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PURDUE UNIVERSITY  
Engineering Experiment Station

Progress Report on  
Theoretical and Experimental  
Investigation of Jet Propulsion Devices

by

O. C. Cromer  
J. E. Yingst  
J. W. Raymond

Army Air Forces Cooperative Research Project

M-125-2

Contract No. W535 ac-38886 ✓

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PURDUE UNIVERSITY, ENGINEERING EXPERIMENT STATION,  
LAFAYETTE, IND.

PROGRESS REPORT ON THEORETICAL AND EXPERIMENTAL INVESTIGATION  
OF JET PROPULSION DEVICES

O.C. CROMER; J.E. YINGST; J.W. RAYMOND 31PP. PHOTOS,  
TABLE, DIAGRS, GRAPHS

USAF CONTR. NO. W535-AC-38886

POWER PLANTS, JET  
AND TURBINE (5)  
DESIGN AND  
DESCRIPTION (18)

ENGINES, JET - DEVELOPMENT  
ENGINES, JET - IGNITION SYSTEMS  
ENGINES, JET - STARTING  
JET PROPULSION - RESEARCH

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I. SUMMARY

This investigation was undertaken to study combustion under conditions that might be encountered in connection with a take-off or other device that might carry a source of high pressure air and fuel. The investigation is concerned with the amount of thrust which will be obtained together with the problem of obtaining satisfactory combustion. To increase the thrust, augmentation might be used and is also studied in the investigation. The investigation to date has primarily been concerned with combustion using various constant air pressures up to 70 psi. This pressure range was selected because of limitations of existing facilities. Even in case a much higher pressure source were available, it would probably be necessary to throttle this source to a pressure of this order in order to obtain satisfactory burner performance and continuous thrust over a reasonable period of time. A combustion chamber was developed which appears to be operating satisfactorily from the combustion standpoint. The method of starting the device, while not worked out in complete detail, seems to be possible of development into a practical method. Heat releases up to 21,400,000 Btu/hr/ft<sup>3</sup> of combustion chamber volume reduced to atmospheric pressure have been obtained.

Some tests were made on augmentation before combustion equipment was available. These tests, while not particularly conclusive, give some information which may be of use later in this study. This report gives a complete summary of the various experiments which were tried and the result of each. To date no attempt has been made to study the relative merits of various combustion chamber materials which might be used in order to give longer combustion chamber and nozzle life. This

particular problem may not be serious in connection with a take-off or other short-life jet-actuated device.

## II. PURPOSE

The possibilities of using jet propulsion for take-off assist or in connection with projectiles have not been fully realized. Some of these devices involve the burning of some kind of fuel using a high-pressure source of air. This investigation to date has been concerned primarily with combustion chamber design and performance. Further work on the design and performance of high-output combustion chambers is contemplated both as a primary source and in conjunction with an augmentor.

### III. COMBUSTION CHAMBER STUDIES

The investigations of combustion chamber design were made with Diesel fuel oil, since it was much safer to work with than gasoline. Recommendations obtained from the General Electric Company and the Bureau of Standards indicated that the results obtained with fuel oil would be somewhat similar to those which might be expected when burning gasoline or kerosene except for the greater ignition problem.

The following paragraphs give a detailed discussion of the various burners which were built and the experience obtained with them. A discussion of the results obtained will be given in the following section.

Burner No. 1 shown in Fig. 1 was made from a 1 1/2" pipe. This burner was a slight modification of the design furnished by the General Electric Company. A fuel oil line entered a reservoir centered in a coupling connecting the burner to the base, Fig. 2, used in the previous experiments on augmentation. A Monarch centrifugal fuel oil nozzle was screwed into this reservoir. The combustion chamber, which was a perforated cone, tapered outward from the fuel nozzle to the top of the outer jacket where the discharge nozzle screwed in. A spark plug was screwed into the bottom of the burner, and pyrex windows were inserted in the jacket so that the characteristics of combustion could be observed. The air entered the annular space between the outer jacket and the combustion chamber. It was admitted to the chamber through numerous small holes drilled into walls of the combustion chamber to facilitate mixing with the atomized fuel. The flow of fuel oil was from a reservoir connected to the air line and controlled by a needle valve. Ignition by means of the spark plug was not successful. Even

when the burner was heated and combustion was started by applying a flame the fuel would not burn completely. The chamber was so small that the oil spray from the nozzle impinged on the chamber walls and drained to the bottom of the chamber without burning.

The next burner was designed with a larger combustion chamber intended to eliminate this difficulty. The combustion chamber of burner No. 2 was made cylindrical of 1 1/2" galvanized pipe turned to a 1/16" wall, and the outer jacket was a 10" length of 2" pipe tapered to the size of the discharge nozzle by welding over slots cut lengthwise. This construction was used to give a varying annular space for air flow around the burner. The nozzle screwed into the bottom of the combustion chamber holding it securely and the jacket fitted over it, screwing into a 1 1/2" x 2" reducer on the base as is shown in Fig. 3. This burner was too small for satisfactory combustion.

The outer jacket of burner No. 3 was made of a 2 1/2" pipe tapered in the same way as No. 2. The combustion chamber was made from a 1 1/2" pipe machined to a 1/16" wall as shown in Fig. 4. Spark ignition worked with some success on this burner. It was decided that better combustion might occur if more air were introduced around the nozzle. After small holes were drilled in the base of the perforated combustion chamber, much more satisfactory combustion was obtained. Conditions still were such that the burning would not continue when the discharge nozzle was attached. The velocity was so high that, with the incomplete atomization, the flame was carried out through the nozzle.

In an effort to improve the atomization of fuel, it was decided to use higher fuel pressures. Instead of using pressure from the air line, a high pressure air bottle was charged by a compressor to about

500 psi and a line connected from it to the oil reservoir. A gage was attached to the fuel line so pressures could be read for the entering fuel. The pressure in the reservoir was maintained by throttling the air from the bottle, only as much air leaving the bottle as fuel leaving the reservoir. This change produced a slight improvement, but the operation was still erratic.

Burner No. 4, Fig. 5, was designed in an effort to eliminate the difficulties encountered with previous designs. In order to provide ample space in the combustion chamber for the fuel to atomize, the fuel oil nozzle was screwed into the apex of an air cone, which was tapered to the diameter of a 2 1/2" pipe. The combustion chamber, a 2 1/2" steel pipe machined to a 1/16" wall, rested on this cone. It was tapered down to the size of the discharge nozzle, and the outer jacket, a 3" pipe, was tapered in the same way, making a tight fit at the top of the combustion chamber. By making this burner 12 1/2 inches long, there was sufficient time allowed for combustion to be completed within the chamber. The outer jacket screwed into a 1 1/2" x 3" reducer coupling which in turn was screwed to the base, and the air cone supported by the fuel line was centered in this coupling. A hole was drilled and tapped in the reducer, into which a spark plug was screwed. An extension welded to the center electrode extended through a hole in the air cone, making a gap with a ground electrode welded to the inside of the cone. A spark coil and batteries provided the current for the spark.

The experiments performed on this burner after some modification were very satisfactory. The fuel was successfully ignited by the spark because the gap was now located in the path of the fuel spray. Combustion was at first incomplete, but was greatly improved by drilling

a sufficient number of holes in the air cone around the nozzle. In addition to admitting primary air for combustion, these holes also provided means for unburned fuel to drain out until the burner was thoroughly warmed up. The results of a test run on this burner are included in the data sheet, Table I.

When good combustion was attained, the gases in the burner were at a temperature of about 2000<sup>o</sup>F. At such a temperature, after about 20 minutes use, the welding material on the combustion chamber melted out, and also the reaction nozzle underwent considerable corrosion. The outside jacket radiated sufficiently to cooler surroundings and was further cooled by convection, so that it held up very well.

In view of these difficulties encountered in burner No. 4, it was decided that the merits of a tapered combustion chamber were nullified by weaknesses imposed. For this reason, burner No. 5 was made with a straight three inch pipe for the outer jacket and a straight coupling into which could be screwed a bushing to retain the reaction nozzle. A flange was inserted in the lower part of the jacket to facilitate removal from the base. The combustion chamber, made of the same 2 1/2" steel pipe, was machined to a 1/16" wall at the bottom in order to provide the maximum area in the annular air space. The holes were drilled so that a greater proportionate amount of air would enter the lower part of the chamber and a lesser amount at the top. The primary air supply was increased by drilling more holes in the air cone. A section view and various detail drawings of this combustion chamber are given in Fig. 6. This burner in addition to being more substantial produced better combustion.

The full capacity of this burner was not being attained since the single 3/8" diameter reaction nozzle used was designed for expanding cold air and was too small to discharge the greater volume of products of combustion. In estimating the discharge area required, this nozzle was used as a flow nozzle, and the air flow into the chamber was determined for the maximum capacity of the compressors supplying air. Analyzing the process of combustion using this quantity of air and a 15:1 air-fuel ratio a new nozzle was designed. This nozzle, shown in Fig. 7, was composed of 7 nozzle openings, each having a 3/8" throat diameter. Experiments were run with successive numbers of these nozzles open and at various fuel and air rates. The results, presented in Appendix II, indicate that the number of nozzles expanding gases correspondingly increases the thrust produced for a given air pressure approximately in proportion to the increase in area. The arrangement of the apparatus using burner No. 5 is shown in Fig. 8.

The temperature of combustion in burner No. 4 using discharge nozzle No. 1 was determined by drawing off some of the gases through a 1/4" pipe inserted in the side of the chamber. A bare platinum-platinum 13% rhodium thermocouple was inserted around a bend in this pipe so it could not "see" the inside of the combustion chamber. In this way, radiation losses from incandescent carbon particles were reduced, and a fairly accurate reading obtained. The temperature indicated with combustion occurring at 45 psig air pressure and 150 psig fuel pressure was 2350<sup>o</sup> F. This thermocouple arrangement was not satisfactory, since the heat completely melted the sampling pipe, and corroded the thermocouple wires.

A pressure drop of 1.4 psi across burner No. 5 was determined by means of a differential mercury manometer attached to the base of the burner and to the upper part of the combustion chamber.

The data and results of various tests run on the combustion chambers are included later in Table 1.

#### IV. AUGMENTATION STUDIES

Before the construction of burners was completed a few experiments were made to study the effect of augmentors when using cold air. These tests were discontinued when the burner investigation got under way. These studies were made by measuring the thrust which resulted when a venturi was placed beyond the mouth of a nozzle which discharged cold air.

Two venturæ were constructed from wood; one 12 in. long with a throat diameter of  $3/4$ " and  $10^\circ$  diverging section, and the other,  $7\ 1/2$ " long with a throat diameter of  $1\ 1/4$ ", and  $10^\circ$  diverging section. The air at 90 psi pressure entered the base shown in Fig. 2 and expanded through a nozzle. The venturæ fitted inside a 3" pipe which screwed down onto the base. These parts are shown in Fig. 9. The air issuing from the nozzle entrained surrounding air as it entered the venturi section. This entrained air had to enter the 3" pipe through the intake port in which was inserted orifice plates, thus making it possible to measure the flow. This assembly was then mounted on a platform scale and the reaction was measured at various air pressures with the venturi in different axial positions relative to the nozzle mouth.

The method of measuring flow was not satisfactory so the venturi was screwed into a collar supported above the nozzle, Fig. 10. Thus, air was entrained from all sides. The position of the venturi mixer above the nozzle was varied by screwing it up and down in the

stand. The results obtained from these experiments shown on curve sheets later in this report were incomplete and inconclusive.

## V. DISCUSSION OF RESULTS

The first successful apparatus that was constructed incorporating a fuel burner was equipped with a Monarch nozzle rated at 0.6 gallon per hour at 100 psi with a  $45^\circ$  spray angle. A nozzle of the lowest obtainable discharge capacity at the smallest possible spray angle was chosen in order to avoid, if possible, impingement of liquid fuel upon the combustion chamber wall. Even with so small a fuel spray, however, it was found necessary to increase the combustion chamber diameter before satisfactory combustion could be obtained.

The development procedure by which the burner in its present form was evolved from the original low capacity burner was a progressive increase in fuel-oil pressure, fuel-nozzle size, area of air supply openings in the burner inner wall, and discharge-nozzle area, while the combustion chamber pressure was decreased. The net effect of these changes was an appreciably increased heat release per unit of combustion chamber volume, which was considered one of the significant objectives of the investigation. A release of less than 2,000,000 Btu/hr/cu ft of corrected combustion chamber volume was increased to more than 21,000,000 Btu.

Employment of a series of progressively larger fuel nozzles culminated in the final selection of a 4 gallon per hour nozzle with an  $80^\circ$  spray angle. Since the fuel was supplied to the nozzle at much higher pressures than that at which it was rated, deliveries up to 15 gallons per hour were obtained. The wider spray angle of this nozzle gave better atomization and dispersion than the  $45^\circ$  nozzles originally used.

It was obviously necessary to provide increased air openings through the combustion chamber wall to compensate for the increased amount of fuel delivered by the larger nozzles operating at higher fuel pressures and the decreased air-supply pressures. A lengthy cut-and-try process at each stage of the development appeared to be the only means of correlating the flow of fuel and air into the chamber and the exit of gases from the discharge nozzle. Until this rather critical combination of flow rates was arrived at, the burner either would not burn at all or else an undesirably long flame would be emitted from the discharge nozzle.

To permit operation at lower and more practical pressures than the original 100 psi while burning greater amounts of fuel, the area of the discharge nozzle was increased by progressive enlargements to seven times the original throat area of 0.11 sq in. The heat release needed to maintain the burner pressure behind this outlet opening proved to be well in excess of that at which the combustion chamber wall could be maintained and necessitated consideration of better materials, surface finishes, and design if continuous operation is to be possible.

Analysis of the effects of the various changes in design and operation of the burners that were made at the several stages of the development leads to generalizations regarding what now appear to be desirable features of such a combustion chamber.

The overall dimensions of a burner for most applications should be kept to a minimum. Because the velocity of flow through the combustion chamber together with the length of path of the gases within the chamber determine the time available for burning the fuel, it appears desirable to reduce this velocity by supplying as little excess air as

is consistent with good combustion. Since all of the air supplied to the burner must either be stored in pressure bottles or compressed to operating pressure as supplied by some form of compressor, any reduction in excess air will also be beneficial by decreasing the air storage or compressor power expenditure requirement. One of the objectives was therefore to burn as much fuel as possible with a given air supply, thus reducing the combustion chamber length and the air supply capacity needed while increasing the heat release per unit of combustion chamber volume.

Any loss in pressure through the burner tends to reduce the pressure of the gases entering the discharge nozzle below that at which air is supplied to the burner and consequently reduces the unit velocity from the nozzle. The pressure drop across the burner was kept at a minimum by providing as easy a path for air flow through the combustion chamber wall as possible without impairing combustion. This consideration led to the use of a smaller number of larger air openings rather than the large number of small openings which seemed at first desirable because of the somewhat better penetration of the air jets formed. A pressure drop of 1.4 psi was found to occur across burner No. 5 at maximum capacity operation. This drop caused an estimated loss in exit velocity of 180 feet per second, about 5.25%.

The distribution of the air openings along the length of the burner sleeve proved very critical. It was found imperative that a substantial portion of the air enter through the cone behind the fuel nozzle and through the first few inches of the cylindrical sleeve. Too great a portion of the air entering near the outlet nozzle was found to cause burning outside of the combustion chamber, thereby offsetting the possible advantage of aiding in cooling the combustion chamber wall.

Observation under best operating conditions revealed that combustion started about three inches beyond the fuel spray nozzle and the hottest point in the burner was about five inches farther from the nozzle. Less satisfactory air distribution moved the combustion zone toward the discharge nozzle.

Fig. 11 shows the effect of operation for about thirty minutes upon the multiple orifice nozzle that was used for exit gases in burner No. 5. Flow lines of the hot gases, probably at temperatures above the 2350 F measured in burner No. 4, can be seen where the plastic metal was carried up through the nozzle openings. The problem of finding materials that will withstand such temperatures is a serious one for any application requiring continuous operation of the burner for any appreciable length of time, but does not affect the short duration operation required in some applications.

It is planned to continue this study of combustion chambers to see if a unit capable of easier starting and better combustion can be developed. It is proposed to introduce the air into the combustion chamber tangentially through very narrow, closely spaced, axial slots. It is hoped that this construction will also provide better cooling of the combustion chamber wall by increasing the area of metal surface scoured by the combustion air in proportion to the inner area absorbing heat.

TABLE I.

## RESULT AND DATA SHEET

Test No.	Pressure, psig		Heat Released B/hr/ft <sup>3</sup>	Air-Fuel Ratio	Thrust Pounds	Fuel Rate lbs/hr	Remarks
	Air	Fuel					
4a	20	150	2,160,000	187:1	3	9.0	Test was run on Burner No. 4 with reaction nozzle No. 1 and fuel oil nozzle - 0.6 GPH
4b	25	150	1,883,000	187:1	3.5	9.0	Air was supplied by an automotive compressor.
5a	40	200	—	—	12	—	Test was run on Burner No. 5, with reaction nozzle no. 2.
5b	40	200	—	—	14	—	3 nozzles open - fuel oil nozzle - 1.5 GPH - 80°. Ingersoll-Rand air compressor supplied air.
5c	35	200	3,780,000	75:1	17	22.5	Same as 5a. 3 nozzles open - fuel oil nozzle - 2.0 GPH - 80°
5d	25	200	4,710,000	75:1	11	22.5	Same as 5a. 4 nozzles open - Fuel oil nozzle - 2.0 GPH - 80°
	18	200	—	—	7	—	Same as 5a. 5 nozzles open - Fuel oil nozzle - 2.0 GPH - 80°
5e	22	200	—	—	10	—	Same as 5d. Automotive air compressor was put on line with Ingersoll-Rand
5f	30	200	5,110,000	75:1	13.5	22.5	Same as 5a. 5 nozzles open - Fuel oil nozzle - 3.0 GPH - 80°. Ingersoll-Rand
	25	200	—	—	10	—	compressor supplied air.
5g(1)	30	200	8,370,000	37.5:1	23.5	45.0	Same as 5a. 7 nozzles open - fuel oil nozzle - 4.0 GPH - 80°. Ingersoll-Rand and auto compressor supplied
(2)	28	200	—	—	18	—	air.
(3)	27	250	21,400,000	18.7:1	17	90.0	Burner No. 5 - Reaction nozzle No. 2 fuel oil nozzle - 4.0 GPH - 80°
6c	32	170	—	31.9:1	22.5	52.9	Ingersoll-Rand and auto compressor

<sup>1</sup> Air temperature remains constant at 100° F.

<sup>2</sup> Heat released in B/hr per ft<sup>3</sup> of combustion chamber volume corrected to standard atmospheric conditions.

VII. CALCULATIONS

Diesel fuel oil - A.P.I. gravity = 35°

Using the Bureau of Standards approximation for Heating Value.

$$\text{H.V.} = 18,690 + (\text{A.P.I.} - 10)36$$

$$\text{H.V.} = 18,690 + (35 - 10)36$$

$$\text{H.V.} = 19,590 \text{ B/lb}$$

Heat released based upon corrected volume of air in combustion chamber:

$$\text{Volume of combustion chamber} = 60.2 \text{ in.}^3 = 0.034 \text{ ft}^3$$

Test 4a

$$\text{Heat Released (B/hr/ft}^3) = 19,590 \text{ B/lb} \times \frac{9 \text{ lbs}}{\text{hr}} \times \frac{1}{60.2 \text{ in.}^3} \times \frac{1728 \text{ in.}^3}{\text{ft}^3}$$

$$\text{H.R.} = 5,060,000 \text{ B/hr ft}^3$$

The pressure in the combustion chamber is approximately the same as the pressure of the air entering the chamber. Therefore, to correct the heat released to a value in terms of the cubic ft of standard air, multiply by the ratio  $\frac{P_{\text{standard}}}{P_{\text{actual}}}$ .

$$\text{H.R.} = 5,060,000 \times \frac{14.7}{34.5} = 2,160,000 \text{ B/hr ft}^3$$

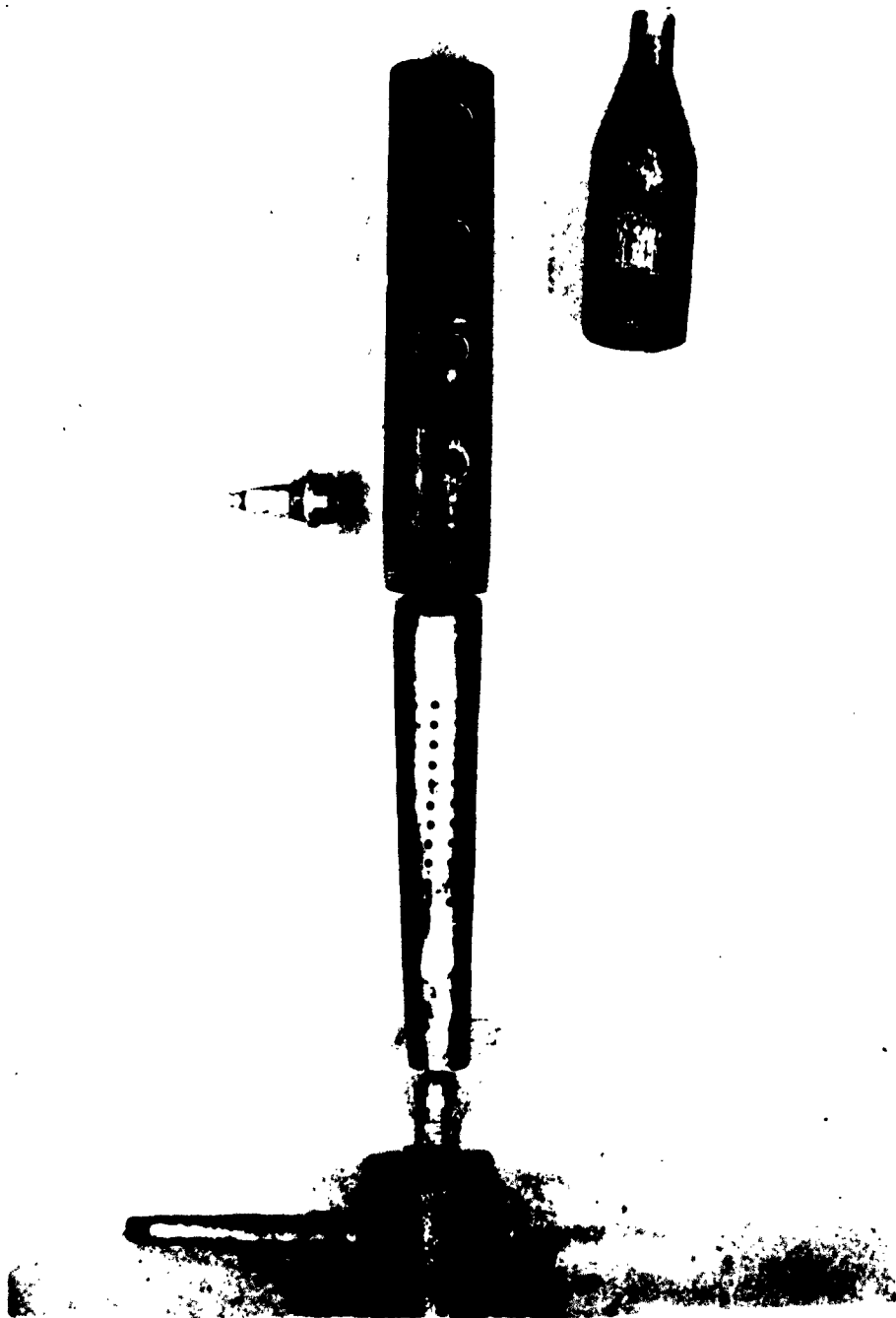


Fig. 1

Exploded View of Combustion Chamber No. 1

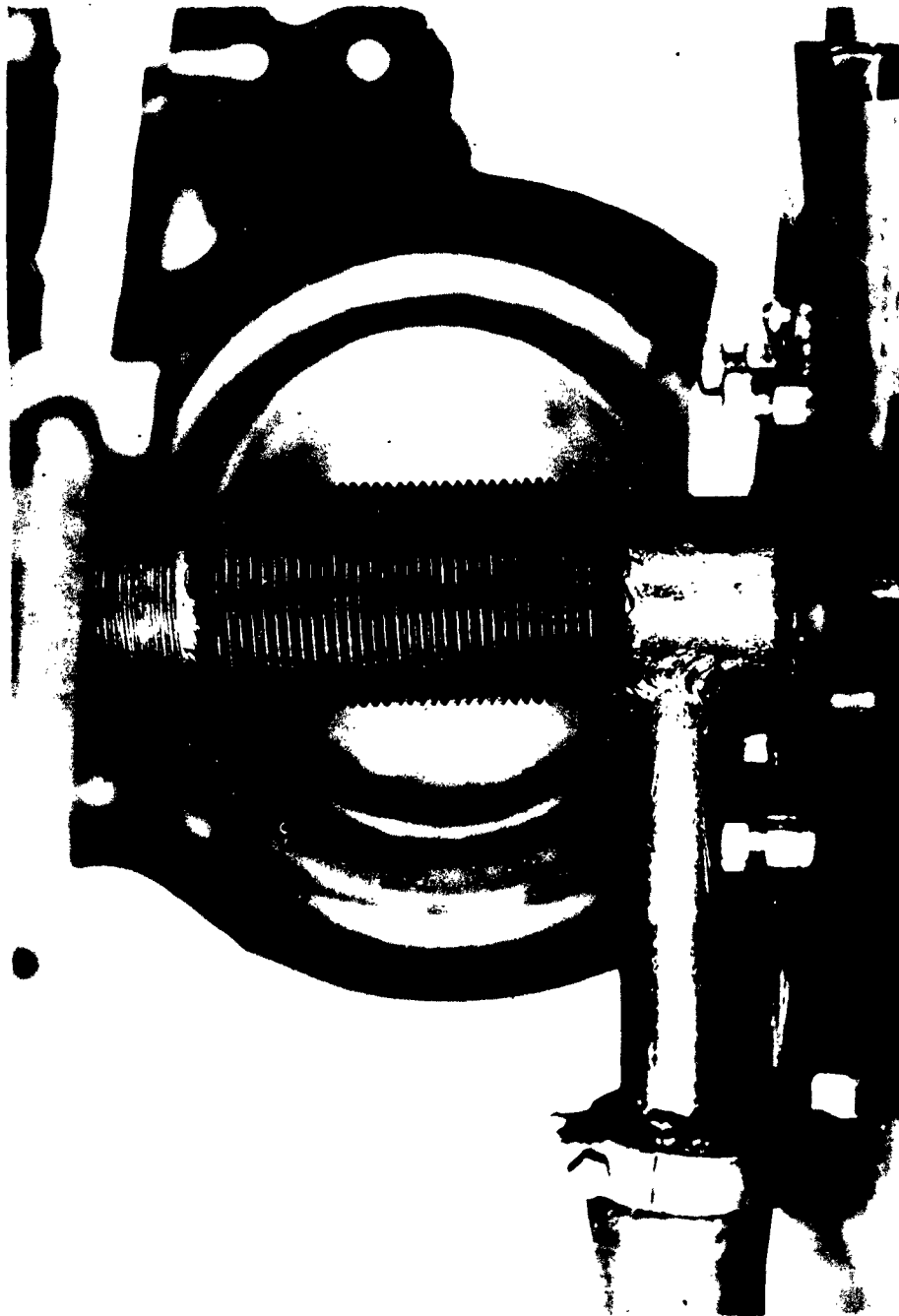


Fig. 2

Base through which Air Enters Combustion Chamber.

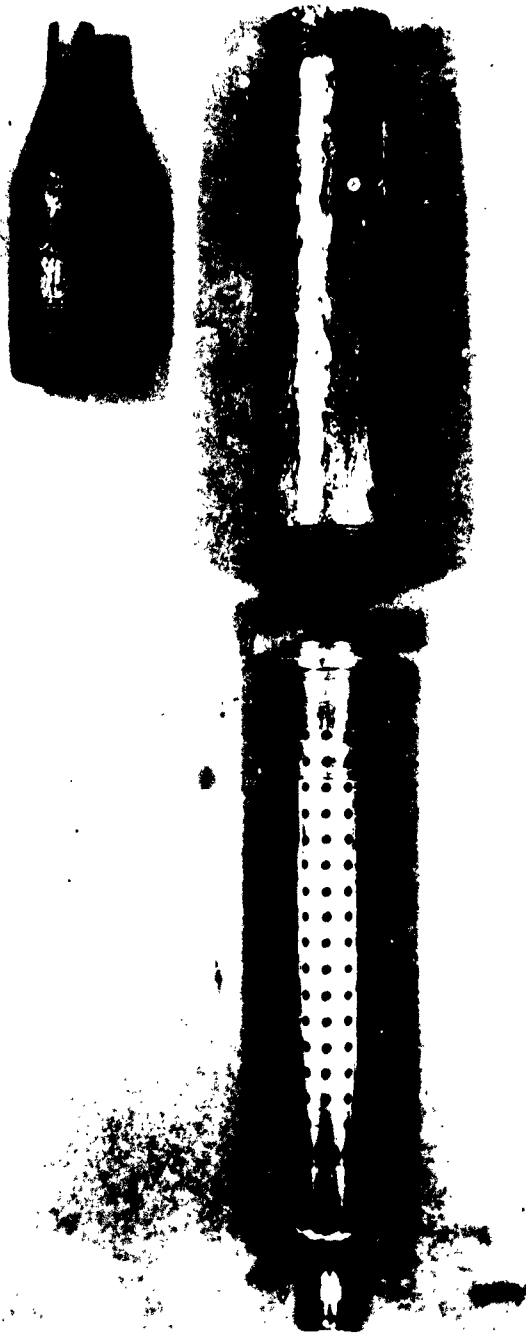


Fig. 3

Exploded View of Combustion Chamber No. 2.

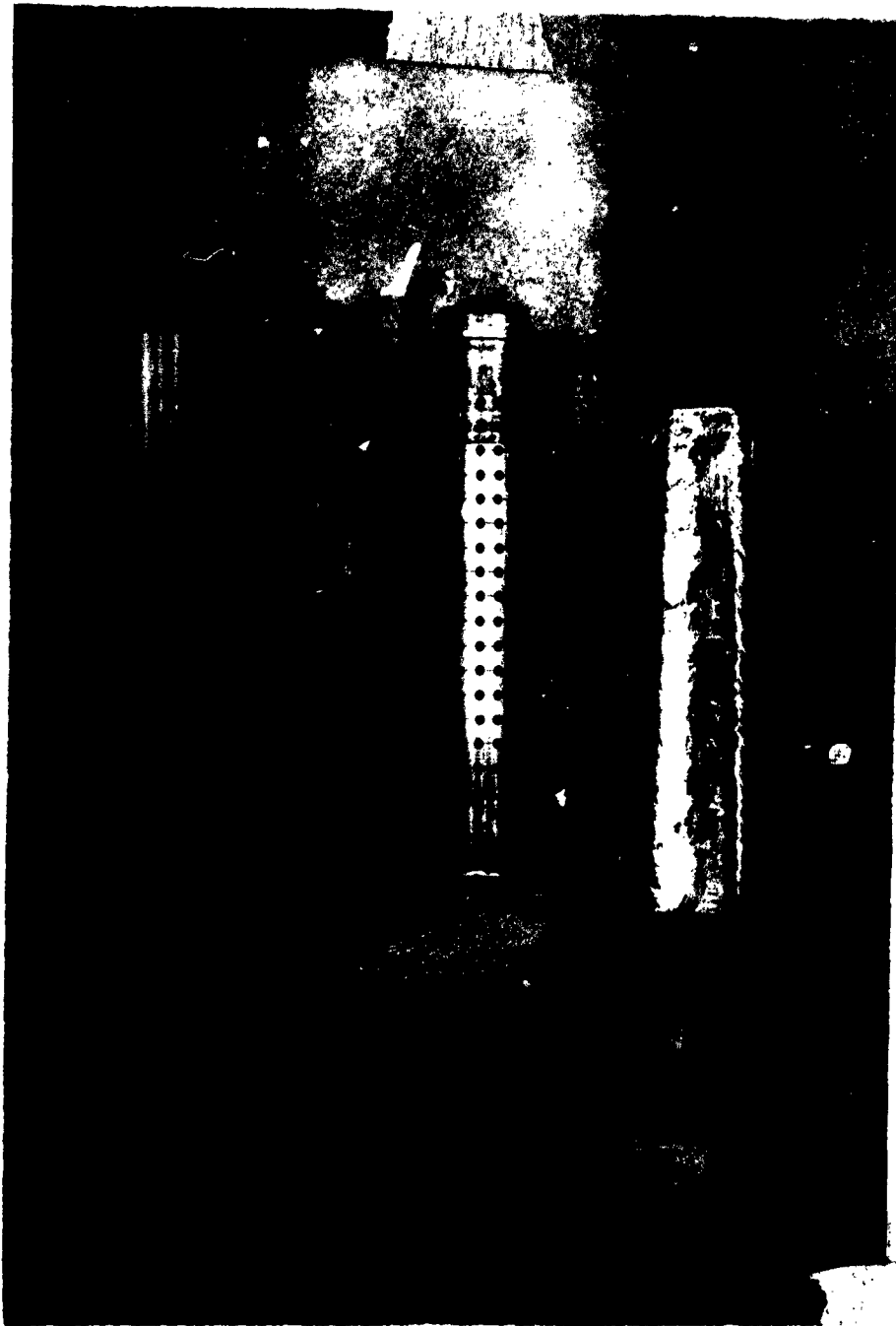


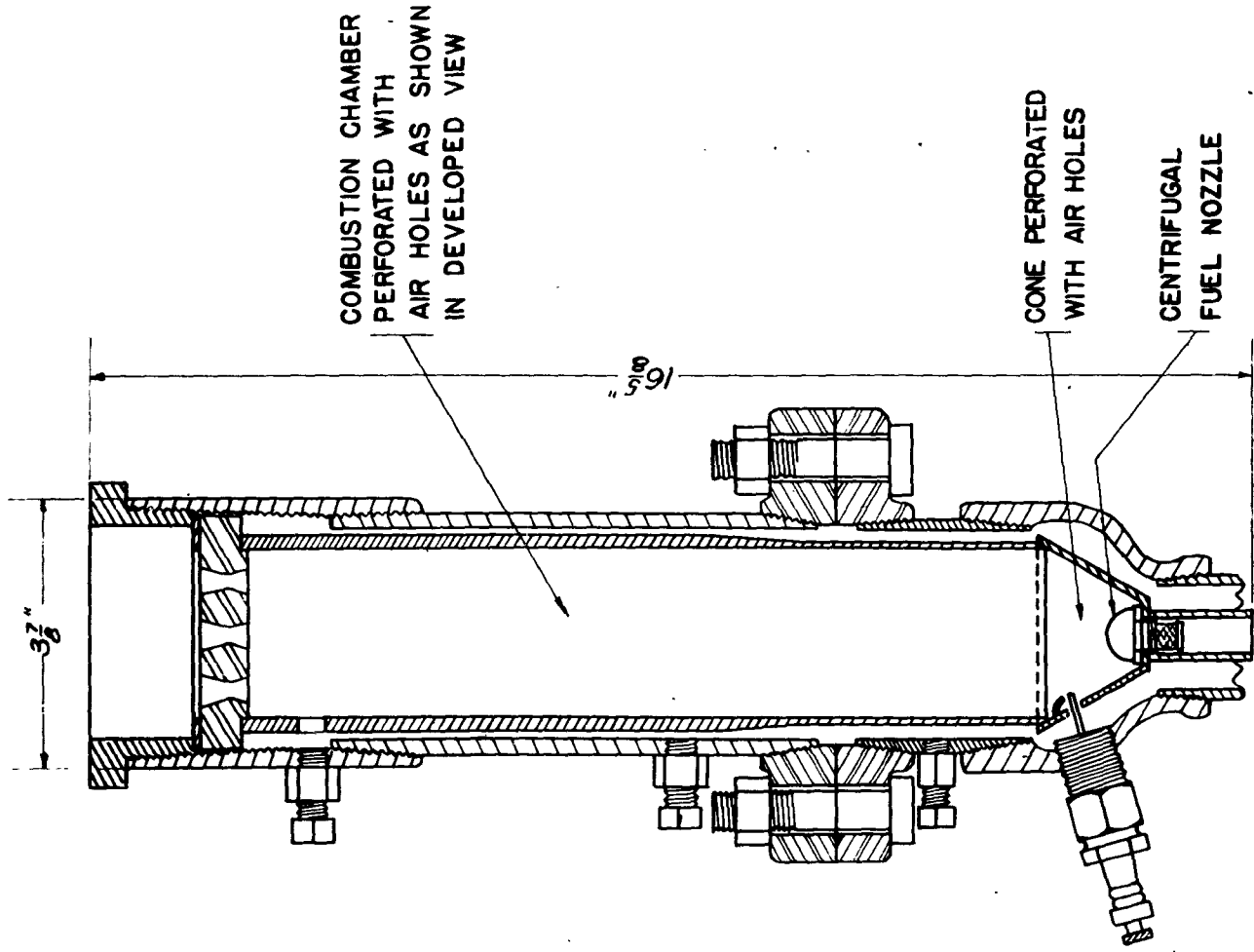
Fig. 4

Exploded View of Combustion Chamber No. 3  
Showing Three Burners



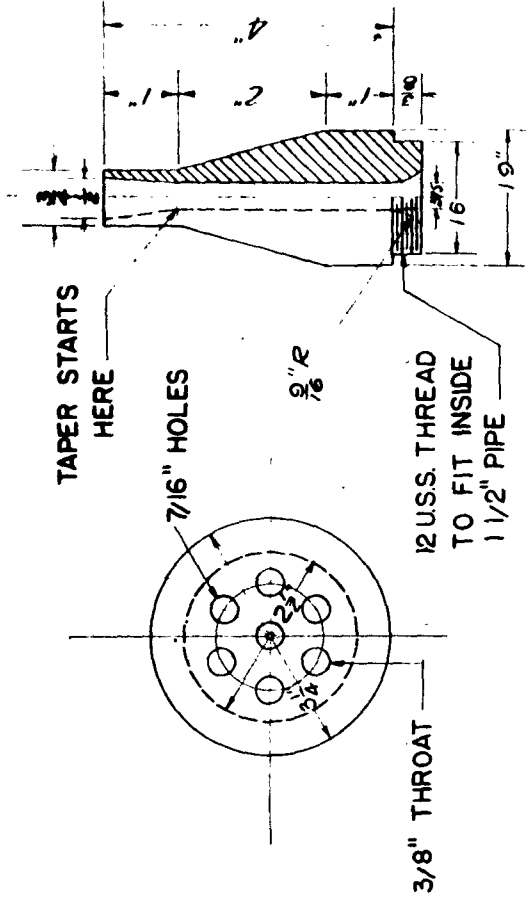
Fig. 5.

Exterior View of Combustion Chamber No. 4, and Nozzle.



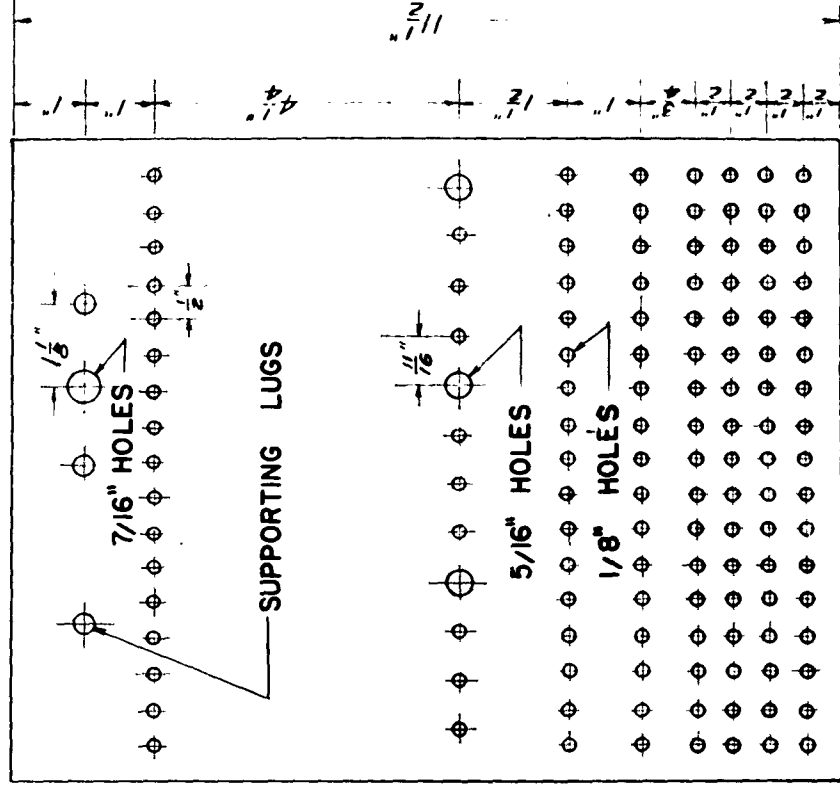
SECTION VIEW OF  
COMBUSTION CHAMBER  
ASSEMBLY

SCALE 1/2" = 1"



NOZZLE NO. 2                      NOZZLE NO. 1

2 1/2" STEEL CONDUIT PIPE LOW C



COMBUSTION CHAMBER  
( DEVELOPED VIEW )



Fig. 7.

Thrust Nozzles: (a) Second Nozzle Design, Nozzle Plate, (b) First Nozzle Design, Single Nozzle.

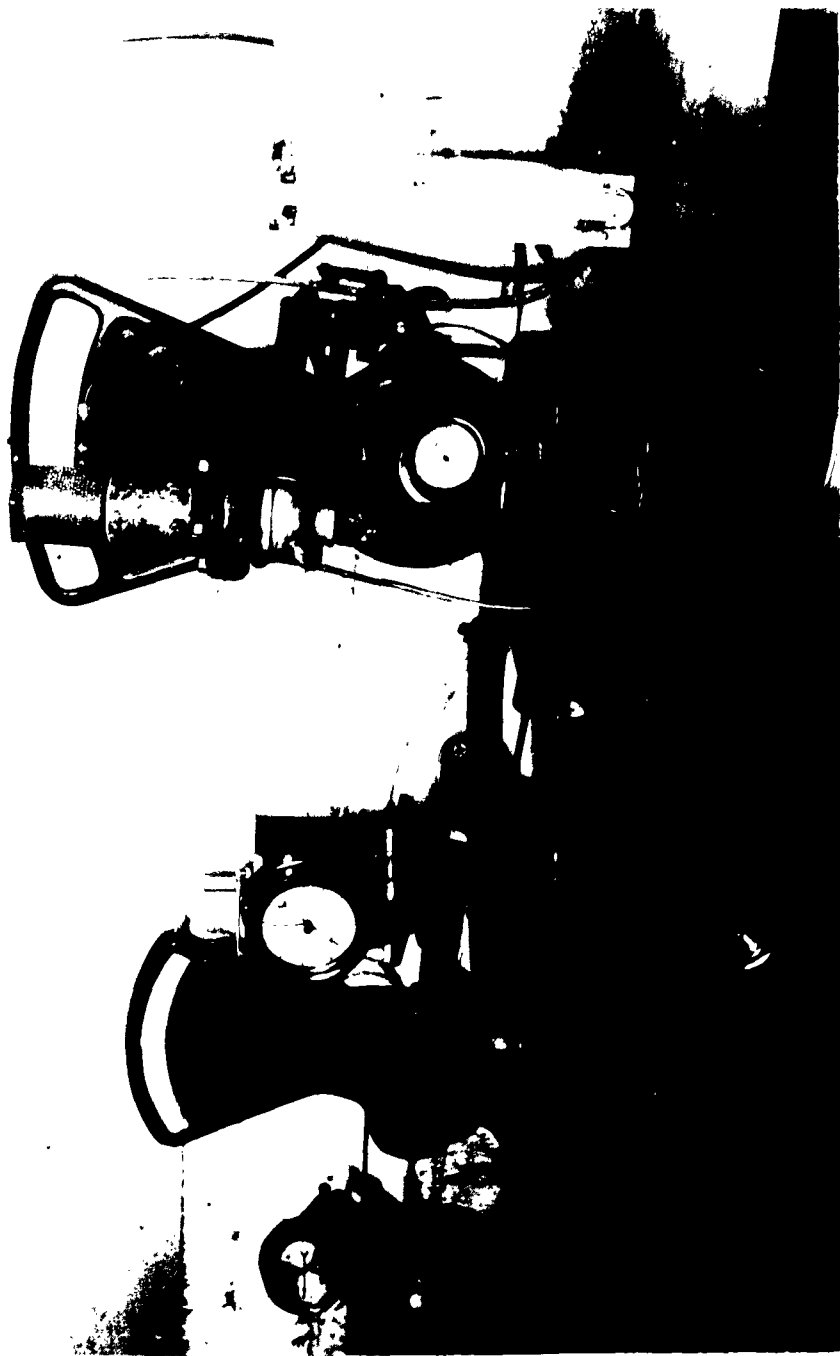


Fig. 8.

Arrangement of Apparatus for Test Purposes  
Showing Combustion Chamber No. 5 in Position.

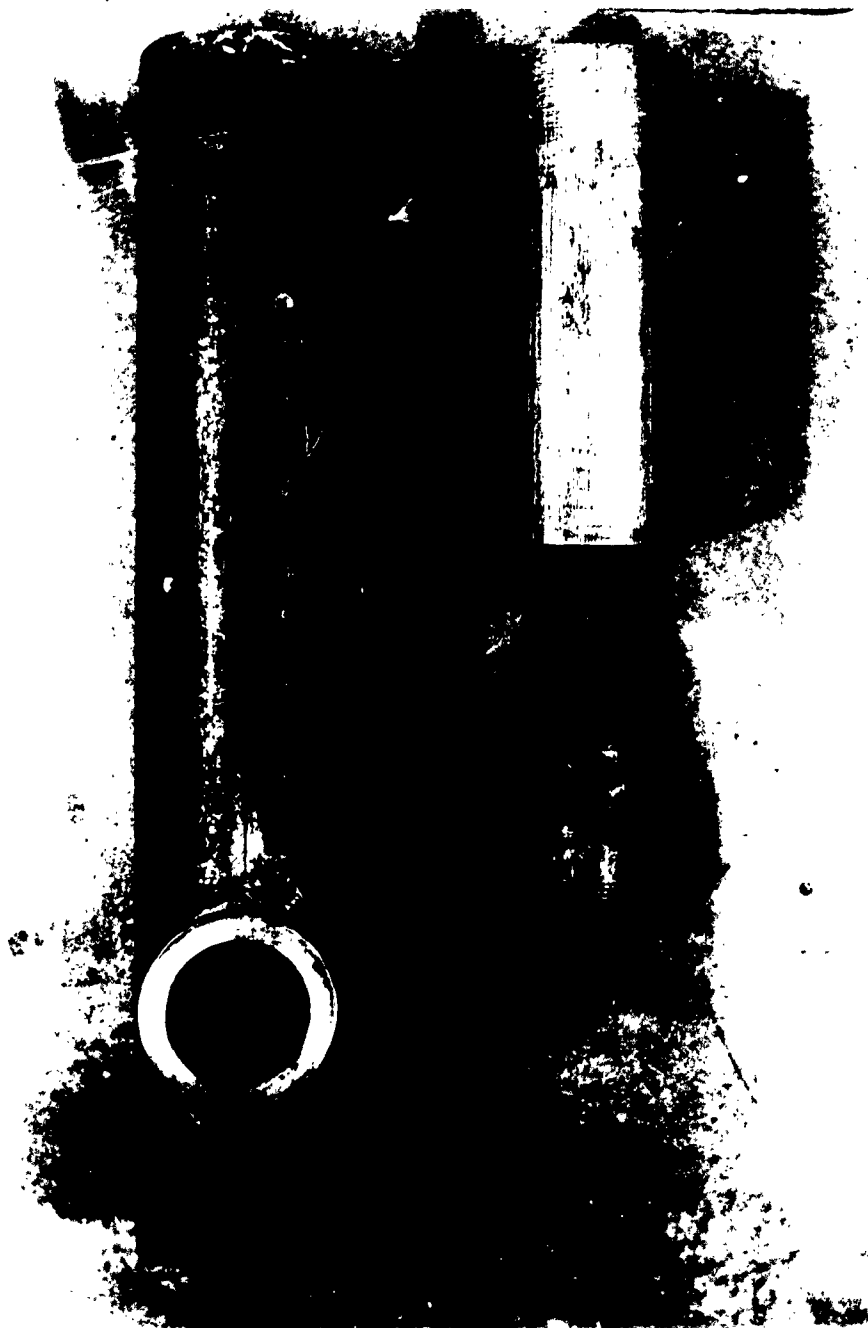


Fig. 9

Venturi, Nozzle, and Orifice Plate  
Arrangement for Measuring Augmenting Air.

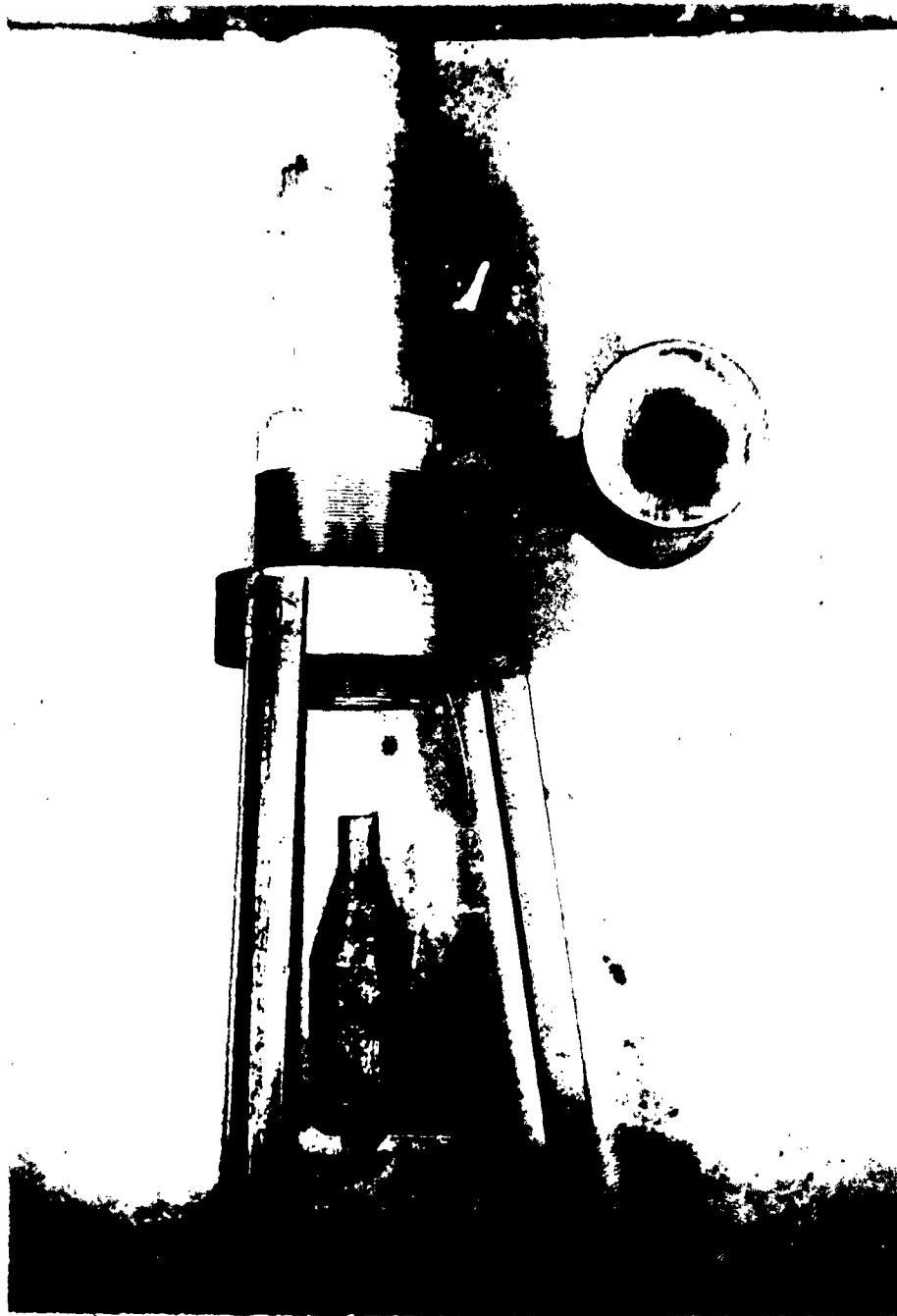


Fig. 10.

Venturi Stand and Venturi Used  
in Augmentation Studies.

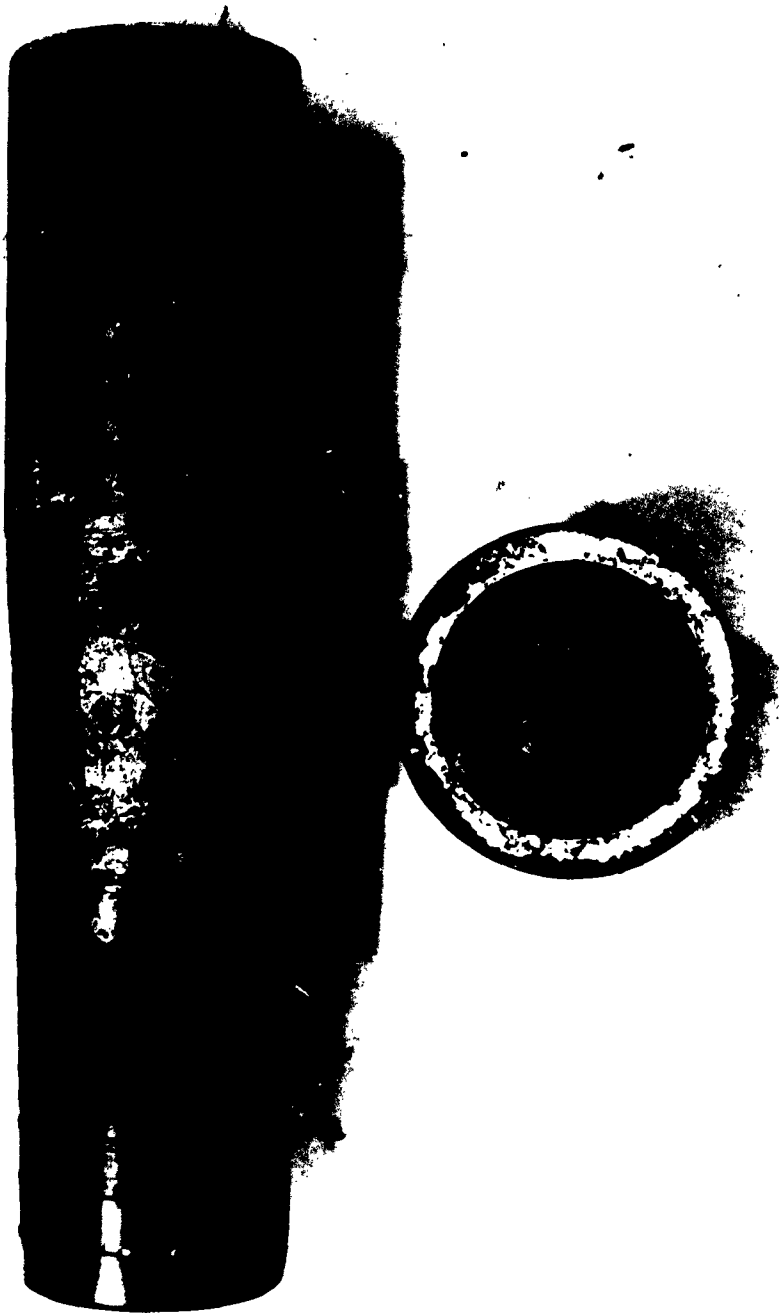
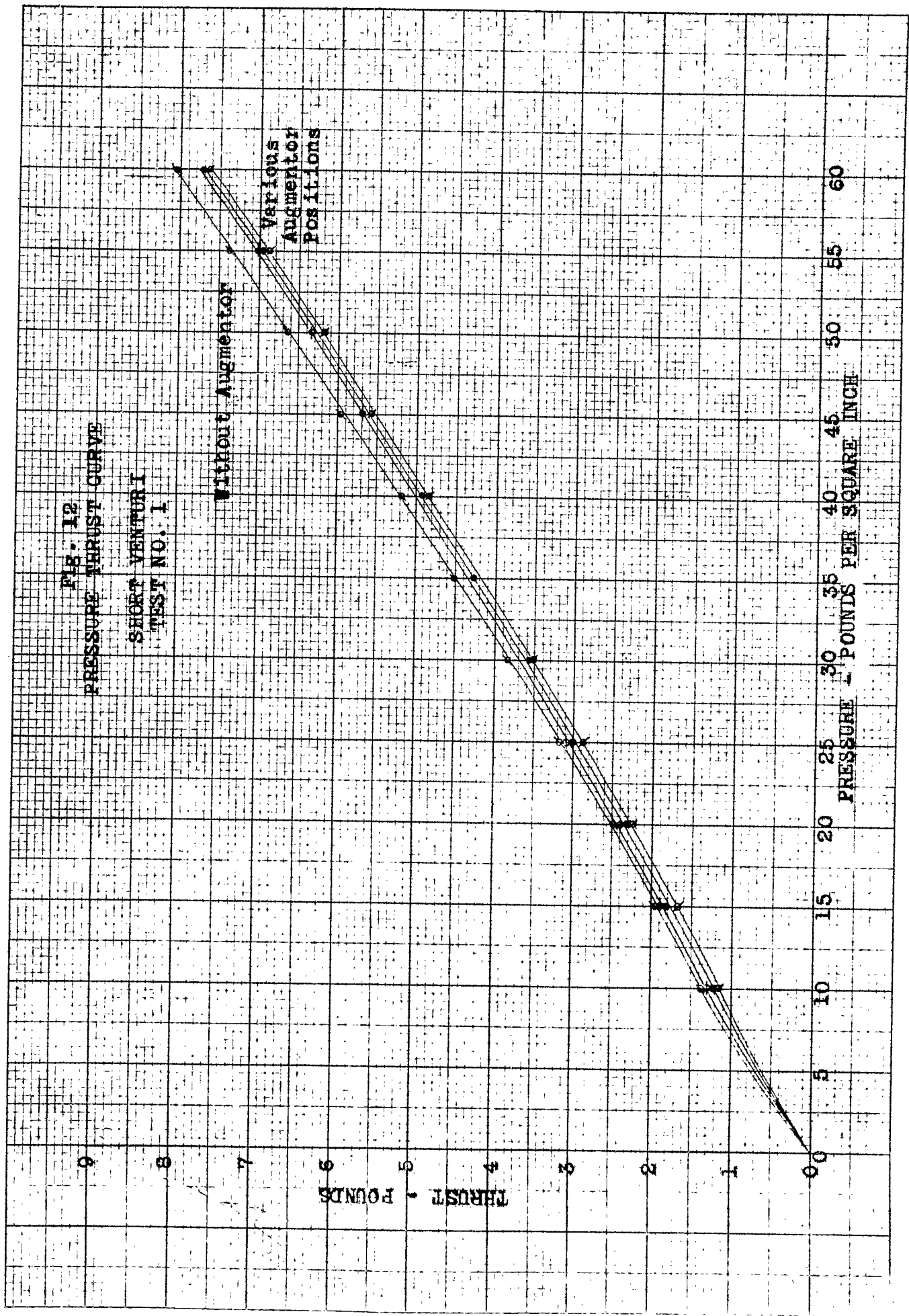
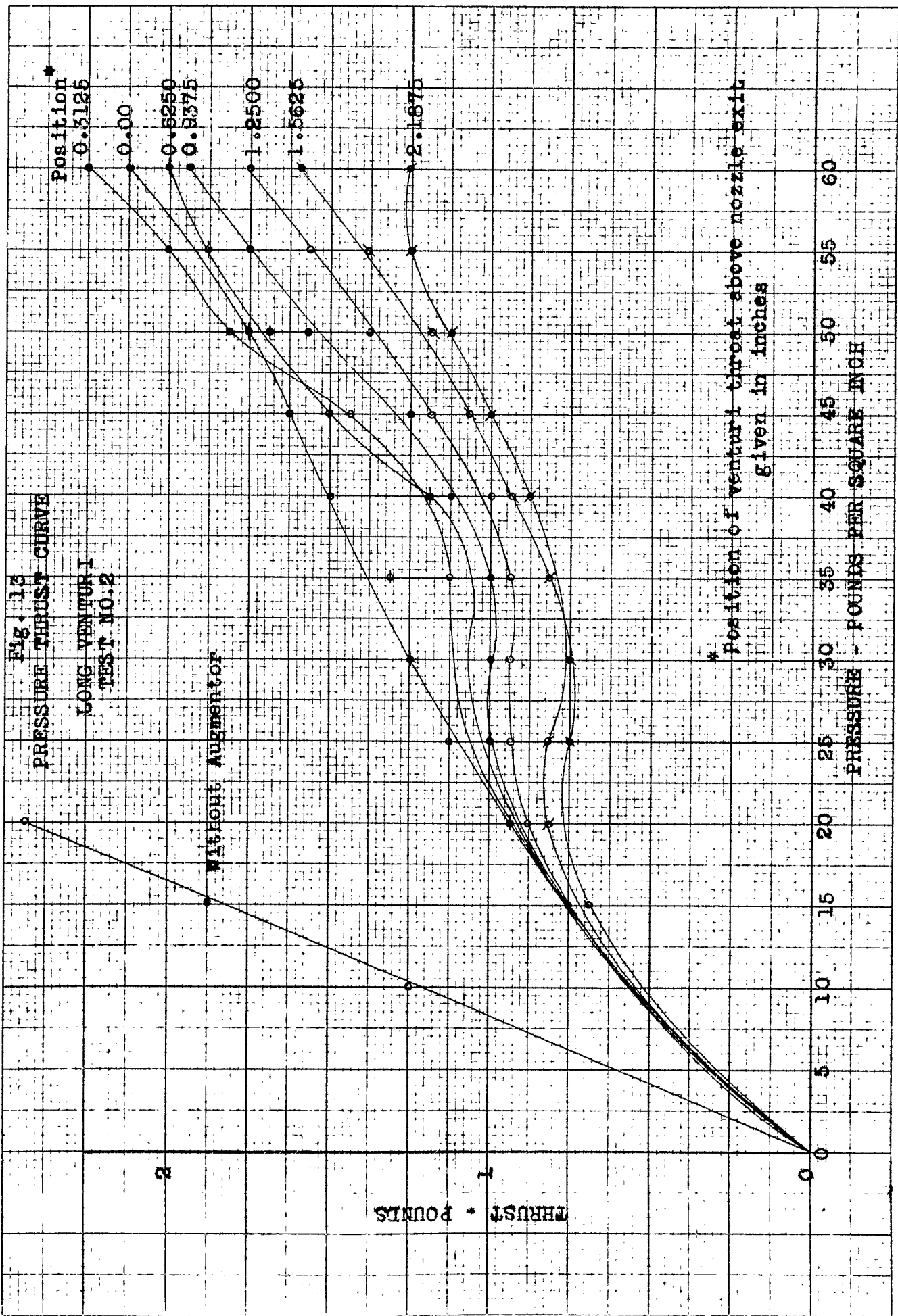
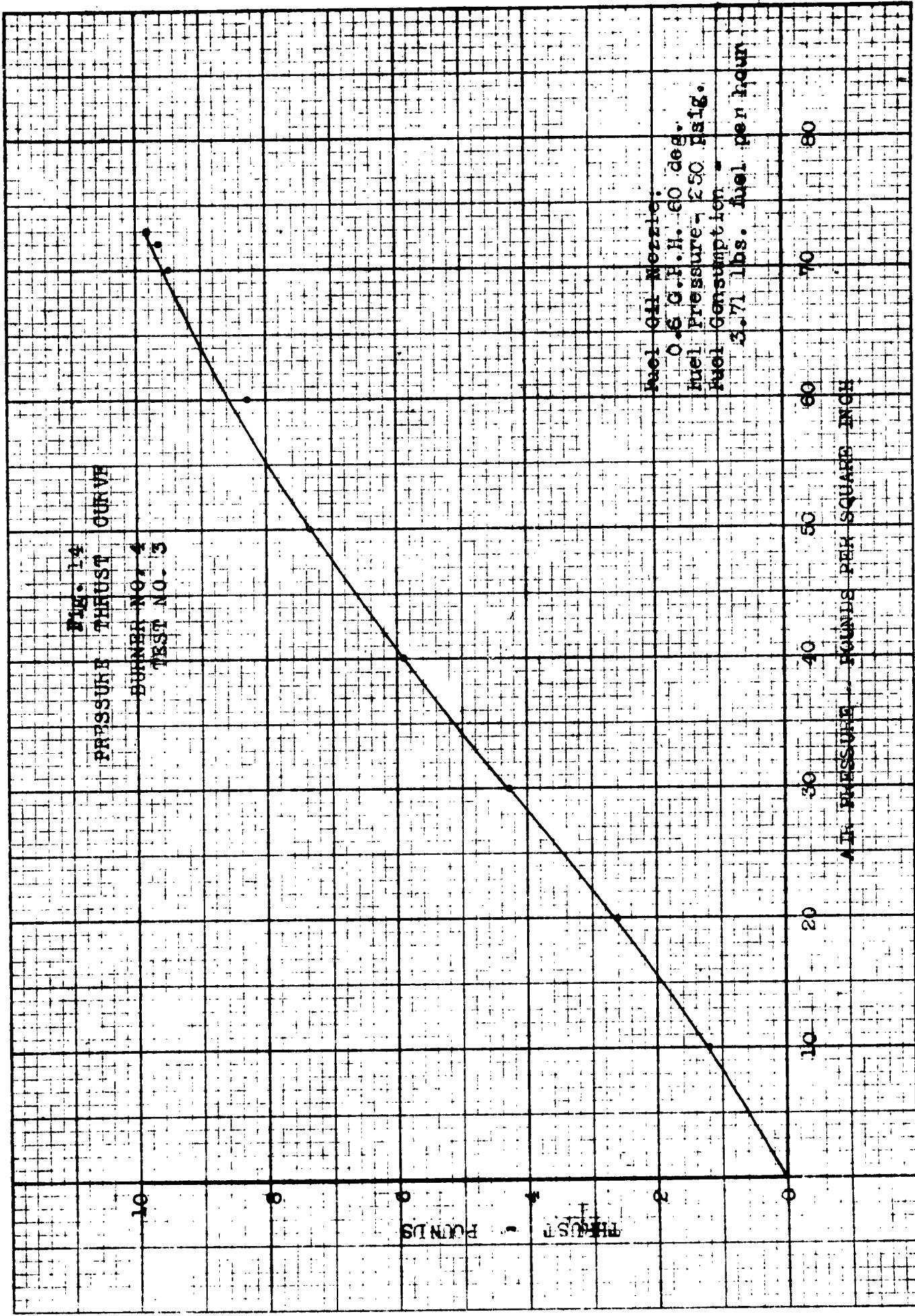


Fig. 11.

Burner No. 5 and the Nozzle Plate Showing  
Corrosion Due to the Exhaust Gases.







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PURDUE UNIVERSITY, ENGINEERING EXPERIMENT STATION,  
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JET PROPULSION - RESEARCH

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Ft. Belvoir, VA 22060-6218

Subject: OSD MDR Case 09-M-0020, DTIC Case No. DTIC-BC

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Robert Storer  
Chief, Records and Declassification Division

Enclosures:

1. DTIC request
2. MDR request
3. Documents ADB804447, ADB805158, ADB815161, and ABD815958



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