AN INVESTIGATION OF THE EFFECT OF DIRECT WATER INJECTION ON DETONATION

BY

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Professor George W. Swett
Secretary of the Faculty
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Cambridge, Massachusetts

Dear Sir:

A thesis entitled "An Investigation of the Effect of Direct Water Injection on Detonation" is herewith submitted in partial fulfillment of the requirements for the degree of Master of Science in Aeronautical Engineering.

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AN INVESTIGATION OF THE EFFECT OF DIRECT WATER INJECTION ON DETONATION

SUMMARY

The purpose of this project was to investigate the effects of direct water injection on detonation. The following conclusions were reached:

1. The addition of water at a constant fuel-air ratio permits the attainment of higher indicated mean effective pressures without detonation. This effect is more pronounced for low fuel-air ratios than for high fuel-air ratios.

2. At a fixed water-fuel ratio, the fuel-air ratio at which the maximum detonation free indicated mean effective pressure occurs increases as compression ratio decreases.

3. At a constant isfc, detonation free imep increases with water-fuel ratio. At fuel-air ratios below .09, islc increases very rapidly with increase in imep while at fuel-air ratios above .09, islc decreases slightly with imep increase.

4. Increasing water-fuel ratio at low (cruising) fuel-air ratios results in a decrease in isfc, but at the expense of a prohibitive increase in islc.

5. Fuel is considerably more effective than water as an anti-detonant at low (cruising) fuel-air ratios.

6. At high (take-off) fuel-air ratios, water is effective as an anti-detonant, while the use of additional

Summary (cont'd)

fuel for this purpose actually results in a decrease of imep.

7. Indicated thermal efficiency is not affected by the addition of water.

8. Water injection permits the use of higher compression ratios by increasing detonation free imep to take-off values. This permits the designer to take advantage of the greatly improved fuel economy in the cruising range resulting from the use of high compression ratios.

AN INVESTIGATION OF THE EFFECT OF DIRECT WATER INJECTION ON DETONATION

INTRODUCTION

It is an established fact that, for a fixed inlet pressure and temperature, increase of compression ratio of an engine increases power output slightly but produces a decided improvement in fuel economy. Therefore, designers of internal combustion engines would desire to use high compression for the purpose of obtaining fuel economy. But increase of compression ratio is limited because of detonation at high powers. Thus, the attempt to improve fuel economy by increasing compression may render an engine unsuitable for use because of the reduction of power for take-off and full load.

The limitations of increased compression ratio on take-off and full load are now being improved by the addition of water to the fuel-air mixture. During the past war, the method of spraying water into the inlet manifold was used with considerable success. According to some reports, the power for take-off was increased by 15% to 30%. A second method of adding water to the fuel-air mixture would be by direct injection of water into the cylinder. This second method has had very little investigation and no practical use at the present date. It is the object of this project to investigate the effect on detonation of direct water injection into the cylinder.

The project was conducted at the Sloan Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, by Comdr. R. F. Seibels, Jr., USN, Comdr. T. Washington, Jr., USN, and Lt. Comdr. J. R. MacLachlan, USN. Mr. W. A. Leary of the M.I.T. staff was supervisor.

EQUIPMENT

The test equipment included a variable-compression, one-cylinder Coordinating Fuel Research Engine delivering power to a dynamometer. Fuel vaporization was accomplished by spraying fuel into a heated vaporizing tank. An injection pump and an injection nozzle were used to spray water directly into the cylinder. Figs. 1, 2, 3, and 4 are photographs of the arrangement of equipment. Fig. 5 is a block diagram of the installation set-up.

The engine of this project was a standard variable-compression, one-cylinder CFR Engine. This engine had a 3.25 in. bore, a 4.5 in. stroke and a 37.33 cu. in. displacement. Compression could be set at any desired compression ratio between 4 and 10. This standard CFR Engine is fully described in Ref. 1.

The dynamometer was a 5 HP motor-generator set manufactured by the Star Electric Motor Company. It was used as a motor to turn over the CFR Engine for starting or motoring, and as a generator to absorb the power delivered by that engine.

The gasoline used in this experiment was standard 80 octane unleaded aviation gasoline. This gasoline was taken from the mains of the Sloan Laboratory and passed through a fuel rotometer to the fuel pump. A Bosch injection pump driven by a small electric motor forced the gasoline at high pressure through an injection nozzle into a heated vaporizing tank. A vernier adjustment on the Bosch pump allowed accurate control of fuel flow.

Air to the vaporizing tank could be taken either from the test room at atmospheric pressure, or from the laboratory high pressure main. A Nash Hytor L-5 Compressor driven by a Sprague Electrical Dynamometer supplied the high pressure air. The air was metered through a calibrated orifice and drawn into the vaporizing tank.

Distilled water was used for injection into the cylinder. This distilled water was stored in a one gallon glass jug. From the jug the water flowed by gravity to a constant level float chamber and thence through a water rotometer to the water pump. The water pump was an engine driven Bosch injection pump equipped with a vernier adjustment for close control of flow. The pump forced water at high pressure through a Bendix KC 50S1 injection nozzle (Fig. 6) into the cylinder at a point opposite the spark plug.

Detonation was detected by a detonation pickup and oscilliograph. The pickup was one of the pressure type, being

sensitive to the rate of change of pressure (dp/dt). The oscillograph was a Dumont 208 Cathode-Ray Oscillograph.

Other apparatus used in preparation for this experiment included balance scales, MIT Pressure-Crank Machine, and MIT Transfer Machine which transferred pressure-crank readings to pressure volume. The latter two machines are described in Appendix II of Ref. 2 and Appendix B of Ref. 3, respectively.

The water injection equipment of this experiment leaves much to be desired. The time of the start of injection can be accurately controlled. But, unfortunately, the length of time of injection varies with the amount of water injected. Detonation takes place somewhere near to the same crank angle forall powers and fuel-air ratios. It would be desirable to have the angle of injection time remain constant no matter what the rate of water flow, and to so adjust the time of injection as to best suppress detonation. With the present apparatus, some of the benefit is lost because the time of mid-point of injection varies with water flow. Optimum utilization of water cannot be realized because at low and moderate flow rates, some of it may be injected too early for best detonation suppression, while at high flow rates, part of the water is injected too late to be effective.

PRELIMINARY PROCEDURE

It was necessary, prior to the commencement of this investigation, to devote considerable time and labor to the arrangement of the test apparatus shown in Figs. 1 through 4. The purpose was two-fold: first, to eliminate or to reduce as far as possible the effects of those variables not pertinent to this investigation; and second, to permit accurate control of all essential variables.

As further preliminaries it was necessary to calibrate both the fuel and water rotometers, the water injection apparatus, and to calibrate the dynamometer mercury manometer in terms of indicated mean effective pressure. As a final preliminary to this investigation, the water injection apparatus was timed to insure start of injection at the desired crank angle.

Calibration curves of the fuel and water rotometers made from the data of Table I appear in Fig. 7. The method of calibration followed in both cases consisted essentially of weighing the amount of liquid which passed through the rotometer in a measured interval of time, during which the rotometer setting was maintained at a constant value. The mass flow per second was calculated and plotted against rotometer setting.

To calibrate the dynamometer mercury manometer, indicator cards were taken using MIT Pressure Crank Angle Machine,

following the procedure outlined in Ref. 2, simultaneously with mercury manometer readings. From the indicator cards, indicated mean effective pressure was determined, using MIT Transfer Machine to transfer pressure crank values to pressure volume values. (Ref. 3). A plot of indicated mean effective pressure versus inches of mercury made from data of Table II appears in Fig. 8.

The calibration of the water injection apparatus in terms of water rotometer reading and duration of water spray in degrees of crank angle, α, is shown in Fig. 9. The start of the spray was set to occur at top center by means of an adjustable coupling on the water pump drive shaft and a stroboscope timed to flash at top center. Top center, itself, was determined by the standard CFR Engine calibrated brass spark timing ring and a flashing neon light. It was found as shown in Fig. 9 that varying the water rotometer setting varied the duration of injection in degrees of crank angle, although the start of injection remained fixed at top center.

In order to determine the optimum angle at which to start injection, the following steps were taken. The compression ratio was set at 6.6, and the fuel-air and water-fuel ratios were set arbitrarily at .08 and .8, respectively. The crank angle at which injection starts and the mass rate of air flow were then varied until, by trial and error, the maximum indicated mean effective pressure without detonation

was obtained. The optimum angle corresponding to this condition was thus found to be 18° after top center. In all subsequent tests in which water was utilized, injection was started at this point. It is realized that this 18° setting probably was not the optimum angle for the entire range of fuel-air ratios and compression ratios. This setting was selected as a compromise in order to reduce the number of variables of the experiment. Since the conditions imposed during selection of this 18° angle for start of injection were about average, the setting is probably near optimum for the vast majority of the readings of this project.

PROCEDURE

The general plan adhered to in this investigation appears below. The following set of operating conditions was adopted as standard: oil temperature 160°F, oil pressure 35 psi., inlet temperature 140°F, jacket temperature 212°F, and engine speed 1200 RPM. The compression ratio was set at 6.2. Test data were taken for five fuel-air ratios - .064 (good cruising), .07, .08 (best power), .09 and .10. For each fuel-air ratio detonation limited indicated mean effective pressure was determined by means of a cathode-ray oscillograph for water-fuel ratios of from 0 to over 1.0. Curves of detonation limited indicated mean effective pressure at various fuel-air ratios are plotted in Fig. 10 from the data of Table III.

The procedure described above was repeated for compression ratios of 6.6, 7.0, and 7.4. The resulting data obtained appear in Tables IV through VI. The corresponding curves are drawn in Figs. 11 through 13.

A warming up period was required as a daily preliminary to the making of record runs. The CFR Engine required approximately one hour before steady operating conditions were obtained with respect to oil pressure and temperature, jacket temperature, inlet pressure, and particularly inlet temperature. To reduce the delay involved in warming up, oil temperature could be raised by means of an electric oil heater in the crank case and engine jacket temperature by means of a steam bleed. During the warm-up and actual runs, inlet temperature was regulated by varying the amount of steam admitted to the jacket surrounding the vaporizing tank.

When steady operating conditions were obtained and with the compression ratio set at 6.2, a fuel-air ratio of .064 (without water) was set by simultaneously varying the mass rates of flow of both air and fuel until, by trial and error, the desired fuel-air ratio was obtained just as incipient detonation occurred. In this way, the detonation limited indicated mean effective pressure at a zero water-fuel ratio for these conditions was obtained. The mass rate of air flow was then increased. At the same time, the resulting detonation was suppressed by the introduction of an excessive amount of water. Next, the mass rate of fuel flow was increased un-

[illegible]

... obtained ... temperature, pressure, temperature, inlet pressure, ... critical inlet temperature. To ... the desired inlet temperature ..., inlet temperature was ... by means of an electric oil heater in the ... tank and ... temperature by means of a steam ... During the warm-up ... runs, inlet temperature ... by varying the amount of steam admitted to the jacket surrounding the vaporizing tank.

When steady operating conditions were obtained and with the ... ratio ... a fuel-air ratio of .004 (without water) was set by ... varying the mass rate of flow of both air and fuel until, by trial and error, the desired fuel-air ratio was obtained just as incipient detonation occurred. In this way, the detonation limited indicated mean effective pressure at a zero water-fuel ratio for these conditions was obtained. The mass rate of air flow was then increased. At the same time, the resulting detonation was suppressed by the introduction of an excessive amount of water. Next, the mass rate of fuel flow was increased until a fuel-air ratio of .064 was again obtained. By reducing the amount of water until a condition of incipient detonation again existed, the detonation limited indicated mean effective pressure and the corresponding water-fuel ratio were readily determined. The compression ratio was held constant at 6.2, and the above procedure followed for fuel-air ratios of .07, .08, .09, and .10. In this manner the family of curves shown in Fig. 10 were determined.

The curves of Figs. 11, 12, and 13 were determined in the same manner from the data of Tables IV, V, and VI. The compression was varied through 6.6, 7.0, and 7.4. In order to obtain more readily comparable results the same series of fuel-air ratios were used in each case.

Additional points at a zero water-fuel rate were obtained at a compression ratio of 7.4, for fuel-air ratios of .075, .085, .095, and .11 in order to compare the effectiveness of water versus fuel as anti-detonants. This data is included in Table VI.

RESULTS AND DISCUSSION

The effect of water-fuel ratio on indicated mean effective pressure at compression ratios of 6.2, 6.6, 7.0, and 7.4 is shown in Figs. 10, 11, 12, and 13, respectively. To obtain readily comparable results, the following fuel air ratios were used throughout: .064, .07, .08, .09, and .10. In Fig. 14 are shown the relative effects of fuel and water as detonation suppressors. A cross plot at a constant indicated mean effective pressure of 115 p.s.i.a., of compression ratio versus water-fuel ratio at various fuel-air ratios is shown in Fig. 15.

It may be seen from Fig. 10 that the addition of water accomplished at a constant fuel-air ratio, permits the attainment of a higher indicated mean effective pressure without detonation. It may be seen further from Fig. 10 that the slopes of the curves became progressively shallower as the mixture becomes richer. This means that the effect of water addition is more pronounced at low fuel-air ratios. Similar trends are noted for all compression ratios investigated. (Figs. 11, 12, and 13).

At a compression ratio of 7.4 (Fig. 13) for any given water-fuel ratio, the maximum detonation free indicated mean effective pressure occurs at a fuel-air ratio of .09. As the compression ratio is decreased (Figs. 12, 11, and 10) the maximum indicated mean effective pressure for a given water-

fuel ratio appears to occur at progressively higher fuel-air ratio. Thus, for a compression ratio of 6.2, the optimum detonation free fuel-air ratio appears to be slightly greater than .10. This phenomenon is considered to be characteristic of this 80-octane unleaded aviation gasoline, and would not necessarily recur for another gasoline.

Superimposed on Fig. 13 are curves of constant indicated specific fuel consumption (isfc) and indicated specific liquid (fuel plus water) consumption (islc). An examination of the figure shows that at a constant isfc, detonation free imep obtainable increases with water-fuel ratio. However, this increase of imep at a constant isfc is obtained at the expense of a considerable increase in islc, as long as the fuel-air ratio remains below .09. When the fuel-air ratio exceeds .09, increasing the water-fuel ratio at a constant isfc is accompanied by two effects: first, a slight increase in imep; and second, a slight decrease in islc. Further, at a given water-fuel ratio and at a fuel-air ratio of .10 or greater, a decrease of fuel-air ratio results in both an increase in detonation free imep and a decrease in islc. Translating the above into practical applications, although increasing water fuel for a given cruise power output results in a lower isfc, the increase in islc is prohibitive.

Continuing in the same vein, Fig. 15 was plotted in order to compare the effects of additional water and fuel as detonation suppressors, both at a cruising fuel-air ratio and at a fuel-air ratio of .09, which was considered to be within the take-off range. Fuel was found to be considerably more effective than water at the low fuel-air ratio. The reverse was true at the high fuel-air ratio. Actually the use of additional fuel as a detonation suppressor at the high fuel-air ratio resulted in a decrease of imep, while the addition of water permits an increase in imep. It is evident that in order to attain high values of imep (in this case, 115) water must be used since these values cannot be attained with fuel alone.

By classical theory, the indicated thermal efficiency is a function both of compression ratio and fuel-air ratio. For a fixed compression ratio and fuel-air ratio, indicated thermal efficiency would be constant if the addition of water had no effect. Tables III through VI show that for a given fuel-air ratio and compression ratio, the indicated thermal efficiency remains constant regardless of the water-fuel ratio. It is therefore concluded that indicated thermal efficiency is not affected by the addition of water.

High compression ratios with their resulting high efficiencies are desirable in order to give fuel economy in the cruise range, but take-off powers are limited by detonation of the fuel-air mixture. The advantage of water in-

jection is that it permits use of high compression ratios, while providing sufficient power for take-off. The curves of Fig. 15 were drawn to illustrate this effect. If an imep of 115 p.s.i.a. was required for the take-off, the compression ratio would be limited to approximately 6.7 in the absence of water. By using a water-fuel ratio of about 1.3, the compression ratio may be increased to 7.4. Since take-off powers would be used for only a short period, the high water-fuel ratio of 1.3 is not prohibitive. Similar trends are apparent for the remaining fuel-air ratios considered. Thus, the airplane designer, by using the high compression ratios and accepting the high water-fuel ratios required for take-off, may obtain greatly improved fuel economy in the cruising range.

In conclusion it may be stated that the percent increase in imep obtainable by using a water-fuel ratio of about 1.0 is in the order of 15%. Thus, the method of direct water injection used in this investigation compares favorably with the method of adding water to the induction system. Had the mechanics of direct water injection used herein been more refined, this method might have proven its superiority over the water-into-induction-system method.

CONCLUSIONS

As a result of this investigation of the effect on detonation of direct water injection into the cylinder of an engine operating on 80 octane unleaded aviation gasoline, the following conclusions were reached:

1. The addition of water at a constant fuel-air ratio permits the attainment of higher indicated mean effective pressures without detonation. This effect is more pronounced for low fuel-air ratios than for high fuel-air ratios.
2. At a fixed water-fuel ratio, and for this gasoline, the fuel-air ratio at which the maximum detonation free indicated mean effective pressure occurs increases as compression ratio decreases.
3. At a constant isfc, detonation free imep increases with water-fuel ratio. At fuel-air ratios below .09, islc increases very rapidly with increase in imep while at fuel-air ratios above .09, islc decreases slightly as imep increases.
4. Increasing water-fuel ratio at low (cruising) fuel-air ratios results in a decrease in isfc, but at the expense of a prohibitive increase in islc.
5. Fuel is considerably more effective than water as an anti-detonant at low (cruising) fuel-air ratios.

6. At high (take-off) fuel-air ratios, water is effective as an anti-detonant, while the use of additional fuel for this purpose actually results in a decrease of imep.

7. Indicated thermal efficiency is not affected by the addition of water.

8. Water injection permits the use of higher compression ratios by increasing detonation free imep to take-off values. This permits the designer to take advantage of the greatly improved fuel economy in the cruising range resulting from the use of high compression ratios.

REFERENCES

1. C F R Handbook -- 1944 Edition.

2. N A C A Technical Note No. 675, The Charging Process in a High Speed, Single-Cylinder, Four-Stroke Engine, by Reynolds, Schehter, and Taylor.

3. N A C A ARR 4J06, A Study of Piston and Ring Friction, by Leary and Jovellanos.

Formulae for Computations

CFR Engine Data

Bore = 3.25" Piston Area = 8.296 in.^{2}

Stroke = 4.50" Displacement Volume = 37.33 in.^{3}

rpm = 1200 (constant)

$$\text{imep} = \frac{\text{Area P-V Diagram}}{5} \times \text{Spring Constant, psia}$$

$$\text{IHP} = \frac{\text{imep} \times \text{Piston Area} \times \frac{\text{Stroke}}{12} \times \frac{\text{rpm}}{2}}{33000} = .0566 \times \text{imep}$$

$$\text{ISFC} = \frac{\text{lb. fuel/hr.}}{\text{IHP}} = \frac{\dot{M}_f \times 3600}{\text{IHP}}$$

$$\text{ISWC} = \frac{\text{lb. water/hr.}}{\text{IHP}} = \frac{\dot{M}_w \times 3600}{\text{IHP}}$$

$$\text{ISLC} = \frac{\text{lb. Liquid/hr.}}{\text{IHP}} = \frac{3600}{\text{IHP}} (\dot{M}_f + \dot{M}_w) = \text{ISFC} + \text{ISWC}$$

$$\eta_i = \frac{\text{IHP} \times 2545}{3600 \times \dot{M}_f \times E_c} = \frac{\text{IHP} \times 2545}{\dot{M}_f \times 3600 \times 19270} = \frac{\text{IHP}}{27250\, \dot{M}_f}$$

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Units

Area P-V Diagram	=	Square inches
Spring Constant	=	Pounds per inch
imep	=	Indicated mean effective pressure, psia
IHP	=	Horsepower
$\dot{M}_f$	=	Fuel flow, pounds per second
$\dot{M}_w$	=	Water flow, pounds per second
ISFC	=	Indicated Specific Fuel Consumption, $\frac{lb/hr}{IHP}$
ISWC	=	Indicated Specific Water Consumption, $\frac{lb/hr}{IHP}$
ISLC	=	Indicated Specific Liquid Consumption, $\frac{lb/hr}{IHP}$
η_i	=	Indicated Thermal Efficiency

TABLE I

Calibration of Fuel and Water Rotometers

Water Rotometer Calibration
3/14/46 $T^{o} = 81$

Roto Reading	Wt Gms	Time Sec	lbs/sec
7.55	10	72.7	.000303
8.1	10	64.35	.000348
6.6	10	105.95	.000208
7.1	10	94.3	.000234
17.1	20	29.9	.001473
14.95	20	39.0	.00113
12.8	20	53.8	.00082
5.1	10	229.5	.000096
15.9	20	34.8	.001268
13.3	20	46.85	.00094
10.1	20	82.95	.000532
13.8	20	45.55	.000969
11.05	20	70.25	.000625
8.2	10	65.5	.000337
8.75	10	56.75	.000389
9.4	10	47.8	.000461
5.65	10	151.2	.000146
5.8	10	141.65	.000156
12.3	20	57.7	.000764
11.1	20	70	.00063
10.65	20	76.1	.000595
9.6	10	56.25	.000392
11.4	20	66.2	.000666
12.1	20	59.4	.000741
7.1	10	96.65	.000228
7.7	10	72.75	.000303
6.25	10	120.35	.000183
13.65	20	45.3	.000973
14.5	20	41.4	.001064
15.5	20	36.1	.00122
13.3	20	47.7	.000925
13.8	20	45.7	.000965
13.65	20	45.6	.000966
13.3	20	49.05	.000900

Gasoline Rotometer Calibration
3/15/46 $T^{o} = 66$

Roto Reading	Wt Gms	Time Sec	lbs/sec
9.7	20	38.3	.00115
8.95	20	43.4	.001018
8.45	20	46.7	.000943
7.85	20	50.4	.000874
7.25	20	55.8	.000789
5.5	20	79.6	.000553
5.9	20	71.9	.000613
6.35	20	64.6	.000681
6.8	10	29.6	.000745
5.15	10	42.5	.000519
3.65	10	66.2	.000332
4.2	10	53.45	.000412
10.4	20	35.5	.001242
11.05	20	33.15	.001329
11.45	20	29.8	.00148
11.8	20	29.55	.001491
12.05	20	28.75	.001535
4.4	10	50.35	.000439
6.25	10	33.9	.000651
6.7	10	31.65	.000696
6.85	10	30.3	.000729
8.95	20	21.5	.001026
9.45	20	19.6	.001124
10.0	20	18.1	.001218
8.9	20	19.3	.001022
11.4	20	15.75	.0014
10.65	20	15.95	.00138
8.05	20	24.5	.0009
7.6	20	26.1	.000845
9.25	20	20.65	.001065
10.3	20	17.8	.001239
9.75	20	19.3	.001141
10.1	20	18.3	.0012

TABLE II

Calibration of Hydraulic Scale

Inches of Mercury vs. IMEP

" Hg.	IMEP
16.7	98.0
19.3	107.6
19.8	114.8
26.3	139.2
29.5	149.6

M.I.T. AERO ENGINE LABORATORY

ENGINE *CFR* BORE 3 1/4 STROKE 4 1/2 COMPRESSION RATIO 6.2

Table III

REMARKS	DATE	TIME	RUN	R.P.M.	TEMP. OIL	TEMP. JAC	OIL PRESS	P_1	P_E	T_1	AIR CONS.	FUEL CONS.	F/A	S.A.	T_1	FUEL ROTO	ROOM TEMP.	BAR. CORR.	H_2O ROTO	$\dot{M}_w$	W/F	" H_g	IMEP	IHP	η_i	ISFC	ISWC	ISLC
	4/17/46	1732	13	1200	160	212	35	30.105	ATM	543	.01011	.000646	.064	25	138	6.20	81	30.105	0	0	0	17.3	101.8	5.76	.3265	.403	0	.403
	"	1741	14	"	"	"	"	"	"	"	.0103	.000659	"	"	142	6.30	"	"	7.5	.000274	.416	17.85	104	5.88	.327	.403	.168	.571
	"	1745	15	"	"	"	"	"	"	544	.0105	.000671	"	"	141	6.39	"	"	8.5	.000366	.545	18.55	106.8	6.04	.330	.399	.218	.617
	"	1754	16	"	"	"	"	"	"	"	.01069	.000684	"	"	"	6.48	"	"	10.0	.000516	.755	19.35	110	6.23	.3335	.396	.298	.694
	"	1803	17	"	"	"	"	"	"	"	.01097	.000701	"	"	"	6.62	"	"	10.5	.000570	.813	19.45	112.3	6.36	.332	.397	.322	.719
	4/18/46	1222	1	"	"	"	33	40.395	"	546	.01095	.000767	.07	"	142	7.09	85	30.045	0	0	0	19.70	111.3	6.30	.301	.438	0	.438
	"	1401	5	"	157	"	34	39.295	"	544	.01124	.000786	"	"	141	7.23	87	"	5.6	.000135	.172	20.35	114	6.45	.301	.438	.075	.503
	"	1425	6	"	"	"	"	37.445	"	545	.01144	.000801	"	"	140	7.34	"	"	8.7	.000385	.481	20.65	115.2	6.53	.299	.442	.212	.654
		1531	7	"	"	"	"	37.345	"	"	.01168	.000817	"	"	"	7.47	"	"	10.3	.000552	.676	21.60	118.9	6.725	.302	.438	.296	.734
	"	1540	8	"	"	"	"	36.795	"	"	.01204	.000842	"	"	138	7.63	"	"	11.8	.000701	.833	22.40	122.2	6.91	.301	.438	.365	.803
	"	1550	9	"	"	"	"	36.645	"	"	.01232	.000862	"	"	140	7.78	"	"	13.8	.000968	1.123	23.35	127.8	7.18	.307	.432	.485	.917
	"	1232	2	"	160	"	"	39.645	"	"	.01261	.00101	.08	"	"	8.85	85	"	0	0	0	23.00	124.5	7.045	.256	.516	0	.516
	"	1508	10	"	157	"	33	36.045	"	"	.01288	.001029	"	"	"	8.98	87	"	7.5	.000274	.266	23.75	127.5	7.21	.257	.514	.137	.651
	"	1516	11	"	"	"	"	35.895	"	"	.01310	.001048	"	"	138	9.10	"	"	11.3	.000652	.622	24.45	130.3	7.375	.258	.512	.318	.830
	"	1528	12	"	"	"	"	40.495	"	"	.01322	.001057	"	"	142	9.17	"	"	13.0	.000857	.812	25.20	133.3	7.55	.262	.503	.408	.911
	"	1540	13	"	160	"	32	40.095	"	544	.01369	.001094	"	"	138	9.38	"	"	14.4	.001052	.962	26.10	136.7	7.73	.259	.510	.491	1.001
	"	1549	14	"	"	"	"	39.795	"	"	.01400	.001122	"	"	140	9.55	"	"	15.7	.001244	1.108	26.85	139.8	7.91	.258	.511	.567	1.078
	"	1302	3	"	157	"	35	39.045	"	542	.01343	.001209	.09	"	138	10.08	83	"	0	0	0	24.75	131.4	7.44	.226	.585	0	.585
	"	1606	15	"	160	"	32	39.795	"	544	.01400	.001260	"	"	140	10.42	87	"	11.5	.000674	.535	26.25	137.3	7.77	.226	.584	.312	.896
	"	1614	16	"	"	"	"	43.045	"	"	.01384	.001247	"	"	138	10.33	"	"	9.9	.000505	.405	25.70	135.2	7.65	.225	.587	.238	.825
	"	1622	17	"	"	"	"	40.395	"	"	.01357	.001221	"	"	"	10.17	"	"	6.2	.000185	.152	25.15	133.1	7.53	.226	.584	.089	.873
	"	1632	18	"	"	"	"	39.245	"	"	.01438	.001293	"	"	140	10.63	"	"	14.0	.000997	.771	26.95	140.3	7.94	.225	.587	.452	1.039
	"	1639	19	"	"	"	"	39.045	"	"	.01466	.001319	"	"	138	10.78	"	"	15.5	.001215	.922	27.40	142.2	8.05	.224	.590	.543	1.133
	"	1320	4	"	157	"	35	"	"	542	.01389	.001389	.10	"	139	11.18	85	"	0	0	0	25.25	133.5	7.55	.1994	.662	0	.662
	"	1655	20	"	160	"	32	42.745	"	544	.01421	.001421	"	"	138	11.38	87	"	8.7	.000384	.271	25.75	135.5	7.66	.198	.668	.181	.849
	"	1702	21	"	"	"	"	42.455	"	"	.01448	.001448	"	"	140	11.53	"	"	13.5	.000924	.638	26.65	139.0	7.86	.199	.663	.423	1.086
	"	1711	22	"	"	"	"	42.345	"	"	.01478	.001478	"	"	138	11.72	"	"	14.8	.001110	.752	27.00	140.5	7.95	.1975	.668	.503	1.171
	"	1726	23	"	"	"	"	41.645	"	"	.01491	.001491	"	"	140	11.78	"	"	16.4	.001352	.908	27.50	142.5	8.06	.1982	.667	.604	1.261
	"	1742	24	"	"	"	"	45.845	"	"	.01124	.000719	.064	"	"	6.74	86	"	12.0	.000725	1.008	20.5	114.7	6.49	.331	.398	.402	.800

M.I.T. AERO ENGINE LABORATORY

ENGINE CFR BORE 3 1/4 STROKE 4 1/2 COMPRESSION RATIO 6.6

Table IV

REMARKS	DATE	TIME	RUN	RPM	TEMPERATURE OIL	TEMPERATURE JAC	OIL PRES	P_1	P_E	T_1	AIR CONS.	FUEL CONS.	F/A	S.A.	T_i	FUEL ROTO	ROOM TEMP.	BAR. CORR.	H_2O ROTO	$\dot{M}_W$	W/F	"H_g	IMEP	IHP	η_i	ISFC	ISWC	ISLC
	4/24/4	1304	1	1200	158	212	33	37.84	ATM	542	.01267	.001267	.10	25	140	10.45	81	30.144	0	0	0	22.9	124	7.02	.2035	.650	0	.650
		1310	2	"	"	"	"	37.54	"	544	.01280	.001280	"	"	138	10.54	"	"	9.3	.000446	.349	23.25	125.5	7.10	.2035	.649	.226	.875
	"	1320	3	"	"	"	"	37.24	"	"	.01291	.001291	"	"	140	10.61	"	"	11.9	.000713	.553	23.45	126.2	7.14	.203	.651	.360	1.011
	"	1330	4	"	"	"	"	36.94	"	"	.01310	.001310	"	"	"	10.73	80	"	13.4	.000912	.696	23.8	127.7	7.22	.202	.653	.455	1.108
		1337	5	"	"	"	"	36.44	"	"	.01330	.001330	"	"	"	10.84	79	"	14.5	.001067	.802	24.15	129.2	7.32	.202	.654	.525	1.179
	"	1353	6	"	"	"	"	38.64	"	545	.01234	.00111	.09	"	"	9.50	78	"	0	0	0	22.35	121.8	6.89	.228	.581	0	.581
	"	1402	7	"	"	"	"	38.24	"	"	.01248	.001122	"	"	"	9.55	77	"	7.4	.000264	.235	22.65	123.0	6.96	.228	.581	.136	.717
	"	1414	8	"	"	"	"	38.04	"	"	.01268	.001139	"	"	138	9.65	"	"	9.6	.000477	.419	23.3	125.6	7.10	.229	.578	.242	.820
	"	1423	9	"	156	"	34	37.54	"	"	.01280	.001152	"	"	"	9.73	78	"	11.0	.00062	.538	23.8	127.7	7.22	.230	.575	.309	.884
	"	1431	10	"	"	"	"	37.04	"	"	.01306	.001175	"	"	140	9.88	80	"	12.9	.000843	.717	24.3	129.7	7.35	.229	.577	.414	.991
	"	1438	11	"	"	"	"	36.74	"	"	.01320	.001188	"	"	"	9.96	"	"	14.4	.001052	.886	24.95	132.2	7.48	.231	.572	.507	1.079
	"	1450	12	"	"	"	"	40.34	"	"	.01152	.000920	.08	"	142	8.2	81	"	0	0	0	20.9	116.2	6.675	.266	.497	0	.497
	"	1458	13	"	"	"	"	39.84	"	"	.01173	.000933	"	"	140	8.29	"	"	7.0	.000228	.245	21.6	118.9	6.725	.264	.500	.122	.622
	"	1514	14	"	"	"	"	39.44	"	546	.01197	.000956	"	"	"	8.46	"	"	8.4	.000355	.371	22.0	120.5	6.82	.262	.505	.187	.692
	"	1523	15	"	"	"	"	38.94	"	"	.01223	.000978	"	"	142	8.62	"	"	12.5	.000792	.81	22.85	123.9	7.00	.262	.503	.407	.910
	"	1531	16	"	"	"	"	38.44	"	"	.01249	.000998	"	"	140	8.77	"	"	14.0	.000998	1.0	23.7	127.2	7.20	.264	.449	.449	.898
	"	1541	17	"	"	"	"	39.14	"	"	.01212	.000969	"	"	"	8.55	"	"	10.2	.000540	.557	22.55	123.6	6.94	.262	.502	.280	.782
	"	1548	18	"	"	"	"	38.94	"	"	.01008	.000705	.07	"	"	6.65	"	"	0	0	0	17.55	102.8	5.82	.303	.437	0	.437
	"	1613	19	"	"	"	"	38.24	"	547	.01032	.000721	"	"	"	6.75	"	"	7.0	.000228	.316	18.3	105.7	5.915	.304	.434	.137	.571
	"	1619	20	"	"	"	"	37.54	"	"	.01056	.000739	"	"	139	6.88	"	"	10.1	.000530	.717	18.95	108.5	6.14	.305	.433	.311	.744
	"	1628	21	"	"	"	"	36.74	"	"	.01087	.000760	"	"	140	7.04	82	"	11.5	.000674	.887	19.5	110.5	6.25	.302	.428	.398	.826
	"	1637	22	"	"	"	"	37.84	"	"	.01043	.000730	"	"	"	6.83	"	"	8.2	.000337	.461	18.55	106.8	6.04	.303	.435	.201	.636
	"	1710	23	"	"	"	"	37.24	"	548	.00881	.000565	.064	"	"	5.57	83	"	0	0	0	14.65	91.1	5.16	.335	.394	0	.394
	"	1720	24	"	"	"	"	36.34	"	"	.009025	.000577	"	"	"	5.67	"	"	5.4	.000118	.205	15.3	93.6	5.30	.337	.392	.0802	.472
	"	1726	25	"	"	"	"	35.64	"	"	.00917	.000587	"	"	"	5.74	"	"	7.6	.000283	.482	15.9	96.0	5.43	.340	.390	.188	.578
	"	1732	26	"	"	"	"	34.84	"	"	.00937	.000600	"	"	"	5.84	"	"	8.5	.000367	.612	16.1	97.0	5.49	.336	.393	.241	.634
	"	1742	27	"	"	"	"	33.94	"	"	.009565	.000612	"	"	"	5.93	"	"	10.1	.00053	.866	16.6	99.0	5.60	.336	.393	.341	.734

M.I.T. AERO ENGINE LABORATORY

ENGINE CFR BORE 3 1/4 STROKE 4 1/2 COMPRESSION RATIO 7.0

Table V

REMARKS	DATE	TIME	RUN	RPM	TEMP. OIL	TEMP. JAC	OIL PRESS	P_I	P_E	T_I	AIR CONS.	FUEL CONS.	F/A	S.A.	T_i	Fuel Roto	Room Temp	Bar. Corr.	H_2O Roto	$\dot{M}_w$	W/F	″Hg	IMEP	IHP	η_i	ISFC	ISWC	ISLC
	4/23/46	1440	1	1200	160	212	24	39.559	ATM.	545	.00801	.000514	.064	25	140	5.15	87	30.009	0	0	0	13.0	84.4	4.77	.340	.388	0	.388
	″	1452	2	″	157	″	32	39.104	″	″	.00838	.000536	″	″	″	5.33	″	″	6.7	.000213	.397	13.9	88.0	4.98	.341	.387	.154	.541
	″	1457	3	″	158	″	33	38.709	″	″	.00866	.000554	″	″	″	5.48	″	″	8.1	.000327	.591	14.3	89.6	5.07	.335	.393	.232	.625
	″	1507	4	″	″	″	″	38.309	″	″	.00905	.000579	″	″	″	5.69	88	″	9.8	.000496	.873	15.3	93.6	5.30	.3355	.393	.337	.730
	″	1518	5	″	″	″	″	37.704	″	″	.00934	.000598	″	″	″	5.83	″	″	11.8	.000698	1.168	16.1	96.8	5.48	.336	.393	.458	.851
	″	1527	6	″	″	″	″	37.609	″	546	.00950	.000608	″	″	″	5.92	″	″	12.6	.000803	1.322	16.32	97.7	5.53	.3335	.396	.523	.919
	″	1536	7	″	″	″	″	37.709	″	″	.00946	.000660	.07	″	″	6.31	″	″	0	0	0	16.0	96.6	5.47	.304	.435	0	.435
	″	1545	8	″	″	″	″	37.209	″	″	.00968	.000677	″	″	″	6.41	″	″	8.2	.000336	.496	16.8	99.8	5.65	.306	.432	.214	.646
	″	1555	9	″	″	″	″	36.809	″	″	.00991	.000694	″	″	″	6.56	″	″	9.5	.000465	.671	17.4	102.1	5.78	.305	.432	.290	.722
	″	1604	10	″	″	″	″	36.509	″	″	.01013	.000709	″	″	″	6.68	″	″	10.8	.000600	.847	17.9	104.2	5.90	.305	.433	.366	.799
	4/24/46	1336	1	″	″	″	32	44.963	″	543	.01054	.000738	″	″	″	6.88	83	29.863	13.3	.000900	1.220	19.5	110.4	6.25	.310	.425	.519	.944
	″	1401	2	″	″	″	34	38.563	″	545	.01029	.000720	″	″	″	6.75	88	″	11.8	.000702	.975	18.7	107.3	6.075	.3096	.427	.416	.843
	4/23/46	1625	11	″	″	″	33	30.009	″	547	.01079	.000862	.08	″	″	7.78	″	30.009	0	0	0	19.2	109.4	6.195	.259	.509	0	.509
	4/24/46	1423	3	″	″	″	35	34.573	″	546	.01097	.000877	″	″	″	7.89	″	29.863	9.6	.000477	.544	20.0	112.5	6.36	.266	.496	.270	.766
	″	1430	4	″	″	″	″	33.263	″	″	.01118	.000893	″	″	″	8.0	″	″	11.0	.000618	.692	20.75	115.6	6.54	.268	.492	.340	.832
	″	1435	5	″	″	″	″	32.763	″	″	.01133	.000907	″	″	″	8.1	″	″	12.2	.000754	.831	21.0	116.7	6.60	.267	.495	.412	.907
	″	1442	6	″	″	″	34	31.813	″	″	.01140	.000911	″	″	″	8.13	″	″	13.0	.000857	.940	21.3	117.8	6.66	.268	.492	.463	.955
	″	1452	7	″	″	″	″	32.263	″	″	.01182	.000945	″	″	″	8.38	″	″	14.7	.001098	1.160	22.3	121.7	6.88	.267	.495	.575	1.070
	″	1615	8	″	″	″	″	40.363	″	″	.01147	.001027	.09	″	″	8.97	86	″	0	0	0	20.8	115.8	6.555	.234	.565	0	.565
	″	1623	9	″	155	″	35	40.063	″	″	.01162	.001046	″	″	″	9.08	85	″	6.9	.00022	.211	21.1	117.9	6.62	.232	.568	.196	.688
	″	1653	10	″	″	″	″	39563	″	″	.01191	.001072	″	″	″	9.24	84	″	13.5	.000924	.862	22.5	122.5	6.93	.237	.557	.480	1.017
	″	1708	11	″	″	″	″	39.663	″	″	.01181	.001063	″	″	″	9.18	″	″	10.3	.000552	.519	21.4	120.0	6.79	.234	.564	.292	.856
	″	1717	12	″	″	″	″	36.463	″	″	.01206	.001084	″	″	″	9.32	″	″	15.0	.00114	1.052	22.7	123.3	6.98	.236	.560	.588	1.148
	″	1730	13	″	″	″	″	34.963	″	″	.01218	.001094	″	″	″	9.38	″	″	17.0	.001442	1.318	22.95	124.2	7.03	.236	.561	.739	1.300
	4/25/46	1228	1	″	160	″	31	41.75	″	547	.01175	.001175	.10	″	138	9.89	87	29.85	0	0	0	20.75	115.6	6.54	.204	.6375	0	.638
		1240	2	″	″	″	32	41.55	″	″	.01188	.001188	″	″	140	~~9.96~~	″	″	8.3	.000347	.292	21.1	117.0	6.62	.204	.646	.189	.835
		1250	3	″	″	″	″	41.15	″	″	.01211	.001211	″	″	142	10.1	″	″	13.0	.000858	.708	21.7	119.3	6.75	.2045	.646	.458	1.104
		1300	4	″	″	″	″	41.55	″	″	.01248	.001248	″	″	140	10.34	″	″	16.3	.001334	1.068	22.4	122.1	6.91	.203	.650	.696	1.346
		1312	5	″	″	″	33	41.25	″	″	.01200	.001200	″	″	138	10.04	″	″	12.1	.00053	.410	21.4	118.1	6.68	.204	.647	.286	.933

M.I.T. AERO ENGINE LABORATORY

ENGINE CFR BORE 3 1/4 STROKE 4 1/2 COMPRESSION RATIO 7.4

Table VI

REMARKS	DATE	TIME	RUN	RPM	TEMPERATURE OIL	TEMPERATURE JAC	OIL PRES.	P_1	P_E	T_1	AIR CONS.	Fuel Cons.	F/A	S.A.	T_i	Fuel Roto	Room Temp.	Bar. Corr.	H_2O Roto	M_W	W/F	"Hg	IMEP	IHP	η_i	ISFC	ISWC	ISLG
	4/25/46	1337	6	1200	160	212	33	40.25	ATM	547	.01072	.001072	.10	25	140	9.25	89	29.85	0	0	0	18.75	107.5	6.08	.208	.635	0	.635
	"	1347	7	"	158	"	34	40.15	"	"	.01088	.001088	"	"	"	9.35	"	"	6.3	.000192	.176	18.85	108.0	6.12	.2063	.640	.113	.753
	"	1353	8	"	"	"	"	40.05	"	"	.01108	.001108	"	"	138	9.47	"	"	9.0	.000413	.373	19.15	109.1	6.175	.2045	.646	.241	.887
	"	1401	9	"	"	"	"	39.65	"	"	.01133	.001133	"	"	"	9.63	"	"	12.9	.000844	.745	19.9	112.2	6.295	.204	.648	.483	1.131
	"	1410	10	"	"	"	"	39.45	"	"	.01153	.001153	"	"	140	9.74	"	"	14.4	.001052	.913	20.35	114.0	6.455	.205	.644	.588	1.232
	"	1425	11	"	"	"	"	40.95	"	"	.01064	.000960	.09	"	"	8.49	"	"	0	0	0	18.8	107.7	6.09	.233	.567	0	.567
	"	1435	12	"	"	"	"	40.75	"	"	.01080	.000972		"	"	8.57	"	"	7.6	.000283	.291	19.3	109.7	6.21	.234	.564	.164	.728
	"	1442	13	"	"	"	"	40.45	"	"	.01102	.000991	"	"	"	8.72	88	"	10.4	.000562	.567	19	111.1	6.29	.233	.567	.322	.889
	"	1452	14	"	"	"	"	40.25	"	"	.01132	.001016	"	"	138	8.92	"	"	14.1	.00101	.994	20.6	115	6.51	.235	.562	.559	1.121
	"	1458	15	"	"	"	"	39.65	"	"	.01156	.001040	"	"	"	9.05	"	"	17.5	.001524	1.465	21.3	117.7	6.66	.2345	.562	.824	1.386
	"	1520	16	"	"	"	"	40.65	"	"	.00953	.000762	.08	"	142	7.05	"	"	0	0	0	16.6	99.1	5.61	.270	.489	0	.489
	"	1531	17	"	"	"	"	40.15	"	"	.00981	.000785	"	"	140	7.23	"	"	7.3	.000242	.309	17	100.6	5.69	.266	.497	.153	.650
	"	1540	18	"	"	"	"	39.85	"	"	.01000	.000800	"	"	"	7.34	"	"	9.1	.000424	.531	17.55	102.8	5.82	.266	.495	.262	.757
	"	1555	19	"	"	"	"	39.55	"	"	.01041	.000833	"	"	"	7.58	"	"	11.2	.000640	.769	18.45	106.3	6.02	.265	.498	.383	.881
	"	1608	20	"	"	"	"	38.55	"	"	.01066	.000852	"	"	"	7.72	87	"	13.5	.000925	1.086	19.65	111.2	6.295	.271	.488	.529	1.017
	"	1618	21	"	"	"	"	38.15	"	"	.01089	.000871	"	"	138	7.84	"	"	14.3	.00104	1.194	20.1	113	6.40	.269	.490	.585	1.075
	"	1640	22	"	"	"	"	29.85	"	548	.00812	.000568	.07	"	"	5.60	"	"	0	0	0	13.1	85	4.815	.311	.425	0	.425
	"	1647	23	"	"	"	"	"	"	"	.00833	.000583	"	"	142	5.72	"	"	5.6	.000135	.232	13.6	87	4.925	.310	.427	.0987	.526
	"	1655	24	"	"	"	"	"	"	"	.00852	.000596	"	"	"	5.81	"	"	8.3	.000348	.584	14.25	89.5	5.07	.312	.423	.247	.670
	"	1659	25	"	"	"	"	"	"	"	.00885	.000619	"	"	140	5.99	"	"	10.3	.000550	.889	14.9	92	5.21	.3085	.428	.380	.868
	"	1707	26	"	"	"	"	"	"	"	.00912	.000638	"	"	"	6.13	88	"	12.5	.000793	1.242	15.45	94.3	5.34	.307	.430	.535	.965
	"	1716	27	"	160	"	"	"	"	549	.00693	.000443	.064	"	142	4.49	89	"	0	0	0	16	72.7	4.12	.340	.388	0	.388
	"	1724	28	"	"	"	"	"	"	"	.00709	.000454	"	"	143	4.59	"	"	5.3	.000102	.225	10.55	74.8	4.23	.342	.386	.0867	.473
	"	1732	29	"	"	"	"	"	"	"	.00727	.000465	"	"	"	4.69	"	"	7.3	.000255	.549	11.1	77.0	4.36	.344	.384	.211	.595
	"	1741	30	"	"	"	"	"	"	"	.00756	.000484	"	"	140	4.87	"	"	9.0	.000413	.854	11.75	79.5	4.50	.341	.387	.331	.718
	"	1748	31	"	"	"	"	"	"	"	.00784	.000502	"	"	"	5.04	"	"	10.4	.000560	1.116	12.1	81	4.58	.335	.394	.439	.833
	5/2/46	1212	1	"	156	"	35	36.78	"	550	.01036	[illegible]	.11	"	"	10	87	29.987	0	0	0	18.6	107	6.05	.186	.711	0	.711
	"	1225	2	"	"	"	"	38.27	"	"	[illegible]	[illegible]	[illegible]	"	"	8.86	"	"	"	"	"	18.7	107.3	6.07	.223	.630	"	.630
	"	1235	3	"	"	"	"	34.78	"	"	[illegible]	[illegible]	[illegible]	"	"	7.85	"	"	"	"	"	17.7	103.4	5.85	.246	.536	"	.536
	"	1250	4	"	"	"	"	40.07	"	"	.00813	[illegible]	[illegible]	"	"	6.38	"	"	"	"	"	14.8	91.7	5.18	.287	.704	"	.704

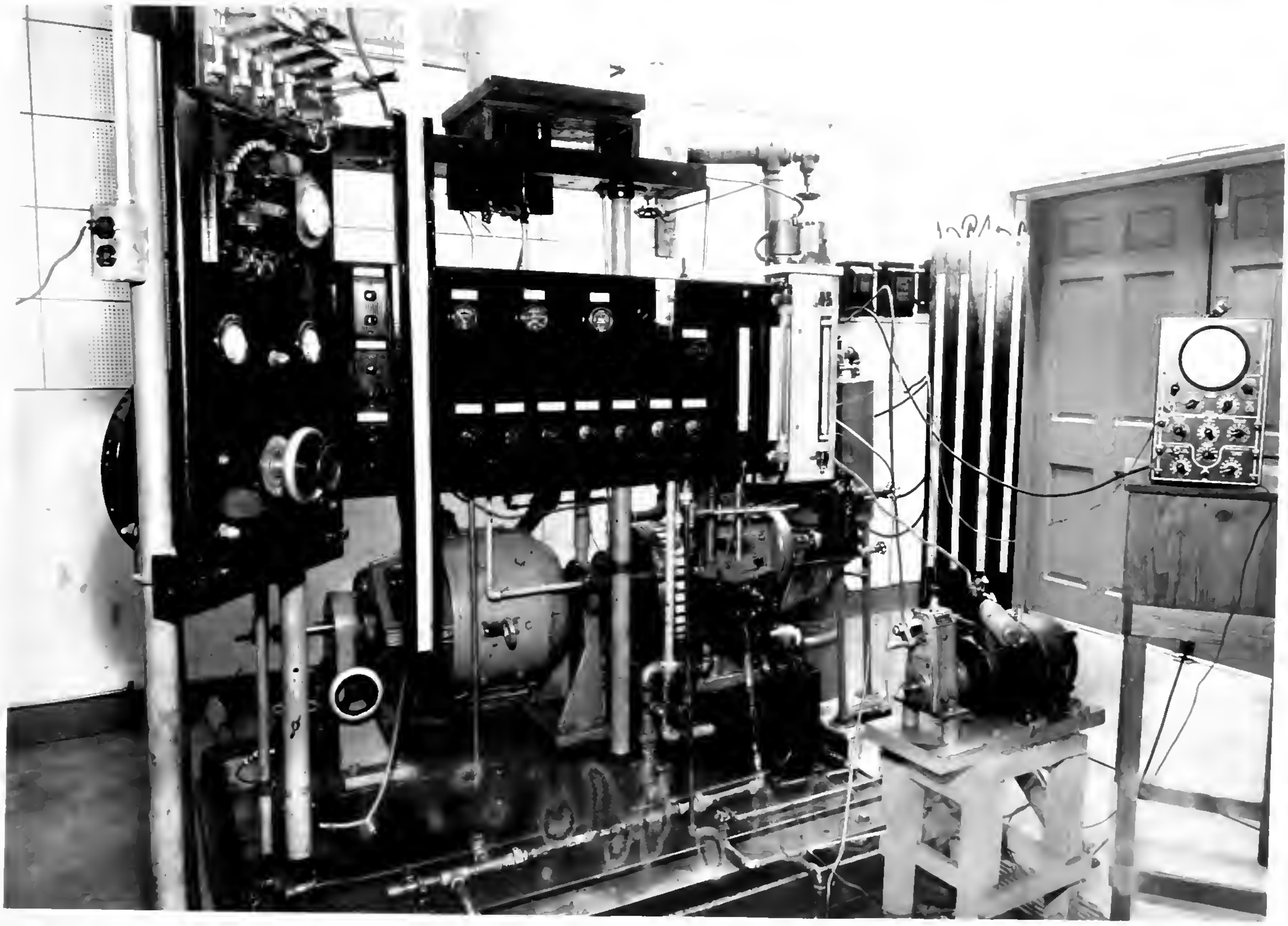


FIG. 1.

FRONT VIEW SHOWING GENERAL ARRANGEMENT OF APPARATUS

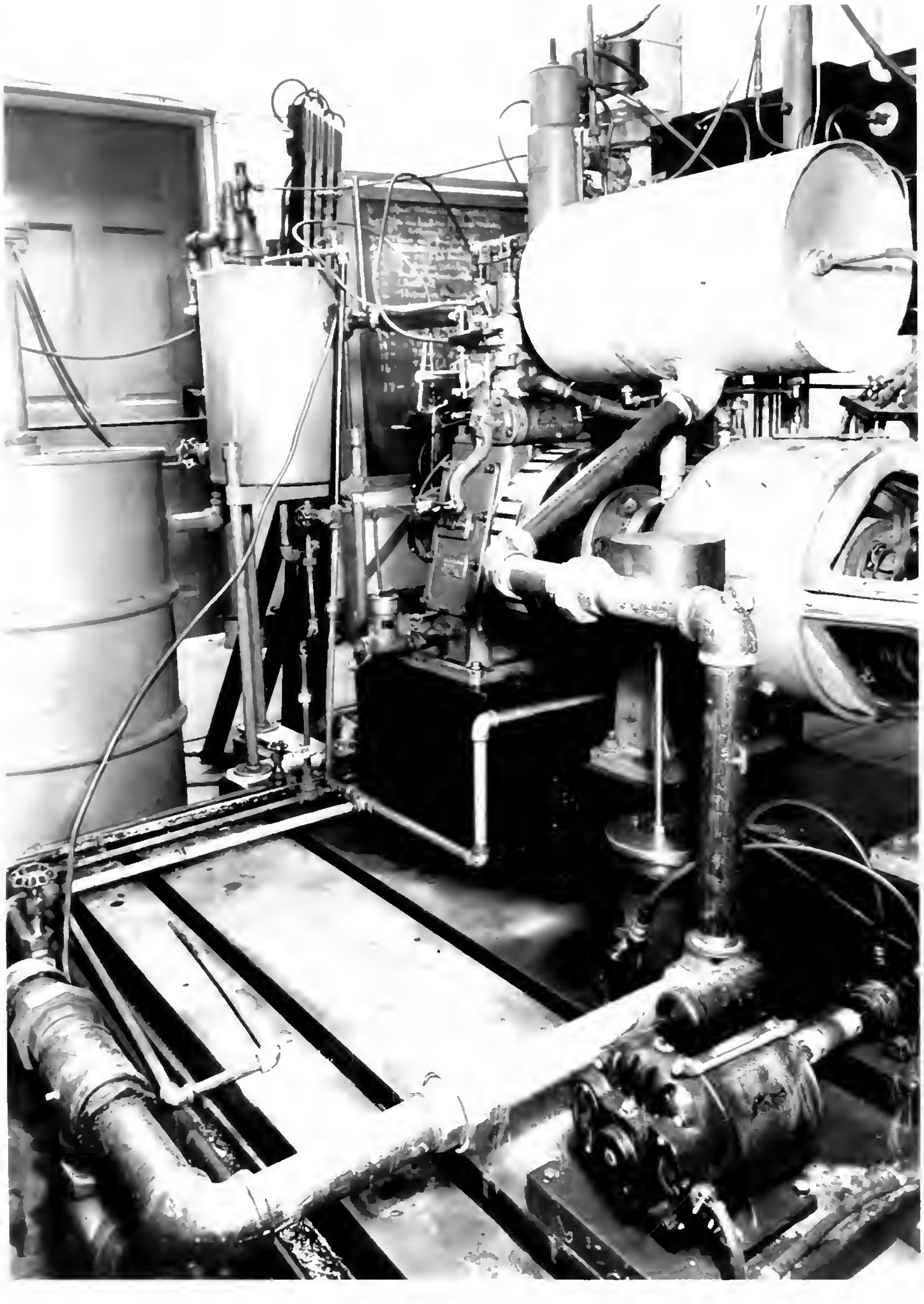


FIG. 2.

REAR VIEW SHOWING GENERAL ARRANGEMENT

OF APPARATUS

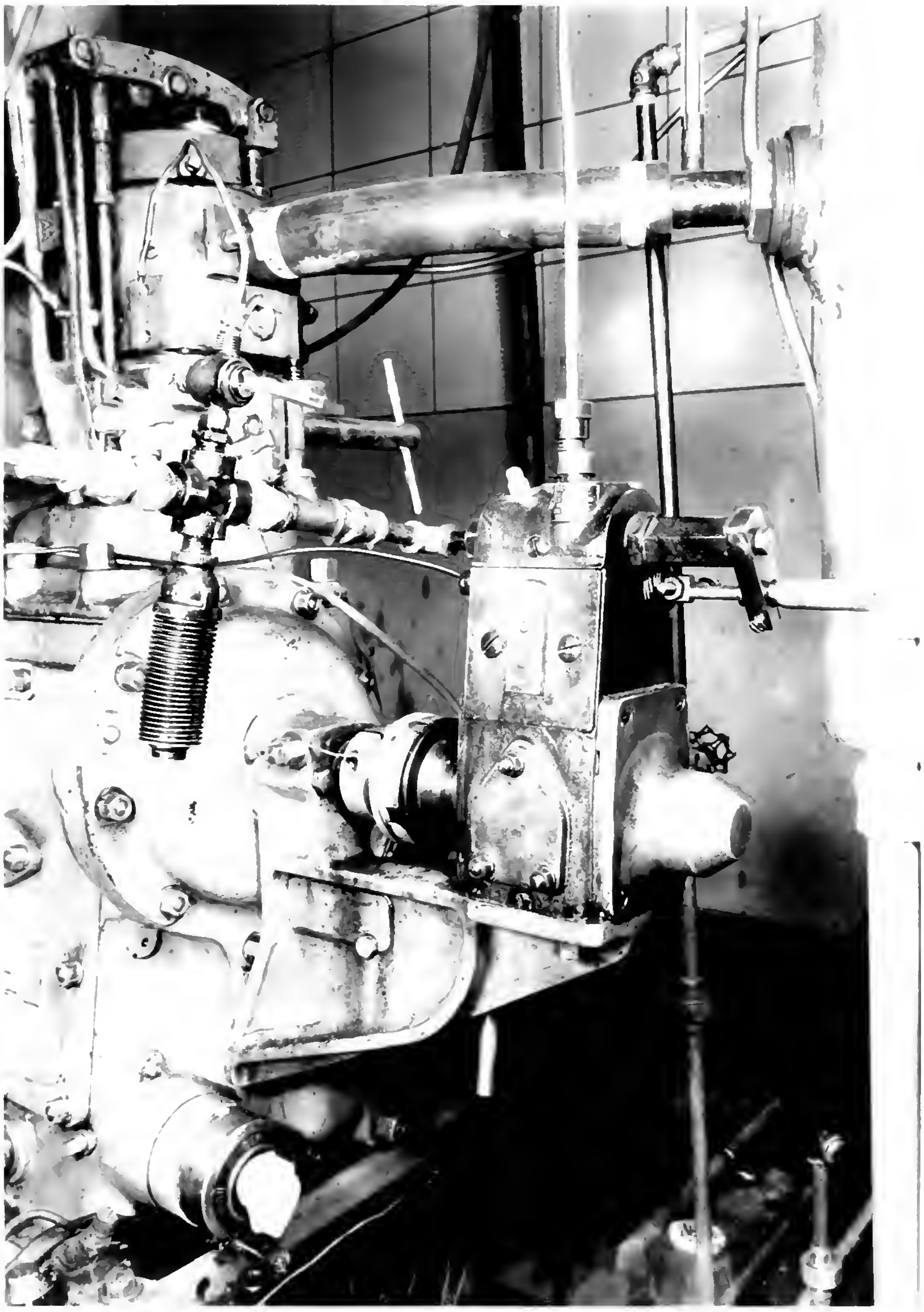


FIG. 3.

BOSCH PUMP USED FOR WATER INJECTION

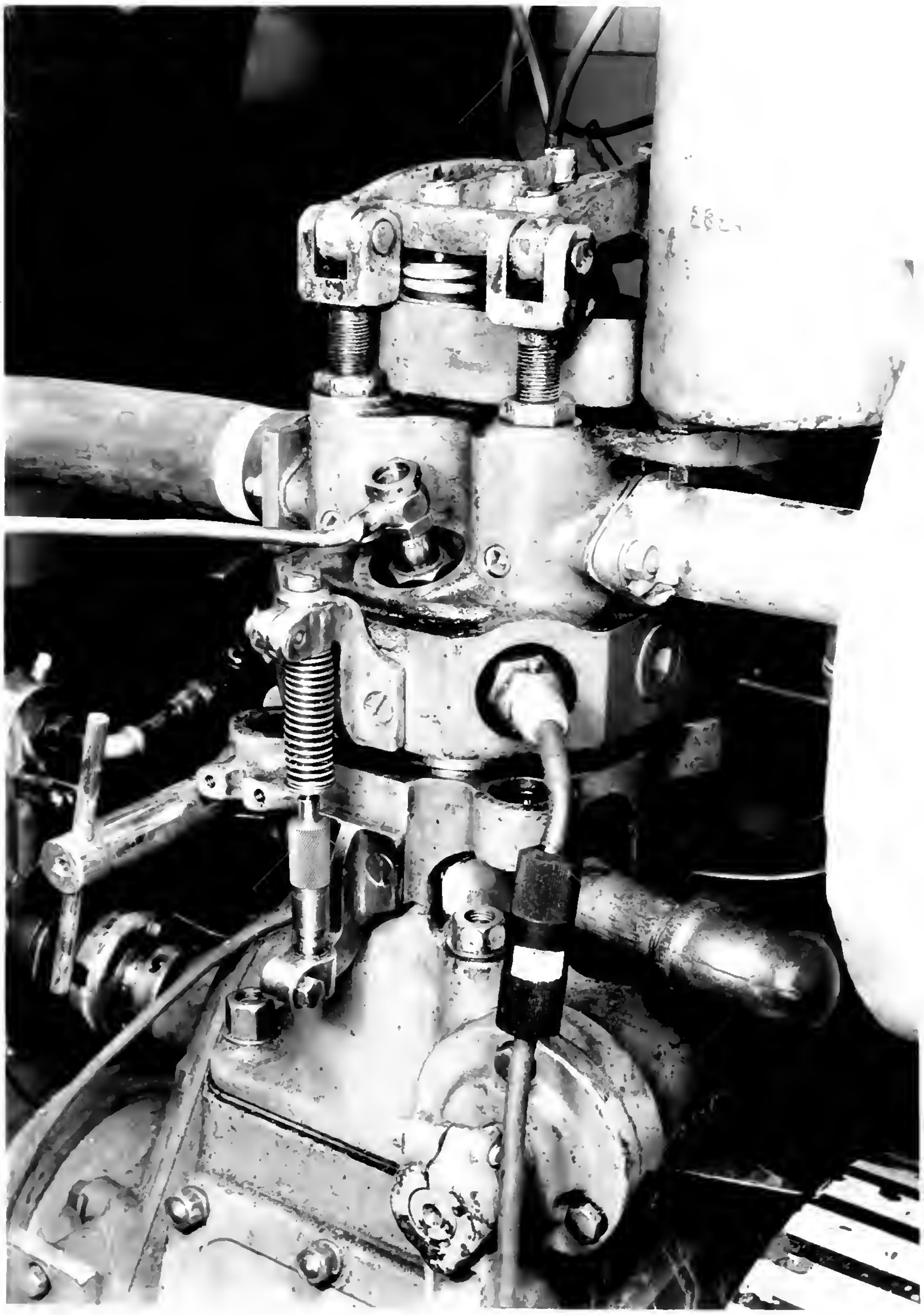


FIG. 4.

LOCATION OF WATER INJECTION NOZZLE

AND COMPRESSION RATIO ADJUSTMENT

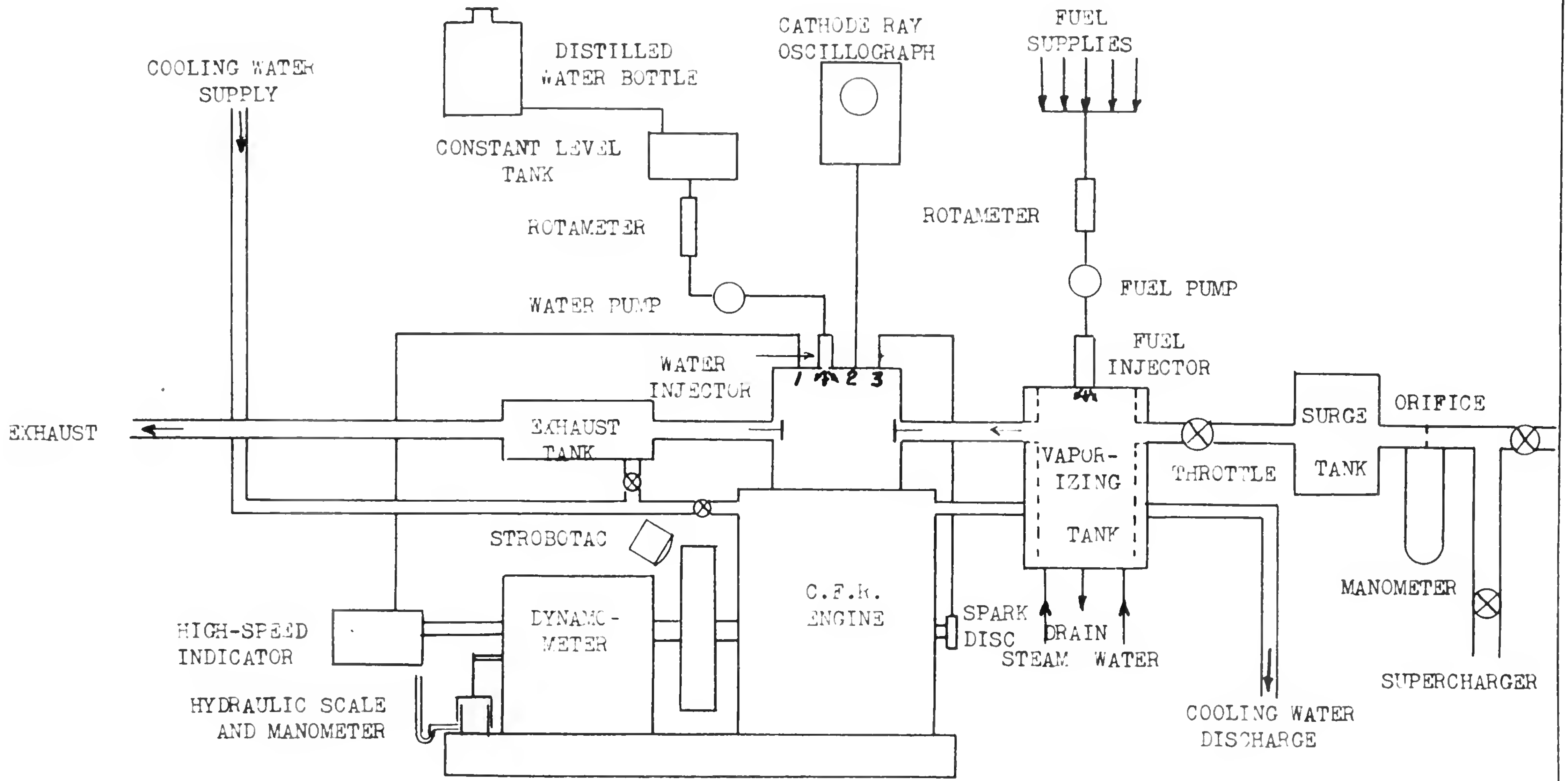


Fig. 5.

1. INDICATOR PICKUP
2. RATE OF PRESSURE PICKUP
3. SPARK PLUG

SLOAN LABORATORY

EXPERIMENTAL C.F.R. ENGINE SETUP

FIG. 6.

[illegible] 5082 [illegible]

[illegible] INJECTION [illegible]

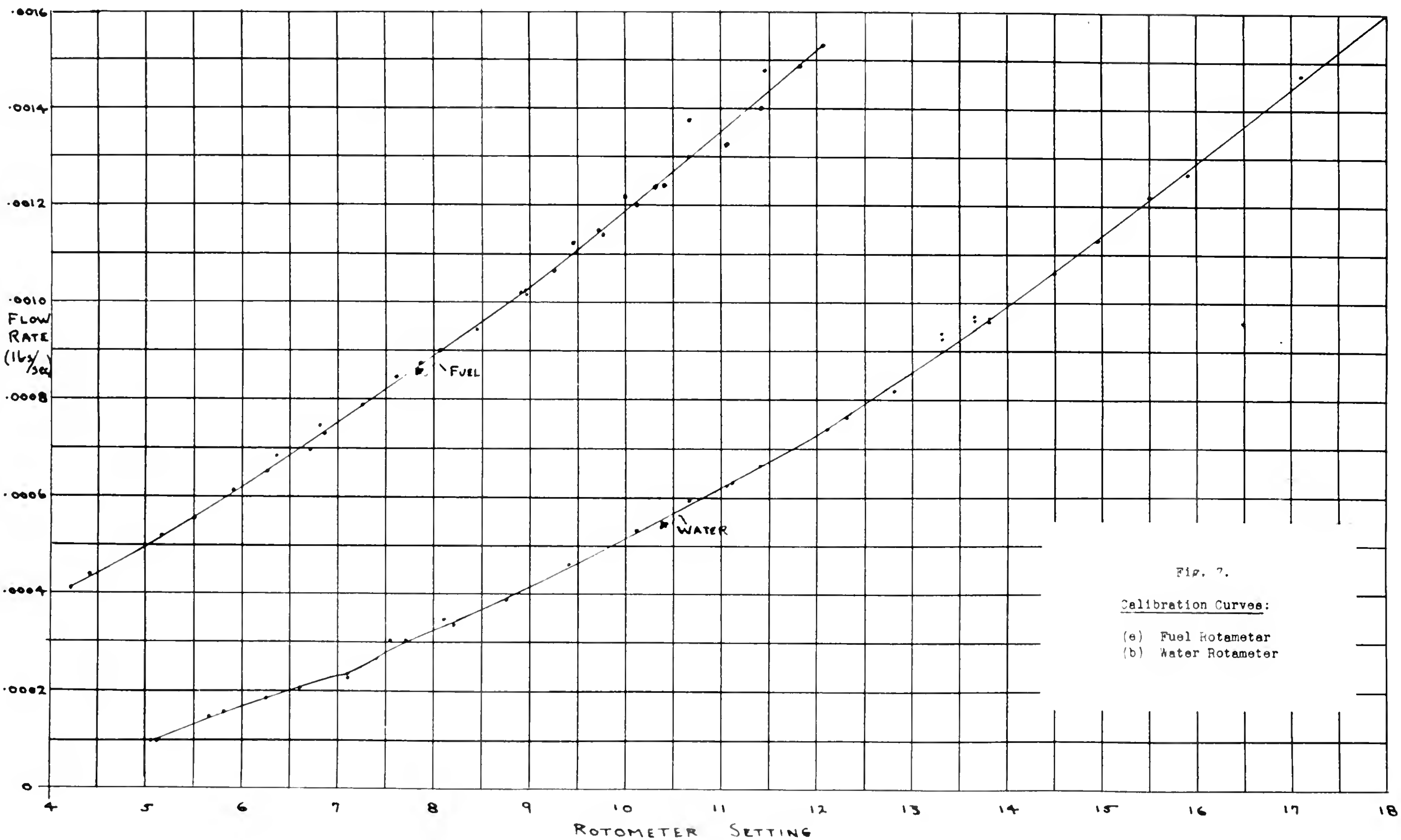


Fig. 7.

Calibration Curves:

(a) Fuel Rotameter
(b) Water Rotameter

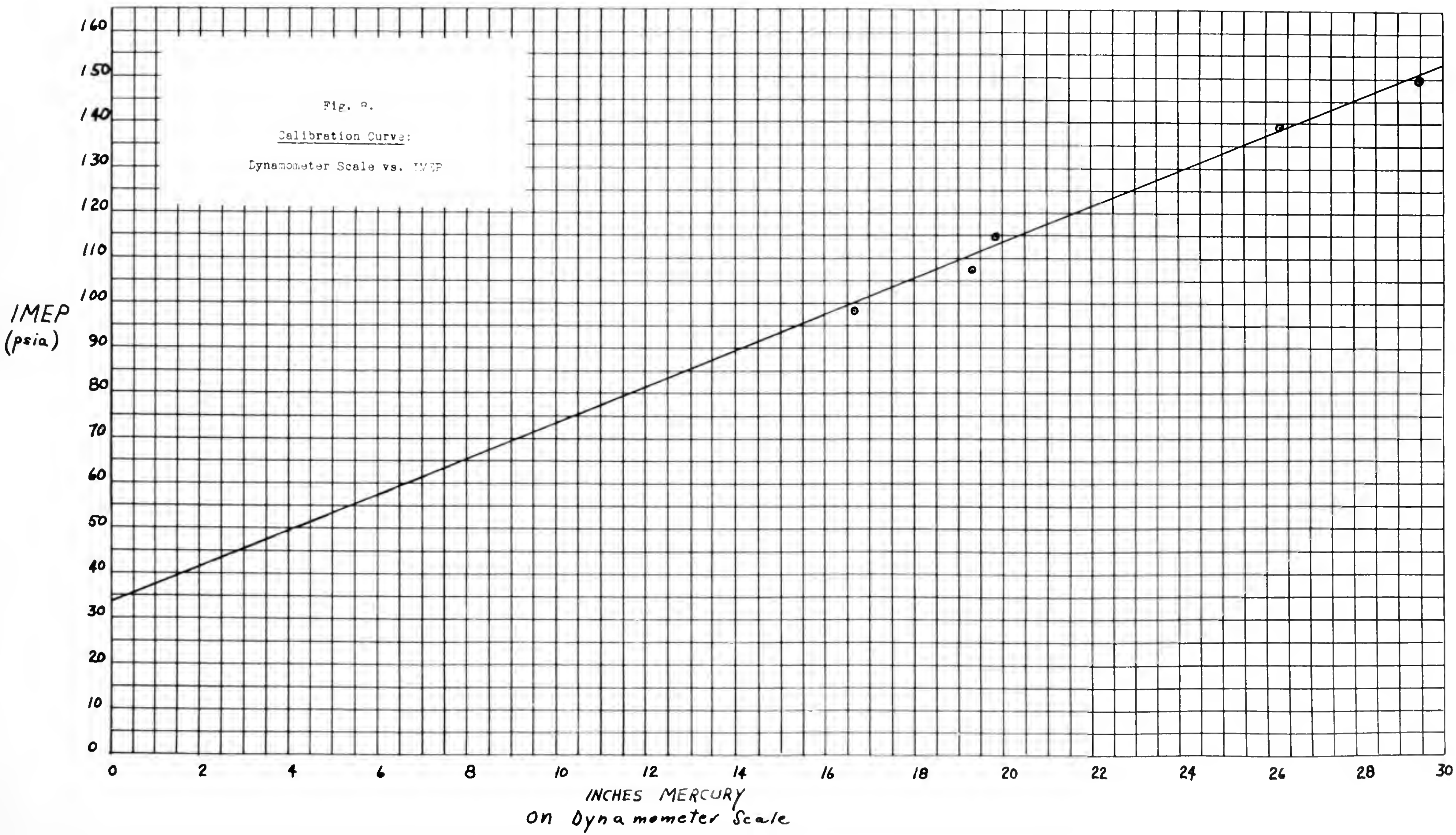


Fig. 8.

Calibration Curve:

Dynamometer Scale vs. IMEP

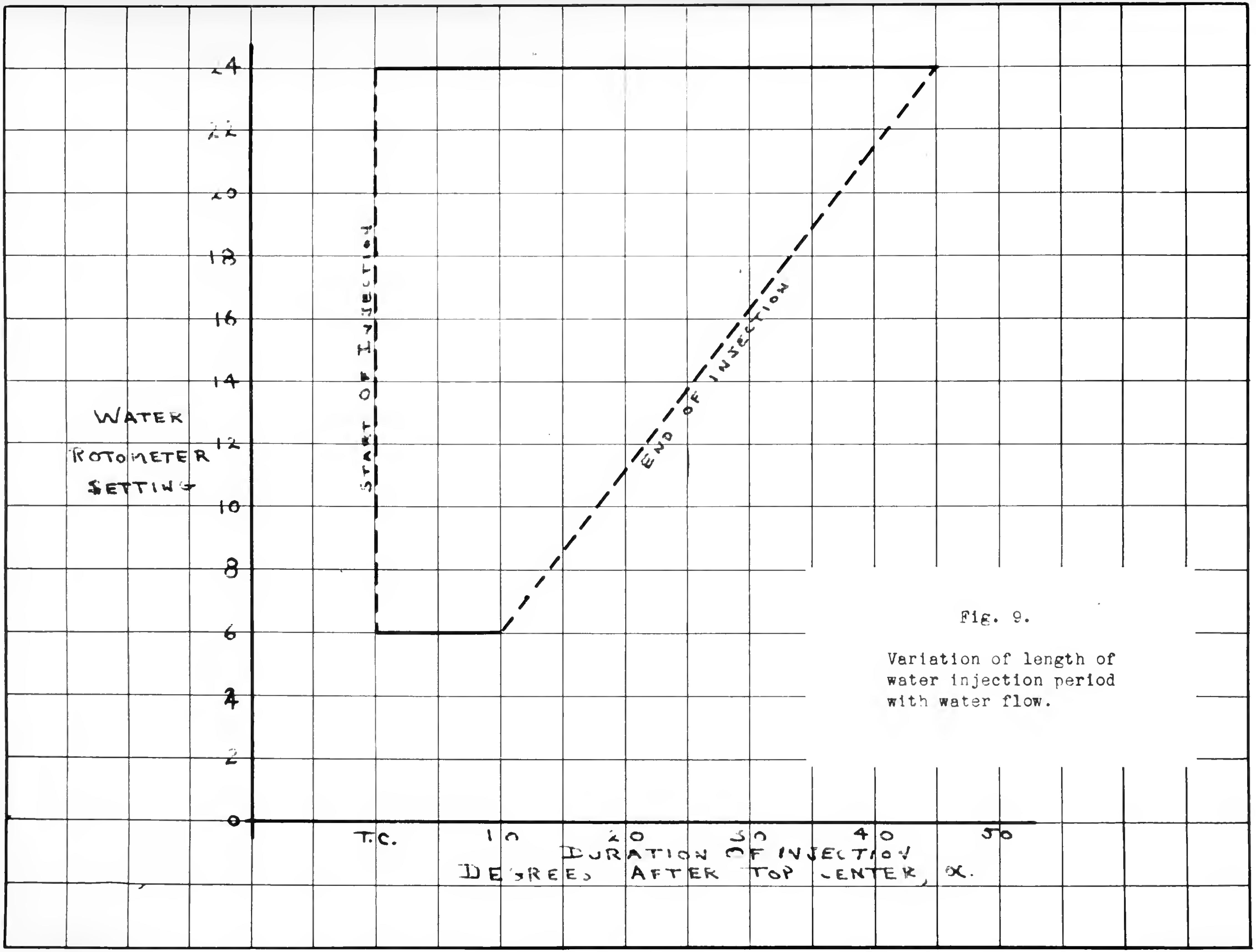


Fig. 9.

Variation of length of water injection period with water flow.

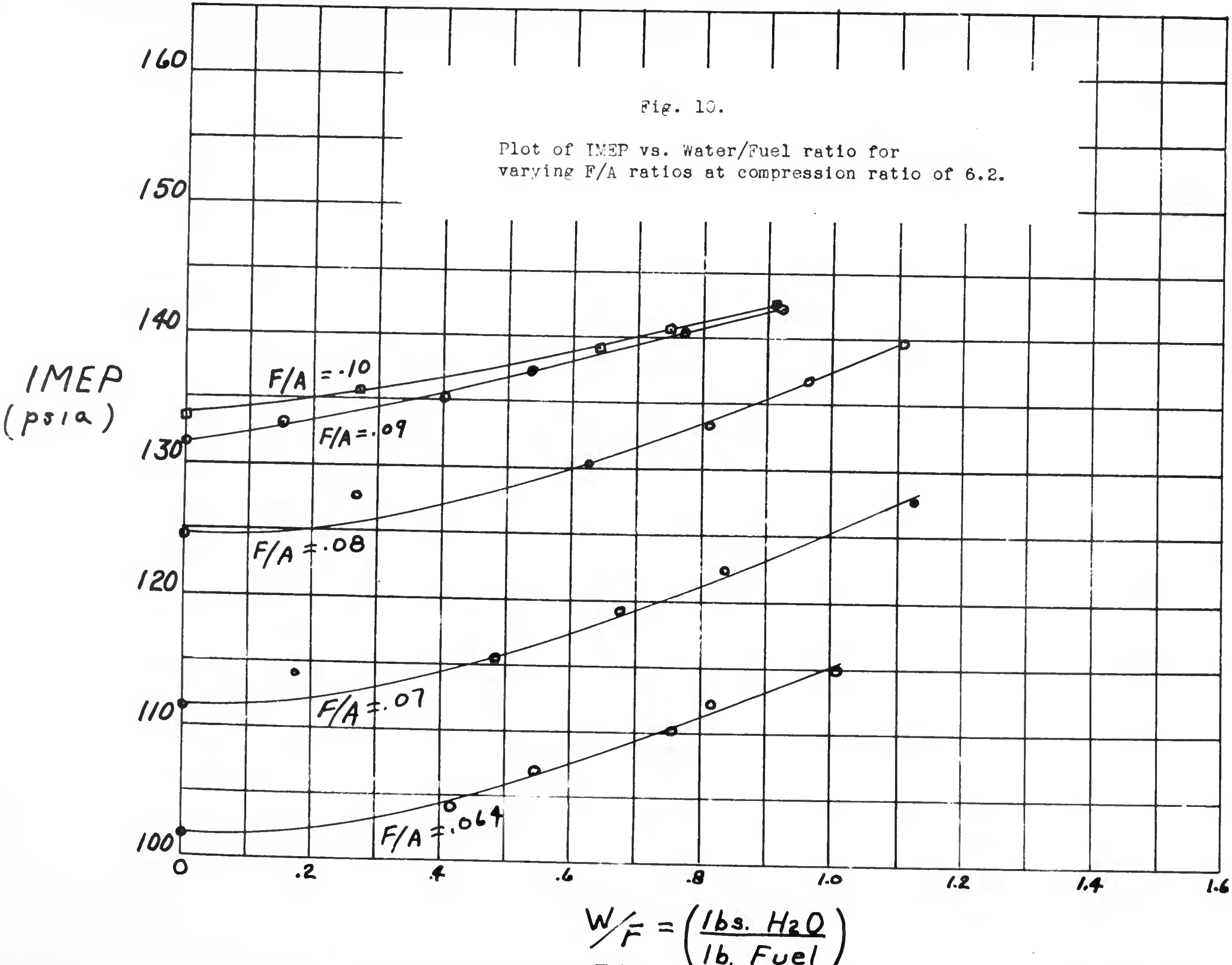


Fig. 10.

Plot of IMEP vs. Water/Fuel ratio for varying F/A ratios at compression ratio of 6.2.

Fig. 12.

Plot of IMEP vs. Water/Fuel ratio for varying F/A ratios at compression ratio 7.0.

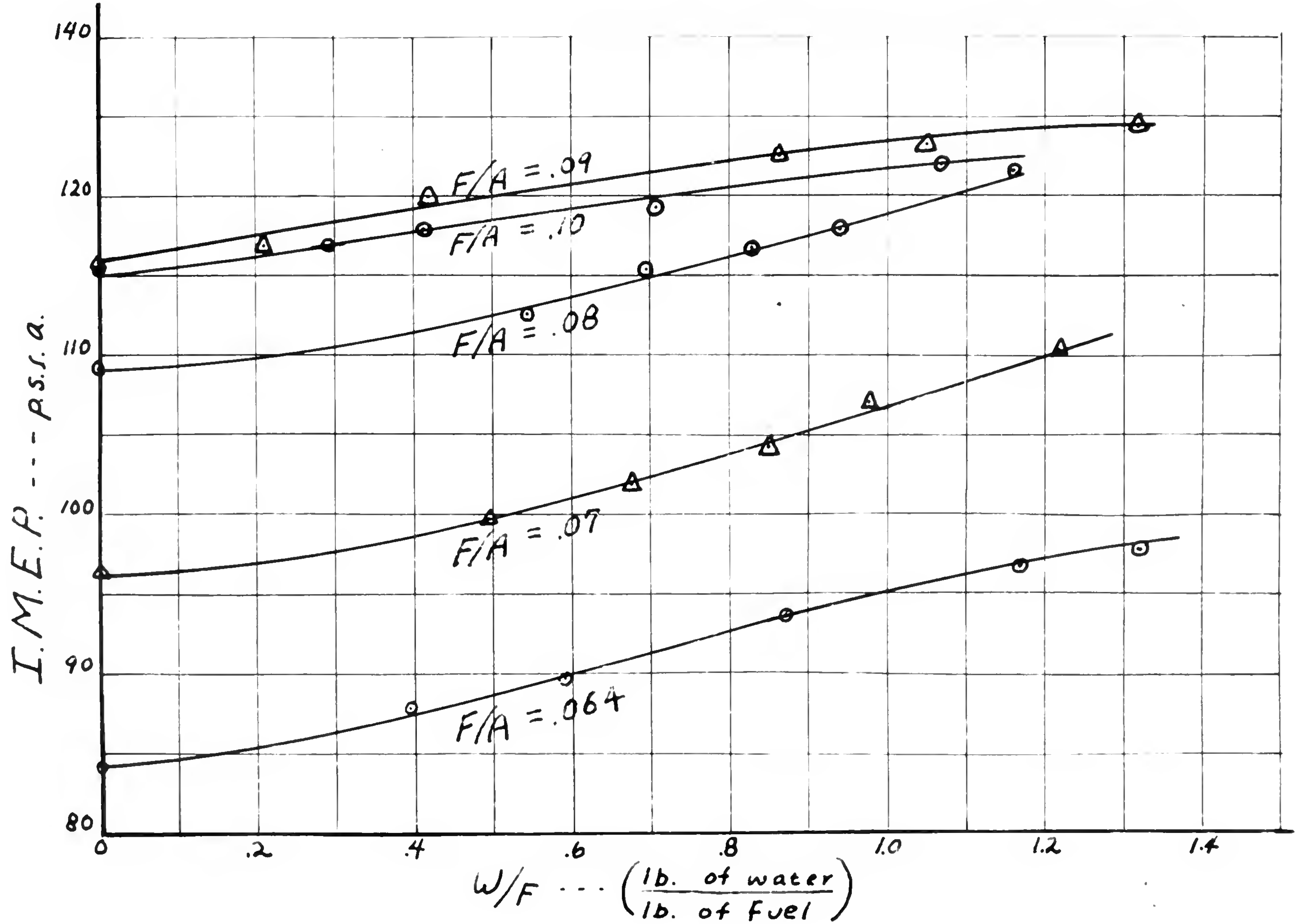
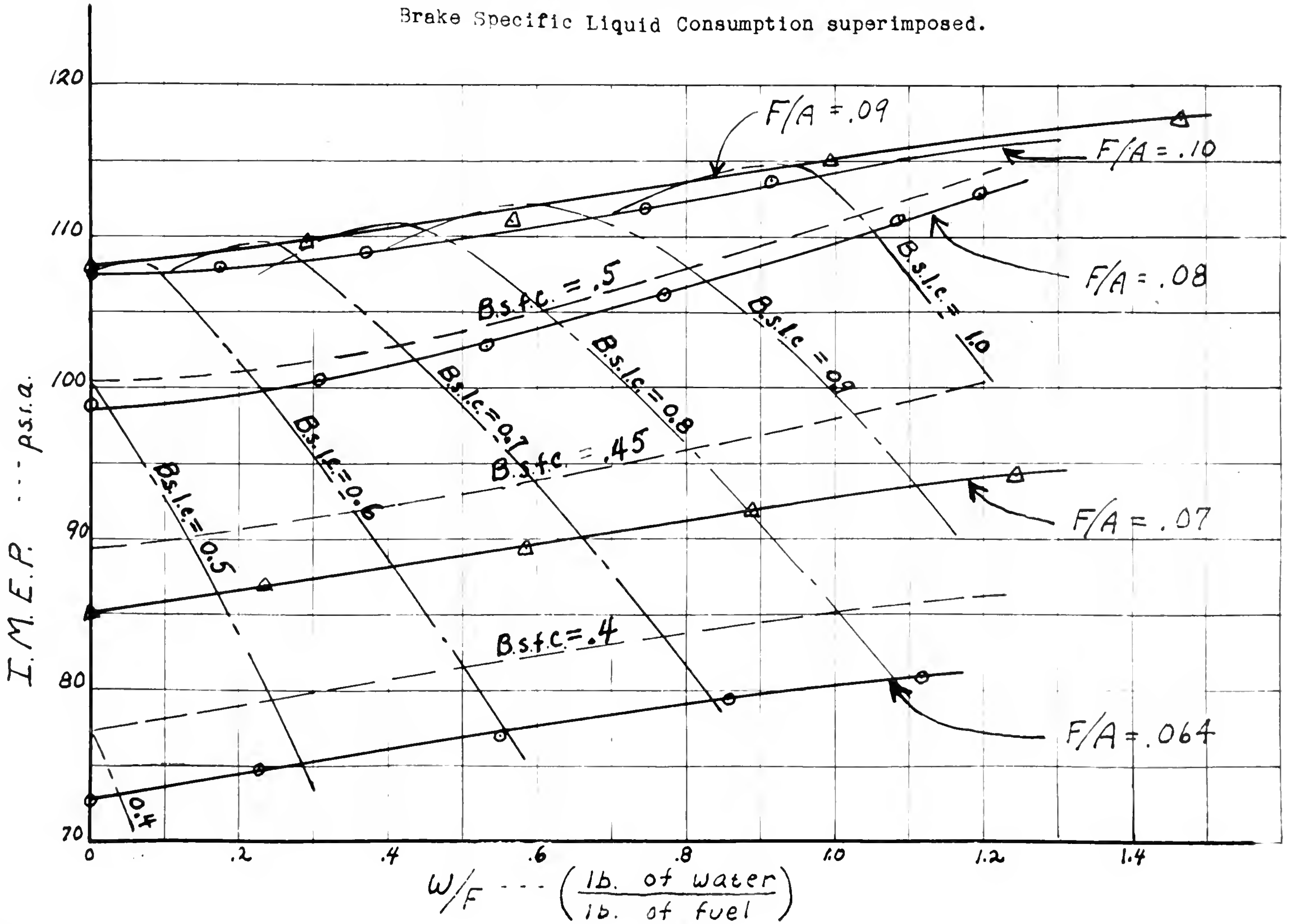


Fig. 13.

Plot of IMEP vs. Water/Fuel ratio for varying F/A ratios at compression ratio 7.4. Lines of constant Brake Specific Fuel Consumption and Brake Specific Liquid Consumption superimposed.



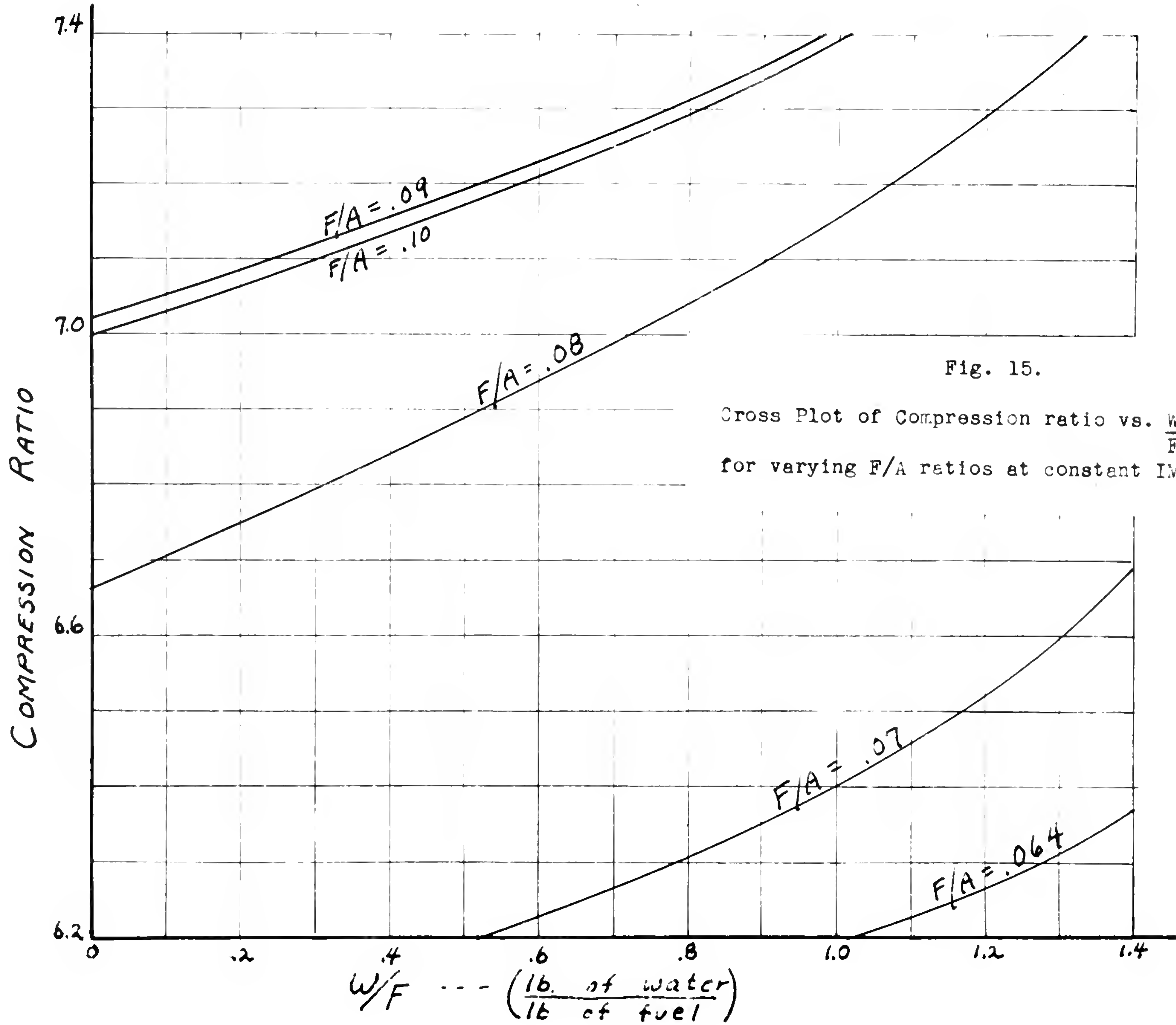


Fig. 15.

Cross Plot of Compression ratio vs. $\frac{\text{Water}}{\text{Fuel}}$ ratio for varying F/A ratios at constant IMEP of 115 psia.

Thesis 15456
S41 Seibels
An investigation of the effect of direct water injection on detonation.