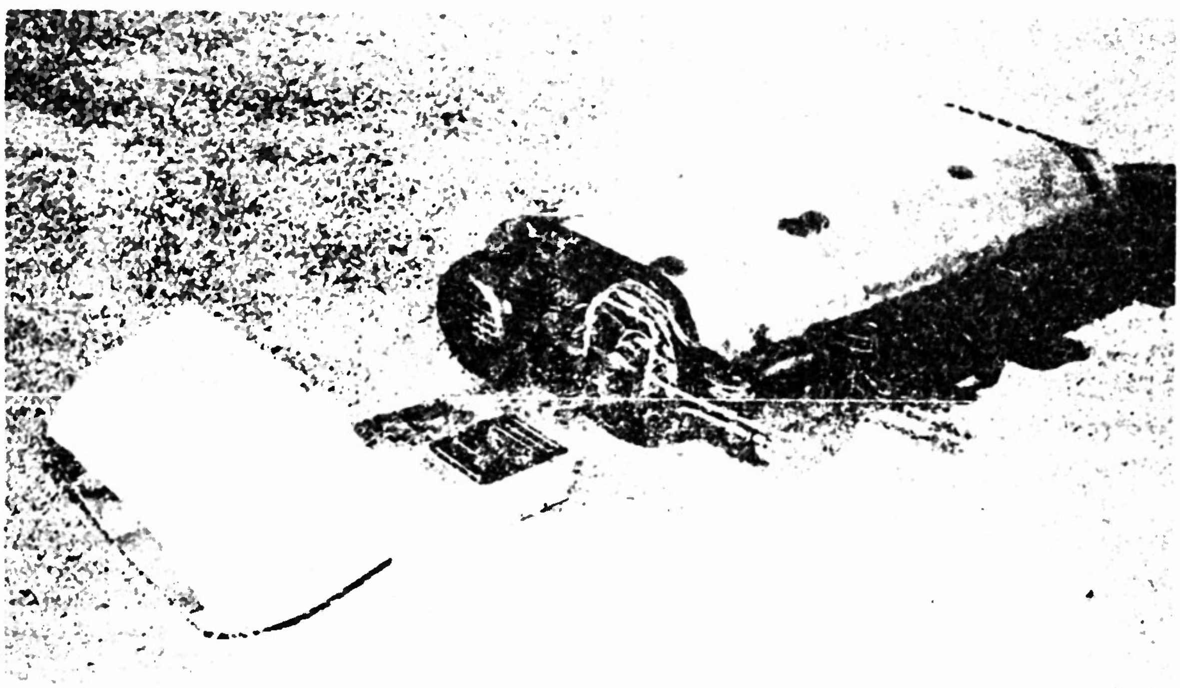
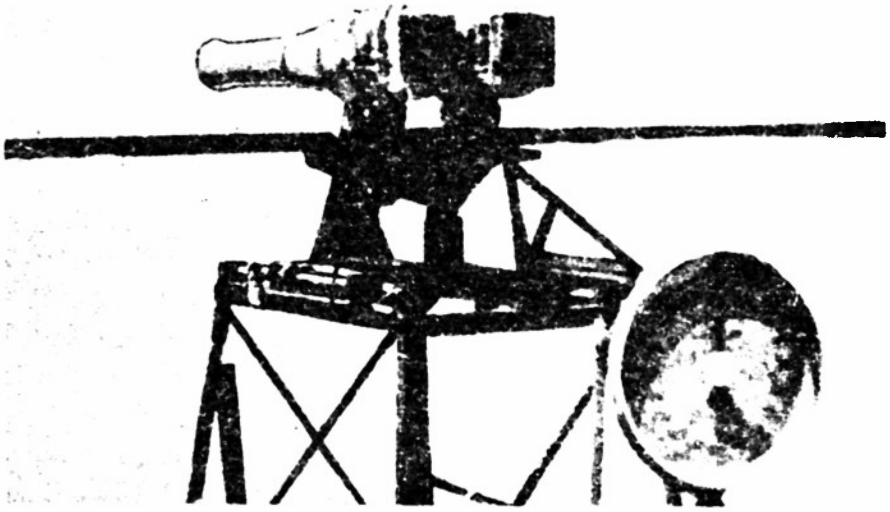


FIGURE 54

EXPLODED VIEW OF DUAL DUCTED ENGINE



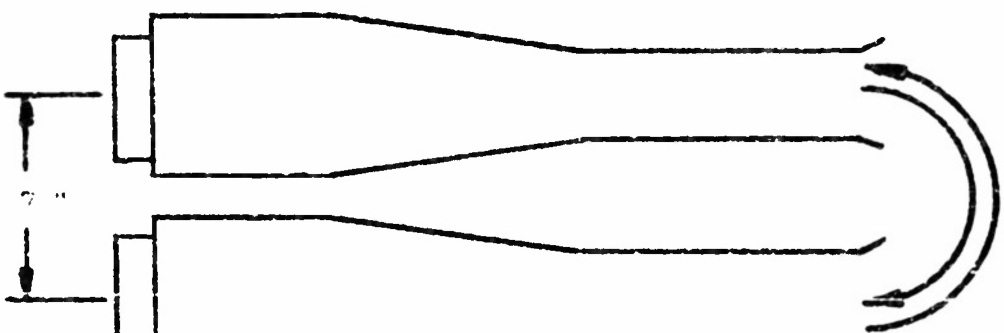


Figure 55

Two [illegible]-6.75 Pulse-Jet Engines Mounted
Side-by-Side to Resonate 180° out of Phase

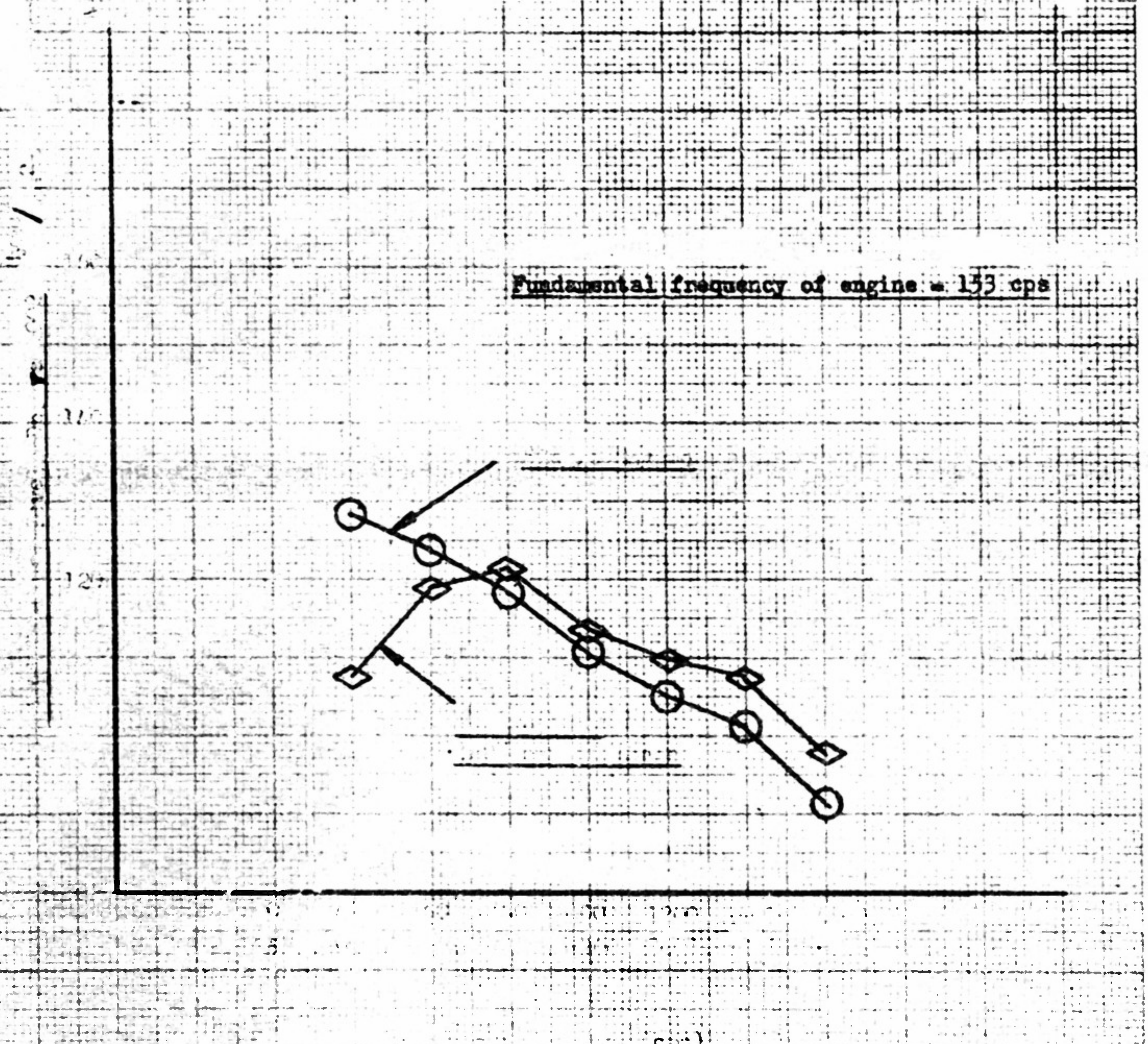


Figure 56

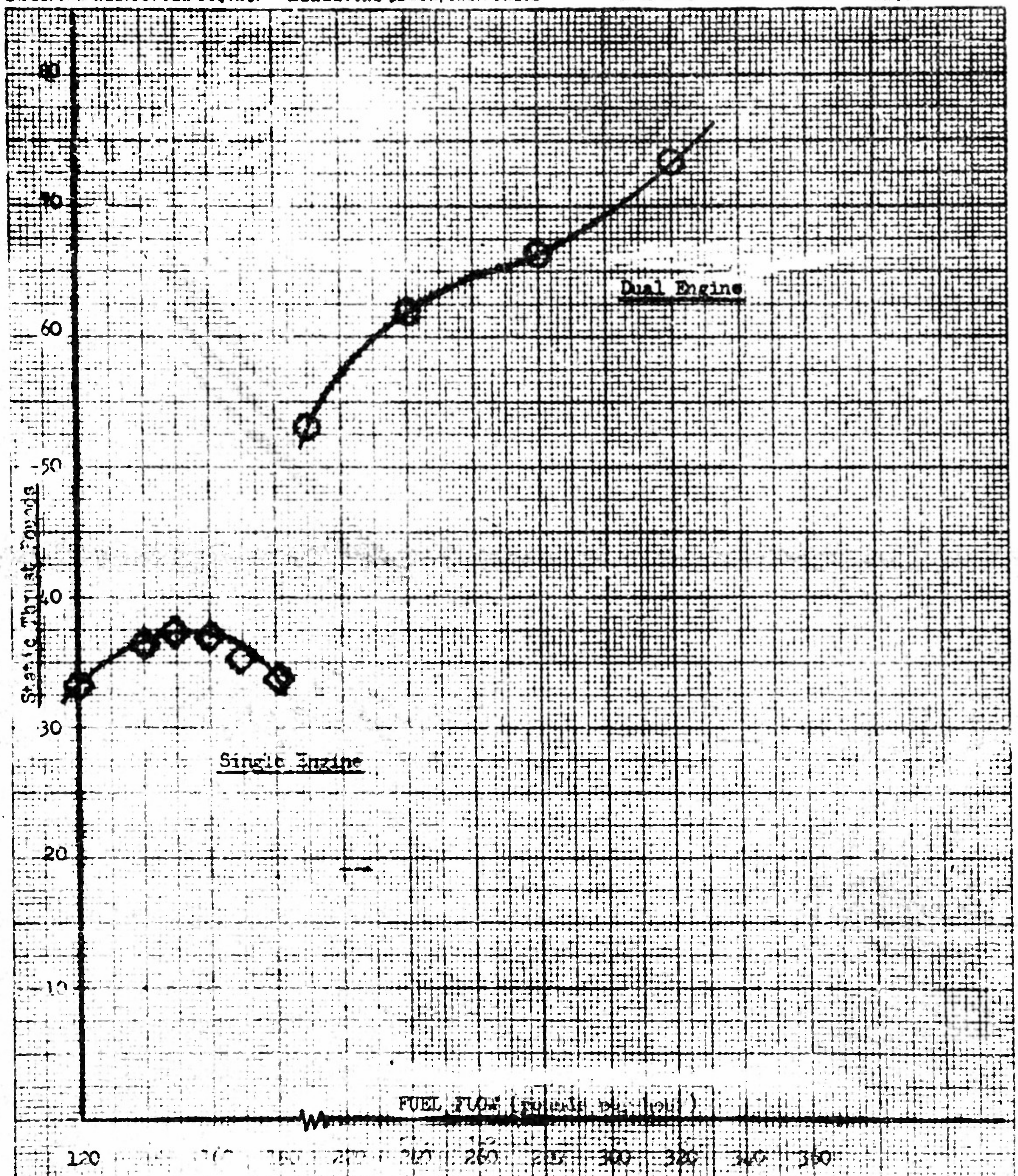


Figure 57

Static Performance Characteristics of Two Pulse-jet Engines Operating Side by Side

Poor Print! Traced over

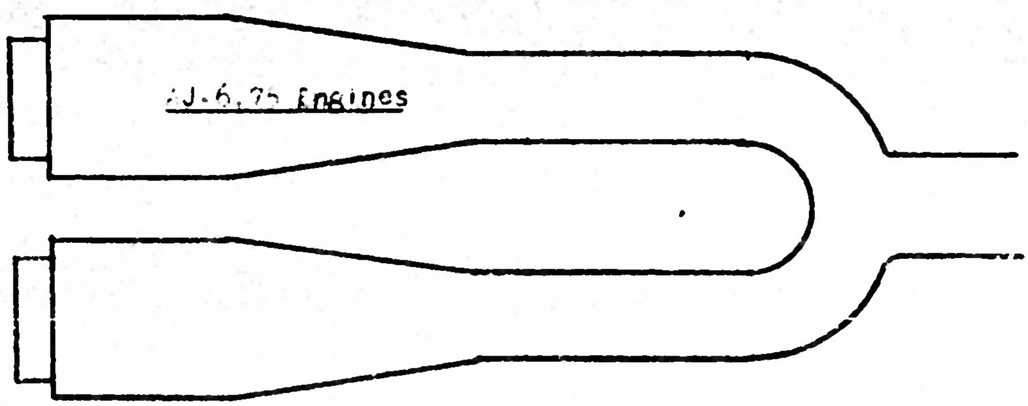


Figure 58

Dual Pulse-jet Engines with a
Common exhaust Duct.

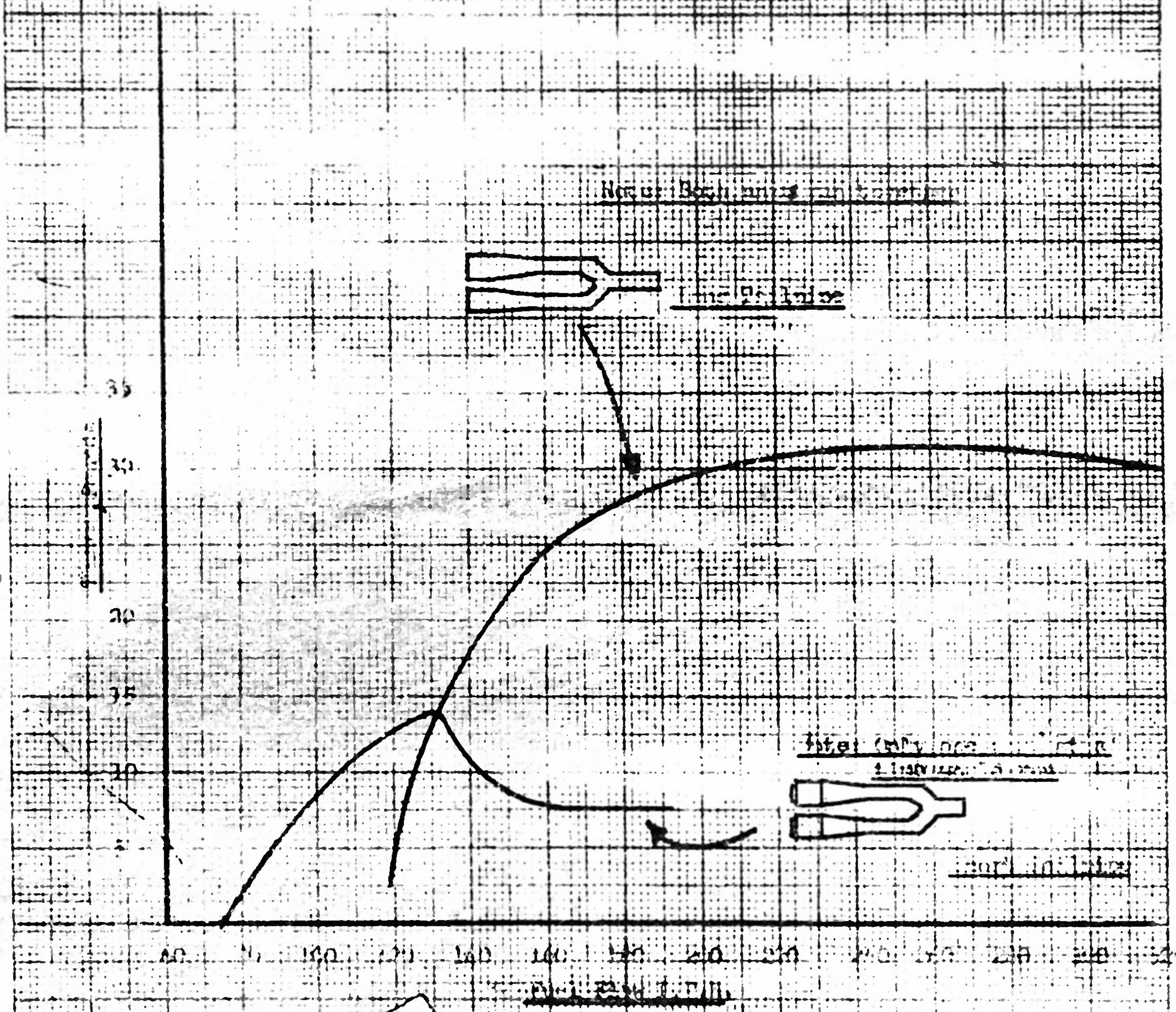
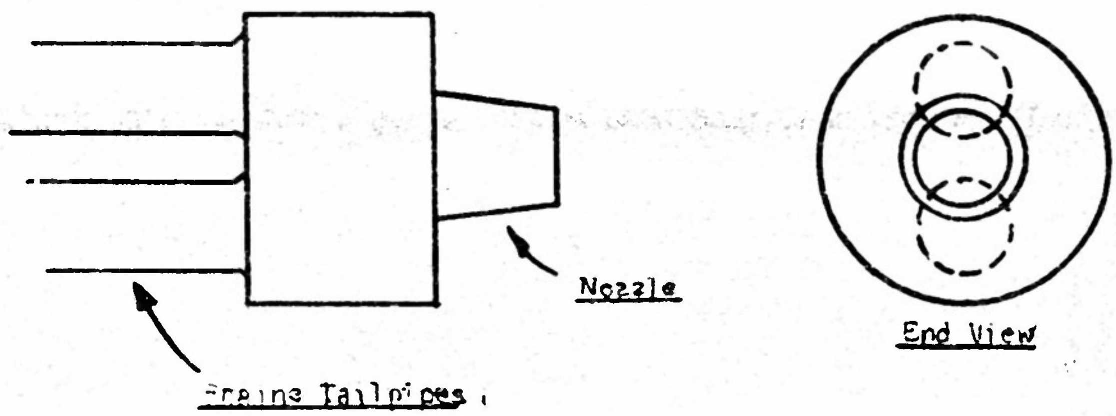


Figure 58

Static Performance of [illegible] Unit

4 Common Exhaust Duct



POOR PRINT! TRACED OVER

Figure 60

Circular Exhaust Plenum Configuration

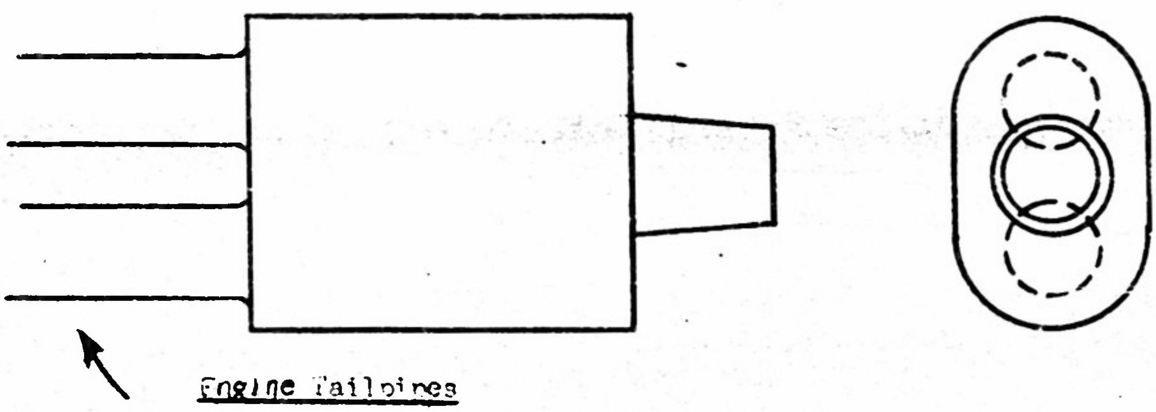


Figure 61

Oval Exhaust Plenum Chamber Configuration

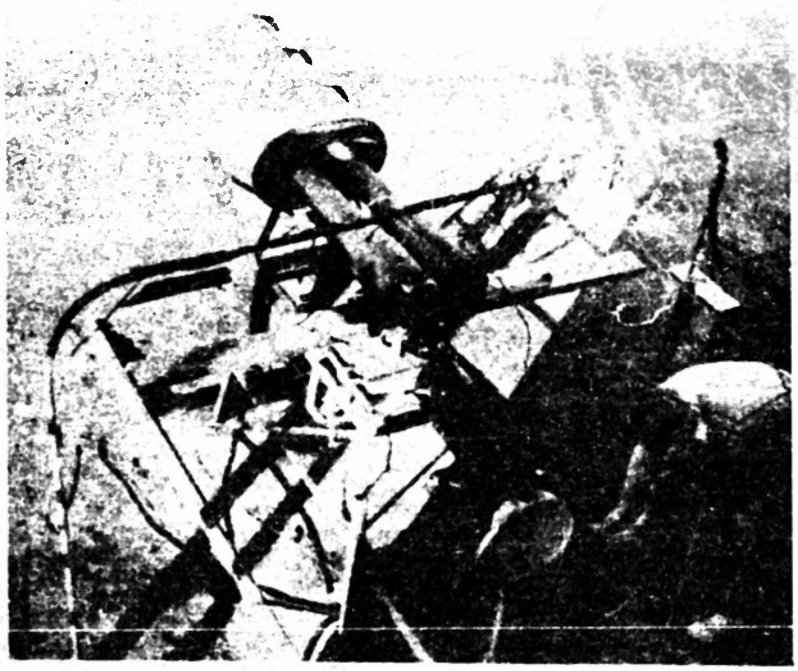
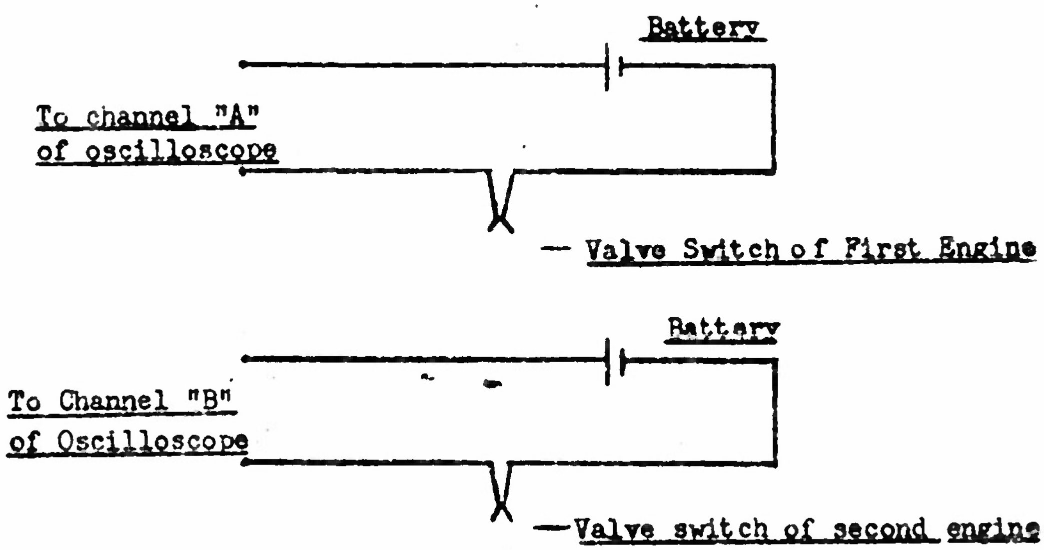


FIGURE 62

SIDE BY SIDE DUAL ENGINES WITH CIRCULAR AND OVAL TAILPIPE SHROUDS.



Valve Reed

FIGURE 63

VALVE SWITCH METHOD FOR DETERMINING PHASING OF DUAL ENGINES

SIMPLIFIED PULSE -JET ENGINE SCHEMATIC

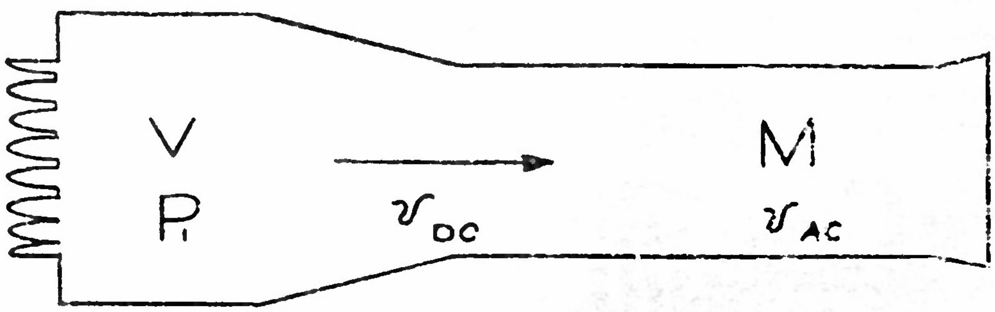


FIGURE 76

SIMPLIFIED PULSE-JET ENGINE ELECTRICAL ANALOGY SCHEMATIC

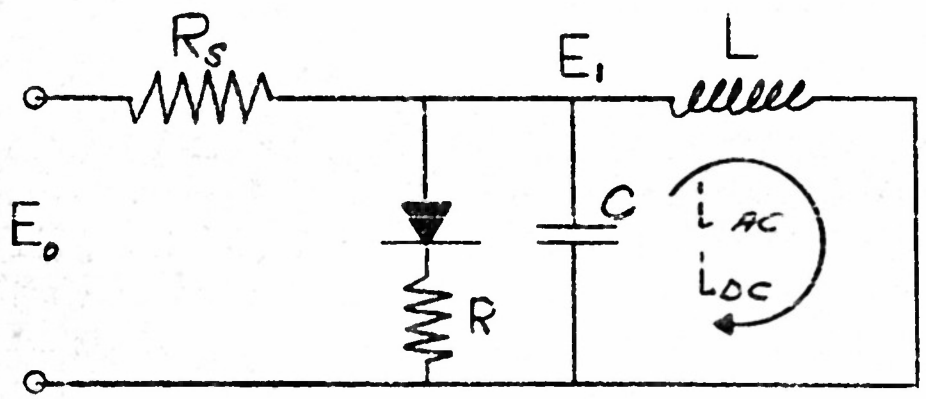


FIGURE 77

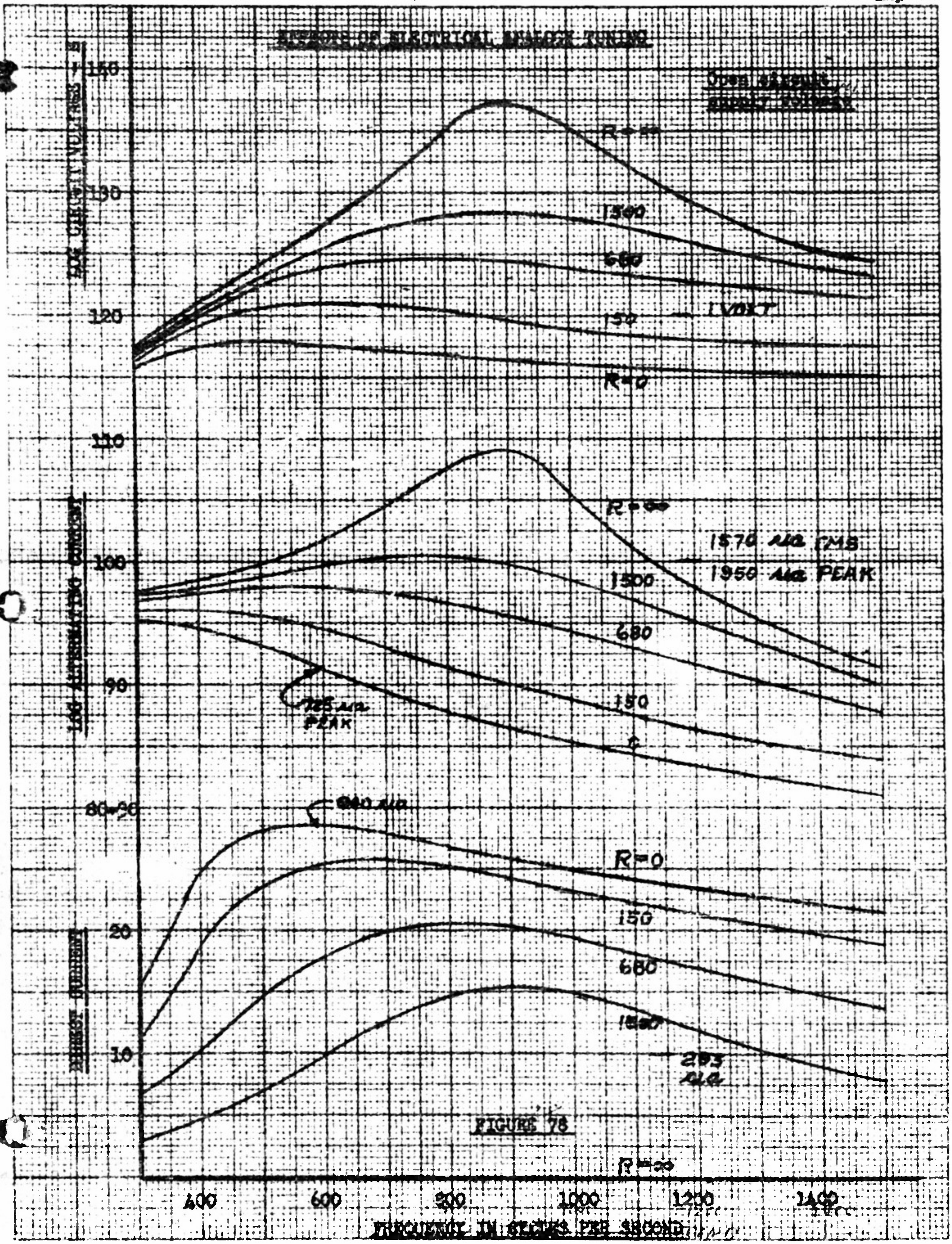

130
120
110
100
90
80
20
10
1500
680
150
1 VOLT
R=0
1570 MA RMS
1950 MA PEAK
725 MA PEAK
840 MA
R=0
150
680
1500
283 MA
400
600
800
1000
1200
1400

FIGURE 78

ELECTRICAL ANALOGY WAVE SHAPES

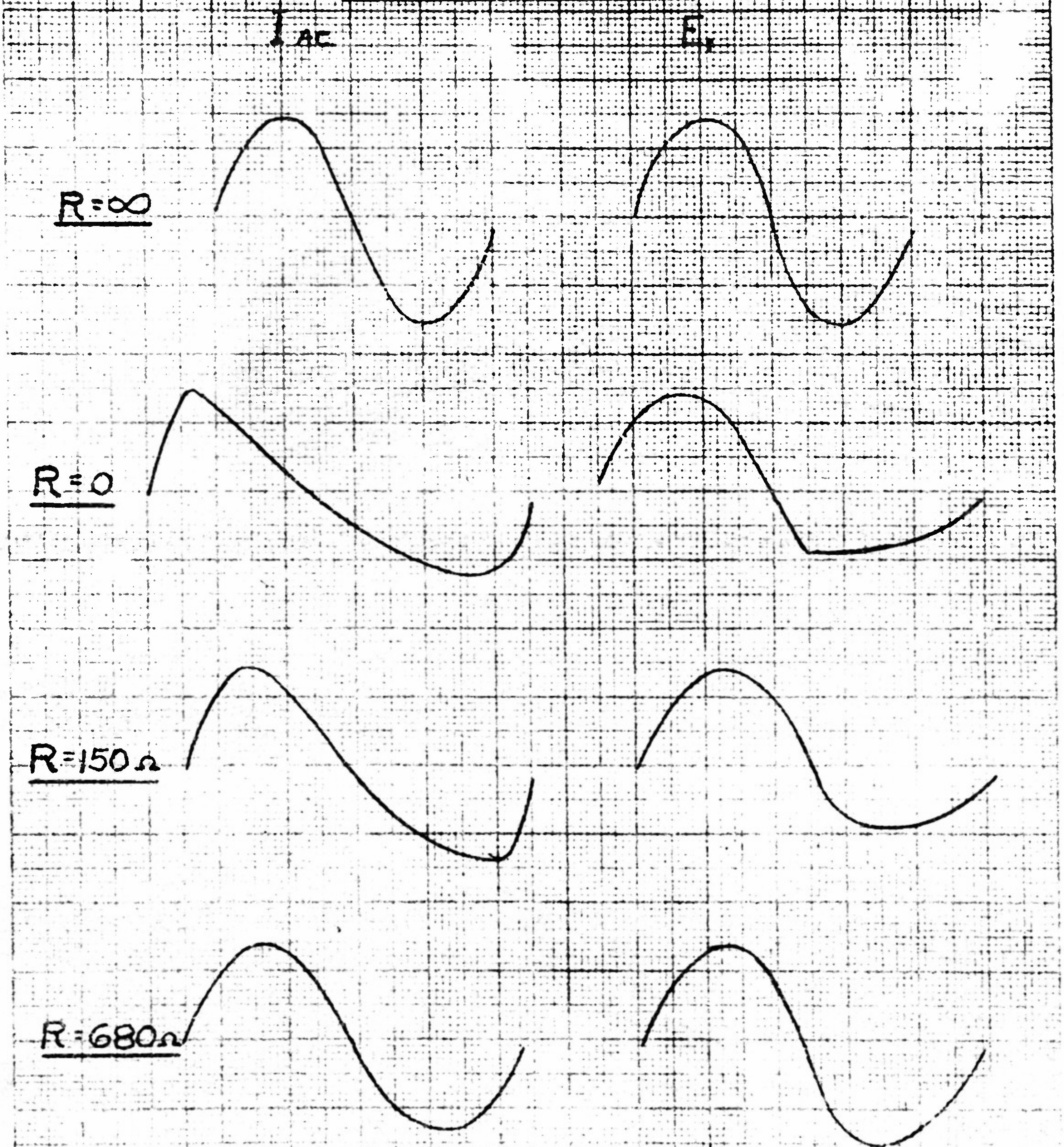


FIGURE 79.

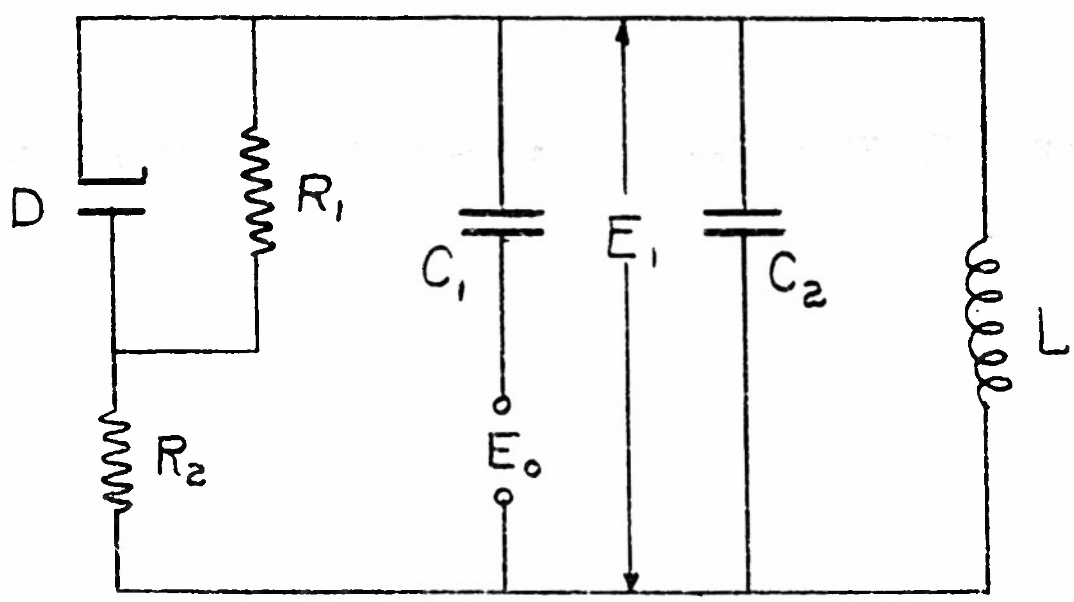


FIGURE 80

ELEMENTARY FORM OF PULSE-JET ANALOGY

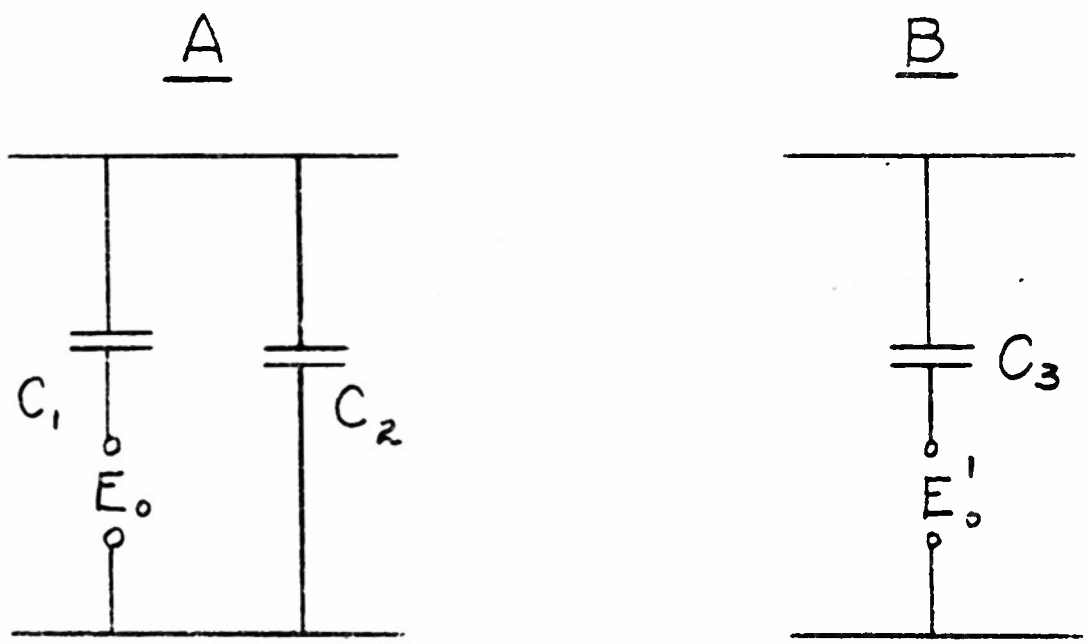


FIGURE 81

EQUIVALENT CIRCUITS

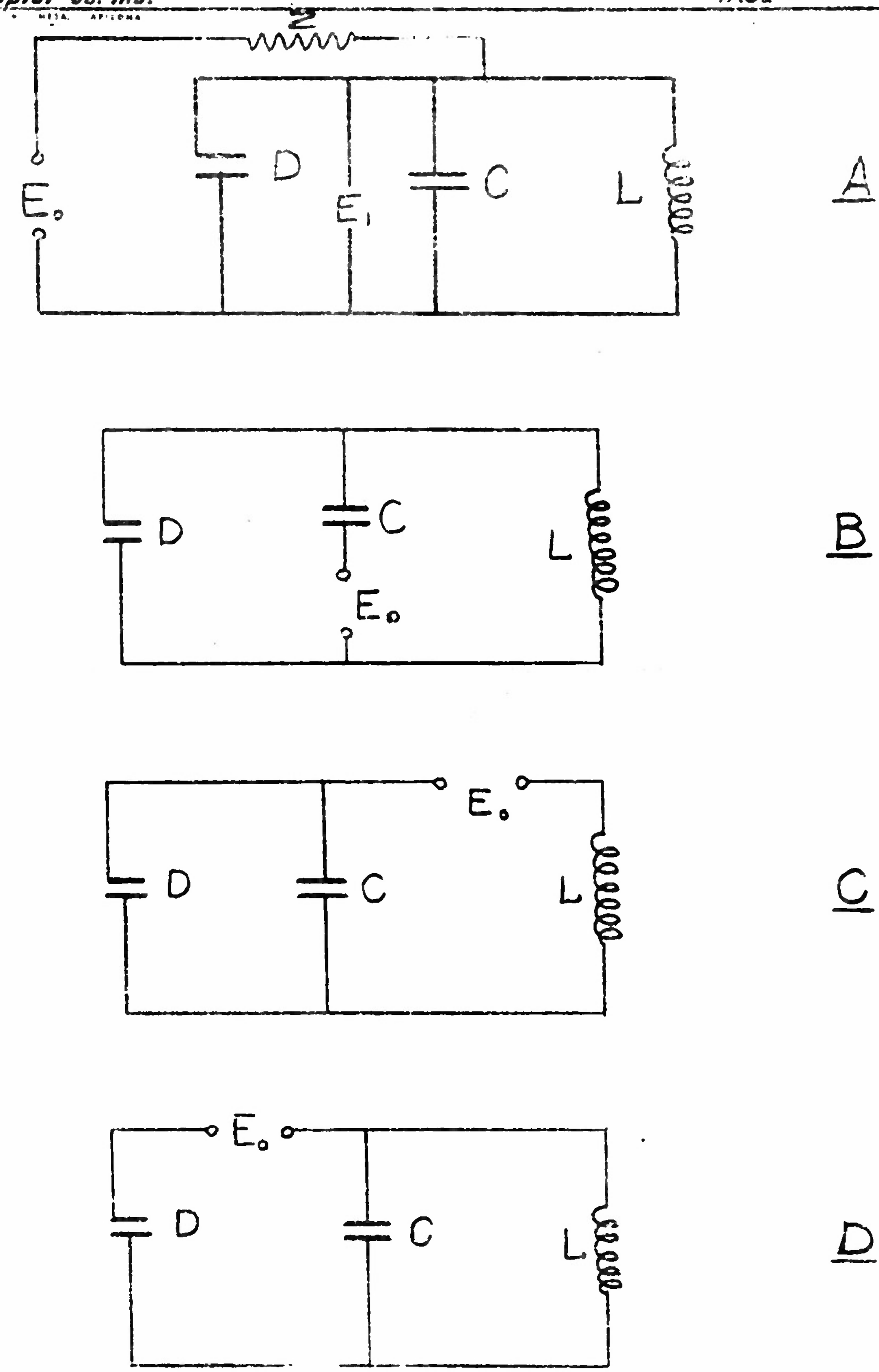


FIGURE 82

SEVERAL POSSIBLE CIRCUITS

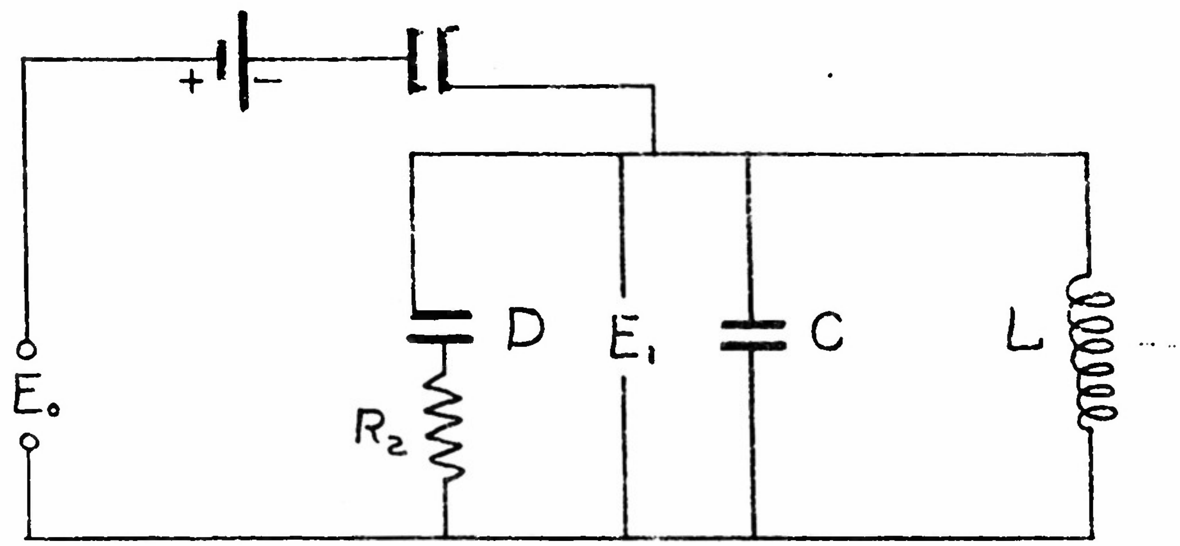


FIGURE 83

CIRCUIT"A" OF FIG. 82 WITH BIASED
DIODE SOURCE FOR PULSE EXCITATION

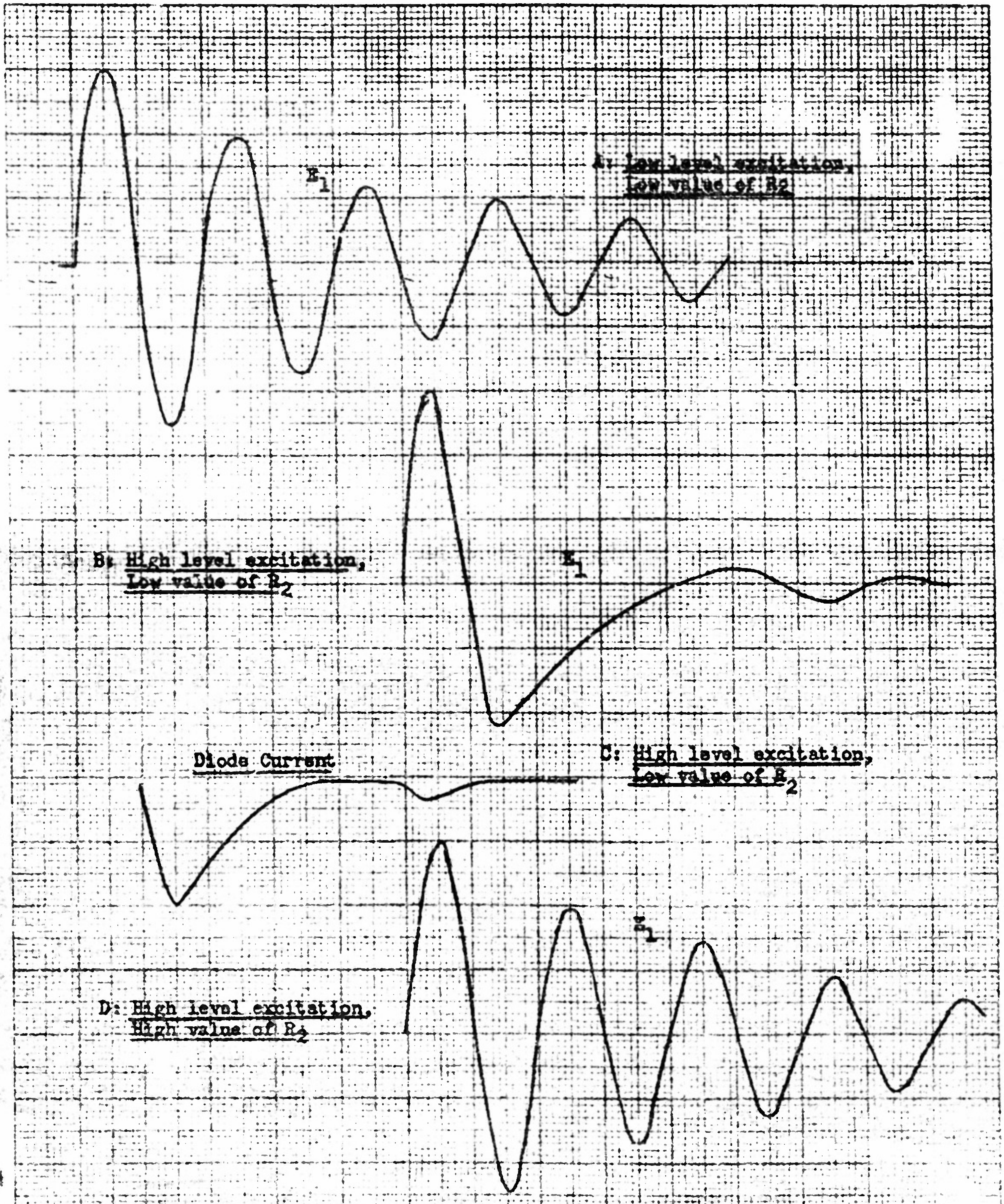


FIGURE 84

PULSE EXCITATION OF EITHER CIRCUIT OF FIG. 80 OR CIRCUIT OF FIG. 83

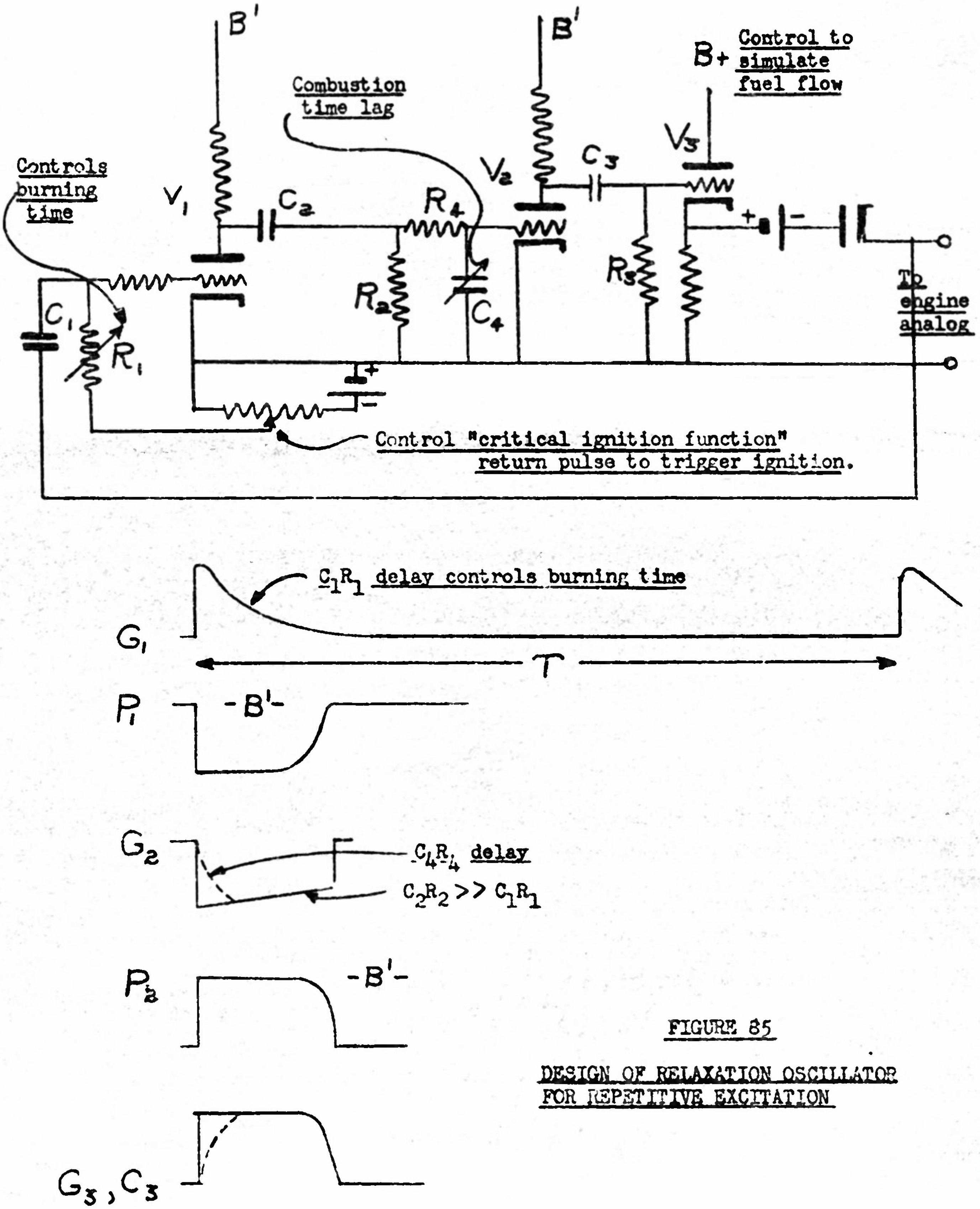


FIGURE 85

DESIGN OF RELAXATION OSCILLATOR FOR REPETITIVE EXCITATION

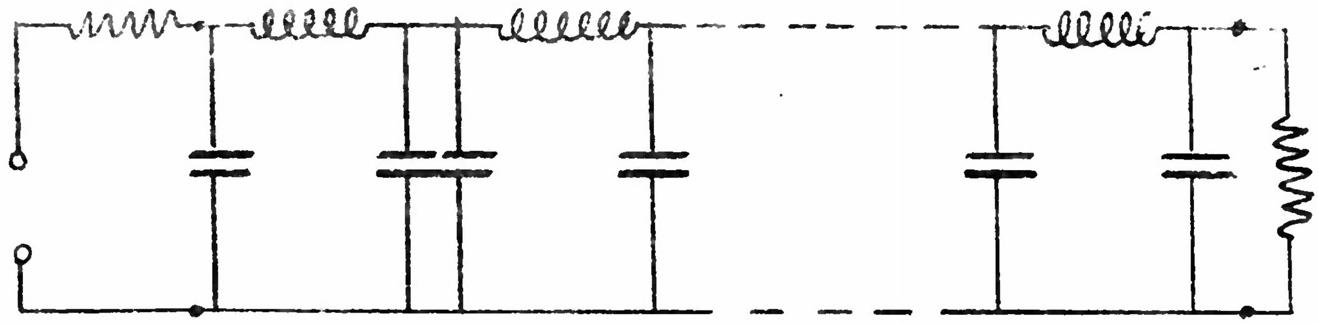
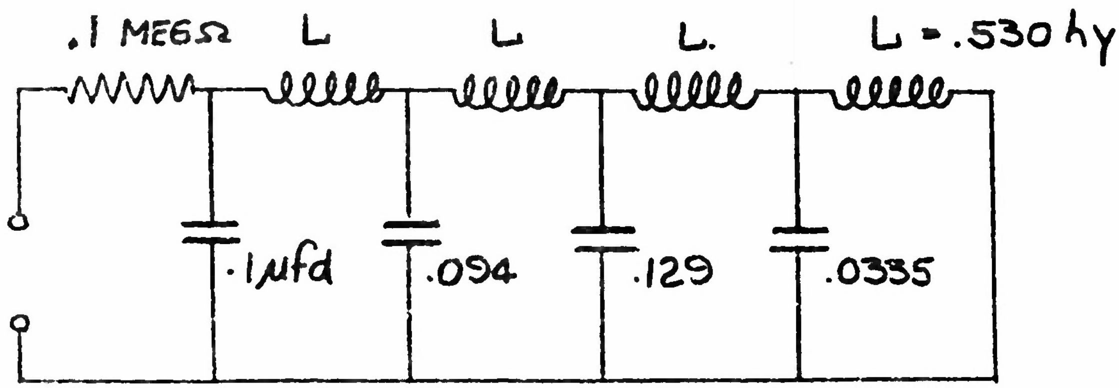


FIGURE 86

ARTIFICIAL LINE CONSISTING OF PI SECTIONS



FREQUENCY RATIOS: 1.00, 2.98, 5.00, 7.08

FIGURE 87

FINAL FOUR MESH LINE

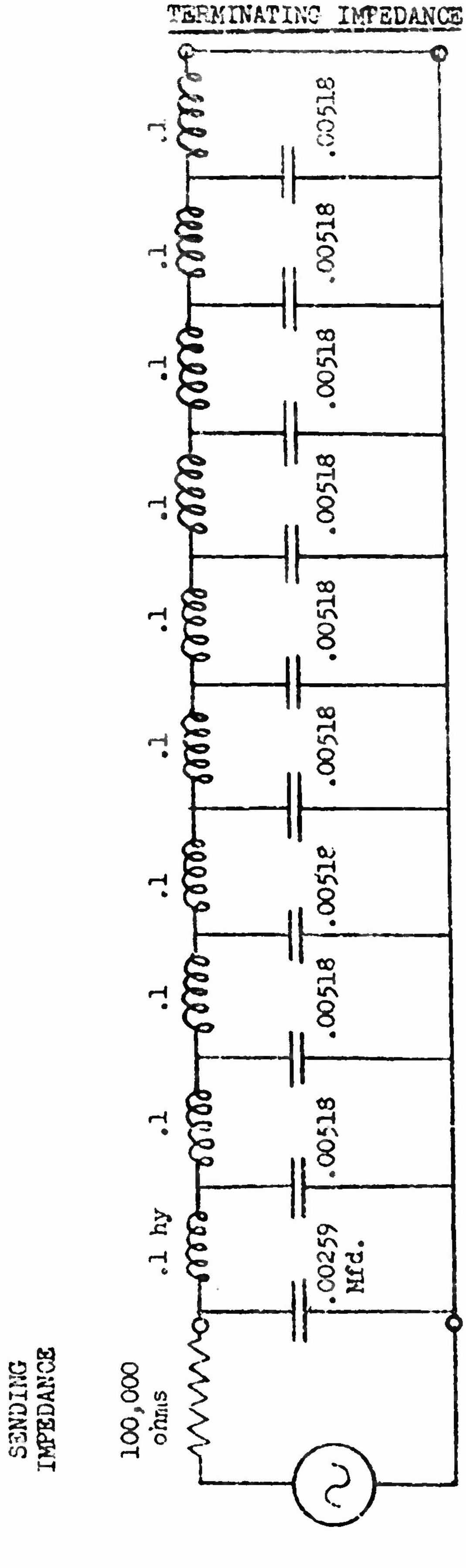


FIGURE 88

ARTIFICIAL LINE

CLASSICAL VALUES

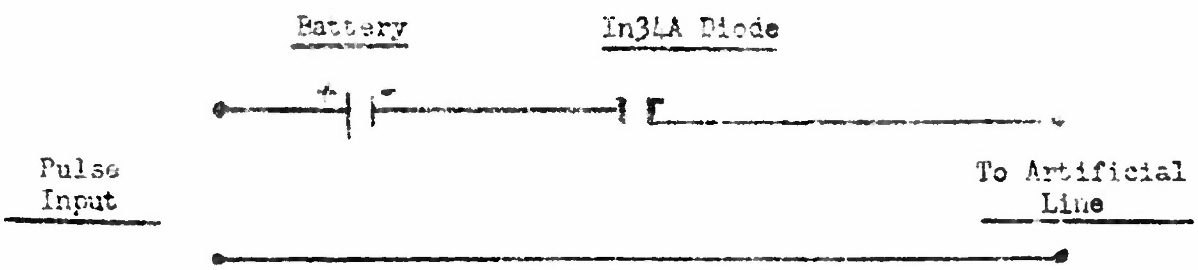


FIGURE 89

CIRCUIT FOR APPLICATION OF VOLTAGE PULSES TO NETWORK

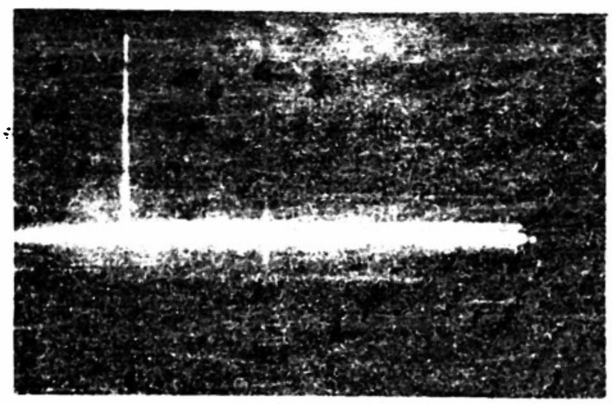


FIGURE 90

VOLTAGE PULSE

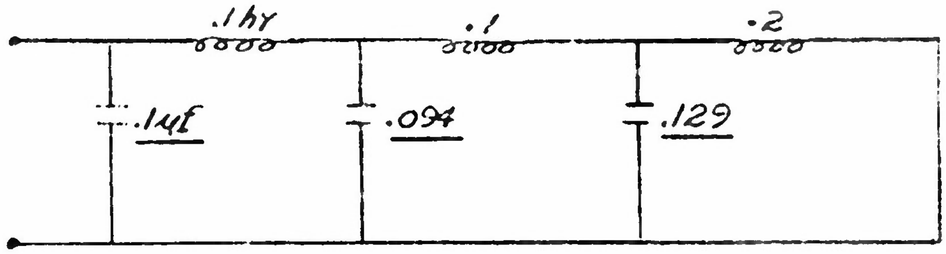


FIGURE 91

THREE SECTION LINE

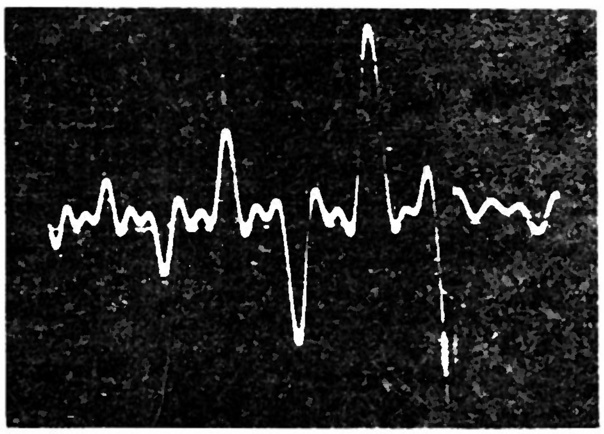


FIGURE 92

RESPONSE OF THREE SECTION LINE TO VOLTAGE PULSES

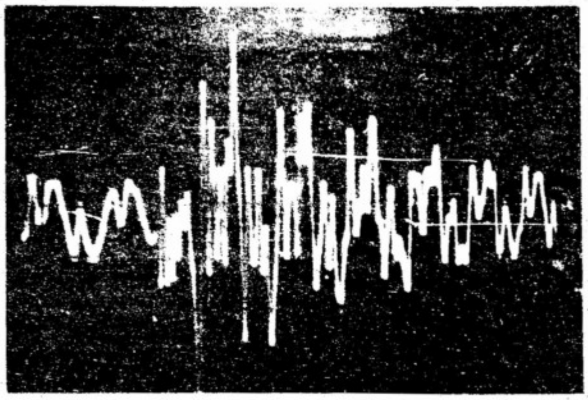


FIGURE 93

PULSE RESPONSE OF CLASSICAL TEN SECTION LINE

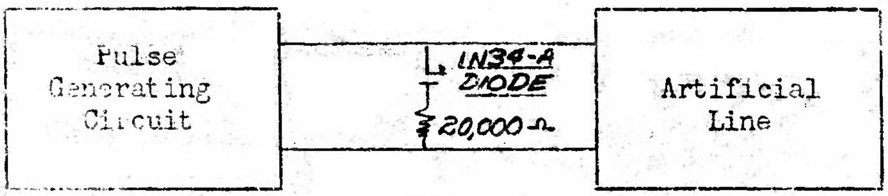


FIGURE 94

DAMPING COMPONENTS ADDED TO INPUT OF NETWORK

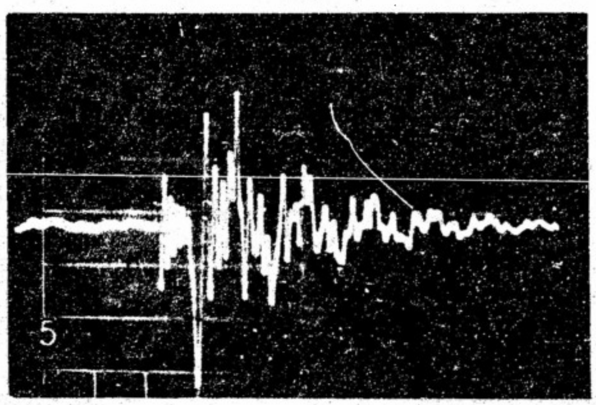


FIGURE 95

PULSE RESPONSE OF CLASSICAL TEN SECTION LINE WITH DIODE DAMPING ON THE INPUT

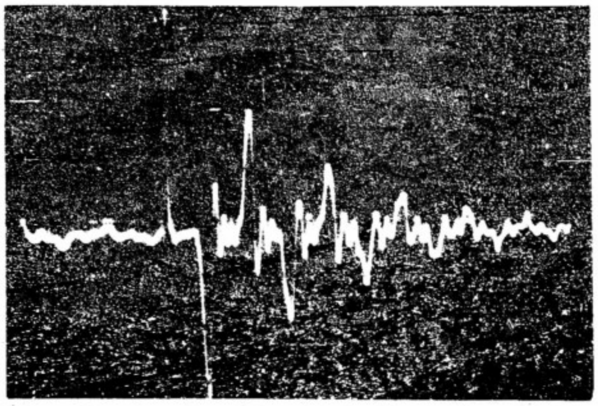


FIGURE 96

PULSE RESPONSE OF TEN SECTION LINE WITH INCREASED OUTPUT CONDENSER

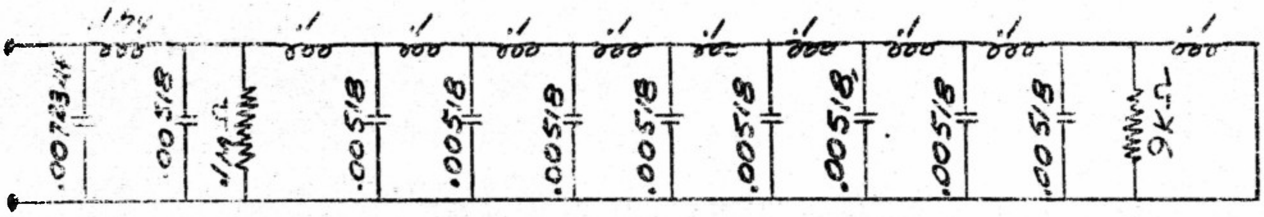


FIGURE 97 A

FINAL FORM OF ARTIFICIAL LINE

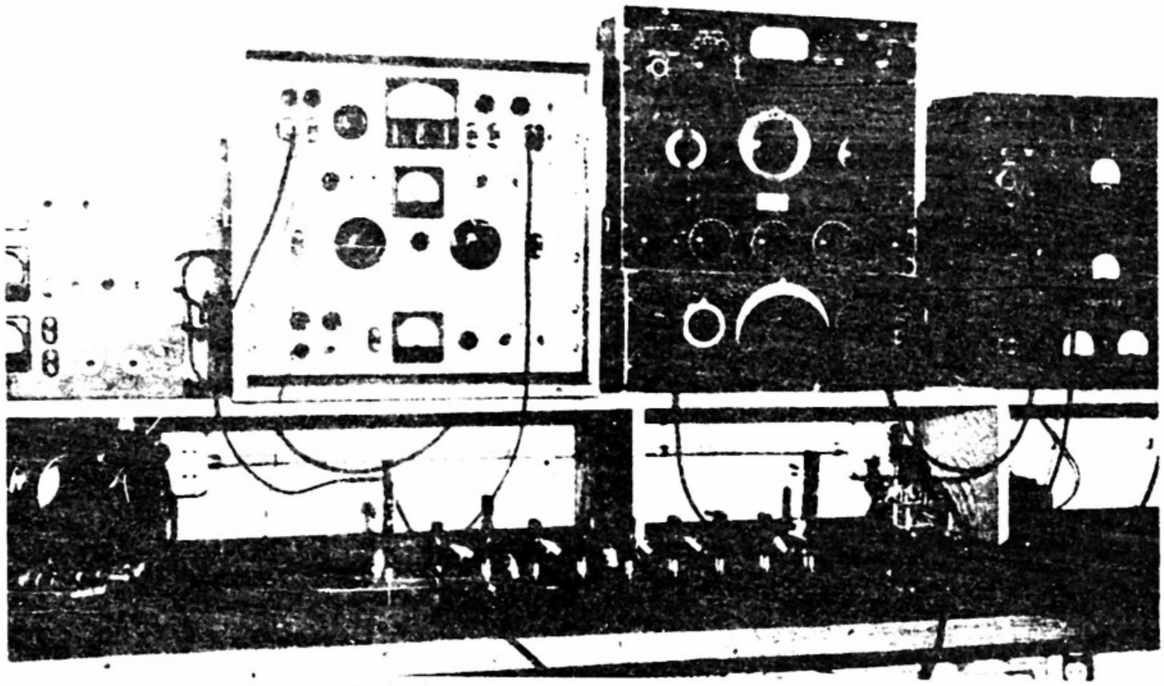


FIGURE 97 B

ARTIFICIAL LINE INSTRUMENTATION SET-UP

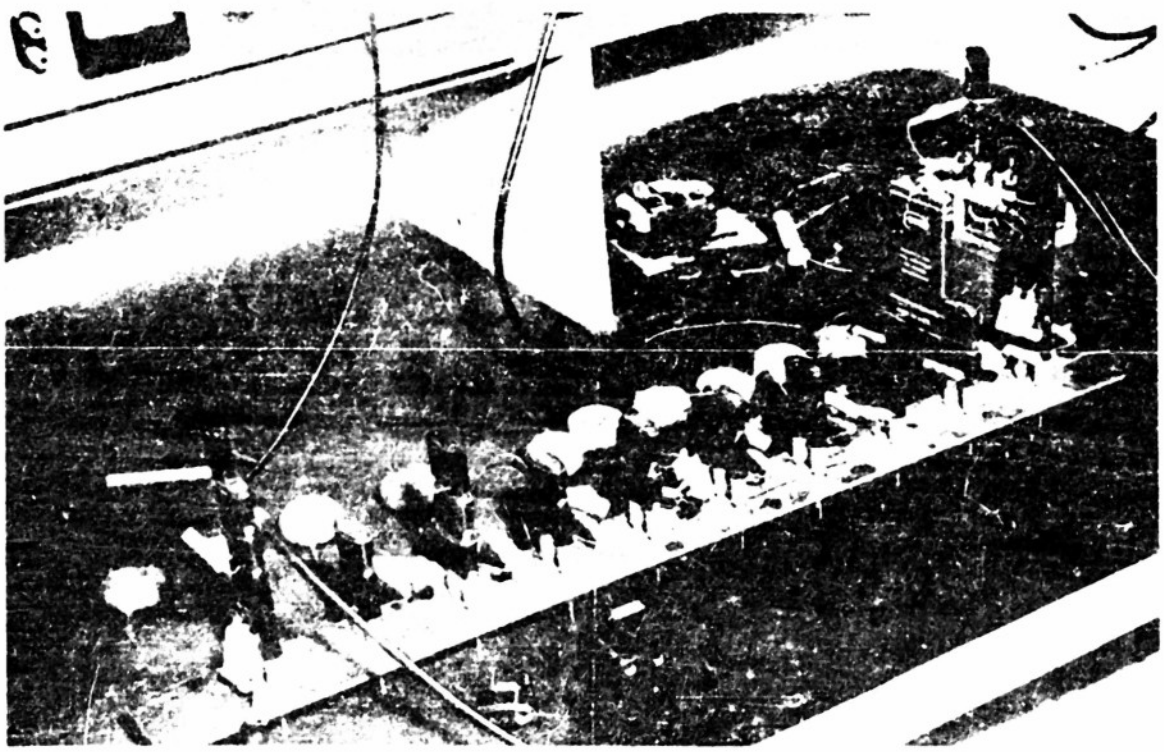


FIGURE 97 C

ARTIFICIAL LINE

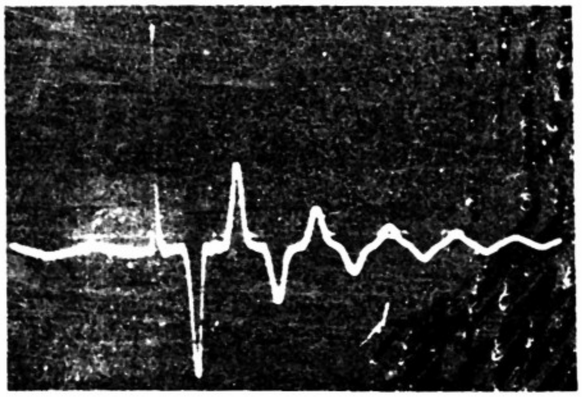


FIGURE 98

PULSE TRANSMISSION OF FINAL LINE

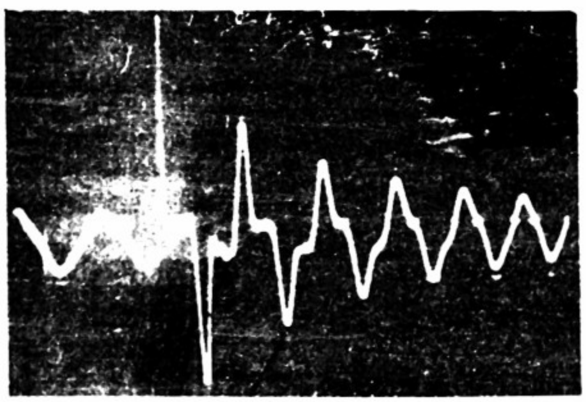


FIGURE 99

PULSE TRANSMISSION OF FINAL LINE WITHOUT DIODE DAMPING

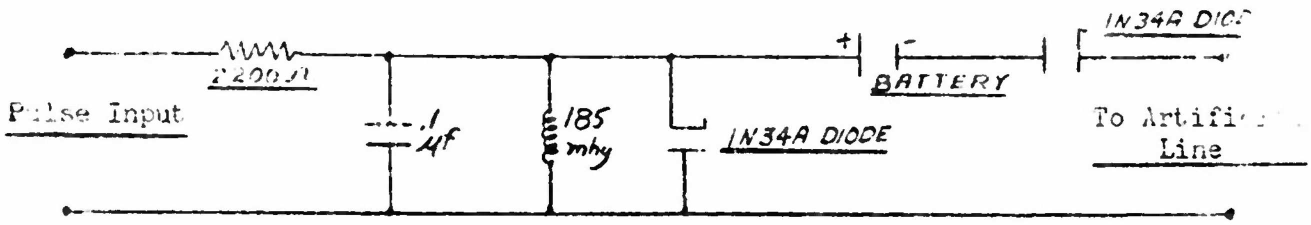


FIGURE 100

CIRCUIT USED TO PRODUCE LONGER PULSES

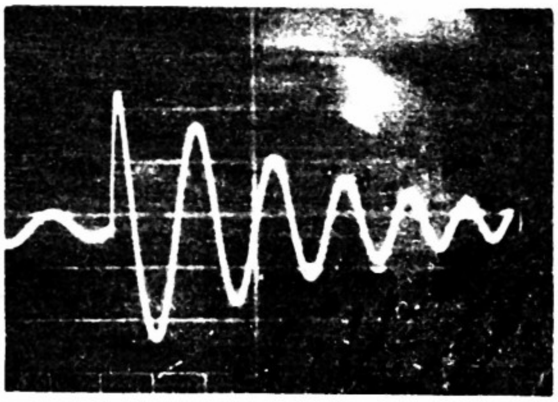


FIGURE 101

DAMPED LINE WAVE TRAIN PORTION OF PULSE PRODUCING NETWORK

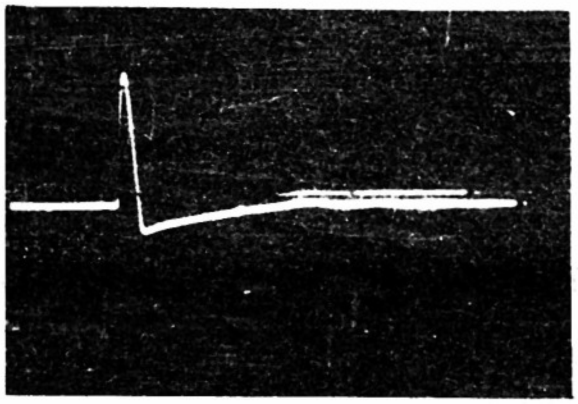


FIGURE 102

WAVE TRAIN DAMPED BY DIODE

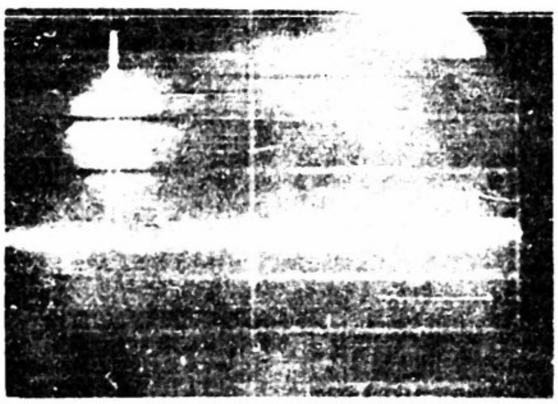


FIGURE 103

SQUARE PULSE AS APPLIED TO NETWORK

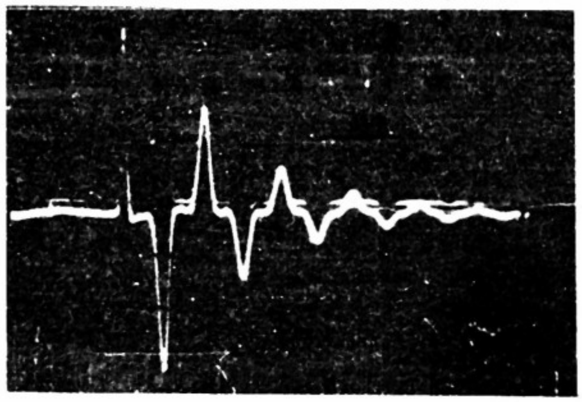


FIGURE 104

RESPONSE OF FINAL LINE TO BROADER PULSE

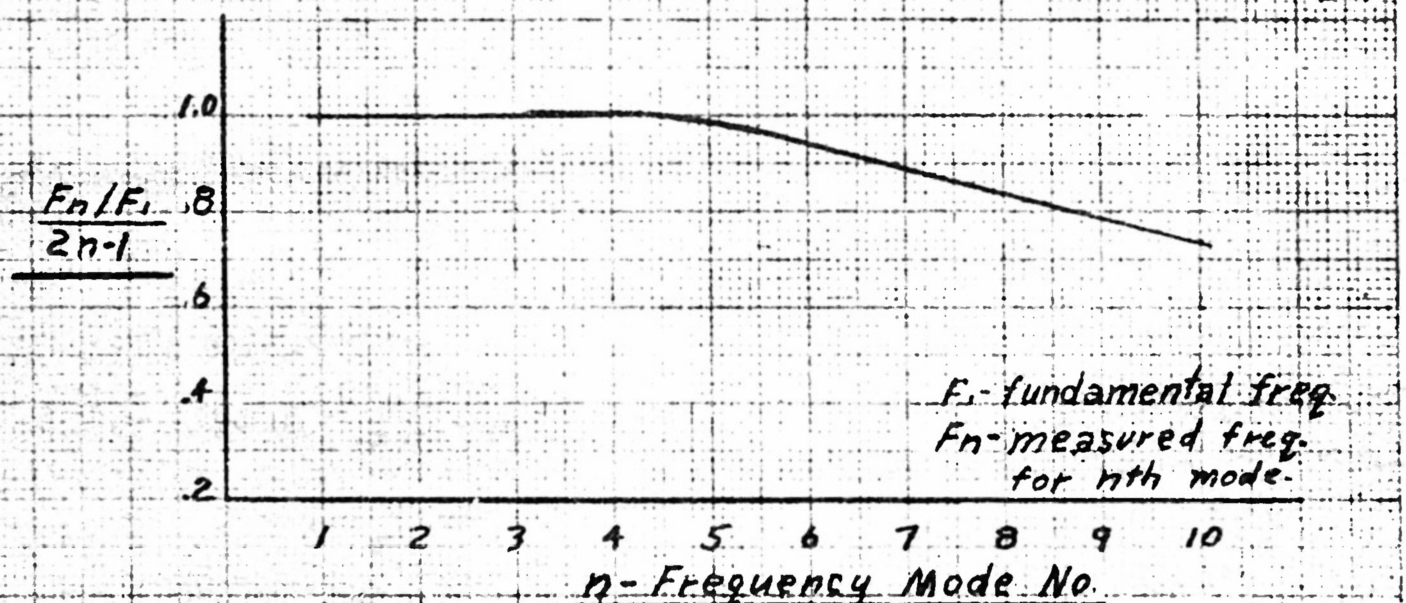


FIGURE 105

FREQUENCY DEVIATION FOR FINAL LINE

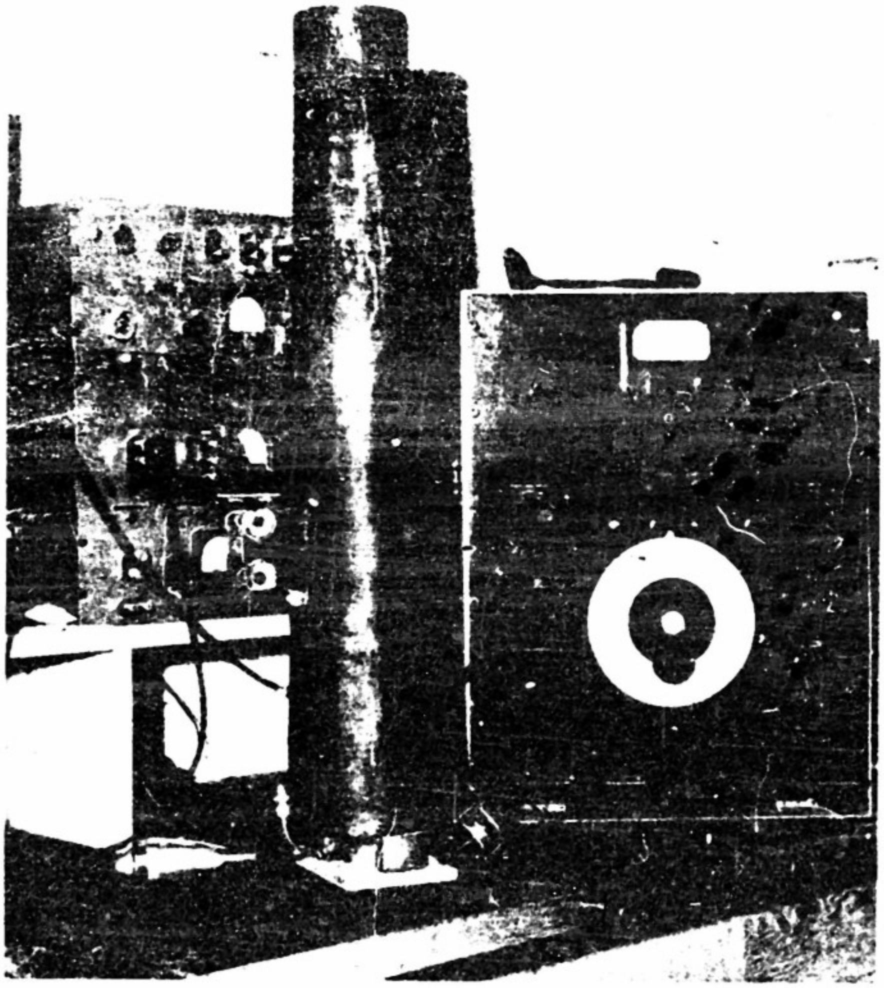


FIGURE 106

TEST SET-UP FOR DETERMINING PULSE-JET ENGINE TUBE RESONANT FREQUENCIES

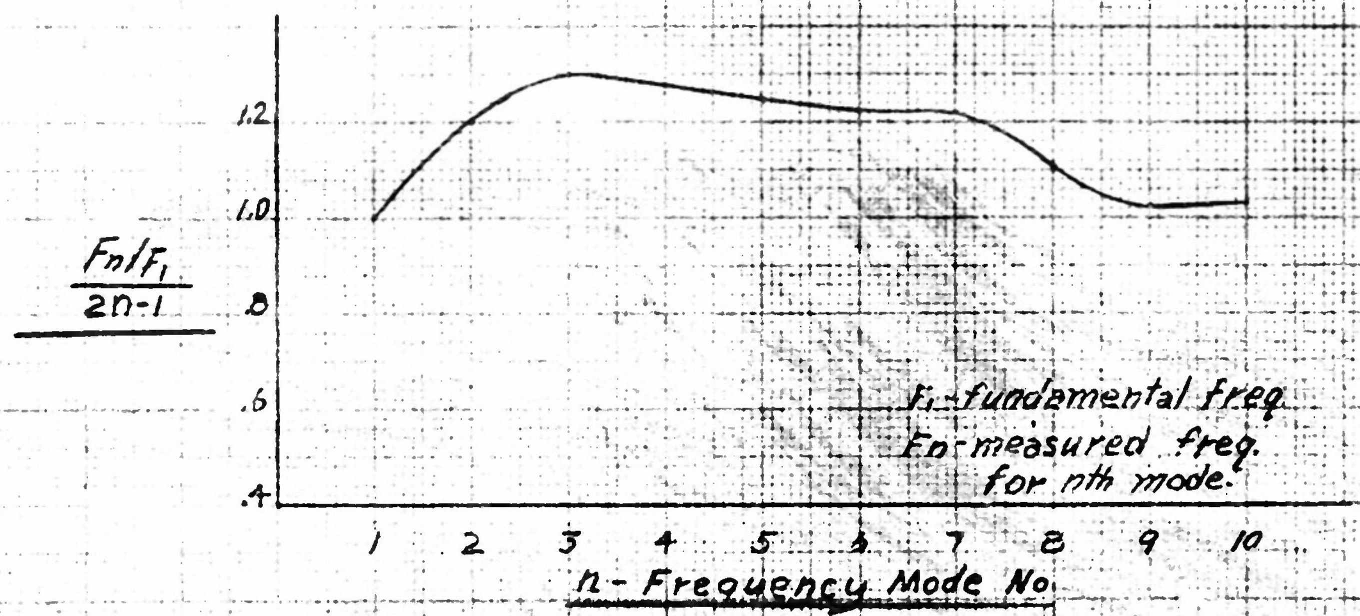


FIGURE 107

FREQUENCY DEVIATION FOR PULSE-JET TUBE