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THE COLLEGE OF AERONAUTICS
CRANFIELD

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THE INFLUENCE OF ENGINE SPEED UPON PRE-IGNITION

by

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SUMMARY

The literature shows conflicting evidence on the effect of engine speed upon tendency to pre-ignition. Typical published results are presented and compared, together with results obtained from a single-cylinder D.V.L. engine at Cranfield, using the heated wire and ionization gap technique.

The D.V.L. results show an initial increase in pre-ignition tendency with increase in engine speed, followed by a reduced tendency with further increase in speed, and are thus similar to certain other published results. The D.V.L. results are less detailed than these published results, since no measurement was made of hot-spot temperatures, but are more extensive since a greater number of fuels was tested for speed effect, and pre-ignition tendency with speed was measured over a range of (reduced) inlet pressure.

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[*] This note includes work reported in a thesis submitted by W/Cdr. M.J. Kirpalani in June, 1955 (ref.9), and in a thesis submitted by F/Lt. M.A.Gee in June, 1956 (ref.10), as part of the requirements for the award of the Diploma of the College of Aeronautics, the research being under the supervision of the author.

1. Introduction

Under normal conditions of operation, each fresh charge taken into the combustion chambers of a spark-ignition piston engine is ignited electrically during the compression stroke, at an instant timed to give peak pressure at about 12° after top dead-centre. Operation under adverse conditions may lead to the creation of hot spots in the chambers, in the form of overheated sparking plugs, exhaust valves, or deposits of combustion products. This, in turn, may give rise to an uncontrolled surface ignition, independent of the spark timing, known as 'pre-ignition'. When pre-ignition is mild, and the surface ignition takes place after the spark-ignited flame has been formed, the condition may not be detected until the spark is switched off and the engine found to continue firing. The effects of severe pre-ignition upon engine performance however are similar to those incurred by an advanced spark timing, and the early release of heat within the chamber can lead rapidly to thermal failure of the piston.

The major factors controlling the tendency to pre-ignition include the characteristics of the charge, and of the hot spot, and the time available for local charge elements to contact the hot spot and to react chemically. In general, the literature shows reasonable agreement between experimental results on the effects of the various controlling factors, with the exception of engine speed. This note has been prepared in order to give:-

i. a survey of existing experimental data on the speed effect upon pre-ignition, and

ii. a presentation of some further test results on the speed effect upon pre-ignition.

2. Existing Data

Pre-ignition test methods in engines require the provision of a hot spot, the temperature of which should be controllable and/or measurable. The hot-spot temperature required for pre-ignition may be reached by the addition of external energy to the hot spot, or by controlling the heat factor of the hot spot so that engine heat is retained to the desired level. The results given in table 1, and illustrated in figs.1 to 5, (refs. 1 to 5) lead to widely-diverging conclusions regarding the speed effect upon pre-ignition tendencies. As shown in the last column of table 1, pre-ignition may be expected to increase, decrease, or remain unchanged, depending upon the reference quoted, and the range of speed concerned.

3. Equipment and Procedure

The engine used at Cranfield for the pre-ignition speed tests was a D.V.L. single-cylinder variable-compression water-cooled engine of 5.12 in. bore and stroke, fitted with two intake and two exhaust overhead valves, and a manifold timed-injection fuel metering system (fig.6). A thermocouple type sparking plug was used in order to indicate the mean temperature of the charge at the condition of standard pre-ignition intensity.

Five independent fuel supply systems were available, each with flow-measuring instrumentation, together with a selector valve. A Cambridge exhaust-gas analyser was used to determine mixture strength. Pre-ignition was initiated by means of an electrically-heated hot spot constructed of five turns of 24 S.W.G. platinum wire. The catalytic action of platinum leads to the rapid consumption of local elements of charge, so that temperatures of about 100 C° higher are necessary to initiate flame (ref.6). This catalytic action can be suppressed temporarily by the use of a leaded fuel (ref.7), and leaded 100/130 grade aviation gasoline was always used for warming-up purposes in order to ensure continuous de-activation, and hence comparable ignition characteristics, of the hot spot. Pre-ignition detection was by means of a water-cooled ionization gap and a spark timing indicator. The technique was, therefore, generally similar to that used by Vichnievsky (ref.3), and by Downs (ref.5) in tests other than those upon engine speed. The locations of the hot spot and ionization gap within the combustion chamber are shown in fig.7, and the associated circuits in fig.8.

The standard test conditions used were as follows:-

Full throttle : compression ratio = 6 : ignition timing = 30° b.t.d.c.
mixture = approx. 10% rich : jacket temperature = 60°C.

A standard intensity of pre-ignition was selected, at which the ionization trace coincided with the spark trace on a time basis. No attempt was made to control air intake temperature or humidity, since previous work had shown that day-to-day changes have negligible effects. The change in air temperature over these tests did not exceed 10 C°, and the humidity varied from 44 to 68%.

The engine was brought onto condition, and the ignition switched off momentarily in order to check against running-on due to mild pre-ignition. Energy was then added to the hot spot until the standard intensity of pre-ignition was reached, and the energy and thermocouple temperature were recorded. The heating current was then switched off, and the procedure repeated at other engine speeds. Several tests were made at each speed, and the average figures taken of the results.

The following fuels were tested:-

Paraffins :	Iso-octane (2:2:4 Trimethyl pentane), C_8H_{18}
Aromatics :	Benzene, C_6H_6 Cumene (Iso-propyl benzene), C_9H_{12}
Alcohols :	Methanol, CH_3OH
Commercial Blends :	100/130 grade aviation gasoline (100/130 Avgas) 73 grade aviation gasoline (73 Avgas)

The results obtained for these fuels are shown in fig.9, (ref.10) and fig.10.

4. Discussion of Results

The test technique used at Cranfield was similar in many respects to that of Vichnievsky, but the results obtained confirmed the general trends shown by Downs with the supercharged Dagger unit. The following explanation for the reversal in effect at a given speed level was given by Downs for the Dagger results, and is considered to fit the present case. It would appear that increased engine speed increases the heat flow to the hot spot up to a certain level of speed, after which such factors as reduced volumetric efficiency at higher speeds cause the heat flow to decrease. This effect is shown by peaks in the mean thermocouple temperature curves in fig.9 at about 2,100 r.p.m., and is illustrated more directly by Downs as a peak, at about 3,250 r.p.m., in the curve of normal operating temperature of the hot spot itself (fig.5). The second controlling factor lies in the contact and ignition delay periods required for pre-ignition processes to occur, and the shorter periods available at higher engine speeds lead to higher hot spot temperatures necessary for pre-ignition. This fact is also shown clearly by Downs in the curve for hot spot 'standard pre-ignition' temperature in fig.5.

On a basis of pre-ignition tendency, the effect of the normal operating temperature curve in fig.5 should be read directly, and that of the pre-ignition temperature curve inversely, i.e. the rising portion of the lower curve represents an increased tendency to pre-ignition, whereas the rising portion of the upper curve represents a decreased tendency. The ordinate difference between these curves, which may be termed the 'hot spot temperature differential', shows the increase in hot spot temperature necessary to cause pre-ignition, and hence represents approximately the quantity of external energy required. The hot spot temperature differential, therefore, is an indication of the resistance to pre-ignition. The overall effect upon pre-ignition of the heat flow and ignition delay variables may be determined from the hot spot temperature differential or from the boost required for standard pre-ignition intensity. Both these curves show a maximum tendency to pre-ignition at an engine speed of just under 3,000 r.p.m., which is somewhat less than the peak of the normal operating temperature curve. It is seen from the above that the hot spot pre-ignition temperature alone is no direct indication of pre-ignition tendency, so that the deduction made from Serruys' results in table 1 is not strictly true. The rising hot spot pre-ignition temperature curve is, in fact, confirmed by Downs results from the Dagger unit, and by the results from the D.V.L. unit.

The D.V.L. results in fig.9 reflect the same trend of a maximum pre-ignition tendency, in terms of a minimum hot spot energy, at a speed somewhat lower than that for peak mean temperature of the charge, with all the fuels shown. No quantitative results could be obtained for methanol, since this fuel was found to pre-ignite readily under the standard test conditions without the addition of energy to the hot spot, (i.e. auto pre-ignition). Benzene was tested on a later occasion, after a new hot spot had been fitted, and the results (fig.10) show that benzene also auto pre-ignites readily, except under low-speed conditions. The combustion temperature with benzene is seen to be high, as expected from the high carbon/hydrogen ratio, and Downs shows that this temperature rises rapidly with compression ratio, to reach a condition of auto pre-ignition at a comparatively low value of compression ratio. Exploratory tests in the D.V.L. engine at a lower compression ratio (4.5) indicated a vast improvement in the pre-ignition performance of benzene, and a tentative pre-ignition rating of about 40. Fig.10 shows that, at the lower compression ratio, benzene exhibits the typical pre-ignition variation with speed. Cumene is seen to be relatively insensitive to speed in the high speed range, and the associated small change in mean charge temperature correlates with the heat-flow theory of Downs. The speed for maximum pre-ignition tendency with the different fuels is seen to rise slightly as the pre-ignition tendency increases. A similar reversal in the resistance to pre-ignition, at a mixture strength in the region of 110% stoichiometric, was found by Male, (ref.8), who plotted the pre-ignition limited i.m.e.p. against engine speed for three fuels. The cumene curves were repeated in the D.V.L. engine with partly-closed throttle, and the tendency to pre-ignition found to decrease, (figs. 11 and 12).

The form of the D.V.L. curves shows clearly that erronuous speed-effects can be derived if tests are made at a limited number of speeds. The conclusions drawn between spot tests at 1500 and 2200 r.p.m., 1500 and 2000 r.p.m., and 1700 and 2200 r.p.m., for example, would confirm those drawn from the first three tests listed in table 1. The overall picture can be seen only by plotting the complete curves.

The fuels show an increasing resistance to pre-ignition in the order:- methanol, benzene, cumene, 73 Avgas, 100/130 Avgas, and iso-octane. Downs used iso-octane and cumene as upper and lower reference fuels respectively for purposes of rating fuels on a pre-ignition basis, and showed that these reference fuels gave a satisfactory straight-line relationship between blend concentration and both hot-spot temperatures and input energy. Fuels were rated by Downs on an input energy basis in an E6 engine, and on a basis of cooling air to a thermally-isolated hot spot in a Napier "Dagger" unit. Using the former technique, the fuels may be rated in the D.V.L. unit as shown in table 2.

Table 2. Pre-Ignition Rating

Fuel	D.V.L.			E6 (Downs)	Dagger (Downs)
	1500 rpm	1800* rpm	2200 rpm	2500 rpm	3000 rpm
Methanol	<< 0	<< 0	<< 0	< 0	< 0
Benzene	< 0	<< 0	< 0	31	9
Cumene	Reference = 0				
73 Avgas	35	15	39	-	-
100/130 Avgas	87	56	67	77	87
Iso-octane	Reference = 100				

* Minimum-energy speed

With increase in engine speed, the pre-ignition ratings of 73 Avgas and 100/130 Avgas are seen to fall sharply to a trough with the input energy curves, and then to increase progressively.

5. Conclusions

1. With increase in engine speed from a low level, the tendency to pre-ignition increases due to the increased heat flow to the hot spot, despite the reduced time available for contact with the hot spot and for preliminary pre-ignition reactions.

2. With further increase in engine speed, the tendency to pre-ignition decreases, due to the reduced time available for contact and preliminary pre-ignition reactions, and to the reduced heat flow to the hot spot.

3. The maximum tendency to pre-ignition, in terms of the minimum hot spot input energy, or the minimum pre-ignition limited boost, is found at an engine speed less than that for peak hot spot, or mean charge, temperature. Inspection of Downs' hot spot temperature results shows that the hot spot temperature differential curve exhibits a trough at a speed close to that of the input energy curve. The hot spot temperature differential is, therefore, an indication of pre-ignition resistance, but neither the normal operating, nor pre-ignition, temperature of the hot spot alone, gives any indication of pre-ignition tendency.

4. The above pre-ignition-speed effect is noted when testing iso-octane, 100/130 Avgas, 73 Avgas, cumene and benzene in the D.V.L. unit, and with leaded iso-octane and leaded cumene in the Dagger unit. Cumene is relatively insensitive to speed in the high speed range.

5. The fuels show an increasing resistance to pre-ignition in the order:- methanol, benzene, cumene, 73 Avgas, 100/130 Avgas, and iso-octane. Methanol is particularly prone to pre-ignition. The fuels may be rated on a pre-ignition basis, using iso-octane and cumene as upper and lower reference fuels respectively, and the speed effects upon the test, and reference, fuels are such that the pre-ignition ratings indicate the changes in pre-ignition tendency.

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TABLE 1. EXISTING EXPERIMENTAL DATA

TYPICAL REFERENCE	ENGINE	PRE-IGNITION SOURCE	PRE-IGNITION DETECTION	ASSESSMENT OF PRE-IGNITION TENDENCY	FUELS TESTED	DEDUCED EFFECT OF INCREASED R.P.M.
Corrington Ref.1.	Single cylinder of liquid-cooled multi cylinder Vee engine	Exhaust sparking plugs and exhaust valve	Sparking plug used as ionization gap	d.p.rate of pre-ignition advance	30% cumene 20% triptane 50% S-ref. fuel blend.	No change (at 2000 and 3000 R.P.M.)
Winch Ref.2.	Unspecified Modern U.S. car engine	Naturally-occurring hot spots during acceleration	Sparking plug used as ionization gap	d.p.extent of pre-ignition advance	Primary ref. blend of 87.5% octane	Pre.ignition increases (2300 R.P.M.upwards)
Vichnievsky Ref.3.	C.F.R.	Electrically-heated wire	Ionization gap and spark timing	i.p.heat to hot spot for pre-ignition	Gasoline. Benzene. Methanol. Ethanol.	Pre-ignition decreases(700 to 1600 RPM) No change with methanol
Serruys Ref.4.	Renault water-cooled single-cylinder engine	Electrically heated surface, with thermo-couple	Indicator diag., or disappearance of controlled misfire	i.p.thermocouple temperature level for pre-ignition	Motor Gasoline	Pre-ignition decreases(300 to 1500 R.P.M.) then tends to increase
Downs Ref.5.	Supercharged Napier"Dagger" unit	Air-cooled Surface	Indicator diagram	i.p.boost for specified intensity of pre-ignition	Iso-octane + 4 c.c.TEL /I.G.	Pre-ignition increases(1500 to 3000 R.P.M.) then decreases

d.p. = directly proportional to some function
i.p. = inversely " " " "

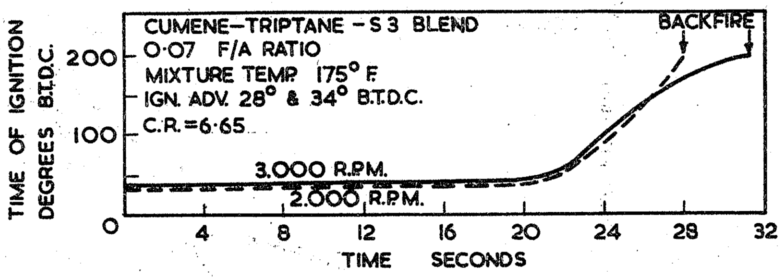

FIG. 1.

EFFECT OF ENGINE SPEED UPON IONIZATION GAP TIME TRACE (CORRINGTON REF. 1.)

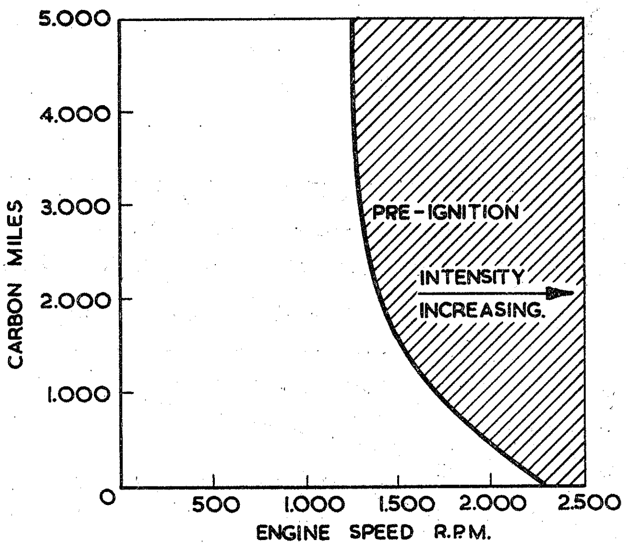

FIG. 2.

EFFECT OF ENGINE SPEED UPON PRE - IGNITION INTENSITY (WINCH REF. 2.)

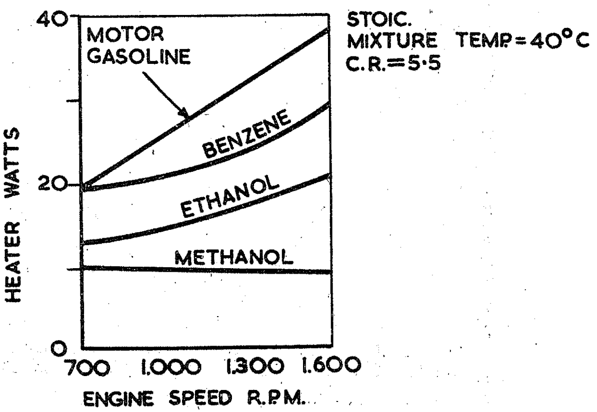

FIG. 3.

EFFECT OF ENGINE SPEED UPON ENERGY REQUIRED TO PRODUCE STANDARD INTENSITY OF PRE - IGNITION (VICHNIEVSKY REF. 3.)

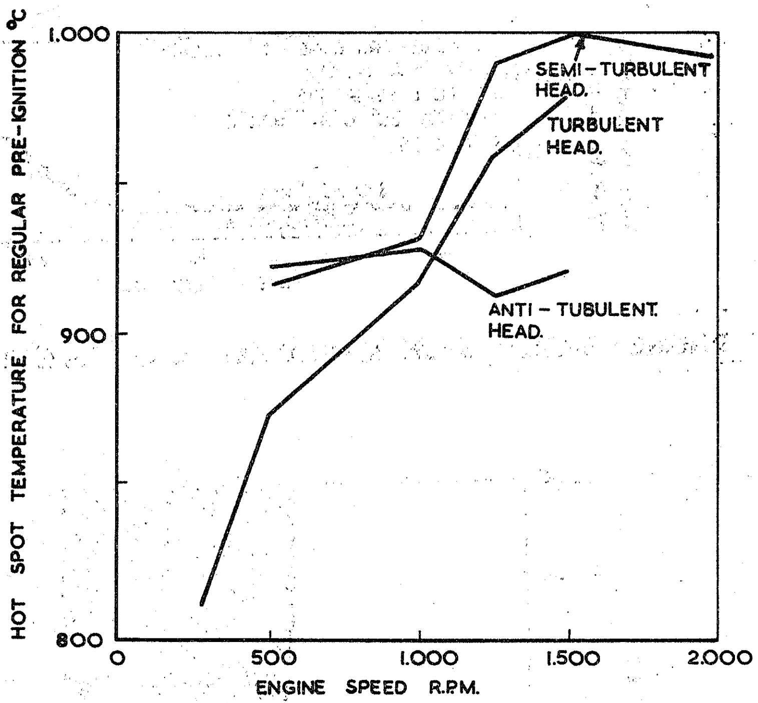

FIG. 4.

EFFECT OF ENGINE SPEED UPON HOT SPOT TEMPERATURE FOR PRE-IGNITION. (SERRUYS REF 4.)

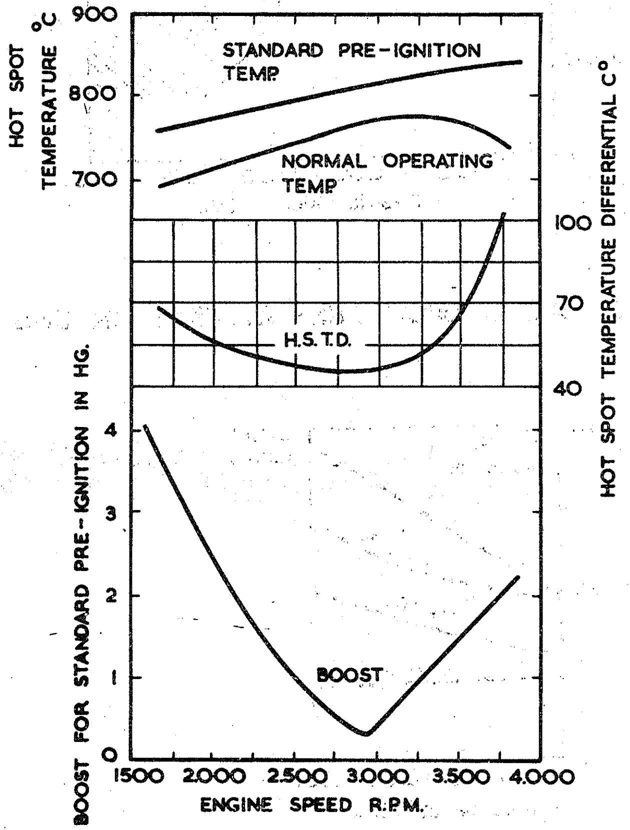

FIG. 5.

EFFECT OF ENGINE SPEED UPON HOT SPOT TEMPERATURES AND UPON BOOST FOR STANDARD INTENSITY OF PRE-IGNITION (DOWNS REF 5)

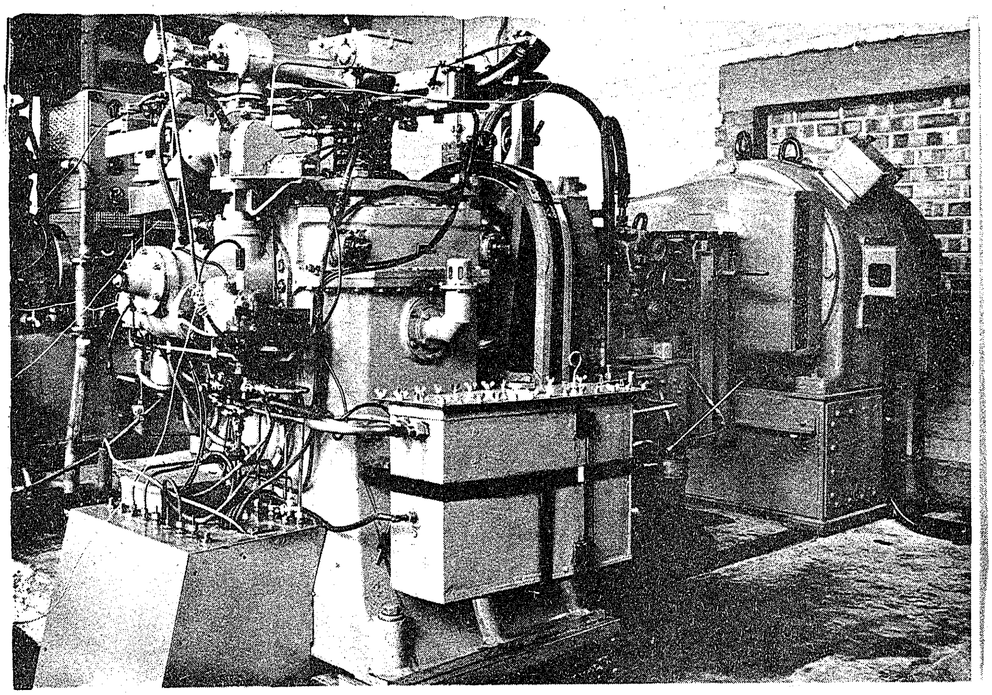

FIG. 6.
D.V.L. VARIABLE – COMPRESSION OVERHEAD – VALVE WATER – COOLED UNIT.

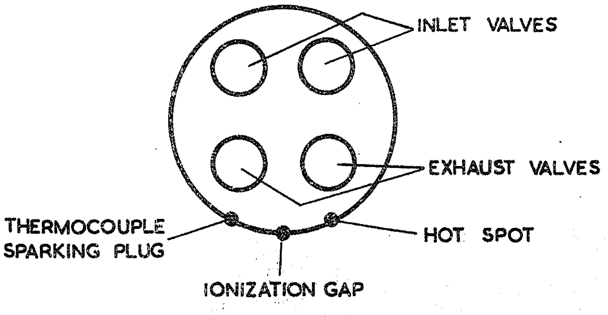

FIG. 7
PLAN OF COMBUSTION CHAMBER SHOWING LOCATION OF TEST UNITS

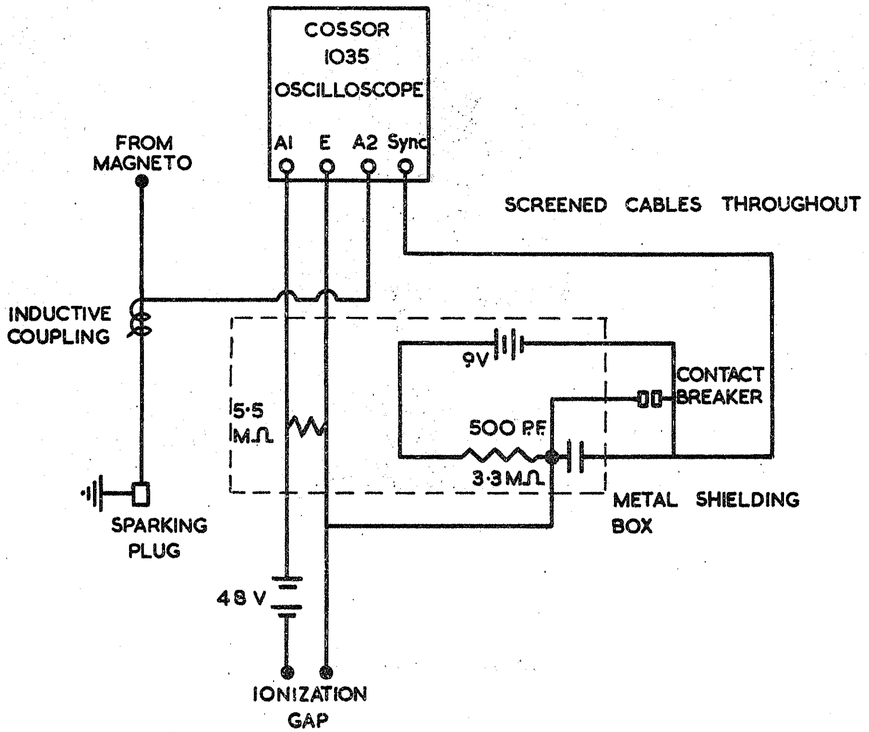

FIG. 8.A.
IONIZATION GAP CIRCUIT

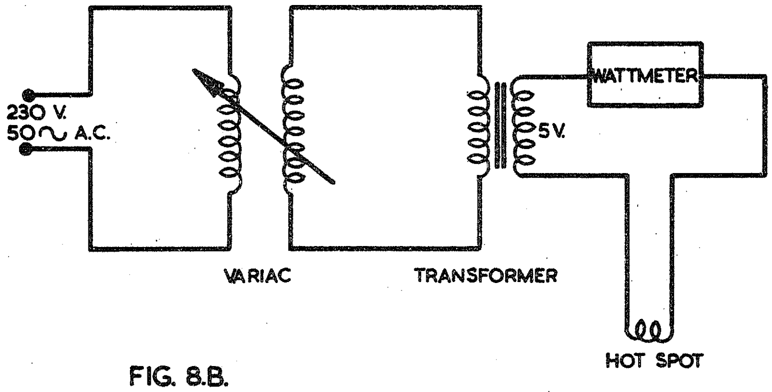

FIG. 8.B.
HOT SPOT CIRCUIT

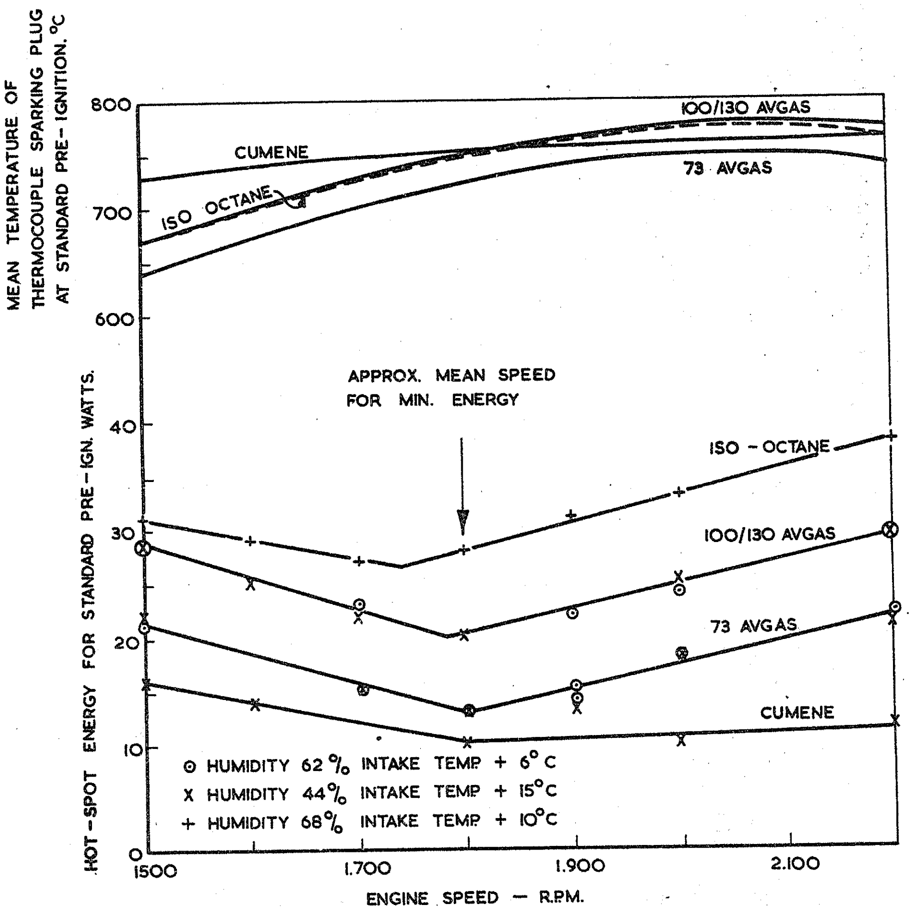

FIG. 9.

EFFECT OF ENGINE SPEED UPON STANDARD PRE-IGNITION IN D.V.L. ENGINE

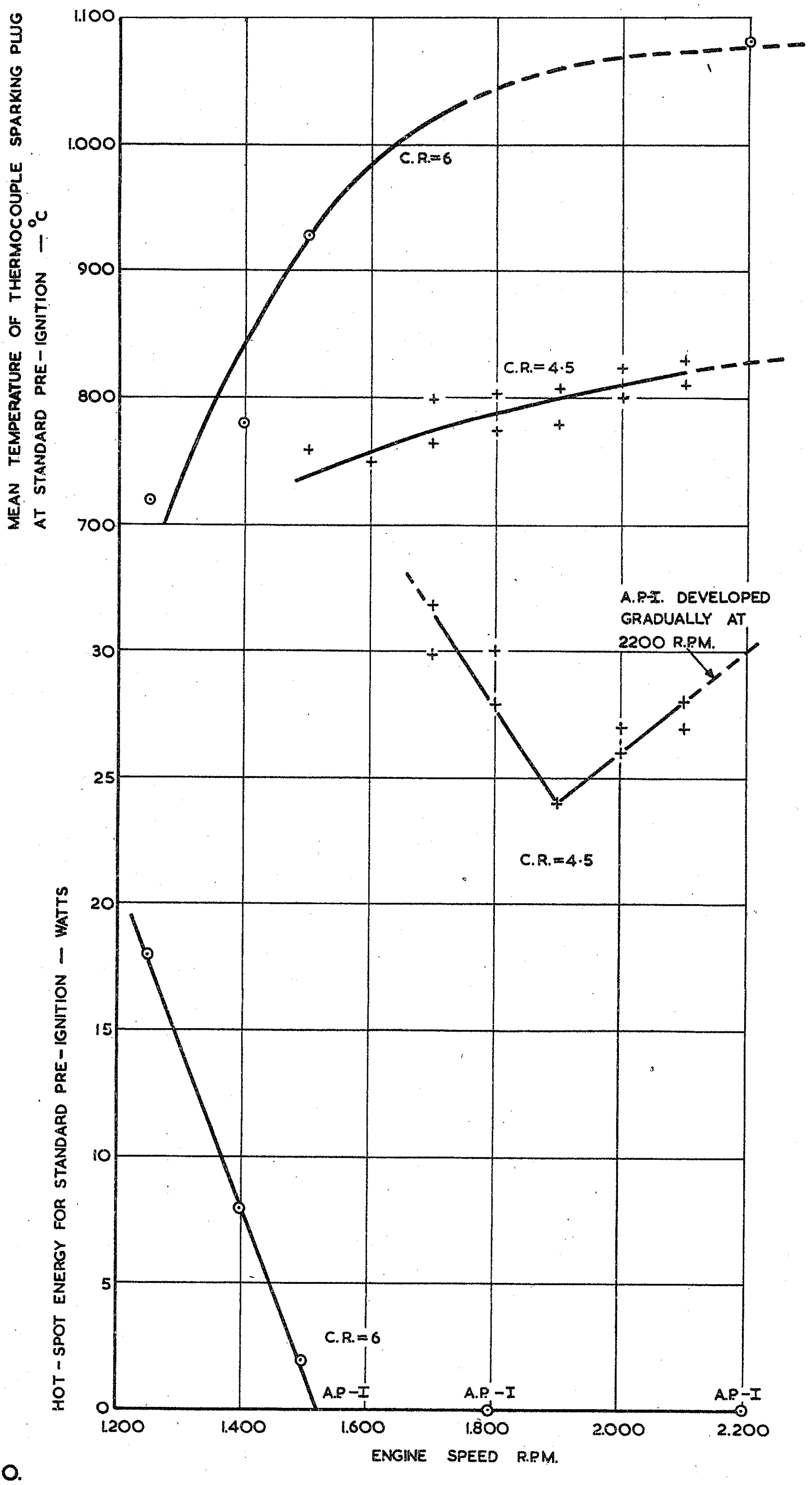

FIG. 10.

EFFECT OF ENGINE SPEED UPON PRE-IGNITION OF BENZENE IN D.V.L. ENGINE.

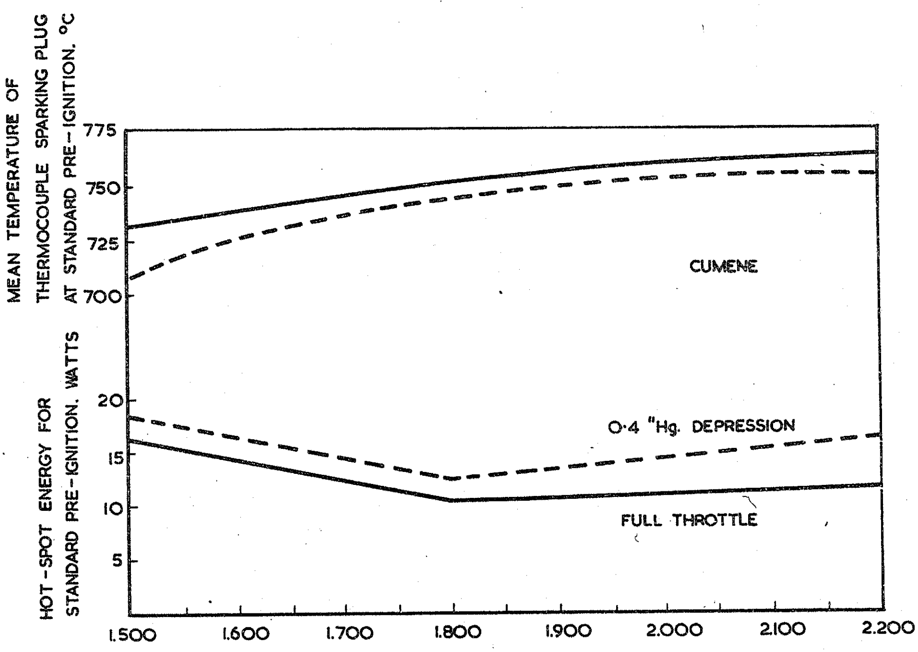

FIG. 11.

EFFECT OF INTAKE-MANIFOLD DEPRESSION UPON HOT-SPOT SPEED CHARACTERISTICS

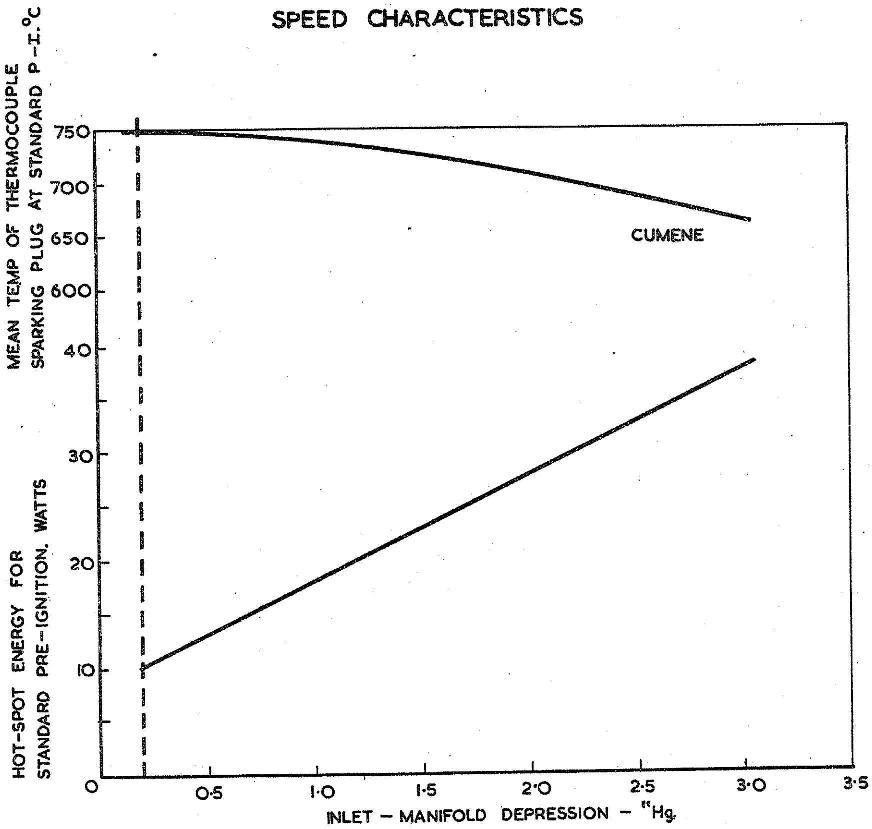

FIG. 12.

EFFECT OF INTAKE-MANIFOLD DEPRESSION UPON HOT-SPOT CHARACTERISTICS