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Flame propagation in fuel oil sprays

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FLAME PROPAGATION IN FUEL OIL SPRAYS

STANLEY H. RICE
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COPY FOR HEAD OF POSTGRADUATE SCHOOL

(Inter-Departmental)

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Cambridge, Mass.

Office of
G. C. Williams

September 24, 1946

Capt. W. H. Buracker
Senior Naval Officer
M.I.T. Rm. 5-233
Cambridge, Mass.

Subject: Research Work for S.M. Thesis Carried Out
by Lt. Comdr. C. E. Leising, U.S.C.G.
Lt. Comdr. S. H. Rice, U.S.C.G.

Dear Sir:

The above-named officers carried out a research program in the field of high output combustion under the direction of Professor H. C. Hottel and myself. The particular problem on which they worked involved the design and fabrication of specialized experimental equipment, which to our knowledge had never previously been constructed. In the course of their work they demonstrated possession of competent facility in the design, construction and operation of their combustion test rig. Because of the specialized and highly experimental nature of the apparatus the desired balance between time spent on construction and effort devoted to research tests and analysis of these tests was less than was desired. In the short time they had available for test work, however, they demonstrated that they were competent to operate a new piece of equipment, to detect mistakes which are almost necessarily a part of the development of such equipment, and a fair degree of facility in analyzing the results of experiments.

The work performed by these officers was in every respect satisfactory.

Very truly yours,

/s/ G. C. Williams

G. C. Williams
Associate Professor in
Chemical Engineering

Cambridge,
Massachusetts
16 September, 1946

Professor J.S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the degree of Master of Science in Naval Construction and Marine Engineering, we submit herewith a thesis entitled "Flame Propagation in Fuel Oil Sprays."

Respectfully,

FLAME PROPAGATION IN FUEL OIL SPRAYS

by

STANLEY H. RICE
Lieutenant, U.S.C.G.
B.S., U.S.C.G. Academy
1942

CHARLES E. LEISING
Lieutenant Commander, U.S.C.G.
Graduate, U.S.C.G. Academy
1938

Submitted in Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE IN NAVAL CONSTRUCTION AND ENGINEERING

from the

Massachusetts Institute of Technology

1946

376

ACKNOWLEDGEMENTS

The authors wish to express their appreciation for the guidance and many helpful suggestions by Professors Hoyt C. Hottel and Glen C. Williams of the Department of Chemical Engineering, Massachusetts Institute of Technology and to Mr. Walter May of the same department who rendered invaluable assistance in the development of the experimental technique and the analysis of the results.

The authors also wish to thank Mr. George Agoston of the same department for his aid in setting up the apparatus and for the use of part of his equipment.

Without the ready cooperation by all personnel in the Boston Naval Shipyard with whom we came into contact, this work could never have been completed.

TABLE OF CONTENTS

I. SUMMARY

A. Object

The object of this thesis was to attempt to design, construct, and operate experimental equipment by means of which a homogeneous mixture of fuel oil and air could be obtained and its ignition and combustion characteristics studied as it flowed through a combustion chamber at different velocities, static pressures, and temperatures. Actually, a perfectly homogeneous mixture was not obtained and the limitations of the equipment available permitted a study only of ignition characteristics of lean fuel-air mixtures with air velocities varying from 40 to 90 ft/sec.

B. Method

The combustion chamber was supplied with air under known conditions of flow at variable velocities, chamber vacuum, and temperature. Fuel oil at room temperature was atomized into the combustion chamber under pressures up to 2000 psi from seven 0.004" or 0.008" orifices distributed over equal areas of the air stream. The fuel-air mixture was then ignited at distances of 16¼" or 35" downstream be means of a continuous 10,000 volt spark in the center of the combustion chamber cross-section. Measurements were made of atmospheric pressure, fuel temperature, temperature of air entering combustion chamber, fuel pressure, combustion chamber vacuum, and air-flow manometer reading. Whether or not ignition was

obtained and other pertinent comments were also recorded.

Computations were made of absolute combustion chamber pressure, air rate, fuel rate, fuel-air ratio, percent theoretical air, and air velocity.

C. Results

The maximum percent theoretical air (minimum fuel-air ratio) at which ignition could be obtained was found for air velocities from 40 to 90 ft/sec (limit of air supply available) and combustion chamber absolute pressures of 10, 15, 20, and 25 inches of mercury.

In addition, the pressure atomization characteristics of 0.008" orifices (l/d equals 4) and 0.004" orifices (l/d equals 5) were obtained.

D. Conclusions

Factors which result in an increase in the degree of atomization of the fuel increase the percent maximum theoretical air at which ignition may be obtained under a given set of conditions.

Fuel-air mixtures of diesel oil can be ignited by a continuous spark without the use of a flame holder at air velocities above 90 ft/sec.

The distances required for pressure atomization in atmospheric air of diesel oil (kinematic viscosity 3.75×10^{-5} ft^2/sec) under 1000 psi pressure from 0.004" and 0.008" diameter orifices are approximately 16" and 26" respectively.

E. Recommendations

It is recommended that further investigations be made with higher air velocities, better fuel atomization, higher air temperatures, and heavier fuels such as Navy Special. It is also recommended that the design of the equipment be changed so that (a) a smaller diameter combustion chamber is used, (b) the fuel may be atomized outside the combustion chamber and then introduced into the air stream, (c) hot wire ignition may be used as well as a continuous spark, (d) a photographic record may be made of all runs.

II. INTRODUCTION

A. Previous Investigation

Heretofore very little investigation into factors affecting ignition and combustion of fuel oil sprays in an air stream has been made. The authors have been unable to find any published literature directly pertaining to the subject and it should be understood that this work is purely exploratory. The work of Dawson and Oldfield at the Massachusetts Institute of Technology in a "Study of a High Output Combustion Chamber" was somewhat similar in nature but with a different objective and under considerably different conditions.

B. Objective

It was apparent from the beginning that because of the lack of information directly pertaining to the problem under study the major task would be the design and construction of the necessary equipment by means of which a homogeneous mixture of fuel oil and air could be obtained and its ignition and combustion characteristics studied. In addition it was necessary to develop an experimental procedure and technique which would yield the desired results.

C. Equipment

The equipment consisted of:

1. A $2\frac{1}{2}$" air metering orifice serving as an air inlet (Figure I).

2. An air heater capable of heating maximum air available up to approximately 300°F by means of steam coils (Figure II).

3. Air entrance section fitted with a thermometer and a piezometer ring and consisting of a diverging $22\frac{1}{2}°$ cone, three screen calming sections, and a converging 30° cone which introduced the air directly into the combustion chamber through the nozzle ring (Figure III).

4. A nozzle ring (Figures IV and XII) which pressure atomized fuel into the combustion chamber.

5. An air-tight combustion chamber made up of three removable pyrex glass sections of 5.75" inside diameter (Figure V).

6. An ignition ring which held two spark electrodes (inserted through porcelain insulators) connected to the secondary of a 230:10,000 volt transformer mounted above. The spark gap and its longitudinal position in the chamber was adjustable (Figures V and VI).

7. An exit section fitted for injection of a cooling water spray and containing a 30° cone section to reduce the diameter of the equipment from 5.75" to 3.0" and to provide drainage for the cooling water (Figure VII).

8. A steam air-ejector.

9. A gas pressure system consisting of bottled nitrogen fed through a manifold into the fuel supply bottle above the level of the oil (Figure VIII).

10. A fuel supply system consisting of the supply bottle, two strainers (.0025" maximum opening), control valve, and thermometer (Figure VIII). The entire fuel oil system was designed for a pressure of 2000 psi.

The air metering orifice, air heater, and steam air-ejector were part of Mr. Agoston's equipment.

FIGURE I.

Air Inlet (2½-in. nozzle on right)

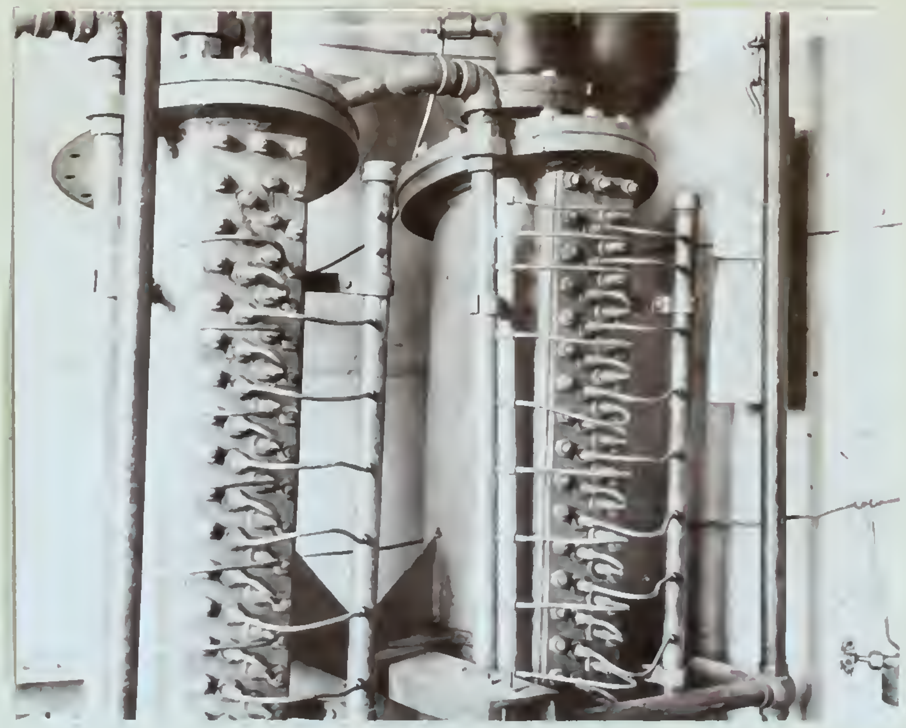


FIGURE II.

Air Heater (on right)

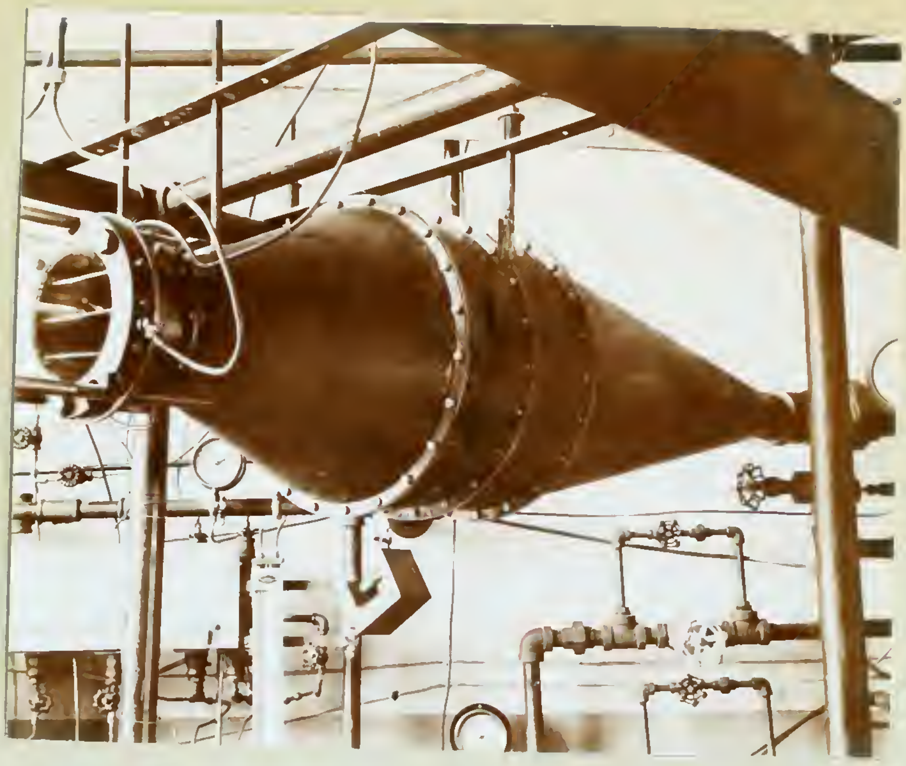


FIGURE III.

Air Calming Section and Nozzle Ring.

FIGURE IV.

Close-up of nozzle Ring showing fuel-oil supply line connections and beginning of Combustion Chamber.

LEFT. FIGURE V.

View of Combustion Chamber looking downstream from Nozzle Ring and showing position of the 230 : 10,000 volt spark ignition transformer.

Spark position, 35-in. from Nozzle Ring.

RIGHT. FIGURE VI.

Close-up of Ignition Ring and electrodes. Spark gap ¼-inch.

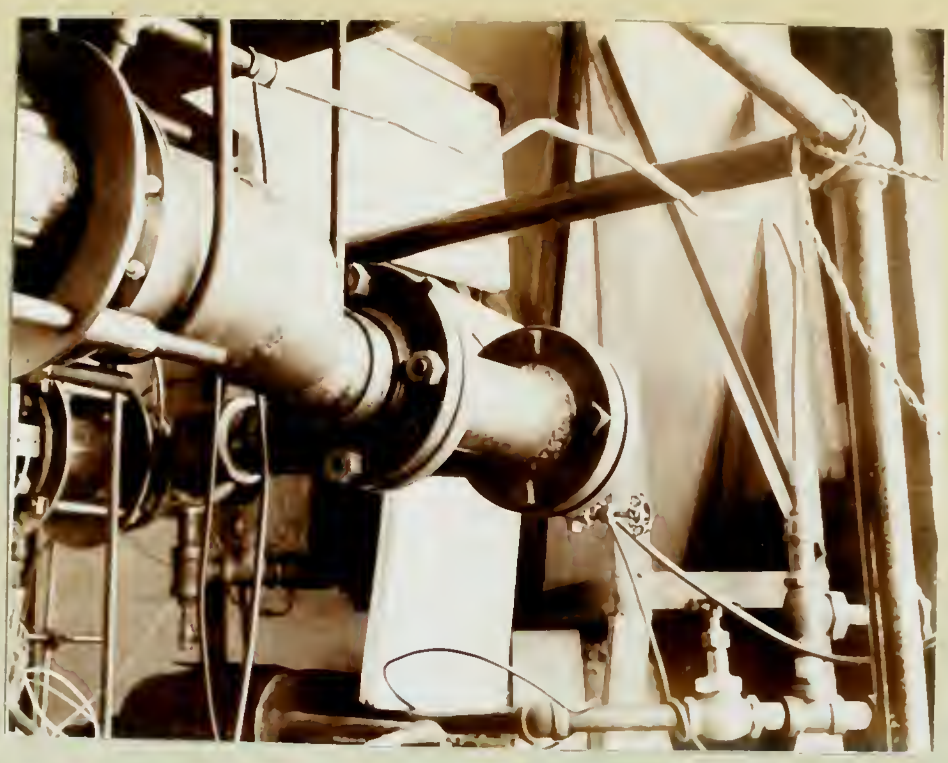


FIGURE VII.

End of Combustion Chamber, Exit Section and Removable Flanged Section.

Cooling water for extinguishing the flame is piped in at top of Exit Section.

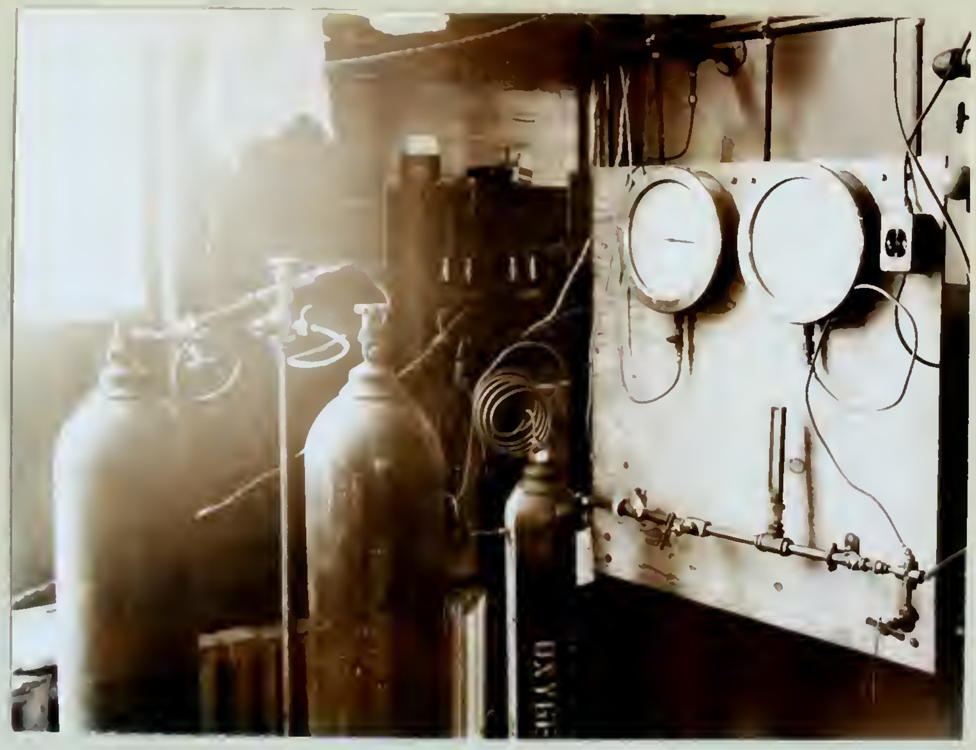


FIGURE VIII.

Gas and Fuel Supply Systems and Control Board.

FIGURE IX.

Close-up of Control Board showing Gas-pressure gage on left, Oil-pressure gage on right, and Oil manifold with Strainer, Oil-Control Valve, Oil-Temp. Thermometer, and Drain Valve at bottom of board.

Figure X

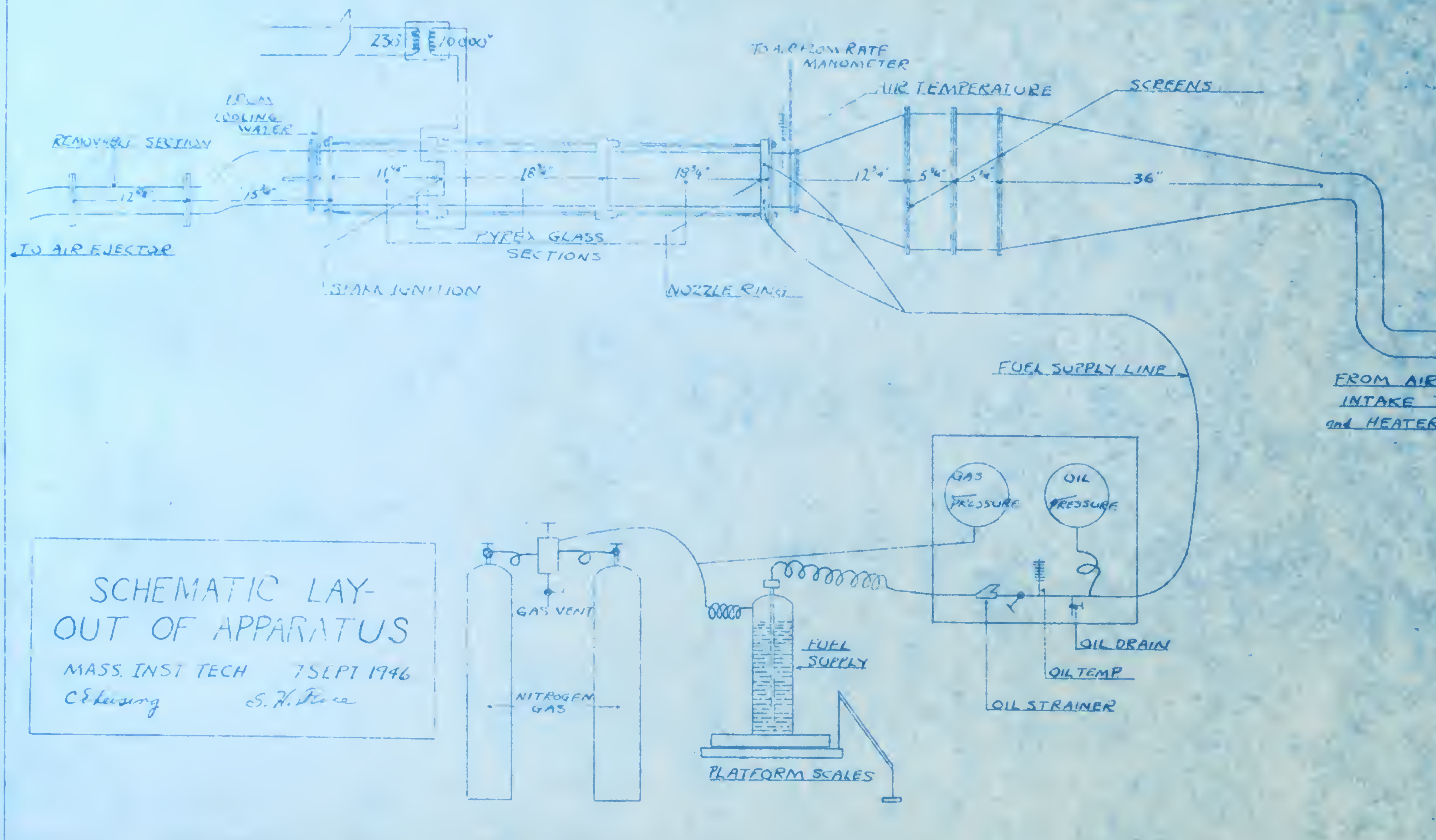

TO A. FLOW RATE MANOMETER
AIR TEMPERATURE
SCREENS
36"
12 1/4"
5 1/4"
5 1/4"
18 3/4"
19 3/4"
11 1/4"
15 3/4"
12 5/8"
230
10000"
REMOVABLE SECTION
COOLING WATER
TO AIR EJECTOR
PYREX GLASS SECTIONS
SPARK IGNITION
NOZZLE RING
FUEL SUPPLY LINE
FROM AIR INTAKE and HEATER
GAS PRESSURE
OIL PRESSURE
OIL DRAIN
OIL TEMP
OIL STRAINER
FUEL SUPPLY
PLATFORM SCALES
GAS VENT
NITROGEN GAS
SCHEMATIC LAY-OUT OF APPARATUS
MASS. INST TECH 7 SEPT 1946

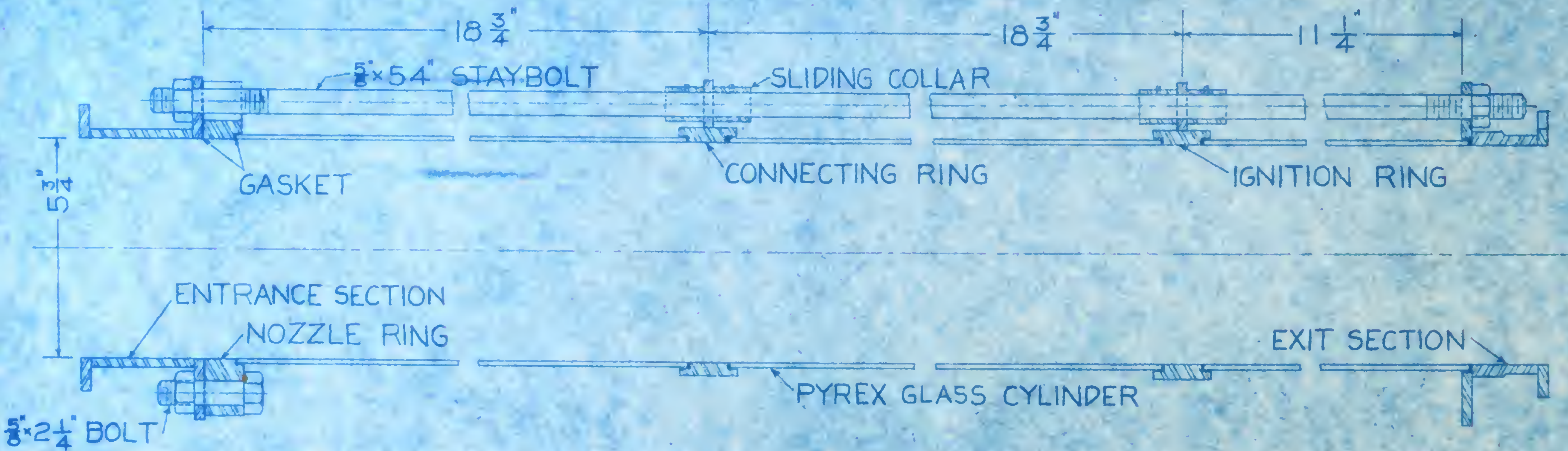
Figure XI

COMBUSTION CHAMBER DETAILS

SCALE: $\frac{1}{4}" = 1"$

MASS. INST. TECH. 7 SEPT. 1946

S. H. Rice C. Eleising



NOTES:

1. PYREX CYLINDERS ARE MADE FROM 6" × 18" PYREX JARS.
2. IGNITION RING IS A CONNECTING RING FITTED WITH TWO ELECTRODES.
3. THREE STAYBOLTS HOLD THE CHAMBER TOGETHER.

DETAILS OF NOZZLE RING

SCALE: 1/2" = 1"

MIT 7 SEPT, 1946

S. H. Rice C. Kheising

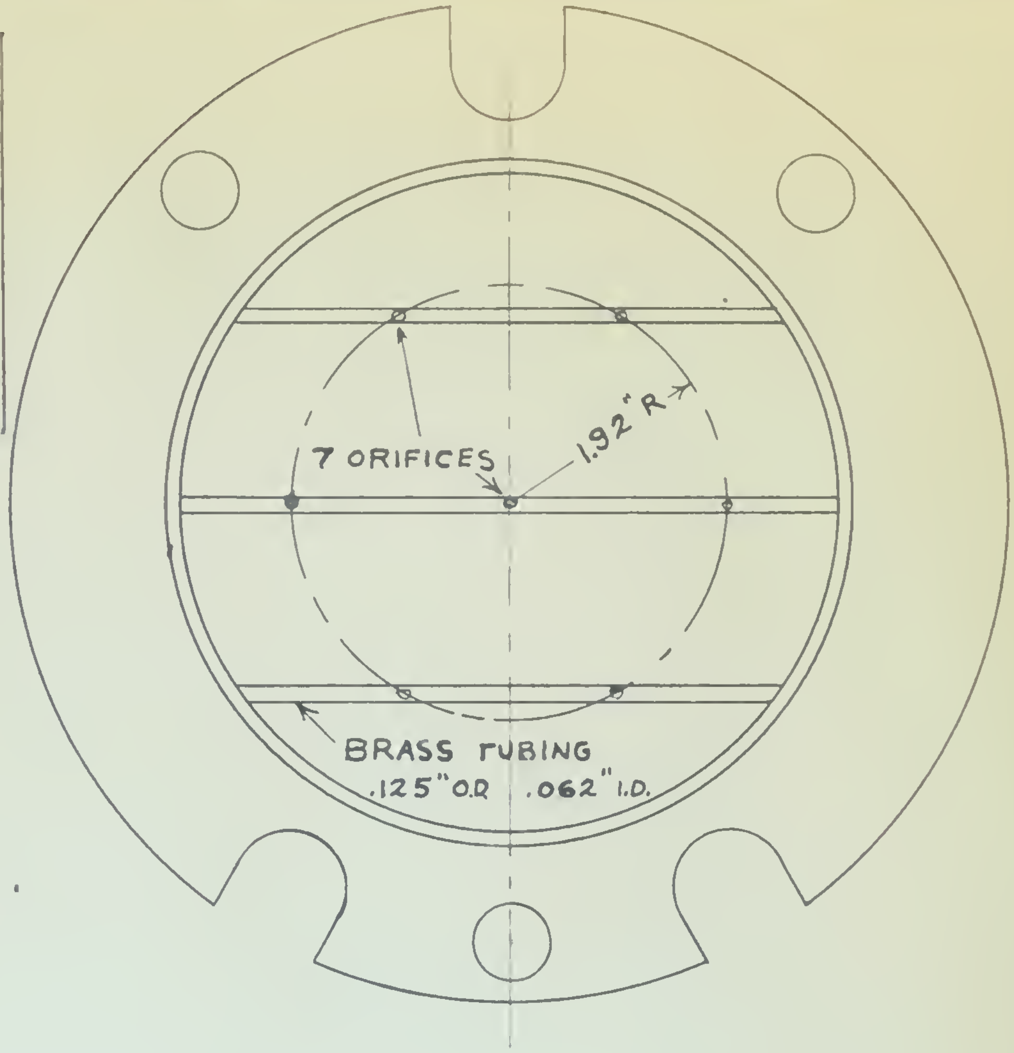
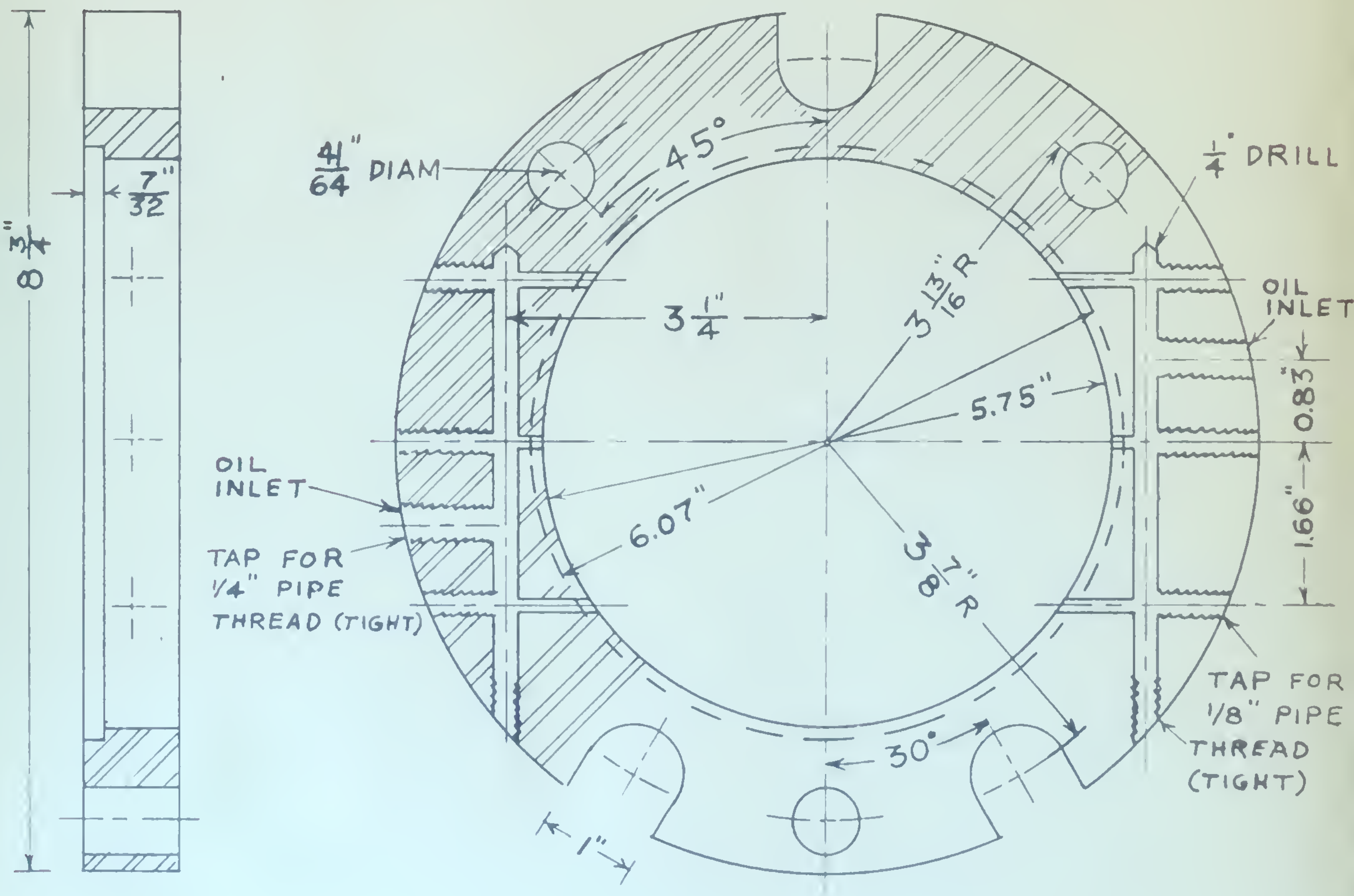


Figure XII



III. PROCEDURE.

A. Calibration of the nozzle ring.

For each calibration run the following observations were made:

1. Weight of fuel oil bottle before run.

2. Weight of fuel oil bottle after run.

3. Time oil flowed during the run.

4. Gas pressure (i.e., fuel oil pressure).

5. Room temperature (assumed that the nitrogen temperature was the same as the room temperature).

The fuel oil and the nitrogen gas systems were connected up in the same manner as for the regular test runs. The fuel was subjected to various gas pressures and caused to discharge through the nozzle orifices to atmospheric pressure. The fuel oil supply bottle was set upon the platform of a set of scales which were graduated to a quarter of a pound but which permitted a good approximation to a tenth of a pound. The scales were read after the fuel oil supply bottle was subjected to the desired gas pressure. The oil supply line valve was then opened and about two pounds of oil were allowed to discharge through the orifices before closing the valve. The gas pressure on the feel oil was kept constant during the run by controlling the valve connecting the gas manifold to the fuel supply bottle. Another reading of the scales was made before changing to the next gas pressure. This procedure permitted taking into account the effect of the weight of nitrogen on the change in

weight of the fuel bottle during the run. It was found that within the accuracy of the pressure gages there was no discernible pressure drop through the oil manifold and hence it was deemed permissable to adjust the gas pressure to the desired point and then assume that the same oil pressure would be obtained as soon as the oil control valve was opened. The same assumption was made in getting the desired atomization pressures during the test runs.

B. Test runs.

All runs except Numbers 21, 22, and 23, were made without use of the air heater. For each test run the following seven observations were made:

1. Atmospheric pressure.
2. Fuel temperature.
3. Temperature of air entering combustion chamber.
4. Fuel temperature.
5. Fuel pressure.
6. Combustion chamber vacuum.
7. Air flow manometer reading.

The combustion chamber pressure was adjusted to approximately 10, 15, 20, amd 25 inches of mercury, absolute. For any given chamber pressure the maximum air velocity was obtained by opening the air intake valve as much as possible and still maintain the desired chamber pressure. For these set conditions, oil was atomized in the combustion chamber under varying pressures and an attempt was made to ignite each of the mixtures by means of the 10,000 volt spark. This was repeated at different fuel atomization

pressures - lower, if ignition was obtained and higher, if ignition was not obtained - until the lowest fuel atomization pressure at which ignition could be obtained for the fixed conditions of chamber pressure and air velocity was determined. These conditions gave a point on the curve entitled, " Air Velocity vs. Maximum Percent Theoretical Air at which Ignition was Obtained" (Figure XIII). Keeping the combustion chamber still unchanged the above procedure was repeated to obtain additional points at successively lower air velocities until such a low velocity was reached that the atomization pressure required was too low for proper atomization (i.e., about 300 psi.).

Since considerable difficulty was encountered, especially in the earlier runs, due to one or more of the orifices becoming plugged a method of unplugging the orifices and flushing out the system was devised. The entire combustion chamber was dismantled and each of the orifices were cleaned with a fine wire of slightly less diameter than the orifice. One branch of the fuel supply line was disconnected at the nozzle ring, capped, and in its place was connected a discharge line to a waste container. The system was then flushed with oil, the orifices cleaned again, and the combustion chamber reassembled for continuation of the tests.

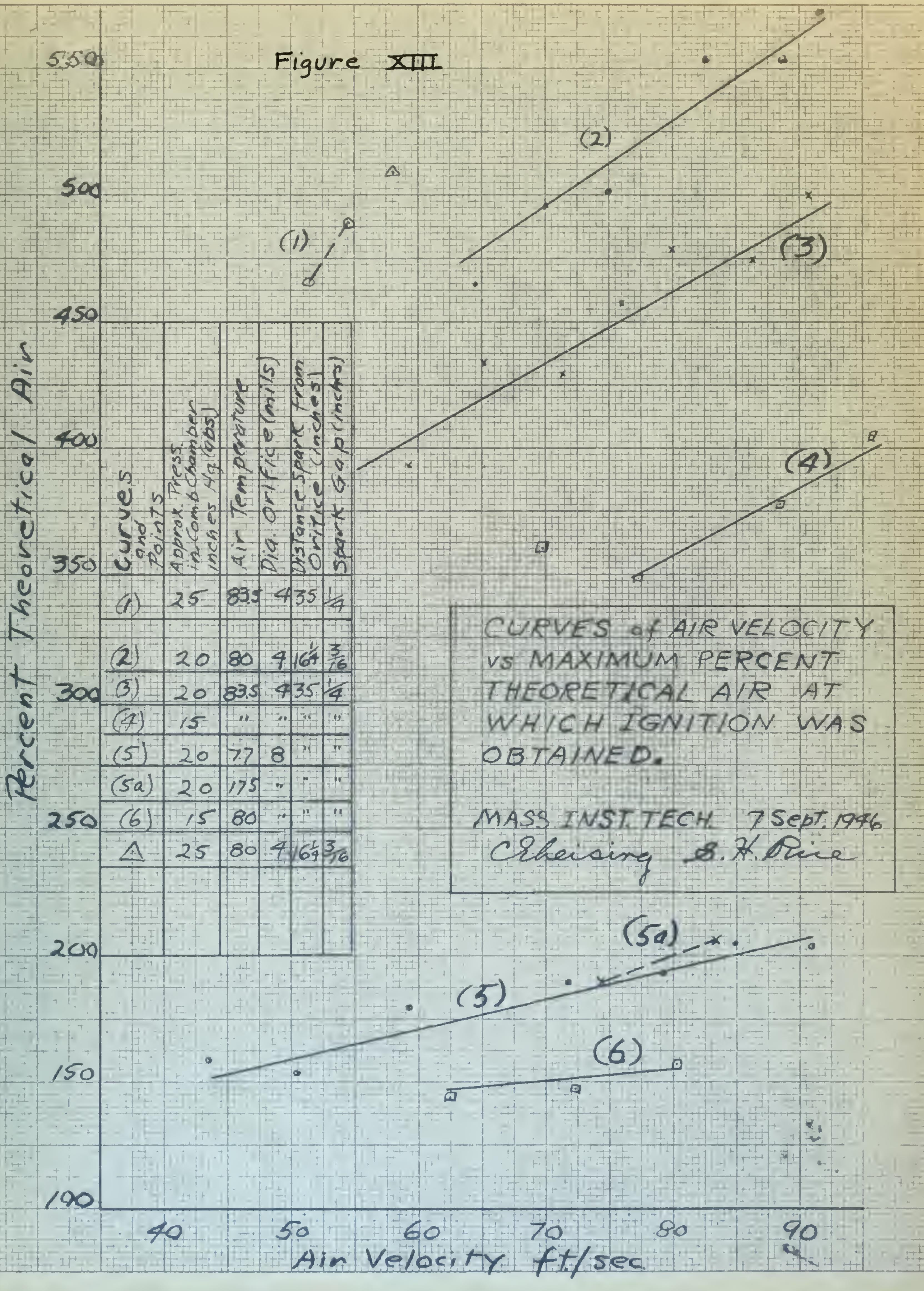
IV. RESULTS AND DISCUSSION

The results of the experimental work appear in tabular form in the appendix and as curves (Figure XIII) accompanying this discussion.

A. Curves of Air Velocity vs Maximum Percent Theoretical Air at Which Ignition Was Obtained

In all cases the maximum percent theoretical air at which ignition could be obtained increased (ie, fuel-air ratio decreased) as the air velocity was increased. It is believed that this was due to the following: as the air velocity is increased, the fuel rate must also be increased to maintain a constant fuel-air ratio. An increase in fuel rate was obtained by an increase in the fuel atomization pressure thus decreasing the mean diameter of the droplets in the spray and, hence, increasing the ratio of the total surface area of the oil droplets to the volume of air. A combustible mixture is thus obtained at lower fuel-air ratios for high air velocities than for lower air velocities. The spark which was used for ignition was large enough to insure combustion if a combustible mixture was present.

As the combustion chamber pressure was increased,the percent theoretical air at which ignition could be obtained increased. It is believeo that this was again a result of better atomization since the mean droplet diameter of the spray is approximately inversely proportional to the air density (Reference 2).



Curves and Points	Approx. Press. in Comb. Chamber inches Hg (abs)	Air Temperature	Dia. Orifice (mils)	Distance Spark from Orifice (inches)	Spark Gap (inches)
(1)	25	83.5	4	35	1/4
(2)	20	80	4	16 1/4	3/16
(3)	20	83.5	4	35	1/4
(4)	15	"	"	"	"
(5)	20	77	8	"	"
(5a)	20	175	"	"	"
(6)	15	80	"	"	"
△	25	80	4	16 1/4	3/16

Decreasing the diameter of the orifices used to atomize the fuel, increased the maximum percent theoretical air at which ignition could be obtained. If it is assumed that the mean droplet diameter varies as the orifice diameter, this effect was also due to better atomization (Reference 5).

Moving the point of ignition closer to the fuel oil nozzle resulted in an apparent increase in the maximum percent theoretical air at which ignition could be obtained. It is believed that this effect is only apparent rather than actual. When the spark was closer to the nozzle, it was in a position unfavorable for homogeneity of mixture, and the fuel-air ratio around the spark was richer than that indicated by the overall weights of air and fuel entering the chamber.

Heating the air seemed to have a negligible effect on the results. If this were true, it would indicate that the evaporation of the oil in the spray was negligible or at least an unimportant factor in determining where ignition can be obtained. Unfortunately, time did not permit the making of sufficient hot air runs from which to draw any valid conclusions.

B. Other Experimental Results

Ignition of the fuel-air mixture is possible at air velocities greater than 90 ft/sec without the use of a flame holder. When the fuel-air mixture was made slightly richer than that required for ignition, an explosion occurred in the combustion chamber due probably to the

sudden decrease in air velocity as described subsequently under "Limitations of Equipment." This made it difficult and somewhat dangerous so far as the life of the glass combustion chamber was concerned to obtain a fuel-air mixture which would result in a sustained cone of flame emanating from the spark. However, on runs number 27 and 33 a sustained cone of flame was obtained. An estimate of cone angle yielded approximate flame speeds of 11.1 and 17.4 ft/sec for these two runs respectively.

In still air at atmospheric pressure and 80°F the distance from the orifices required for complete atomization of the fuel oil at pressures of 1000 psi or greater was approximately 26" for 0.008" diameter orifices and 16" for 0.004" diameter orifices. These distances increased somewhat as the atomization pressure was lowered. The atomization from the 0.004" diameter orifices was particularly good: the oil was broken up into a very fine fog approaching the consistency of smoke.

With the experimental apparatus used it would have been possible to investigate the distances required for pressure atomization at various chamber pressures and zero air velocity by running the air ejector, closing the main air valve to the combustion chamber, and using the by-pass valve to control the chamber pressure.

C. Validity of Results

All runs were reproducible at any time. The exact results obtained were not independent of the apparatus;

however, it is believed that the qualitative results are valid regardless of the apparatus used.

D. Limitations of the Equipment

The type and capacity of air supply and the room available for the experimental set-up placed narrow limitations on the ranges of fuel-air ratios and air velocities that could be investigated. It was impossible to get air velocities in excess of 90 to 95 ft/sec or rates of air flow in excess of 0.81 pounds per second. Hence, as a result of the low fuel-air ratios at which combustion was obtained, it was necessary to operate the fuel atomization nozzles at low pressures of 300 to 600 psi rather than in the 1000 to 2000 psi range for which they were designed. This prohibited the attainment of the desired degree of atomization and was a major factor contributing toward the failure to obtain the desired homogeneity of the fuel-air mixture.

The limitations of the steam air-ejector made it difficult to study sustained combustion in the chamber since the capacity of the ejector in pounds of air per second is severely reduced when it has to handle either the hot gases of combustion or cooling water, if used. The use of an air-compressor as originally planned instead of an air-ejector would eliminate this difficulty but would make it impossible to study the effect of the combustion chamber pressure on ignition and combustion. A better solution to this problem would be to use a

combustion chamber of 2" to $2\frac{1}{2}$" diameter followed by a cooling water section. It is estimated that with sustained combustion in such a chamber the air-ejector could produce air velocities up to 200 to 300 ft/sec.

At high air velocities a homogeneous mixture of fuel and air could not be obtained in the 35" of travel from the orifices to the spark. At least two or three times this distance would be required. The maximum available distance for this travel was approximately 44" which was definitely not enough.

The exact determination of the actual fuel-air ratio at the point of ignition was difficult because the position in the chamber where homogeneity of the fuel-air mixture existed, if indeed it did exist at all, varied for different atomization pressures and air velocities. This would indicate the desirability of making the position of the spark ignition more easily adjustable. Time available for the test runs caused a deviation from the original plans to make a more thorough study to determine the optimum position for ignition.

The fuel jets from the orifices exert such a powerful effect on the air stream that it is questionable as to whether the flow conditions of the air entering the combustion chamber are of any importance provided the flow rate is uniform across the cross section of the entrance.

All of the aforementionned difficulties could be lessened by atomizing the oil at about 1500 psi with orifices of 0.004" diameter or less into a chamber

separate from the combustion chamber and then introducing the resulting droplets into the air stream prior to its entering the air calming sections. Admittedly, the construction and calibration of such a system would be extremely difficult but it would have the additional advantage of eliminating the effect of atomization pressure and orifice diameter since the amount of fuel introduced into the air stream could be controlled independently of these two factors. Also, since a homogeneous mixture of fuel and air would be entering the chamber, the ignition point could be placed close to the entrance. If the effect of the degree of vaporization of the fuel (assuming there is an effect) upon ignition and combustion is to be studied, the combustion chamber would have to be long enough to get the desired separation of ignition points.

It would have been very desirable to have had a photographic record of each run on which ignition was obtained. If flame speeds were to be studied, photographs would also be very useful.

E. Flame Arrestors

It was originally intended that, if the apparatus could be operated so as to obtain ignition, flame arrestors of various designs would be inserted in front of the spark gap. Time did not permit the carrying out of this plan but it seems logical to assume that under any conditions which permitted ignition stable combustion could have been obtained with the employment of the proper

design flame arrestor. As it was, burning ceased as soon as the ignition spark was stopped.

V. CONCLUSIONS

1. The following factors caused an increase in the value of the Maximum Percent Theoretical Air at Which Ignition Was Obtained:

   a. An increase in combustion chamber air velocity.

   b. An increase in the absolute pressure of the combustion chamber.

   c. A decrease in the diameter of the orifices thru which the fuel is atomized.

2. A mixture of diesel fuel oil and air can be ignited over a wide range of fuel-air ratios by a 10,000 volt spark without the use of a flame arrestor at air velocities greater than 90 ft/sec.

3. The distance required in atmospheric air for the pressure atomization of diesel oil (kinematic viscosity 3.75×10^{-5} ft^2/sec) under 1000 psi pressure is approximately 26" through an 0.008" orifice and 16" through a 0.004" orifice.

VI. RECOMMENDATIONS

1. it is recommended that further investigations be made with:

   a. Higher air velocities.

   b. Better fuel atomization (ie, higher atomization pressures).

   c. High air temperatures (200 to 300°F).

   d. A heavier fuel such as Navy Special fuel oil.

2. The following changes and additions to the experimental equipment are recommended:

   a. The use of the present air ejector with a 2" to 2½" diameter combustion chamber.

   b. Atomization of the oil at constant pressure (about 1500 psi) thru orifices of 0.004" diameter or less into a separate chamber and then introducing the resulting oil droplets into the air stream prior to the air calming and converging sections.

   c. Provision for the use of either a continuous hot spark or a hot wire for ignition.

   d. Provision of means for making a photographic record of all runs.

PART VII.

APPENDIX.

A. Summary of Data and Calculations

Results of Runs at which Ignition was obtained with Maximum Percent Theoretical Air.

Orifice Diam = 8 mils.

Ignition point 35" downstream from injection point.

Run No.	Comb. Chamb. Pressure "Hg (abs.)	lbs. air / sec	lbs fuel / sec	F/A ratio	% Theo Air	Atomization Pressure psi	Air Velocity ft/sec	Air Temp °F
6 e	19.95	.808	.0279	.0345	204	750	91.0	77
7 c	19.85	.750	.0258	.0344	205	650	85.0	77
9 c	20.04	.707	.0258	.0365	193	650	79.3	77
10 d	20.04	.640	.0237	.0370	190	550	71.8	77
11 a	19.94	.527	.0215	.0408	173	450	59.4	77
12 c	19.94	.387	.0172	.0444	159	250	43.6	80
13 b	19.94	.448	.0205	.0457	154	400	50.5	80
15 b	14.94	.530	.0238	.0449	157	550	80.2	81
16 c	14.84	.476	.0227	.0476	148	500	72.5	81
17 d	14.94	.412	.0200	.0485	145	375	62.2	81
21 b	19.94	.630	.0215	.0341	207	455	83.6	173
23 c	19.84	.554	.0205	.0370	190	405	74.5	178

Results of Runs at which Ignition was obtained with Maximum Percent Theoretical Air.

Orifice Diameter 4 mils.

Ignition point: Runs 24-43 incl. 35" from injection.
Runs 44-52 incl. 16 1/4" " "

Run No.	Comb. Cham. Pressure "Hg (abs.)	lbs. air / sec.	lbs. fuel / sec.	F/A ratio	% Theor. Air	Atomization Pressure (psi)	Air Velocity ft/sec	Air Temp °F.
24a	25.05	.601	.00863	.0144	490	300	54.4	83.5
25a	"	.570	.00863	.01515	466	300	51.5	83.5
26b	20.00	.801	.0113	.01411	500	700	90.75	83.5°
27b	20.00	.760	.0113	.01488	474	700	86.30	"
28c	19.95	.701	.0103	.01470	480	550	79.60	"
29a	"	.670	.0103	.01538	458	550	76.10	"
30b	"	.628	.0103	.01640	430	550	71.40	"
31c	"	.575	.0093	.01619	435	400	65.30	"
32b	"	.520	.0093	.01789	394	400	59.20	"
35b	14.90	.630	.01096	.01742	405	650	95.8	83.5
36a	15.00	.570	.01062	.01868	378	600	86.0	"
37c	14.95	.510	.01030	.02050	349	550	77.3	"
38c	15.00	.462	.00898	.01948	362	350	69.8	"
44c	19.92	.810	.0100	.01234	572	450	91.6	80°
45f	"	.785	.0100	.01275	554	450	88.75	"
46a	"	.730	.0093	.01275	554	400	82.50	"
47a	"	.663	.0093	.01405	502	400	75.0	"
48b	"	.620	.0088	.01420	496	325	70.0	"
49a	"	.570	.00863	.01518	465	300	64.5	"
50b	24.82	.638	.00863	.01353	510	300	57.9	80°

B. Sample Calculations.

1. Calibration of the nozzle ring.

Calculation for the 8-mil orifice at 1800 psi

(Gas pressure = Oil pressure) $p = 1800$ psi

Weight of fuel bottle before run (lbs.) $45\frac{3}{4} = 45.750$

" " " " after run (lbs) $43\frac{3}{8} = 43.375$

Time of oil flow (secs.) $t = 63$

Specific weight (w_N) of N_2 @ 82°F $= .00484\,p$

$$\text{where} \quad w_N = \frac{1}{v} = \frac{p \times 144}{RT} = \frac{144\,p}{(54.99)(460+82)}$$

$$w_N = (.00484)(1800) = 8.71 \text{ lbs/ft}^3$$

From Temp.-Sp. gravity curve (Fig. XVI) for 82°F read specific gravity = .8375

$$\therefore \text{specific weight of oil} = (.8375)(62.4) = 52.3 \text{ lb/ft}^3$$

$$\text{Total weight of oil flow} = \frac{52.3\ \Delta W}{\text{sp. wt. oil} - \text{sp. wt. gas}}$$

where ΔW = change in weight of fuel bottle during run $= (45.750 - 43.375)$

$$\text{Total weight of oil flow} = \frac{(52.3)(2.375)}{(52.3 - 8.71)} = 2.845 \text{ lbs}$$

$$\text{Rate of oil flow} = \frac{2.845}{63} = \underline{\underline{4.52}} \text{ lbs. oil/sec.}$$

2. Test Runs

Calculations for Run No. 28C.

Burometer reading 29.95" Hg.
Comb chamber vacuum manometer reading 10 00 " Hg.
Comb. Chamber (absolute) pressure 19.95 " Hg. $= P_c$

Air flow manometer reading 49.9 cm H_2O

From The "Air Flow Rate vs. Manometer Reading" curve (Figure XV) read $\omega_a = 0.701$ lbs. air/second.

Fuel pressure reading 550 psi.

From The curve of Calibration Data "Rate of Oil Flow vs. Oil Pressure" (Figure) read

$$\omega_f = 0.0103 \text{ lbs fuel / second.}$$

Then Fuel-Air Ratio $\left(F/A\right) = \dfrac{\omega_f}{\omega_a} = \dfrac{.0103}{.701} = \underline{0.01470}$

From Reference (1) Chart A we find that one pound of this fuel requires theoretically about 14.20 pounds of air for complete combustion.
Hence:

$$\text{Percent Theoretical Air} = \frac{100}{14.20} \div \frac{\omega_f}{\omega_a} = \frac{.0705}{(F/A)} \times 100$$

$$= \frac{7.05}{.0147} = \underline{480\ \%}$$

For Air Velocity V_a (ft/sec) we have relations:

$$A V_a = v_a \omega_a \qquad \text{or} \qquad \omega_a = \frac{A V_a}{v_a}$$

where A = chamber cross-sectional area $= \dfrac{\pi \left(\frac{5.75}{12}\right)^2}{4} = 0.1802\ ft.^2$

v_a = specific volume of air $= \dfrac{RT}{P_c \times 70.7}$

where P_c = Comb. Chamber pressure in inches of mercury
and $T = (460 + t)$ t = air temp. °F

Then $w_a = \dfrac{A V_a (70.7 P_c)}{R(460+t)}$ R = 53.3 lb-ft/°F for air.
t = 83.5 F.

$$V_a = \frac{R(460+t)\, w_a}{(70.7)(.1802) P_c} = \frac{4.18\,(460+t)\, w_a}{P_c}$$

$$V_a = \frac{(4.18)(543.5)(0.701)}{19.95} = \underline{79.60 \text{ ft/sec}}$$

C. Supplementary Discussion

1. Combustion Chamber:

When the combustion chamber was first designed, it was assumed the ignition would not be obtained with air velocities above 40 ft/sec without a flame arrestor and that a maximum distance of 10" to 12" would be required for atomization. As it turned out, both of these estimates were too low. The large diameter of the combustion chamber was selected to reduce to a minimum the local effects of the chamber walls on the air stream in the center and to provide sufficient air to mix with the amount of fuel which was expected to flow through seven small orifices at atomization pressures above 1000 psi. The exact diameter (5.75") of the chamber was determined by the inside diameter of the pyrex jars which were used (with their bottoms cut off) instead of pyrex tubing which could not be obtained in the desired size.

2. Nozzle Ring:

The nozzle ring was designed so as to obtain as nearly an equal flow as possible through each of the seven orifices. Brass tubing was used because it is easier to drill than copper or steel tubing.

The flow rates through the orifices were calculated by using the discharge coefficients for sharp-edged orifices (diameter ratio 0.20) as given in Fig. 21 of Reference (3). The experimentally determined flow rates

pulled oil out of the nozzle and apparently pulled particles of scale or dirt from within the nozzle ring itself.

Because of the high atomization pressures the equipment was designed for, the rate of oil flow was measured by the atomization pressure and not by a flow orifice which would have required a manometer capable of withstanding 2000 psi. This method proved to be very satisfactory because for the small orifices used the curve of flow rate versus atomization pressure was quite flat and a relatively large change in pressure caused only a small change in rate of flow. In addition, this method permitted rapid and easy determination of the rate of oil flow.

3. Spark:

It was intended to use a 5000 volt continuous spark but trials quickly showed that a gap of less than 1/16" would be required to keep the spark from blowing out. Therefor, both sides of the transformer were used to give a 10,000 volt spark across a ½" gap which worked quite satisfactorily. Due to the fact that there was always some oil spray passing thru the combustion chamber, the electrodes became coated with oil between runs and some occasional difficulty was experienced in getting the spark started. In view of this fact, when the spark was moved up to within 16¼" of the nozzle ring, the spark gap was

reduced to 3/16" and no further trouble was experienced.

During any run, even when ignition was not obtained, there was always a small cone of flame (tapering to a point downstream) about one inch long extending downstream from the electrodes. It is felt that this served as a very good ignition source and that, if ignition of the mixture was at all possible without a flame holder, it was obtained.

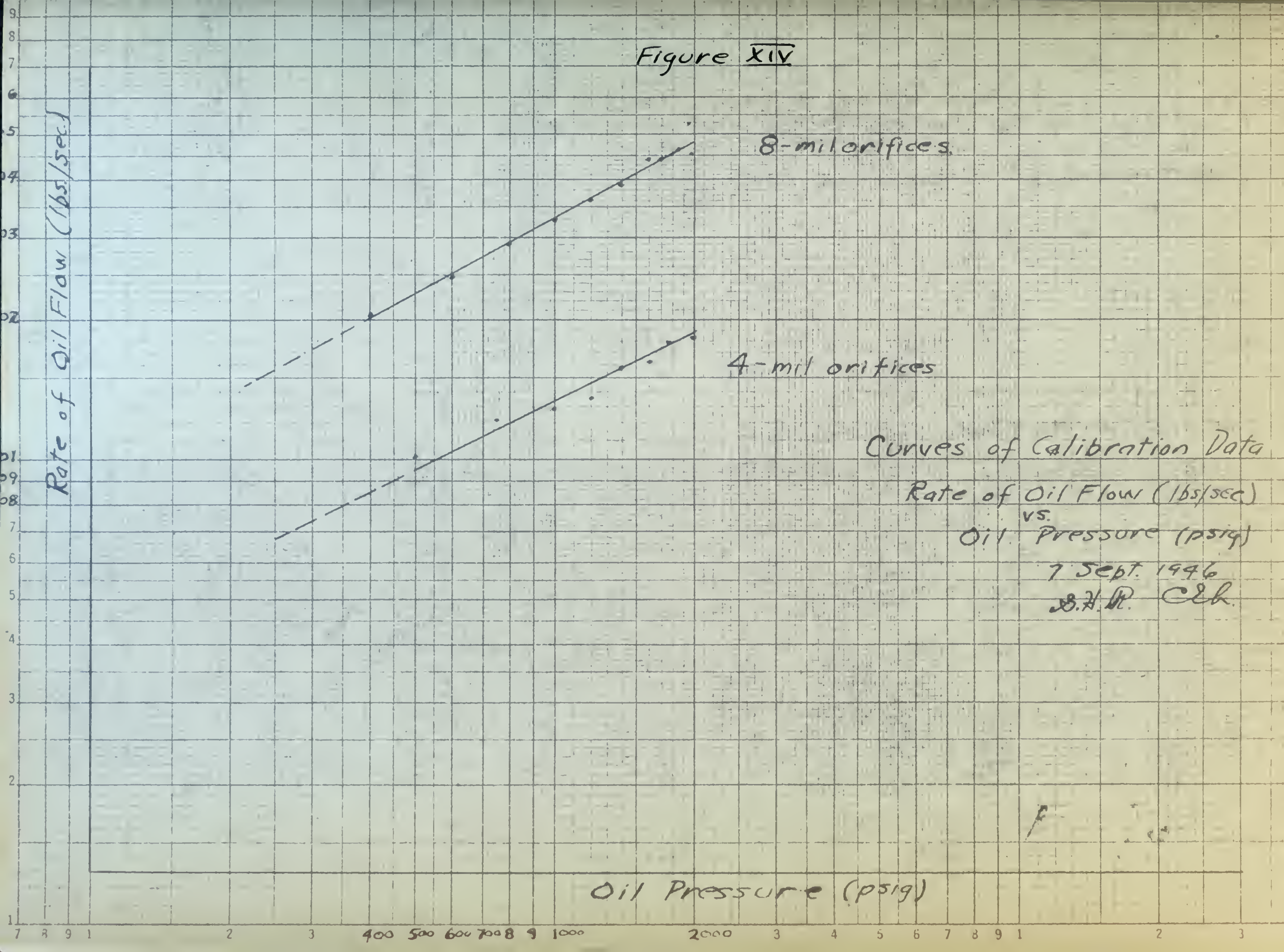
4. Protection:

A 1/8" Lucite shield was hung around the bottom and sides of the combustion chamber (center-line of chamber was about six feet off the floor) to protect the personnel in the room from flying glass splinters in case of an explosion breaking the pyrex glass.

PART VII. D

ORIGINAL DATA.

Figure XIV


8-mil orifices.
4-mil orifices
Curves of Calibration Data
Rate of Oil Flow (lbs/sec)
vs.
Oil Pressure (psig)
7 Sept. 1946
S.H.R. C.E.L.
Rate of Oil Flow (lbs/sec)
Oil Pressure (psig)
400 500 600 700 8 9 1000
2000
.02
.03
.04
.05
.01
.09
.08

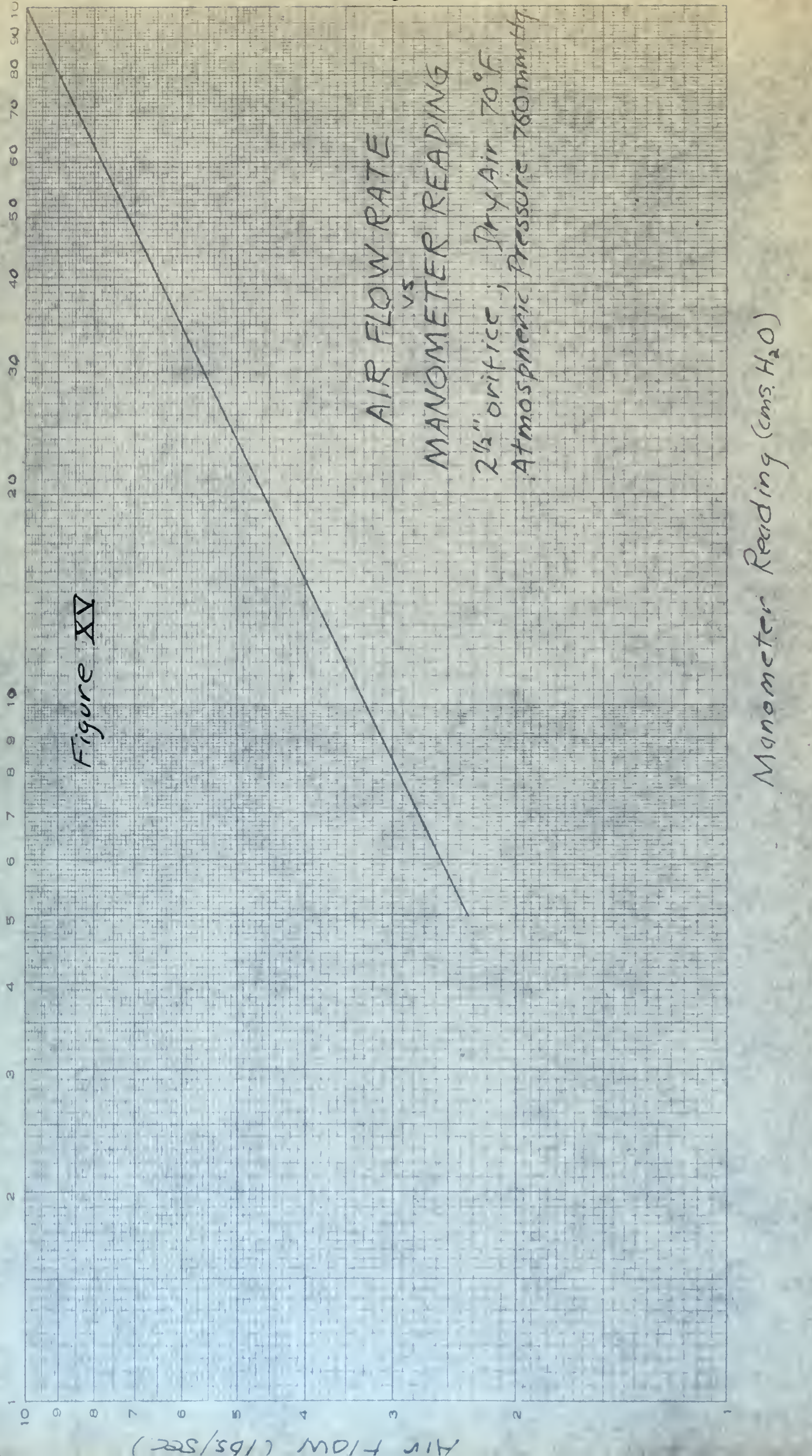


Figure XV
AIR FLOW RATE
vs
MANOMETER READING
2½" orifice ; Dry Air 70°F
Atmospheric Pressure 760 mm Hg
Manometer Reading (cms H_2O)
Air Flow (lbs/sec)
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100

Calibration Data for 8-mil orifice nozzle ring.

$Q(\text{spec. wt oil} - \text{spec wt. } N_2) = \Delta W$

Specific weight of fuel @ 82°F = (.8375)(62.4) = 52.3 lbs/cu ft.

Specific weight of N_2 gas @ 82°F = (.00484) p ; (p = psia)

Gas and Oil Pressure (psig)	Change in Weight of Fuel Tank (lbs) ΔW	sp. wt. N_2 82°F (lbs/cu.ft.)	Total Weight of Oil Flow (lbs.)	Time of Oil Flow (sec.)	Rate of Oil Flow (lbs/sec.)
1990	1.50	9.63	1.84	40.25	.0457
1940	2.00	9.38	2.49	47.20	.0528
1840	2.125	8.90	2.56	55.20	.0464
1800	2.375	8.71	2.845	63.00	.0452
1700	2.625	8.22	3.110	70.2	.0444
1600	2.00	7.74	2.340	52.8	.0443
1400	2.00	6.77	2.30	59.0	.0390
1200	2.00	5.80	2.242	62.0	.0362
1000	1.875	4.84	2.065	62.8	.0329
800	1.750	3.87	1.890	65.2	.0290
600	1.875	2.90	1.980	79.7	.0248
400	2.000	1.935	2.070	101.6	.0204

Calibration Data for 4-mil orifice nozzle ring.

Q (sp. wt of oil − sp. wt of N_2) = ΔW.

Specific weight fuel @ 82°F = (.8375)(62.4) = 52.3 lbs./cu.ft.

Specific weight N_2 @ 82°F = (.00484)p ; (p = psia)

Gas and Oil Pressure (psig)	Change in Weight of Fuel Tank (ΔW) lbs.	Sp. wt. N_2 82°F (lbs./cu.ft.)	Total Weight of Oil Flow (lbs.)	Time of Oil Flow (sec)	Rate of Oil Flow (lbs./sec)	
2000	2.25	9.82	2.765	152.2	.0182	
1780	2.00	8.69	2.400	135.0	.0178	
1600	2.40	7.98	2.240	138.2	.0162	doubtful point.
1400	1.80	6.65	2.06	129.7	0159	
1200	1.55	5.97	1.75	128.6	.0136	
1000	185	5.01	2.04	158.4	.0129	
750	1.90	3.80	2.05	168.0	.0122	
500	1.70	2.42	1.78	175.9	.0101	

DATA

(Runs 1 thru 23 made with orifices 8 mils in diameter.)

ΔP_{CV} = Combustion Chamber Vacuum in inches of Mercury.

ΔP_A = Air Flow Manometer Reading in cms of Water.

ΔP_F = Fuel Pressure (psi gage)

Run No.	ΔP_{CV}	ΔP_A	ΔP_F	Ignition	Comments
Barometer 30.50" Hg		Air Temp. 75°F		Fuel Temp. 75°F	
1	10.0	44.2	1590	Yes	Center orifice plugged. Flashes of flame 8" downstream.
2	10.7	19.3	900	No	Center orifice plugged
3	10.0	46.0	1655	Yes	Flame back into air entrance cone. Chamber vacuum up to + 4" Hg
4	10.6	63.3	1000	Yes	Upper left orifice intermittent. Flame not as voluminous as in run #3.
5	20.35	16.1	1000	No	Upper left orifice plugged
Barometer 30.45" Hg		Air Temp. 77°F		Fuel Temp 80°F	
6 a	10.5	63.9	500	No	
b	10.5	63.9	700	No	
c	10.5	63.9	900	Yes	
d	10.5	63.9	800	Yes	Pulsing, Explosive
e	10.5	63.9	750	Yes	Flashing
f	10.5	63.9	775	Yes	Flashing, occasional explosion
7 a	10.6	55.0	450	No	
b	10.6	55.0	600	No	Very occasional flash and explosion
c	10.6	55.0	650	Yes	Occasional flash
d	10.6	55.0	700	Yes	Flashing Intermittent explosions
e	10.6	55.0	750	Yes	Flashing Intermittent explosions
f	10.6	55.0	800	Yes	Flashing Intermittent explosions

Run No.	ΔP_{cv}	ΔP_A	ΔP_F	Ignition	Comments
8 a	10.5	49.8	500	No	
b	"	"	550	No	Very occassional flash
c	"	"	600	No	" " "
d	"	"	650	No	Occasional flash + explosion, hole partly plugged.
e	"	"	750	No	"
f	"	"	800	No	"
g	"	"	700	No	Occasionol flash
h	"	"	800	No	
i	"	"	900	No	Occasional flash
j	"	"	1000	Yes	Flashing
k	"	"	1240	Yes	"
l	"	"	500	No	
m	"	"	550	No	
9 a	10.4	49.0	500	No	
b	"	"	600	No	Very occasional flash
c	"	"	650	Yes	Some flashing
d	"	"	800	Yes	Explosive, flame fills chamber
10 a	10.4	39.5	400	No	
b	"	"	450	No	
c	"	"	500	No	
d	"	"	550	Yes	Very occasional flashing
e	"	"	575	Yes	" " "
11 a	10.5	26.5	450	Yes	
b	"	"	400	Yes	
c	"	"	350	No	
d	"	"	—		

Run No	ΔP_{cv}	ΔP_A	ΔP_F	Ignition	Comments
12 a	10.5	14.0	350	Yes	
b	"	"	300	Yes	} Jet seems concentrated in middle of chamber
c	"	"	250	Yes	
d	"	"	450	Yes	Quite explosive
13 a	10.5	19.0	350	No	
b	"	"	400	Yes	
14 a	15.5	29.2	400	No	
b	"	"	450	No	
c	"	"	500	—	All orifices plugged

Barometer 30.44 "Hg Air Temp 81°F Fuel Temp 83°F

Run No	ΔP_{cv}	ΔP_A	ΔP_F	Ignition	Comments
15 a	15.5	26.8	500	No	
b	"	"	550	Yes	
16 a	15.6	21.5	500	Yes	
b	"	"	450	No	
c	"	"	500	Yes	
d	"	"	475	No	
17 a	15.5	16.0	450	Yes	
b			400	Yes	
c			350	No	
d			375	Yes	
18 a	20.45	13.0	350	No	
b			400	No	
c			450	No	
d			500	No	
e			550	No	
f			600	No	Middle orifice plugged

Run No	ΔP_{cv}	ΔP_A	ΔP_F	Ignition	Comments
18 g	20.45	13.0	730	No	
h	"	"	800	No	Flashes far downstream
i	"	"	930	No	inside of exit section.
j	"	"	1010	No	
k	"	"	1700	Yes	1 orifice plugged
19 a	20.20	13.0	600	No	
b	"	"	1000	No	
c	"	"	1200	No	
d	"	"	1500	No	
20 a	5.5	29.6	400	No	
b	"	"	300	No	
c	"	"	300	No	

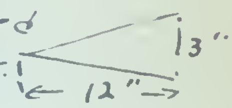
Barometer 30.44   Air Temp. 174°F.   Fuel Temp 86°F

21 a	10.5	38.4	400	Yes	Very faint flashes
b	"	"	450	Yes	Definite flashes
22 a	10.6	29.7	400	Yes	
b	"	"	350	Yes	
c	"	"	300	No	Orifices plugged
23 a	10.6	29.4	330	No	Air Temp 178°F
b	"	"	350	No	" " "
c	"	"	400	Yes	" " "

DATA

(Runs 24 thru 52 made with 4-mil orifice)
ΔP_{CV} = Combustion Chamber Vacuum in inches of Hg.
ΔP_A = Air Flow Manometer Reading in cms. of water.
ΔP_F = Fuel Pressure (psi. gage)

RUN No.	ΔP_{CV}	ΔP_A	ΔP_F	Ignition	Comments
	Barometer 29.95" Hg.;		Air Temp. 83.5°F; Oil Temp. 80°F.		
24a	4.9	36.4	300	Yes	Very faint flashes
25a	4.9	31.3	300	Yes	"
26a	9.95	65.0	600	No	
b	"	"	700	Yes	Very faint
27a	9.95	56.0	600	No	
b	"	"	700	Yes	Very faint
c	"	"	750	Yes	
d	"	"	1300	"	For flame speed V_f = 11.1 ft/sec.
28a	10.0	48.9	700	Yes	
b	"	"	600	"	
c	"	"	550	"	Very occasional
29a	10.0	44.1	550	Yes	
b	"	"	500	No	
30a	10.0	38.3	500	No	
b	"	"	550	Yes	
31a	10.0	32.0	500	Yes	
b	"	"	450	"	
c	"	"	400	"	
d	"	"	350	No	



Run No.	ΔP_{CV}	ΔP_A	ΔP_F	Ignition	Comments
32a	10.0	27.3	350	No	
b	"	"	400	Yes	
33a	10.0	20.7	400	Yes	Stable flame
b	"	"	350	"	Flame speed 
c	"	"	300	"	V_f = 17.42 ft/sec
34a	9.95	12.2	300	Yes	Explosion
35a	15.05	38.4	700	Yes	Very faint
b	"	"	650	"	
c	"	"	600	No	
36a	14.95	31.1	600	Yes	Occasional flash
b	"	"	650	Yes	"
c	"	"	700	Yes	
37a	15.0	25.4	650	Yes	
b	"	"	600	"	
c	"	"	550	"	Very occasional flash
d	"	"	500	No	
38a	14.95	20.5	500	Yes	
b	"	"	400	"	
c	"	"	350	"	occasional flash
d	"	"	300	No	
39a	14.95	11.8	300	Yes	Explosion

Barometer 29.95"Hg; Air Temp 85°F; Oil Temp 80°F.

40a	19.95	18.0	800	No	

Run No.	ΔP_{CV}	ΔP_A	ΔP_F	Ignition	Comments.
40b	19.95	18.0	900	No	
c	"	"	1000	No	
d	"	"	1100	No	
e	"	"	1200	?	Flash doubtful.
f	"	"	1300	No	
g	"	"	1500	"	
h	"	"	1700	"	
i	"	"	2000	"	
41a	19.95	13.7	1950	Yes	Explosion.
42a	20.01	14.4	1830	Yes	Very faint.
43a	19.95	10.2	1820	Yes	Explosions.
b	"	"	1600	"	"
c	"	"	1400	"	"
d	"	"	1200	"	"
e	"	"	1000	"	"
f	"	"	800	"	"
g	"	"	600	"	"

All of the remaining runs were made with the spark moved up to within 16.25" from nozzle ring and with spark gap closed to 3/16".

Barometer 29.92" Hg.; Air Temp. 80°F; Oil Temp. 80°F.

Run No.	ΔP_{CV}	ΔP_A	ΔP_F	Ignition	Comments.
44a	10.0	65.2	400	No	
b	"	"	500	Yes	
c	"	"	450	"	
d	"	"	400	No	

RUN No.	ΔP_{CV}	ΔP_A	ΔP_F	Ignition	Comments
45a	10.0	60.0	400	No	
b	"	"	500	"	
c	"	"	600	Yes	
d	"	"	550	"	
e	"	"	500	"	
f	"	"	450	"	
g	"	"	400	No	
46a	10.0	51.4	400	Yes	
b	"	"	350	No	
47a	10.0	43.0	400	Yes	
b	"	"	350	No.	
48a	10.0	37.5	350	Yes	
b	"	"	325	"	
c	"	"	300	No.	
49a	10.0	31.1	300	Yes	
b	"	"	250	No	
c	"	"	275	"	
50a	5.1	39.1	350	Yes	
b	"	"	300	"	
c	"	"	275	No	
51a	20.15	16.2	300	No	
b	"	"	400	"	
c	"	"	600	"	
d	"	"	800	"	
e	"	"	900	"	
f	"	"	1100	"	

Run No.	ΔP_{CV}	ΔP_A	ΔP_F	Ignition	Comments.
51g	20.15	16.2	1200	No	
h	"	"	1400	"	
i	"	"	1600	"	
j	"	"	1800	"	
k	"	"	350	"	
l	"	"	400	"	
52a	20.00	9.0	1800	No	
b	"	"	1200	"	
c	"	"	900	"	
d	"	"	600	Yes	
e	"	"	400	"	
f	"	"	350	No	

Analysis of Diesel Fuel Oil as made by Chemical Laboratory, Boston Naval Shipyard on 31 July, 1946.

Gravity, A.P.I. 60°F	35.85
Specific Gravity, 60°F	0.8456
Flash Point	156°F
Pour Point	5°F
Water and Sediment	0.10%
Sulphur	0.24%
Carbon Residue (10% Bottoms)	0.05%
Ash	None
90% Distillation Temperature	596°F
Color (A.S.T.M.)	1½
B.T. U. per pound (calculated)	19,479
Cubic Ft. Air to Burn 1 Pound (calculated)	195

Refer to
File No.
(356)248273

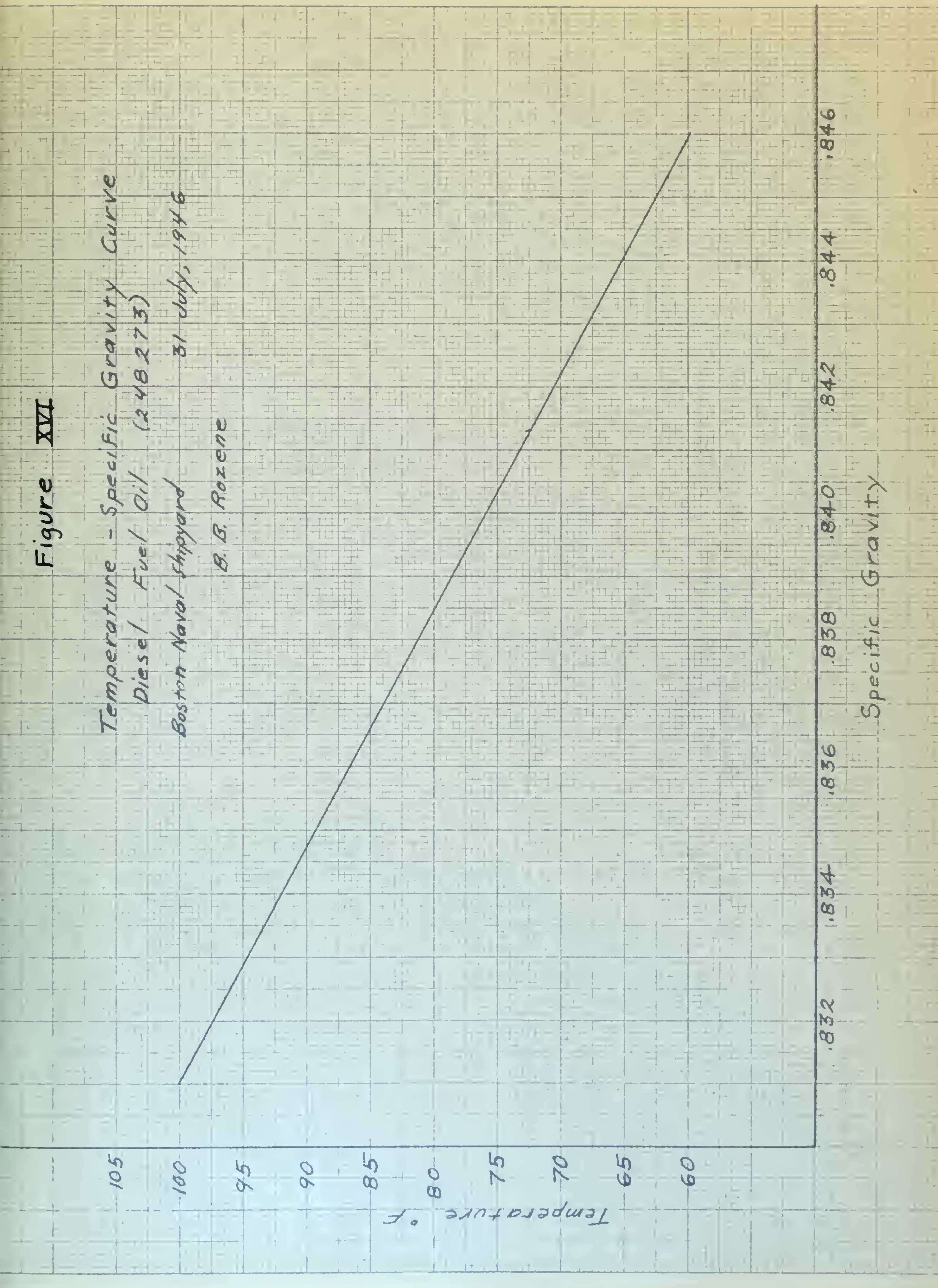
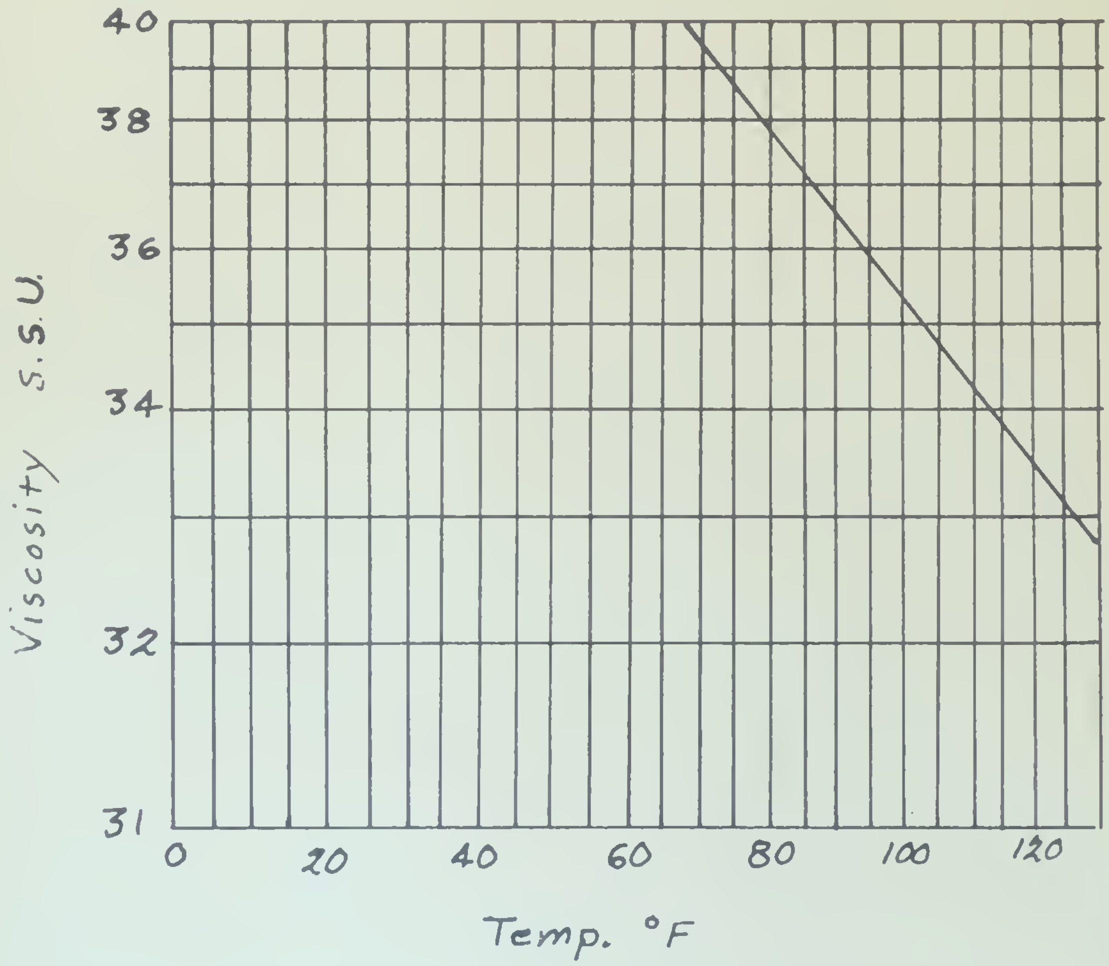


Figure XVI
Temperature - Specific Gravity Curve
Diesel Fuel Oil (248273)
Boston Naval Shipyard 31 July, 1946
B. B. Rozene
Specific Gravity
.832
.834
.836
.838
.840
.842
.844
.846
Temperature °F
105
100
95
90
85
80
75
70
65
60

Figure XVII.

Viscosity Temperature Curve
Diesel Fuel Oil (248273)

Boston Naval Shipyard 31 July, 1946



E. References

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4. J.C.Oldfield and W.S.Dawson, "Study of a High Output Combustion Chamber," M.I.T. Thesis, 1944.

5. John Longwell, "Atomization," M.I.T. Thesis, ScD 1943.

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1. Samuel Letvin, " Overall Boiler Efficiency Determination," Journal A.S.N.E., 1942, Volume 54, p175.

2. A. C. Roesch and R. F. Rose, " A Survey of the Literature on the Subject of Atomization," D.I.C. Progress Report No. 1-46, Feb. 28, 1946, Mass. Inst. Tech.

3. Walker, Lewis, [redacted] McAdams, and Gilliland, Principles of Chemical Engineering," pages 60, 61.

4. J. C. Oldfield and W. S. Dawson, " Study of a High Output Combustion Chamber," M.I.T. Thesis, 1944.

5. John Longwell, " Atomization," M.I.T. Thesis, Sep. 1943.