EFFECTS OF BLENDING OF FUELS ON THEIR IGNITION QUALITY AND PERFORMANCE IN C. I. ENGINES

A dissertation submitted in partial fulfilment
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CERTIFICATE

CERTIFIED that dissertation entitled "EFFECTS OF BLENDING OF FUELS ON THEIR IGNITION QUALITY AND PERFORMANCE IN C.I. ENGINES," which is being submitted by Sri GAJENDRA SINGH in partial fulfilment for the award of the Degree of Master of Engineering in APPLIED THERMODYNAMICS of University of Roorkee is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

This is further to certify that he has worked for a period of 9 months from 1st October 1964 to 30th June 1965 for preparing dissertation for Master of Engineering Degree at the University.

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ABSTRACT

In compression-ignition engines there is always some time lag between the point of injection and start of burning of fuel which is known as "Ignition delay". The magnitude of this delay governs, to a large measure, the subsequent performance of the fuel in the engine. Generally speaking, we endeavour to reduce the ignition delay as much as possible.

The effect of blending of fuels on their ignition quality were studied at different operating conditions of the engine by means of their ignition delay. Secondary reference fuels were used as a standard of comparision for different blends. Pressure-time diagrams were recorded to study the performance of the engine.

Data obtained with diesel-petrol blends at various operating conditions of the engine, indicate that the delay angle of the blend increases as the percentage of petrol in the blend increases. Thus the addition of petrol deteriorates the ignition quality of diesel fuel although, under some conditions, the engine runs smoother and quieter. The addition of lubricating oil in diesel as well as petrol, however, improves their ignition behaviour, but this improvement is at the cost of carbon deposit on the cylinder walls. Addition of diethyl ether to diesel fuel increases the cetane number slightly. Amyl-nitrate has been shown to be as a good ignition accelerator for both diesel as well as petrol. Manifold introduction of petrol did not show any improvement in the ignition quality of pure diesel, while diethyl ether

showed considerable improvement.

On the basis of the experimental data a correlation relating the pressure and temperature of intake air, the effective compression ratio at the point of injection, the cetane number of the fuel and the ignition delay has been proposed. The results from this correlation are compared with those obtained on CFR engine by other investigators, and it has been shown that the difference is very small. Further, it has been shown that this correlation has a wide range of application.

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CHAPTER I

SURVEY OF PREVIOUS WORK AND STATEMENT OF THE PROBLEM

1.1 INTRODUCTION

In compression-ignition engines when fuel is injected into the engine cylinder, it does not ignite immediately, but rather there is a delay period which is known as "Ignition lag" or "Ignition delay". The phenomena occuring during this period have been observed and studied ever since the diesel engine first assumed its role as one of the primary sources of power. That these studies have been helpful is evidenced by the constant improvement in efficiency and flexibility of diesel engines. Nevertheless, a complete understanding of the phenomena that occur during the ignition delay period has still to be achieved. Unlike S.I. engines, combustion studies in a diesel engine are complicated by the heterogeneous nature of fuel-air mixture. Hence any detailed information on events occuring during ignition delay is of interest.

1.2 SIGNIFICANCE OF IGNITION DELAY

For many years we have been using the term ignition delay, although it has never been precisely defined. Start of the injection is a logical and accepted choice for the start of the ignition delay period. Choice of the end of the delay period is not so clear cut. Different investigators have defined it according to their convenience. For example, Hurn et al defined the end of delay as the time at which the cylinder pressure rose to 10 pound above the charging pressure. Yu et al defined the end of the ignition delay as occurring when the rate of pressure rise due to combustion exceeds the maximum rate of pressure rise during compression. However, the end of ignition delay is most commonly taken as the time when the combustion curve departs from the compression curve.

But, whatever may be the definition of ignition delay, it is an accepted fact that this period is made up of two parts i.e. physical delay and chemical delay. The period of physical delay is the time between the beginning of injection and the beginning of chemical-reaction. During the physical delay period, the fuel is atomized, vaporized, mixed with air and raised in temperature. In the next stage, called the chemical delay, reaction starts slowly and then accelerates until inflammation or ignition takes place. However, in running engines it is difficult to distinguish between these two periods, so the delay period is measured from the beginning of the injection to the moment of ignition.

The delay period presents a great interest, as it materially influences the operation of an engine and it is used invariably as a measure of the ignition quality of fuels. A shorter delay period gives a smoother operation; a longer delay period results in a rougher and noise running engine.

Although we want to keep the delay period short, there is, however, a lower limit beyond which we must not go.

Let us consider what would happen if there is no delay period at all, and if the droplets ignited immediately they left the injector nozzle. We would then have a concentration of burning droplets so closely packed that it would be impossible to distribute among them the air needed for their complete combustion. We need, therefore, a certain delay period in order to allow the droplets to disperse, to some extent at least, before ignition takes place. Generally speaking, however, the delay period imposed upon us is greater than what we need or desire and our efforts are devoted towards shortening it as much as we can.

1.3 REVIEW OF PREVIOUS WORK ON IGNITION DELAY MEASUREMENTS

A considerable amount of research work has already been carried out in studying the ignition delay phenomena and its measurements in compression-ignition engines. Some of the early experiments were made with pressure bombs or pressure vessels and they were correlated with engine conditions while most of the later investigations were carried out on actual engines. These studies were undertaken with the following objectives:

(i) to explore the various factors that affect the delay and how they can be controlled to improve the overall performance of the engine.

(ii) to make a detailed study of the various components of ignition delay with a view to improving the combustion phenomena of the engine.

Boerlage et al have shown that although the actual value of the ignition delay may vary from engine to engine, the order of magnitude of these values can be correlated for all ordinary compression-ignition engines with the cetane number. Their experimental work was generally directed towards measuring this quantity and to correlate it under specified conditions with the cetane number.

Le Mesurier and Stansfield investigated the influence of temperature upon delay in an actual engine. They maintained the temperature of the air received by the engine and also that of the jacket water uniform, and varied it over a wide range of temperature (from 20°C to 100°C) with engine running at a speed of 1000 rpm. Tests of several fuels of different ignition quality exhibited a progressive decrease in delay as the temperature was increased. The fuels having good ignition quality were less sensitive to temperature variation than those of lower ignition quality but all showed the same trend.

Boerlage and Broeze investigated the influence of air density upon the delay in an engine and showed that a reduction in air density involves a very material increase in the delay period of all fuels, together with an increase in the rate of pressure rise and in the tendency towards roughness in running. They employed a method of throttling the air intake and thus reducing the density of air received by the engine.

Tsao et al measured the gas temperatures during compression for fired and motored diesel engines under various operating conditions and studied their effects on ignition delay. Some of their significant results are mentioned below:

(i) The observed ignition delay decreases as the fuel quantity increases at high loads. Probably the higher gas temperature at higher loads helps to decrease the delay. Dicksee has also shown that the ignition delay decreases with an increase of load.

(ii) An increase in the ratio of $\frac{P_i}{P_o}$ decreases the ignition lag. It is quite probable that the increased $\frac{P_i}{P_e}$ ratio increases turbulence during the intake process, and this increased turbulence causes a decrease in delay over and above that caused by the increased pressure.

(iii) The ignition delay increases in terms of crank angle degrees, and it decreases in terms of absolute time, as the engine speed increases. They, however, kept the temperatur and pressure at the point of injection constant as the speed wa varied. The probable causes for the above reduction in igniti delay was due to the changes in the air flow pattern inside th cylinder, the spray characteristics, and possibly the change i fuel impingement.

(iv) They observed no significant effect on compress temperature by varying the cetane number of the fuel.

EL-Wakil et al have summarized some of the known experimental facts concerning ignition lag as follows:

(i) An increase in inlet air pressure and temperatur in fuel temperature, and in jacket water temperature, all decrease ignition lag to varying degrees.

(ii) Ignition lag (measure in absolute time units) decreases with engine speed. This is generally attributed to an increase in turbulence with speed. However, Small found that in a bomb, increased turbulence did not give decreased ignition lag. Probably, actual compression temperature increases with speed.

(iii) There is reasonably good inverse relationship between the cetane and octane scales. Since ignition delay i a spark-ignition engine is predominantly chemical, octane number would presumably be related to chemical delay. This would indicate that chemical delay is rate-determing.

(iv) While fuel volatility seems to affect ignition lag, the accompanying change in fuel structure seems more important. For example, iso-octane and n-heptane have markedly different ignition lags but about the same volatility, while cetane and iso-octane are markedly different in both volatili and ignition lag.

(v) Small concentrations of additives affect ignitio lag. Although possibly these small concentrations (0.5 - 1.0% or less), affect spray formation and physical delay, it seems more likely that they act in a chemical manner.

(vi) In a constant volume bomb with everything else held constant, an increase in quantity of fuel injected increases ignition lag if combustion begins near the end of ignition. This would indicate a fuel cooling or a concentration effect.

Some investigators at the University of Wisconsin under the guidance of Myers and Uyehara made a detailed study of physical and chemical components of ignition delay in an operating diesel engine. They used the hot-motored technique which consisted of obtaining two successive pressure-time records —

a normal, fired cycle, and the next with the injector rack pulled back so that no fuel is injected. In addition to the hot-motored cycle, a nitrogen cycle was also used in some of the experiments. Their findings can be summarized as follows:

(i) As distance from the spray center increases, the air-fuel mixture becomes leaner with consequently higher air-vapour temperatures. Under these conditions adiabatic saturati is approached less rapidly.

(ii) The closeness and rate of approach to adiabatic saturation condition varies with distance from the spray core in a different manner for fuels of different viscosities and volatilities.

(iii) A volatile fuel does not receive heat that much more rapidly than a non-volatile fuel, as would be expected f differences in their volatility.

(iv) Physical delay is not a negligible portion of total ignition delay. It forms a part of about 50-60% of the total ignition delay for fuels having cetane number between 4 to 80.

(v) Injection delay is not of negligible magnitude in an operating engine. However, it does not vary much with different cetane number fuels.

(vi) While there are some differences in the way in which different fuels receive heat following spray break-up, major difference between fuels of varying cetane number lies in the manner in which they release chemical energy during very early reactions.

(vii) For the same fuel, total, physical and chemical delays are smaller in an operating engine than in a combustion bomb operated at the highest temperatures estimated to exist in the engine. It is attributed due to the fact that macroscopic turbulence (as opposed to microscopic turbulence) tends to bring fresh air into the spray center and thus aids in eliminating adiabatic saturation conditions and increasing possibilities of achieving a combustible mixture at self-ignition temperature. This same reasoning also explains decrease in ignition delay with increase in engine rpm, although compression temperature undoubtedly increases somewhat with rpm.

(viii) Different fuels and different nozzle configurations give different spray characteristics. These different spray characteristics result in different local air fuel ratios, and thus affect the adiabatic equilibrium temperature.

(ix) Since the physical characteristics of the fuel affect the adiabatic equilibrium temperature and the spray characteristics and since chemical reaction rates are markedly affected by temperature, it follows that physical characteristics of the fuel affect the chemical delay as well as the physical delay.

(x) After chemical reaction have started there are differences between fuels in the rate at which the chemical reaction proceed. This rate of increase is higher for high-cetane fuels and this is undoubtedly the cause of the less harsh combustion experienced with the high cetane fuels. On the other hand, low cetane fuels seem to have comparatively slower early reaction rates followed by very rapid reactions and harsh combustion.)

1.4 CORRELATIONS PROPOSED BY VARIOUS INVESTIGATORS

As already discussed the ignition delay in a diesel engine depends primarily upon the following factors:

(i) pressure of the charge
(ii) temperature of the air charge
(iii) atomization of the fuel
(iv) timing of injection
(v) engine speed, and finally
(vi) ignition quality of the fuel, its cetane number, and its physical characteristics.

Although all these factors affect the length of the delay period appreciably, tests indicate that, for a given fuel, the influence of temperature and pressure of the air in the combustion chamber are more pronounced than all other factors.

Based on these factors, various correlations between ignition delay and other engine variables have been proposed by various investigators from time to time. Some of these were based on theoretical analysis whereas others were entirely on experimental values. Here in this section we are going to consider them individually and see how far they are applicable to suit all requirements in modern compression-ignition engines.

1.4.1 Wolfer's Correlation

A valuable investigation was carried out in 1939 at

Cambridge University by Dr. Wolfer who used chain reaction theory to relate ignition delay to pressure and temperature by the following equation:

$$\text{Ignition delay} = f\left[\frac{e^{\frac{a}{T}}}{P^{n}}\right]$$

where a and n are constants ($a = \frac{E}{R}$ where E is a constant characteristic of the reaction and known as the energy of activation and R the molar gas constant) T and P are the absolute temperature and pressure of air at the point of injection respectively. This relation indicates that ignition lag is decreased by an increase in temperature and pressure.

Dr. Wolfer evaluated the constants by using data from experiments in which liquid paraffin hydro-carbons were sprayed into heated air in bomb's and expressed the above equation as follows:

$$t = \frac{0.44\ e^{\frac{4650}{T}}}{p^{1.2}}$$

where

t = Ignition lag in millisecs

p = air pressure in atmospheres at the point of injection

T = air temperature in $^{\circ}$K at the point of injection (a = 8200, when T is in $^{\circ}$R)

e = base of Naperian log.

He later on used two different fuels namely Persian 'Diesoleum' of specific gravity 0.85, and Venezuelan 'Britoleum' of specific gravity 0.92 and found no marked difference between the values.

He, however, revised the pressure dependence and finally expressed the equation as follows:

$$t = \frac{0.44\, e^{\frac{4650}{T}}}{p^{1.19}}$$

Other investigators also supported the above expression.

This equation is very valuable as it is based on theoretical considerations but cannot be used in modern practice due to the following limitations:

1. Strictly speaking the equation applies only to chemical delay in a homogeneous gas-phase reaction.

2. The values of the constants evaluated by Dr. Wolfer was from the bomb experiments. But the values of ignition lag are much higher in bombs than in fired engines. Tsao et al have actually plotted the values for bombs as well as for fired engines and a marked difference in ignition delay values were obtained.

3. The values of the constants evaluated should not be the same for different fuels and may be different under different operating conditions of the engine.

1.4.2 Olson's Correlation

While developing a mathematical relationship between combustion characteristics and fuel physical properties, Olson et al expressed a general form of regression equation as follows:

$$Y = a + b(C) + c(A) + d(P) + e(O) + f(10) + g(50) + g(90)$$

where

Y = Ignition delay deg. or
Average rate of pressure rise, psi/deg or
Maximum combustion pressure, psig
C = Cetane number
A = Volume percent aromatics
P = Volume percent paraffins
O = Volume percent olefins
10 = Distillation temperature for 10% recovered, F
50 = Distillation temperature for 50% recovered, F
90 = Distillation temperature for 90% recovered, F

Here the values of constant a and the regression coefficients b, c, d etc. are dependent on the engine and operating conditions. The above equation can be evaluated after numerous experiments on a particular engine by the use of a computer.

The above equation would seem to be very useful but it cannot be applied easily in daily practice due to the following reasons:

1. It requires a very large amount of experimental data for evaluating the various constants.

2. Physical properties of the fuel used should be known. For each case the constants will vary appreciably.

1.4.3 EL-Wakil's Correlation

EL-Wakil et al analysed ignition delay from self-ignition of fuel drops when subjected to air stream at high temperatures and at atmospheric pressure. They have suggested the following two correlations for physical and total ignition delays separately:

$$t_p = 1.10\,D_o^{0.5}\left(0.025 + \frac{1}{T_B - 1850}\right)n^{0.465}$$

$$t_t = 10.3\,D_o^{0.85}\,e^{A + Bn}$$

where

t_p = Physical ignition delay in Secs.

t_t = Total ignition delay in Secs.

D_o = Initial diameter of drop in.

T_B = Free stream air temp. ^oR

$A = 20.5 - 35.9\left(\frac{T_B}{1850}\right)^2 + 13.2\left(\frac{T_B}{1850}\right)^4$

$B = 0.364\,(7.775 - \log T_B)$

n = number of carbon atoms in a molecule

The accuracy of the above two correlations is ± 7%. They are useful for the following ranges of operation:

n between 8 and 16

D_o between 0.050 and 0.070 inches

Initial drop liquid temperature between 200 and 250°F.

These correlations again are not of much utility as they cannot be used in engines due to the following reasons:

1. They are found out for pure-hydrocarbon fuel drops. They cannot equally be applied for fuels whose molecular struc-

ture is a complex one.

2. Initial diameter of the drop cannot be found out easily in engine case.

3. Temperature of the air in the engine will be different than the free stream air temperature due to turbulence.

1.4.4 Tsao's Correlation

Tsao et al studied the effect of operating variables on compression temperature, both in motored and fired engines. During this investigation they tried to develop an expression for ignition delay as a function of air pressure, air temperature, and engine r.p.m. In order to get the desired expression, data were taken for.

(i) The variation in ignition delay with variation in pressure at the point of injection at constant rpm and temperature at the point of injection.

(ii) The variation of ignition delay with variable temperature at the point of injection at constant rpm and pressure at the point of injection.

(iii) The variation of ignition delay with engine rpm at constant temperature and pressure at the point of injection.

The empirical relationship developed relating the temperature, pressure, engine speed, and ignition delay is:

$$D = 1000\, e^{X} - 1000$$

where

$$X = \frac{1}{1000} \left(\frac{123}{P} + 0.415\right) \left\{ \left(- \frac{36.3}{T} + 0.0222\right) N + \left(\frac{47.46}{T} - 26.66\right) + \left(\frac{T}{1000} - 1.45\right)\left(\frac{1000 - N}{60}\right) \right\}$$

which can be simplified as:

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

where

D = Ignition delay, millisec.

T = Temperature at the point of injection °R

P = Pressure at the point of injection, psia

N = Engine speed, rpm

The maximum deviation found between the experimental and calculated values was ± 5%.

The above correlation is of great utility and help because any one of the missing value can be readily found out very accurately by simple calculations. However, it suffers from the following shortcomings:

1. The expression does not account for any change of fuel. Changing the fuel for the same pressure, temperature and speed, will also alter the value of delay angle. Hence the same expression cannot be used. The above expression is applicable to 40 cetane number fuel only.

2. By changing the engine, the constants in the

expression may be changed.

3. Measurements of pressure and temperature at the point of injection also involve a good amount of instrumentation on the engine.

Thus we see that the study of the previous investigators was concentrated towards studying the ddtailed phenomena of ignition delay under various operating conditions using one single fuel in diesel engines. They, however, tried to correlate this delay with engine variables, but no single correlation could satisfy all operating conditions. At the same time, so far, no attempt seems to have been made to find out the ignition characteristics of various fuel blends and their ignition delays.

1.6 STATEMENT OF THE PROBLEM

In view of the foregoing remarks, it appeared desirable to conduct some experimental work on various fuels in compression-ignition engine. The present investigation was, therefore, undertaken with the following aims:

A. To find the effects of blending of fuels on their ignition quality and performance in C.I. engine.

B. To arrive at some correlation between ignition delay and other engine variables.

CHAPTER II

EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 EXPERIMENTAL SET-UP

The experimental apparatus comprises the following:

2.1.1 Testing Unit

The Testing Diesel Unit BASF has been chosen and instrumented for this project. Cetane numbers determined by this testing unit agree with the ratings of other acknowledged Testing Diesel Units, especially that of the ASTM D-613 Method (CFR - Engine). The set up of the unit is in accordance with the German Standard Method: "DIN 51773", which describes the determination of ignition quality of diesel fuels.

The unit consists of the following parts:

1. Testing engine
2. Electrical equipment
3. Measuring devices

Testing Engine

The main specifications of the testing engine are summarised in Table 1 and the cross-section of the engine is shown in Fig. (1).

TABLE 1

Test Engine Specifications

Type: Single cylinder compression-ignition engine, four stroke cycle with vortex chamber.

Dimensions:

Bore	95 mm. ($3\frac{3}{4}$ in.)
Stroke	120 mm. ($4\frac{3}{4}$ in.)
Capacity	850 cm^3 (52 cu. in.)
Compression ratio	18.2:1

Valve timing:

Inlet valve opens	10 deg. btdc
Inlet valve closes	26 deg. atdc
Exhaust valve opens	36.5 deg. bbdc
Exhaust valve closes	10.5 deg. atdc
Valve clearance (cold)	0.20 mm. (0.008 in.) both valves
Power	6.8 BHP approximately at 1000 RPM
Speed	1000 RPM

Engine accessories include an evaporative-type cooling system (212°F water-jacket temperature), and a lubricating oil system composed of a cooler, a filter, and a pump.

Electrical equipment

The electrical equipment mainly consists of a three phase A.C. Motor 220/230 volts, 4 kilowatts for cranking and loading, coupled with the test engine, and which maintains a speed of 1000 RPM.

Measuring devices

Delay angle can be measured by two means:

(i) By means of Neon-flash indication.

(ii) By means of Electronic ignition delay meter.

①The neon-flash indication device has a contact on the injection needle, which opens when the needle begins to left. This contact serves as a pick-up for the commencement of the injection.②The beginning of combustion is indicated by means of Neumann's inertia pick-up which is screwed into the combustion chamber. (Refer Figs. 2 and 3.)

③To obtain electronic ignition delay indications the Ignition-Delay Meter ECS I of the Solatron Electronic Group Ltd. is attached to the Testing Diesel Unit BASF. ✓ The indications of the Ignition-Delay Meter are derived from electrical impulses of short duration, which are produced by the beginning of fuel injection and the combustion commencement, respectively, from electro-magnetic pick-ups. These impulses are led to the amplifier, where they are changed electrically for the purpose of reading the crank angle interval between the two time marks of the ignition delay mentioned above. It is possible to measure crank angles by an accuracy of $\pm \frac{1}{4}^{\circ}$ and to discriminate to $\frac{1}{10}^{\circ}$ of crank angle.

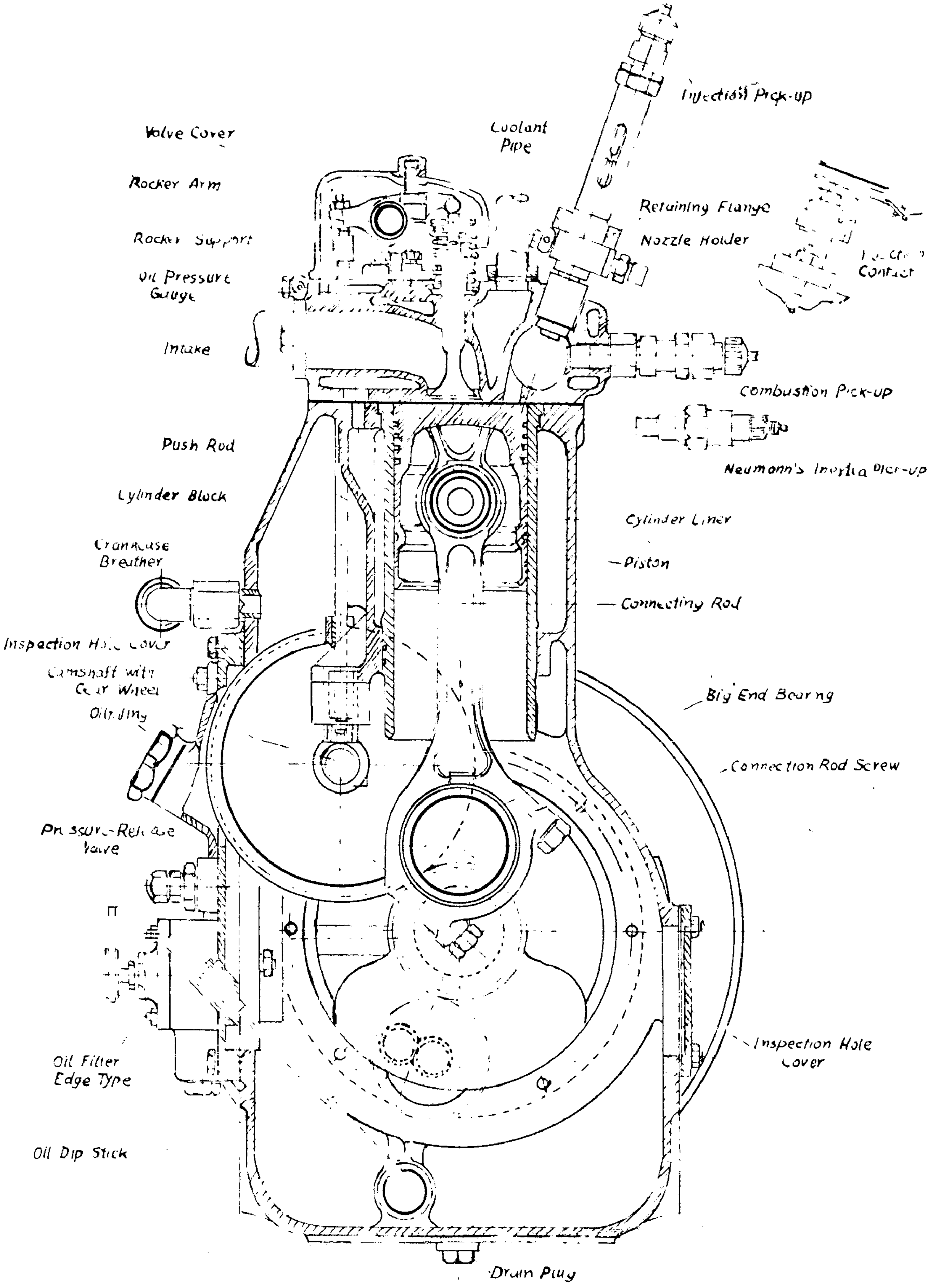


FIG 1. CROSS SECTION OF THE TESTING DIESEL UNIT BASE

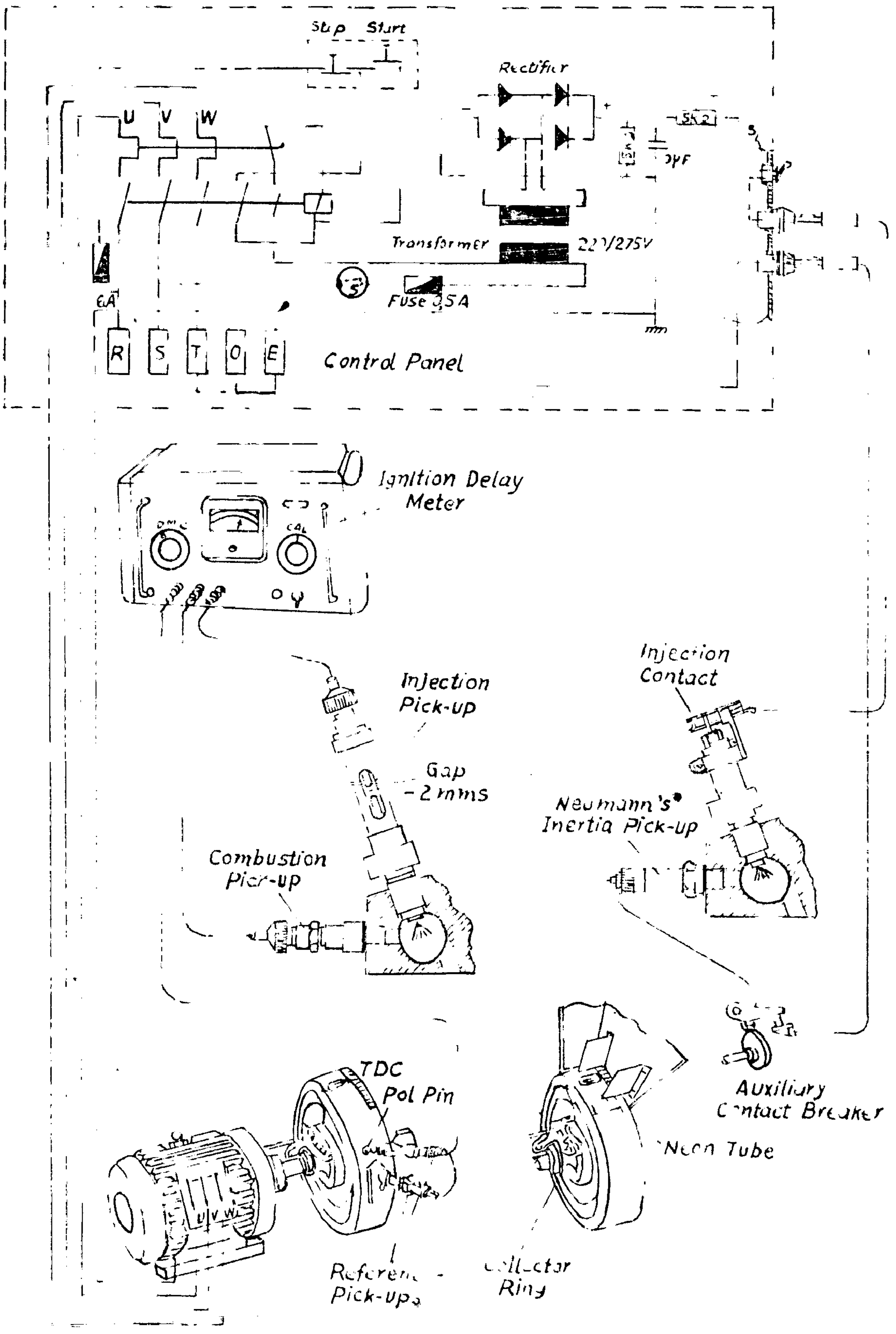
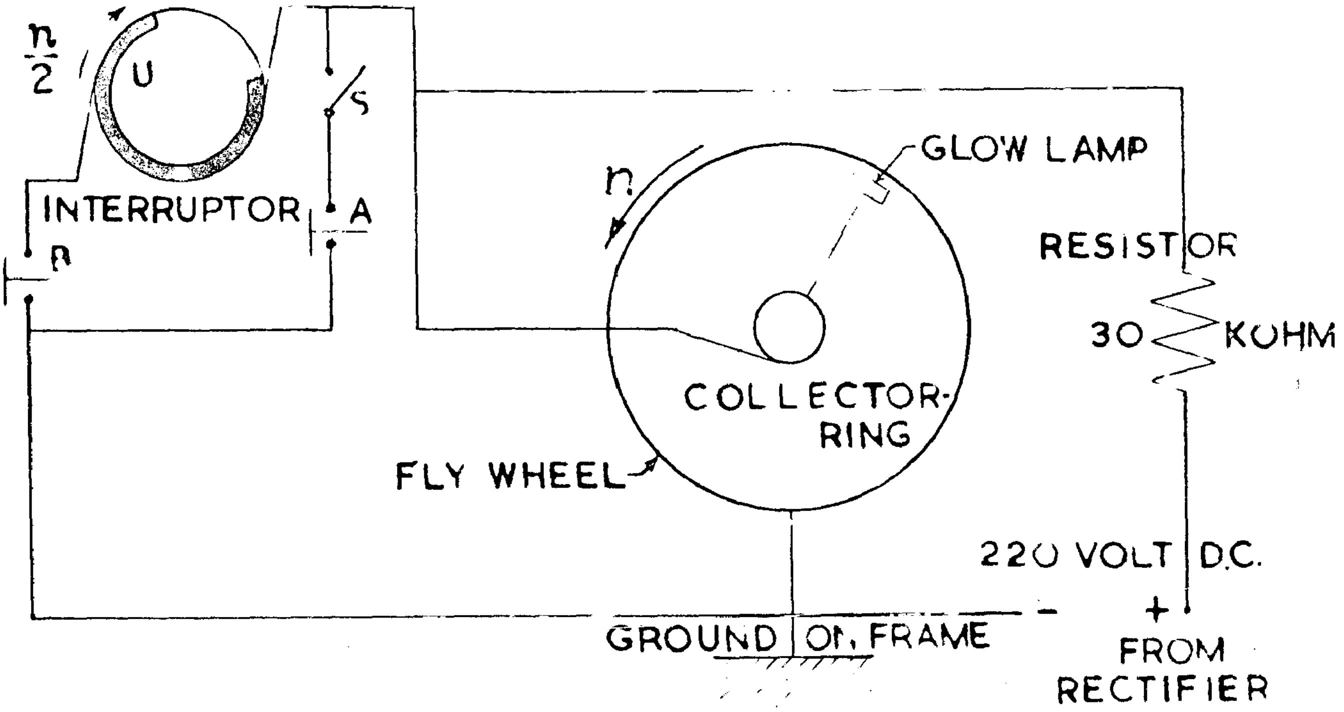


FIG. 2 WIRING DIAGRAM FOR TESTING DIESEL UNIT BASF

A. INJECTION START CONTACT ON THE NOZZLE NEEDLE
B. COMBUSTION BEGINNING CONTACT (INERTIA PICK-UP)
S. CUT OUT FOR INJECTION START INDICATION
U. INTERRUPTOR ON THE CAM SHAFT OF THE INJECTION PUMP.



POSITION	INTERRUPTOR	NOZZLE NEEDLE CONTACT	INERTIA PICK-UP	GLOW LAMP	INDICATION
1	OPENS	CLOSED	CLOSED	OFF	—
2	OFF	OPENS	CLOSED	ON	INJECTION START
3	CLOSED	OFF	CLOSED	OFF	—
4	CLOSED	OFF	OPENS	ON	COMBUSTION BEGINNING
5	CLOSED	CLOSES	CLOSES	OFF	—

WITH THE CUT-OUT **S** OPENED THE INDICATION OF POSITION 2 FALLS OUT.

WIRING DIAGRAM OF IGNITION DELAY INDICATION

FIG. 3

2.1.2 Recording of Pressure-Time Diagrams

To study the pressure variations with respect to various crank position, pressure time diagrams were taken during the tests. The following components were employed for this purpose:

(i) Dual Beam Oscilloscope
(ii) Pressure Transducer
(iii) Charge Amplifier
(iv) Magnetic Pick-up
(v) Recording Camera.

Dual-Beam Oscilloscope

A Tektronix, type 502 oscilloscope was used. It provides linear dual beam displays with a wide range of sweep rates combined with high input sensitivity. In addition, it may be used to provide dual-beam X-Y displays at medium sensitivities, and a single beamX-Y displays at high sensitivities. Vertical amplifiers for both beams may be operated with single ended inputs for conventional operation, or with differential inputs for cancellation of common mode signals.

Pressure Transducer

The pressure pick-up was piezo-electric type and was fitted on the engine with the help of a special adapter at a place where the inertia pick-up for measuring delay angle was installed. It has the following main specifications:

Pressure range	to 3000 psi
Sensitivity	4 pcb/psi
Temperature range	-400°F to + 500°F
Maximum gas temperature	3000°F
Insulation resistance	10^{14} ohms.
Cable connector	Special (use Kistler 470 cable)

Charge Amplifier

The charge amplifier of electro-static type was used. It is a multi-range, line powered feed back amplifier which is particularly well adapted to those applications where the recorder must be directly driven by the amplifier output. It has the following specifications:

Model	566 multi-range
Make	KISTLER Instruments Corporation
Ranges	0.05, 0.1, 0.2, 0.5, 1.0, 2.0, 5.0, 10, 20, 50 and 100 mv/pcb
Frequency response	dc to 150,000 cps

Magnetic pick-up

The timing marks were obtained by employing a magnetic pick-up and the signals were given on the lower beam of the oscilloscope. This pick-up is of variable - reluctance type and, in it's simplest form, consists of a coil wound on a permanent magnet core. Any variation of the permeance of the magnetic circuit causes a change in the flux. As the field expands or collapses, a voltage is developed in the coil.

Two different type of pick-up arrangements were made during the course of our study:

(i) By cutting teeth at intervals of 10 deg. on a steel disc coupled with engine crank shaft and placing the pick-up in such a way that the teeth portion passes in-between the poles of the magnet. It gave a signal of 10 deg. interval between two peaks.

(ii) By fixing tapered screws on the flywheel at an interval of 5 deg. and allowing the tapered tip of the screws to pass in-between the poles. A longer screw was employed at top dead center position to differentiate this position without difficulty.

The second arrangement was the modification over the first, and gave better timing marks.

2.2 PROCEDURE

In order to study the effects of blending of fuels on their ignition quality, the measurements of delay angle of test blends at various operating conditions were made by means of delay meter. Cetane number determination of the blends were made by comparing them with secondary-reference fuel blends at standard operating conditions of the engine which is as follows:

Engine speed	1000 RPM
Coolant temperature	100°C (automatically produced by the evaporating system of the engine).

Ignition delay	20 deg.
Fuel rate	20 ml/150 sec.

The secondary-reference fuels used are T-16 having a cetane number 71.0 and U-9 having a cetane number 22.5. The SRF blends were made by mixing porportionately on volume basis to get the desired cetane number.

For accurate measurements of cetane number, the test fuel was bracketed between two reference fuels differing not more than five cetane numbers and the rating was calculated by interpolation. However any of the following curves can be used for its determination quite accurately:

(i) Cetane number versus Air meter reading at top dead centre position firing.

(ii) Cetane number versus vacuum reading at top dead centre position firing. (20 deg. injection advance and 20 deg. delay angle).

(iii) Cetane number versus vacuum reading at the point of misfiring keeping 20 deg. injection advance.

The study of variations of pressure with respect to crank position was made by taking p-t diagrams of various blends on the oscilloscope screen and getting them photographed by the camera.

The calibration of pressure pick-up at four different combinations of oscilloscope sensitivity and amplifier sensitivity is shown in Fig. (29).

2.3 REPRODUCIBILITY AND ACCURACY OF EXPERIMENTAL RESULTS

The accuracy of the experimental results is judged by the reproducibility. For this reason the engine was calibrated once in the beginning of starting the experimental work and then at the end. Fig. (20 & 21) show two different curves, and it is observed that there is some difference in the air-meter reading and vacuum gauge reading corresponding to a particular cetane number.

One of the reasons of this difference is the slight change in the operating conditions of the engine on these two different dates. The slight change in intake air temperature was expected which must have changed the values.

CHAPTER III

EXPERIMENTAL RESULTS AND GRAPHS

TABLE - 2

CETANE NUMBER OF DIFFERENT BLENDS BY VARIOUS METHODS

S.No.	Blend	Cetane Number			
		Calibration Curve Used for			Bracketing for Air-Meter Reading
		Air-Meter	Vacuum at t.d.c. firing	Vacuum at incipient misfiring	
1.	Diesel	51.5	51.5	52.0	51.5
2.	75% Diesel + 25% Petrol	46.0	47.0	47.0	46.5
3.	50% Diesel + 50% Petrol	39.0	40.0	39.5	39.8
4.	25% Diesel + 75% Petrol	32.0	31.0	30.5	31.5
5.	97.5% Diesel + 2.5% Lub. Oil S.A.E.30	51.5	52.5	-	51.5
6.	95% Diesel + 5% Lub. Oil S.A.E. 30	54.0	53.0	-	53.5
7.	90% Diesel + 10% Lub. Oil S.A.E. 30	57.0	57.0	-	56.5
8.	80% Petrol + 20% Lub. Oil S.A.E. 30	33.0	34.5	-	34.0
9.	85% Petrol + 15% Lub. Oil S.A.E. 30	32.0	31.0	-	31.7
10.	90% Petrol + 10% Lub. Oil S.A.E. 30	-	27.5	-	-
11.	95% Diesel + 5% Ether	-	-	54.0	-
12.	90% Diesel + 10% Ether	-	-	57.0	-

TABLE - 3

EXPERIMENTAL VALUES OF IGNITION DELAY FOR VARIOUS PERCENTAGE OF DIESEL (INJECTED) + PETROL (CARBURETTED) AT DIFFERENT OPERATING CONDITIONS

PRESSURE: ATMOSPHERIC TOTAL FUEL RATE: 8cc/mt.

Fuel	Injection Advance Deg. C.A.	Ignition Delay Deg. C.A.
75% Diesel (injected) + 25% Petrol (carburetted)	15	7.5
	20	9.0
	25	9.4
50% Diesel (injected) + 50% Petrol (carburetted)	15	7.5
	20	9.0
	25	9.6
30% Diesel (injected) + 70% Petrol (carburetted)	15	7.5
	20	9.3
	25	11.0

No Firing of Pure Petrol Carburetted at 20 c.c./150 secs.
i.e. 0.28 x 10^{-4} lbs./cycle

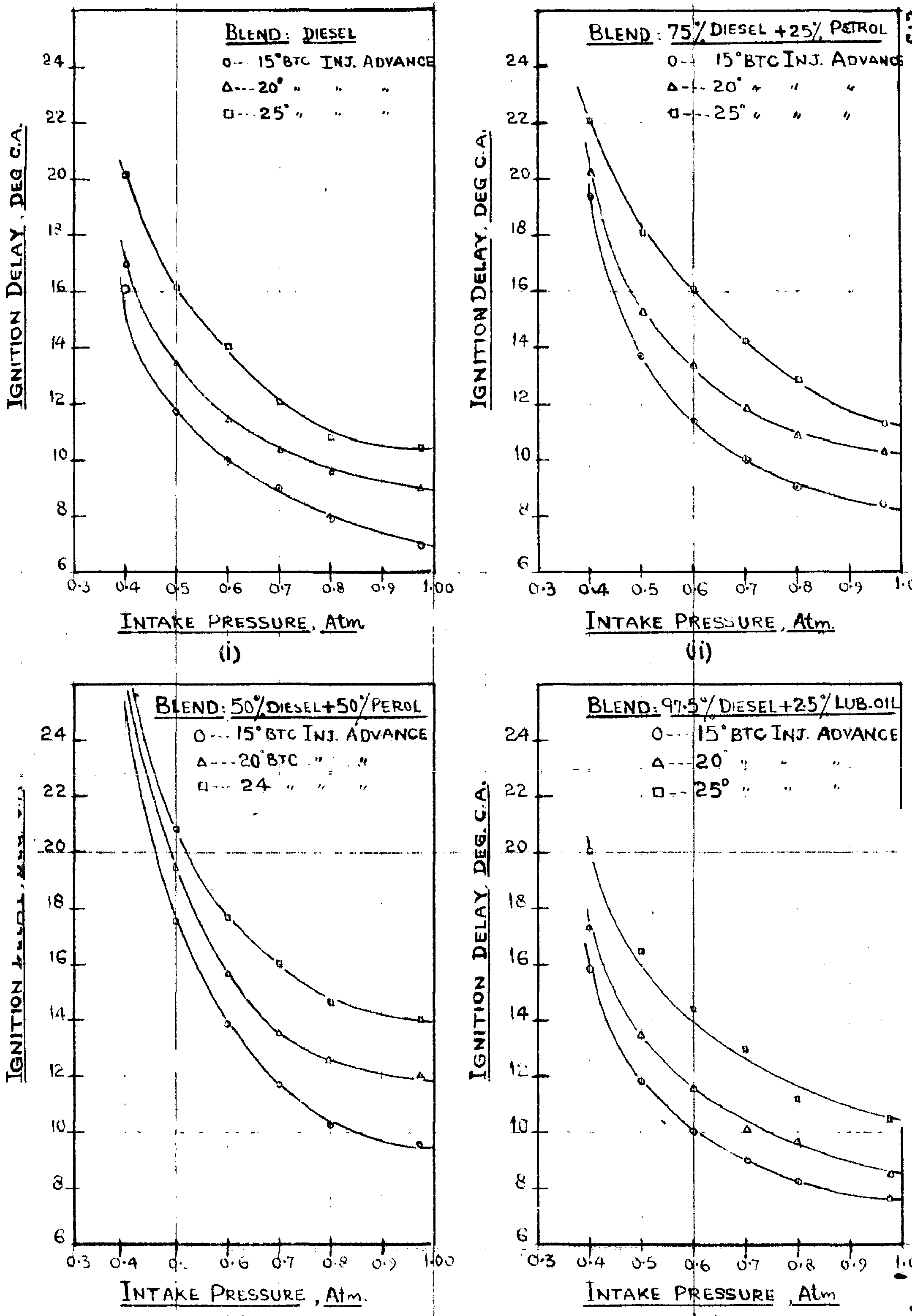
Firing of Pure Petrol Carburetted/started at 20 c.c./72 secs.
i.e. 0.60 x 10^{-4} lbs./cycle

TABLE - 4

EXPERIMENTAL VALUES OF IGNITION DELAY FOR VARIOUS PERCENTAGE OF DIESEL + ETHER BOTH INJECTED AT DIFFERENT OPERATING CONDITIONS.

PRESSURE: ATMOSPHERIC TOTAL FUEL RATE: 8cc/mt.

Fuel	Injection Advance Deg. C.A.	Ignition Delay Deg. C.A.
75% Diesel + 25% Ether (both injected)	15	7.3
	20	8.5
	25	8.7
50% Diesel + 50% Ether (both injected)	15	Does not indicate any particular value
	20	-do-
	25	-do-



(i) (ii)

(iii) (iv)

FIG. (4). EFFECT OF THROTTLING INTAKE AIR ON IGNITION DELAY

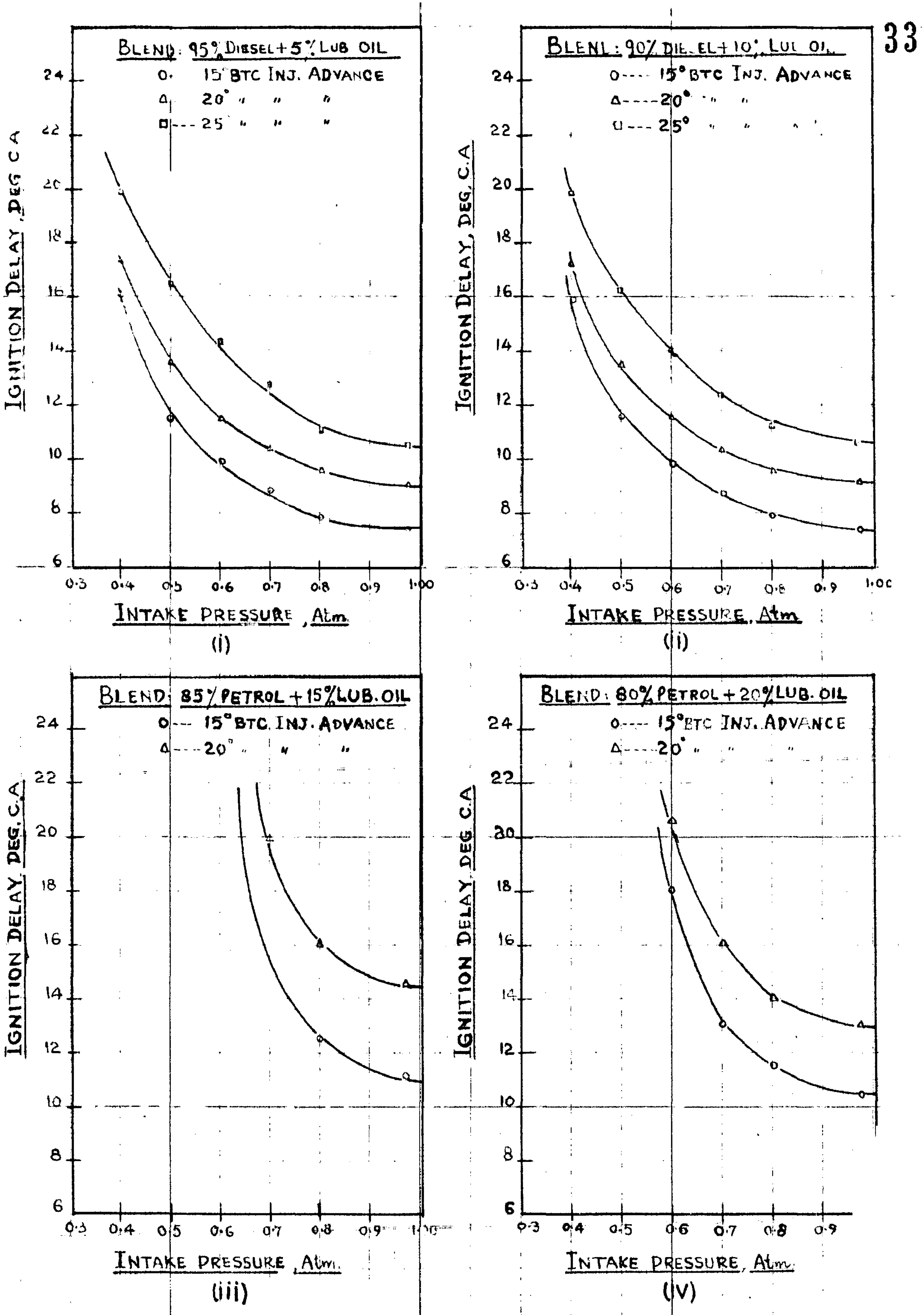
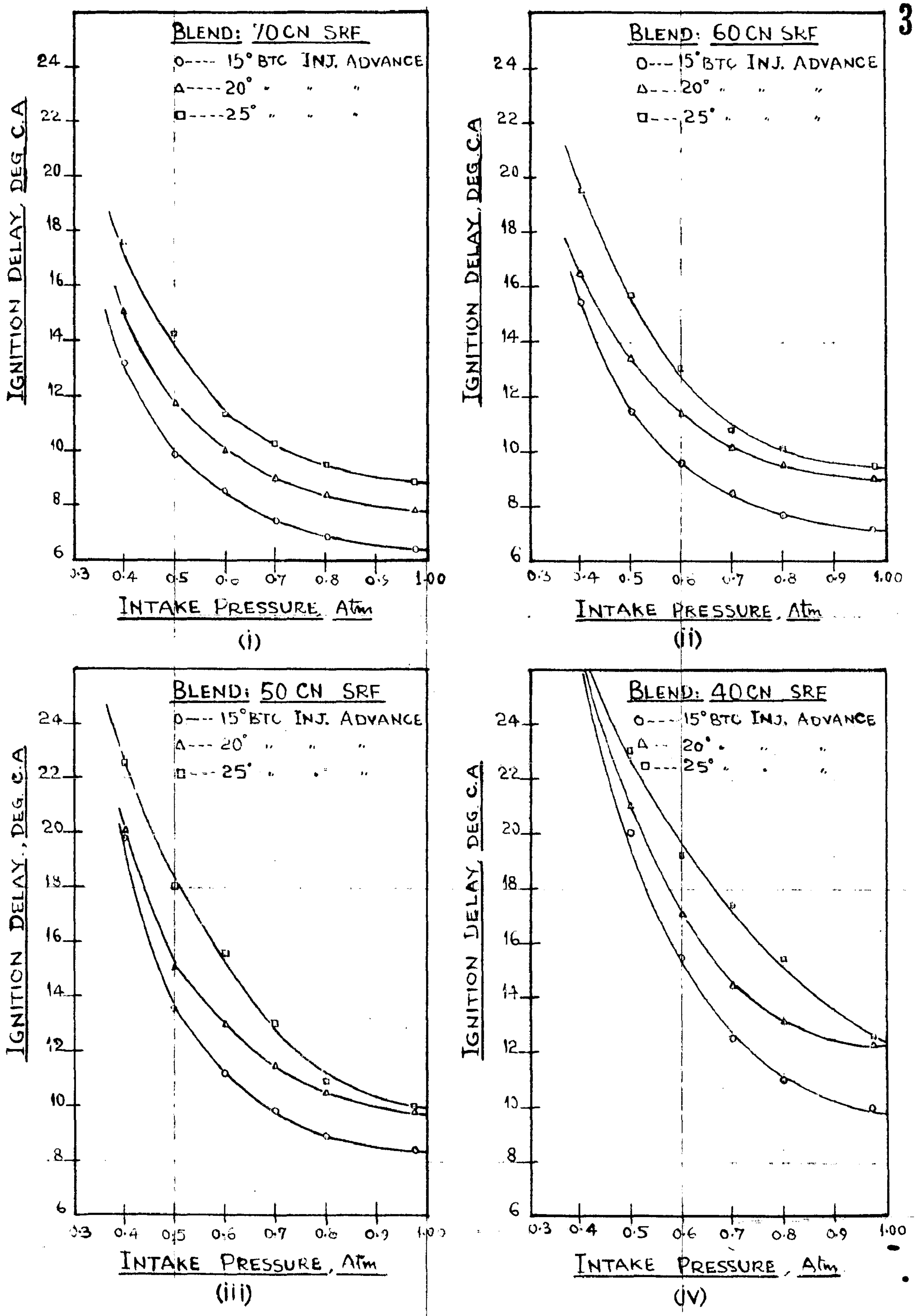
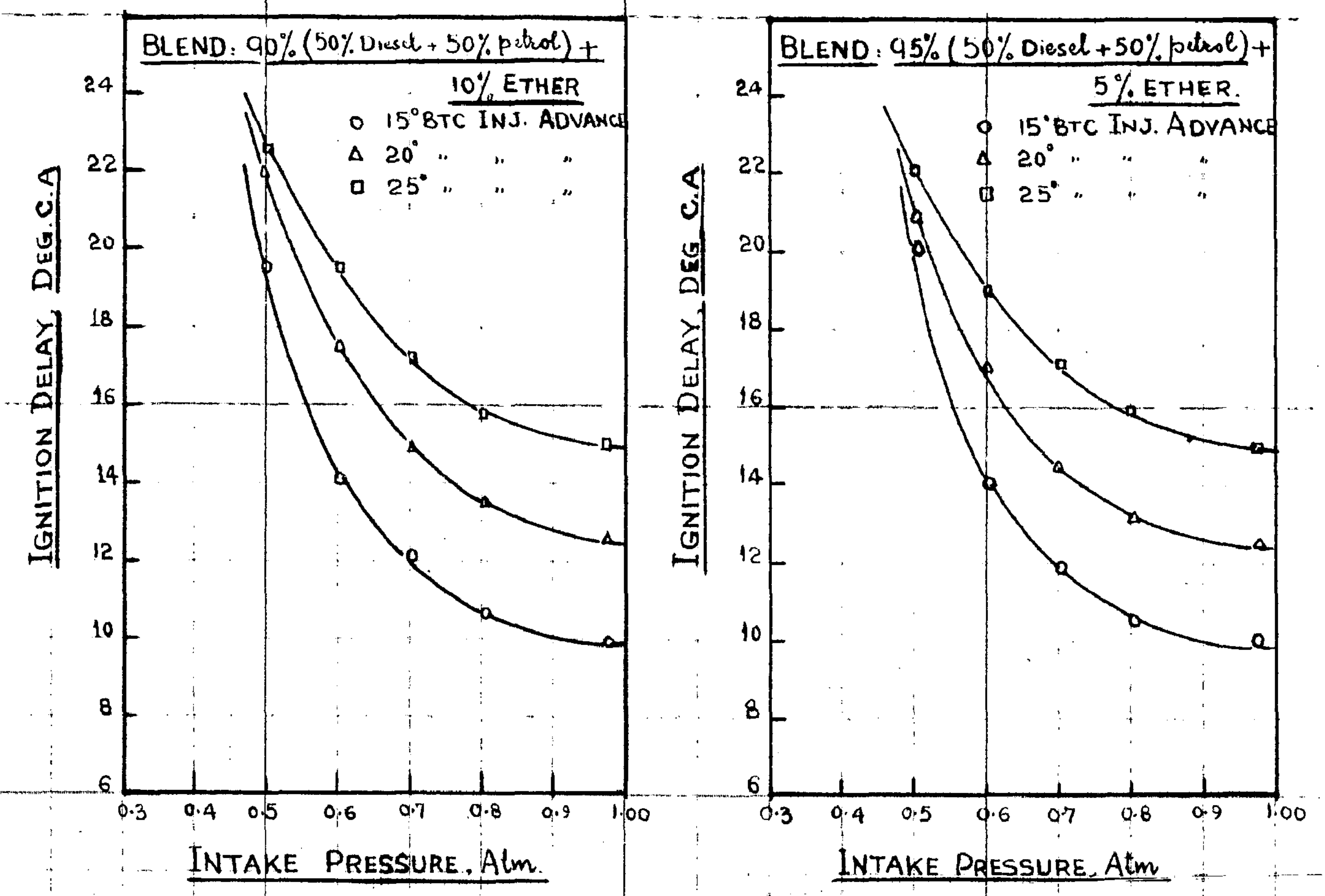


FIG.(5) EFFECT OF THROTTLING INTAKE AIR ON IGNITION DELAY



(i) (ii) (iii) (iv)

FIG.(6) EFFECT OF THROTTLING INTAKE AIR ON IGNITION DELAY



(i) (ii)

FIG. (7) EFFECT OF THROTTLING INTAKE AIR ON IGNITION DELAY

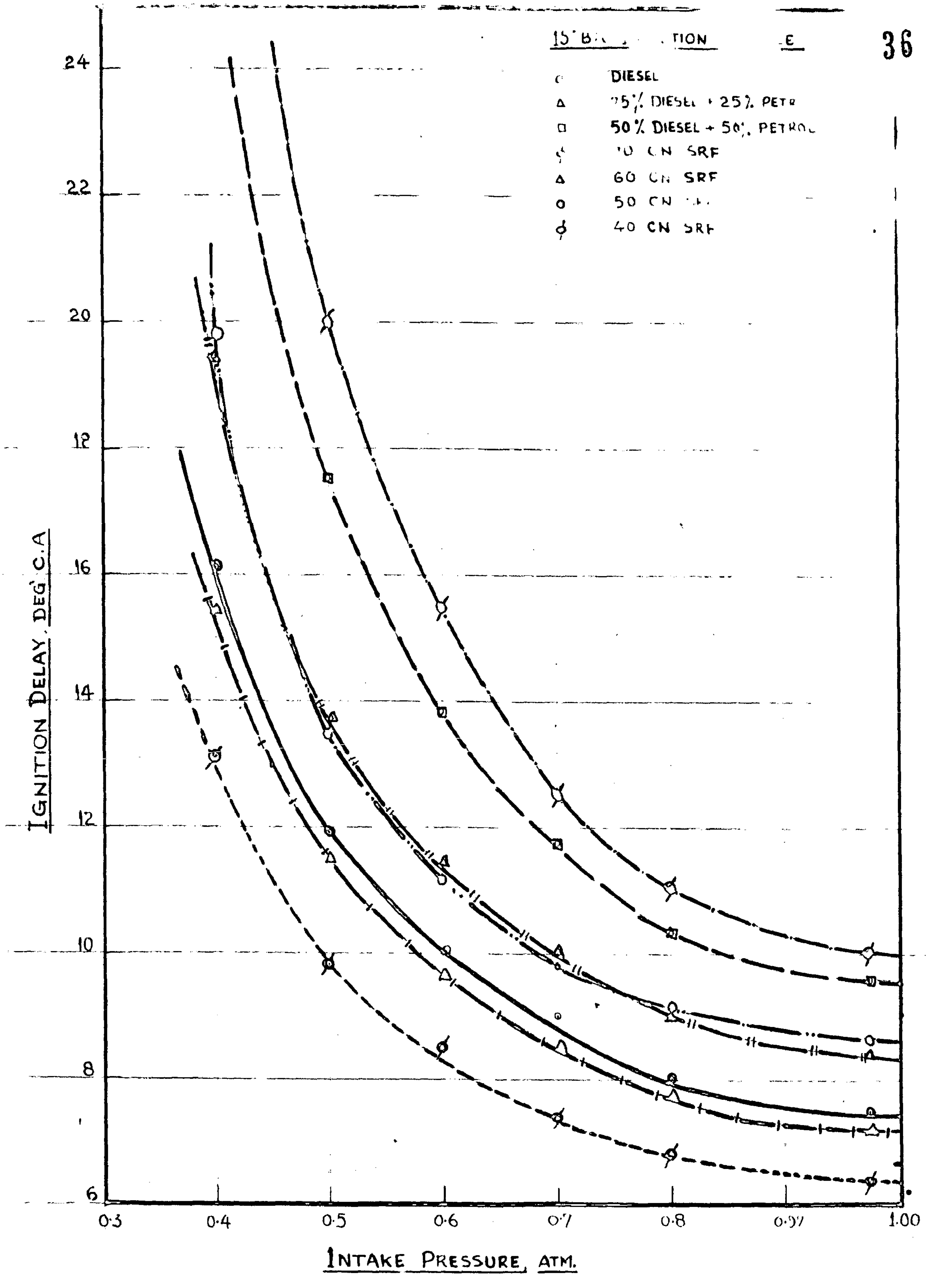


FIG.(8) EFFECT OF THROTTLING INTAKE AIR ON DELAY

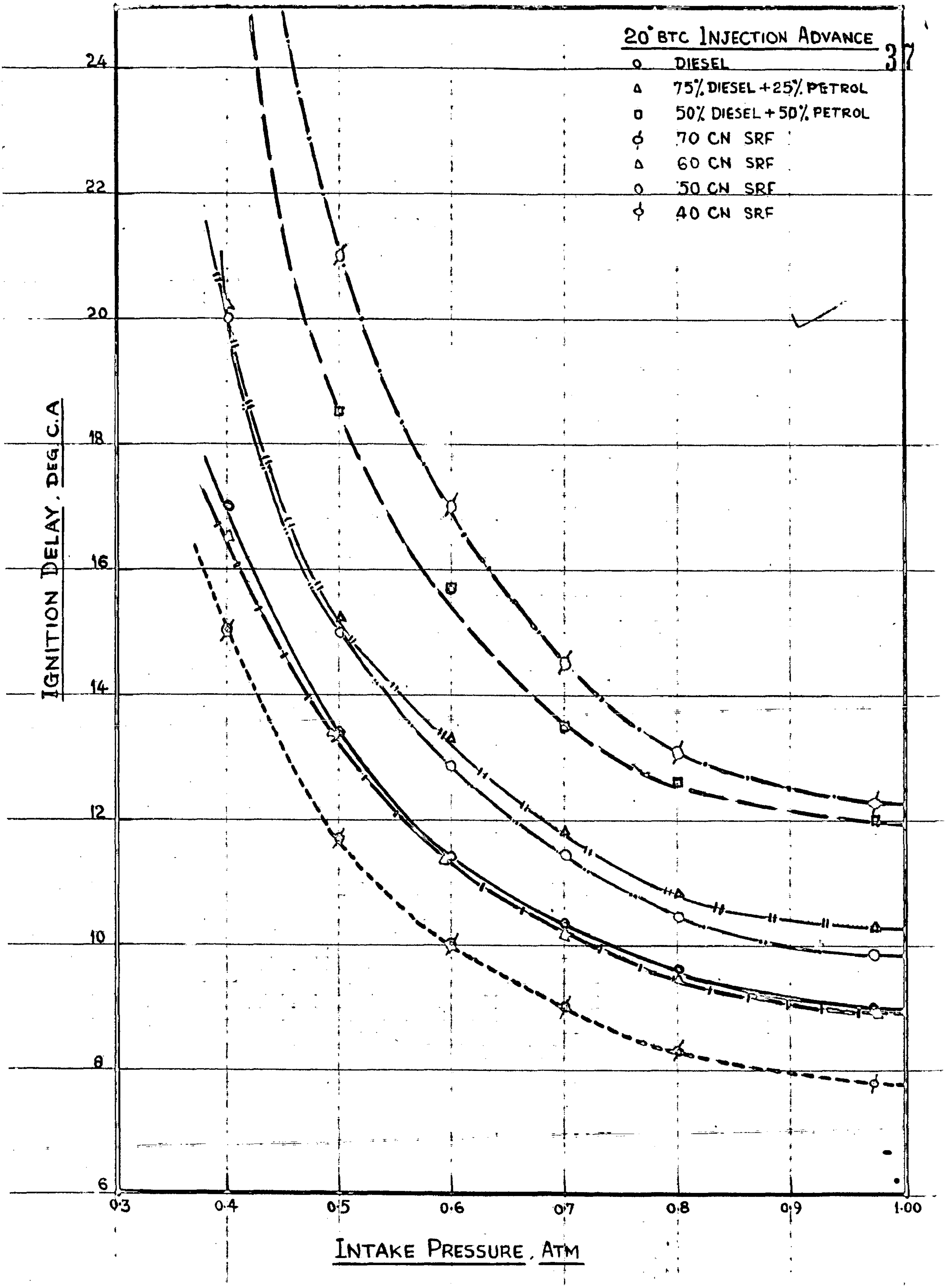


FIG.(9) EFFECT OF THROTTLING INTAKE AIR ON DELAY

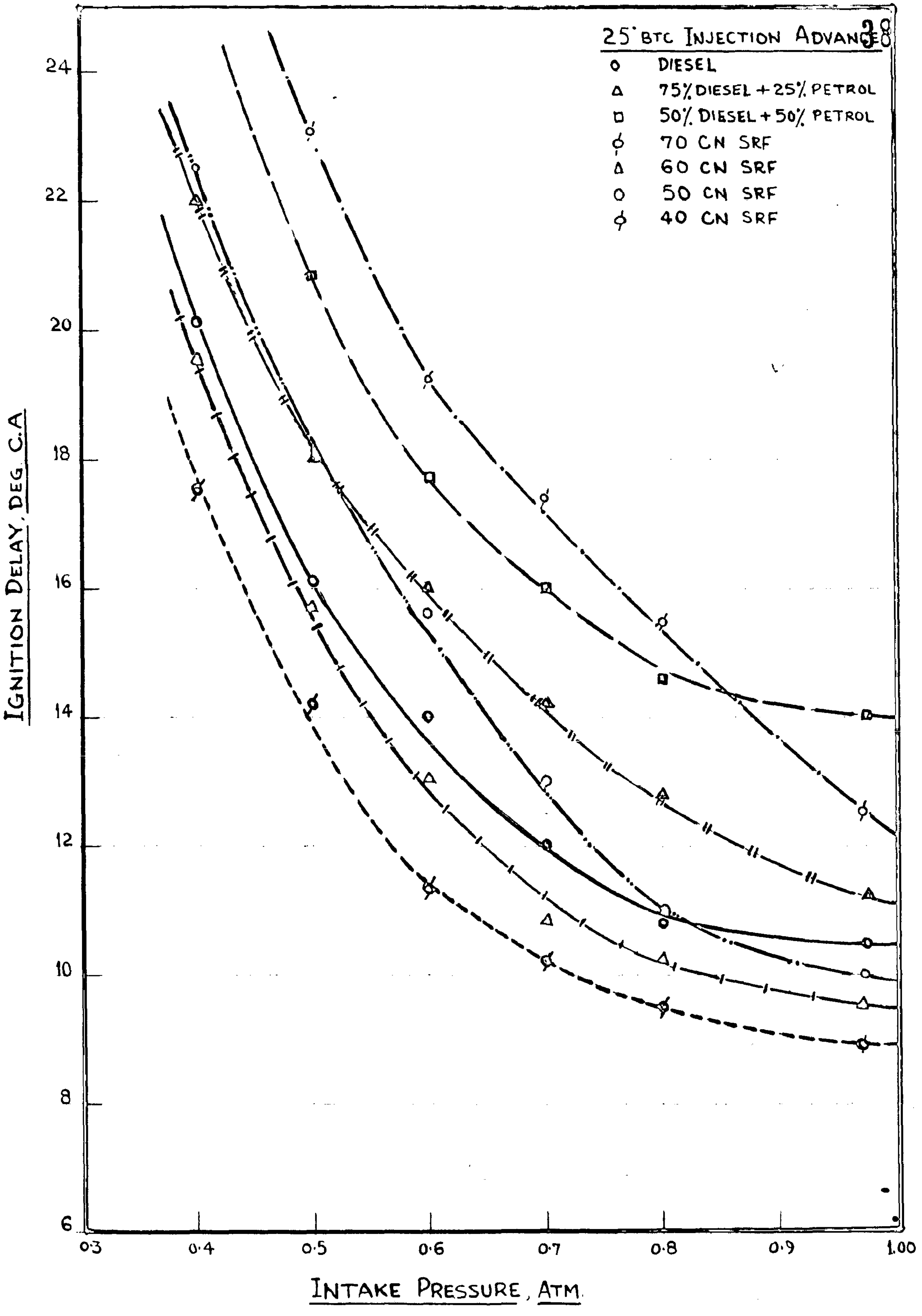


FIG. (10) EFFECT OF THROTTLING INTAKE AIR ON DELAY.

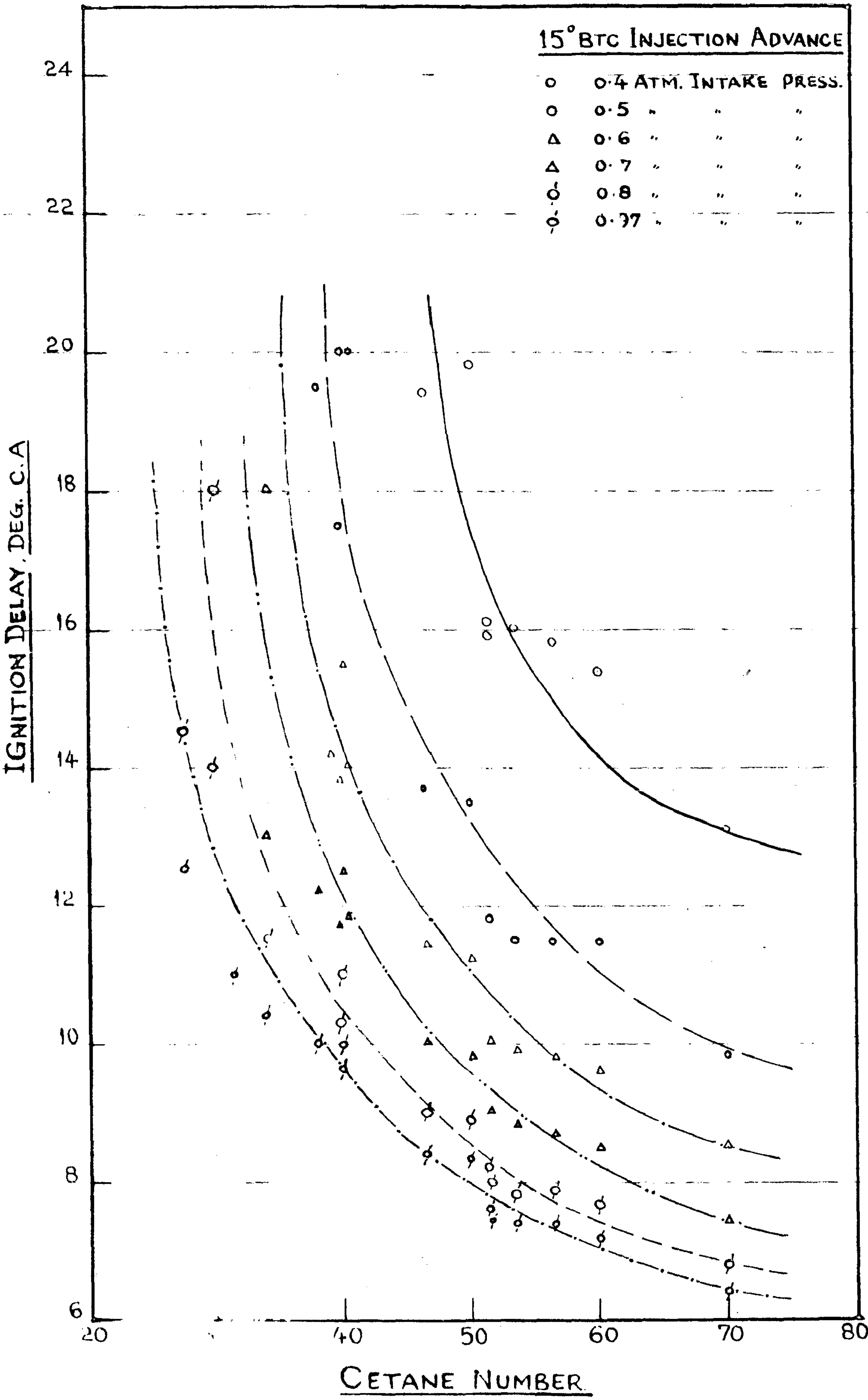


FIG. (11) EFFECT OF CETANE NUMBER ON IGNITION DELAY

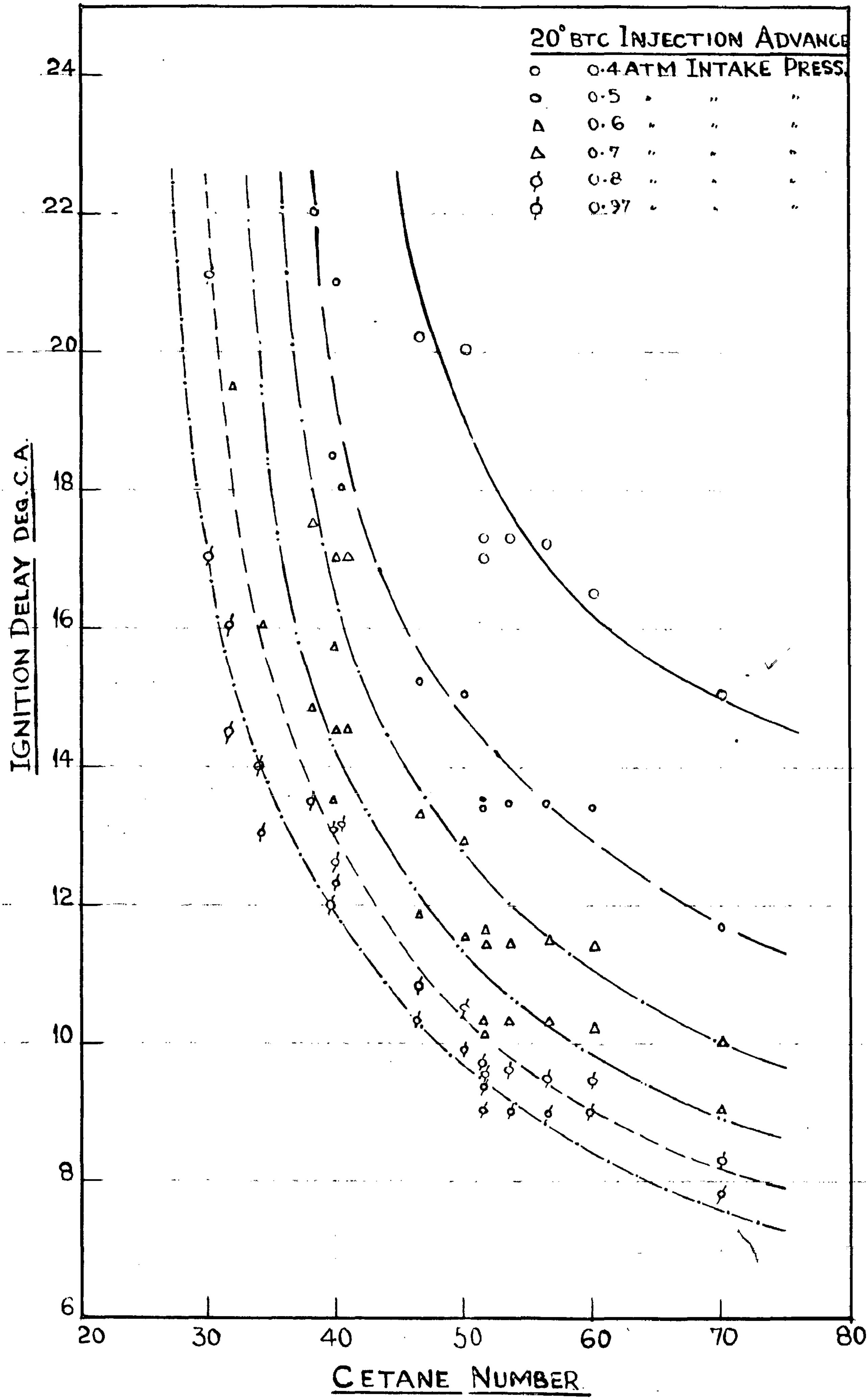


FIG. (12) EFFECT OF CETANE NUMBER ON IGNITION DELAY

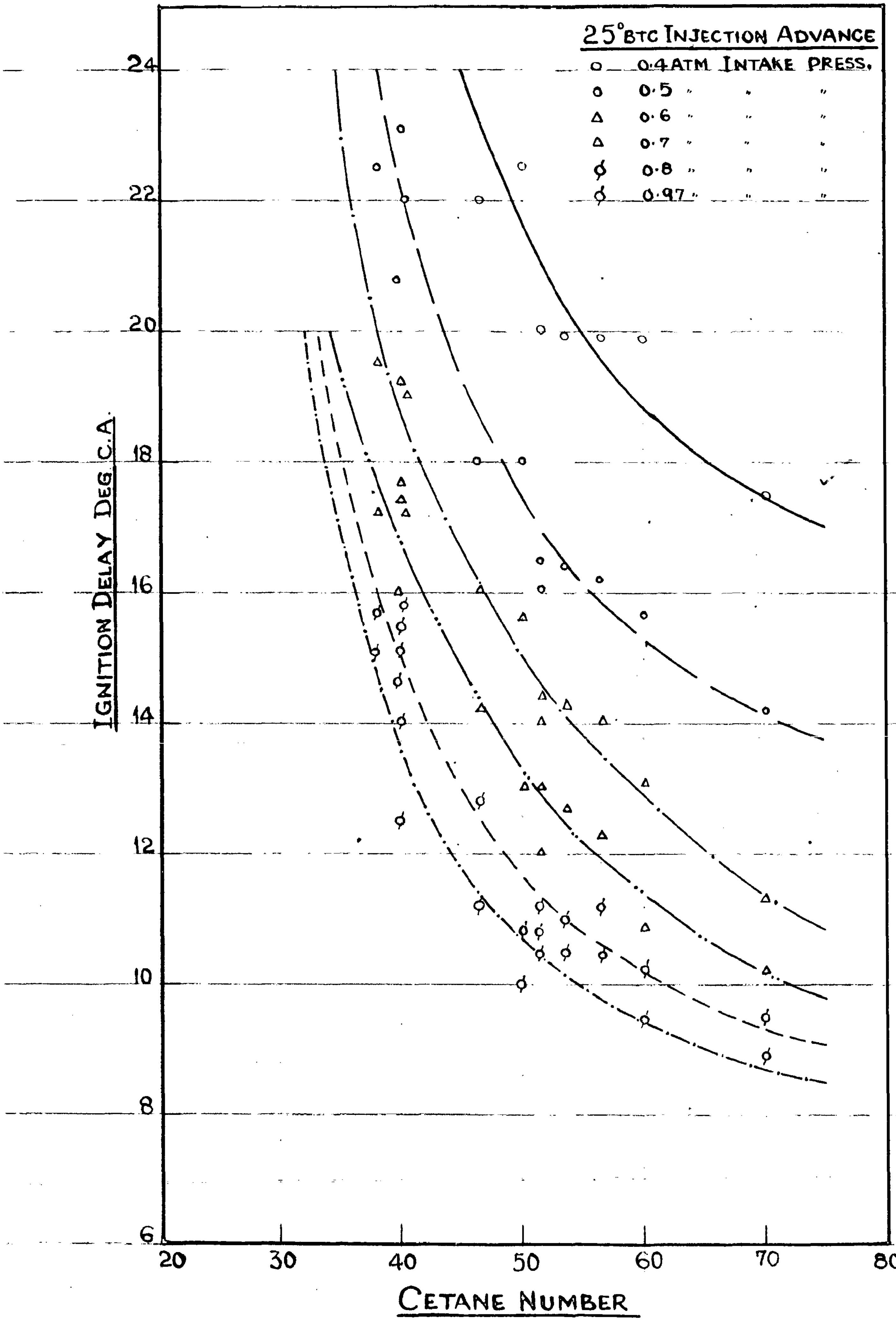


FIG.(13). EFFECT OF CETANE NUMBER ON IGNITION DELAY

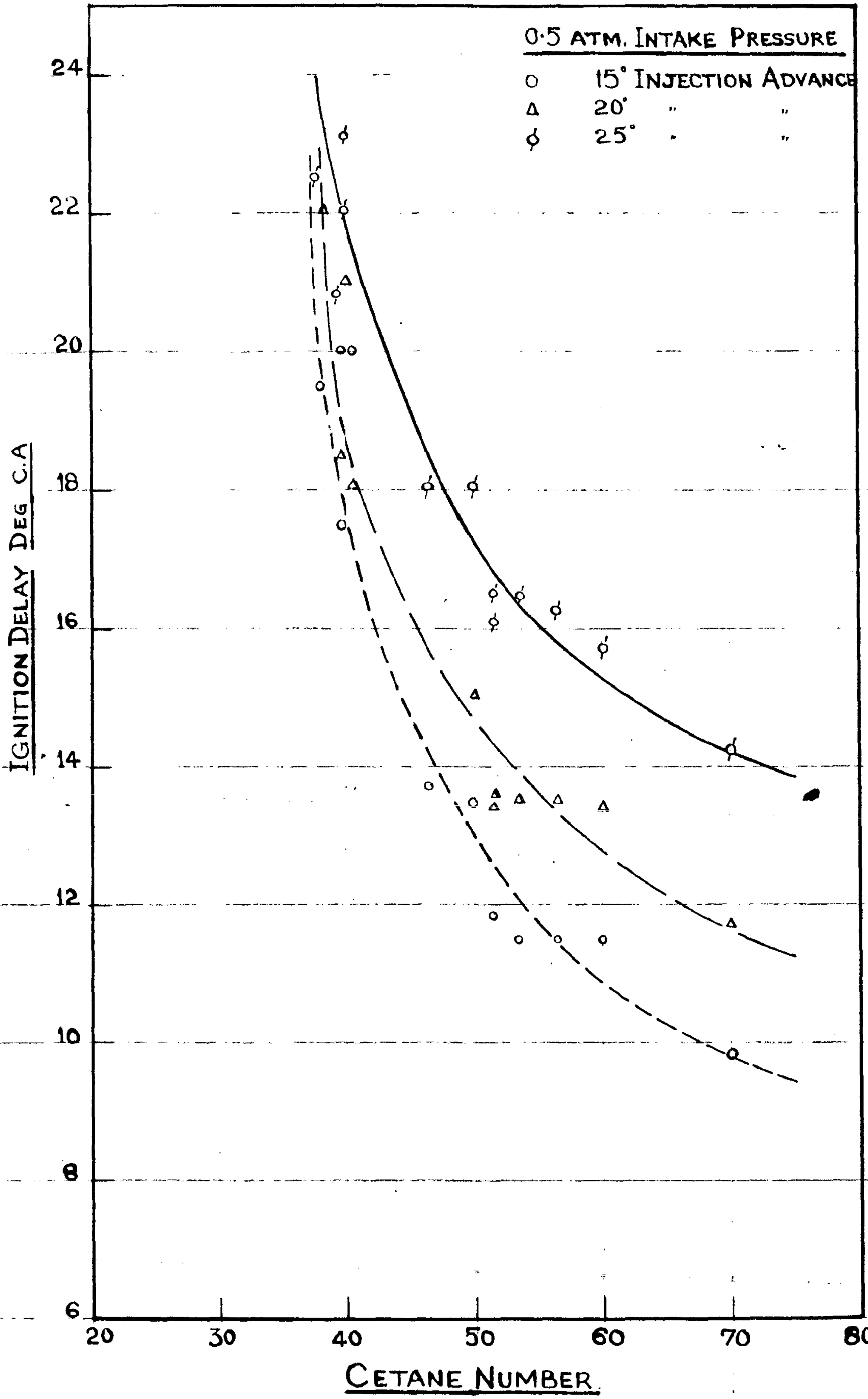


FIG.(14) EFFECT OF CETANE NUMBER ON IGNITION DELAY

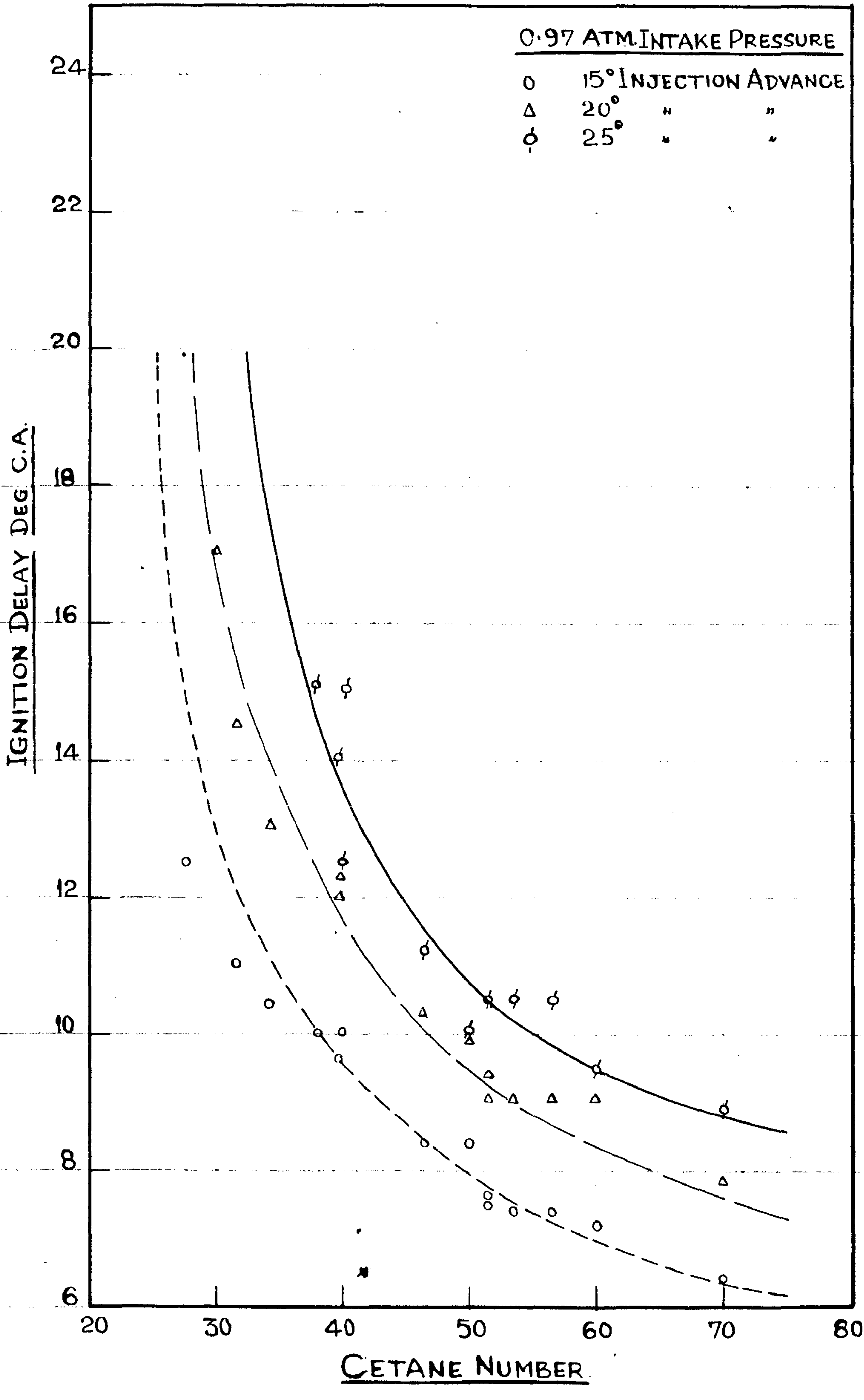


FIG. (15) EFFECT OF CETANE NUMBER ON IGNITION DELAY

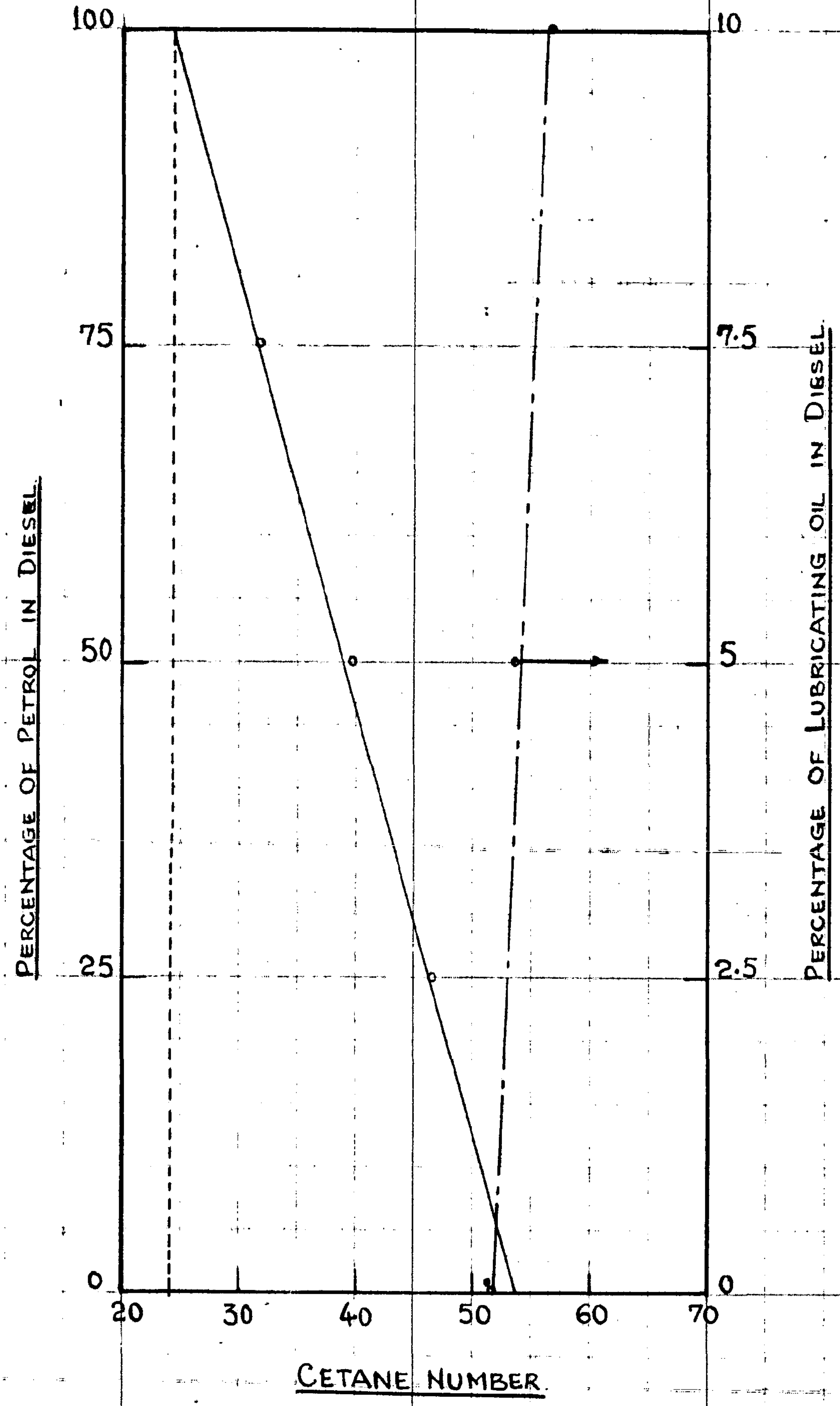


FIG. (16) EFFECT OF LUBRICATING OIL AND PETROL ON DIESEL

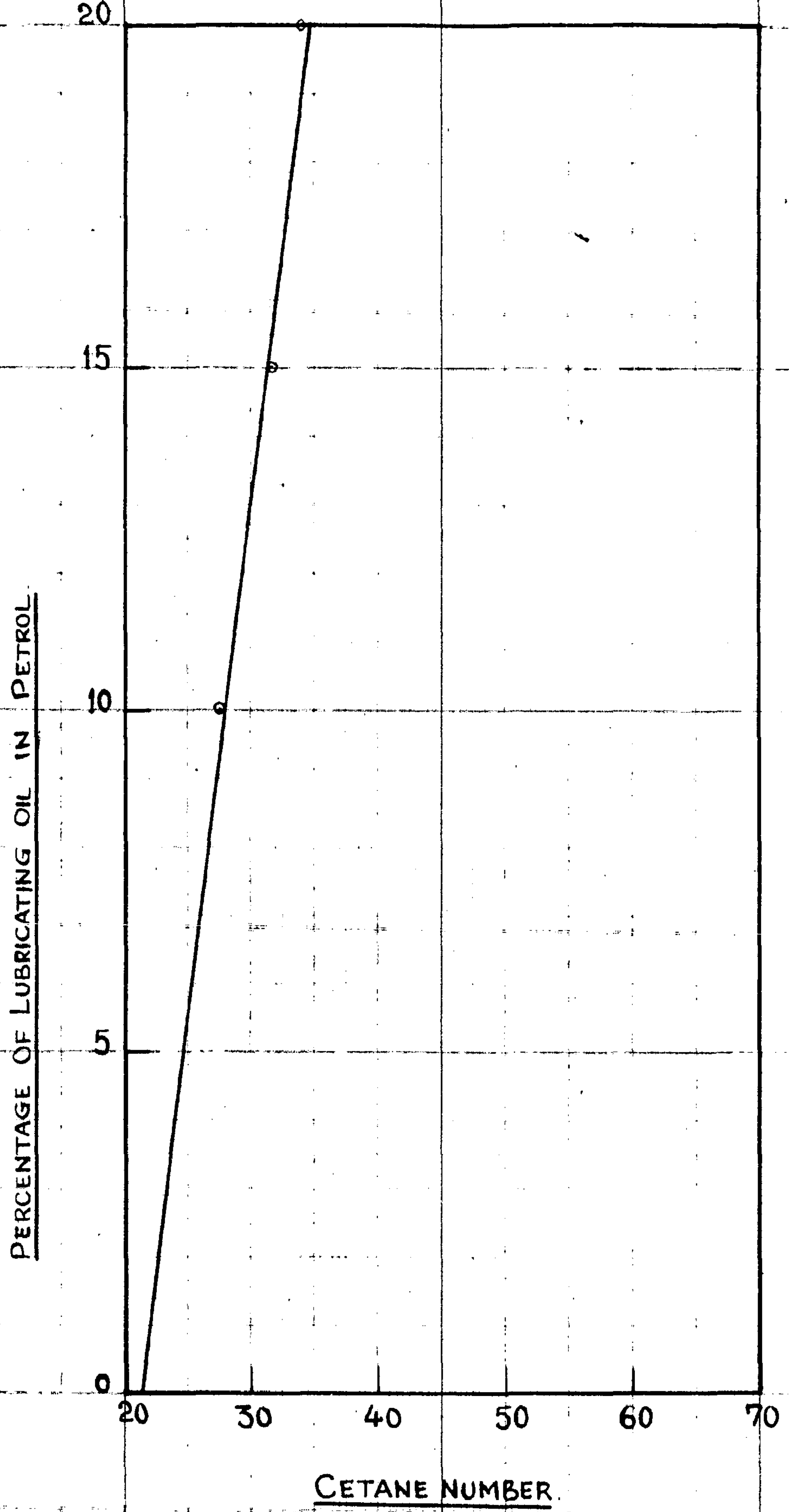


FIG. (17) EFFECT OF LUBRICATING OIL ON PETROL

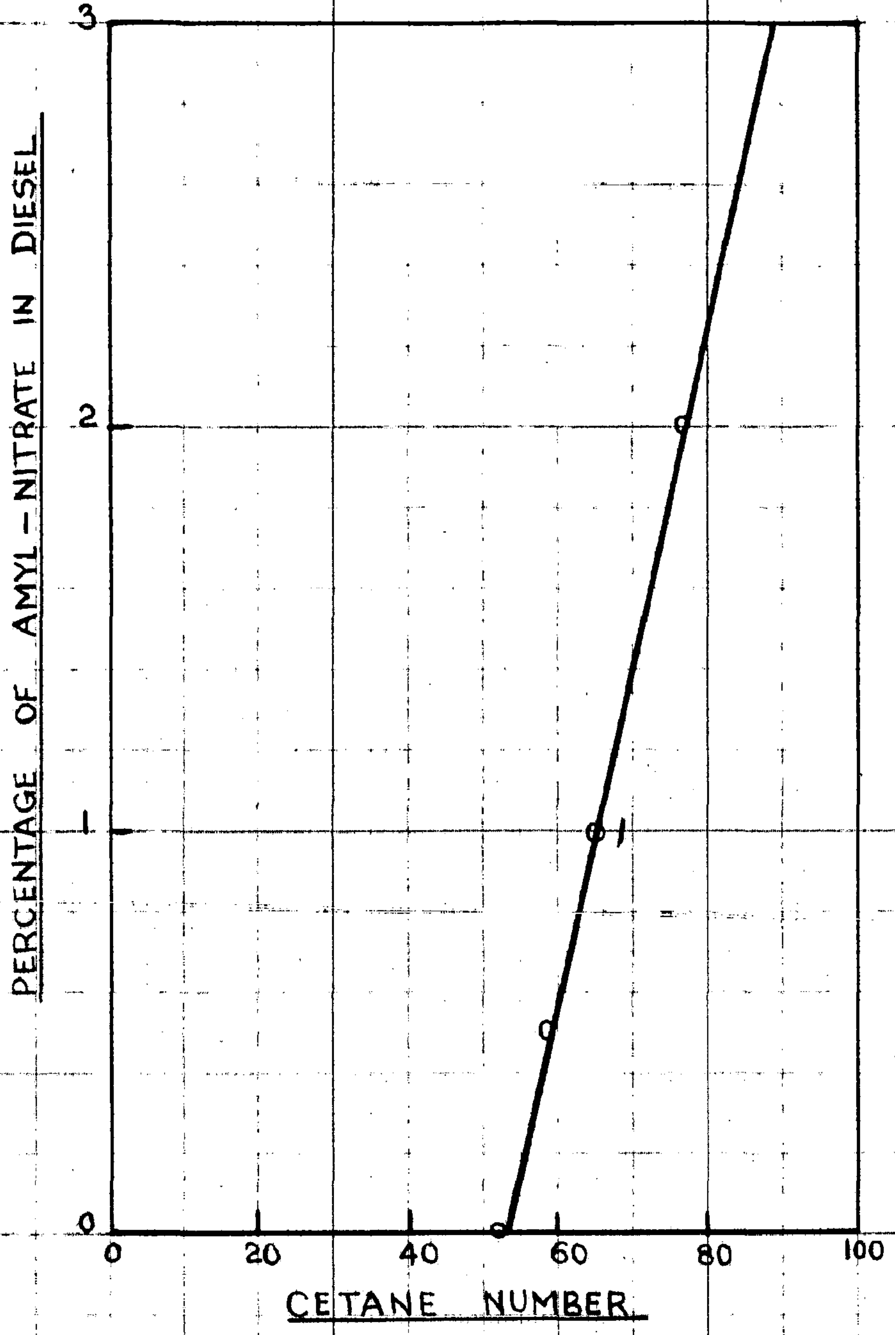


FIG. 18. EFFECT OF AMYL - NITRATE ON DIESEL

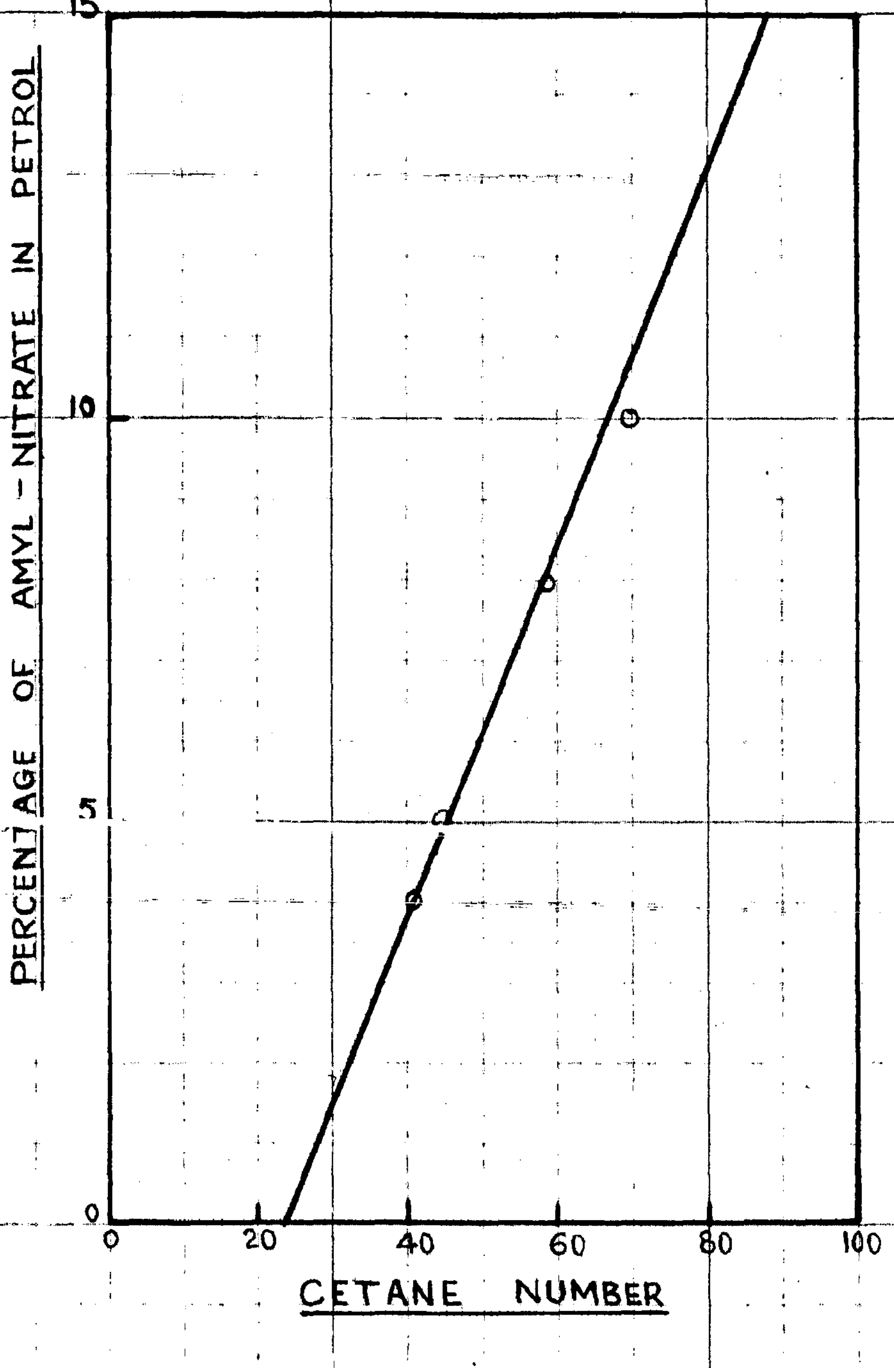


FIG. 19 EFFECT OF AMYL-NITRATE ON PETROL

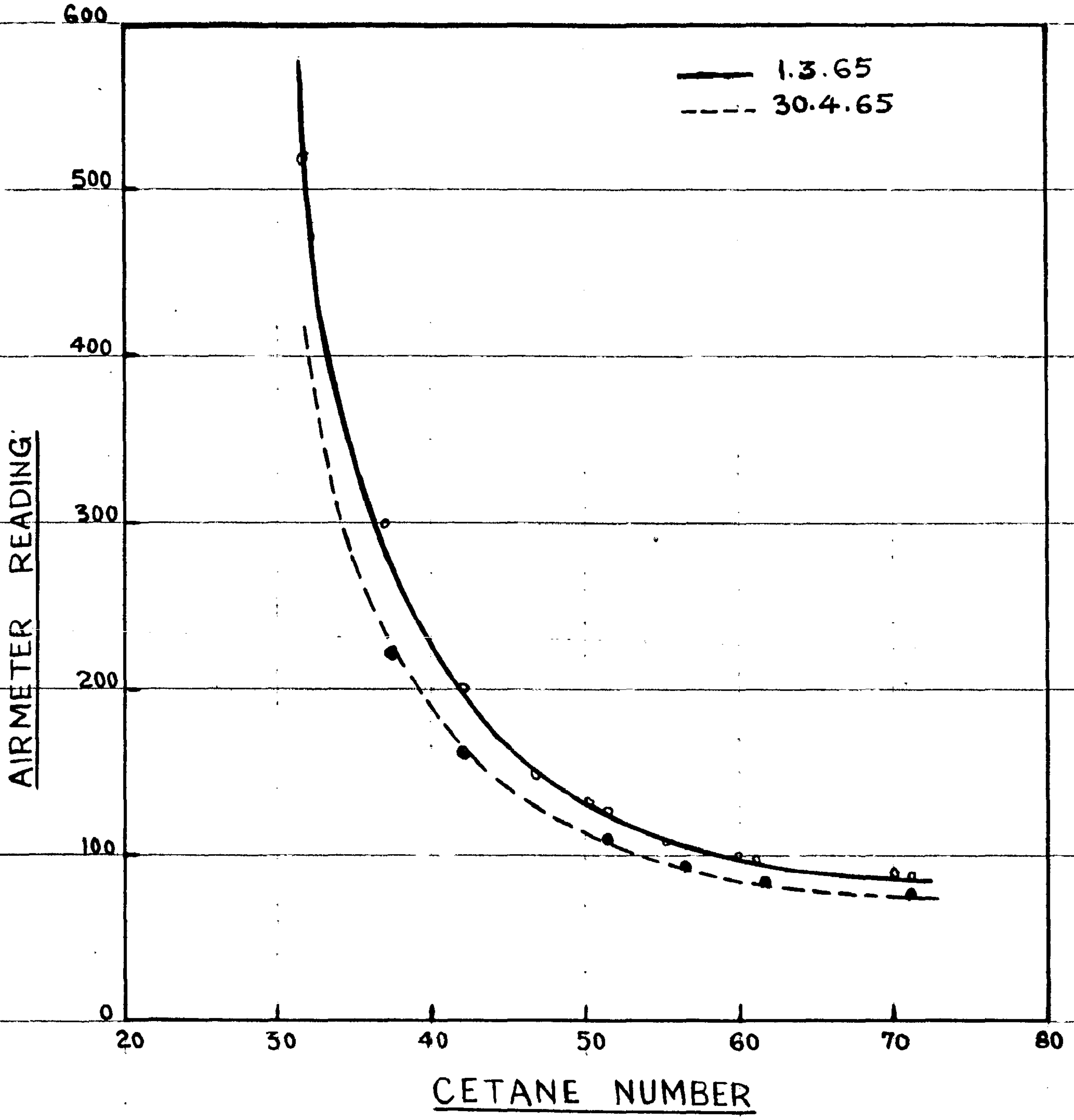


FIG. 20 CALIBRATION CHART (BURNING AT T.D.C.)

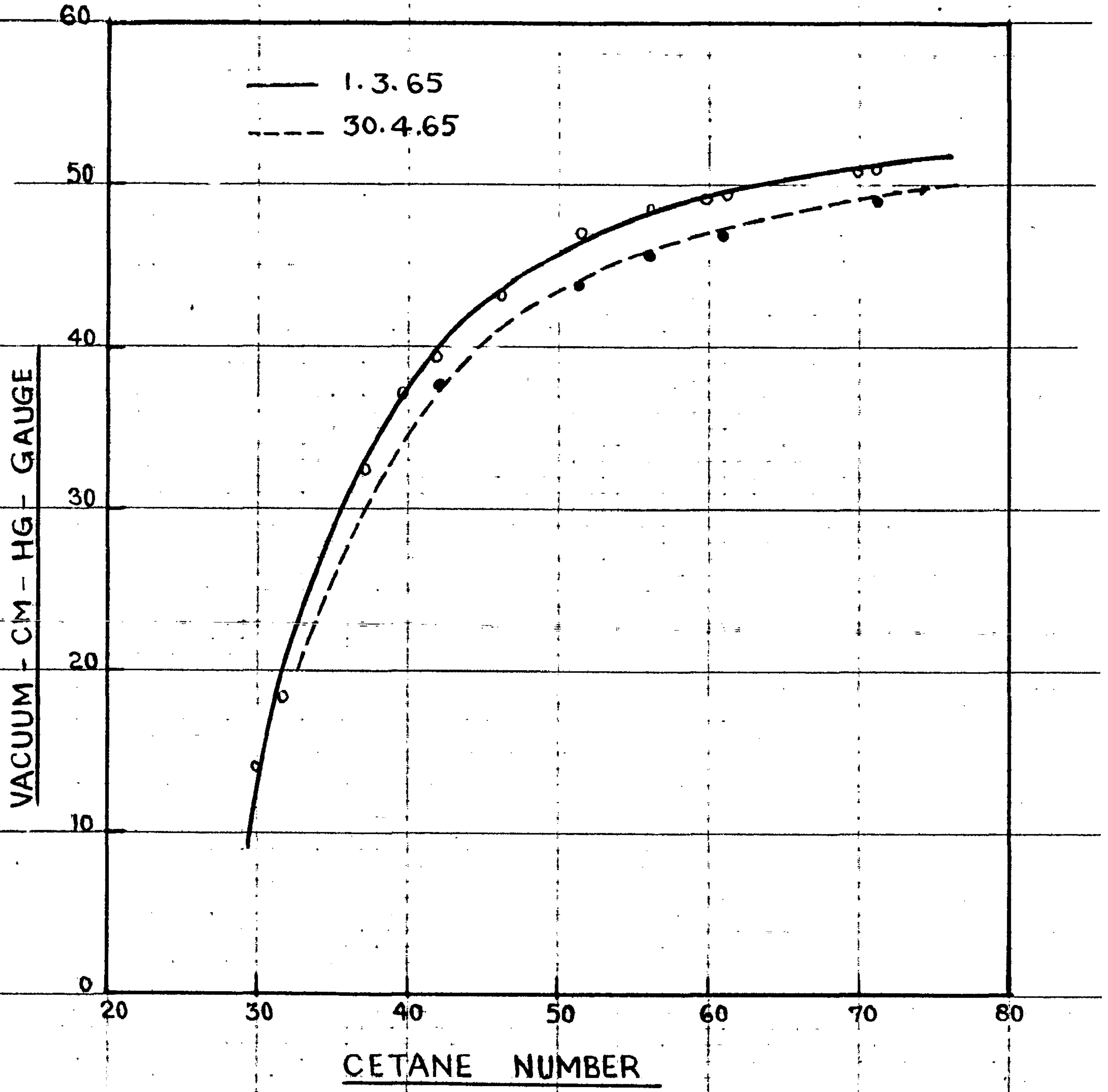


FIG. 21 CALIBRATION CHART (BURNING AT T.D.C.)

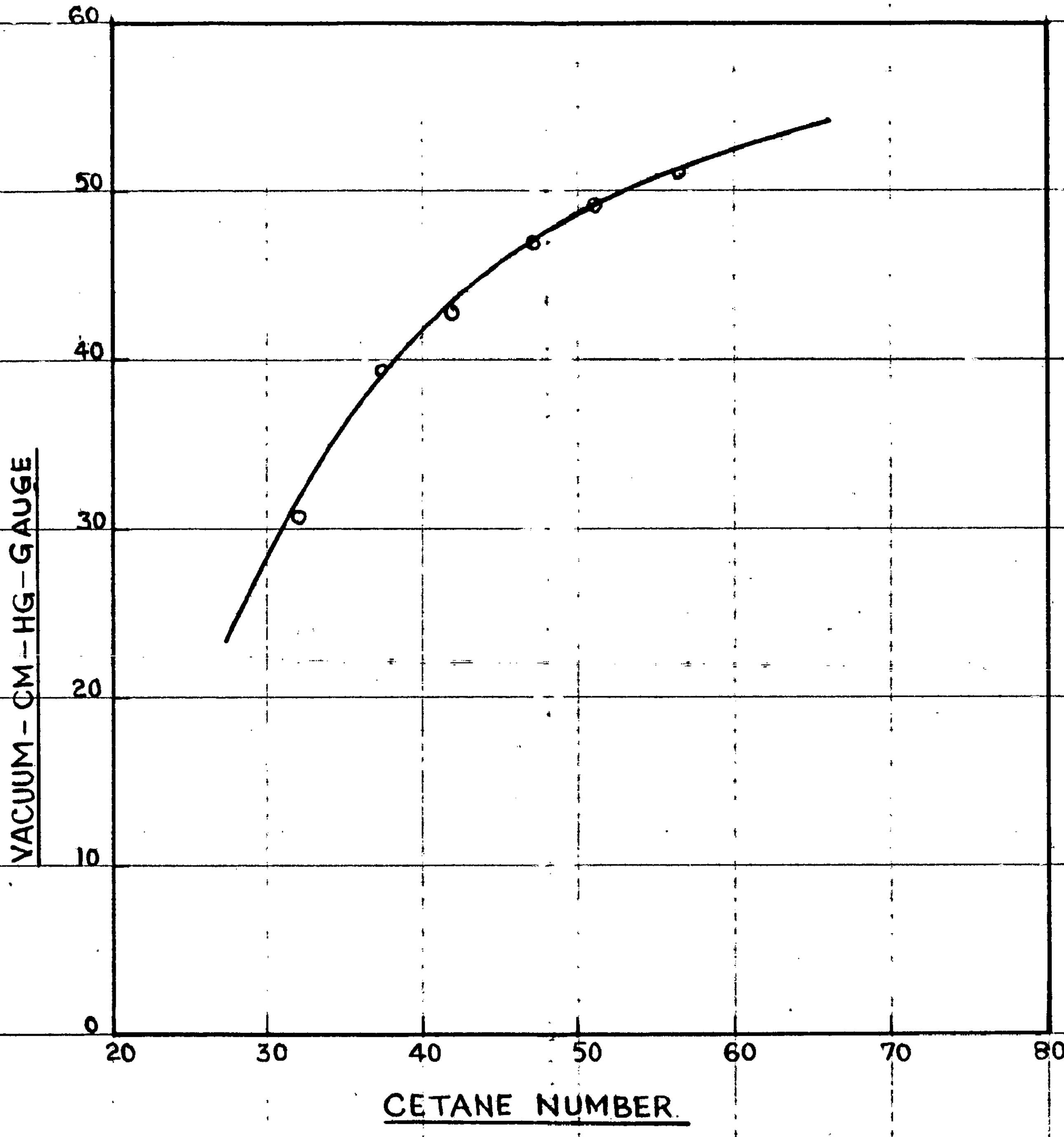


FIG. 22 CALIBRATION CHART (INCIPIENT MISFIRING)

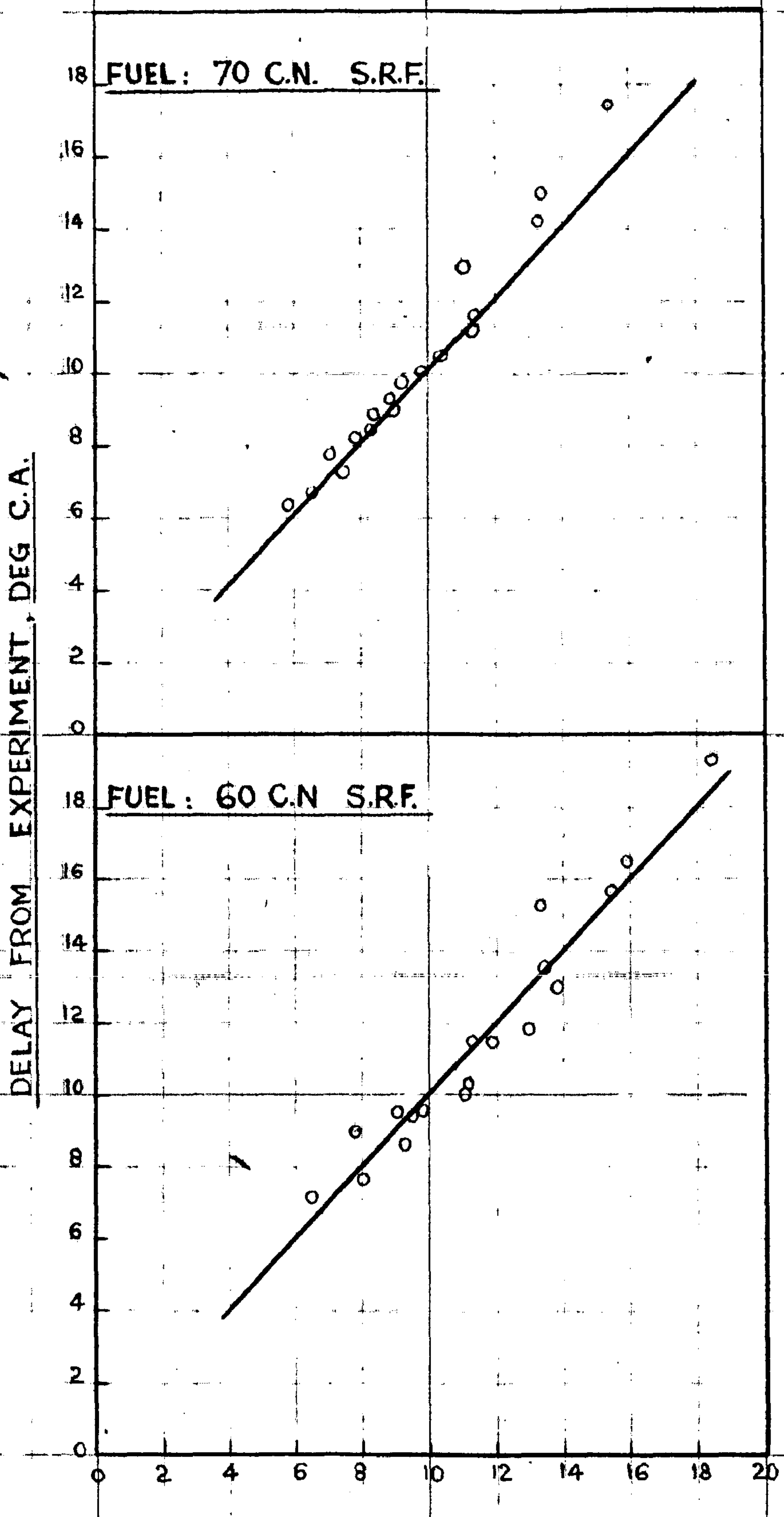


FIG. 23 EXPERIMENTAL DELAY VERSUS COMPUTED IGNITION DELAY

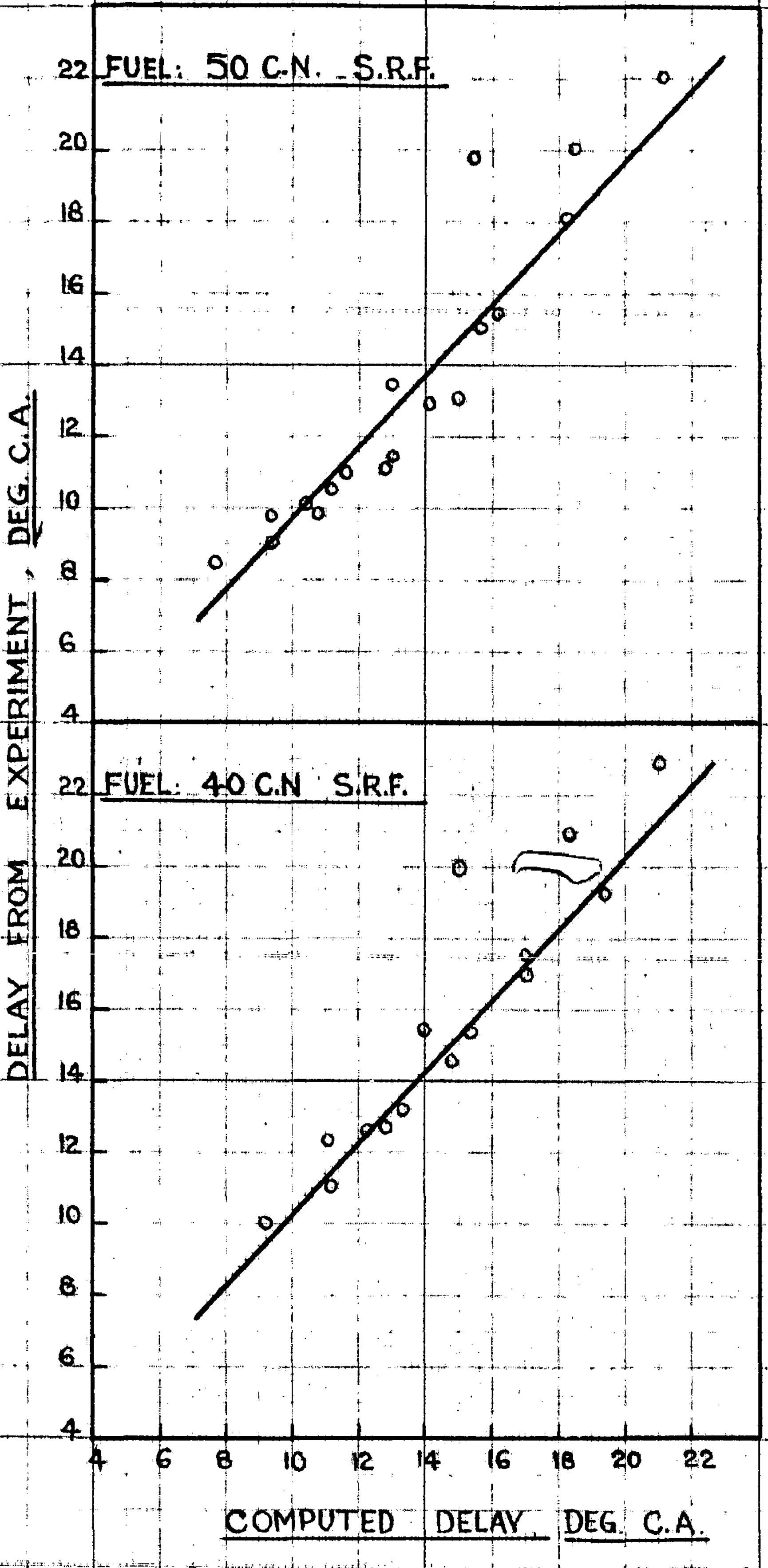


FIG. 24. EXPERIMENTAL DELAY VERSUS COMPUTED IGNITION DELAY

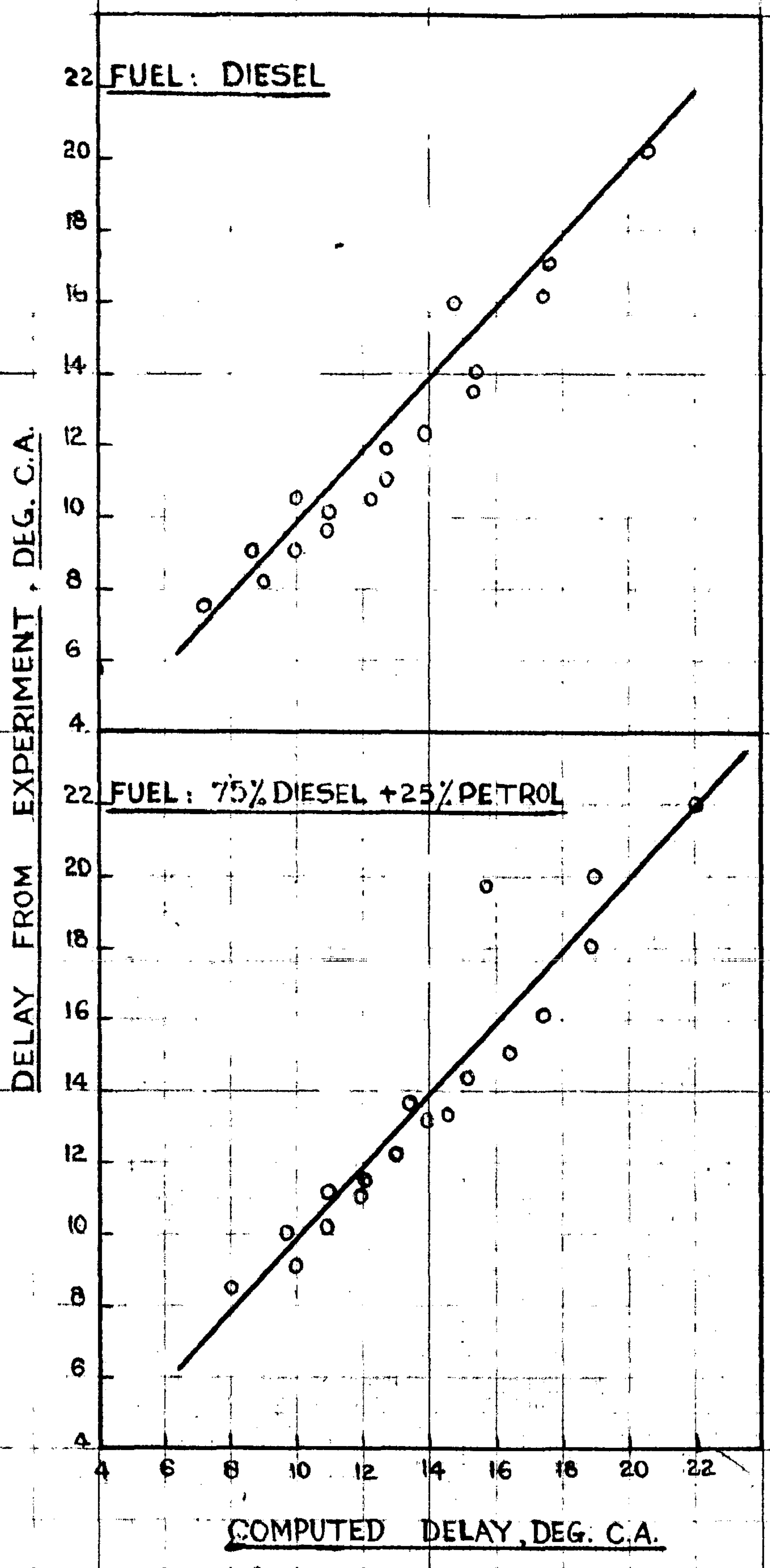


FIG. 25. EXPERIMENTAL DELAY VERSUS COMPUTED IGNITION DELAY

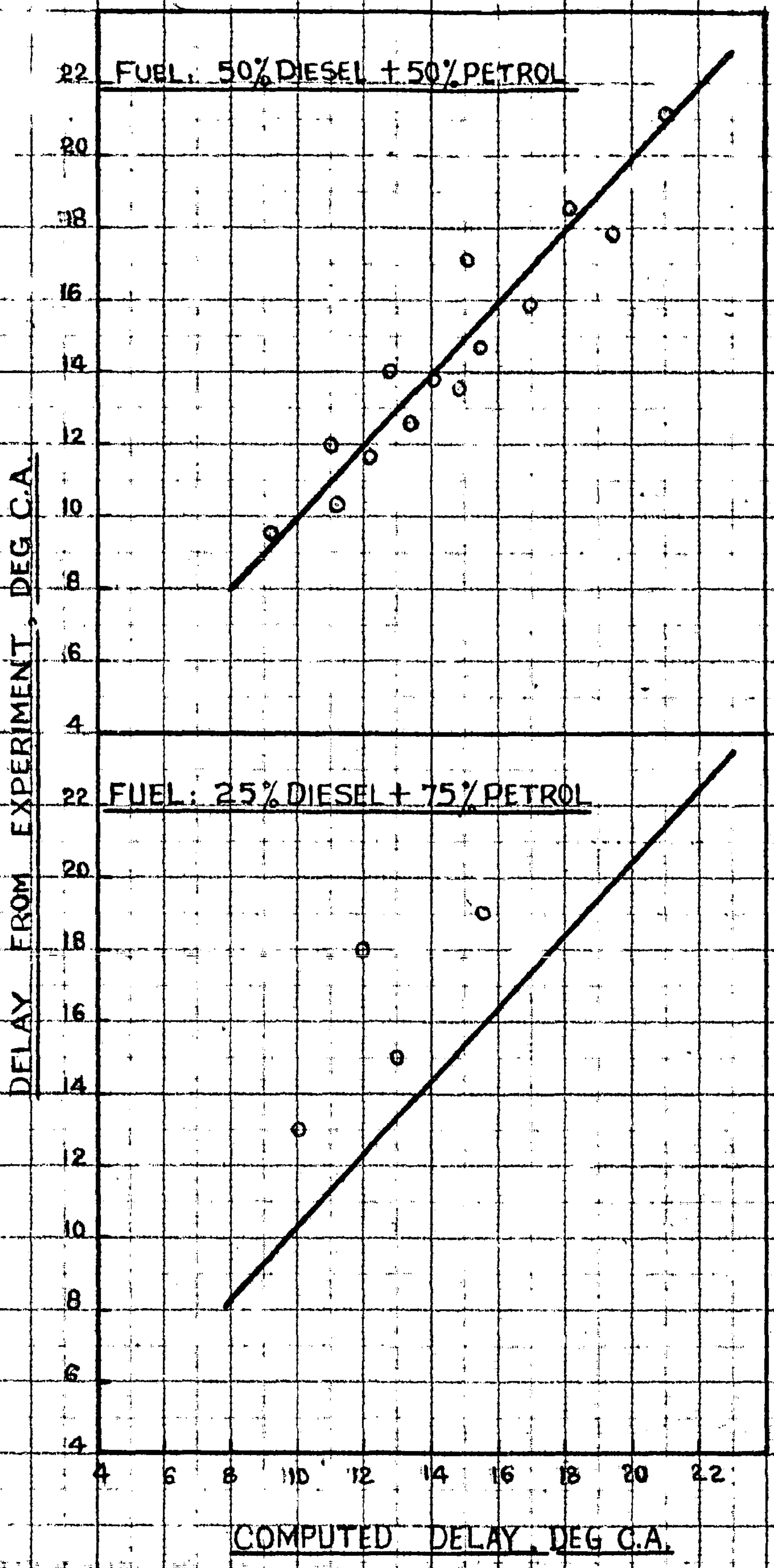


FIG. 26. EXPERIMENTAL DELAY VERSUS COMPUTED IGNITION DELAY

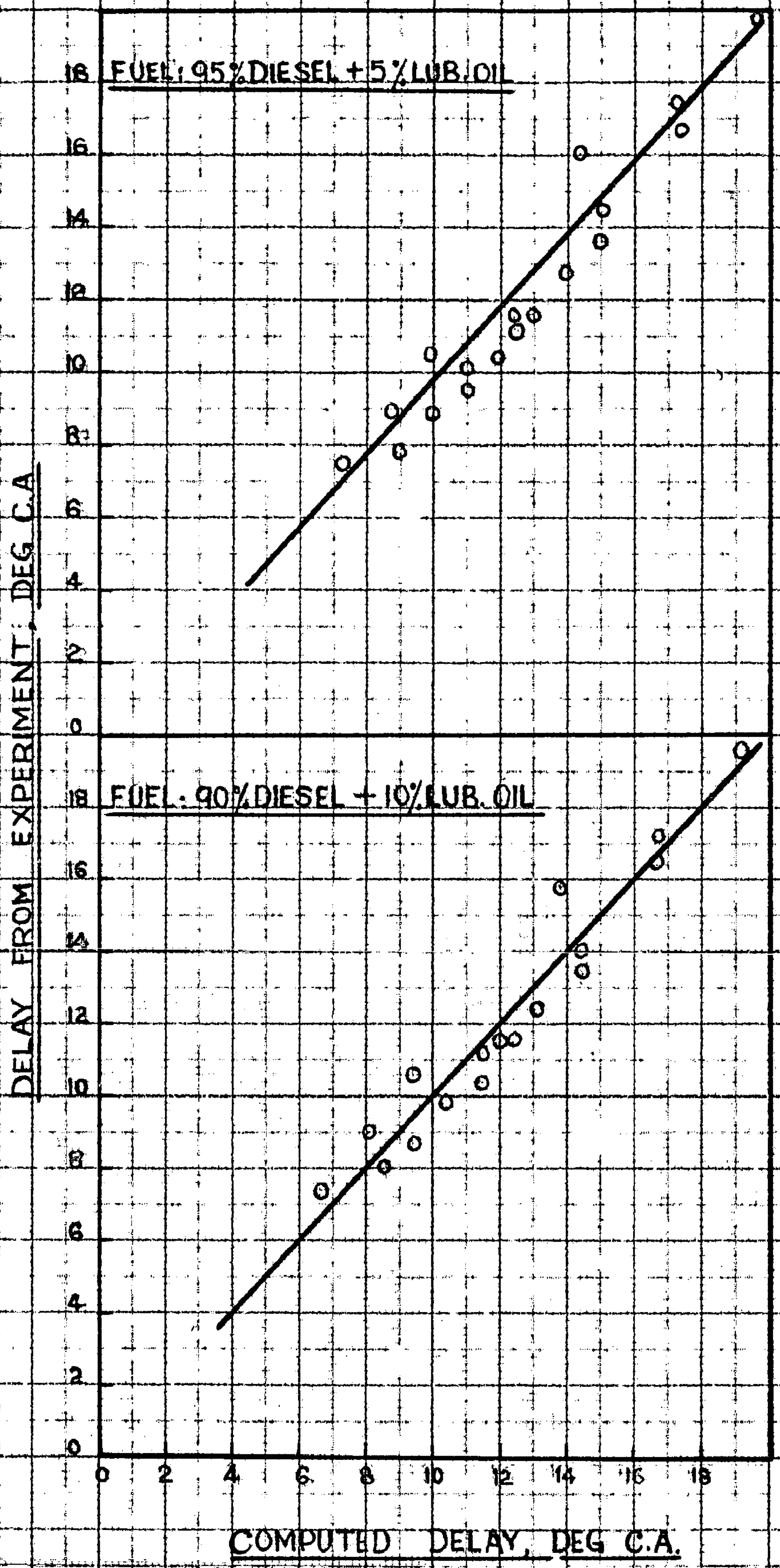


FIG. 27. EXPERIMENTAL DELAY VERSUS COMPUTED IGNITION DELAY

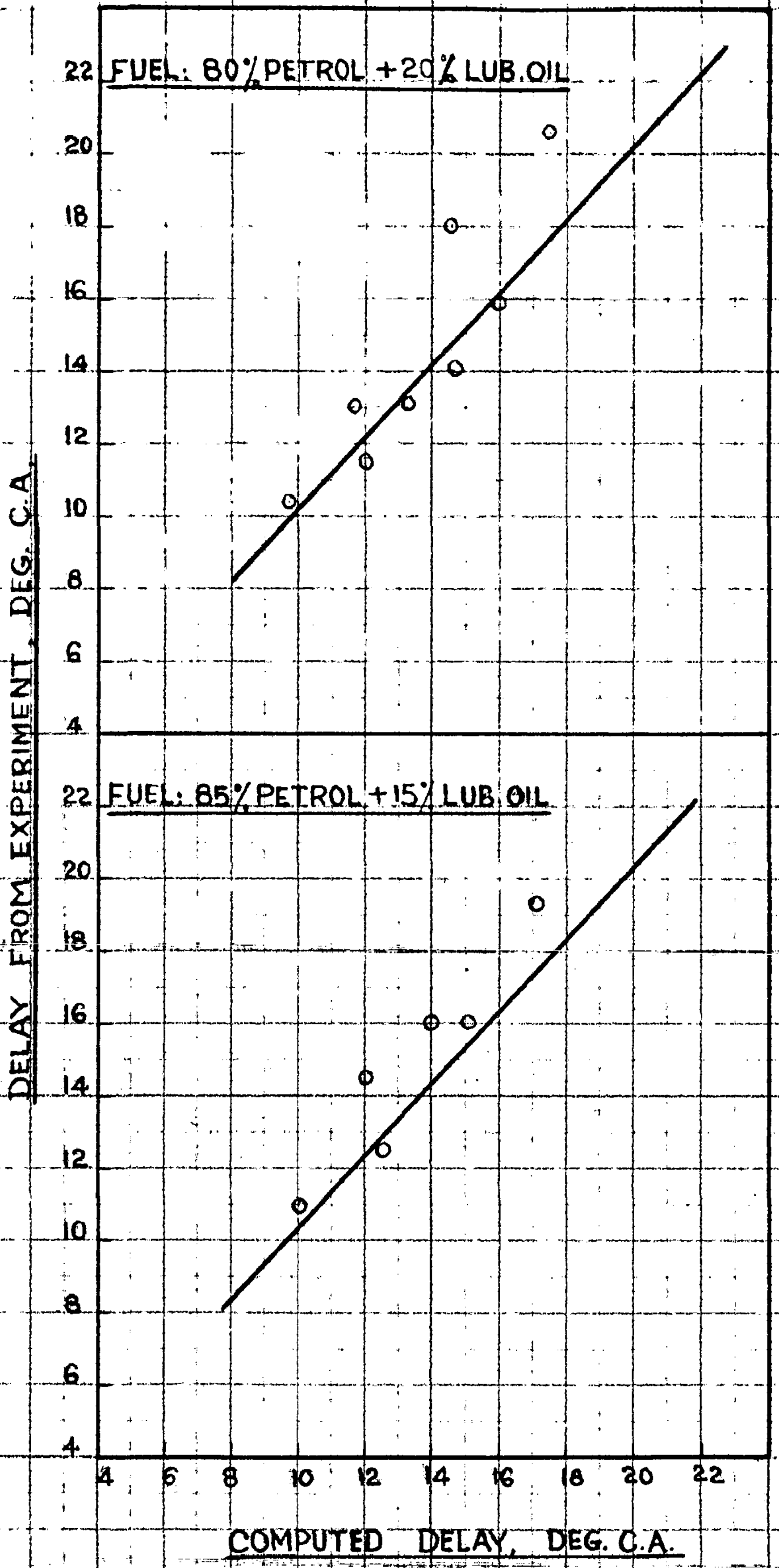


FIG. 28. EXPERIMENTAL DELAY VERSUS COMPUTED IGNITION DELAY

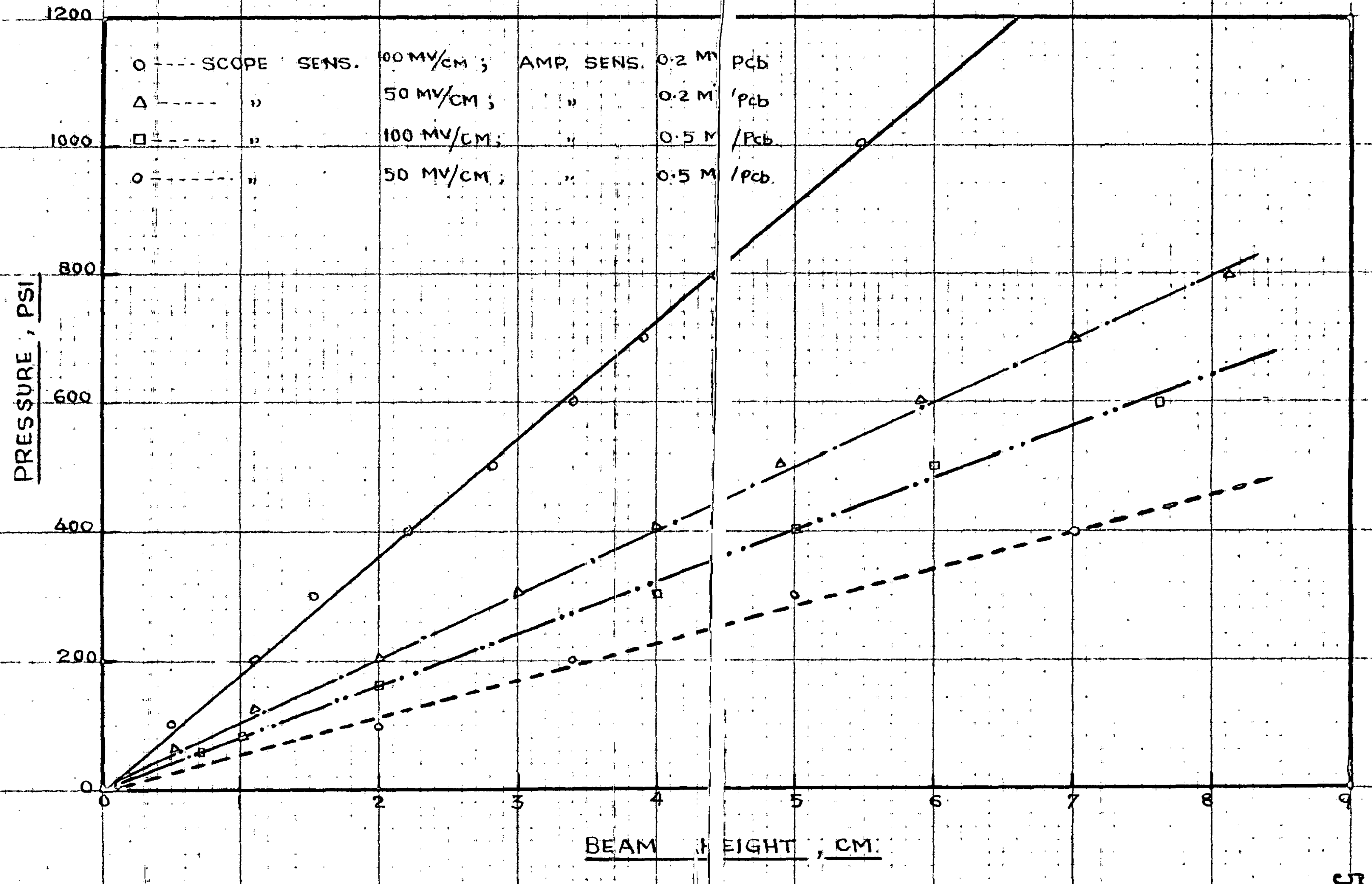


FIG. (29) PRESSURE PICKUP CALIBRATION CHART

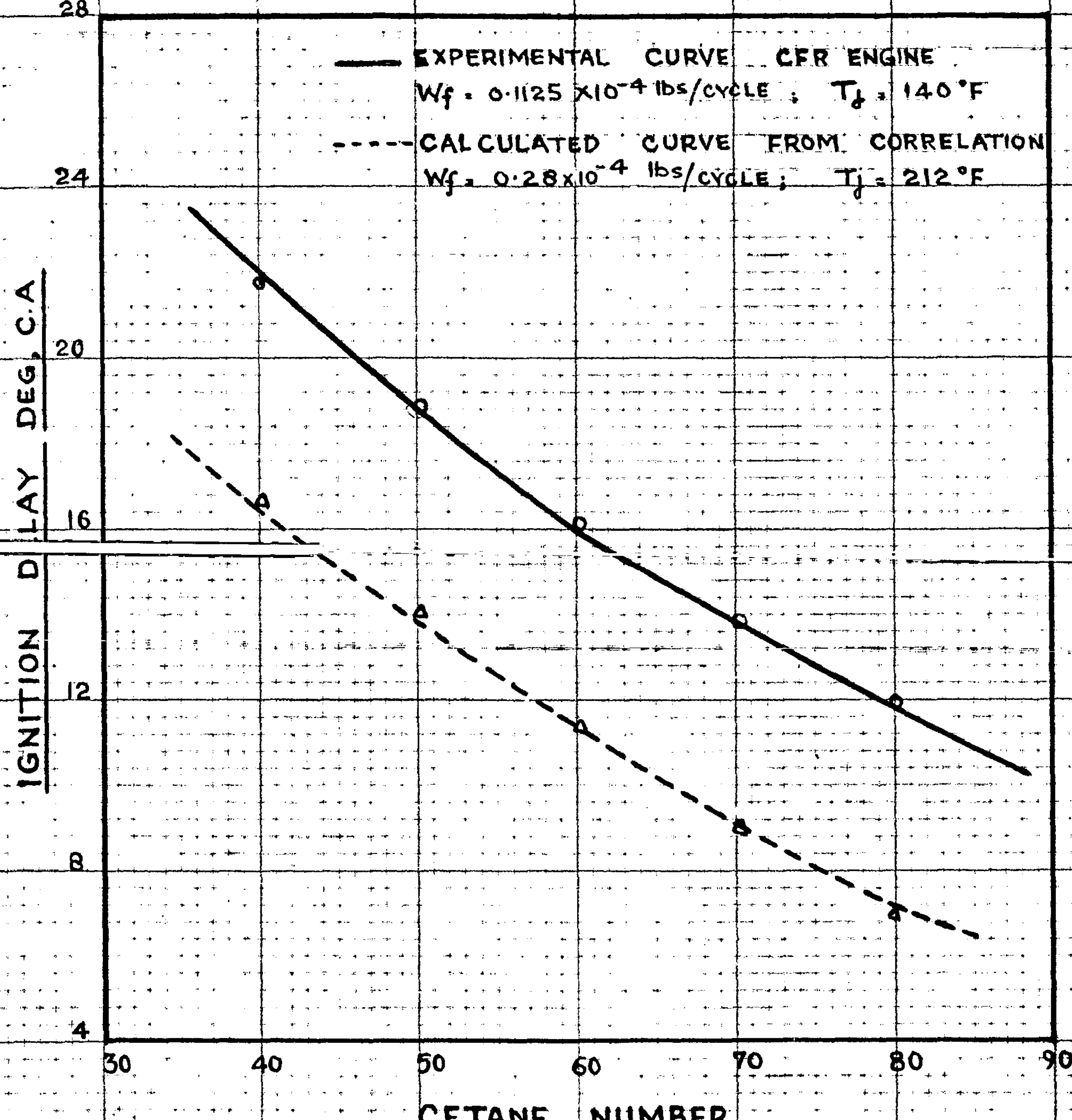


FIG. (30) COMPARISION OF CALCULATED VALUES WITH EXPERIMENTAL VALUES OF C.F.R ENGINE (TSAO et al)

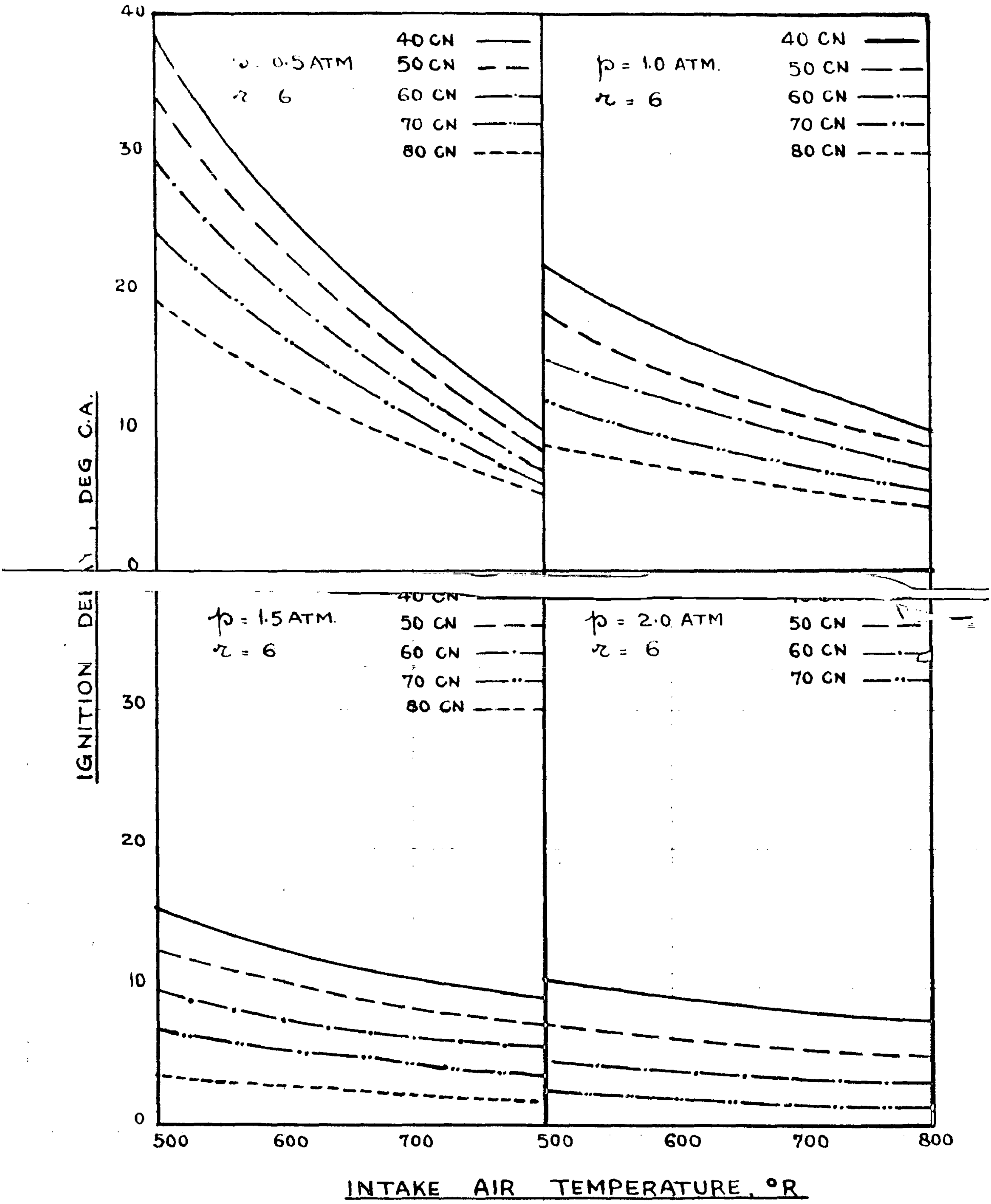
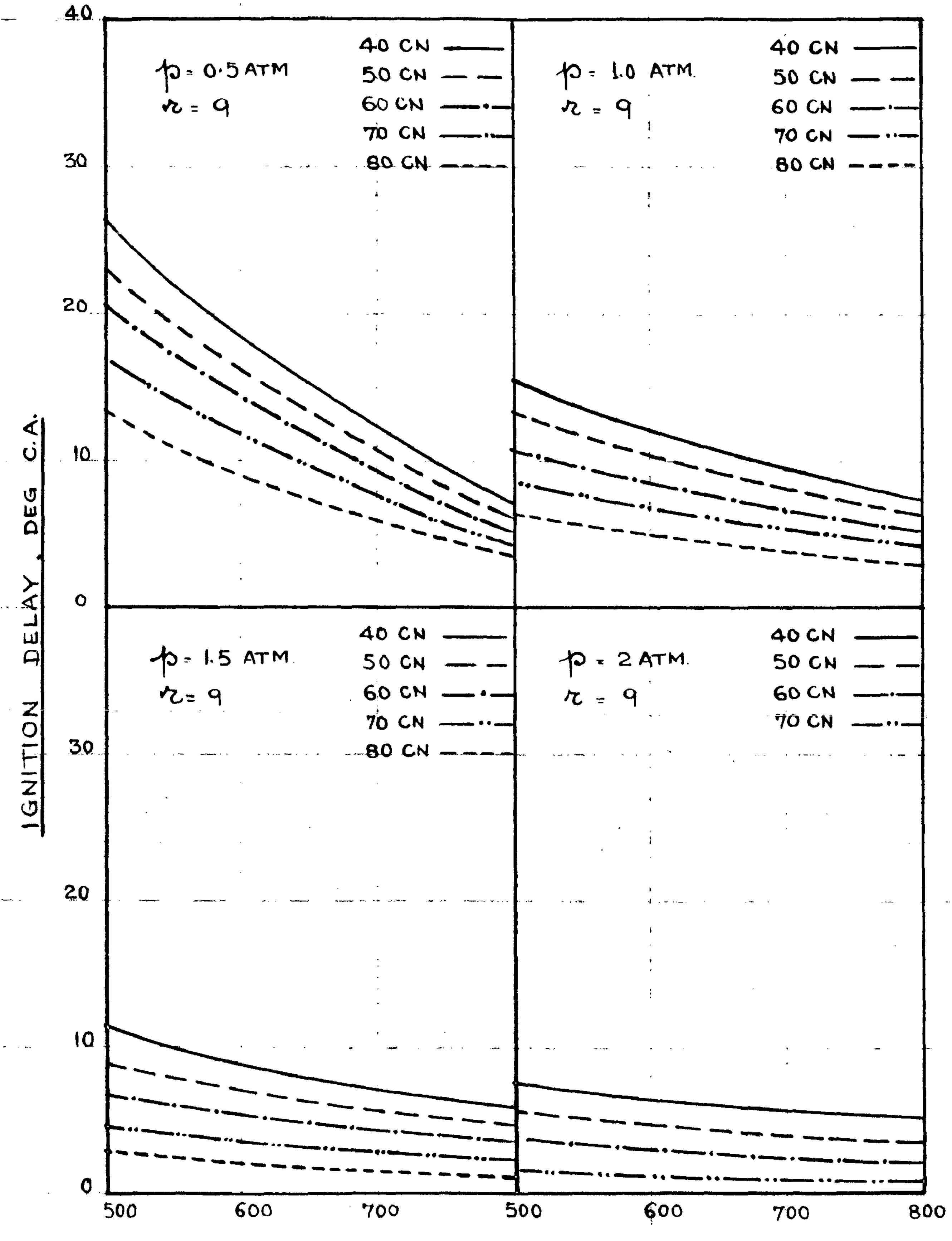


FIG. 31. EFFECT OF INTAKE AIR TEMPERATURE ON IGNITION DELAY IN PROPOSED CORRELATION



INTAKE AIR TEMPERATURE, °R

FIG.32. EFFECT OF INTAKE AIR TEMPERATURE ON IGNITION DELAY IN PROPOSED CORRELATION

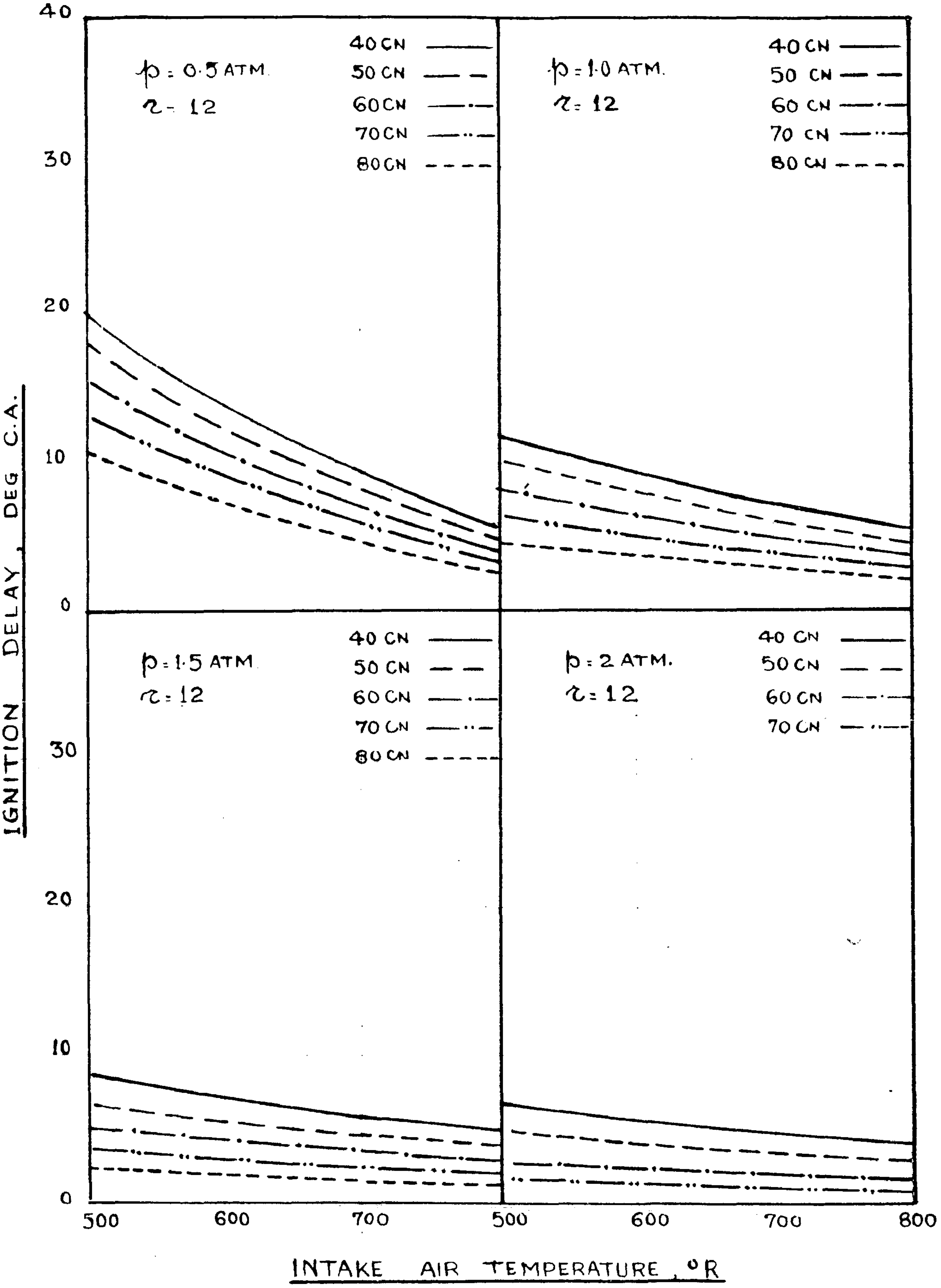


FIG. 33. EFFECT OF INTAKE AIR TEMPERATURE ON IGNITION DELAY IN PROPOSED CORRELATION

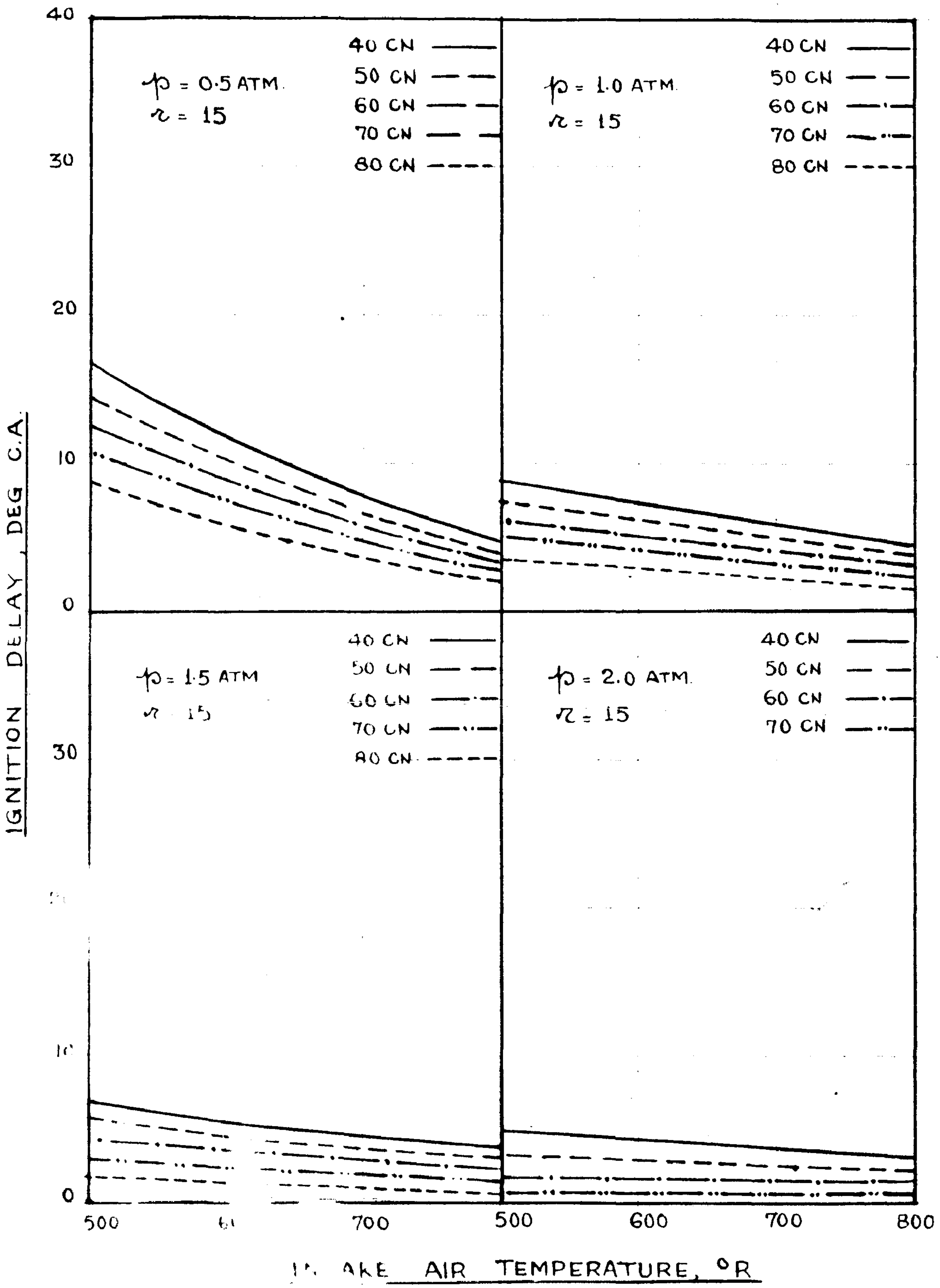


FIG. 34. EFFECT OF INTAKE AIR TEMPERATURE ON IGNITION DELAY IN PROPOSED CORRELATION

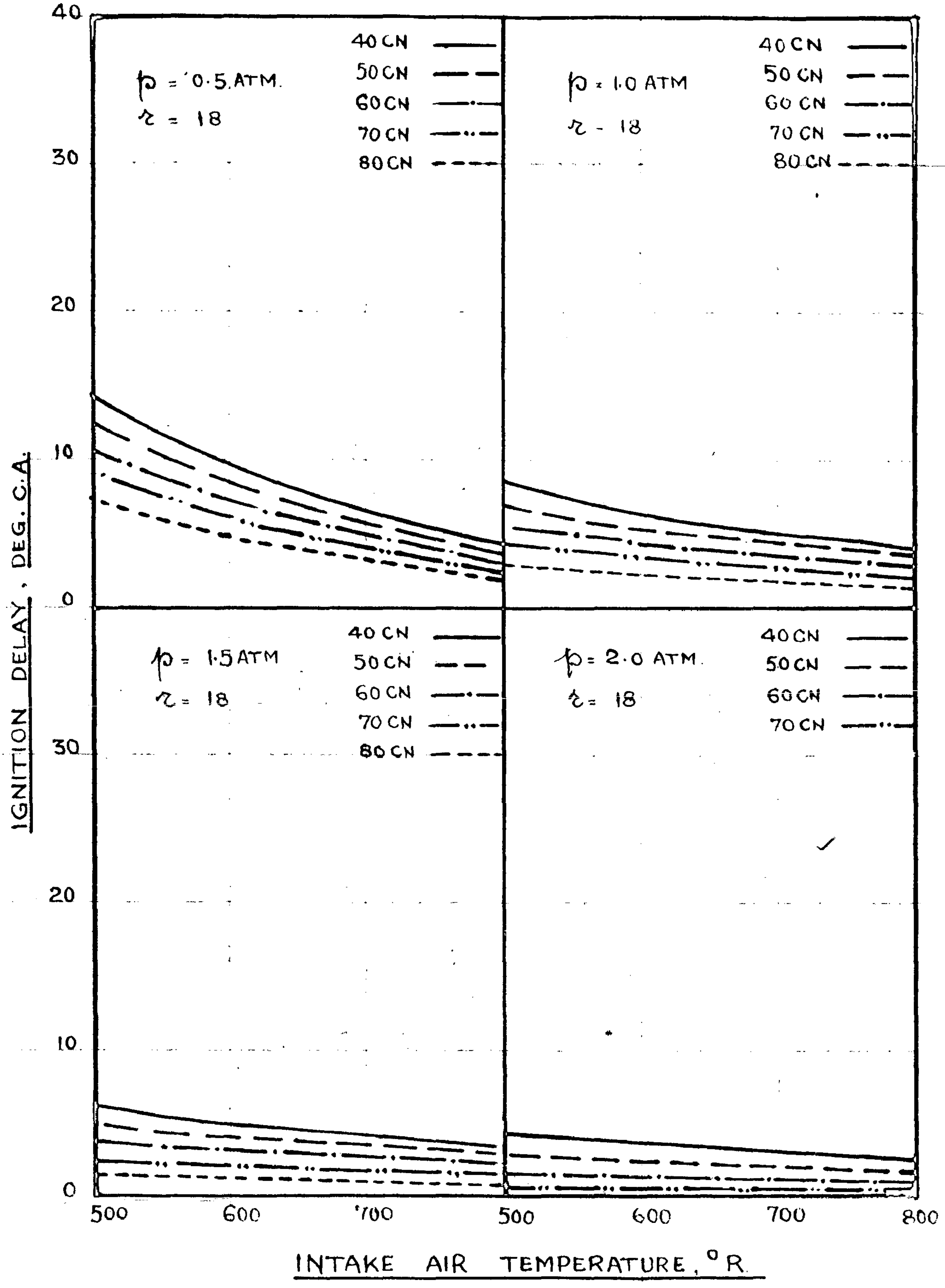


FIG.35. EFFECT OF INTATKE AIR TEMPERATURE ON IGNITION DELAY IN PROPOSED CORRELATION

CHAPTER IV

DISCUSSION OF RESULTS AND CORRELATION OF EXPERIMENTAL DATA

Different operating conditions of the engine were the following:

A. Injection timing

(i) 15° BTC
(ii) 20° BTC
(iii) 25° BTC

B. Intake air pressure in atmospheres

0.4, 0.5, 0.6, 0.7, 0.8, 0.97

C. Intake air temperature

80°F (540 °R)

D. Speed 1000 RPM

E. Fuel rate 8 cc/mt.

4.1 EFFECTS OF BLENDING OF PETROL WITH DIESEL

The blends of diesel-petrol tested were as follows:

(i) 100% diesel
(ii) 75% diesel + 25% petrol
(iii) 50% diesel + 50% petrol
(iv) 25% diesel + 75% petrol
(v) 100% petrol

Figs. (4, 5, 6, 7, 8 & 9) show the variation of ignition delay with the change in intake air pressure at different timings of injection advance. The delay angle increases as the intake air pressure decreases and also when injection advance increases.

These curves also show that the delay angle increases as the percentage of petrol increases in the diesel-petrol blend. These curves become more steep at lower pressures but the trend of the curves remains the same for all blends. With the increase of delay angle, it was observed, that a stage comes when the engine stops firing. 50% diesel + 50% petrol blend does not fire at 0.4 atm. intake pressure whereas 25% diesel + 75% petrol blend stops firing at 0.7 atm. intake pressure. Pure petrol does not fire atall. This can be explained as follows:

From the knowledge of pure hydro-carbon individual drop combustion data, we know that the more volatile the fuel, the smaller the initial diameter of the drops and shorter the physical, chemical and total ignition delays. But this theory is not equally applicable to gasoline when injected into diesel engines. EL-Wakil explains that the commercial fuels are mixtures of many hydro-carbons. The molecular structure of these hydro-carbons has a bearing on drops in a dense spray, and in diesel combustion chamber it results in cooling of the core of the spray far below the temperature of the atmosphere in which the fuel droplets are injected and thus affects the ignition delay.

The above fact can further be explained by studying two representative members of these fuels, namely cetane and n-octane with chemical structures of $C_{16}H_{34}$ and C_8H_{18} respectively. As a matter of fact, cracking of cetane, which starts at 100 psi pressure and 725°F temperature evidently does not allow the fuel droplets to reach the temperatures and pressures existing in the combustion chamber without interferring with the liquid structure. Consequently, there seems to be no possibility of a normal vaporization process due to latent heat supply; whereas n-octane due to its more stable molecule will vaporize in the combustion chamber of a diesel engine. Consequently the cracking process in the case of n-octane must occur after evaporation, i.e., at a much later instant than that for diesel fuels. Cracking is another name for the production of free radicals. As soon as free radicals are formed they may react with oxygen present and give rise to an explosion. In short, we may say that free radicals are produced with cetane while it is still in liquid phase. Free radicals are not produced with n-octane until it is evaporated.

The cetane number of pure diesel, 75% diesel + 25% petrol blend and 50% diesel + 50% petrol blend were found out to be 51.5, 46.5 and 39.8 respectively. This shows that the addition of petrol in diesel lowers the cetane number appreciably and rate of the decrease is greater as the percentage of petrol is increased.

From the pressure-time diagrams obtained, it was observed that the maximum pressure is more in the case of diesel than for 75% diesel + 25% petrol blend and decreases with an increase in the percentage of petrol. It is interesting to note that the engine operation was comparatively smoother and quieter with an increase in the percentage of petrol despite the decrease in cetane number. In this instance, cetane number falls down as a fuel rating method. The study of p-t diagrams also confirmed that the tendency of engine knocking was more pronounced at lower pressures for all blends.

Further experimental work was carried out with the object to see the effect of manifold introduction of petrol on the combustion of C.I. engines. In this case petrol was carburetted instead of injecting it along with diesel. The same percentages of petrol were tested at atmospheric condition of intake air under the same operating conditions of the engine and the ignition delay was the same as for pure diesel. Table 3 shows it clearly. It may probably be due to the completion of oxidation process of carburetted fuel before diesel fuel gets into the engine cylinder.

A significant effect was, however, observed that no firing of the carburetted petrol occurred at 0.28×10^{-4} lbs/cycle fuel rate; while increasing the fuel rate to 0.60×10^{-4} lbs/cycle, firing was observed with severe knocking. It is probably due to the reason that the whole of the petrol could not be oxidized till it attained its self-ignition temperature.

4.2 EFFECTS OF BLENDING OF LUBRICATING OIL WITH DIESEL

The blends of diesel-lubricating oil (S.A.E. 30) tested under various operating conditions are as follows:

(i) 95% diesel + 5% lubricating oil

(ii) 90% diesel + 10% lubricating oil

Tests with these blends indicate that the delay angle decreases very slightly with an increase of lubricating oil and the decrease is more with an increase of lubricating oil. Figs. (4-iv, 5-i & 5-ii) show the variation of ignition delay with other engine variables and the trend of the curves is the same as that of pure diesel. The decrease in ignition delay is probably due to the fact that the self-ignition temperature of lubricating oil is lower than that of diesel. 5% lubricating oil blend gives an increase in cetane number by 2 whereas a further addition of 5% increases the cetane number by 3. But this addition is not very desirable because it results in carbon deposition in the engine cylinder. However, it is beneficial for the injection equipment.

4.3 EFFECTS OF BLENDING OF LUBRICATING OIL WITH PETROL

The blends of petrol-lubricating oil tested are as follows:

(i) 90% petrol + 10% lubricating oil
(ii) 85% petrol + 15% lubricating oil
(iii) 80% petrol + 20% lubricating oil

Figs. (5-iii & 5-iv) show the trend of ignition delay variation with other operating variables. These tests indicate that delay angle decreases with an increase in the percentage of lubricating oil in petrol, resulting in an improvement of ignition of pure petrol. The cetane number of petrol was increased from 23.0 to 27.5 by adding 10% lubricating oil and increased to 31.7 and 34.0 by adding 15% and 20% respectively. This improvement in ignition quality is also at the cost of carbon deposition in the engine cylinder.

4.4 DATA OBTAINED FOR SECONDARY REFERENCE FUEL BLENDS

Secondary reference fuels u-9 and T-16 having cetane numbers 22.5 and 71.0 respectively were used as a standard of comparision for different blends. Different SRF blends tested are (i) 70 CN; (ii) 60 CN; (iii) 50CN; (iv) 40 CN and (v) 30 CN.

The variation of ignition delay for these SRF blends with different operating conditions of the engine is shown in Figs. (6-i, 6-ii, 6-iii & 6-iv).

From these curves it is seen that 20 °BTC injection advance is the most standard condition of the engine, because by changing the injection timing from 20 °BTC on either side, the change in delay angle with throttling of air does not follow a regular fashion. Fig. (6-ii) shows that the decrease in injection timing does not effect the ignition delay appreciably at lower throttling pressures whereas this change is very significant at higher pressures. On the contrary, by increasing the injection timing this change is very significant at lower pressures and is not appreciable at higher pressures. Further Figs. (6-iii & 6-iv) show that these changes become more pronounced as the cetane number of the fuel blend is decreased. This is probably due to the fact that the physical properties of these two secondary reference fuels are not much different. The changes are only in their chemical behaviour.

4.5 EFFECTS OF DIETHYLE ETHER $(C_2H_5)_2O$ ON DIESEL AND PETROL

The following tests were conducted at atmospheric condition of intake air with different injection timings (15°BTC, 20°BTC & 25°BTC).

A. (i) 75% diesel + 25% either, both injected together.

(ii) 50% diesel + 50% ether, both injected together.

B. (i) 75% diesel (injected) + 25% ether (carburetted).

(ii) 50% diesel (injected) + 50% ether (carburetted).

C. Petrol injected + Ether carburetted.

Results of 75% diesel + 25% ether both injected are shown in Table 4. It is observed that there is a decrease in ignition delay from what is obtained for pure diesel. It was expected also because ether is more volatile and has a lower self-ignition temperature than diesel. An addition of 5% and 10% ether gave an increase in cetane number of 3 and 5.5 respectively.

50% diesel + 50% ether blend, both injected, however, did not give any definite value of ignition delay - rather the needle was fluctuating. No definite conclusions could be drawn on this account, however, an appreciable decrease in ignition delay was expected.

It was surprising to note that delay meter did not show any value of ignition delay when 75% diesel (injected) + 25% ether (carburetted) blend weretested at different positions of injection timings. P-t diagrams obtained for it, however, showed that there were traces of pressure rise during the compression of air plus ether charge before the point of injection of diesel. This is, of course, due to the fact that ether has a low self-ignition temperature and is more volatile. The same results were obtained while testing 50% diesel (injected) + 50% ether (carburetted). P-t diagrams for both are shown on pages 97.

Tests of petrol (injected) + ether (carburetted) did not show any significant result. The engine did not fire, however, some traces of auto-ignition were observed on p-t diagrams.

4.6 EFFECT OF AMYL-NITRATE ($C_5H_{11}NO_3$) ON DIESEL AND PETROL

Fig. (18) shows the effect of amyl-nitrate on the ignition quality of diesel fuel. The curve shows that an addition of 1.0% amyl-nitrate increases the cetane number of diesel fuel from 51.5 to 65.

Similarly, Fig. (19) shows the effect of amyl-nitrate on the ignition quality of petrol. 10% of amyl-nitrate addition increases the cetane number of petrol from 23 to 55. Thus we see that it improves the ignition quality of diesel as well as petrol considerably by an addition of even a small amount.

4.7 EFFECT OF CETANE NUMBER ON IGNITION DELAY

Figs. (11, 12, 13, 14 & 15) show the delay angle variation with cetane number at different conditions of injection advance and intake pressure. All these figures show that the rate of decrease of delay angle decreases as the intake pressure increases. However, the trend of curves for different pressures at a particular injection timing is maintained. But, they have a tendency to become flat as the timing increases.

4.8 EMPIRICAL CORRELATION FOR IGNITION DELAY

In order to establish some empirical correlation between ignition delay and other engine variables, the experimental data obtained for different fuel blends tested, were used. It was thought that the various variables which were likely to be involved in the expression were as follows:

(i) Pressure of the air charge
(ii) Temperature of the air
(iii) Injection timing or effective compression ratio
(iv) Cetane number of the fuel
(v) Speed of the engine

Since our engine could not run at variable speed, the experimental data available was only for a particular speed of 1000 RPM. Unlike other investigators our efforts were to involve the intake air pressure and temperature in the expression instead of the pressure and temperature of the air charge at the point of injection.

The empirical relation was first found out for the secondary reference fuel blends and then tested for other blends. The procedure was entirely by trial and error, although the basic factors effecting the delay were always kept in mind while developing the relation.

The empirical relation developed relating the pressure, temperature, effective compression ratio, cetane number of fuel, and the ignition delay is:

$$D = \frac{86}{r + 1}\left[\frac{1130 + (70 - CN)17}{500\,p} - 1\right]\left[\frac{17.1}{T^{0.1}(1.1 - 0.06p)} - 8.05\right]$$

where

D = Ignition delay in deg. crank angle

r = Effective compression ratio at the point of injection

p = Intake air pressure in atmospheres

T = Intake air temperature in ^{o}R

CN = Cetane number of the fuel

In order to determine the accuracy of the correlation, the experimentally measured delay is plotted against the calculated ignition delay for all tested fuels as shown in Figs. (23 to 28). The mean line for all fuel blends show that the correlation is sufficiently accurate and can be relied upon for all conditions of the engine. It should, however, be equally applicable to other standard engines also.

The expirical correlation was checked with the CFR experimental values of Tsao et al. Fig. (30) show both curves, i.e. actual curve from Tsao et al and the calculated curve from our empirical relation. It was observed that these two curves are not actually different. Whatever difference there is can be ascribed to the following differences in the operating conditions of the engine:

(i) difference in speed

(ii) difference in jacket water temperature

(iii) difference in fuel rate

Difference in speed is not much, hence it effect may be neglected. But there is an appreciable difference in jacket water temperature and fuel rate. The temperature of jacket water and fuel rate from Tsao et al data was 140°F and 0.1125×10^{-4} lbs/cycle respectively whereas in our case it was 212°F and 0.28×10^{-4} lbs/cycle respectively. The increase in both, decreases the delay angle which has already been shown by previous investigators also, hence these two differences are responsible for a difference of about 5° crank angle in ignition delay.

The correlation was also checked for different values of intake air temperature from Tsao et al data and found to be in reasonably good agreement.

However, in order to investigate the limitations of the correlation, certain plots shown in Figs. (31 to 35) were made ignition delay and the pressure, temperature and effective compression ratio as the variables, keeping the cetane numbers as parameter. The following limitations have been suggested on this account:

(i) The proposed expression is not equally applicable for higher supercharged pressures. Above 1.5 atm., it does not give accurate values of ignition delay.

(ii) The expression is not very accurate for very high cetane number fuels. The range for reliable results is 40-70 CN.

(iii) Any difference in jacket water temperature and fuel rate should be accounted for while evaluating the value of ignition delay.

CONCLUSIONS

The following conclusions can be drawn from the experimental work conducted during the course of our study:

1. The blending of petrol with diesel increases the delay angle in compression ignition engines. Although petrol is more volatile, its self-ignition temperature is much higher than that of diesel fuel which offsets the reduction in vaporization lag and forces the fuel to ignite later. The maximum pressure achieved during the cycle is lower in case of petrol addition than pure diesel and this is because the calorific value of petrol on volume basis is lower than diesel. This decrease in calorific value also makes the engine to run smoother and quieter inspite of decreasing the cetane number of the fuel blend. The increase in delay angle with addition of petrol slows the burning process and thus a decrease in power output is obtained.

2. The increase in pressure of intake air decreases the ignition delay of all fuel blends irrespective of their ignition quality. This decrease in delay is less marked at higher pressures. Thus throttling of intake air is not desirable; it produces a tendency to knock which is directly responsible for loss of power.

3. Advancing the injection timing decreases the effective compression ratio which in turn decreases the pressure and temperature of air charge at the point of injection and so the delay angle is increased. However, the increase of ignition delay is faster at larger injection timings.

4. The addition of lubricating oil in diesel and petrol increases the ignition quality of both diesel and petrol. This is because the self-ignition temperature of lubricating oil is lower than that of diesel as well as petrol. This addition, however, is not desirable because the calorific value of the blend being small, the consumption of the fuel is more and also it is directly responsible for carbon deposition in the engine cylinder.

5. The addition of diethyl ether has shown an increase in cetane number of diesel fuel. It has already been recognised as one of the means for cold starting of the engine. Hence its importance.

6. The addition of amyl-nitrate, even in very small quantities, increases the cetane number of fuels tremendously. Thus it is a very good ignition accelerator. 1% addition of amyl-nitrate in diesel increases the cetane number from 51.5 to 65, and similarly 10% addition of amyl-nitrate increases the cetane number of petrol from 23 to 85.

7. The cetane numbers determined for various blends are shown in Table 2. The values determined by various methods do not differ much, hence any of the methods can be employed for its determination. However, for accurate measurements, bracketing method is preferred.

8. Manifold introduction of petrol does not change the delay angle of the diesel fuel injected.

9. Manifold introduction of ether while petrol is injected into the combustion chamber, has no effect on engine working. The engine does not fire at all.

10. An empirical correlation relating the intake air pressure, intake air temperature, effective compression ratio, the cetane number of the fuel and the ignition delay is:

$$D = \frac{86}{r + 1}\left[\frac{1130 + (70 - CN)17}{500p} - 1\right]\left[\frac{17.1}{T^{0.1}(1.1 - 0.06p)} - 8.05\right]$$

This correlation is very helpful in finding out any of the unknown value from other known values. It is a simple correlation because the temperature and pressure at intake conditions can always be found out without difficulty.

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APPENDIX - A

EXPERIMENTAL AND CALCULATED VALUES OF IGNITION DELAY FOR VARIOUS OPERATING CONDITIONS OF THE ENGINE

(Speed, rate of fuel and intake air temperature are 1000 R.P.M., 8cc/mt., and 540°R respectively for all readings)

TABLE A-1

FUEL: 70 CN SRF

Injection Advance Deg. C.A.	Intake Pressure in ATM.	Ignition Delay Deg. C.A.	
		Experimental	Calculated
15 (r = 13.5)	0.4	13.1	11.0
	0.5	9.8	9.4
	0.6	8.5	8.2
	0.7	7.4	7.4
	0.8	6.8	6.5
	0.97	6.4	5.8
20 (r = 11.2)	0.4	15.0	13.4
	0.5	11.7	11.4
	0.6	10.0	9.9
	0.7	9.0	8.9
	0.8	8.3	7.9
	0.97	7.8	7.0
25 (r = 9.7)	0.4	17.5	15.5
	0.5	14.2	13.2
	0.6	11.3	11.3
	0.7	10.2	10.3
	0.8	9.5	9.1
	0.97	8.9	8.2

TABLE A-2

FUEL: 60 CN SRF

Injection Advance Deg. C.A.	Intake Pressure in ATM.	Ignition Delay Deg. C.A.	
		Experimental	Calculated
15 (r = 13.5)	0.4	15.4	13.2
	0.5	11.5	11.2
	0.6	9.6	9.9
	0.7	8.5	9.3
	0.8	7.7	8.0
	0.97	7.2	6.4
20 (r = 11.2)	0.4	16.5	15.9
	0.5	13.4	13.5
	0.6	11.4	11.9
	0.7	10.2	11.2
	0.8	9.5	9.7
	0.97	9.0	7.8
25 (r = 9.7)	0.4	19.5	18.5
	0.5	15.7	15.6
	0.6	13.0	13.8
	0.7	10.8	12.9
	0.8	10.2	11.1
	0.97	9.5	8.9

TABLE A-3

FUEL: 50 CN SRF

Injection Advance Deg. C.A.	Intake Pressure in ATM.	Ignition Delay Deg. C.A.	
		Experimental	Calculated
15 (r = 13.5)	0.4	19.8	15.2
	0.5	13.5	13.0
	0.6	11.2	11.7
	0.7	9.8	10.8
	0.8	8.9	9.3
	0.97	8.4	7.6
20 (r = 11.2)	0.4	20.0	18.4
	0.5	15.0	15.7
	0.6	12.9	14.1
	0.7	11.5	12.9
	0.8	10.5	11.2
	0.97	9.9	9.2
25 (r = 9.7)	0.4	22.5	21.4
	0.5	18.0	18.2
	0.6	15.6	16.2
	0.7	13.0	15.0
	0.8	10.8	12.8
	0.97	10.0	10.6

TABLE A-4

FUEL: 40 CN SRF

Injection Advance Deg. C.A.	Intake Pressure in ATM.	Ignition Delay Deg. C.A.	
		Experimental	Calculated
15 (r = 13.5)	0.4	25.0	17.2
	0.5	20.0	15.0
	0.6	15.5	14.0
	0.7	12.5	12.2
	0.8	11.0	11.2
	0.97	10.0	9.1
20 (r = 11.2)	0.4	25.0	21.0
	0.5	21.0	18.2
	0.6	17.0	17.0
	0.7	14.5	14.7
	0.8	13.1	13.5
	0.97	12.3	11.0
25 (r = 9.7)	0.4	25.0	24.0
	0.5	23.0	21.0
	0.6	19.2	19.5
	0.7	17.4	17.0
	0.8	15.5	15.6
	0.97	12.5	12.7

TABLE A-5

FUEL: DIESEL
(CN = 51.5)

Injection Advance Deg. C.A.	Intake Pressure in ATM.	Ignition Delay Deg. C.A.	
		Experimental	Calculated
15 (r = 13.5)	0.4	16.1	14.7
	0.5	11.8	12.7
	0.6	10.0	11.2
	0.7	10.0	10.2
	0.8	8.0	9.2
	0.97	7.5	7.2
20 (r = 11.2)	0.4	17.0	17.7
	0.5	13.4	15.3
	0.6	11.4	13.4
	0.7	10.3	12.2
	0.8	9.6	11.0
	0.97	9.0	8.7
25 (r = 9.7)	0.4	20.1	20.5
	0.5	16.1	17.6
	0.6	14.0	16.5
	0.7	12.0	14.2
	0.8	10.8	12.7
	0.97	10.5	10.0

TABLE A-6

FUEL: 75% DIESEL + 25% PETROL
(CN = 46.5)

Injection Advance Deg. C.A.	Intake Pressure in ATM.	Ignition Delay Deg. C.A.	
		Experimental	Calculated
15 (r= 13.5)	0.4	19.4	15.8
	0.5	13.7	13.6
	0.6	11.4	12.1
	0.7	10.0	11.0
	0.8	9.0	10.0
	0.97	8.4	8.0
20 (r = 11.2)	0.4	20.2	19.2
	0.5	15.2	16.4
	0.6	13.3	14.5
	0.7	11.8	13.2
	0.8	10.8	10.0
	0.97	10.3	9.7
25 (r = 9.7)	0.4	22.0	22.0
	0.5	18.0	18.9
	0.6	16.0	16.7
	0.7	14.2	15.3
	0.8	12.8	13.9
	0.97	11.2	11.1

TABLE A-7

FUEL: 50% Diesel + 50% Petrol
(CN = 39.8)

Injection Advance Deg. C.A.	Intake Pressure in ATM.	Ignition Delay Deg. C.A.	
		Experimental	Calculated
15 (r = 13.5)	0.4	25.0	17.2
	0.5	17.5	15.0
	0.6	13.8	14.0
	0.7	11.7	12.2
	0.8	10.3	11.2
	0.97	9.6	9.1
20 (r = 11.2)	0.4	25.0	21.0
	0.5	18.5	18.2
	0.6	15.7	17.0
	0.7	13.5	14.7
	0.8	12.6	13.5
	0.97	12.0	11.0
25 (r = 9.7)	0.4	25.0	24.0
	0.5	20.8	21.0
	0.6	17.7	19.5
	0.7	16.0	17.0
	0.8	14.6	15.6
	0.97	14.0	12.7

TABLE A-8

FUEL: 25% Diesel + 75% Petrol
(CN = 31.5)

Injection Advance Deg. C.A.	Intake Pressure in ATM.	Ignition Delay Deg. C.A.	
		Experimental	Calculated
15 (r = 13.5)	0.4	-	-
	0.5	-	-
	0.6	-	-
	0.7	-	-
	0.8	15.0	15.0
	0.97	13.0	10.0
20 (r = 11.2)	0.4	-	-
	0.5	-	-
	0.6	-	-
	0.7	-	-
	0.8	19.0	15.5
	0.97	18.0	12.1

TABLE A-9

FUEL: 95% Diesel + 5% Lub. Oil S.A.E. 30
(CN = 53.5)

Injection Advance Deg. C.A.	Intake Pressure in ATM.	Ignition Delay Deg. C.A.	
		Experimental	Calculated
15 (r = 13.5)	0.4	16.0	14.3
	0.5	11.5	12.4
	0.6	9.9	10.9
	0.7	8.8	10.0
	0.8	7.8	9.0
	0.97	7.4	7.1
20 (r = 11.2)	0.4	17.3	17.3
	0.5	13.5	14.9
	0.6	11.4	13.1
	0.7	10.3	12.0
	0.8	9.6	10.8
	0.97	9.0	8.6
25 (r = 9.7)	0.4	19.8	19.8
	0.5	16.4	17.3
	0.6	14.3	15.1
	0.7	12.7	13.9
	0.8	11.0	12.5
	0.97	10.5	9.8

TABLE A-10

FUEL: 90% Diesel + 10% Lub. Oil S.A.E. 30
(CN = 56.5)

Injection Advance Deg. C.A.	Intake Pressure in ATM.	Ignition Delay Deg. C.A.	
		Experimental	Calculated
15 (r = 13.5)	0.4	15.8	13.9
	0.5	11.5	12.0
	0.6	9.8	10.3
	0.7	8.7	9.5
	0.8	7.9	8.5
	0.97	7.4	6.7
20 (r = 11.2)	0.4	17.2	16.8
	0.5	13.5	14.4
	0.6	11.5	12.4
	0.7	10.3	11.5
	0.8	9.5	10.2
	0.97	9.1	8.1
25 (r = 9.7)	0.4	19.8	19.4
	0.5	16.2	16.7
	0.6	14.0	14.3
	0.7	12.3	13.1
	0.8	11.2	11.7
	0.97	10.5	9.3

TABLE A-11

FUEL: 80% Petrol + 20% Lub. Oil S.A.E. 30
(CN = 34.0)

Injection Advance Deg. C.A.	Intake Pressure in ATM.	Ignition Delay Deg. C.A.	
		Experimental	Calculated
15 (r = 13.5)	0.4	-	-
	0.5	-	-
	0.6	18.0	14.5
	0.7	13.0	13.2
	0.8	11.5	12.1
	0.97	10.4	9.7
20 (r = 11.2)	0.4	-	-
	0.5	-	-
	0.6	20.5	17.5
	0.7	16.0	15.8
	0.8	14.0	14.6
	0.97	13.0	11.7

TABLE A-12

FUEL: 85.0% Petrol + 15.0% Lub. Oil S.A.E. 30
(CN = 31.7)

Injection Advance Deg. C.A.	Intake Pressure in ATM.	Ignition Delay Deg. C.A.	
		Experimental	Calculated
15 (r = 13.5)	0.4	-	-
	0.5	-	-
	0.6	-	-
	0.7	16-19	14.0
	0.8	12.5	12.5
	0.97	11.0	10.0
20 (r = 11.2)	0.4	-	-
	0.5	-	-
	0.6	-	-
	0.7	19.5	17.0
	0.8	16.0	15.1
	0.97	14.5	12.1

APPENDIX - B

TABLE B-1

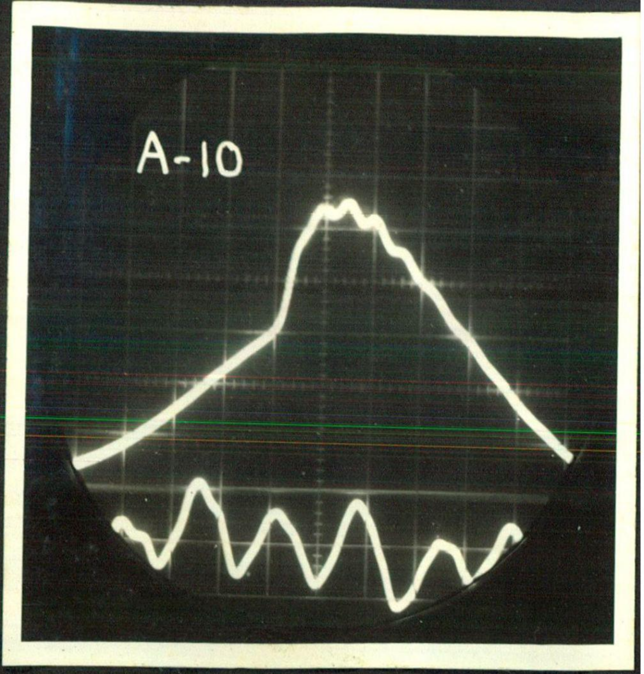
EFFECTIVE COMPRESSION RATIO FOR VARIOUS COMPRESSION RATIO AND INJECTION ADVANCE POSITION

(Connecting rod/Crank = 5.0)

Injection Advance Deg. C.A.	Effective Compression Ratio			
	20 C.R.	18 C.R.	16 C.R.	14 C.R.
10	18.1	16.3	14.1	12.0
15	14.4	13.4	12.25	11.1
20	11.9	11.15	10.4	9.5
25	10.2	9.5	9.1	8.4
30	8.0	7.65	7.3	6.9

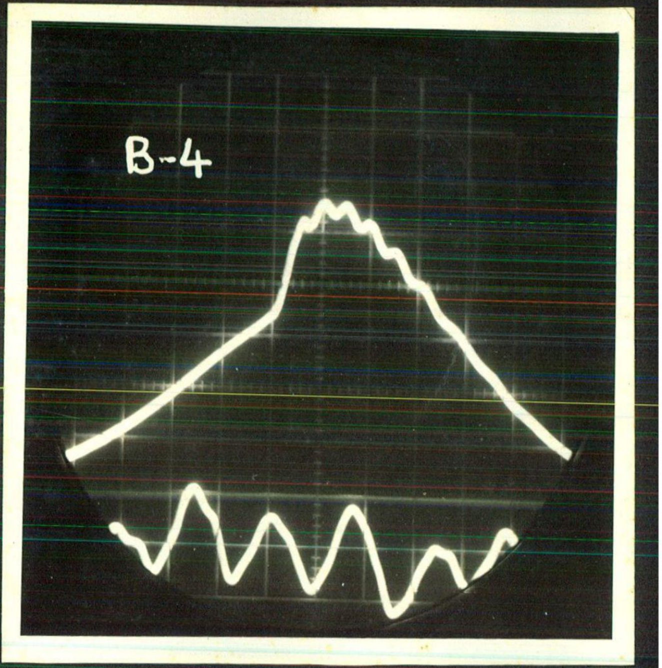
A-10

FUEL : DIESEL
Injection Advance = 15°BTC
Intake Pressure = 0.97 ATM
scilloscope Sensitivity = 100 mv/cm.
mplifier Sensitivity = 0.2 mv/pcb.



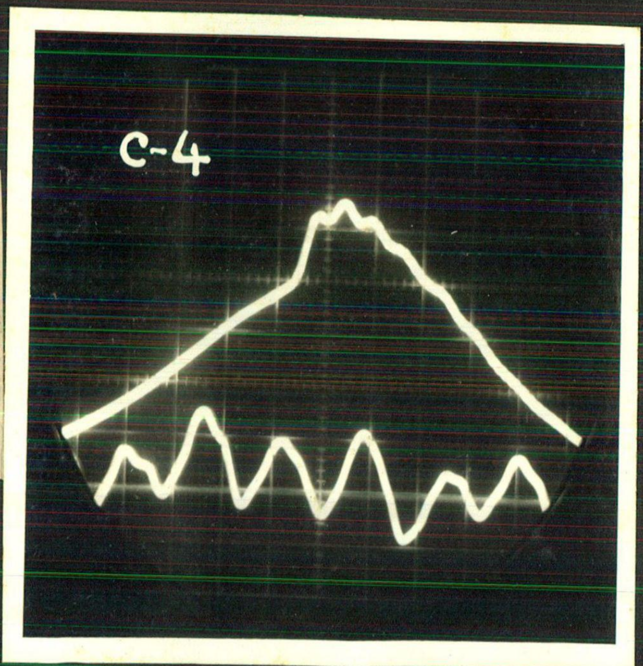
B-4

FUEL : 75% DIESEL + 25% PETROL
Injection Advance = 15°BTC
Intake Pressure = 0.97 ATM
Oscilloscope Sensitivity = 100 mv/cm.
Amplifier Sensitivity = 0.2 mv/pcb.



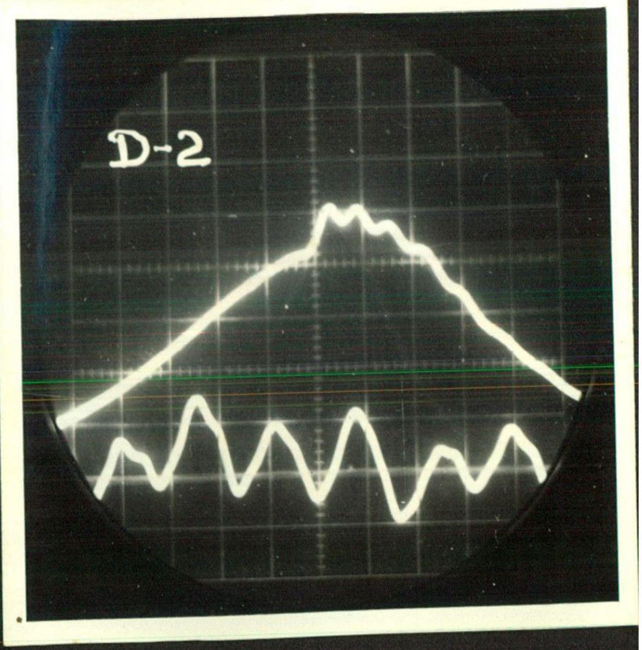
C-4

FUEL : 50% DIESEL + 50% PETROL
Injection Advance = 15°BTC
Intake Pressure = 0.97 ATM
Oscilloscope Sensitivity = 100 mv/cm.
Amplifier Sensitivity = 0.2 mv/pcb.



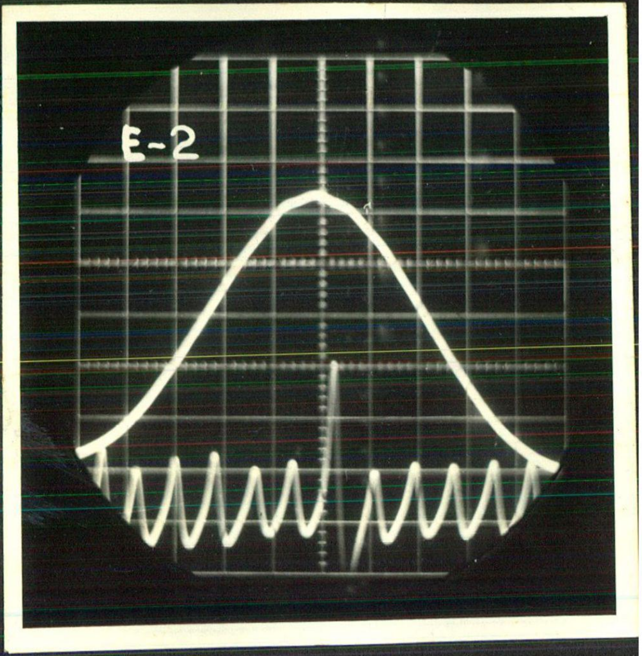
D-2

FUEL : 25% DIESEL + 75 % PETROL
Injection Advance = 15°BTC
Intake Pressure = 0.97 ATM
Oscilloscope Sensitivity = 100 mv/cm.
Amplifier Sensitivity = 0.2 mv/pcb.



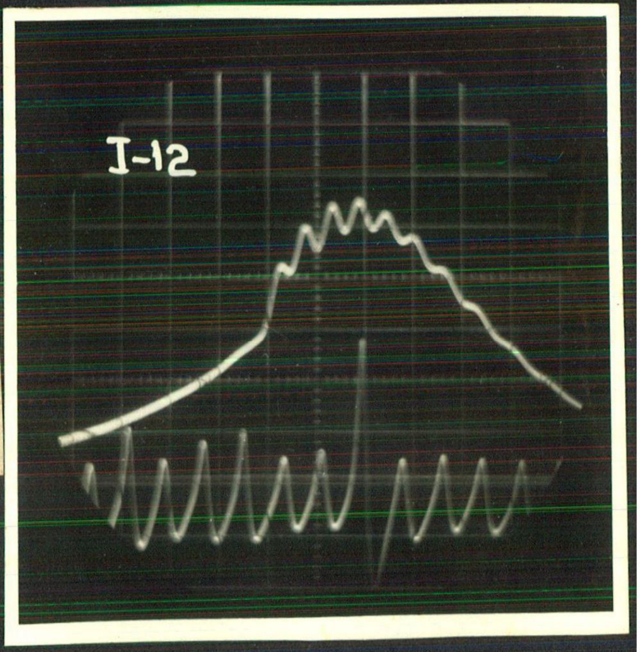
E-2

FUEL : 100% PETROL
Injection Advance = 15°BTC
Intake Pressure = 0.97 ATM
Oscilloscope Sensitivity = 50 mv/cm.
Amplifier Sensitivity = 0.2 mv/pcb.



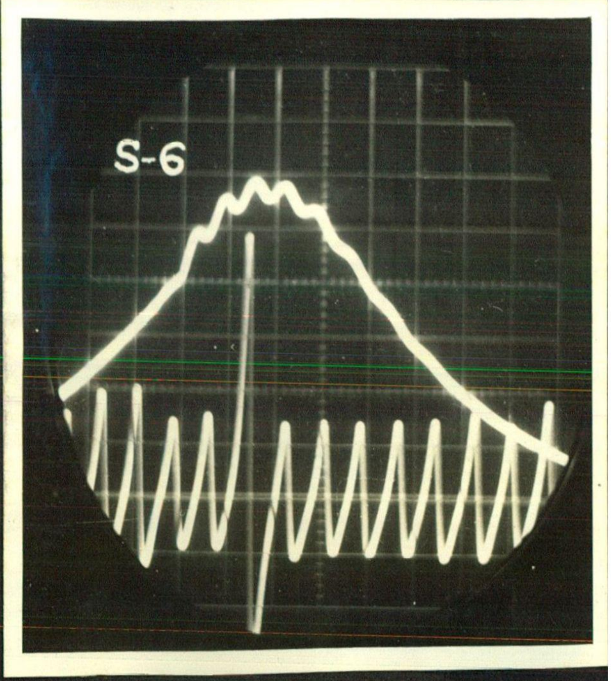
I-12

FUEL : 40 CN SRF
Injection Advance = 25°BTC
Intake Pressure=0.97 ATM
Oscilloscope Sensitivity = 100 mv/cm.
Amplifier Sensitivity = 0.2 mv/pcb.



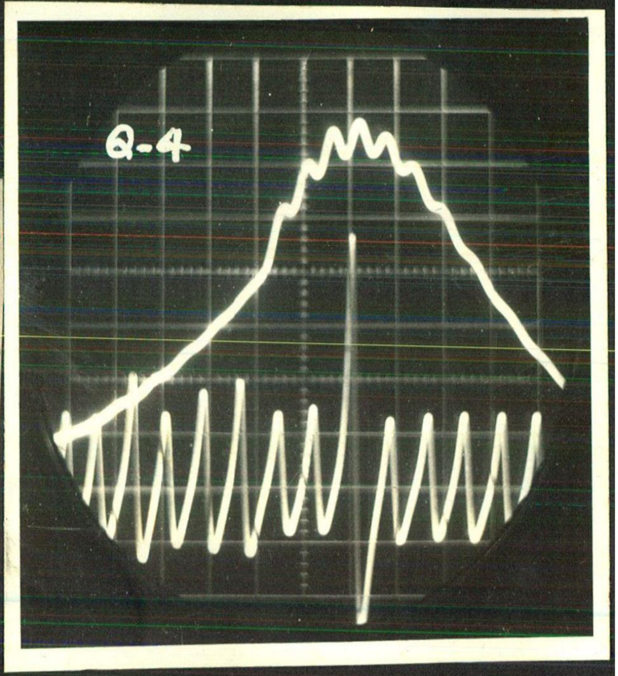
S-6

FUEL : 30% DIESEL (INJECTED) +
70% PETROL (CARBURETTED)
Injection Advance = 20°BTC
Intake Pressure = Atmospheric
Oscilloscope Sensitivity = 100 mv/cm.
Amplifier Sensitivity = 0.2 mv/pcb.



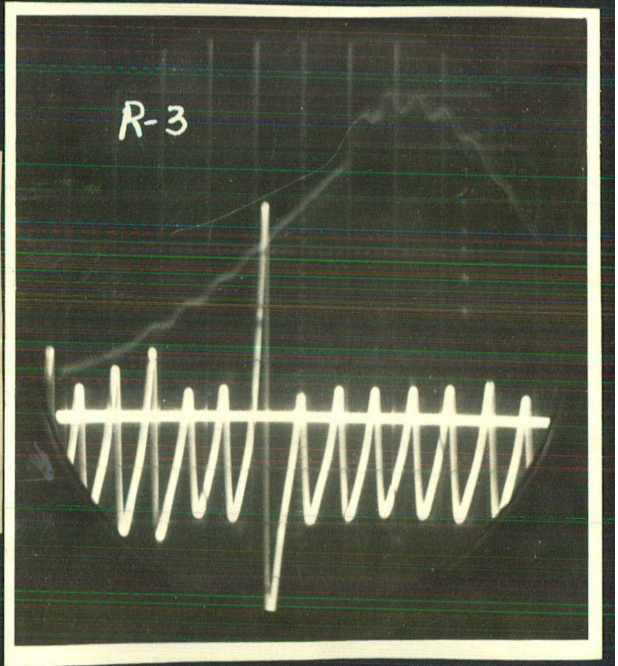
Q-4

FUEL : 50% DIESEL (INJECTED) +
50% ETHER (CARBURETTED)
Injection Advance = 20°BTC
Intake Pressure = Atmospheric
Oscilloscope Sensitivity = 100 mv/cm.
Amplifier Sensitivity = 0.2 mv/pcb.

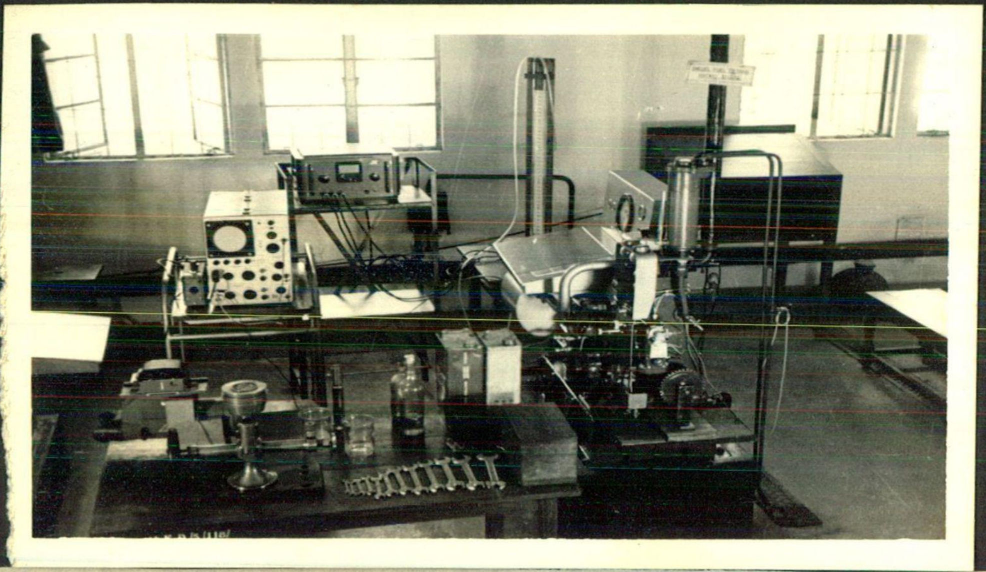


R-3

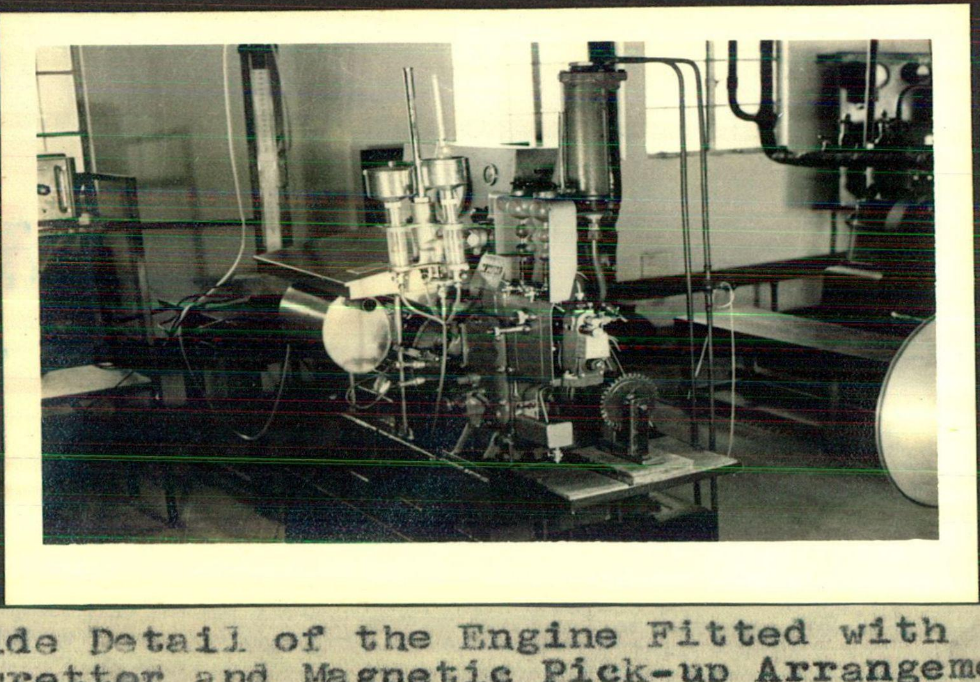
PETROL (INJECTED) @ 20 cc/150 secs. +
ETHER (CARBURETTED) @ 20 cc/150 secs.
ion Advance = 15°BTC
Pressure = Atmospheric
oscope Sensitivity = 100 mv/cm.
ier Sensitivity = 0.2 mv/pcb.



Complete Set-up - Engine Running and Camera Fitted on the Oscilloscope



Various Components of the Complete Set-up from a Distance



Outside Detail of the Engine Fitted with Carburettor and Magnetic Pick-up Arrangement