PROGRESS REPORT NO. 6

DIESEL ENGINE IGNITION AND COMBUSTION

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TABLE OF CONTENTS

I. BACKGROUND

A program to study the combustion process in supercharged diesel engines has been developed at The University of Michigan. This program is primarily concerned with the ignition delay and the effect of the different parameters on it. A special concern is given to the effect of pressure, temperature, and density on the ignition delay.

The different types of delay have been studied and an emphasis is made on the pressure rise delay and illumination delay. The instruments needed for the measurement of these two delay periods have been developed and a continuous effort is being made to improve their accuracy.

This research is being made on two experimental engines. One is the ATAC high output open combustion chamber engine, and the other is a Lister Blackstone swirl combustion chamber engine.

II. OBJECTIVES

A. To study how gas pressure at the time of injection affects ignition delay and combustion. The effects will be studied at pressures ranging from approximately 300 to 1000 psia.

B. To study how gas temperature at the time of injection affects ignition delay. The temperatures will range from approximately 900°F to 1500°F.

C. To study various combinations of pressures and temperature to determine whether density is an independent variable affecting ignition delay.

D. To conduct all these studies with three fuels: CITE refree grade (Mil-F-45121) fuel, diesel no. 2 fuel, and Mil-G-3056 refree grade gasoline.

III. CUMULATIVE PROGRESS

A. Lister Engine

This engine has been set on a test stand, connected to a dynamometer, and completely instrumented to measure power, rates of flow of air, fuel, and coolant, and temperatures at different points in the engine. Traces can be obtained for cylinder pressure, fuel pressure, needle lift, illumination, surface temperature, and crank angles. Shop air is used to supercharge the engine, and a surge tank is placed between the airflow meter and the engine.

The original combustion chamber of this engine has been modified so that compression ratios can be adjusted from 14:1 to 22:1. A quartz window with a diameter equal to that of the swirl chamber has been manufactured to fit into the modified combustion chamber, for more accurate observation of illumination delay.

Four series of tests have been made to investigate the effect of factors other than pressure, temperature, and density on ignition delay. The purpose is to eliminate their effects on measurements of delay periods, or at least to have them under control. These factors are fuel-air ratio, fuel injection pressure, engine speed, and cooling-water temperature. The results of these series having shown that these factors affect the delay period significantly, it has been decided to keep them constant during the runs made to investigate the effect of pressure and temperature.

B. ATAC Engine

The instrumentation of this engine has been completed. The engine has been connected to an electric dynamometer. It is supercharged with shop air that has been passed through a surge tank fitted just before the engine. Another surge tank is fitted on the exhaust side. The pressures in the two tanks can be regulated to the required valves.

A Kistler pressure transducer is fitted in the hole furnished by the International Harvester Company. Two more holes were drilled in the cylinder head above the piston cavity. One hole is fitted with a quartz window, and the other is to be fitted with a surface thermocouple.

The top dead center of the engine determined by the dial gage method, was found to be 1/2 crank degree past the top dead center mark engraved on the flywheel.

The degree marks are produced by a steel disc 18 inches in diameter and 1/8 inch thick, mounted on the coupling between the crankshaft and the dynamometer. Holes 1/16 inch in diameter are drilled around the periphery at 3° intervals, and larger holes, 1/8 inch in diameter, at 45° intervals. A magnetic pickup has been used to produce corresponding pips on the oscilloscope screen every 3°, with bigger pips every 45°. One of the bigger holes is aligned at top dead center.

The temperature of the inside surface of the combustion chamber is to be measured by a surface thermocouple placed between the inlet and exhaust valves.

The fuel-injection system is instrumented so that the start and rate of injection can be calculated from measurements of the needle lift and fuel pressure before the nozzle. The position of the plunger w.r.t., the barrel, and the injection timing are both controlled by micrometers.

IV. PROGRESS DURING THIS PERIOD

The results obtained from the tests on the Lister engine were analyzed to find a correlation between the cylinder pressure and the pressure rise delay. A computer program was made for this purpose. The best correlation was found to be of the form

$$I.D._p = \frac{C}{P^n} \qquad (a)$$

This form was found to be in agreement with the forms given by previous investigators as shown in the Addendum.

To examine the validity of Eq. (a), the previously published experimental results on bombs and engines were analyzed using the same computer program. It was found that all previous experimental results on ignition delay could be correlated with an equation similar to Eq. (a). However, the values of C and n were found to be different for each set of data. The details of this analysis is given in the Addendum.

A thermodynamic analysis was also made by taking into consideration the different types of energy that affect the pressure rise delay. This analysis indicated that the measured pressure rise delay is partially dependent on several thermodynamic characteristics of the chamber including its volume, rates of heat addition and loss, and any work done during the delay period. A portion of the differences in the ignition delays reported for bombs and engines are due to these factors. The details of this thermodynamic analysis is also given in the Addendum.

V. PROBLEM AREAS AND CORRECTIVE ACTION

One of the Kistler pressure transducers, recently received, has a leakage problem. It was sent back to the Kistler Company for repair or replacement.

VI. FUTURE PLANS

A. Next Period

To investigate the effect of pressure and injection timing on ignition delay in the ATAC engine, for the three test fuels listed in the contract.

B. Overall

1. To investigate the effect of pressure, temperature, and density on ignition delay with the different fuels.

2. To process the experimental data on a digital computer.

3. Report results.

C. Changes from Original

Since turbulence has been found to affect ignition delay significantly, it will be studied along with temperature, pressure, and density.

VII. SIGNIFICANT ACCOMPLISHMENTS

A paper has been prepared and scheduled for presentation at the Annual Meeting of S.A.E. on January 9, 1967. The title of the paper is "Ignition Delay in Diesel Engines" by N. A. Henein and Jay A. Bolt. A complete copy of the paper was sent to ATAC for clearance.

VIII. PROJECT STATUS

Funds and Expiration Date of Contract

Original contract
July 1, 1964, to January 1, 1965.......................... $23,020

Modification No. 1
Extension of contract to March 1, 1965;
no increase in funds................................

Modification No. 4
Extension of contract to June 1, 1965;
no increase in funds................................

Modification No. 7
Extension of contract to February 28, 1966;
addition of $18,000 to contract funds for a total of. $41,020

Modification No. 8
Extension of contract to February 27, 1967;
addition of $37,000 to contract funds for a total of. $78,020
(funds will be exhausted about January 1, 1967)

A continuation contract is being negotiated which will become effective December 1, 1966.

Addendum

IGNITION DELAY IN DIESEL ENGINES

(S.A.E. Paper No. 670007)

by

N. A. Henein
Jay A. Bolt

To be presented at S.A.E. Annual Meeting, January 9, 1967

ABSTRACT

The ignition delay in diesel combustion has been studied in a turbulent chamber engine. The criteria used to define the end of this period are the pressure rise and illumination due to combustion. The pressure rise delay is generally shorter and more reproducible than the illumination delay. The effect of the following factors on the ignition delay were studied: cylinder pressure, fuel/air ratio, fuel injection pressure, cooling water temperature, and engine speed. The data concerning the effect of cylinder pressure on the pressure rise delay period, at constant air temperature, were correlated and compared with previous experimental results.

The analysis indicated that the pressure rise delay is affected by physical and chemical factors as well as thermodynamic parameters that control the several forms of energy during the delay period.

INTRODUCTION

Previous investigators have shown that it is practical to divide the diesel combustion process into stages. The first stage that follows the start of injection, and precedes burning, is called the delay period. The duration of this period greatly affects the intensity of the subsequent burning and the resulting noise and roughness.

During the past fifty years many observations have been made with constant volume bombs, and in engines, to determine the factors which influence this delay period. A survey and correlation of the available past published work was carried out to provide background for our own experimental work.

Many definitions have been used to denote the duration of the delay period, mainly because different phenomena were used to indicate the end of this period. The pressure rise due to combustion, or the illumination from combustion, have most commonly been used to define the end of this period. In some cases the temperature rise due to combustion was considered the end of this period.

The work reported here is the first part of a research project to study the effect of high pressures and temperatures corresponding to very high supercharge conditions on the ignition delay and combustion phenomena in diesel engines. In the course of assembling the instrumentation and developing the necessary test techniques it became more apparent that the influence of other factors should be determined, because they could not be kept entirely constant. These included the fuel/air ratio, the fuel injection pressure, air turbulence, and the cooling water temperature. The effects of these variables, and the effect of air pressure are included in this paper. The work concerning the influence of cylinder air temperature on combustion has not been completed, and will be reported separately in a later paper.

IGNITION DELAY—DEFINITIONS

Numerous definitions for the ignition delay have been used. All are agreed on the definition of ignition delay as the period extending from the beginning of injection to measurable combustion. The problem arises from measuring the point where combustion begins. In the majority of the investigations combustion is considered to begin at the point of a measurable pressure rise due to the release of the energy of combustion. In other work, the point of temperature rise or the point of light emission is used. Definitions that will differentiate between the different delay periods will help to clarify and understand the phenomena. The following definitions are proposed:

1. Physical delay is defined as the period of time required for the physical changes to occur to the fuel from its liquid phase at the injection temperature to the vapor phase at the self-ignition temperature. It can be considered equal to the period of time between the beginning of injection and the beginning of preflame reactions. This period will be referred to as $I.D._{Ph}$.

2. Chemical delay is defined as the period of time elapsed from the end of the physical delay to the beginning of ignition. During this period preflame reactions are considered to occur, and will be referred to as $I.D._{Ch}$.

3. Illumination delay is the time that elapses between the beginning of injection and the start of illumination. This period will be referred to as $I.D._{Il}$.

4. Temperature rise delay is the time that elapses between the beginning of injection and a measurable temperature rise due to combustion. This period will be referred to as $I.D._{T}$.

5. Pressure rise delay is the time that elapses between the beginning of injection and a measurable pressure rise due to combustion. This period will be referred to as $I.D._{p}$.

Other definitions which were not used frequently will be referred to in the literature review. The methods used in previous studies for measuring these delay periods will be briefly reviewed.

LITERATURE REVIEW

A great variety of equipment and procedures have been used to measure the ignition delay associated with the self-ignition of hydrocarbon fuels. The different combustion chamber configurations used included constant volume bombs, rapid compression machines, as well as motored and fired engines. In this review some description of the combustion chambers used and the means for measuring the ignition delay is included, to help the reader understand the reasons for some of the variations in the reported results.

Studies of the autoignition of fuel and air mixtures, and measurement of the delay periods were started as early as 1922 by Tizard and Pye.[1,2*] They did their experimental work on a high compression machine with a cylinder 3 inches in diameter and with an 8-inch stroke. The compression ratio was varied from 6:1 to 9:1. Their experiments were made on gaseous fuels under static and turbulent conditions. They produced turbulence in the gaseous mixture by means of a fan fitted at the top of the cylinder. They observed that a delay period existed before the occurrence of pressure rise due to combustion, which they found to decrease with increase in turbulence.

Otto Alt[3] in 1923, followed by Kurt Neumann[4] in 1926, and F. Sass[5] in 1927, made investigations on combustion of liquid fuels in diesel engines and proposed the idea that preliminary evaporation of the fuel was not necessary for producing ignition. In other words, they considered that there was no physical delay before ignition of the liquid fuel.

Tausz and Schulte[6-7] between 1925 and 1928 established the idea of physical delay period in liquid fuel combustion. They indicated that no incipient ignition can take place in the liquid fuel and that, it should be evaporated before being ignited. They observed also that increase in pressure reduces the self-ignition point, and that the self-ignition temperature of a fuel is lower in pure oxygen than in air.

The presence of the physical delay was further established by photographs taken by Rothrock and Waldron[9] in 1932. They photographed the fuel spray in the NACA combustion apparatus[10] and observed that vaporization precedes ignition, and that its rate affects the process of combustion.

The variation in the pressure rise delay with increase in pressure was measured by Boerlage and Broeze[11] in 1931. They made tests utilizing a single cylinder, direct injection, 4-stroke cycle, slow speed diesel engine, for

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*Numbers refer to Bibliography.

compression pressures ranging from 375 psi to 600 psi. They proposed a hyperbolic relationship between the pressure rise delay and compression pressure.

$$I.D._p = \frac{K}{P} \qquad (1)^*$$

They also concluded[12] that the pressure rise delay depends on the thermal stability and structure of the fuel molecule. This conclusion was reached after they compared cetene ($C_{16}H_{32}$) and Tetraisobutylene ($C_{16}H_{32}$) and found that the latter has a poor ignition quality due to its molecular structure.

Gerrish and Voss[13] in 1932 used a different definition of the delay period from the above five definitions. They considered the end of ignition delay to be the point on the indicator card, where 4.0×10^{-6} pound of fuel had been effectively burned. The engine used for their test was the single-cylinder NACA universal test engine.[14] They found that an increase in inlet temperature, air pressure, compression ratio and engine speed reduce the delay period. They also found that a variation in the amount of fuel injected (or F/A ratio) has no appreciable effect on the delay, thus defined.

Wentzel[15] in 1936 computed the ~~physical~~ delay period by making a theoretical analysis of the process of heating and vaporization of fuel droplets in the diesel engine. He compared the computed values for the physical delay with measured values of pressure rise delay in constant volume vessel.[16] He found great deviation between the two values. In his discussion he attributed this great deviation to improper assumptions in his calculations or to the existence of a chemical delay period.

Otto Holfelder[17] in 1936 measured the illumination delay at different air temperatures and densities in a constant volume bomb, under conditions of no turbulence. He took pictures (500 pictures/second), of the process of combustion of different fuels.

Wolfer[18] in 1938 measured the pressure rise delay in two different constant volume bombs, and provided an expression for this delay period as a function of the air pressure and temperature.

$$I.D._p = \frac{0.44\, e^{4650/T}}{P^{1.19}} \qquad (2)$$

where P is in atmospheres and T in degrees Kelvin.

As this formula is of great interest in diesel combustion the experimental

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*A list of symbols is given in Appendix I of the Addendum.

equipment and procedure used will be described in some detail. His first bomb was a cylinder, 3.13 inches in diameter and 19 inches long. The second bomb was spherical, 7.88 inches in diameter. Turbulence was produced in the second bomb by means of two shaft-driven rotating hemispherical shells adjacent to the interior bomb walls. The effective bomb volume between the heater shells had a height of 2 inches. The air pressure before injection ranged from 118 psia to 393 psia in the first vessel and 172 psia to 705 psia in the second vessel. The tests covered temperatures ranging from 600°F to 947°F. Wolfer did not reach a definite conclusion concerning the effect of the air turbulence and no values were given concerning the speed of rotation of the two spherical shells. He concluded that his equation gave fairly accurate results for all fuels having cetane number greater than 50. He also concluded that ignition delay was "more or less" independent of fuel/air ratio, shape of the combustion chamber, the fuel nozzle, the injection pressure, air turbulence, and the fuel temperature if it is not initially higher than 100°C.

Small[19] continued the work started by Wolfer on the spherical bomb and investigated the effect of turbulence on the ignition delay. He made two tests, one with the air static and the other with the heater shells spinning at 1000 rpm. He reported that no marked difference in the pressure rise delay was observed between the static and swirling conditions.

Robert Selden[20,21] in 1938 and 1939 studied the effect of air temperature and density on the pressure rise delay. He carried out his tests in a cylindrical bomb, 3 inches in diameter and 3-7/8 inches long. The range of temperatures covered was 870°F to 1255°F and the densities from 0.69 lb/cu ft to 1.18 lb/cu ft. Fuel/air ratios covered were from 13.3:1 to 60:1. He also concluded that the fuel/air ratio had no effect on the ignition delay. He indicated that the possible decrease in ignition delay for a given increase in air temperature or density became quite small at temperatures and densities in excess of those generally occurring in C.I. engines.

Schmidt[22] in 1939 provided a formula for the chemical ignition delay for the simple case of bimolecular reaction between two gases without a chain reaction.

$$I.D._{Ch} = \frac{e^{-(E/RT)}\sqrt{T}}{P} a'B \qquad (3)$$

where:

P and T are the initial pressure and temperature, respectively.

B = factor that allows for the reduction of ignition delay resulting from the increased rate of burning during the delay period, which is due to the temperature rise within this interval.

a' = factor dependent on the fuel/air ratio.

He considered that the chemical portion of ignition delay for normal engine fuels could be reproduced by a formula similar to Eq. (3). Because of the intermediate chain reactions the pressure would appear as a power with an exponent n. Equation (3) took the form:

$$\text{I.D.} = \frac{e^{-(b'/T)}\sqrt{T}}{P^n}\, a'B \qquad (4)$$

where:

b' represents E/R.

Schmidt reduced Eq. (4) to the Wolfer equation because he noticed that the effect of the exponential function was so predominant that the lesser changes in T, a', and B were not important. Equation (4) then took the form:

$$\text{I.D.} = \frac{c\ e^{b/T}}{P^n} \qquad (5)$$

Bauer[23] in 1939 put forward a formula in which the ignition delay, to a first approximation, is a function of T log P, where P is in atmospheres, and T in degrees Kelvin, or

$$\text{I.D.} = \text{Fn}\ (T \log P)$$

or

$$\text{I.D.} = \text{Fn}\ (P\ e^{T}) \qquad (6)$$

He measured the illumination delay in an engine of 3-3/8-inch bore by 5-inch stroke. Compression temperatures and pressures at the end of the illumination delay period were calculated by assuming a polytropic index of 1.3. He found the above expression by trial and error, which he believed to cover the experimental data with reasonable accuracy.

It is to be noted that Eq. (6) indicates that ignition delay is a function of e^T while Wolfer's, Schmidt's, and Semenov's[24] equations indicate that the ignition delay is a function of $e^{b/T}$.

West and Denis Taylor[25] in 1941 measured the pressure rise delay by running tests on a single-cylinder open chamber diesel engine, 4.5-inch bore, 5.75-inch stroke, C.R. = 15.8:1 at a speed of 1000 rpm, at intake pressures ranging from 30 inches Hg to 56 inches Hg. The results of ignition delay tests were correlated in terms of T log P suggested by Bauer and are shown in Figure 1.

Starkman[26] in 1946 studied the effect of pressure, temperature, and fuel/air ratio on the pressure rise delay in a C.F.R. diesel engine and in a bomb. The volume of the bomb was equal to the clearance volume of the engine. He found that the pressure rise delay is reduced by the increase in any of the above factors, and that it is shorter in the engine than in the bomb.

Elliott[27] in 1949 made a detailed analysis to find the effect of temperature on the pressure rise delay. He used the results of Muller[28] and Wolfer as reproduced by Jost.[29] Elliott gave a formulae for the ignition delay as being the sum of the physical and chemical delays, and which he found to be in agreement with the results of Starkman.[26] For methylnaphthalene the formula is:

$$\text{I.D.} = 0.977\, e^{1070/T} + 2.18 \times 10^{-8}\, e^{14510/T} \tag{7}$$

For cetane the formula is:

$$\text{I.D.} = 0.710\, e^{1070/T} + 3.47 \times 10^{-4}\, e^{17620/T} \tag{8}$$

Hurn and Hughes[30] in 1952 investigated the effect of pressure, temperature, and fuel composition on the pressure rise delay in a constant volume bomb. The bomb, 2.5 inches in diameter, and 3.5 inches long, was externally heated, and contained air or artificial atmospheres with different partial pressures of oxygen. The temperatures ranged from 850°F to 1050°F, the pressures varied from 275 psi to 675 psi, the oxygen percentage varied from 15% to 40% and the cetane number of fuels varied from 37.2% to 53.7%.

They found that there is a certain percentage of oxygen that results in a minimum delay. They found also that the difference in ignition delay shown by the fuels became less as the air pressures and temperatures were elevated.

Hurn, et al.,[31] in 1956 studied the factors that govern the heating of injected fuels and the release of chemical energy in the autoignition process. They injected fuels of different volatility in a constant volume bomb, 2-1/2 inches in diameter and 4 inches long, containing different gases. Their data showed that chemical heat released occurred only after an appreciable interval of time during which the fuel was heated and partly or wholly vaporized. The rapidity of this heating, and associated ignition delay, were influenced markedly by the physical properties of the surrounding gas. Fuel volatility

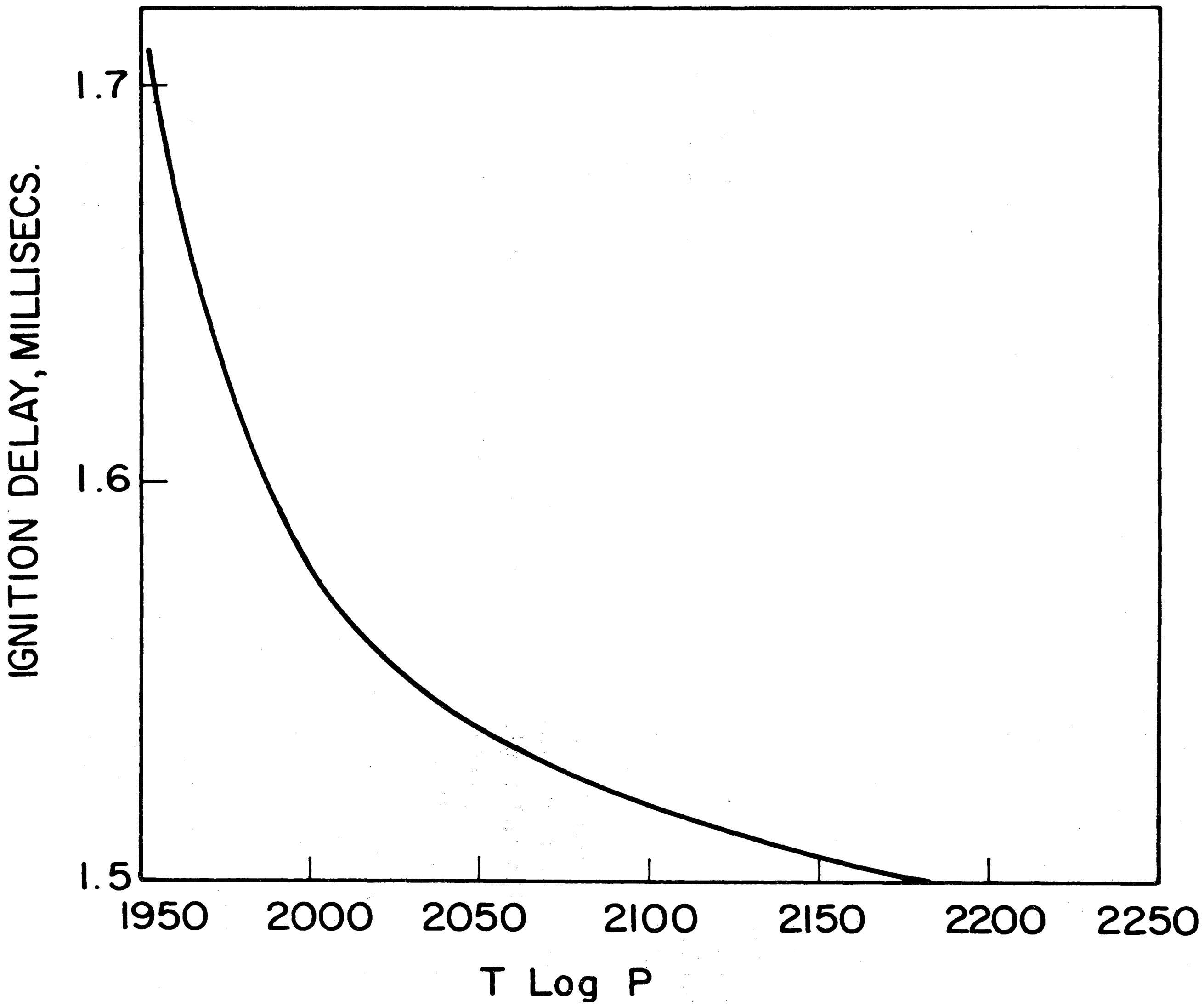


Figure 1. Relation between I.D.$_p$ and T log P, by West, *et al.*

and chemical structure had relatively little influence on the rate of heat transfer to the fuel during the physical delay period. The chemical delay was influenced by the composition of the fuels and by gas-to-fuel heat transfer rates during the pre-reaction period.

Yu, et al.,[32] in 1956 measured the small pressure changes occurring during the ignition delay in a single cylinder GM-71 engine. They also studied fuel vaporization with no oxidation reactions present by injecting fuel into nitrogen instead of air in the combustion chamber. These small pressure changes were measured by applying the hot motored technique. This technique includes taking pressure-crank angle traces for the engine fired and misfired in two consecutive cycles. They found the maximum pressure drop to depend upon the properties of the fuel, and mainly, on the cetane number. The fuel volatility had little effect on the rate of heating of the fuel.

El-Wakil, et al.,[33] in 1956 analyzed the events that occur to the fuel from the beginning of injection to the end of the pressure rise delay period. They analyzed the process of jet break up, drop vaporization with and without interaction with other drops. They indicated that spray break up was not an important part of the physical delay period. Their analysis on the spray evaporation showed that the condition of adiabatic saturation was approached very closely in the spray core, while the fuel/air ratio varied with the distance from the spray core in a different manner for fuels of different viscosities and volatilities. They found that under adiabatic saturation conditions a nonvolatile fuel has as good or a better chance as a volatile fuel to achieve the combination of temperature and vapor-air ratio required for self ignition and rapid combustion. They compared pressure rise delays in bombs[31] and in engines[32] and found that they are smaller in the engines than in combustion bombs.

Garner, et al.,[34] in 1957 measured the illumination delay in a C.F.R. diesel testing unit which incorporated a precombustion cylinder head. They found that the illumination delay decreased as the compression ratio was increased until some critical point was reached, after which the illumination delay again began to lengthen. They found that this applied at all fuel/air ratios for the following two fuels: DI parafinnic secondary reference fuel of 70 cetane number, and a naphthenic gas oil of 32 cetane number. This critical compression ratio was 23:1 for the low cetane naphthenic fuel and 25:1 for the higher cetane fuel. They noticed a break (zero illumination delay) at a compression ratio = 24.5:1 for both fuels.

Garner, et al.,[35] in 1961 continued their work and calculated the energy released during the delay period. They concluded that the preflame energy release is constant for any given fuel and the energy released is directly proportional to the delay period.

Tsao, et al.,[36] in 1962 measured the temperature rise delay in a modified C.F.R. engine. They measured the gas temperature inside the cylinder by the "Null Method," of the infrared technique. The operating variables investigated were the intake air temperatures, the fuel quantity per cycle, the intake air pressure, the engine speed and the fuel cetane number.

The empirical relationship they developed to correlate the temperature, the pressure, the engine speed, and the temperature rise delay is as follows:

$$I.D._T = 1000\ e^x - 1000 \tag{9}$$

where:

$$x = \frac{1}{1000}\left(\frac{123}{P} + 0.415\right)\left\{\left(\frac{-36.6}{T} + 0.0222\right) N + \left[\left(\frac{47.45 \times 10^3}{T}\right) - 26.66\right] + \left(\frac{T}{1000} - 1.45\right)\left(\frac{1000 - N}{60}\right)\right\} \tag{10}$$

This equation in the simplified form is as follows:

$$I.D. = \left(\frac{123}{P} + 0.415\right)\left\{\left(\frac{-36.3}{T} + 0.0222\right) N + \left(\frac{47.45 \times 10^3}{T} - 26.66\right) + \left(\frac{T}{1000} - 1.45\right)\left(\frac{1000 - N}{60}\right)\right\} \tag{11}$$

It is noted that this is the first formula to include the engine speed as a factor affecting the ignition delay period.

Sitkei[37] in 1963 measured the illumination delay, in a single cylinder precombustion chamber diesel engine and in an air cell engine. He divided the chemical portion of the illumination delay into three phases, so the illumination delay can be given by:

$$I.D._{Il} = I.D._{Ph} + I.D._{C.F.} + I.D._{B.F.} + I.D._{E.F.} \tag{12}$$

where:

$I.D._{C.F.}$ = ignition delay of the cold flame

$I.D._{B.F.}$ = ignition delay of the blue flame

$I.D._{E.F.}$ = ignition delay of the explosion flame

He found that the last two terms of Eq. (12) are difficult to separate and suggested that they be combined in one term where:

$$I.D._{(B+E)F} = I.D._{B.F.} + I.D._{E.F.}$$

thus the Eq. (12) becomes:

$$I.D._{Il} = I.D._{Ph} + I.D._{C.F.} + I.D._{(B+E)F} \tag{13}$$

He estimated the physical delay as being equal to 0.5 millisec and evaluated $I.D._{C.F.}$ and $I.D._{(B+E)F}$ in the above described engines, and gave the following formula for the illumination delay.

$$I.D._{Il} = 0.5 + \frac{0.135\ e^{7800/RT}}{P^{0.7}} + \frac{4.8\ e^{7800/RT}}{P^{1.8}} \tag{14}$$

where P is in atmospheres and T in degrees Kelvin.

Lyn and Valdmanis[38] in 1966 studied the effects of air temperature, air pressure, and injection system parameters on the pressure rise delay, in two engines with modified chambers to accommodate schlieren photography.[39] They applied the motored engine technique with single shot injection. They concluded that the cylinder temperature and pressure, and the injection timing are the mian factors that affect the pressure rise delay. Air velocity, fuel injection pressure and nozzle configuration have a secondary effect. Injection quantity (or fuel/air ratio) has negligible effect.

From the literature review it can be noticed that different delay periods were measured in a variety of combustion chambers under different operating conditions. The formulae available now for the ignition delay are mainly that by Wolfer for the pressure rise delay in bombs, Bauer and West for the pressure rise delay in an open-chamber engine, Tsao, et al., for the temperature rise delay in a modified open chamber C.F.R. engine, and Sitkei for the illumination delay in a divided combustion chamber engine.

From an engineering point of view the pressure rise delay or the temperature rise delay are the most important but the pressure rise delay is much easier to measure. In the previous investigations on the pressure rise delay most of the experiments were done in bombs or in open combustion chambers where the turbulence is limited to relatively small values. Among all the formulae available on ignition delay in engines there is only the formulae by Tsao, et al., that took into consideration the effect of engine speed. In the present study the effect of turbulence and other factors that affect the pressure rise delay will be studied in a turbulent combustion chamber.

THERMODYNAMIC CONSIDERATIONS

In this theoretical analysis a study is made of the factors that affect the pressure rise delay in a constant volume bomb and in an engine. A discussion is given of the thermodynamic factors that cause differences in the delay periods of bombs and engine cylinders.

Consider the gas in the combustion chamber as a system. The end of the pressure rise delay for this system is determined from the pressure trace at the point where a change in the slope $(dP/d\theta)$ occurs due to combustion. The slope $(dP/d\theta)$ can be computed from the balance of the different types of energies involved, from the time of start of injection to the end of the pressure rise delay. The energies involved are as follows:

1. Work done by or on the system. In a bomb this work is equal to zero since the volume is constant, but in an engine the volume is continuously changing during the delay period. If all the delay occurs during the compression stroke, then work will be done by the piston on the system resulting in an increase in its internal energy. However, if a portion of the delay occurs after T.D.C. then during this portion work will be done by the system on the piston, which results in a corresponding drop in the internal energy of the system, and longer pressure rise delays.

2. Heat exchange between the system and the surroundings which depends on the combined effect of convection and conduction.

3. Sensible internal energy changes due to evaporation and heating of the vapor to the self-ignition temperature of the fuel.

4. Chemical internal energy changes due to the exothermic reaction between the fuel and oxygen.

The slope of the pressure trace is derived in Appendix II and is given in Eq. (26):

$$\left(\frac{dP}{d\theta}\right) = \frac{R}{c_V} \cdot \frac{1}{V}\left[\frac{dQ}{d\theta} - P\,\frac{dV}{d\theta}\left(\frac{c_V}{R} + 1\right) - T\,c_V\,\frac{dm}{d\theta}\right] \qquad (15)$$

This equation indicates that the rate of pressure rise depends upon the following factors:

1. The volume of the mixture, V. The bigger the volume of the container, with all parameters constant, the smaller will be $dP/d\theta$. From the review of previous experimental work done on ignition delays, it is noticed that the combustion chambers used were of different volumes. It is believed that this is one of the factors that contribute to the differences between the results of different investigators.

2. The rate of heat addition to the mixture $dQ/d\theta$. This represents the net heat added to the mixture as a result of the heat of reaction $dQ_{Ch}/d\theta$ and the heat transfer losses to the walls, $dQ_C/d\theta$. The heat added to the system can be given by,

$$\frac{dQ}{d\theta} = \left[\frac{dQ_{Ch}}{d\theta} - \frac{dQ_C}{d\theta}\right] \tag{16}$$

$dQ_{Ch}/d\theta$ is proportional to the velocity of the chemical reaction, the volume of reactants and their concentration. The velocity of reaction was given by Semenov[25] for simple elementary reactions as:

$$W = K_1 \, a^n \, e^{-(E/RT)} \tag{17}$$

The reactions included in the autoignition of hydrocarbon fuels are in general very complicated, and the detailed mechanisms are not known. However, there is nearly general agreement that autoignition of hydrocarbons proceeds by a mechanism involving a chain of simple reactions for which Eq. (17) can be applied.

$$\frac{dQ_{Ch}}{d\theta} = \frac{d}{d\theta}\left[K \cdot V' \cdot U_R \cdot a^{n'} \cdot e^{-(E/RT)}\right] \tag{18}$$

where V' is the sum of the elementary volumes containing a combustible mixture. V' is a function of many factors that influence the fuel injection, evaporation and distribution in the combustion chamber. Therefore it depends upon the type of fuel, rate of fuel injection, type of fuel nozzle, mean diameter of droplets, jet velocity, air turbulence, air temperature and density. Almost all these factors can be kept the same in bombs and in engines, except for the air turbulence which is believed to be one of the factors that cause the difference between the two cases.

Equation (18) indicates that the energy released by the chemical reaction is a function of the factors that affect V' together with the average concentration of fuel and air in the different parts of the combustion chamber, the heat of reaction, the activation energy and the absolute temperature.

The heat loss to the walls, $dQ_C/d\theta$, is a function of the temperature difference between the gas and the walls, the area of heat transfer, and the coefficient of heat transfer. It can be given by

$$\frac{dQ_C}{d\theta} = \frac{d}{d\theta}\left[\alpha \cdot A \cdot (T_g - T_W)\right] \tag{19}$$

The heat losses in an engine are in general greater than in a bomb of the same size and under the same gas and wall conditions because of the higher coefficient of heat transfer.

Equation (15) can take the form:

$$\frac{dP}{d\theta} = \frac{R}{c_v} \cdot \frac{1}{V}\left[\left(\frac{dQ_{Ch}}{d\theta} - \frac{dQ_C}{d\theta}\right) - P\,\frac{dV}{d\theta}\left(\frac{c_v}{R} + 1\right) - T\,c_v\,\frac{dm}{d\theta}\right] \tag{20}$$

The different types of energy included in Eq. (20) are represented in Figures 2 and 3. The last term in Eq. (20) will be neglected for simplicity since its effect is very small. Figure 2 is for an engine without injection. Figure 3 is for the same engine with fuel injection and combustion. In Figure 2, curve "a" represents the work done by the piston on the system. This work causes an increase in internal energy of the system before T.D.C. and a drop in internal energy after T.D.C. The change in internal energy at T.D.C. due to piston work is zero. Curve "b" shows the leat loss from the gas to the cylinder walls. Its effect is to decrease the internal energy of the system at different rates which mainly depend upon the turbulence in the chamber. Curve "c" is the algebraic sum of curves "a" and "b." It represents the energy to be released by combustion before the end of the pressure rise delay can be detected at any crank angle. The balance between the chemical energy released and the other types of energies is shown in Figure 3. In this figure curve "c" is inverted to simplify the analysis. Three cases of energy release rates are considered. Case 1 is for a high rate of energy relase where the delay period ends during the compression stroke. Case 2 is for a lower rate of energy release where the delay period ends during the expansion stroke, resulting in a longer delay period. Under such conditions the energy released $(dQ_{Ch}/d\theta)_2$ should be more than $(dQ_{Ch}/d\theta)_1$, released in the first case. The increase in the rate of energy release in the second case is mainly to account for the work of expansion after T.D.C. Case 3 is for a very low rate of energy release where no pressure rise due to combustion can be detected.

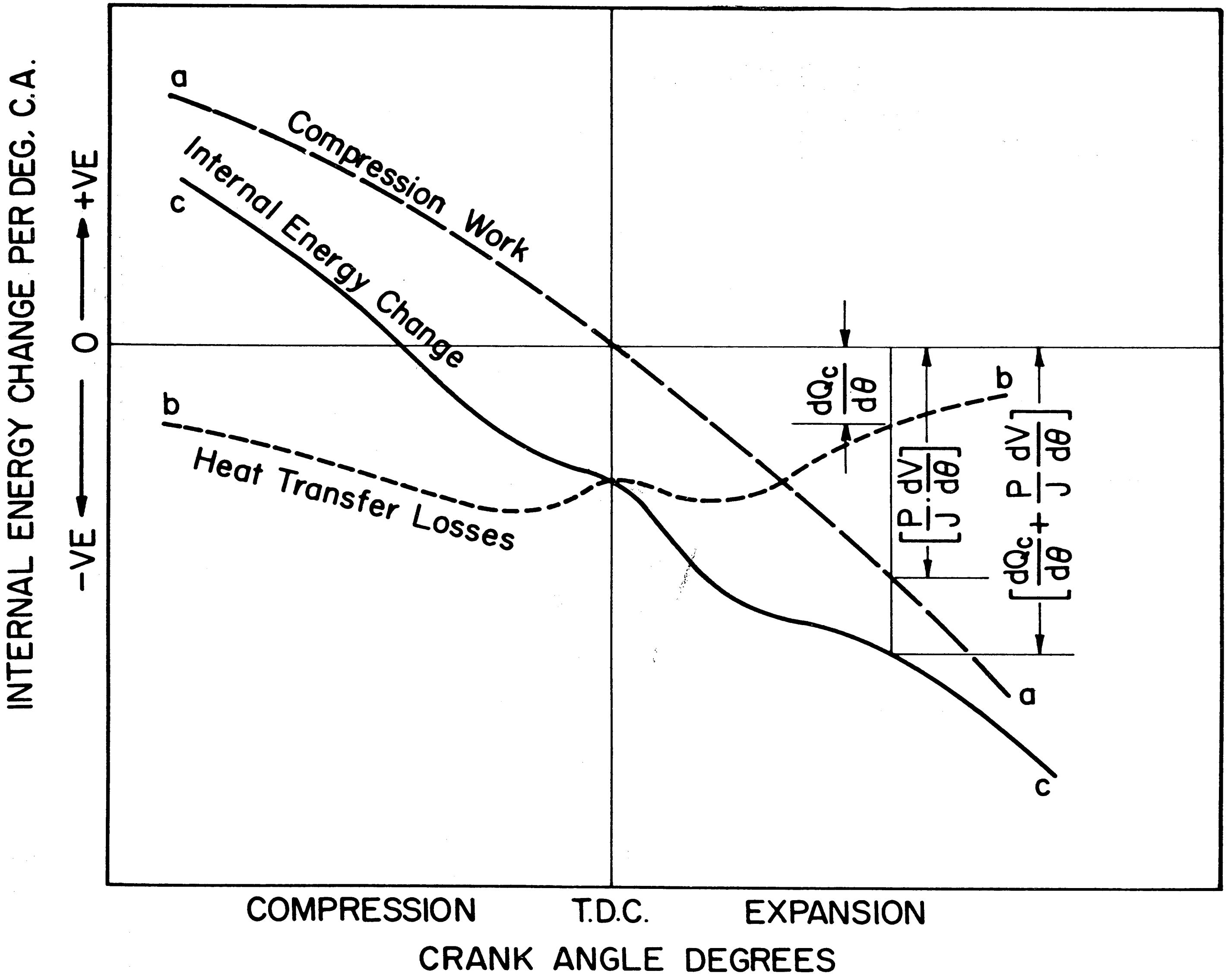
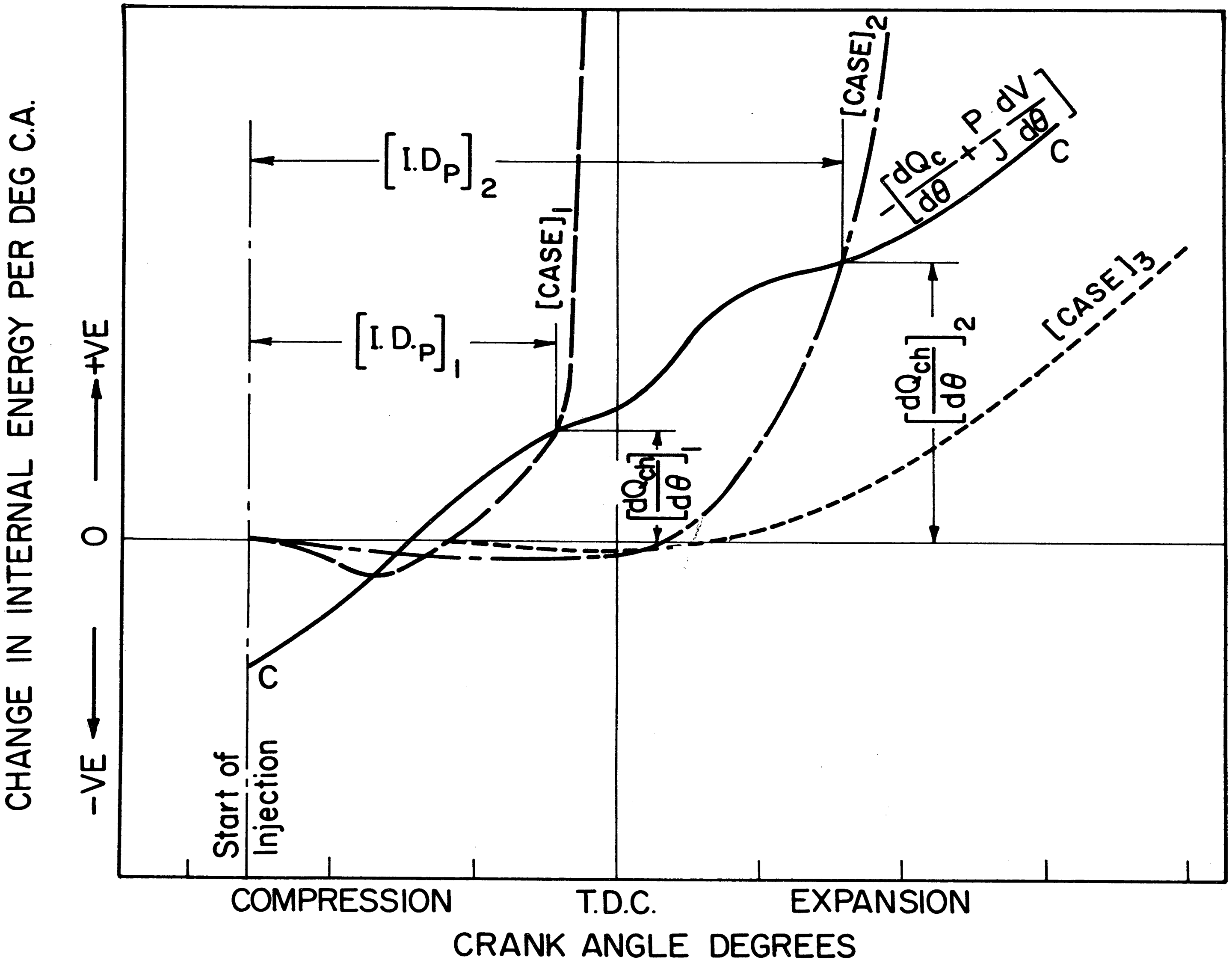


Figure 2. Change of internal energy of the system near T.D.C. without injection.



CHANGE IN INTERNAL ENERGY PER DEG C.A.
−VE
0
+VE
$\left[I.D_P\right]_2$
$\left[I.D_P\right]_1$
$[CASE]_1$
$[CASE]_2$
$[CASE]_3$
$-\left[\frac{dQ_c}{d\theta}+\frac{P}{J}\frac{dV}{d\theta}\right]$
C
C
$\left[\frac{dQ_{ch}}{d\theta}\right]_1$
$\left[\frac{dQ_{ch}}{d\theta}\right]_2$
Start of Injection
COMPRESSION
T.D.C.
EXPANSION
CRANK ANGLE DEGREES

The conditions in a bomb are different from an engine for the following reasons:

1. No work is done on or by the system since the volume is constant.

2. The turbulence in a bomb is negligible compared to the engine. The main effect of turbulence is on the heat transfer losses and the mixing of the fuel and air. It causes the heat transfer losses in engines to be greater than in bombs of the same size and under the same conditions of pressure and temperature. However, the effect of the increased heat transfer losses due to turbulence is small compared to the increase in the rate of chemical release due to the better mixing. Equation (18) indicates that the rate of chemical energy release depends on, V', the volume having optimum concentrations for the reaction. It is believed that the chances are better in engines to obtain better concentrations and higher combustion reaction rates.

3. In some of the bomb tests the walls are used to heat the air, so heat is added to the system during the delay period instead of being lost from the system to the walls as in the engines.

This analysis indicates that the pressure rise delay is not only a function of the physical and chemical delays, it is also a function of the thermodynamic factors that affect the balance between the energy generated from the chemical reaction, the heat lost to the surroundings, the work done on or by the system.

EQUIPMENT

A general view of the experimental Lister-Blackstone engine is shown in Figure 4. The engine is a single cylinder, four-stroke cycle, liquid cooled, 4-1/2-inch bore, 4-3/8-inch stroke, and has a rated power of 8 BHP at 1200 rpm. This engine is especially useful for combustion research because of easy access to the swirl chamber, or turbulent chamber. The design, therefore, makes it practical to modify the swirl chamber, and to place pressure pick-ups and other instruments into the wall of the swirl chamber. It was also found to be practical to modify the combustion chamber to permit change of compression ratio. Figure 5 shows a section of the cylinder head with its original auxiliary chamber and the compression ratio changeover valve. Figure 6 shows the cylinder head after modification and shows the variable compression ratio sleeve and the chamber plug. The construction of this plug allows the compression ratio to be varied from 13.92:1 to 22:1. For the experimental part of the paper, all the tests were run at a constant compression ratio of 13.92:1.

Shop air was used to supercharge the engine after being passed through a surge tank fitted just before the engine. The pressure in the tank is measured and considered equal to the supercharging pressure. The temperature is measured in the tank and in the cylinder head before the inlet valve. The air comsumption is measured by a critical pressure-type flowmeter.

The gas pressure inside the cylinder is obtained by the use of an oscilloscope, together with a Kistler pressure transducer and a degree-marking unit. The Kistler transducer is mounted on the combustion chamber plug as nearly flush as possible with the inside surface of the combustion chamber. The output of the transducer is fed to a charge amplifier and then to a dual-beam oscilloscope. The trace obtained on the screen is photographed by a Polaroid camera attached to the oscilloscope.

The crank angles are measured every three degrees in a manner similar to that used in previous work.[40]

The fuel injection system consists of a Bosch single hole injector and a Bosch injection pump driven by the engine camshaft. The injector opening pressure was varied from 1000 to 4000 psi. Unfortunately, the injector timing could not be varied on this engine.

The fuel injector is instrumented, Figure 7, so that the start and rate of injection can be calculated from measurements of the needle lift and fuel pressure before the nozzle. The needle lift is measured by a Bentley D-152 distance detector system. The injection is considered to begin at the instant the needle lift begins. The fuel pressure before the nozzle is ob-

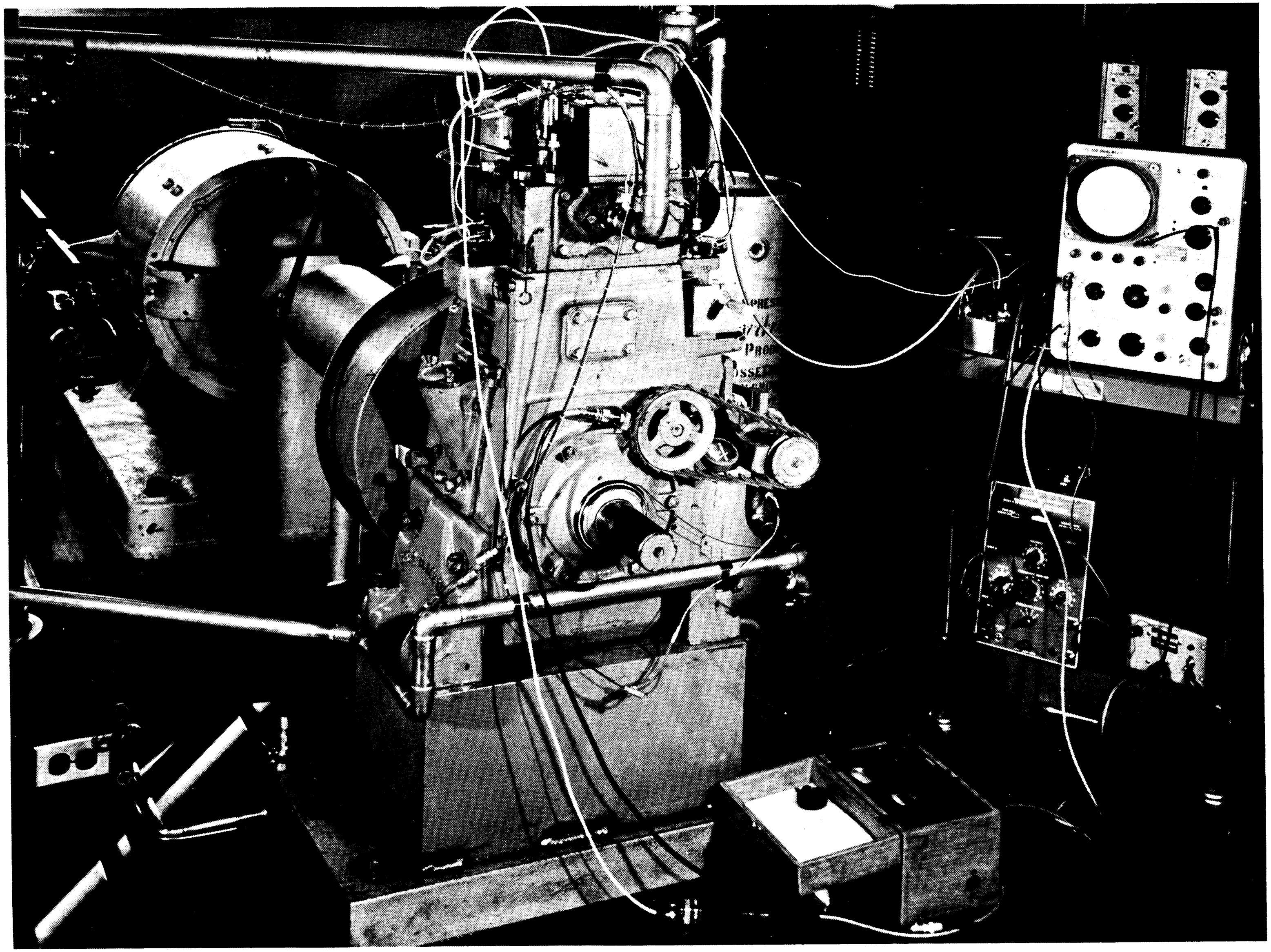


Figure 4. Photograph of Lister-Blackstone engine and equipment.

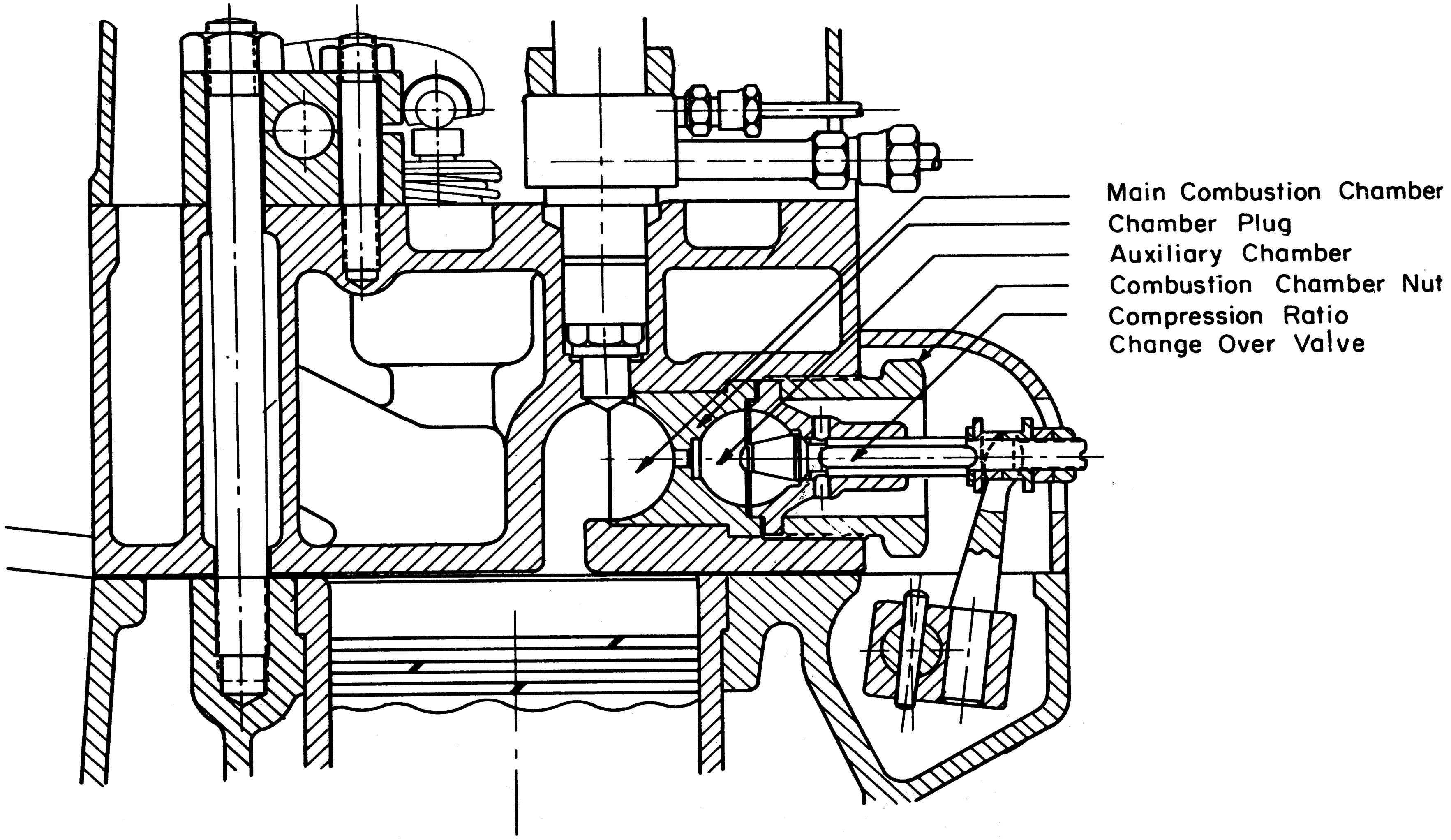
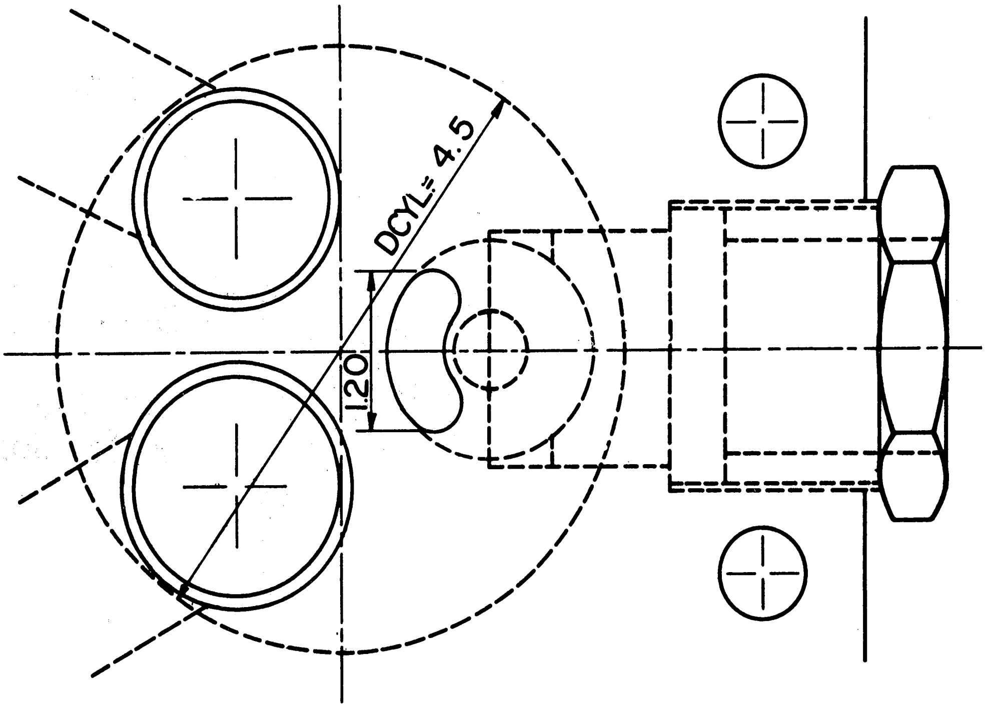
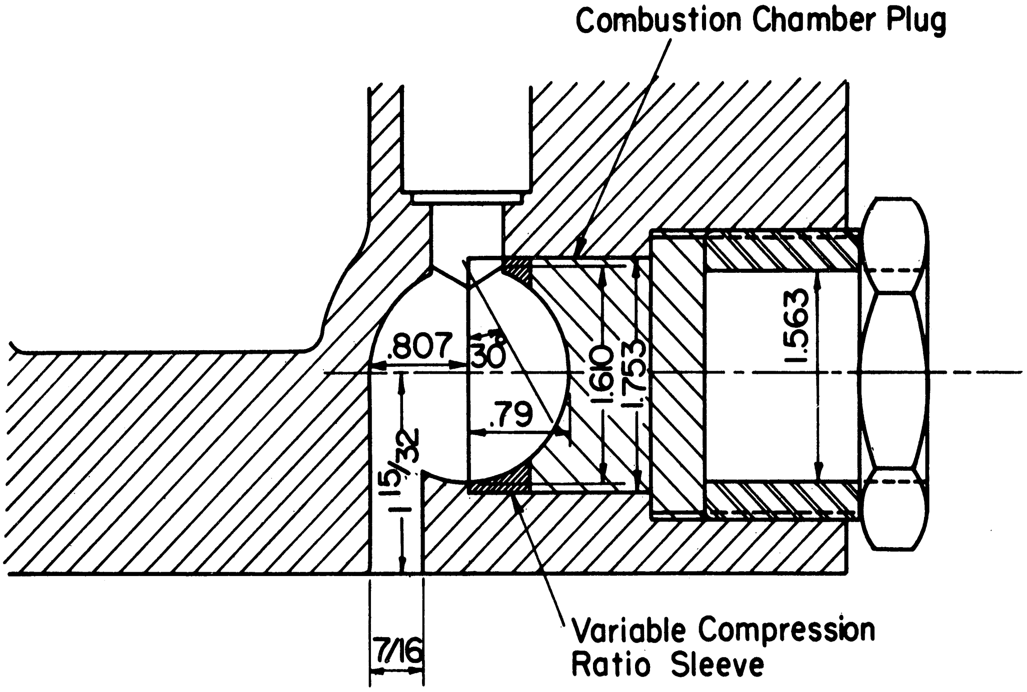


Figure 5. Original combustion chamber of Lister-Blackstone engine.



TOP VIEW



SECTIONAL VIEW

Figure 6. Modified combustion chamber of Lister-Blackstone engine.

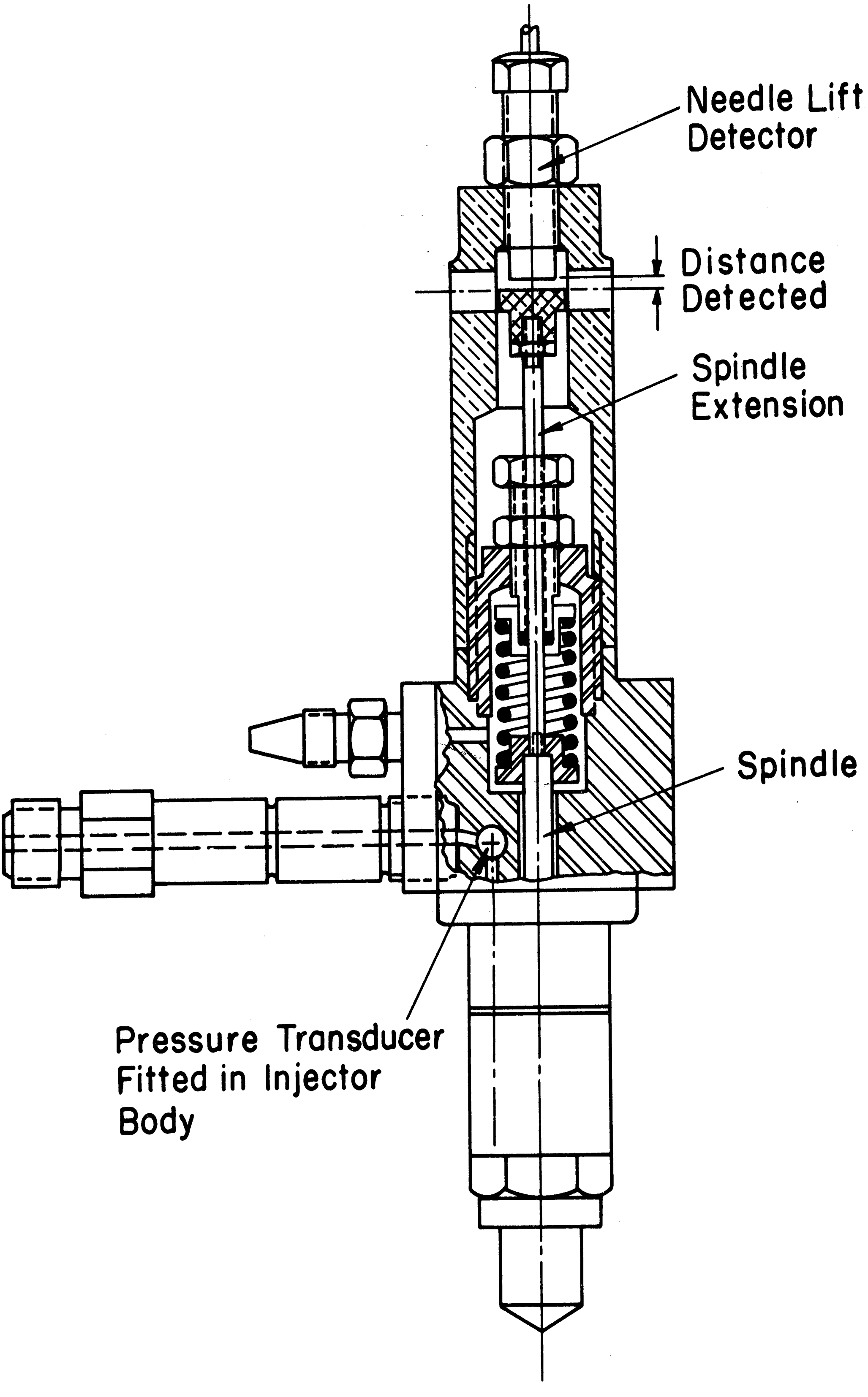


Figure 7. Fuel injector fitted with a needle lift detector and a pressure transducer.

tained by a Kistler transudcer fitted on the injector body. The rate of injection (especially during the delay period) is calculated from the pressure difference before and after the nozzle and the areas of flow as computed from needle lift measurements. A cross section of the nozzle is shown in Figure 8.

A sample of the traces obtained for the gas pressure, fuel pressure, needle lift, solar cell output and crank degrees is shown in Figures 9 through 12.

The engine is connected to a 25 hp G. E. dynamometer. The intake air pressure was controlled by a regulating valve and could be varied over a wide range; but the exhaust was kept at atmospheric pressure. The fuel used in these tests was Standard Oil Company No. 2 diesel fuel.

The point of illumination was determined by using a Hoffman silicon solar cell (type 55C).

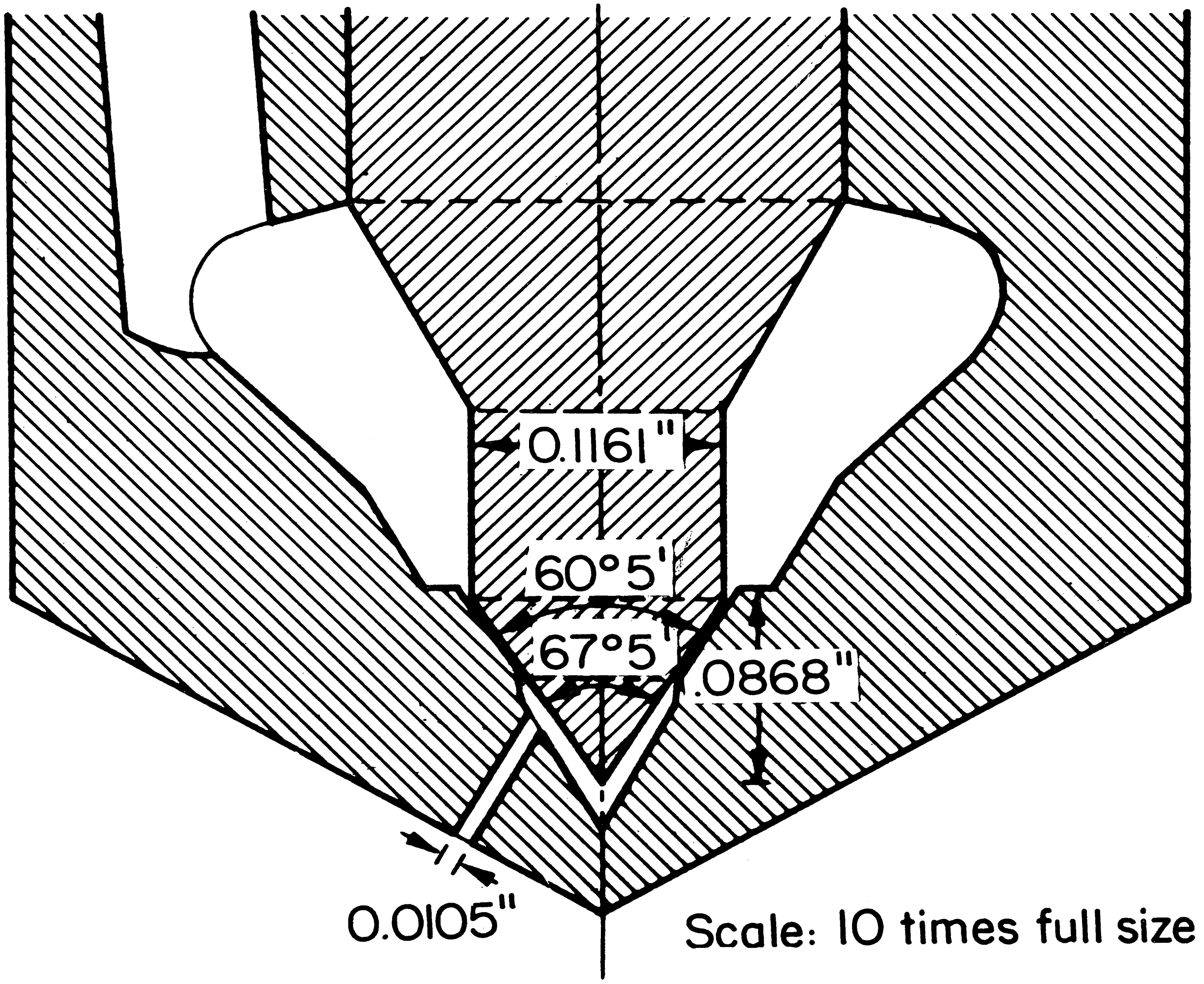


Figure 8. Nozzle needle assembly.

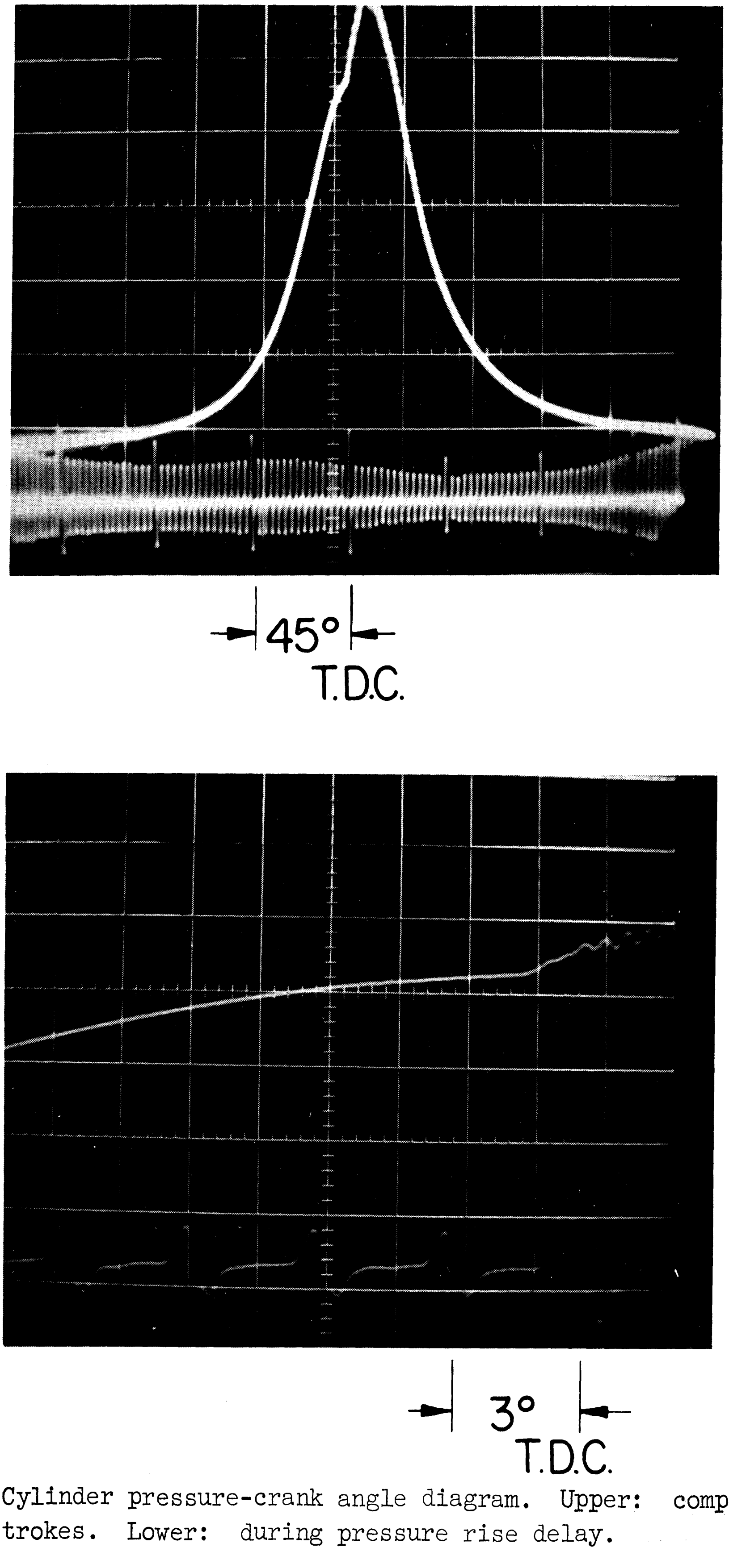


Figure 9. Cylinder pressure-crank angle diagram. Upper: compression and expansion strokes. Lower: during pressure rise delay.

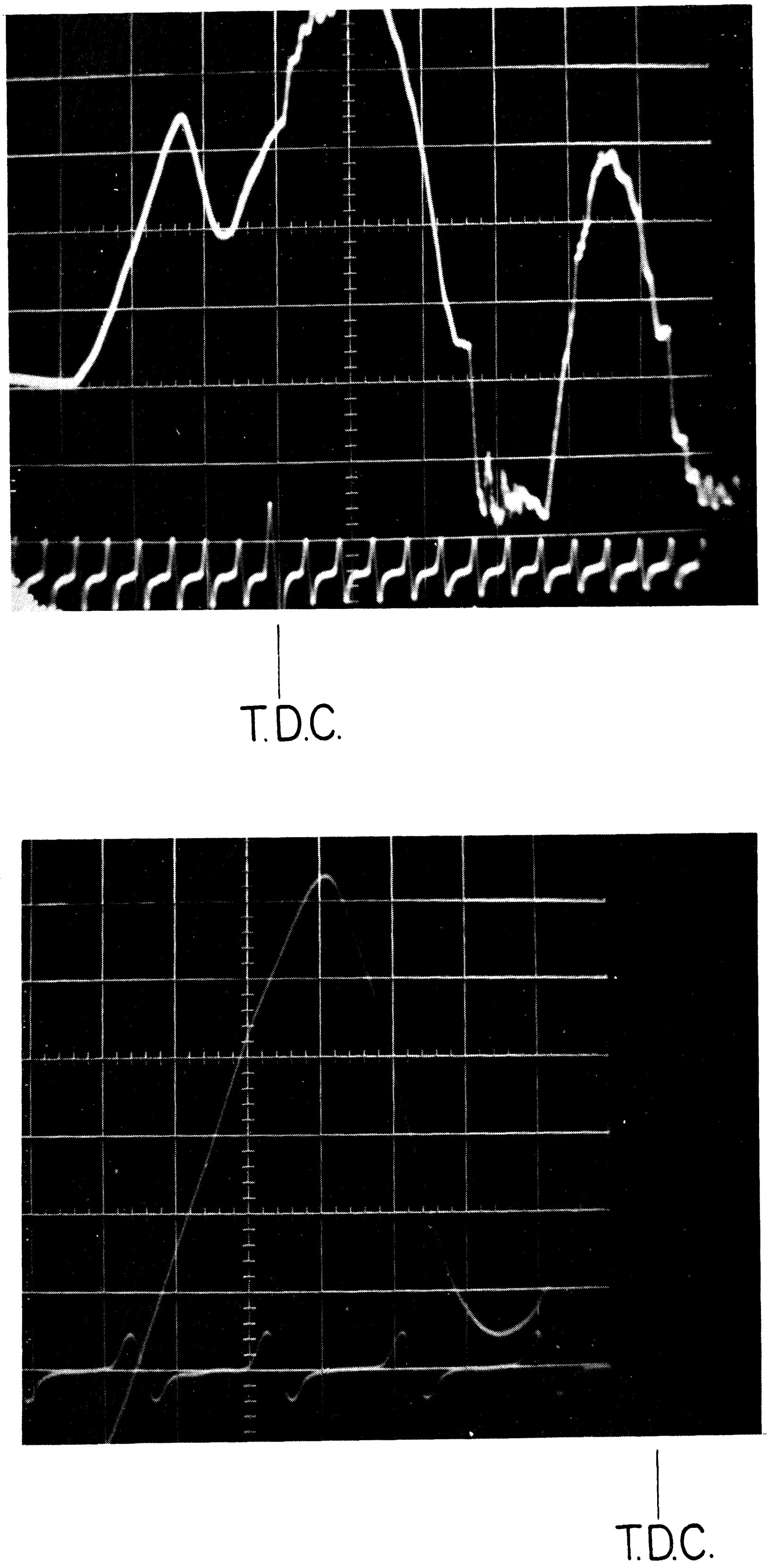


Figure 10. Fuel pressure-crank angle diagram. Upper: for whole period of injection. Lower: at start of injection.

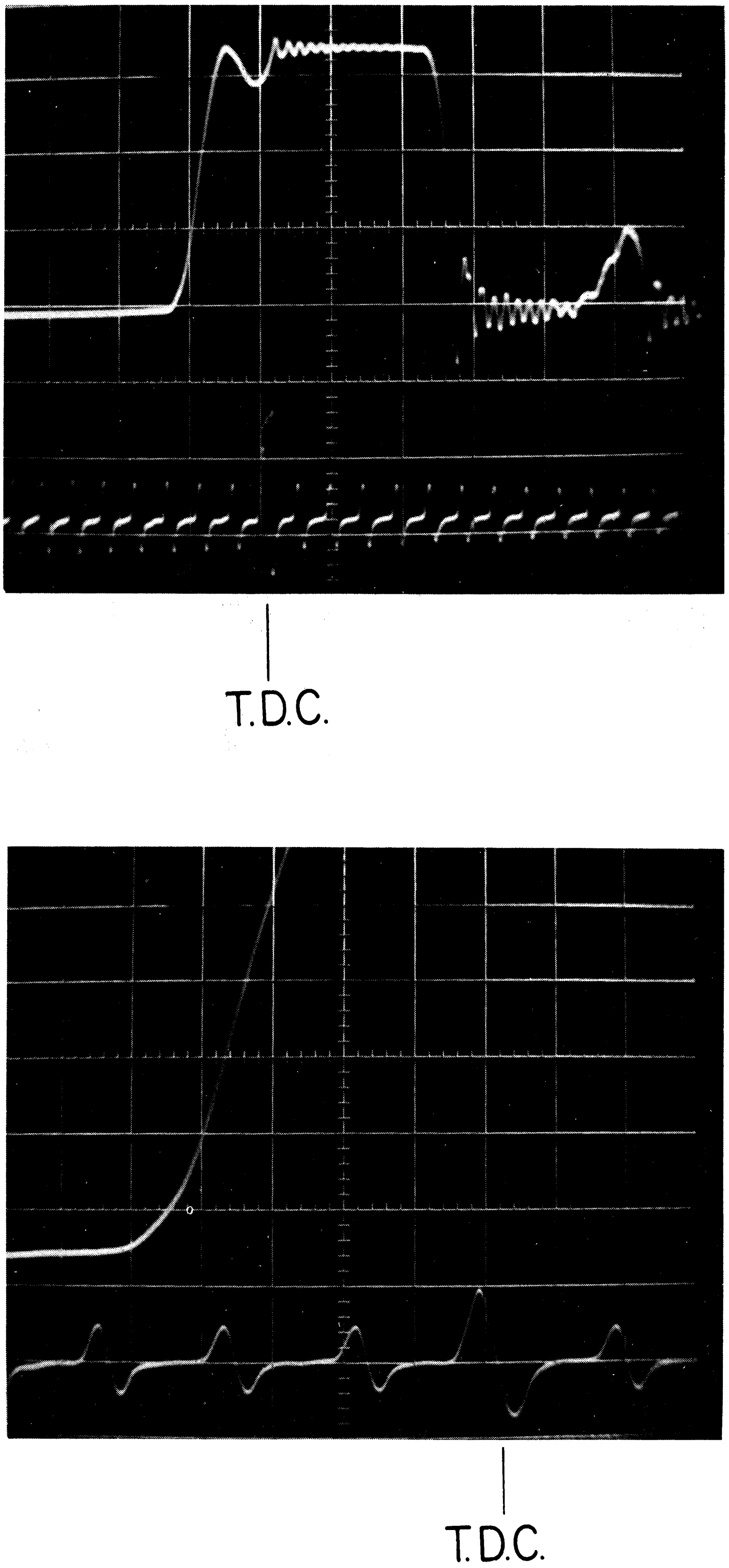


Figure 11. Needle lift-crank angle diagram. Upper: for whole period of injection. Lower: at start of injection.

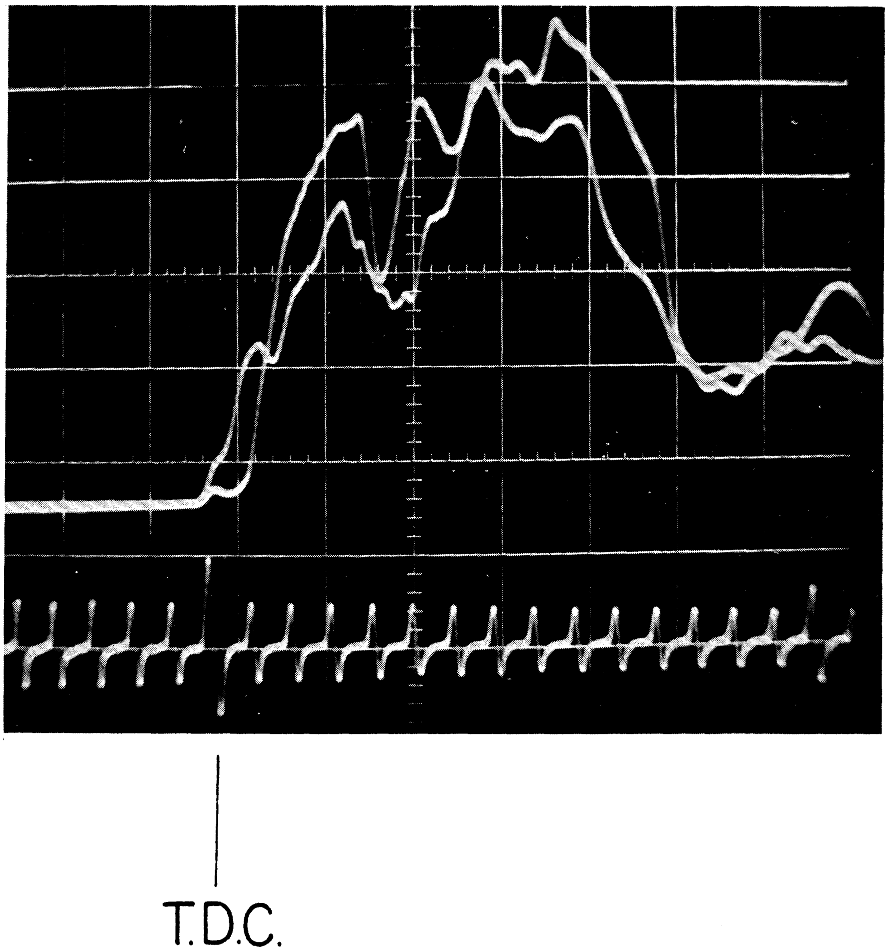


Figure 12. Illumination-crank angle diagram.

EXPERIMENTAL RESULTS AND DISCUSSION

The main purpose of the experimental work was to study the effect of pressure on the pressure rise delay. However, it was found necessary, in the early stages of the work to make a preliminary study of the other parameters that affect the delay period. These parameters include the fuel/air ratio, the injection pressure, the coolant temperature, and turbulence. This was done to establish a test procedure for the runs that would be made to investigate the effect of pressure.

In this section, the different series of tests are reported in their chronological order in which they were carried out.

EFFECT OF FUEL/AIR RATIO ON PRESSURE RISE AND ILLUMINATION DELAYS

These tests were run at variable fuel/air ratios with the other parameters kept constant. On the lean side the engine was motored with fuel injection and combustion. The amount of fuel injected was reduced, and fuel/air ratios as low as 0.0022 (0.0325 stoichiometric), were reached. With the engine producing power the fuel/air ratio was increased up to 85% the stoichiometric ratio. With higher fuel/air ratios, erratic operation of the engine occurred due to a very late after-injection. By examining the cylinder pressure under these conditions it was noticed that injection of the left over fuel from the previous cycle occurred before the start of injection.

The results of this series of runs are plotted in Figure 13. The general trend of this figure indicates that both the pressure rise and illumination ignition delays decrease with increase in fuel/air ratio. An increase in fuel/air ratio from .0022 to .0431 caused the illumination delay to decrease by 38.2%. It was noticed that at higher fuel/air ratios, the solar cell did not operate properly. The decrease in pressure rise delay amounted to 37.6% by an increase in fuel/air ratio from 0.0022 to 0.0567. The effect of fuel/air ratio on decreasing the ignition delay is actually more than that indicated in Figure 13, because at higher fuel/air ratios fuel injection starts at an earlier angle before T.D.C., i.e., at lower air pressures and temperatures, and densities. The advance in the start of fuel injection at different fuel/air ratios is shown on the same figure.

An examination of this figure indicates that at very lean fuel/air ratios the ignition delay reaches very high values. The variations in the delay at fuel/air ratios below 0.011 are believed to be due to changes in fuel injection timing. Ignition or combustion were not observed at fuel/air ratios less than 0.0022. The minimum fuel/air ratio probably differs from one engine to another and depends on many factors that influence the balance be-

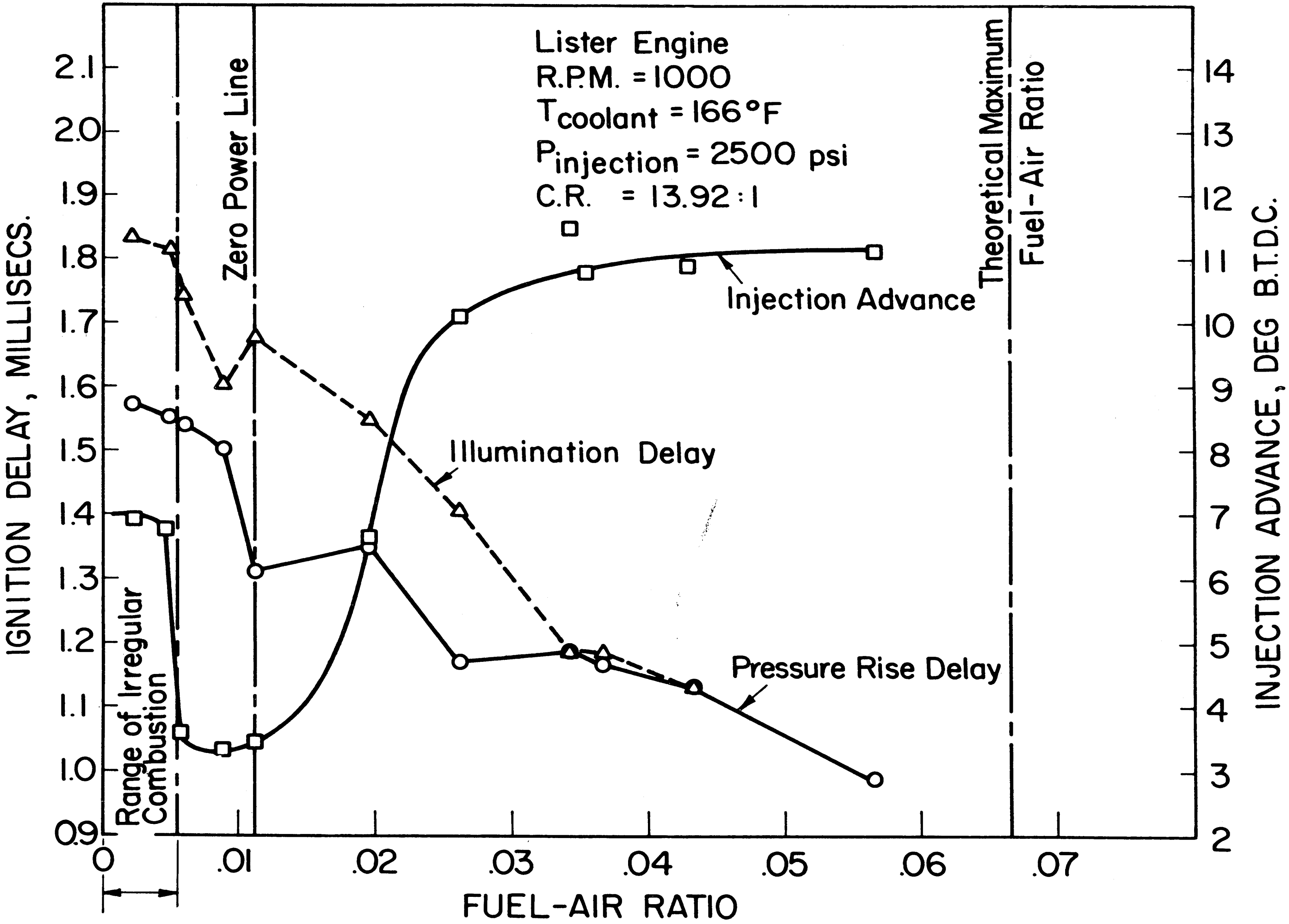


Figure 13. Effect of fuel/air ratio on ignition delay.

tween the energy added to and lost from the system as indicated in Figure 3. In photographic work concerning combustion in a diesel engine, Miller[41] indicated that the minimum fuel/air ratio was 0.01 when illumination was not observed.

By comparing the traces for the illumination and pressure rise delays in Figure 13, it is noticed that for fuel/air ratios up to 0.035, the illumination delay is longer than the pressure rise delay. For higher fuel/air ratios the two types of delay have equal values. For fuel/air ratios less than 0.035 it seems that pre-illumination reactions take place in the combustion chamber and cause a temperature rise with a corresponding pressure rise. For mixtures richer than 0.035 it seems that the pre-illumination reactions are not enough to produce a temperature rise sufficient to produce a measurable pressure rise before illumination occurs.

EFFECT OF INJECTION PRESSURE ON IGNITION DELAY

Many factors influence mixture formation in the diesel engine, including the mean spray velocity at the nozzle, atomization, penetration, evaporation, and mixing with air. The differential pressure across the nozzle orifice substantially affects the mixture formation especially near the beginning of the injection process. The fuel pressure before the nozzle is primarily a function of the setting of the needle opening pressure. In order to investigate the effect of changing the fuel atomization and distribution in the combustion chamber the opening pressure was changed from 1000 psi to 4000 psi. The experimental results for the effect of injector opening pressure on the pressure rise and illumination delays are shown in Figure 14. As the injector opening pressure is increased, from 1000 psi the illumination delay is reduced reaching a minimum at a pressure of 2100 psi. At higher injection pressures the illumination delay is again increased. Sitkei[37] also noticed such an increase in illumination delay with an increase in the injection pressure.

The pressure rise delay remains constant for all injector opening pressures. The increase in the injection pressure is expected to increase the initial jet velocity at the tip,[42] reduce the average drop size,[43] and has some effect on penetration.[44] These changes in the spray pattern seem to have a small effect on the rate of combustion which starts in the spray envelope.[17]

EFFECT OF COOLING WATER TEMPERATURE ON IGNITION DELAY

Preliminary engine tests indicated that the pressure near T.D.C. is affected by the heat losses because maximum pressure occurred before T.D.C. in the motored engine. The crank position for maximum pressure and temperature in the motored engine is shown in Appendix III. Since the ignition delay depends on gas pressure and temperature, it is to be expected that cooling

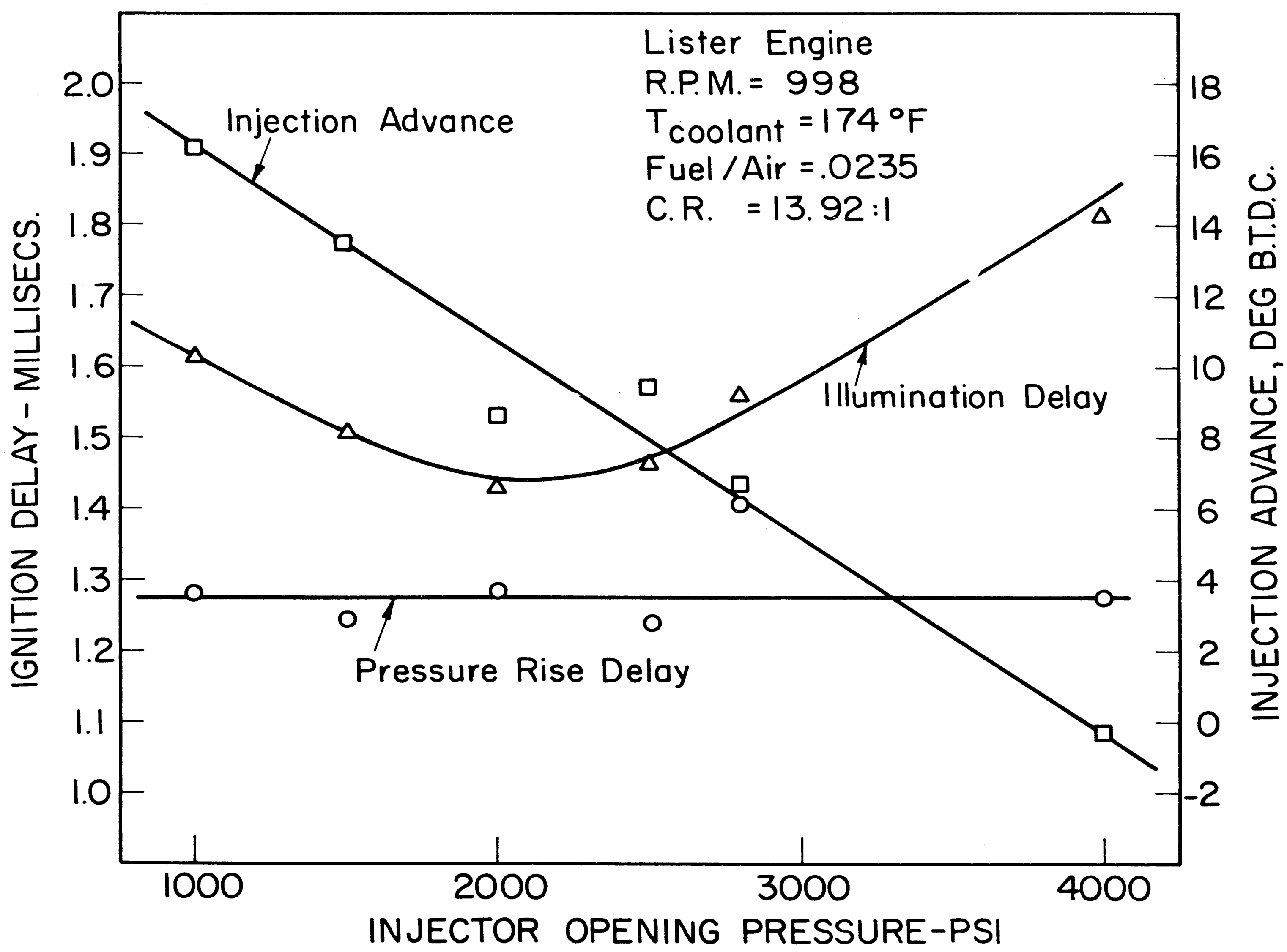


Figure 14. Effect of injector opening pressure on ignition delay.

water temperature would affect ignition delay. To investigate this point a series of tests were carried out on the engine at various cooling water temperatures ranging from 70°F up to 200°F. The results are plotted in Figure 15. This curave was drawn through every plot point rather than attempting to present a faired curved. It can be noted that the shape of the ignition delay curve follows the same pattern as that of the injection advance. However, the curve generally indicates that at higher temperatures, the ignition delay is reduced. The reduction in pressure rise delay amounted to 14.8% by increasing the cooling temperature from 70°F to 200°F.

EFFECT OF PRESSURE ON PRESSURE RISE DELAY

The influence of pressure on the pressure rise delay is shown for a speed of 1000 rpm in Figure 16, which reveals that the pressure rise delay decreases with increase in air pressure at the time of injection. This is believed to be mainly due to the following factors:

1. The drop in the self-ignition temperature of the fuel at higher air pressures, as indicated by Tausz and Schulte.[9]

2. The increase in the availability of oxygen at higher air pressures, which increases the rate of release by oxidation reactions in the early stages of combustion.[35]

3. The increase in the heat transfer rate from the air to the fuel droplets caused by the increased density of air, resulting in a shorter physical delay period.

The increase of the air pressure also affects other important variables, including the spray pattern, local fuel concentrations, and the local cooling effect due to fuel evaporation.

After trying to correlate ignition delay with air pressure it was found that the best correlation is between log $I.D._p$ and log P.

Figure 17 is a plot of $\log_e I.D._p$ vs. $\log_e P$, and indicates that, at a constant temperature, the relation between the two variables has a linear relationships, or

$$I.D._p = \frac{C}{P^n} \tag{21}$$

under these conditions C = 64740 and n = 1.774.

This relationship has the same form as that of Schmidt at a constant tem-

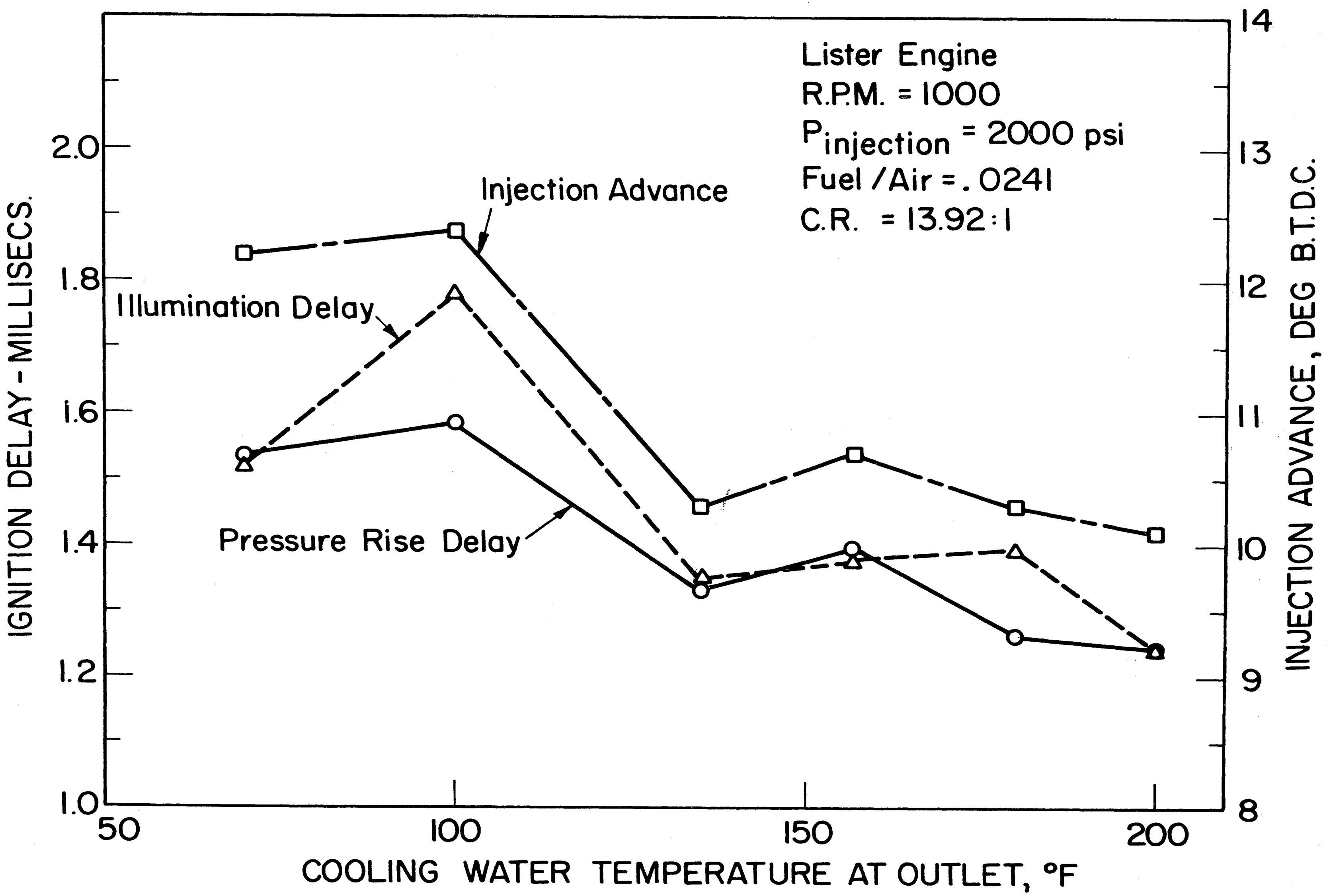


Figure 15. Effect of coolant temperature on ignition delay.

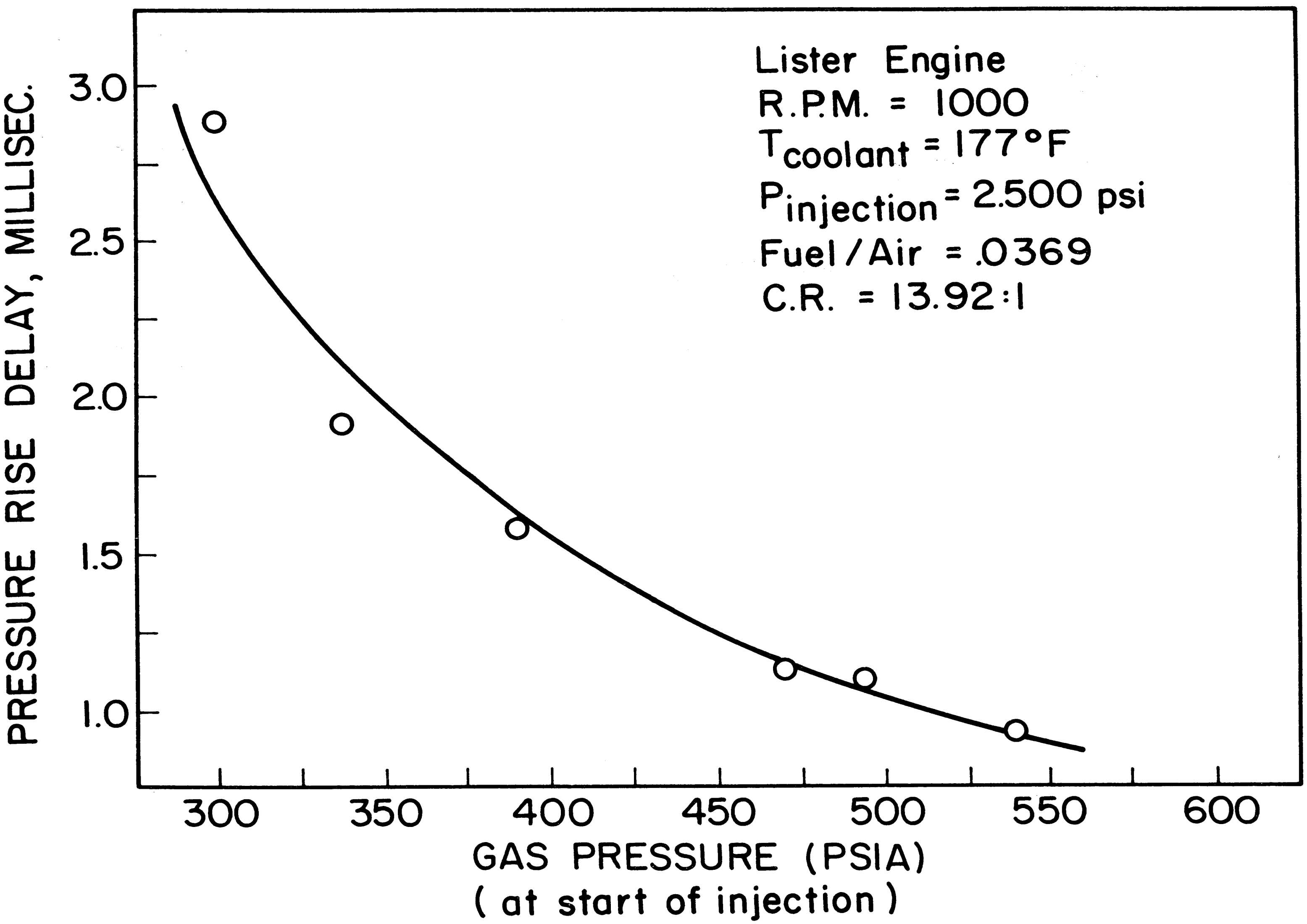


Figure 16. Effect of cylinder pressure on pressure rise delay at 1000 rpm.

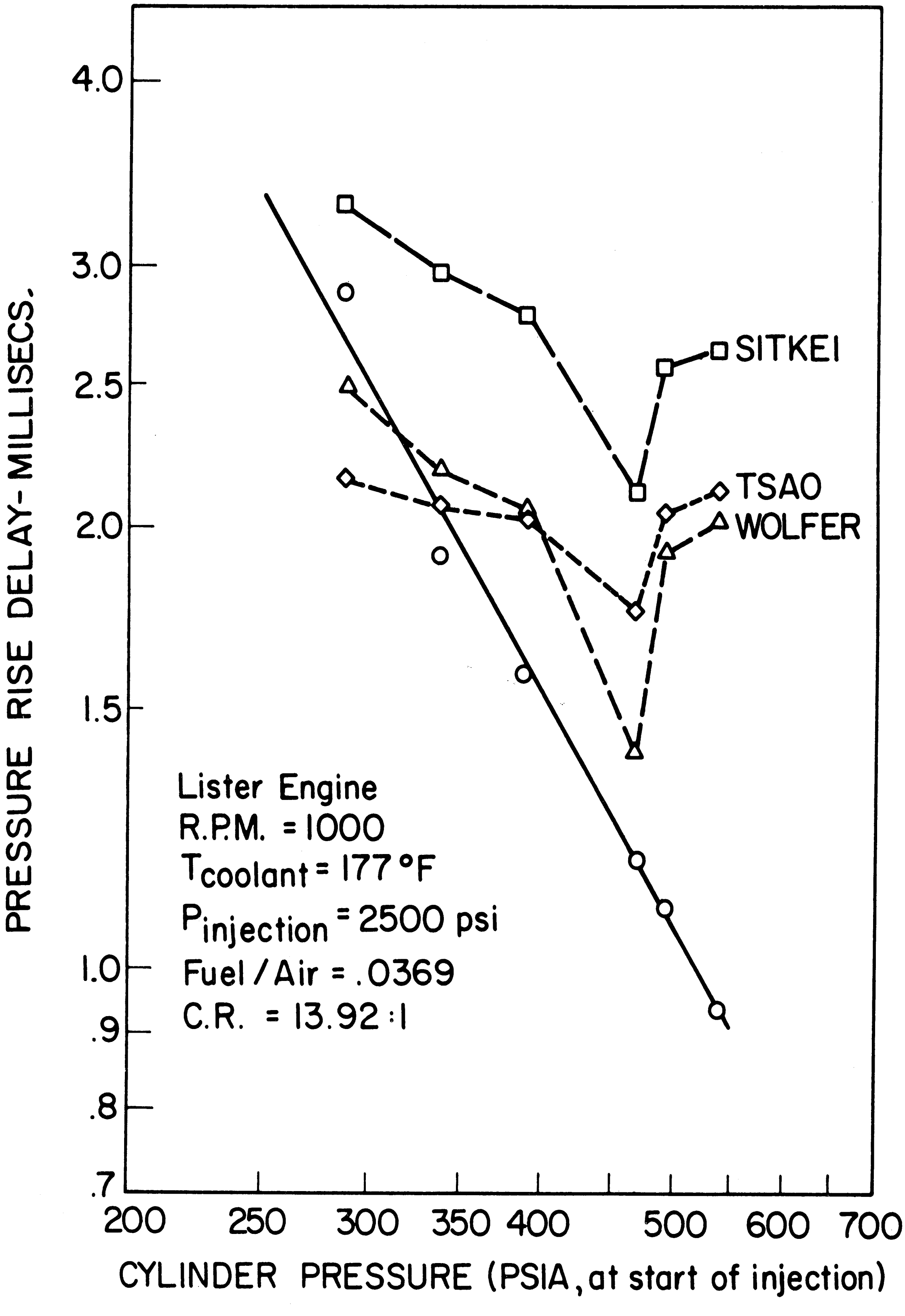


Figure 17. Effect of cylinder pressure on pressure rise delay at 1000 rpm.

perature, Eq. (5). The constant C, and exponent n differ from those reported by Wolfer.[18] The difference between Wolfer's equation, determined from bomb experiments, and Eq. (21) is believed to be principally due to the turbulence, and other factors that will be discussed later.

A comparison is made between the measured ignition delays (solid line) and the values calculated from the available formulae of Wolfer, Tsao, et al., and Sitkei. The results are shown on Figure 17.

EFFECT OF TURBULENCE ON IGNITION DELAY

In the Lister engine the turbulence at the end of the compression stroke is caused by forcing the air through the tangential passage between the main chamber and the spherical prechamber, as shown in Figure 18. At the compression ratio of 13.92:1 used for the runs reported, the volume of the swirl chamber is equivalent to 6.55% of the total swept volume, and the area ratio of the connecting passage to the piston area is 3.22%. With this configuration, the air in the passage is estimated to obtain velocities as high as 164 ft/sec during the compression stroke, at an engine speed of 1000 rpm.[45] The swirl produced in the swirl chamber is directly proportional to the air velocity in the tangential passage.

In order to find the effect of turbulence on the ignition delay and the index n in Eq. (21), a series of runs was carried out at an engine speed of 600 rpm. This will be compared with the previous series at 1000 rpm. During these runs the air surge tank pressure was changed to allow the measurement of the pressure rise delay at different pressures ranging from 260 psia to 650 psia. The results of these runs are shown in Figure 19 together with the results computed from the equations of Wolfer, Tsao, and Sitkei.

By comparing the ignition delays in Figures 17 and 19 it can be noted that the increase in turbulence at the higher engine speed shortens the delay period. The increase in turbulence results in better mixing of fuel and air, and better chances for the production of optimum concentrations and higher rates of chemical reactions. Turbulence also increases the heat loss to the walls. However, the increase in the rate of chemical energy release is believed to exceed the effect of increased heat loss, resulting in shorter delays at higher speeds. The effect of turbulence on reducing the delay period has also been shown by Boerlage and Broeze,[46] Gerrish,[13] Elliott,[27] in a discussion by Landen,[27] El Wakil,[33] Tsao,[36] and Bassi.[47]

Figure 19 indicates also that the linear relationship can express the variation of $I.D._p$ with change in pressure. It is noticed that the index n changes with increase in engine speed. It increases from 1.46 at 600 rpm to 1.775 at 1000 rpm.

One of the factors that contributes to the discrepancy between Wolfer's

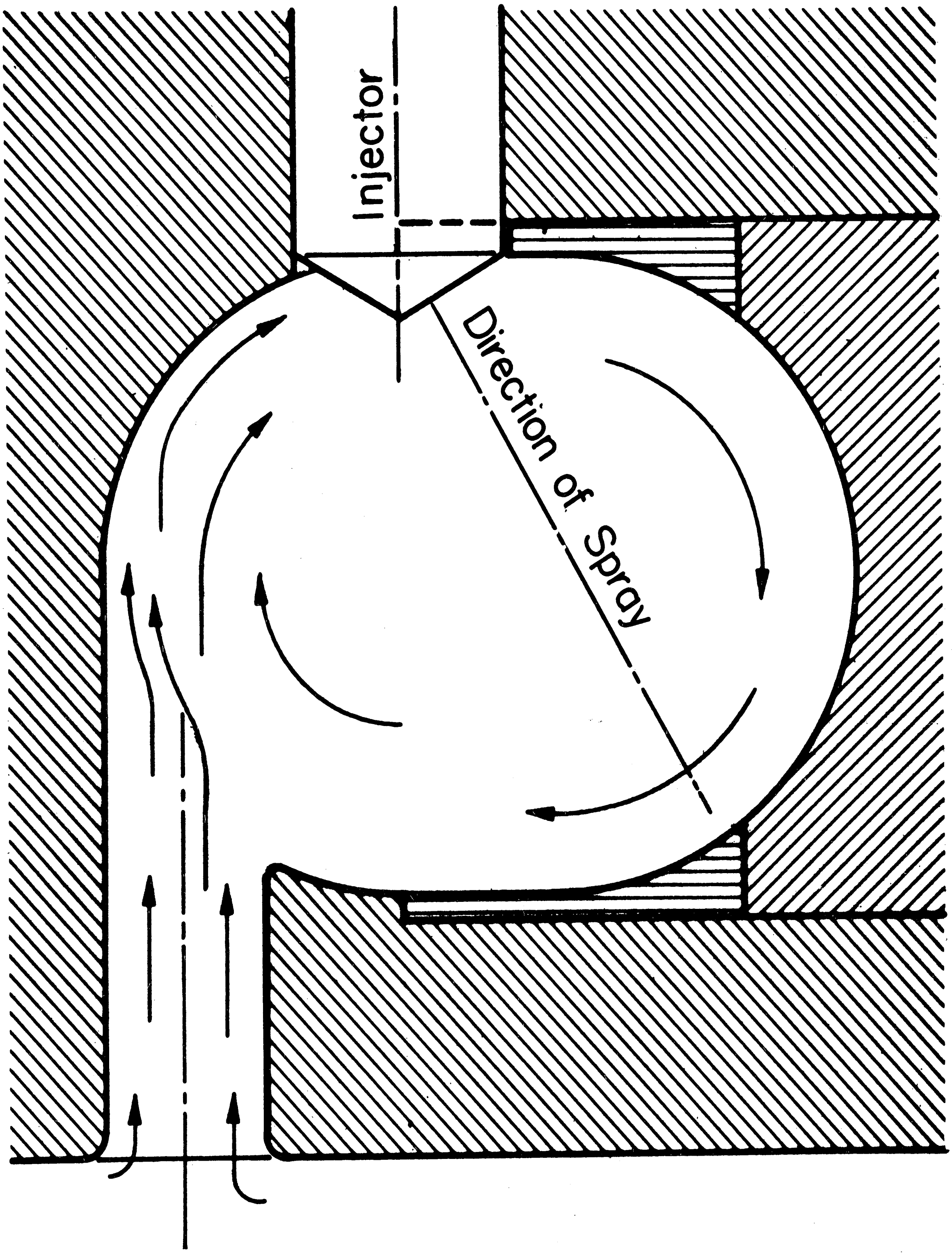


Figure 18. Turbulence in modified combustion chamber of Lister-Blackstone engine.

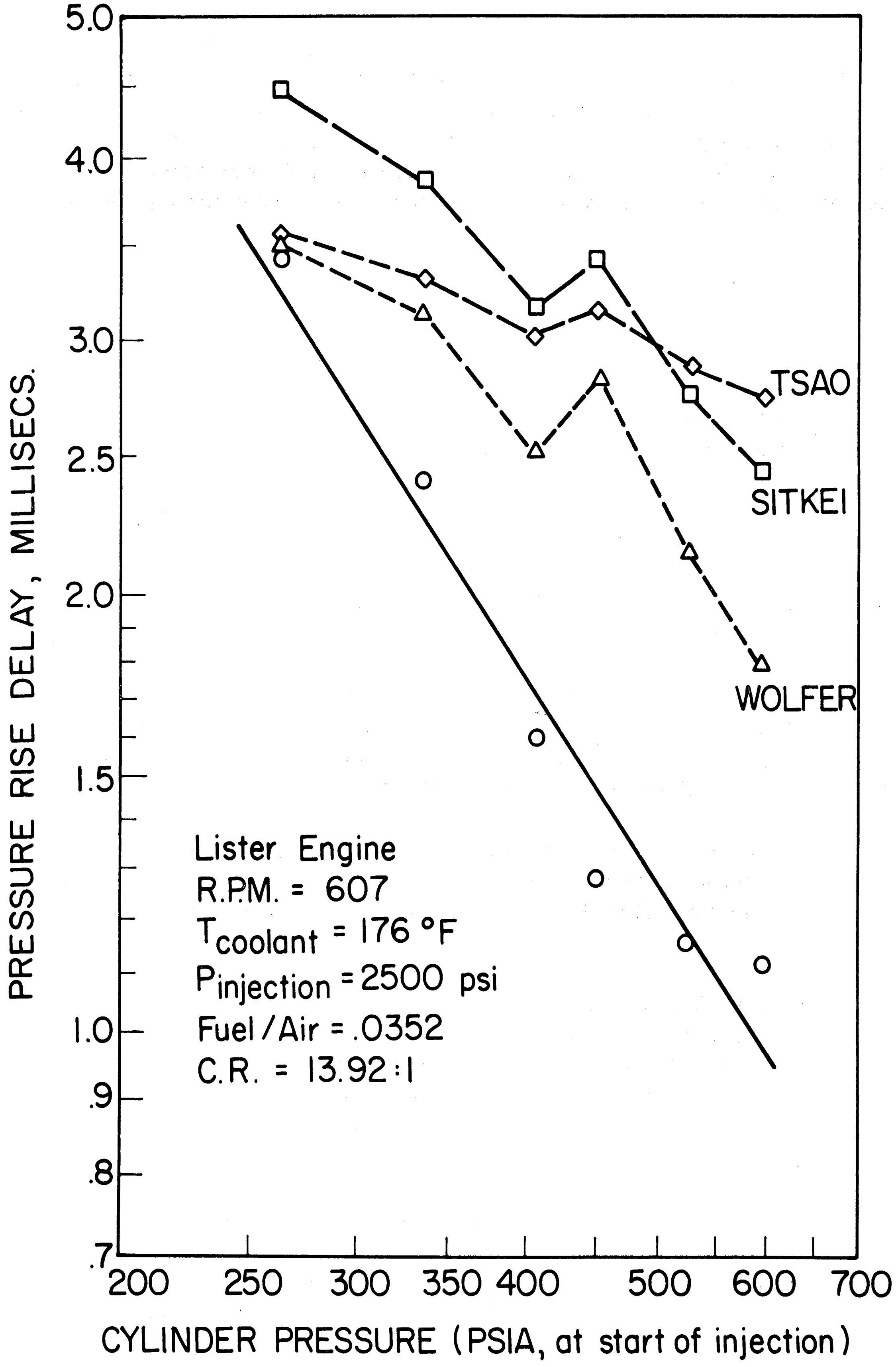


Figure 19. Effect of cylinder pressure on pressure rise delay at 600 rpm.

equation obtained from tests on bombs and the present experiments on an engine is the change of air pressure and temperature during the delay period. In the bomb the pressure is steady and the volume is constant, but in the engine, the volume changes and consequently the pressure changes. In order to account for this effect, the index n and constant C in Eq. (21) were calculated by using the mean pressure during the delay period as found from this relationship:

$$P_{mean} = \frac{\int_{\theta_1}^{\theta_2} P \, d\theta}{\theta_2 - \theta_1} \tag{22}$$

where θ_1 and θ_2 are the crank angle degrees at the beginning and the end of the pressure rise delay, respectively.

The value of n is found to be lower with the mean pressure than with the pressure at the start of injection. This applies for the two engine speeds. The values of n were also computed for all the runs at 600 rpm and 1000 rpm in terms of the pressure at the start of injection and the mean pressure, and were found to be 1.575 and 1.499, respectively.

Comparison of values of pressure rise delay obtained with the Lister engine with those calculated from the equations of Wolfer,[18] Tsao, et al.,[36] and Sitkei,[37] reveal that the Lister engine values are in general shorter than the computed values. This is believed to be due to the following:

1. Except for Wolfer's formula, these formulae were obtained by observing different phenomena. Tsao, Myers, et al., used the temperature rise delay, while Sitkei used the illumination delay.

2. Different types of combustion chambers were used. Wolfer used a constant volume bomb; Tsao, et al., used an open combustion chamber, and Sitkei used a precombustion chamber. In the Lister engine, the turbulence is believed to be higher than for all these engines. This results in different rates of heat addition to, and rejection from the chamber.

3. The volume of the different combustion chambers is not the same. For Wolfer the volume is 146.1 cu in., for Hurn it equals 17.2 cu in., for Tsao it equals 2.52 cu in., for Sitkei it equals 4.63 or 6 cu in., and for our engine it equals 5.377 cu in. The effect of using different volumes on the pressure rise delay can be shown by using Eq. (20). In general larger volumes have longer delays, if all the other factors are kept constant.

4. The rates of injection during the delay period are expected to be different.

5. The fuels used in the different investigations are expected to have different combustion qualities.

To examine the validity of the form of Eq. (21) for ignition delay computations, the published experimental data of West,[25] Tsao, et al.,[36] and Hurn and Hughes[30] were put in a computer program and the values of n and C evaluated. The results are plotted in Figure 20 and given in Table 1. The standard deviation was found to be within 2.4% for all data except that of Hurn and Hughes at an oxygen concentration of 21% where the standard deviation reached 6.0%.

TABLE 1

	Combustion Chamber	No. of Points	C	n	Standard Deviation
West	Engine	6	8.85	0.271	1.8%
Tsao	Engine	5	32.4	0.411	0.9%
Hurn and Hughes at					
1510°R		6	15.9	0.286	0.4%
1460°R	Bomb	6	29.4	0.339	1.5%
1410°R		6	55.4	0.397	2.4%
21% O_2		4	196.0	0.635	6.0%

From Table 1 it can be noted that Eq. (21) correlates very well the experimental data on ignition delay in bombs and engines, at a constant temperature. The exponent "n" is different for each set of data and is different from the exponent given by Wolfer. The turbulence seems to be a factor that influences the exponent "n." The variation in the constant "C" is believed to be mainly due to differences in the gas temperature between the different sets of runs.

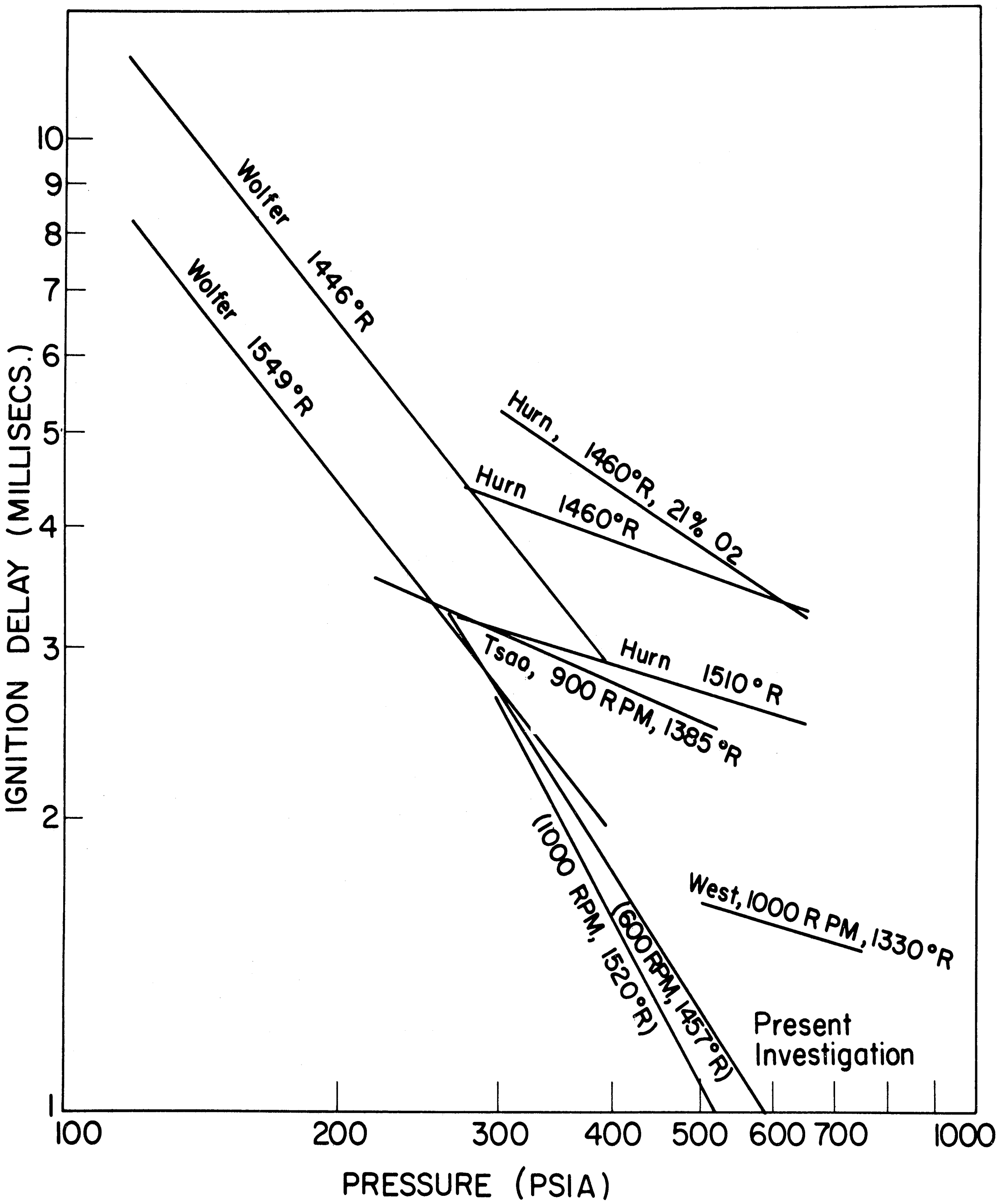


Figure 20. Effect of pressure on ignition delay for different bombs and engines.

CONCLUSIONS

1. The criteria which are most useful to indicate the start of diesel combustion are the pressure rise due to combustion, and the illumination resulting from combustion.

2. Our experimental work showed that in general illumination due to combustion does not occur simultaneously with the pressure rise. Illumination usually occurs after measurable pressure rise, or in other words, the illumination delay period is longer than the pressure rise delay.

3. Measurement of ignition delay in terms of the pressure rise is the most practical, and was found to be the more reproducible. It also has the greater engineering significance.

4. The engine tests demonstrate that increase in cylinder air pressure, fuel/air ratio, cooling water temperature, and engine speed shorten the delay period. Change in fuel injection pressure has a little effect on the pressure rise delay, but greatly affects the illumination delay.

5. The best equation for correlating the pressure rise delay and the cylinder air pressure at the start of injection with constant air temperature, is found to be similar to that of Wolfer,[18] and is

$$\mathrm{I.D.}_p = \frac{C}{P^n}$$

the value of n is found to be a function of speed. At 600 rpm it has a value of 1.46, and at 1000 rpm, $n = 1.77$. This is believed to be due to the increase in turbulence with increase in speed. These values of n are greater than those reported by Wolfer, taken in a bomb with some induced turbulence. It is probable, however, that this turbulence was much less than that of the swirl chamber of the Lister-Blackstone engine.

6. Analysis indicates that the measured pressure rise ignition delay is partially dependent on several thermodynamic characteristics of the chamber including its volume, rates of heat addition and loss, and any work done during the delay period. A portion of the differences in the ignition delays reported for bombs and engines are due to these factors.

APPENDIX I

LIST OF SYMBOLS

a' = concentration

A = area

b, b' = constants

c, C = constants

C.A. = crank angle

C.R. = compression ratio

c_v = specific heat at constant volume

d = diameter

E = energy of activation

F_n, F_n' = functions

I.D. = ignition delay, milliseconds

J = mechanical equivalent of heat

K, K_1 = constants

m = mass

n, n' = exponents

N = engine speed, rpm

P = pressure

Q = heat quantity

R = gas constant

T = temperature

U = internal energy

U_r = energy of reaction

V, V' = volume

w = velocity of chemical reaction

W = work

x = exponent

θ = crank angle, degrees

α = overall coefficient of heat transfer

Subscripts

c = cooling

Ch = chemical

g = gas

Il = illumination

p = pressure

Ph = physical

T = temperature

W = wall

APPENDIX II

CALCULATION OF $dP/d\theta$

According to the first law of thermodynamics for a closed system

$$\frac{dQ}{d\theta} = \frac{dU}{d\theta} + \frac{dW}{d\theta}$$

The internal energy U of the system is equal to the sum of the internal energies of the air and the fuel. For this analysis the system is assumed to follow the ideal gas laws because the fuel is found to be evaporated immediately after injection,[46] and its amount during the delay period is very small compared to the mass of air. Therefore

$$\frac{dQ}{d\theta} = m\, c_v \frac{dT}{d\theta} + P \frac{dV}{d\theta} \tag{23}$$

From the equation of state $dT/d\theta$ is given by:

$$\frac{dT}{d\theta} = \frac{1}{mR}\left[P\frac{dV}{d\theta} + V\frac{dP}{d\theta} - TR\frac{dm}{d\theta}\right] \tag{24}$$

Substituting in Eq. (23)

$$\frac{dQ}{d\theta} = P\frac{dV}{d\theta}\left[\frac{c_v}{R} + 1\right] + V\frac{dP}{d\theta}\cdot\frac{c_v}{R} - T\,c_v\frac{dm}{d\theta} \tag{25}$$

The slope $dP/d\theta$ is obtained from Eq. (25) as

$$\frac{dP}{d\theta} = \frac{R}{c_v}\cdot\frac{1}{V}\left[\frac{dQ}{d\theta} - P\frac{dV}{d\theta}\left(\frac{c_v}{R} + 1\right) - T\,c_v\frac{dm}{d\theta}\right] \tag{26}$$

Equation (26) relates the slope of the pressure trace to the rate of heat addition to the system, pressure, volume, mass, specific heat, and the gas constant.

APPENDIX III

CRANK POSITIONS FOR MAXIMUM PRESSURE AND TEMPERATURE IN A MOTORED ENGINE

It has commonly been assumed that the maximum pressure occurs at T.D.C. in a motored engine and the pressure would rise during compression and fall again symmetrically during expansion. Often the maximum pressure points has been used to determine the phase relationship. In our experimental data on the Lister engine it was noticed that the point of maximum pressure occurs in advance of the T.D.C. as shown in Figure 21. In this report the difference between the crank angle at which maximum pressure occurs, and the T.D.C., will be called the maximum pressure advance in a motored engine. After re-examining the accuracy of the marking unit, which is set to determine the crank degrees on the scope screen, the engine was motored in the reverse direction. The pressure traces obtained indicated that maximum pressure also occurs, at almost the same point, before T.D.C. The difference between the maximum pressure advances in the two opposite directions is 0.2° of a crank angle. This is considered to be due to the change in heat losses caused by the change in valve timing when the engine was cranked in the opposite direction. This test indicated that the settings of the degree marking disc and pickup probe are correct.

A thermodynamic analysis was then made on the air during the compression stroke and the following formula was obtained for the pressure gradient at T.D.C.

$$\frac{dP}{d\theta} = \frac{R}{c_V} \cdot \frac{1}{V} \cdot \frac{dQ}{d\theta}$$

where $dQ/d\theta$ = rate of heat transfer to the air with repsect to crank angle.

At the end of the compression stroke the heat transfer $dQ/d\theta$ has a negative sign because heat is lost from the air to cylinder walls. Therefore $dP/d\theta$ should have a negative sign indicating that the maximum pressure for a motored engine should occur before T.D.C. In Figure 22 the pressure and temperature are plotted vs. crank angles for the motoring run shown in Figure 21. The maximum temperature advance amounts to 4.5 crank angle degrees. The drop in air temperature at T.D.C. is 11.7°F below the maximum temperature.

This conclusion is also supported by published data of Tsao, et al.,[36] for the compression temperature in a diesel engine. The compression temperature was measured by applying the infrared null method. Figures 3, 5, and 9, of this reference, indicate that the maximum temperature occurs before T.D.C.

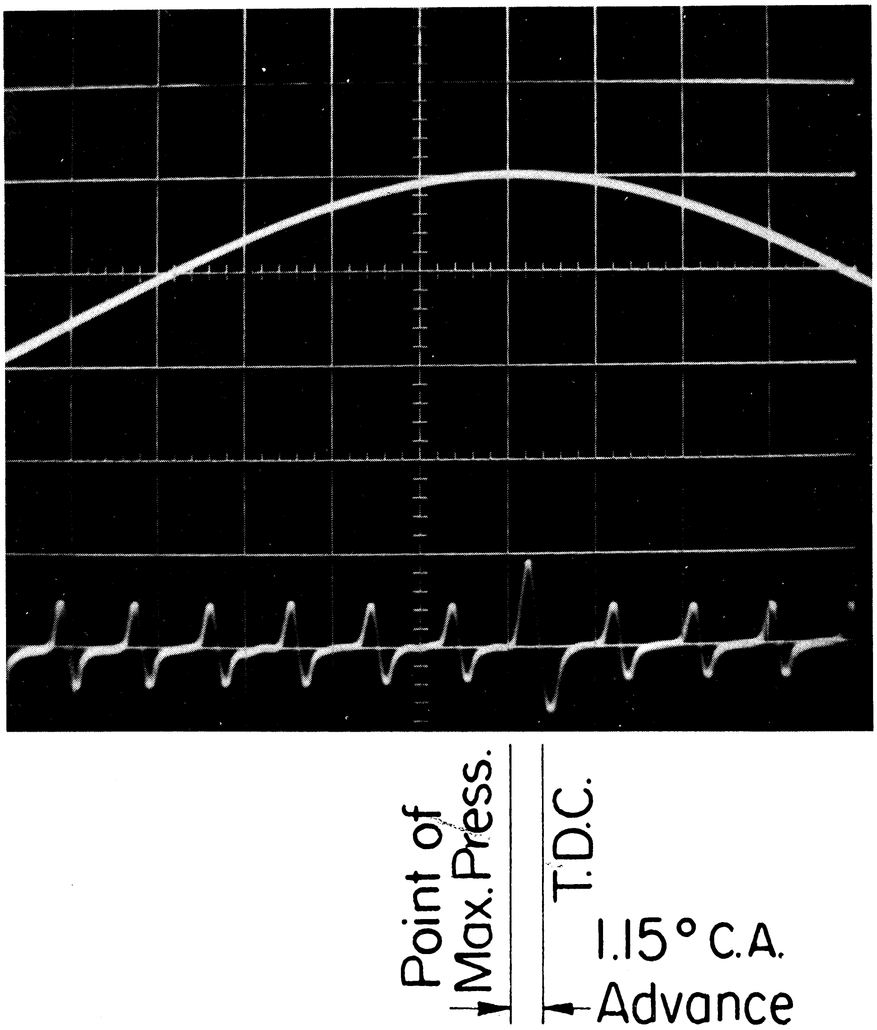


Figure 21. Maximum pressure advance in motored Lister-Blackstone engine.

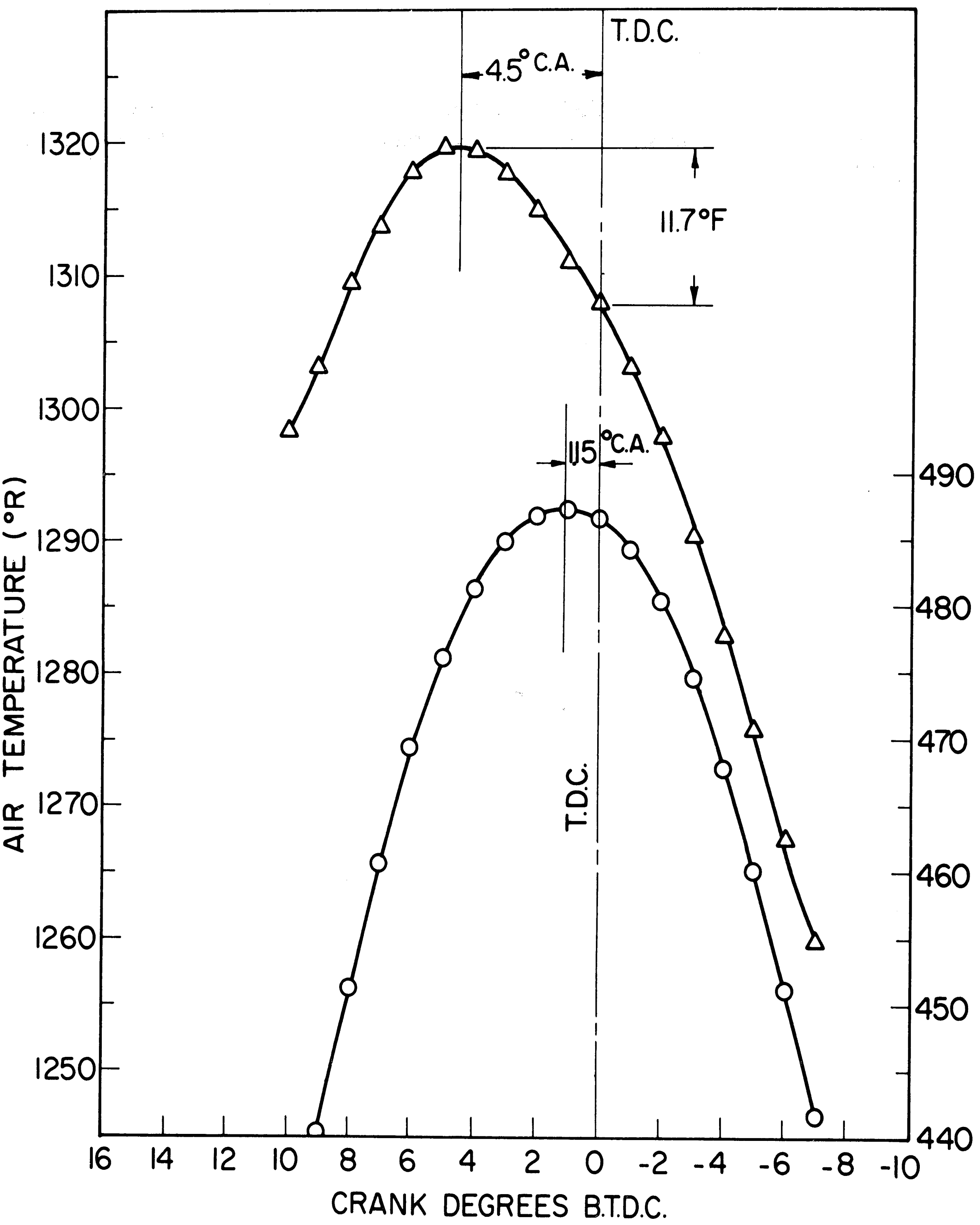


Figure 22. Maximum pressure and temperature advances in motored Lister-Blackstone engine.

during the compression stroke.

This analysis indicates that the maximum pressure and temperature advances at the end of the compression stroke of a motored engine are mainly caused by the cooling losses.

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