EFFECT OF WATER INJECTION ON COMBUSTION CHARACTERISTICS OF A SPARK-IGNITION INTERNAL-COMBUSTION ENGINE

THESIS FOR THE DEGREE OF M. S.
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EDWARD E. TOWE

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This is to certify that the

thesis entitled

Effect of Water Injection on Combustion Characteristics of a Spark-Ignition Internal-Combustion Engine

presented by

Edward E. Towe

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Louis L. Otto
Major professor

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EFFECT OF WATER INJECTION
ON
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OF A
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The author also wishes to thank Mr. Richard Jenkins for his aid in setting up the test equipment. He would like to thank his wife, Deonne, for her help in typing the manuscript.

VITA

The author was born April 2, 1931 at Battle Creek, Michigan. Elementary and college preparatory education was taken at the Maurer and Charlotte High School respectively. Graduating from high school in June, 1949 he entered Michigan State College in September of the same year. In March, 1954 the author received a Bachelor of Science degree in Mechanical Engineering. He was married in Febuary, 1954.

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Edward E. Towe

ABSTRACT

This investigation was carried out to determine the effect of water injection on the combustion characteristics of a spark-ignition engine. Among the items investigated was the effect of water upon power output, relative peak pressure, knock-severity, timing of initial pressure rise, delay of peak pressure and the slope of the initial pressure rise.

In an ordinary nonknocking combustion process the progress of the flame front is more or less orderly across the combustion chamber. The knocking process has the same flame progress for part of the flame travel, but terminates with the extremely rapid inflammation of the balance of the unburned fraction.

A comparatively high local pressure occurs as the result of the almost instantaneous combustion of the last fraction of the charge to burn when knocking occurs. This inequality of pressure in the combustion chamber is of very brief duration, for the last fraction of the charge almost immediately expands to equalize the pressure. This creates a pressure-wave disturbance that increases the heat transfer and results in loss of power in the case of severe knocking. Also, this pressure wave travels with the speed of sound, back and forth through the gases in the combustion chamber, until dissipated by friction effects. The frequency is dependent

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on the velocity of the waves and the space in which they are confined, and the knocking sound, or ping, is determined either by the frequency of the pressure waves, or by natural frequency of the vibrating member.

As an aid to pictorial representation of combustion characteristics, a pressure pickup and flywheel-graduation magnetic pickup were used and the corresponding signals fed into a dual-beam osilloscope. A normal nonknocking pressure curve will be smooth in the rise and fall of pressure. In a knocking process the pressure curve will rise smoothly, but when falling off the pressure curve has a superimposed pressure wave which indicates knock.

Among the factors which influence the knock process are fuel characteristics, mixture conditions, compression ratio, ignition timing and combustion chamber design. One method to eliminate combustion knock is the cooling of mixture before induction into the engine. The most simple method of cooling the intake charge is to inject a volatile fluid with high latent heat into the charge. In this investigation the volatile fluid used was water.

This investigation indicates that the addition of water to the intake charge has some effect upon all the items investigated. A standard knock pattern was obtained by using a 87.5% octane fuel at a 7 to 1 compression ratio, and 30 inches of Hg. absolute manifold pressure. The injection of a 32% water-to-fuel ratio, resulted in a complete elimination of knock. The power output measured in indicated mean effective pressure decreased as the percentage of water increased. The relative peak pressure was decreased by over one-half with the addition of 79% water. The timing of the initial pressure rise and the delay of peak pressure point were both delayed the same amounts with an increase in water injected. In other words the pressure curve was shifted to the right with the rise of pressure occuring on the left side. The slope of the initial pressure rise decreased as the addition of water increased. The maximum amount of water injected was 79%. As the water increased toward this amount the output became unsteady, indicating a tendency to completely drown out the combustion. If the water was injected in amounts over 80%, a complete loss of power would occur.

This investigation produced satisfactory conclusions to most of the questions indicated above. However, more work should be done to explain the wide variance in the peak pressure which occured even during normal combustion. This was a serious handicap for the author in obtaining desirable results and photographs of the effect of water injection.

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INTRODUCTION

Knocking has imposed a serious limitation upon the maximum power obtainable from an internal-combustion engine. Increasing compression ratio or manifold pressure or both will increase power output, but both also increase the tendency to knock. Reduction in knock can result in increased power. One method of decreasing knock is the addition of water to the intake charge.

The addition of water also has an effect upon other characteristics connected with combustion. If the related effects are not too adverse, the addition of water could be an important factor in the ability to incrase power output and efficiency of an internal-combustion engine.

DISCUSSION OF THE PROBLEM

Much work has been done with water injection, with the primary interest in the gain in the resulting power output without knock. It is accepted that water acting as an internal coolant will suppress knock by lowering the intake-charge temperature. Little is known about the effect of water on the actual combustion process. With that in mind this investigation was instigated to obtain some results that pictorially represent the effect of water injection on combustion characteristics.

In the selection of variables the compression ratio, manifold pressure, air temperature, and engine temperature were either considered constant or held constant. The air temperature during the runs varied from 113 degrees F. to 115 degrees F. Both the oil and and air temperature were considered as being constant. The compression ratio was 7 to 1 and the manifold pressure was held at 30 inches of Hg. absolute.

A single-cylinder, variable-compression, CFR knock-testing engine was used. A pressure pickup was inserted into the cylinder head, and its signal fed through a monitor into a dual-beam oscilloscope. A magnetic pick-up was used to pick up the flywheel graduations, which were also fed into the scope. A Palaroid-Land camera was used to record the signals. This camera was selected because of the ability to observe the photograph when the test run is being made. The water injection equipment consisted of a small cylindrical tank, which was filled with water. Regulated compressed air acting upon the top of the water forced water out the bottom line to a nozzle into the intake manifold. By varying the air pressure the amount of water injected could be changed.

The testing procedure was divided into two sections. In the first section the octane number was lowered in order to obtain a standard knock pattern. Runs were made at 100%, 90%, 87.5% and 85% octane and photographs were made of each run. The power output was found by using the brake force in pounds, subtracting the friction force in pounds and multiplying by 4.23, which gives the units in pounds per square inch (Imep). The brake force is the scale reading when engine is running and the friction force is the scale reading when the engine is being motored. A octane number of 87.5% was selected as the one with a standard knock pattern, which could be held on the scope satisfactorly. If the knocking was too intense the pressure signal would jump off the range of the oscilloscope and be very difficult to photograph.

Using a 87.5% octane gasoline, water was injected in various amounts measured in percent of fuel used. During all the runs the air and fuel flow were measured and the fuel-air ratio calculated. Photographs were taken of each run.

Due to the wide variance of pressure in the engine all of the photographs have to be interpreted in respect to an average pressure curve. The timing signal appears on the scope as a series of pips, which are five degrees apart measured on the flywheel. Top dead center is one of the pips which is a little bit higher than the rest. In all the photographs this top dead center point is indicated by an arrow.

TABLE I

PRELIMINARY INVESTIGATION

The Determination of Octane
Number for Desired Knock Pattern

Conditions of Operations:

7:1 Compression Ratio
Constant Manifold Pressure
(30 in. Hg. abs.)
Constant Air Temperature
Constant Engine Temperature

Vary Octane Number

Run	Octane No.	Air Min/1/4 #	Fuel Min/1/4 #	F/A	Brake Force #	Friction Force #	Imep #/in^2	Knock Condition
A	100	.215	2.88	.075	23.2	8.4	62.6	no knock
B	90	.214	2.54	.084	23.0	8.5	61.5	no knock
C	87.5	.224	2.64	.085	23.0	8.5	61.5	some knock
D	85	.224	2.66	.084	23.0	8.4	61.9	more knock very unstable

TABLE II

Water Injection Investigation

The Determination of the Effect
of Water Injection on Combustion Characteristics

Conditions of Operations:

7:1 Compression Ratio
Constant Manifold Pressure
(30 in. Hg. abs.)
Constant Air Temperature
Constant Engine Temperature
Constant Octane Number (87.5)

Vary Water to Fuel Ratio

Run	Water %	Air Min/1/4 #	Fuel Min/1/4 #	F/A	Brake Force #	Friction Force #	Imep #/in^2	Knock Condition and General Operation
E	12.2	.250	2.78	.090	22.6	8.6	59.2	light knock
F	19.8	.240	2.62	.091	22.5	8.5	59.2	very light knock
G	32	.217	2.08	.104	21.5	9.2	52.0	no knock output steady
H	34.6	.240	2.64	.091	21.4	8.9	54.0	no knock output steady
I	39	.225	2.32	.097	21.2	9.0	51.6	no knock output steady
J	62	.238	2.48	.096	20.2	9.6	44.9	no knock output steady
K	73	.238	2.34	.102	19.6	9.0	44.8	no knock output unsteady
L	79	.227	2.50	.091	20.0	9.0	46.5	no knock output unsteady

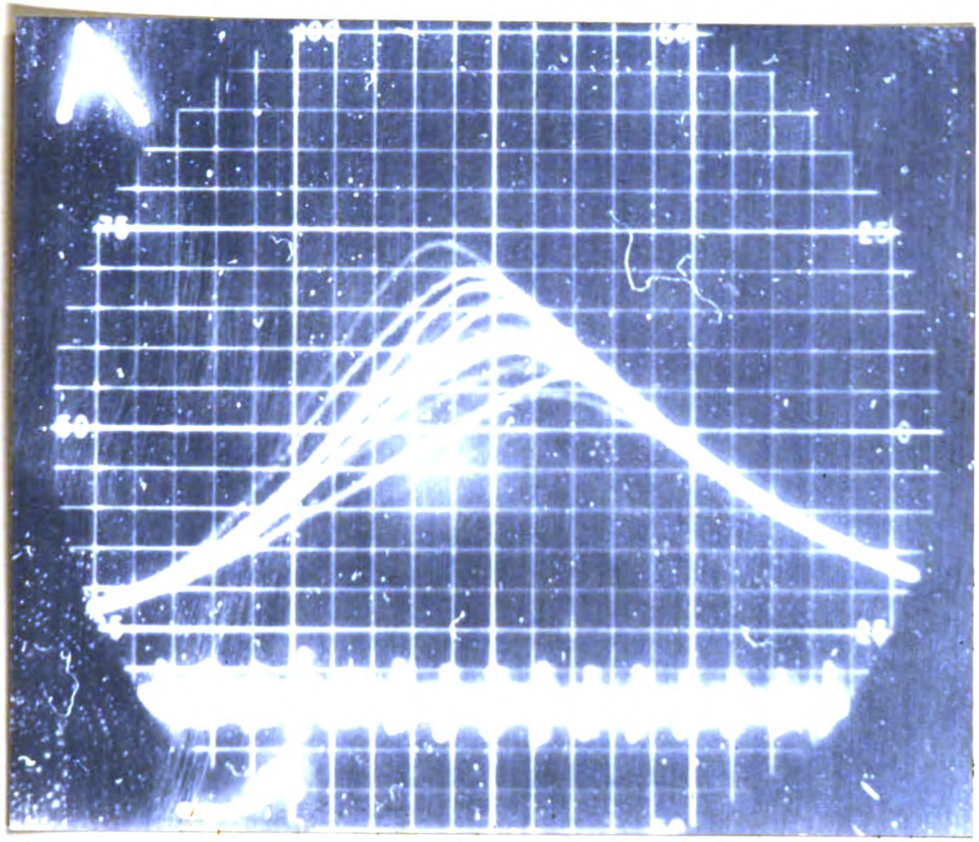


Fig. 1 100% Octane
No Water-Run A

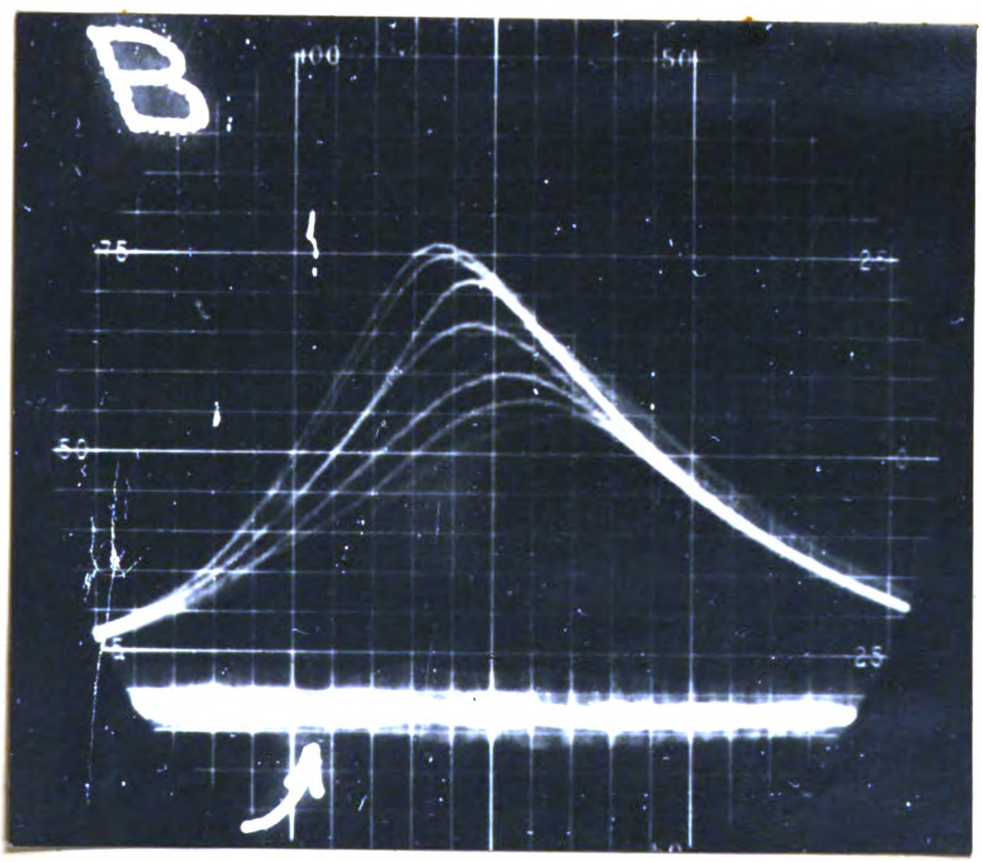


Fig. 2 90% Octane
No Water-Run B

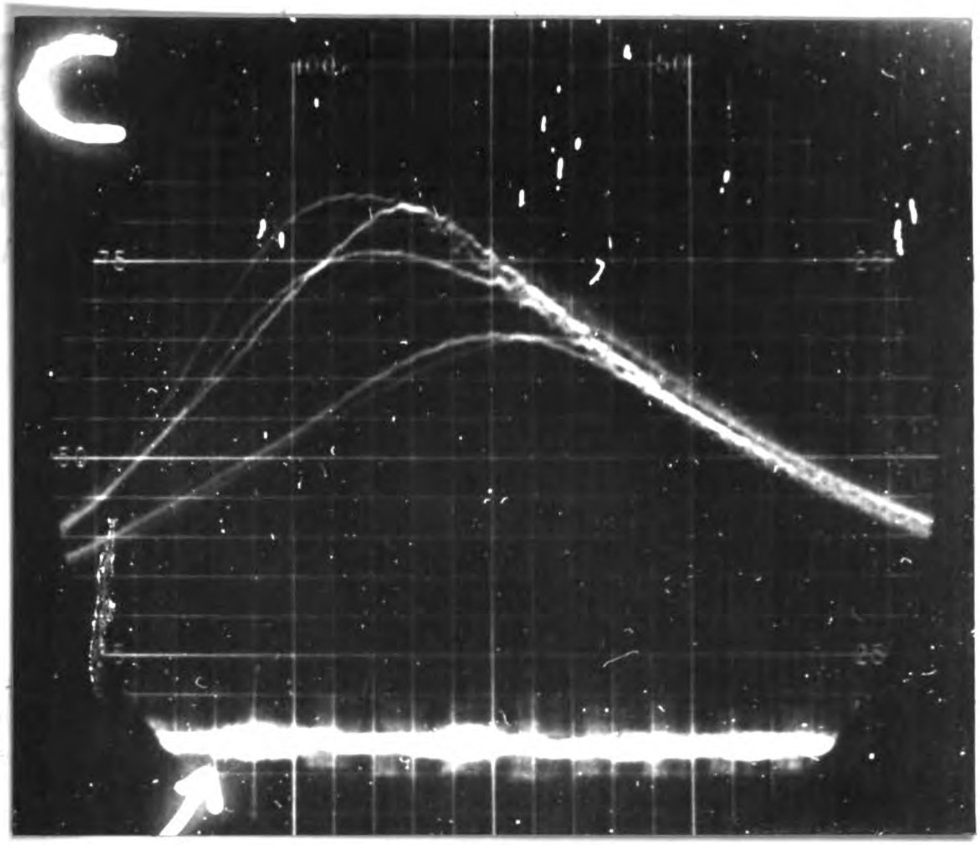


Fig. 3 87.5% Octane
No Water-Run C

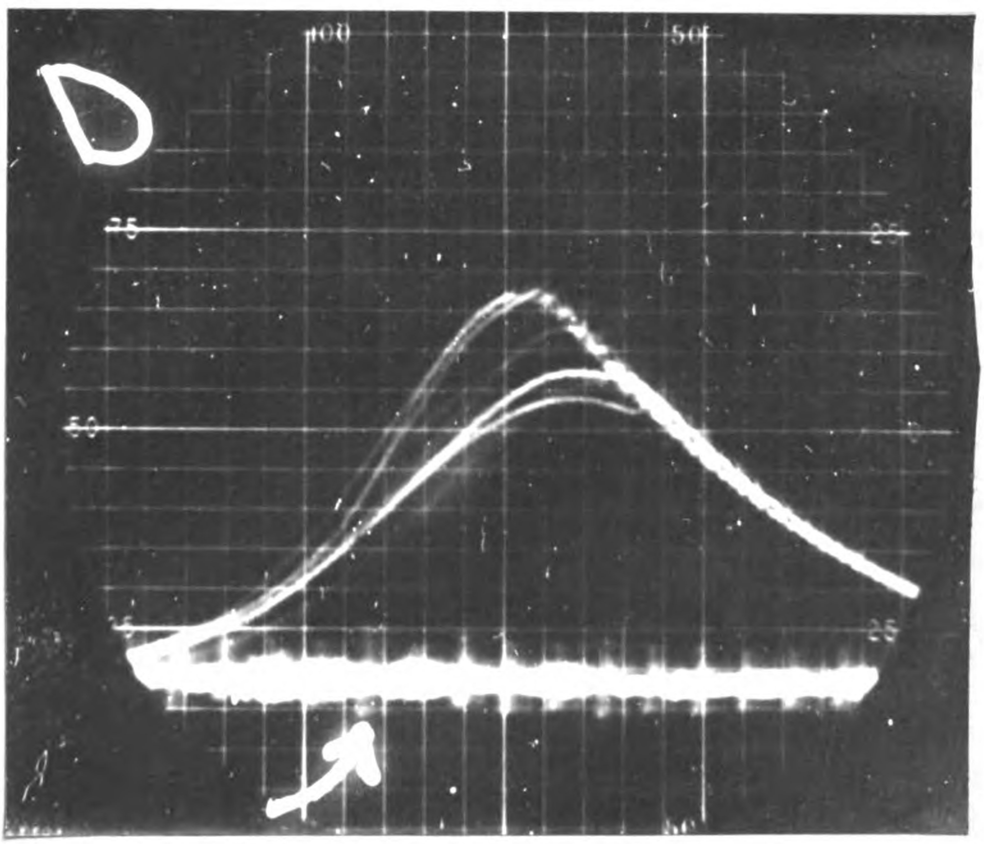


Fig. 4 80% Octane
No Water-Run D

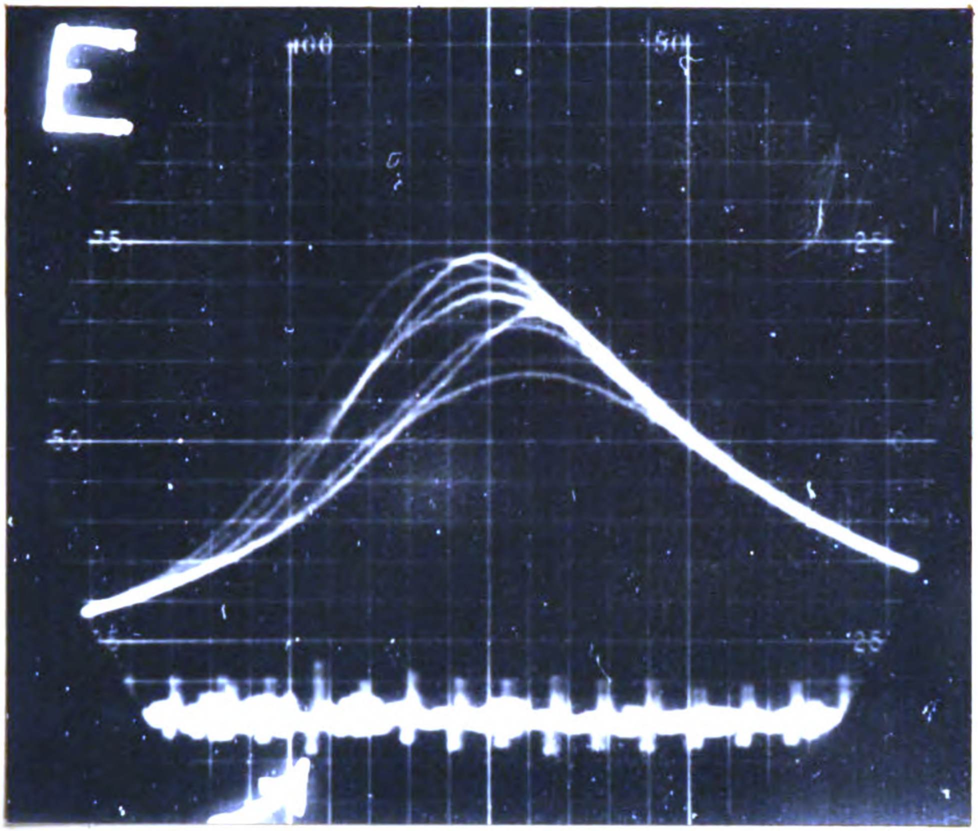


Fig. 5 87.5% Octane
12.2% Water-Run E

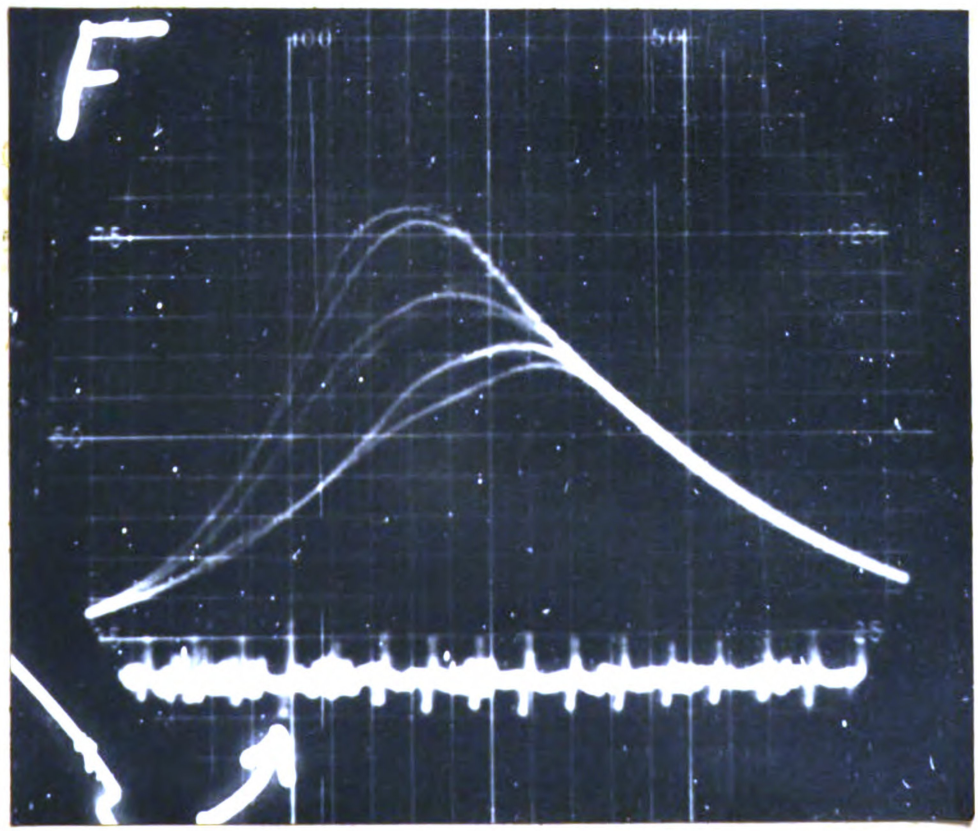


Fig. 6 87.5% Octane
19.8% Water-Run F

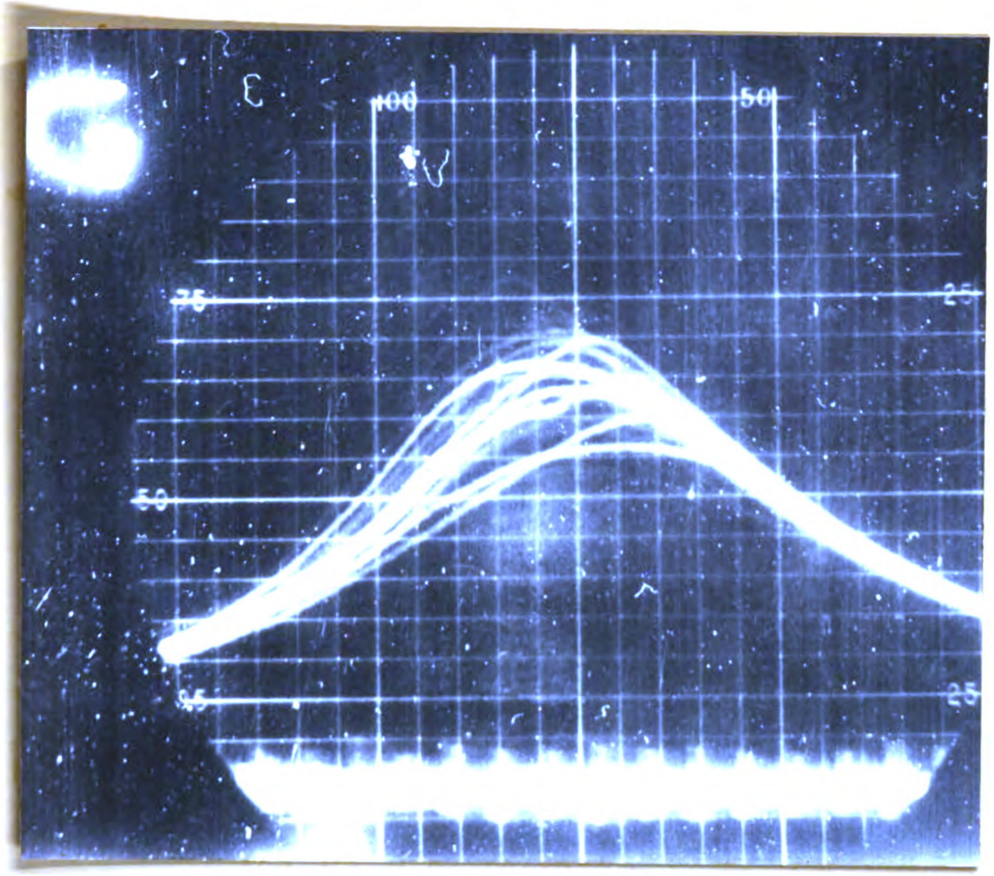


Fig. 7 87.5% Octane
32% Water-Run G

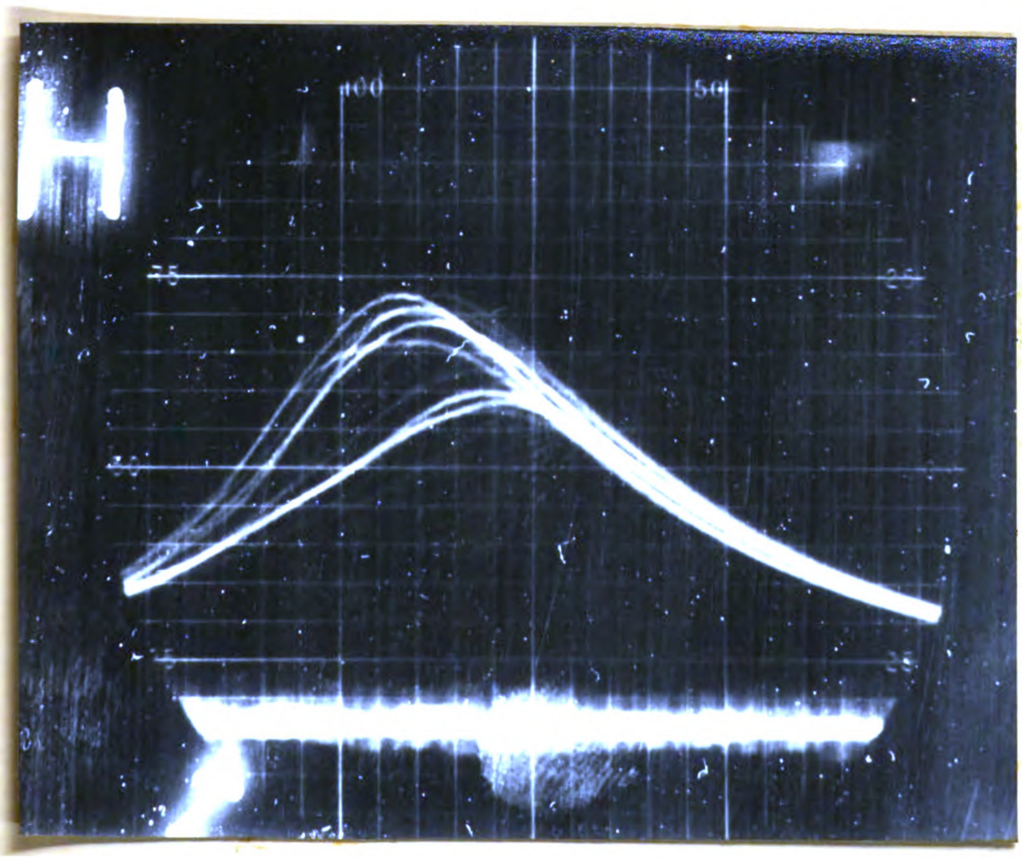


Fig. 8 87.5% Octane
34.6% Water-Run H

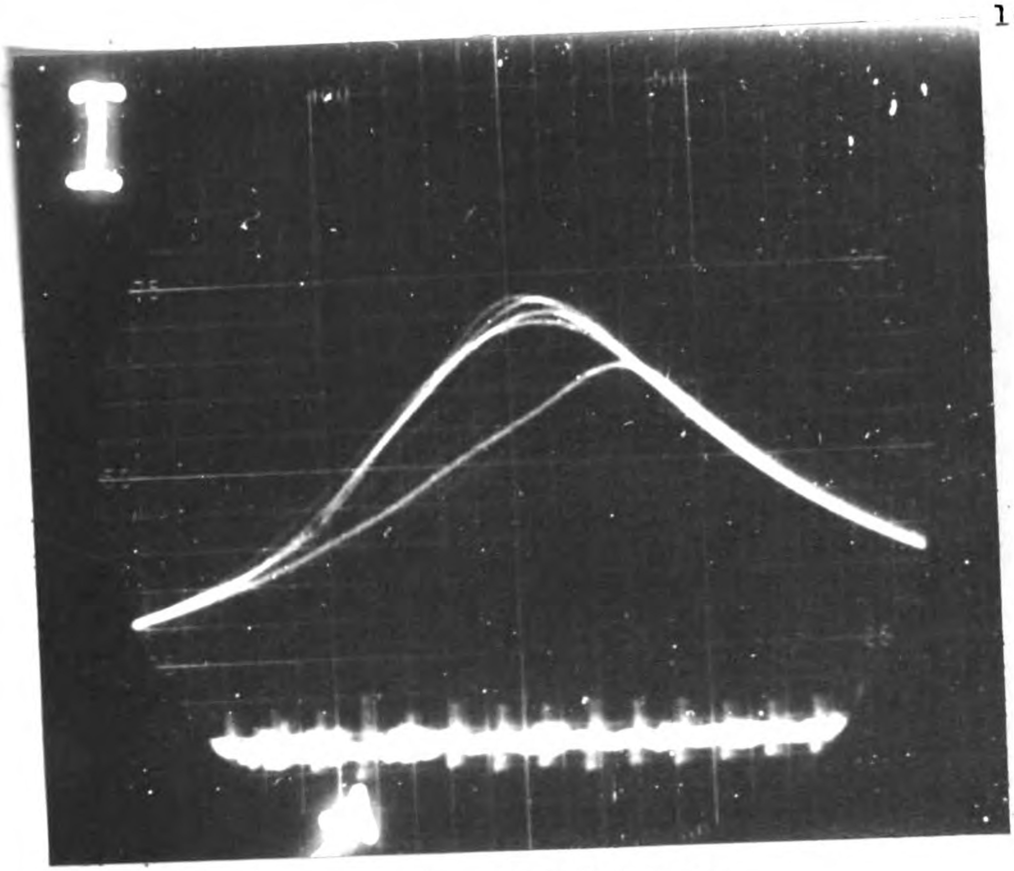


Fig. 9 87.5% Octane
39% Water-Run I

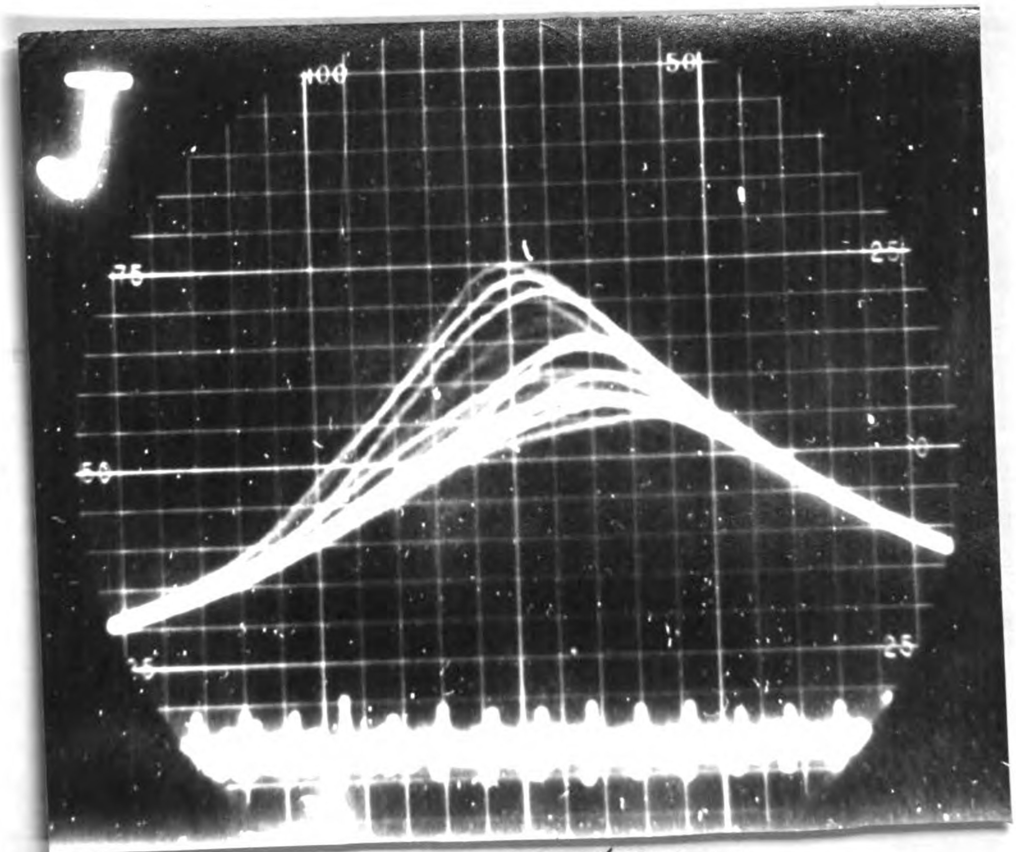


Fig. 10 87.5% Octane
62% Water-Run J

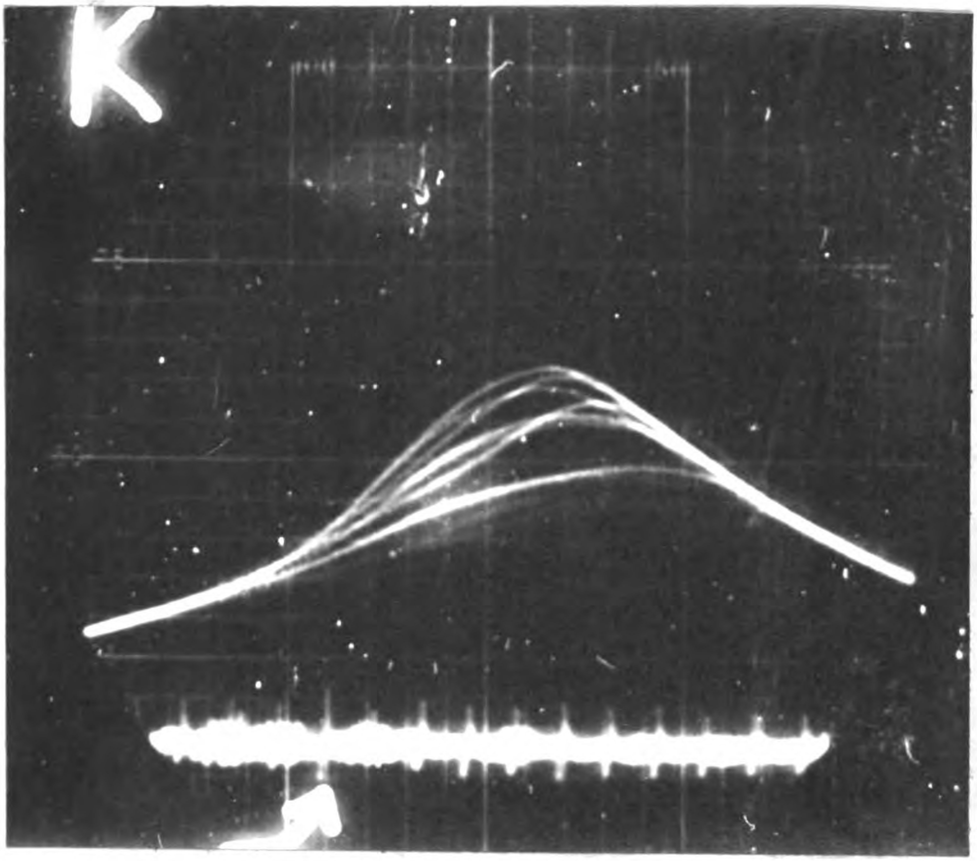


Fig. 11 87.5% Octane
73% Water-Run K

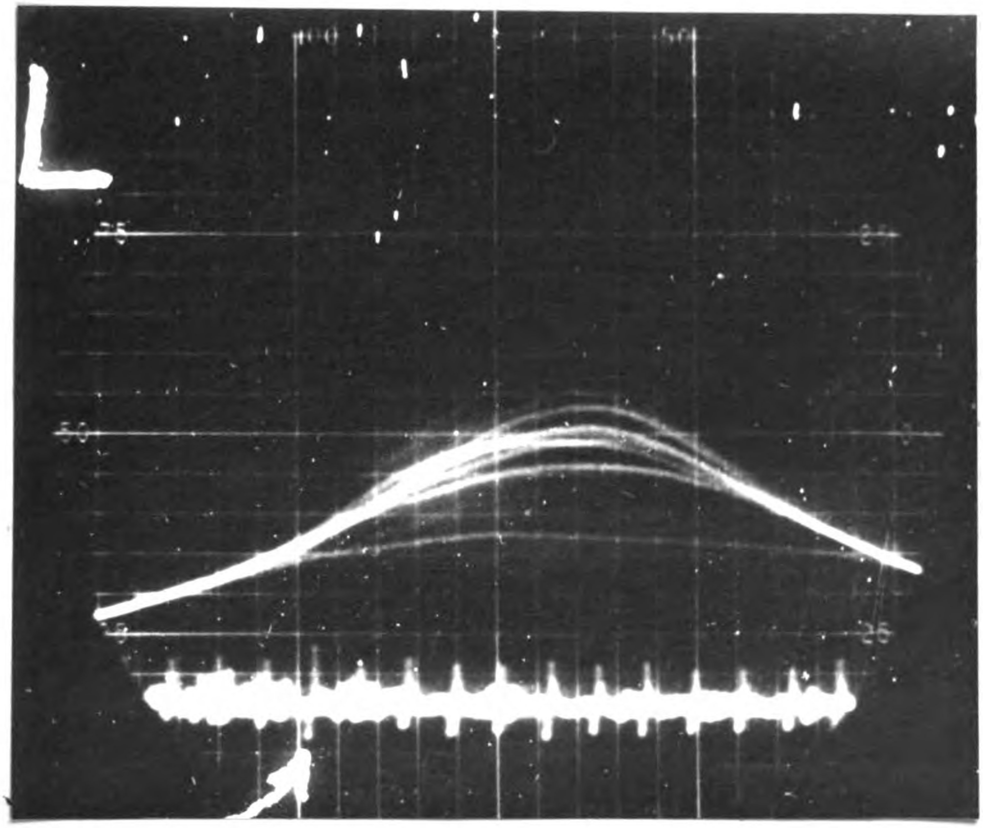


Fig. 12 87.5% Octane
79% Water-Run L

CALCULATED RESULTS

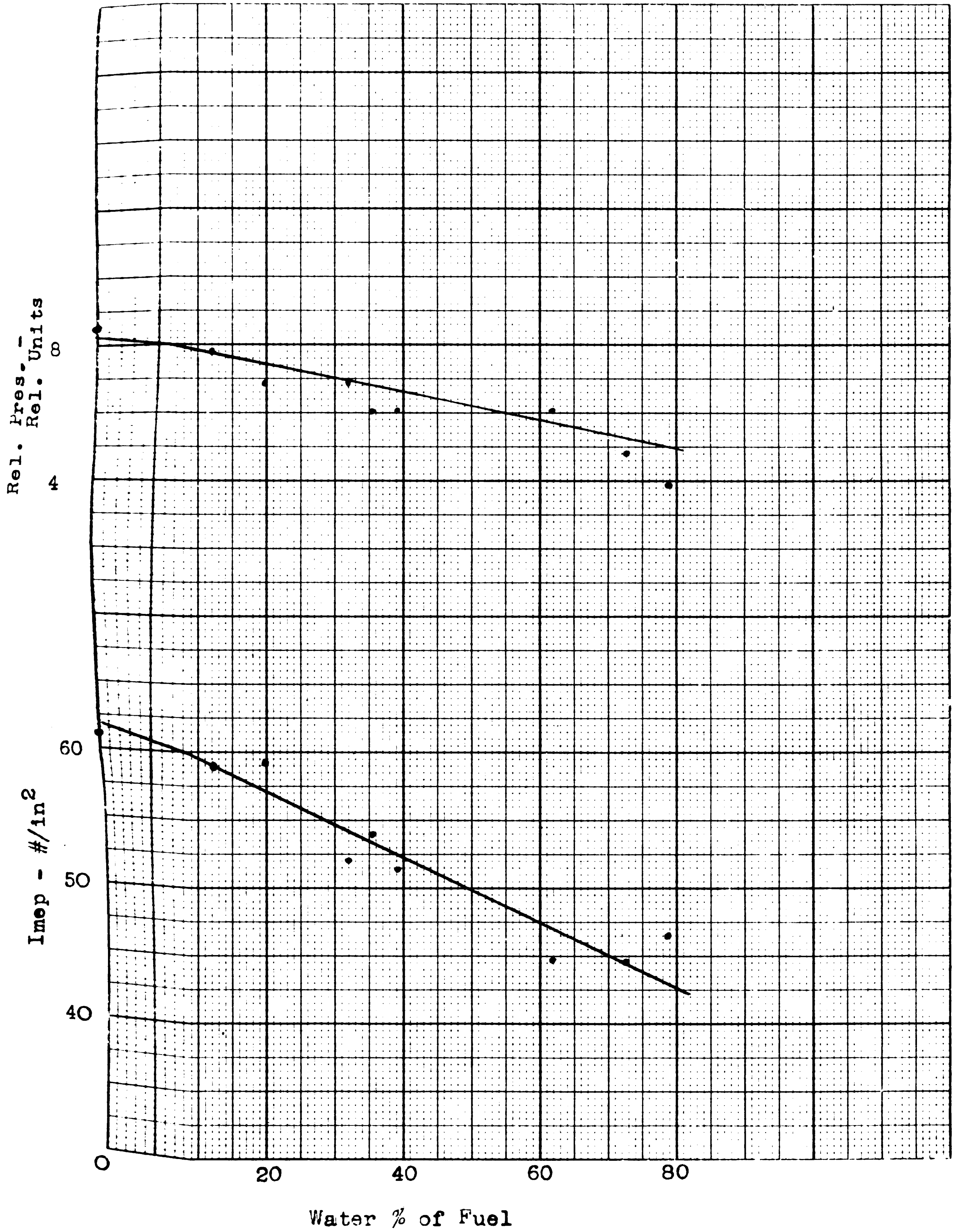
Water (% of fuel) vs. ---

Power Output (Imep)
Peak Pressure (Relative)
Timing of Initial Pressure Rise (deg. before TDC)
Delay of Peak Pressure (deg. after TDC)
Slope of Initial Pressure Rise (deg.)

Water (%)	0	12.2	19.8	32	34.6	39	62	73	79
Power Output (Imep)	61.5	59.2	59.2	52.0	54.0	51.6	44.9	44.8	46.5
Peak Pressure (Relative)	8.7	8.0	7.0	7.0	6.0	6.0	6.0	5.0	4.0
Timing of Initial Pressure Rise (deg. before TDC)	12	10	10	6	5	5	5	3	2
Delay of Peak Pressure (deg. after TDC)	18	20	20	22	22	22	22	25	28
Slope of Initial Pressure Rise (deg.)	40	39	38	37	35	35	34	33.5	32

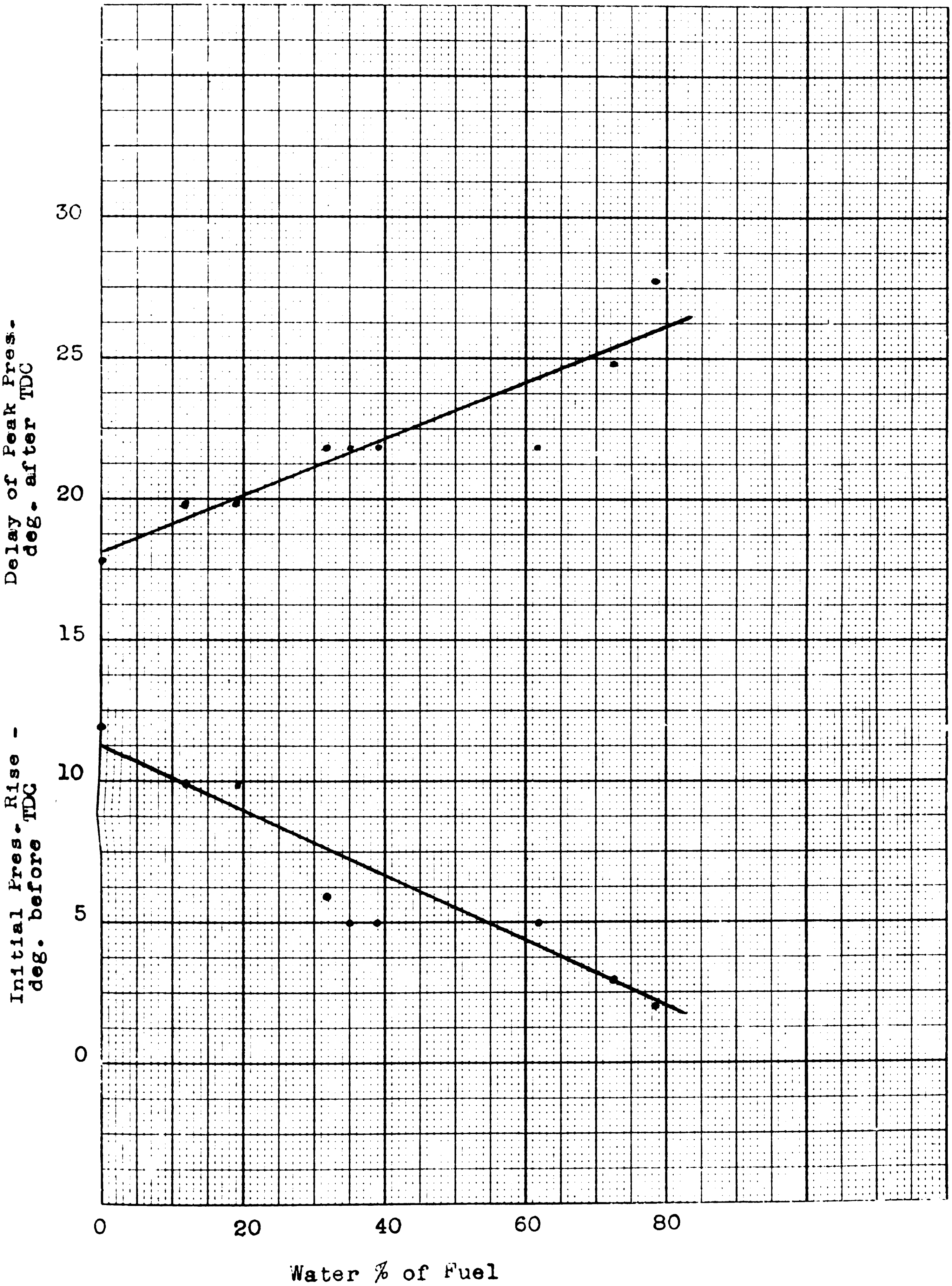
PERFORMANCE CURVES

Water(%) vs Imep and
Relative Pressure



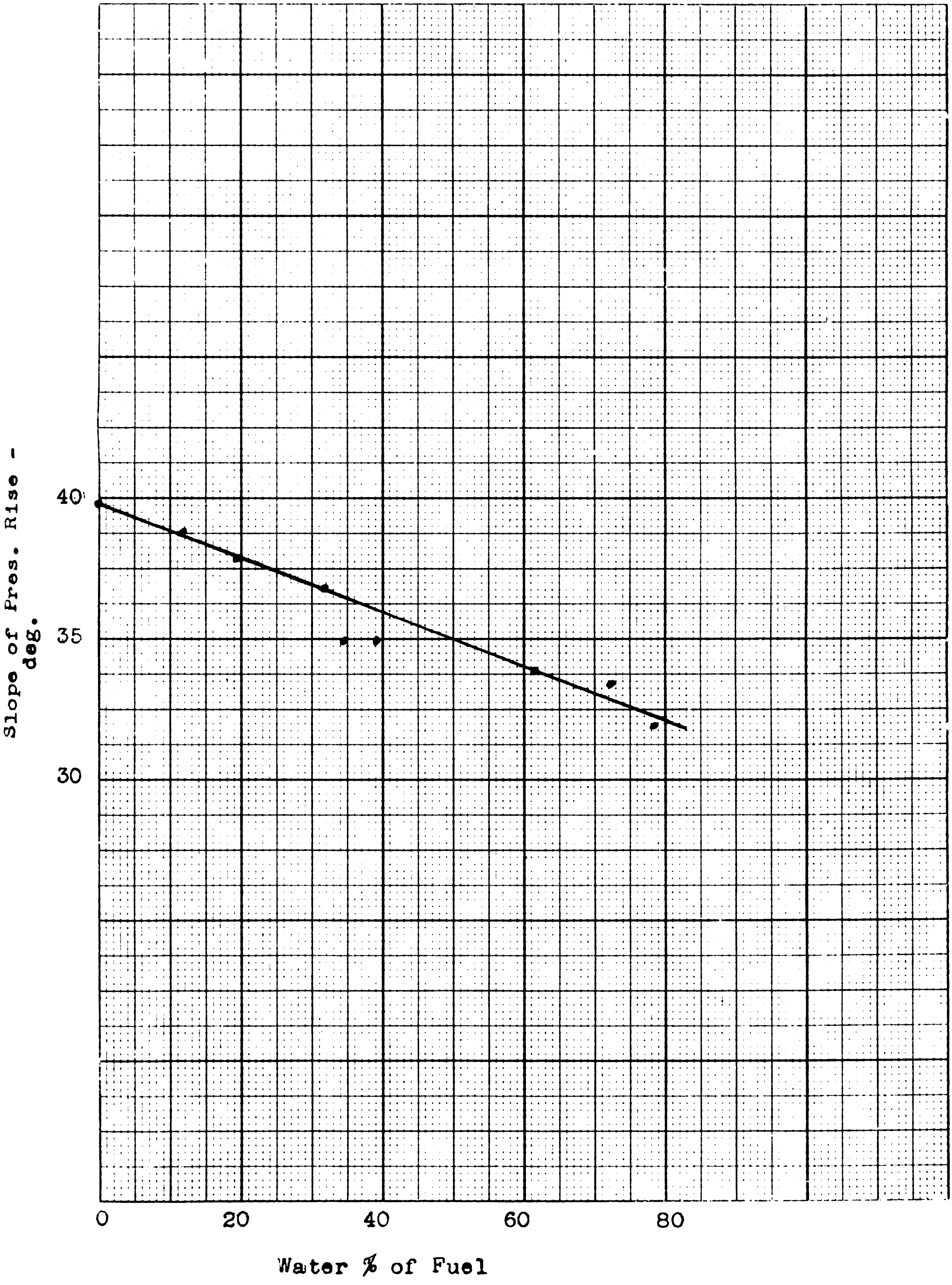
PERFORMANCE CURVES

Water(%) vs Initial Pressure
Rise and Delay of
Peak Pressure



PERFORMANCE CURVES

Water(%) vs Slope of Initial Pressure Rise



DISCUSSION OF RESULTS OBTAINED

As expected the addition of water was very successful in completely eliminating knock. When the percentage of water had reached 32% all traces of knock had been removed from the pressure wave. With the addition of a maximum of 79% water the Imep. was reduced by about 25% in roughly a straight line relationship. The same addition reduced the relative peak pressure by over 50%. This might indicate a means of having the same power output without a high peak pressure. The timing of initial pressure rise as measured in degrees before TDC decreases as the water injected increases. The delay of peak pressure as measured in degrees after TDC increases. When these two items were plotted on the same graph it can be seen that the two slopes are nearly equal. This fact when applied to the pressure diagrams means that the curves are displaced down on the combustion cycle. The slope of the initial pressure rise decreases as the amount of injected water increases.

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CONCLUSION

The effect of water injection on the combustion characteristics of an internal-combustion engine is something that can not be readily found by just the measurement of shaft output. Observation of the pressure wave and timing signal pattern and their relationship to one another provides an excellent means of finding the actual effect of water on the combustion process. The items that were investigated include the relative peak pressure, knock-severity, timing of initial-pressure rise, delay of peak pressure and the slope of the early-combustion line. All of these factors can be found by inspection of the photographs taken during each run. The indicated mean effective pressure is calculated from the scale reading.

As the amount of water injected into the manifold increased the indicated mean effective pressure decreased in straight line relationship with a 25% drop occuring with a 79% water injection. This drop in power could be explained as a result of one or two factors. If part or all of the water vaporizes during the intake stroke this would decrease the amount of air available for combustion and thus lower the Imep. The water will probably be heated into the

superheated steam region, which will require energy. Some of this energy will be returned to the cycle on the power stroke, but a good percentage would be exhausted into the atmosphere as in any Rankine steam cycle. This would also result in a overall power decrease.

The latent heat of the water injected will decrease the temperature of the intake charge, which will lessen the severity of knock. This was verified by the author as the severity of knock decreased with water addition. The complete elimination of knock under test conditions was accomplished with 32% water injection.

The relative peak pressure was decreased by over one-half with the addition of 79% water.

The timing of the initial-pressure rise and of the peak pressure point were both delayed the same amounts with an increase in water injected. In other words the combustion pressure curve was shifted to the right (rise of pressure occuring on the left side). As the addition of water increased, the slope of early-combustion line decreased. When the amount of water reached 73% the output became unsteady, and in amounts over 80% there was a tendency to completely drown out the combustion, which might result in a complete loss of power.

APPENDIX

A. Description of Equipment

The engine used in this investigation was a ASTM-CFR knock-testing engine made by the Waukesh Motor Co. This engine is a single-cylinder four-stroke valve-in-head engine with a 3 1/4 - in. bore and a 4 1/2 - in. stroke. It is of the variable-compression type having a compression ratio from 4:1 to 10:1. The test compression ratio was 7:1. The same engine may be run in five ASTM methods; motor, research, aviation, supercharge and cetane. The supercharge method was used in this investigation.

The engine is connected to a synchronous induction motor, which maintains a constant engine speed. The motor is used for starting purposes and then floats on the line. Fig. 13 is a photograph of the supercharge unit.

Water for injection purposes was obtained by compressed air acting upon a small cylindrical tank forcing water through a nozzle into the intake manifold. Water flow was varied by changing tank pressure by means of a pressure regulator. Fig. 15 is a photograph of the water injection tank.

A. cont.

The timing signal was obtained by a magnetic pick-up mounted to record the flywheel graduations.

For pressure measurement a EP-2000 model pressure pickup made by Control Engineering Corportion was used. This pickup has a range of -15 to 2000 psi for dynamic pressures up to 20,000 cyclés per second.

A DuMont twin-beam cathode-ray oscilloscope Model 332-A was used to observe the pressure-wave and timing graduations. A Polaroid-Land camera recorded the corresponding patterns on film. Fig. 14 is a photograph of the camera, pressure monitor and oscilloscope.

B. Description of Test Equipment Assembly

The supercharge induction system consists of a compressed air line with a control valve which is connected to an air tank. Between this air tank and a second tank is a calibrated orifice with a water monometer attached. From the second tank the air goes through an adjusting valve to a surge tank mounted over and connected to the intake manifold.

The fuel system uses an injector pump connected to a corresponding injector nozzle.

The scale connected to the dynamoneter is calibrated in pounds of friction force and brake force which read to the left and right of zero respectively.

C. Calibration of Measuring Equipment

The air flow manometer is calibrated in minutes to consume 1/4 lb. of air. The fuel calibration was in minutes to consume 1/4 lb. of fuel. By dividing the first by the second the F/A ratio can be found directly. The water injected was calibrated the same as the fuel so the percentage could be found by dividing the two.

The manifold pressure reads in inches of mercury absolute.

The timing signal observed on the oscilloscope photographs show relatively high pips. These pips are 5 degrees apart.

D. Calculations Leading to Published Results

The results were obtained by in large from the inspection and measurment of the combustion process photographs. The mean effective pressure was found by multiplying the indicated load by 4.23. The indicated load is the difference between brake load and friction load.

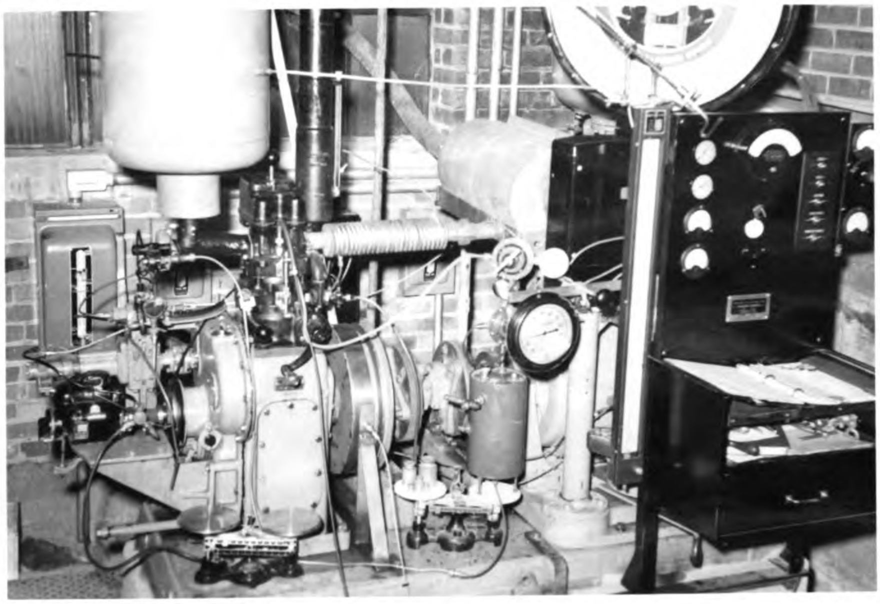

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Fig. 13 Supercharged
Engine Assembly

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Fig. 14 Camera, Pressure
Monitor and Oscilloscope

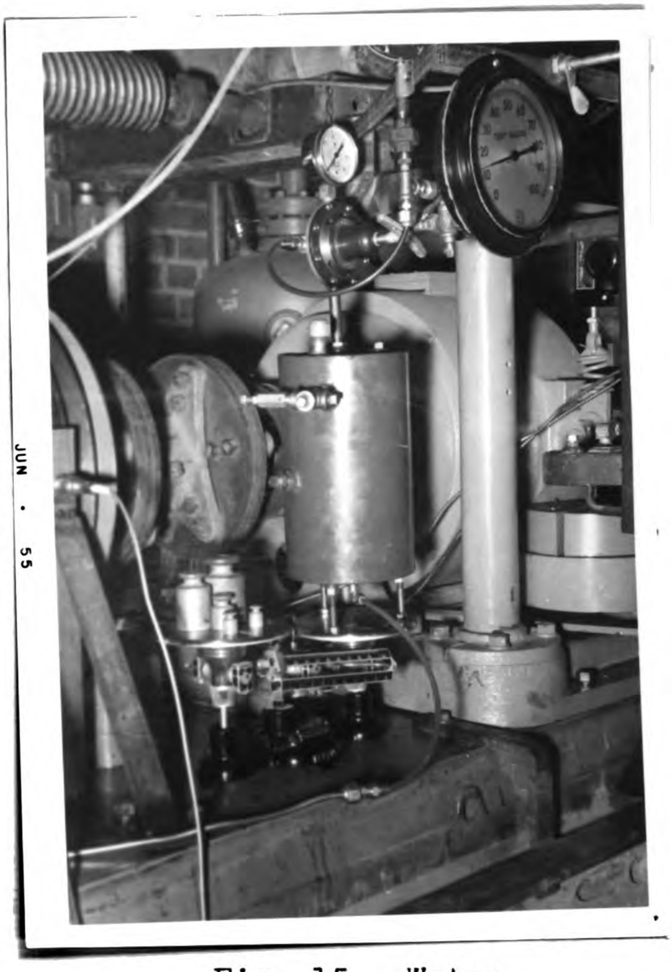

Fig. 15 Water
Injection Tank

BIBLIOGRAPHY

1. Lichty, Lester C., Internal Combustion Engines, Sixth Edition, McGraw-Hill, New York, 1951.

2. Rowe, M.R. and Ladd, G.T., Water Injection for Aircraft Engines, SAE Journal, Jan. 1946, pp-26-37

3. Cattaneo, A.G., Bollo, F.G. and Stanly, A.L., A Petroleum Engineer Looks at Aircraft Fuels, SAE Journal, Feb. 1946, pp-55-63.

4. Eaton, D.C., Cruising Economy by Use of Water Injection, SAE Journal, Feb. 1946, pp-81-87.

5. Thompson Products, Inc., Thompson Vitameter Brochure, 1951.