THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

CONTROL OF THE COMBUSTION OF COMPRESSION IGNITION ENGINES

E. T. Vincent
A. R. Ibrahim

April 1961

IP-506

TABLE OF CONTENTS

LIST OF FIGURES

NOMENCLATURE

μ	Ignition lag in milliseconds
τ	Time characteristic
	$\dfrac{\text{Crank angle for sudden pressure rise}}{\dfrac{\text{Max pressure-Compression pressure}}{\text{Compression pressure}}}$
F/A	Fuel air ratio
T_{exh}	Exhaust gas temperature
P.F.	Primary fuel injected
T.F.	Total fuel injected

INTRODUCTION

In the compression ignition engine a charge of air is compressed in the cylinder and fuel is injected into this heated air which is so hot, because of the approximately aidabatic compression, that the fuel spray ignites. The word ignition, as used here, covers a multitude of unknowns associated with such problems as, how soon, and how much vaporization occurs, how fast some undefined chemical reactions begin and proceed after the injection of the fuel into the hot swirling air, etc.

The mixture in the energy cell of the combustion chamber is heterogeneous at T.D.C. since it consists of air and exhaust residuals from the previous cycle. Into this chamber atomised liquid fuel is injected and large variations in local fuel air ratios undoubtedly exist including the possibility of pockets where there is little or no fuel.

There is an additional inherent property of the fuel that must be taken into account, the delay period, adding further difficulty to the combustion problem. It is apparent that the engine speed can be limited by the delay and rate of combustion; if the rate is high and complete air and fuel mixture is achieved the after-burning will be short, enabling higher rotative speed to be achieved yet still maintaining high efficiencies, and power output.

It was considered that, by injecting a small part of the fuel early in the cycle directly into the hot gases remaining in energy cell, sufficient concentration of active radicals, mainly hydroperoxides, necessary for rapid combustion, could be prepared and be available in the cell at the time the main injection occurs thus activating the hot flame reaction, shorting the ignition delay, increasing the combustion rate.

The effect of this small early addition of fuel called primary fuel injection was examined as regards timing, pressure, cooling water temperature, engine speed, and fuel additive, upon engine performance, lag, etc. in an attempt to define the optimum condition.

THEORY

The theory of degenerate branching chains which is generally used to explain the long induction period in hydrocarbon combustion appears to be a feasible one, thus to accelerate the beginning of rapid combustion in an engine, in order to burn a hydrocarbon fuel quickly, it is at least necessary to establish some minimum possible quantity of radicals that suffices to bring about a quick reaction. The method employed to achieve this, necessitates introducing some of the fuel, into the hot energy cell to form a suitable F/A ratio, which will after a certain elapse of time result in the fuel undergoing a chain reaction process which probably leads to cool flame reaction developing a suitable radical concentration to accelerate the main fuel combustion process immediately on its injection. The formation of this radical concentration should occur just before the main fuel is injected, timed so as to maintain the point of maximum pressure rise inside the cylinder at about 10° to 15° A.T.C. in order to realize the maximum availability of the chemical energy of the fuel.

The energy cell combustion chamber engine was selected as representing a relatively easy means of locating suitable conditions to produce such a process. The so-called primary part of the fuel injection was supplied into the energy cell at relatively low pressure to form a locally rich mixture of fuel and air. Since the cell is at a temperature, on the average, corresponding to the cool flame range and is also filled with hot exhaust gas, the conditions for the formation of the required radicals seem to be met.

The effect of such primary injection, with a resultant reduction in ignition lags should be evident in an earlier and more rapid rise of the pressure in the main chamber together with a shorter period of flame in the engine cylinder; if this is achieved it should enable a considerable rise in the engine speed without loss of mean pressure producing a significant decrease in the specific weight of the engine with little if any change in specific fuel consumption.

EXPERIMENTAL APPARATUS

A vertical single-cylinder, four-stroke cycle, liquid cooled Nordberg Diesel engine was used in the experimental work. The engine had 4-1/2 inches bore, 5-1/4 inches stroke and a compression ratio of 14-1/2:1. For the purpose of the tests the engine was equipped with a second injection valve and pump as the simplest method of achieving the range of primary injection. A quartz window and photoelectric cell was used to detect the beginning of flame, together with its period and intensity, inside the cylinder. The flame intensity, the time of opening the primary injection valve, together with the pressure time diagram inside the cylinder were recorded by the aid of a dual beam oscilloscope. Figures 1 to 6 show the components of the apparatus. Complete description of the apparatus is given in reference 1.

EXPERIMENTAL RESULTS

Tests were carried out on the engine in its normal condition, as supplied by the manufacturer, and all data regarding combustion,

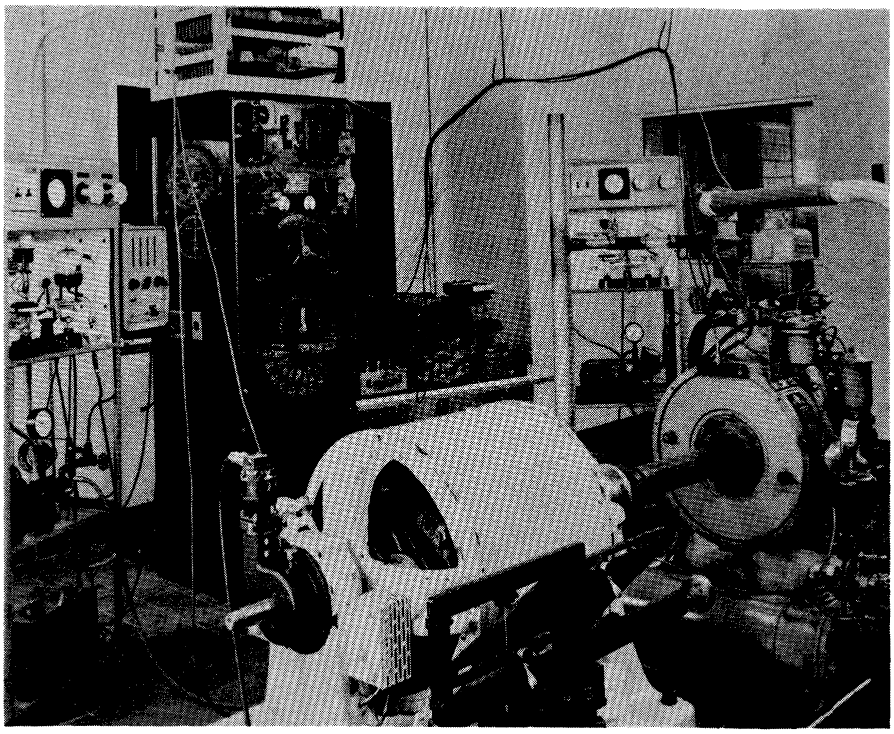

Figure 1. General Layout of the Experimental Setup.

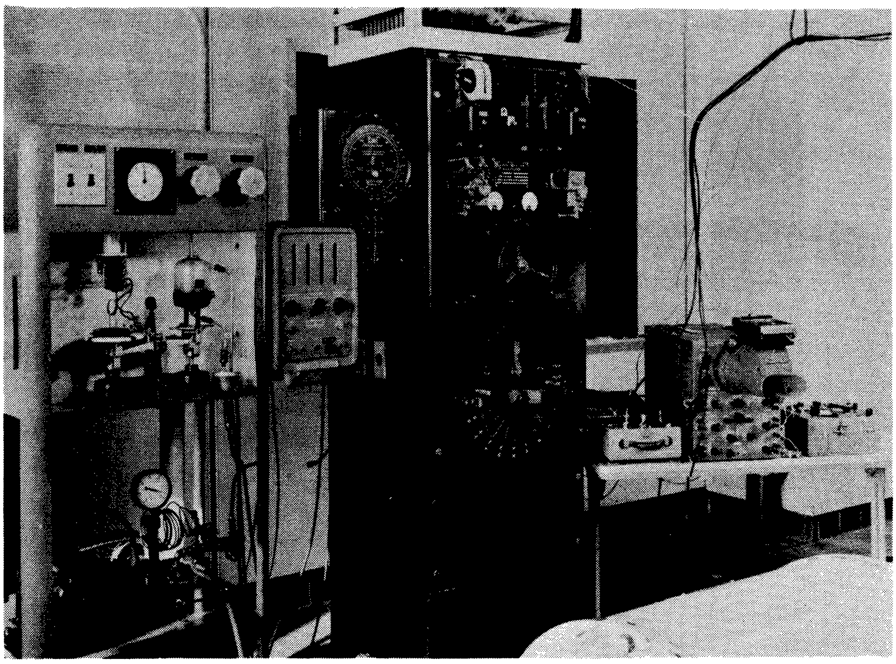

Figure 2. Fuel Weighing System, Control Panel, Amplifier and Oscilloscope, and Potentiometer.

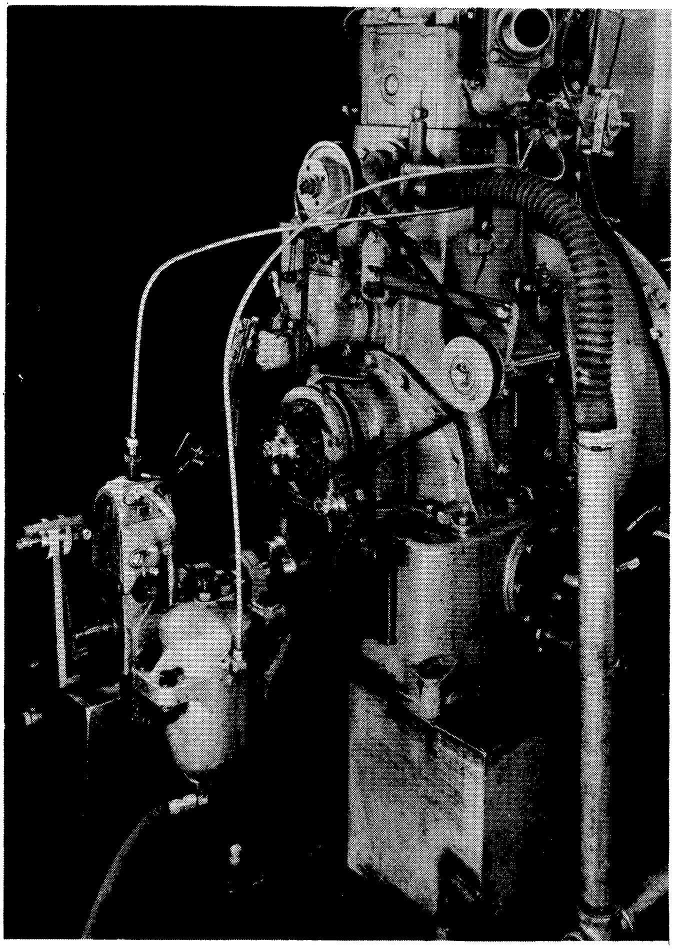

Figure 3. The Primary Fuel Injection Pump, its Drive and Control.

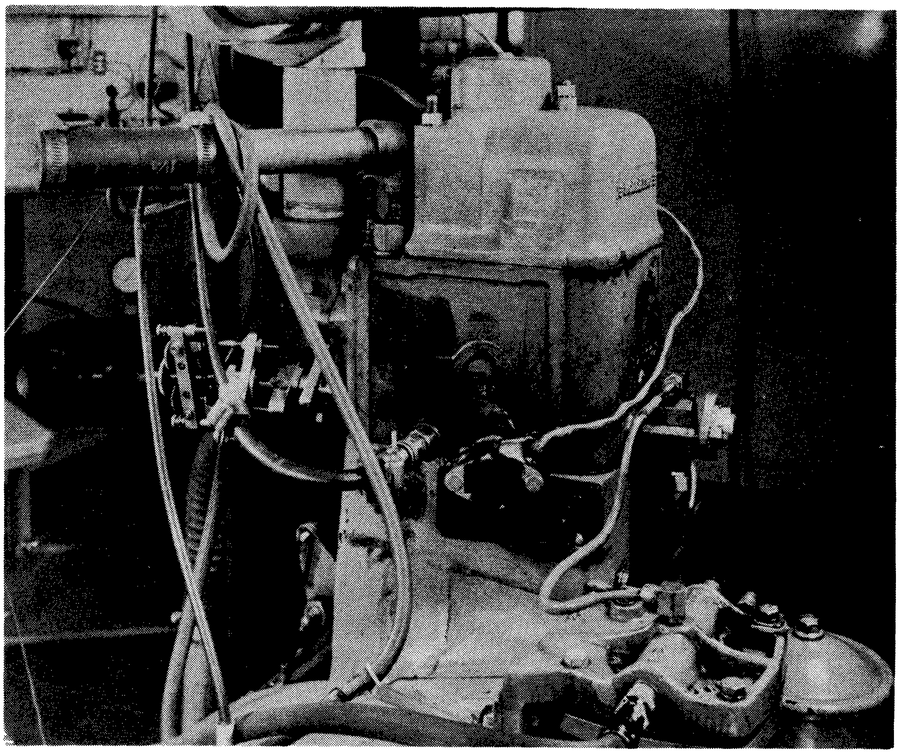

Figure 4. Cylinder Head View, Showing the Two Injection Valves, Pressure Pick-up and Photoelectric Cell.

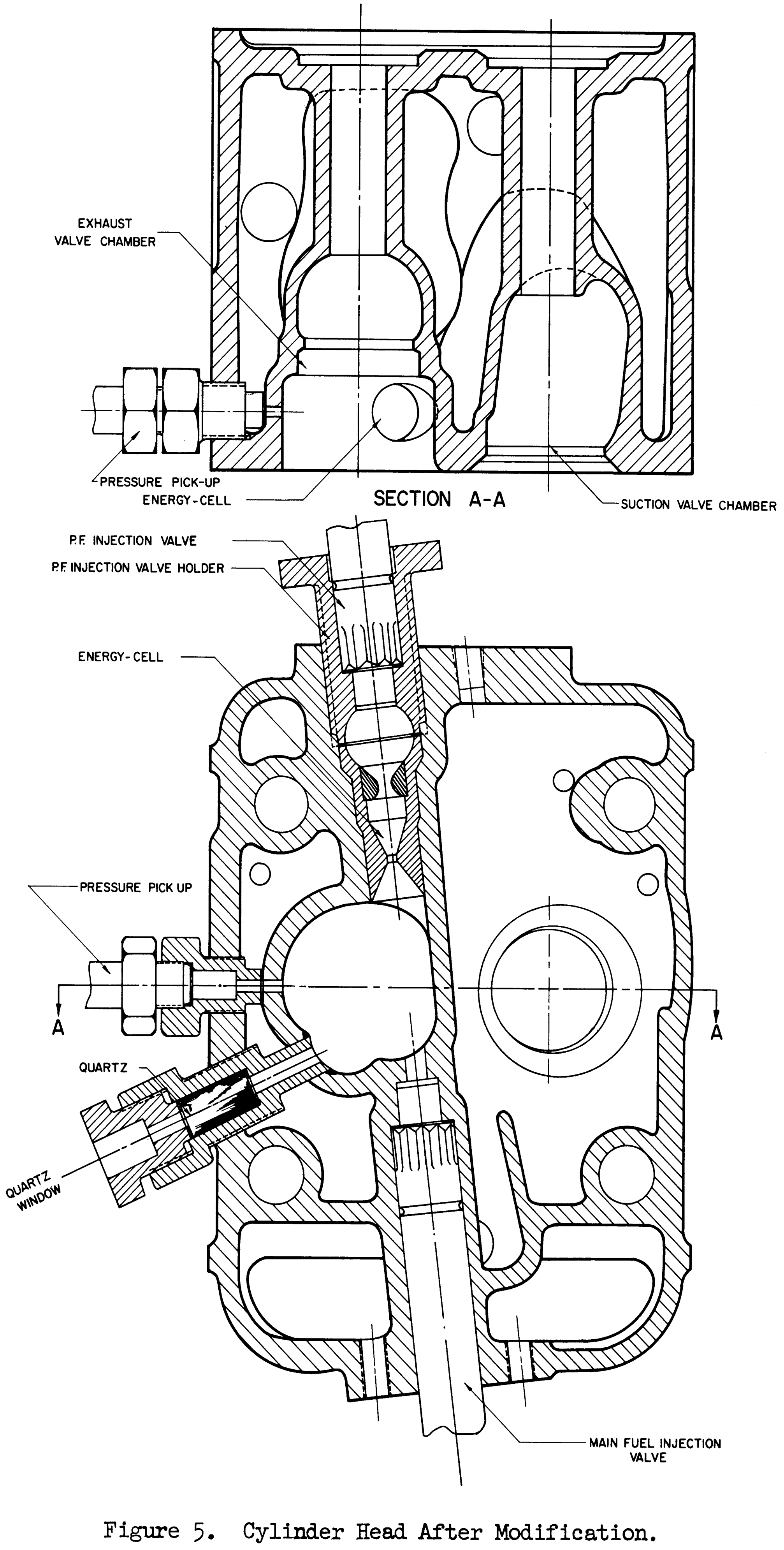

Figure 5. Cylinder Head After Modification.

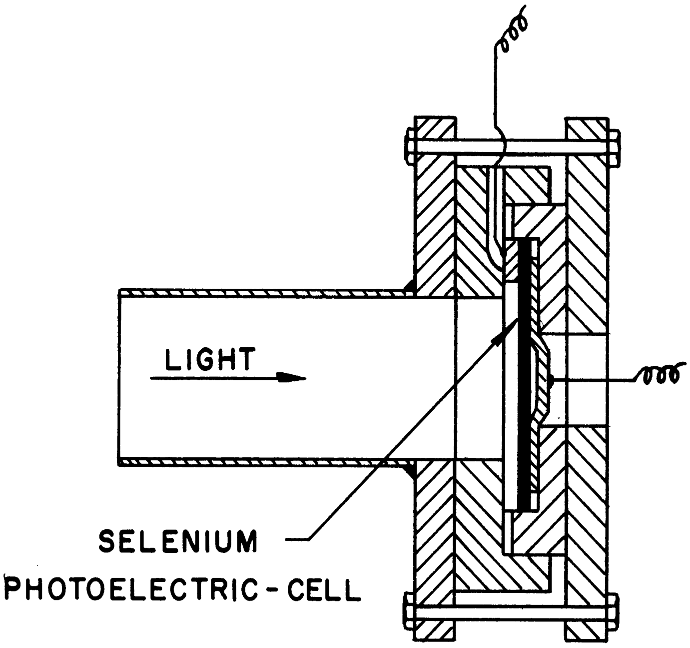

Figure 6. Photoelectric Cell Mounting.

pressure rise, ignition lag, etc., secured over a range of loads at a constant speed of 1600 rpm. These results are shown and referred to in various diagrams throughout the report and forms a basis for comparison of the subsequent tests where early peroxide accumulation was obtained.

The tests carried out with primary fuel injection included investigation of the following points:

(a) Variable timing of injection of the primary fuel.

(b) Effect of primary fuel injection value pressure setting.

(c) Variation of cooling water temperature.

(d) Variable engine speed.

(e) Effect of main fuel injection timing.

(f) Effect of Cumene Hydroperoxide addition.

(a) Variable Timing of Injection of the Primary Fuel

The primary fuel could be adjusted to inject into the energy-cell at any desired point of the cycle, with this as the variable, tests were run at a constant speed of 1600 rpm for a constant output of 54.3 lbs/in.^{2} B.M.E.P. while the primary fuel was varied from 0 to about 60% of the total fuel required. Some of the results are shown in Figure 7, where curves are plotted for this injection process occurring at 60% and 5° B.T.C. on the exhaust stroke and 45° B.T.C. on the compression stroke. Intermediate timings were tested and recorded, however the results in Figure 7 show the general trend.

It is seen that with the primary fuel injected at 5° B.T.C. of the exhaust stroke maximum economy was secured together with reduced ignition lag, the performance fell off on each side of this timing.

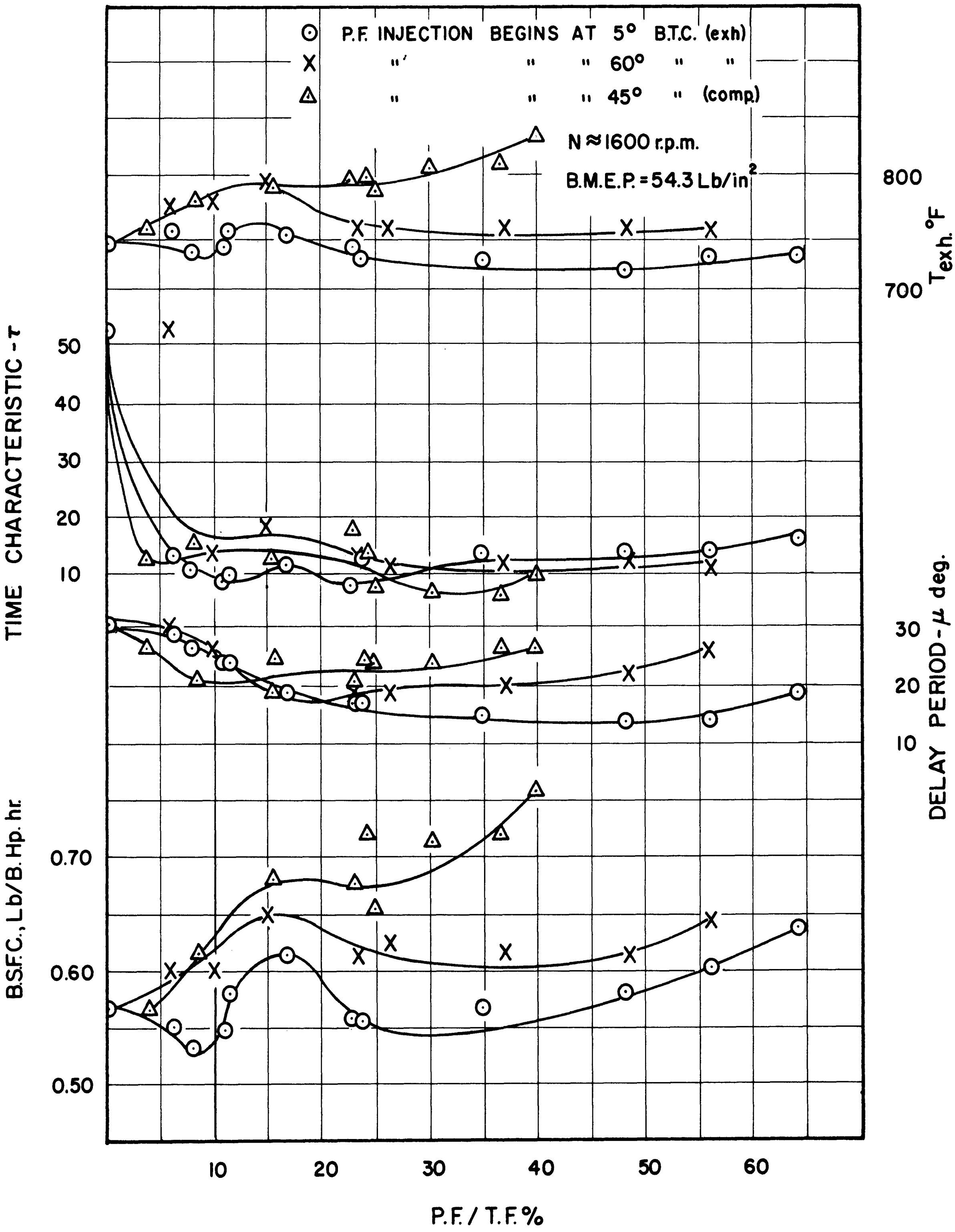

Figure 7. Effect of P.F. Injection Timing Upon Engine Performance. (Series II).

Operation at variable B.M.E.P. at 1600 rpm employing optimum primary fuel injection timing and quantity results in Figure 8.

Consideration of these diagrams indicates that, for the 5° injection curve, a decrease in S.F.C. for a given output occurs until a minimum value is reached at the ratio of primary to total fuel of about 9 to 10%; further increase beyond this ratio results in an increasing S.F.C. It should be emphasized that the points plotted are the average of a number of tests and the general shape of the curves were reproducible to quite a high degree. In addition under optimum conditions the maximum power output without smoke was increased, accompanied with a reduction in S.F.C.; up to as much as 17.8% power increase with a 12% reduction in S.F.C. Under the most favorable overall conditions these values were about 12% and 8% respectively.

The manner in which the cylinder pressure-time diagram was affected by change in the primary fuel quantity is shown in Figure 9 for P.F. injection 60° B.T.C. of the exhaust stroke together with the flame intensity records, time progresses from right to left.

It is seen that the combustion is accelerated to a fairly large extent by the action of the primary fuel, but despite this acceleration in rate of combustion the engine remained smooth as far as combustion was concerned until rather large quantities of primary fuel were employed.

In Figure 9a the two diagrams show the process in the engine cylinder. The upper diagram gives the conditions without primary fuel while the lower one is a magnification of the same process near T.D.C.

Figure 9b shows the effect of adding a small percentage (6.22%) of primary fuel early in the exhaust stroke to the energy cell, the total

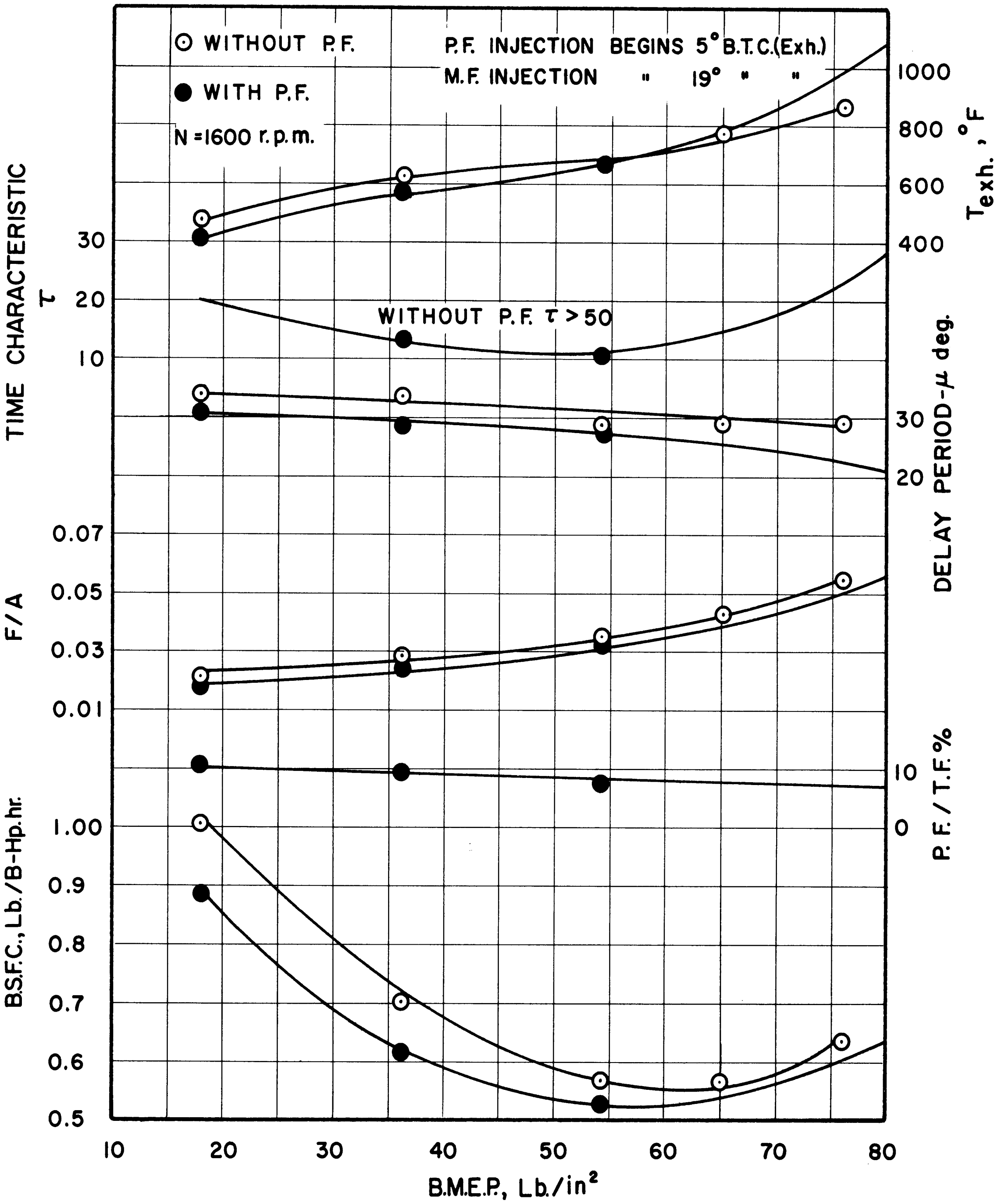

Figure 8. Effect of Primary Fuel Injection Upon Optimum Engine Performance. (Series VI).

fuel supply being maintained at that sufficient for the same B.M.E.P. as in Figure 9a. The change in the combustion process is apparent.

The effect of primary fuel on the period of flame in the cylinder is also quite remarkable; this is shown by the small pip in the lower trace of the oscilloscope, both the intensity and duration of flame is affected, this is also a factor of the improved and accelerated combustion, resulting in a reduction of smoke which normally would become incandescent producing much of the flame intensity near T.D.C. Thus these diagrams check the observed conditions of improved S.F.C., power output, and reduced smoke.

With an addition of 9.62% of primary fuel (approximately the optimum) the combustion processes are shown in Figure 9c and it is observed that the luminous flame is still further reduced.

Diagrams with large percentages of primary fuel become as shown in Figure 9d; under these conditions the combustion was getting somewhat rough again.

Other diagrams (Figure 13) record some results at the 5° B.T.C. position.

(b) Primary Fuel Injection Pressure

The effect of the setting of the valve opening pressure for the primary injection was investigated and its value varied from 600 to 1400 p.s.i. The results being shown in Figure 10. It can be observed that minimum fuel consumption was achieved with an injection valve opening pressure of 800 p.s.i. while minimum delay occurred with the valve set at 1000 p.s.i.

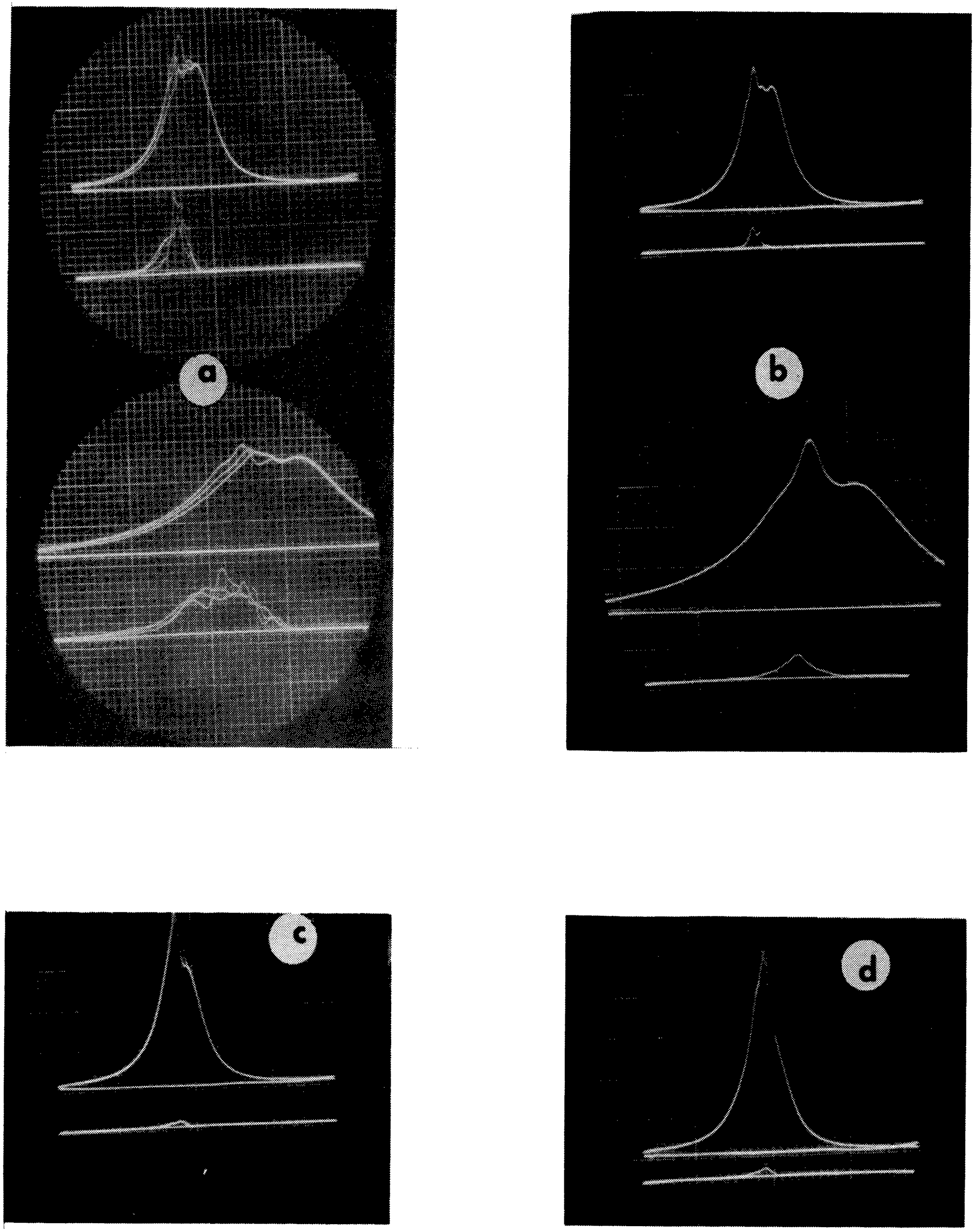

Figure 9. Pictorial Traces of Pressure-Time Diagrams at Various P.F./T.F.% (Series II).

P.F. Injection Begins 60° B.T.C. [exhaust]

	Run No.	P.F./T.F.%		Run No.	P.F./T.F.%
a	1	0	f	184	26.2
b	180	6.22	g	185	36.8
c	181	9.62	h	186	48.5
d	182	14.92	i	187	56
e	183	23.2	j	188	

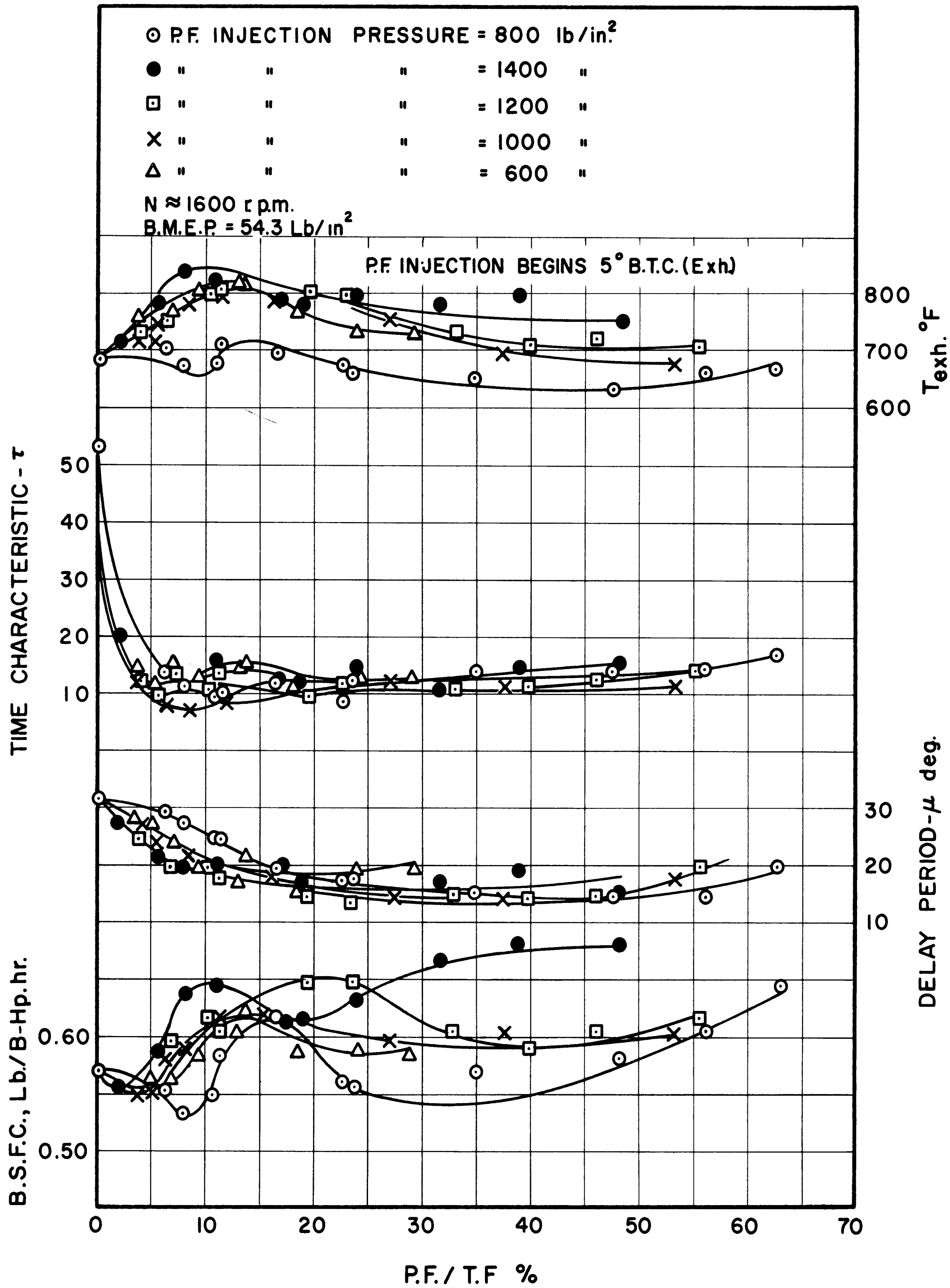

Figure 10. Effect of P.F. Injection Pressure Upon Engine Performance. (Series III).

(c) Cooling Water Temperature

It is well known that engine temperature has some effect on ignition lag and tests were run to record this for the particular conditions of these tests. The engine was operated at a constant speed of 1600 r.p.m. with a constant ratio of primary to total fuel of 5% approximately, at a constant mean pressure of 54.5 p.s.i.; the primary fuel being added at 5° B.T.C. of the exhaust stroke. The results are shown in Figure 11 where increasing jacket temperature is associated with a decreasing ignition lag, from 34° to 22°, while the fuel consumption at first reduces by about 3% and then increases. These effects are rather minor but indicate the possibilities of improved operation with speed increase.

(d) Engine Speed

Perhaps the most interesting results are presented in Figure 13 where the delay period in milliseconds is recorded for all speeds from 900 to 2000 r.p.m.; corresponding pressure time diagrams with and without primary fuel are given in Figure 13. These results are for the case when the primary fuel is constant at 15.8% of the total fuel (approximately minimum lag).

Comparison of the diagrams show the increased rate of pressure rise accompanying the addition of primary fuel but in all cases this rise was at a sufficient low rate that the combustion was smooth and quiet.

It is of interest to observe the more or less constant time reduction in the lag between conditions with and without primary injection from 1.0 milliseconds at 900 r.p.m. to 1.2 at 2000 r.p.m. that is the preflame reactions appeared to reduce the ignition lag by a more or

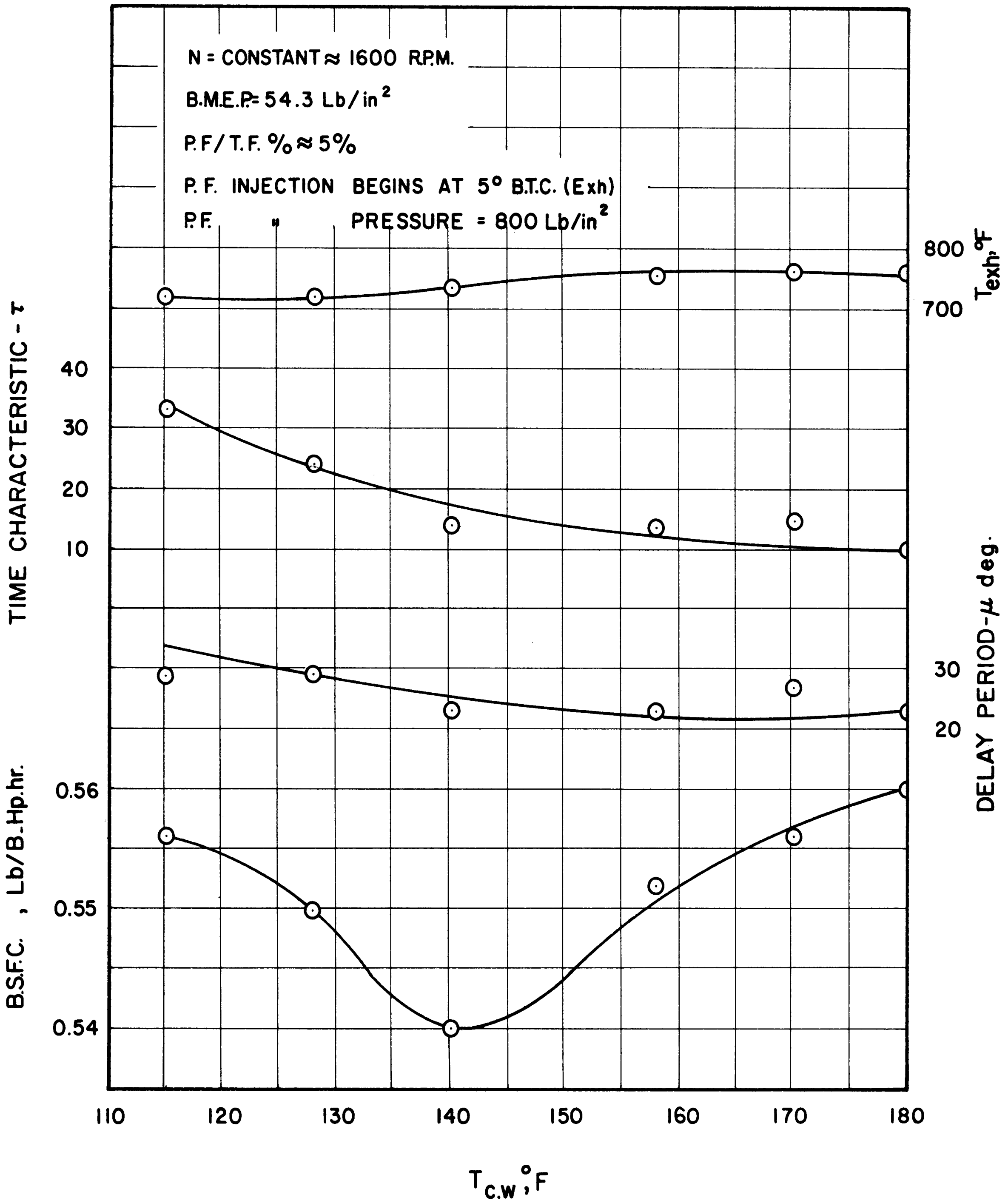

Figure 11. Effect of Cooling Water Temperature Upon Engine Performance. (Series IV).

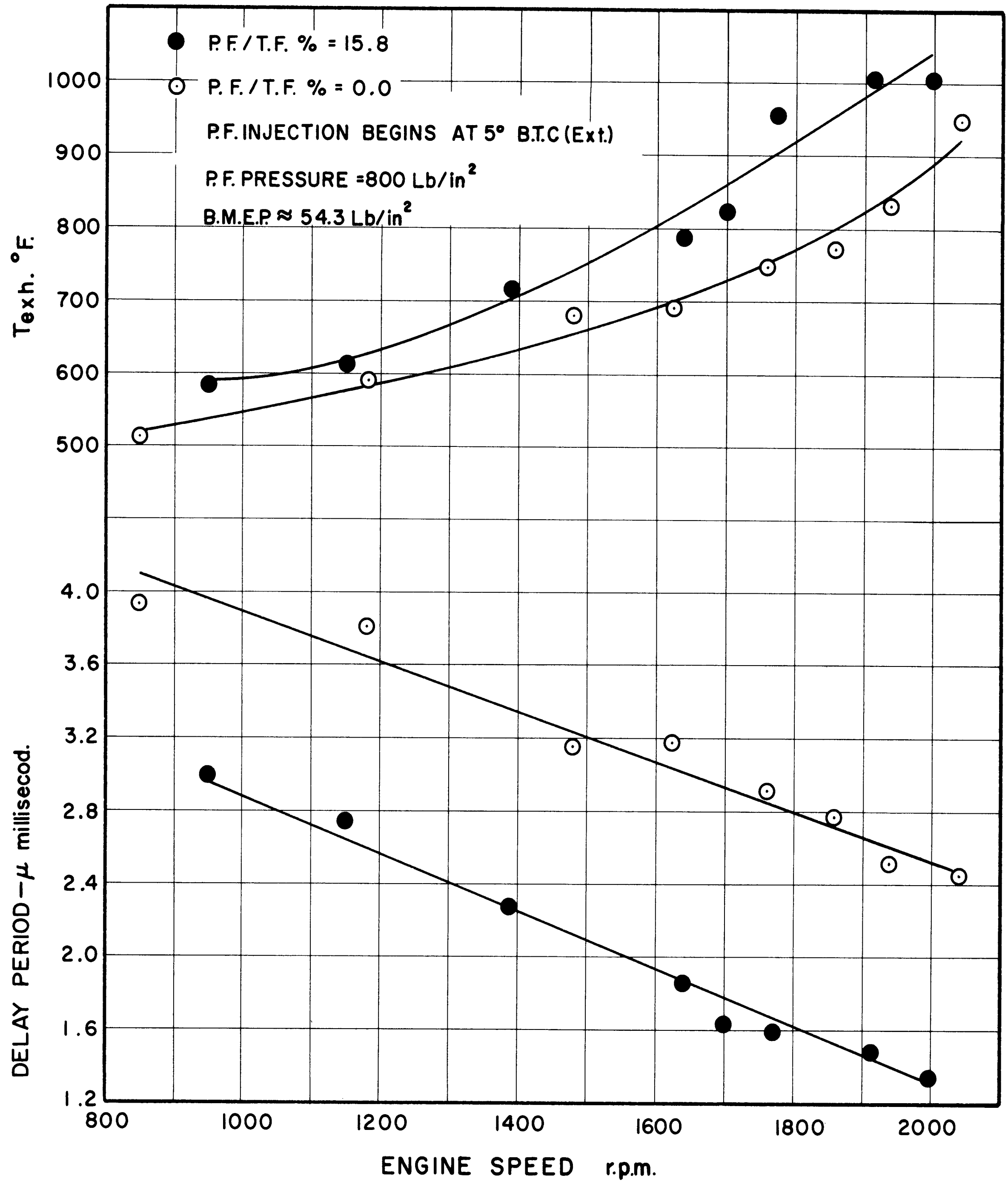

Figure 12. Effect of Engine Speed Upon Delay Period and Exhaust Gas Temperature. (Series V).

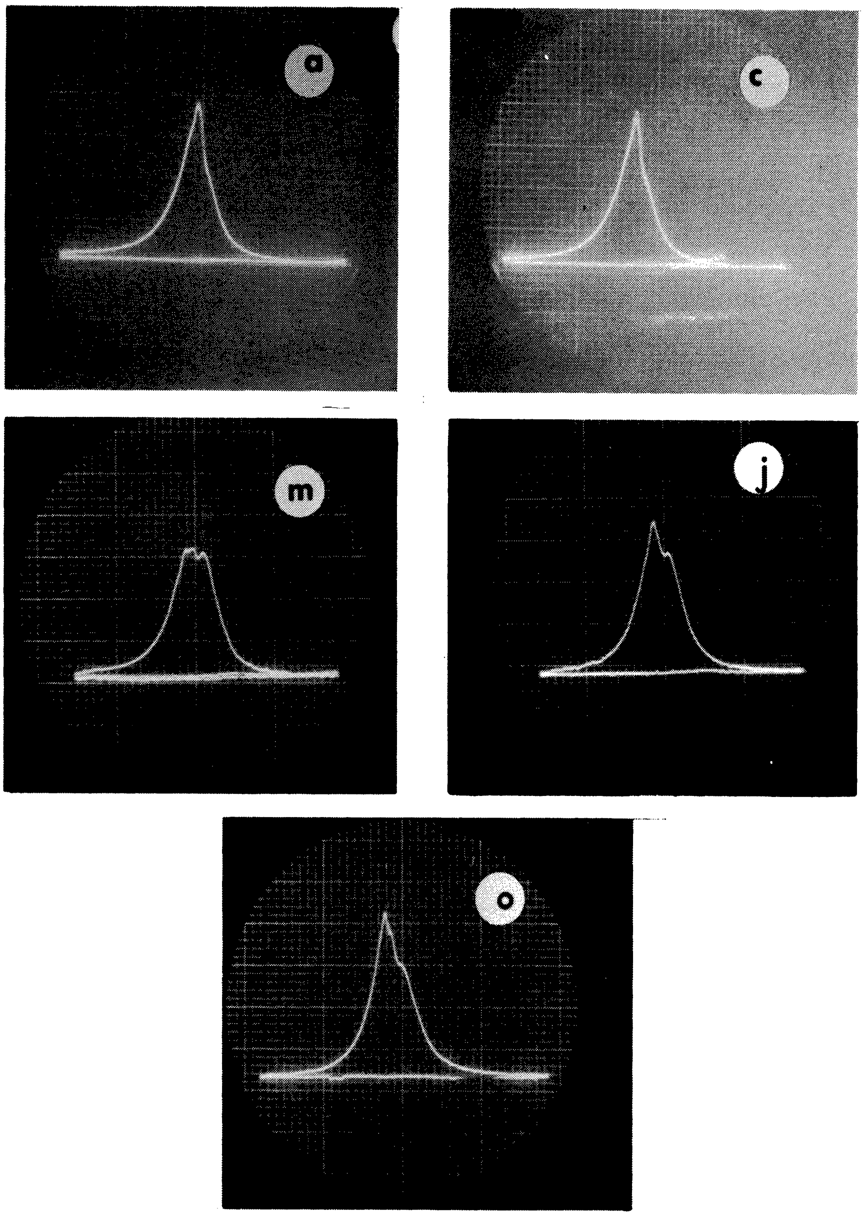

Figure 13. Pictorial Traces of Pressure-Time Diagrams at Variable Engine Speed. (Series V).

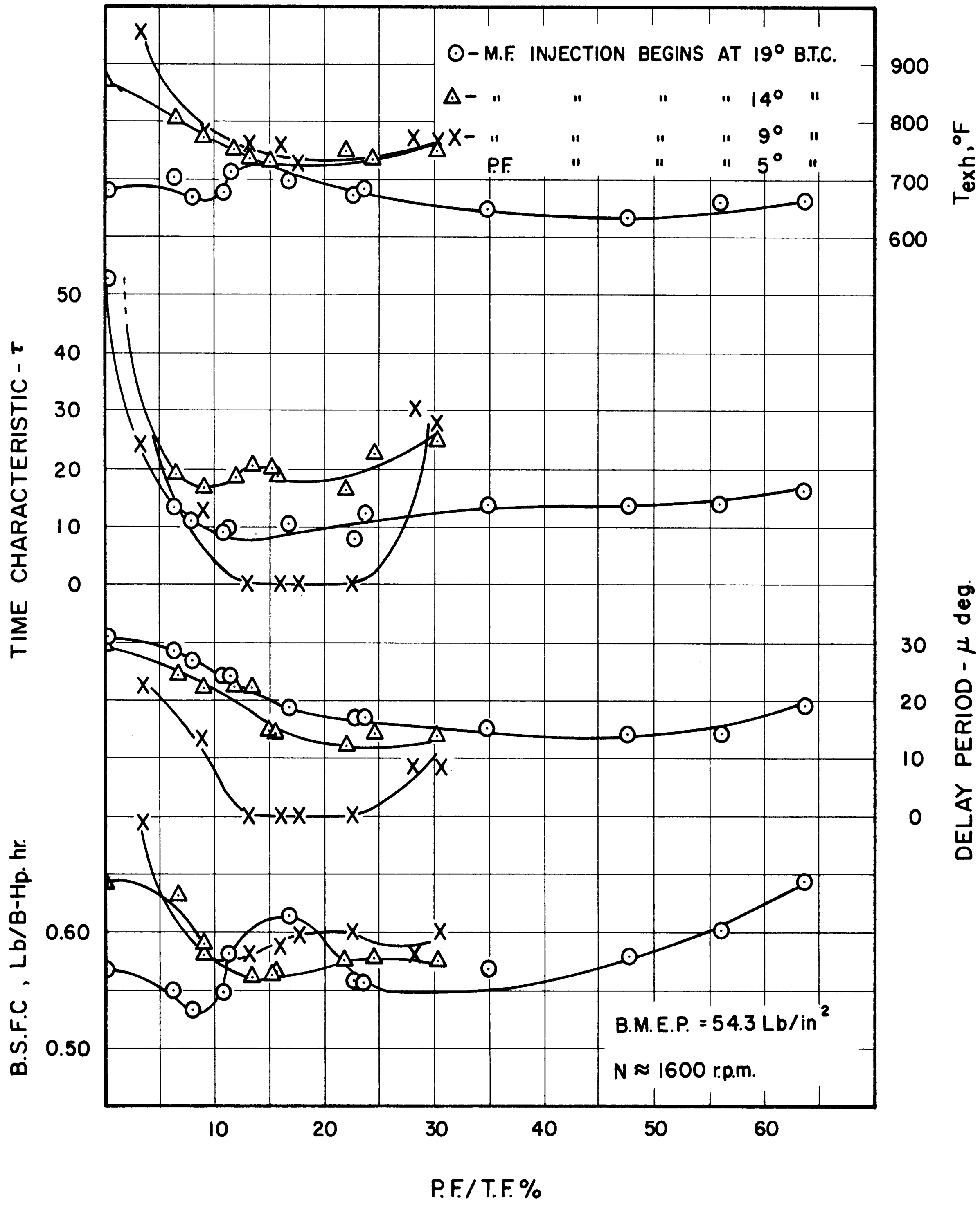

Figure 14. Effect of Main Fuel Injection Timing Upon Engine Performance. (Series VI).

less constant time irrespective of the engine speed. The total lag in this case decreased approximately linearly with engine speed mainly resulting from the increased temperature at the end of compression as the speed increases. Of course the crank angle change in the lag increases directly with the engine speed, primary fuel injection approximately reducing the delay from 23° without, to 16° with, primary injection at 1600 r.p.m. while at 2000 r.p.m. the change is from 31° to 15° of crank angle, a 2:1 ratio. The 15.8% of primary fuel in these tests was the quantity giving the maximum reduction in the ignition lag.

(e) Main Fuel Injection Timing

The engine was not fitted with an injection timing device thus changes of main fuel timing could only be made by change of clearance between the fuel pump tappet and cam, which of course would also change plunger velocity at injection to a small extent; thus these tests are, perhaps, not too representative since a retardation of the injection was the only possible change that could be made.

As would be expected the performance fell off rapidly when no primary fuel was added as the injection was retarded, and the normal full load of the engine could not be carried. The addition of primary fuel, even in the retarded condition restored power and S.F.C. to normal, while at the manufacturer's recommended timing of the injection, additional power with a reduced S.F.C. was possible. Figure 15e shows the pressure-time diagram for maximum load giving minimum S.F.C. with a primary injection of 7.6%. The absence of uncontrolled combustion should be noted even under these overload conditions.

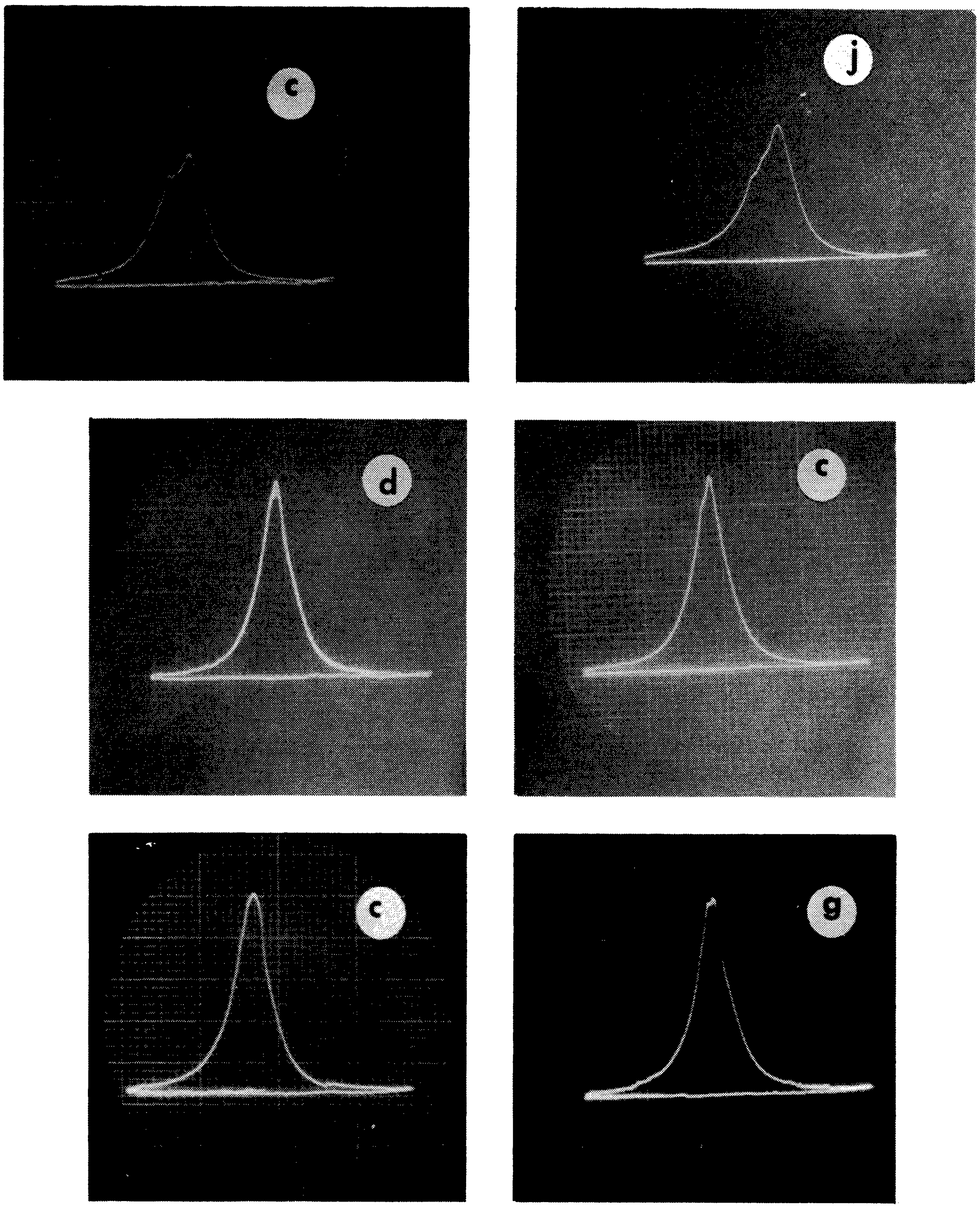

Figure 15. Effect of Main Fuel Injection Timing.

(f) Addition of Cumene Hydroperoxide

The engine was in general operated on a normal high speed diesel fuel; and, as a comparison with the effects of primary fuel on the combustion process, a good chain initiator, cumene hydroperoxide, was added to the fuel, both primary and main, in stages so that the individual effect could be seen. The results are shown in Figure 16 where diagrams a and e both represent normal engine operation without primary injection but in the case (e) the additive has been added to the fuel and its effect on accelerating the combustion is apparent. Comparing diagram (b), no additive in either source of fuel but 13% primary injection, indicates a greater acceleration of the combustion process than the addition of cumene hydroperoxide to the fuel.

In case (c) the additive has been added to the primary fuel only, while (d) has the additive in all the fuel. Comparison of (c) and (f) shows the results with additive in the main fuel only, the 12% of primary fuel being untreated.

DISCUSSION

It will be observed that, as the P.F./T.F. % increases, the B.S.F.C. decreases which can be attributed to the fact that the rate of formation of the active intermediate products are functions of the fuel concentration in the cell (eq. 4-11 of Ref. 1). The higher the concentration of the radicals, the shorter the delay and the higher the rate of energy released from the fuel, resulting in higher pressure and temperature rise, i.e., higher availability for useful work.

Increasing the P.F./T.F. beyond that corresponding to the most economical ratio results in both the B.S.F.C. and eventually the lag increasing due to the following possibilities:

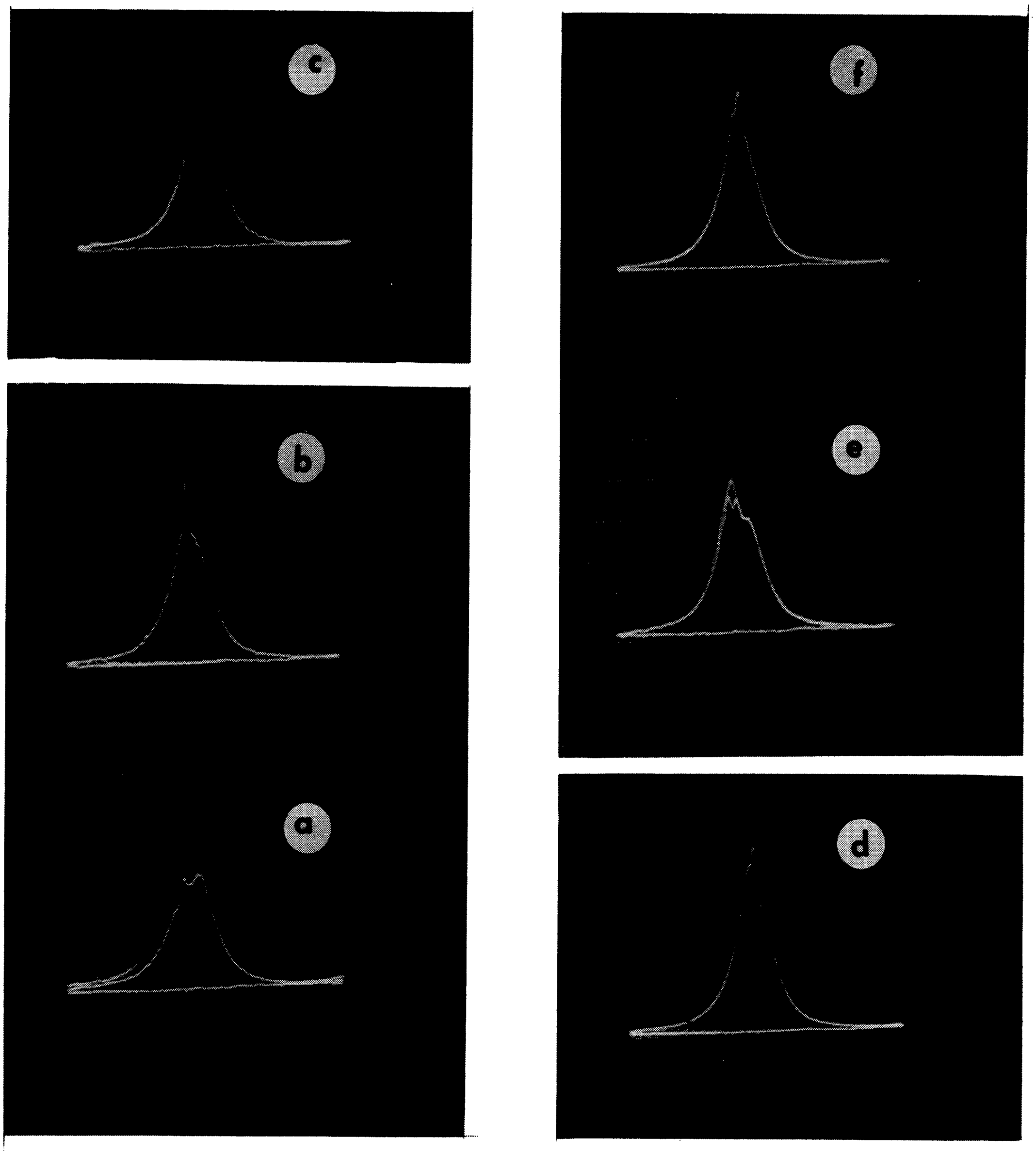

Figure 16. Pictorial Traces of Pressure-Time Diagrams, Additive Effect. (Series VII).

M.F. Injection Begins 19° B.T.C.
P.F. Injection Begins 5° B.T.C.
B.M.E.P. = 54.3 lb/in^2

	Run No.	P.F./T.F.%	Additive P.F.	Additive M.F.
a	445	0	-	No
b	446	13.1	No	No
c	447	12.7	Yes	No
d	448	13.2	Yes	Yes
e	449	0	-	Yes
f	450	12.1	No	Yes

1. The delay period continues to decrease for some time and the combustion rate increases resulting in an increase in the negative work on the piston during the compression stroke. Adjustment of injection timing was not possible since the engine was fitted with a fixed timing injection pump.
2. Some of the primary fuel could burn in the energy cell early in the cycle at a low level of availability.
3. The temperature of the energy cell increases into the range where a negative coefficient exists and/or part of the P.F. is subject to chain breaking due to the increasing effect of the wall surface as the quantity goes up. Both reasons will retard the combustion and this is shown in the humped part of the τ curves.
4. Considerable increase in P.F./T.F. may decrease the temperature of the energy cell due to the latent heat of evaporation absorbed by the larger quantity of fuel, thus slowing of the radical formation and increasing the lag.

When the P.F. is injected too early in the exhaust stroke there is the possibility that part of it will escape with the exhaust gas showing up as an increase in B.S.F.C. On the other hand late injection into the cell during the compression stroke with the relatively short time between the P.F. addition and the main fuel injection gives insufficient period for the production of the necessary concentration of radicals again resulting in an increase in B.S.F.C. The injection of P.F. during the exhaust stroke when active molecules still exist reduces the lag, improves the combustion and engine performance since the active products from the previous cycle may assist as reacting centers, to start the chain reactions.

With regard to injection pressure the effect of the higher P.F. injection pressure is the result of better atomization producing a larger surface volume ratio of the droplets. Increasing the surface area will tend to increase the formation of radicals, on the other hand the increased ratio will result in an increase of evaporation with more termination of radicals at the chamber surface. Moreover the high pressure will increase the penetration with the possibility of the diffusion of some part of the P.F. to the relatively cold main chamber.

At low pressures the opposite is true and the reaction rate will be slower.

Between the two limits there appears to be a limiting value of the atomization for best economy and another value for shorter delay.

The variable speed test showed that the reduction in the delay in milliseconds due to the increased temperatures and swirl resulting from speed is almost the same (Figure 12) with and without P.F. injection. But the delay in milliseconds or crank angles is much shorter with the use of P.F. injection. The fact that the combustion, with P.F., is approaching the constant volume process at 2000 r.p.m. while it is almost a constant pressure one without P.F. at the same load and speed, indicates the possibility of raising the engine speed to a much higher value than its designed speed with but little change in performance. It was not able to demonstrate this completely because, of safety considerations, the engine speed was not carried beyond 2000 r.p.m. since its maximum design speed was 1800 r.p.m. However, it can be stated that, despite no change in fuel nozzle, injection pump characteristics etc., excellent combustion characteristics were secured at the higher speeds with a gain in both maximum economy and output.

Figures 17, 18 and 19 show the relative changes of pressure-time, pressure-volume, and log pressure-log volume diagrams, with and without primary fuel superpositioned for comparison. The three cycles illustrated are at the same load and speed, Run No. 3 being the original engine, No. 190 with P.F., giving minimum S.F.C. and No. 102 minimum delay approximately.

CONCLUSIONS

It is concluded that one means of control of the combustion process permitting considerable increase in the engine speed was established. At the same time improved specific power output and efficiency of air utilization was demonstrated in the higher overload without increase of smoke accompanied by a decrease in the B.S.F.C. over most of the load range of the engine.

It is believed that the correlations which were derived from this type of combustion chamber may be applied to other types, particularly of the pre- and ante-combustion type.

The test results showed that the combustion lag does depend to a definite degree upon the pre-combustion reactions and that acceleration of both the lag and combustion can be effected by encouraging such pre-reactions to occur early in the cycle. Such increase in the speed of reaction can be utilized in an increase of engine speed without reduction of mean pressure in order to improve the specific outputs of the compression ignition engine.

A moderate increase in the rate of combustion could be tolerated in the engine under test without inducing rough combustion and noise, in fact somewhat quieter operation existed with small amounts of primary injection accompanied with improved power and efficiency.

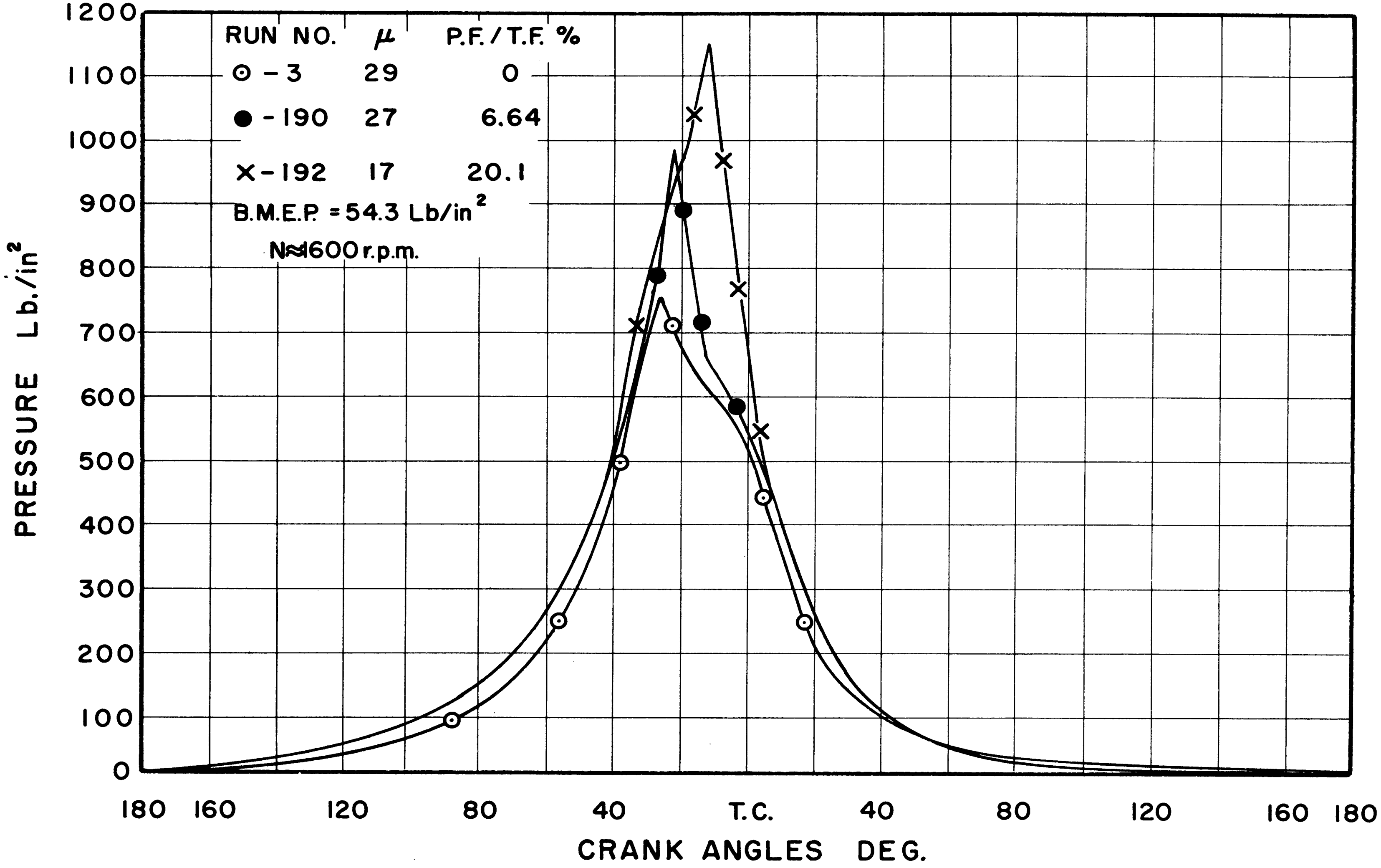

Figure 17. Pressure-Time Diagrams.

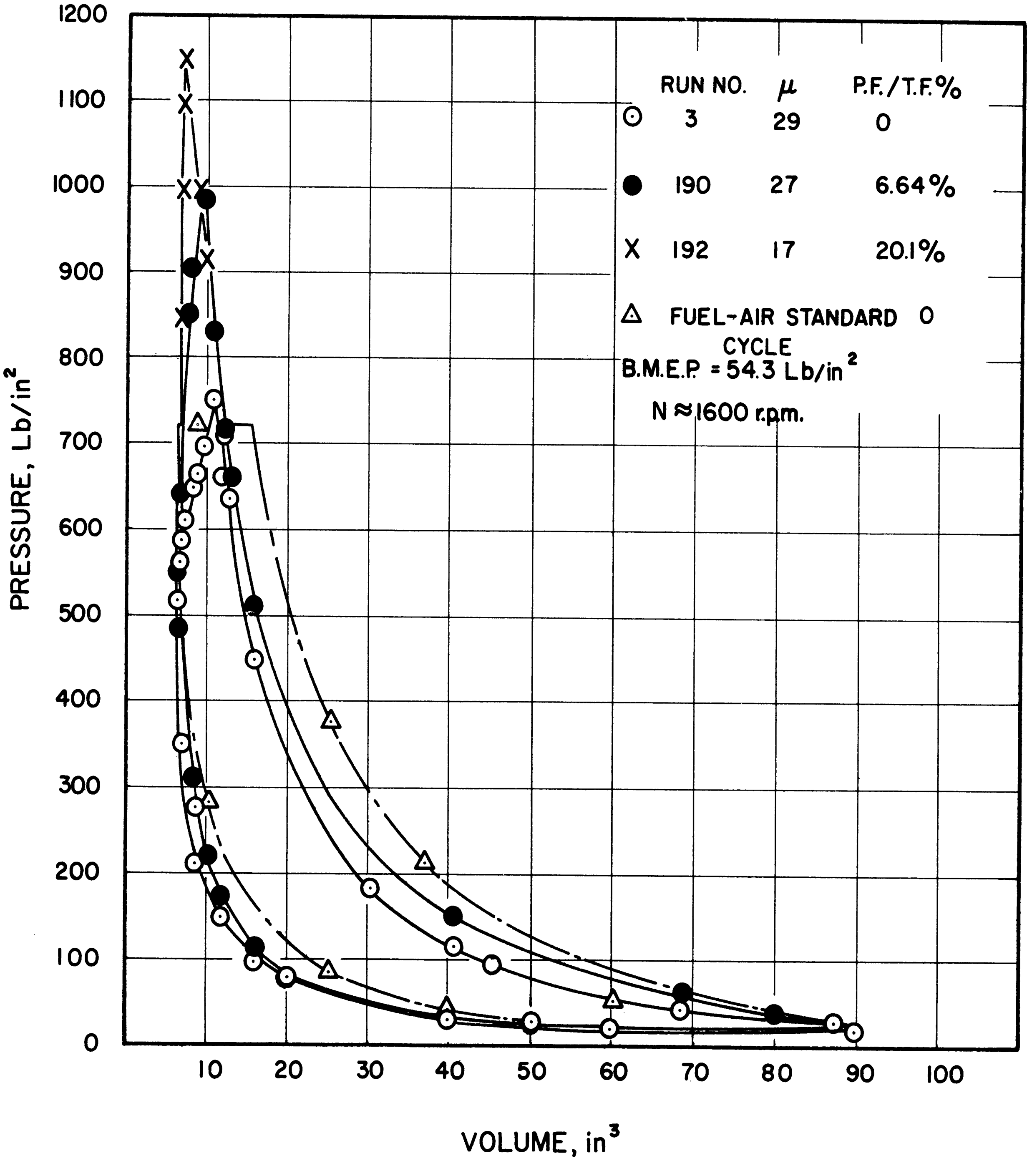

Figure 18. Pressure-Volume Diagrams.

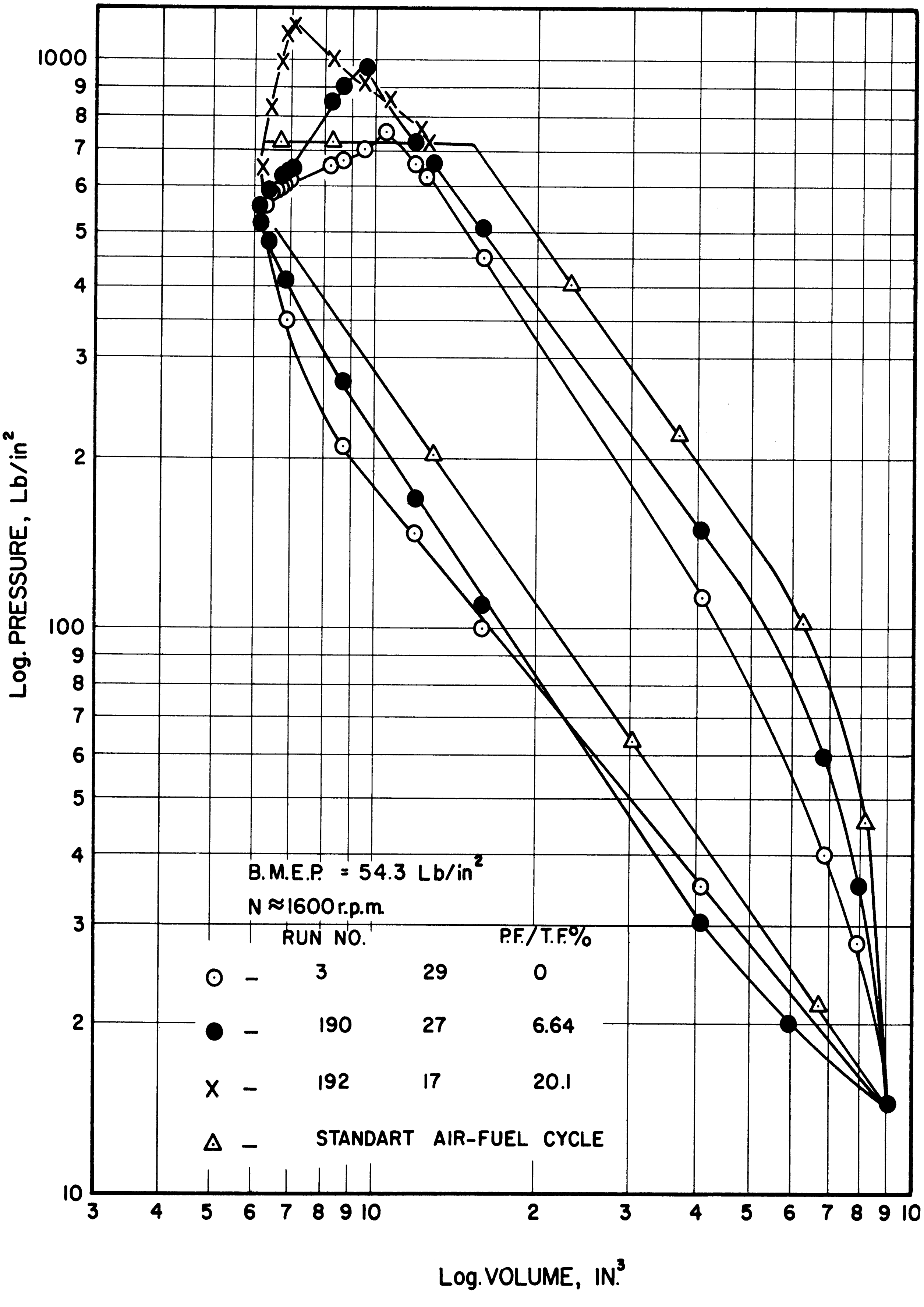

Figure 19. Log. Pressure-Log. Volume Diagrams.

REFERENCES

1. Ibrahim, Abdel R. "Control of the Combustion of Compression Ignition Engines", University of Michigan I.P. 436, 1960.

2. Rathrock, A. M. and Waldron, C. P. "Effects of Air-Fuel Ratio on Fuel Spray and Flame Formation in a Compression-Ignition Engine." NACA Report No. 545, 1935.

3. Schmidt, F.A.F. Verbrennungsmotoren, Springer, Berlin, 1945.

4. Lewis, B. and Von Elbe, G. Combustion Flames and Explosions of Gases. New York: Academic Press, 1951.