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No. 873

EXPERIMENTAL STUDY OF IGNITION BY HOT SPOT IN INTERNAL COMBUSTION ENGINES

By Max Serruys

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PART I

INTRODUCTION

In order to carry out the contemplated study, it was first necessary to provide hot spots in the combustion chamber, which could be measured and whose temperature could be changed.

It seemed extremely difficult if not downright impossible to realize both conditions by working solely on the temperature of the cooling water in a way so as to produce hot spots on the cylinder wall capable of provoking autoignition. Moreover, in the majority of practical cases, autoignition is produced by the spark plug, one of the least cooled parts in the engine. The first procedure therefore did not resemble that which most generally occurs in actual engine operation.

All these considerations caused us to reproduce similar hot spots at the spark plugs. The hot spots produced were of two kinds and designated with the name of thermoelectric spark plug and of metallic hot spot.

1. Thermoelectric Spark Plug

The insulator of the spark plug is, as will be recalled, often the hot spot which determines the autoignition in actual operation. Hence it was logical to use it as artificial hot spot by heating it, for example, with a coil of wire wound around the spark plug barrel. The degree of heating, and consequently the temperature of the insulator is controlled by the amperage in the coil.

*"Étude Expérimentale de L'Allumage par Point Chaud dans les Moteurs à Explosion." Publications Scientifiques et Techniques du Ministère de L'Air, No. 115, 1937.

The variable temperature of the hot spot having thus been obtained, the method used in making the measurements consisted in replacing the central rod by two wires, one of constantan, the other of iron, to form a thermocouple. The soldering of the couple which was obtained electrically, extends somewhat beyond the tip of the insulator, just like the central electrode of a common spark plug (fig. 1). The insulator is made of the same material used in the Gilardoni spark plugs, and whose heat/conductivity is much higher than that of the porcelain commonly used in spark plugs. The details of the thermoelectric spark plug are exactly as those of the conventional type (material, arrangement, size, mounting, etc.). The only difference is the thermocouple substituting for the central electrode.

This thermoelectric spark plug was first used to measure the exhaust gas temperature where its behavior proved perfectly satisfactory.

When the temperature required for the study is not very high, the electric heating may be dispensed with by preventing the cooling through conductivity. It suffices to wrap the outside of the spark plug with a flexible heat insulator. The manipulation is easy, but the temperature control requires some trials.

In the case where heating is necessary the operation is more difficult; first, the outer metallic mounting must be energetically heated so that the inside insulator attains the desired temperature (which, as will be seen, is quite considerable), then the heating-up process itself is fairly slow. Since the insulator is a poor conductor of heat, one does not know if an error has been committed in the temperature measurement by taking the electromotive force created by the soldering as a basis. Then, too, the control is not easy. (Whereas the heating is easy, it is difficult to promote the rapid cooling which is necessary when autoignition is established, so that the engine may have to be stopped.)

These drawbacks caused us to replace the insulator by a metallic mass of which the ease of control is infinitely superior.

Before proceeding to the description of the metallic hot spot it should be noted that the two methods are equivalent as far as autoignition is concerned; that is to say, that for identical engine-running conditions, the temperature is measured at the same moment of autoignition as is experimentally proved. The discrepancy of the measurements is of the order of 10°, or less than the fluctuations produced in the readings.

This experimental check demonstrates in effect two important facts:

1) The possibility to replace the spark plug insulator by a metallic hot spot without disturbing the measurements, a possibility which is not at all evident.

2) The fact that the effective temperature recorded is entirely that of the wall.*

Consequently:

1) The metallic hot spot is substantially equivalent to the spark plug insulator and may be readily substituted for the latter.

2) The temperature of the solder of the thermocouple placed in the thermoelectric spark plug is practically the same as that of the insulator wall.

2. Metallic Hot Spot

In the realization of the metallic hot spot the two following facts were aimed at in particular:

1) Establish walls having a temperature that may be changed and regulated as desired, and amenable to prompt change of regime. The last point is essential in order that the experiments may be quickly and safely repeated, as the autoignition produced in a powerful engine may quickly become dangerous (as is the case in some of these

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*Obviously, if the surface temperature of the hot spot is substantially different from the measured temperature, the discrepancy will not be the same when the material constituting the hot spot presents thermal conductibilities, which are themselves different from those of the ceramic material and that of the metal employed.

tests). It is therefore necessary to check the autoignition as soon as the tests are made and the calorific inertia of the hot spot extremely lowered.

2) Assure equal temperature at any part of the hot spot directly exposed to contact with fresh gas. The accuracy of the measurements is much dependent upon this.

In effect, in autoignition by hot spot, it is well to take into account the part whose temperature is highest and, as the measurements are practically restricted to one region of the hot spot, every heterogeneity of the thermal state might involve errors of indeterminable order of magnitude.

Metal is obviously best fitted to meet these conditions. It permits bringing the electric heating current to the particular spots and its high conductivity renders the temperature of more remote parts uniform. Besides, metal surfaces exposed in an internal combustion engine are never subjected to temperature fluctuations in excess of some 10 or 20° C.

The metallic hot spot is sectionalized in figure 2. The shell A (with ordinary spark plug thread) receives threaded bushing B extending with its thinner part E F beyond the base to which a central rod C and a constantan thermocouple is soldered. A spacing wedge D shifting between A and B adjusts the position of the base of bushing B with respect to the base of the shell A. The hot part can be retracted or released by varying the thickness of E.

The thickness of the bushing at E F is only a few tenths of a millimeter. It constitutes the weakest section of the electric circuit, and consequently the point of strongest current density. Thus it becomes bright right under intensive heat, while the rest of the shell remains dark. This was verified by direct observation for hot-spot temperatures above 1000° C. It is therefore certain that the temperature of the base part of the shell does not reach values high enough to provoke autoignition itself.

The temperature of the metallic hot spot is controlled by electric current entering at C and returning through the mass. As the whole electric circuit is one of low resistance it should be fed under low voltage. Since, in certain cases, the temperature must be carried to 1000° C. the amperage should be high. A special transformer was constructed for this purpose. The secondary armature has only a few coils of very thick wire.

To assure flexibility of control and wide amplitude two means are resorted to. The secondary carries six binding posts in arithmetical progression, while the feeding of the primary of the transformer is effected with a potentiometer (fig. 3). By combining these two, the temperature can be varied by degrees in the zone of operation.

Measurement of Hot-Spot Temperature

The temperature of the gas with which the hot spot is in contact varies with the moment of the cycle. They are particularly pronounced in the combustion, expansion, and exhaust phase. In the rest of the period of the cycle it departs little from the average. The metal walls whose calorific inertia is not negligible do not follow faithfully the rapid temperature changes of the gas. From precise theoretical considerations based upon the classic laws of heat transmission Veron has calculated that, in the case of explosion engines, the surface layer influenced by the gas is only of the thickness of the order of magnitude of a few tenths of a millimeter. The amplitude of temperature variation is, moreover, much less in the metal than in the gas (order of 10° only on the surface of the metal).*

In practice the temperature of this metallic wall can be considered as constant equal to its mean value. In fact, it is temperature of the hot wall toward the end of compression which produces the autoignition. At this very moment the temperatures of hot spot and gas have a value approaching their average. Lastly, if the preceding hypothesis is correct, a well damped galvanometer which gives the mean value of the temperature of the hot spot indicates also the superficial temperature of the metal at the instant of autoignition.

However, nothing prevents taking the mean temperature of the hot spot as representative argument for defining its

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*Based on the assumption of heat flow proportional to the square root of the time (hypothesis which Vernotte was led to formulate following his research on heat transfer between gas and metal) the calculated amplitude is not very different.

heat status. The incidence of this new variable on the phenomenon to be studied should present in this case as much interest as an exact measurement of the instantaneous temperature.

All the same, we considered it necessary to experimentally check that the thus recorded mean temperature is almost identical to the instantaneous temperature to be considered.

This was effected with a device controlled by cam turning at one-half engine speed and actuated by it. The cam controls a push rod which alternatively opens and closes the circuit: thermocouple-galvanometer at stated instants (fig. 4). This cam is so designed that the electrical connection between galvanometer and thermocouple exists for one phase of the cycle: the compression. For the rest of the periods of the cycle the galvanometer is in open circuit.

While keeping constant the conditions of engine operation and those of the hot spot two successive measurements are made by observing the mean current in the galvonometer:

1) When short circuiting the part A B which suppresses the cam action,

2) When it is left open.

If the electromotive force is constant and the engine speed high enough the amount of electricity passing through the galvonometer in 1 second should be in the ratio of 4:1 in both cases (the current i should be 4 times stronger when the cam does not operate).

This is precisely what we found for the adopted angular speed. It is therefore justified to take this mean temperature as representative factor.

Correction of Readings

We finally eliminated the cam device in the final tests since it afforded no added precision in the measurements.

For convenience of measurement the cold junction of the thermoelectric circuit consisted of a second couple dipped in a test tube partly filled with very thin oil in which soaks a mercury thermometer. The test tube itself is plunged into a vessel containing almost boiling water (about 5° below boiling point) whose temperature is kept constant at a value T_f. The two couples are mounted opposite to each other (fig. 5).

If T_E is the corresponding temperature of a galvanometer reading the temperature of the hot spot is

$$T = T_E + T_f$$

The use of a galvanometer of relatively low internal resistance called for a correction due to the resistance of the leads. The total resistance of the galvanometer is 55 ohms, the resistance of the leads is 5 ohms. Thus the true temperature of the hot spot with E denoting the electromotive force is:

$$\left(T = T_E \frac{R + r}{R} + T_f\right)$$

Since, in other respects, the variation of the different measurements taken under identical conditions may reach 10° and even more, no allowance was made for other corrections of secondary importance.

Detection of Autoignition

The examination of the diagrams corresponding to the successive cycles on the ground glass of a low-inertia manograph should evidently be one of the most accurate means for observing the phenomena accompanying the combustion. In the present case the beginning of autoignition is readily noted and one gathers at the same time the evolution of the regime and about the details of the combustion itself. But despite these evident advantages we did not utilize this method in all tests and for the following reasons:

1) In the majority of cases analyzed the autoignition causes a severe detonation making the use of extremely sensitive pressure gages very difficult because of the very violent increases in pressure of knocking which result in damage.

2) When the combustion produced by the hot spot differs little from that corresponding to electric ignition, it is difficult to distinguish by naked eye if it is autoignition.

In order to be absolutely certain in regard to the detection of autoignition we adopted the following method which consists of producing intermittent and regular misfiring.

An insulating disk, whose rotatory motion is controlled by the engine over a worm gear, carries a metallic sector which periodically passes before two electrodes, one leading to the spark plug, the other grounded. The whole is mounted in such a way that for each disk revolution the sector grounds the spark plug once for one misfired ignition. The frequency of the misfiring thus depends on the disk speed. Experience has shown that for 1250 r.p.m. engine speed one misfiring every 10 cycles lends itself well to auditive observation. (For greater frequency the ear does not follow the phenomena and for lower frequency the irregularity of the misfires are hard to distinguish.)

The autoignition is observed as follows: the engine runs at normal speed, all factors being controlled at their correct values, then the spark plug is connected to the misfire producer and the engine load is again regulated. When no autoignition exists, it produces regularly one misfire every ten cycles which is easily registered either by oscillation of the tachometer which follows directly or by the dull noise of the violent combustion following immediately after misfire.

This method of observation permits checking. When the grounding is effectively made over the spark plug, a spark is seen to jump between the disk and the electrodes at the moment the sector passes before them. It is therefore possible to follow the agreement of the phases between the sparks and the sharp noise following the misfiring if no autoignition takes place.

Test Engine

The test engine is a single-cylinder, water-cooled, Renault engine of 6 hp. with side valves and built-up cylinder head which eliminates the accidental test errors involved with a multicylinder engine and permits the use of special cylinder heads fitted with multiple orifices and of different forms.

Principal Dimensions of Engine

bore	85 mm
stroke	140 mm
connecting-rod-crankshaft ratio	5
valve diameter	40 mm
Valve timing:	
delay of opening, inlet	10°
delay of closing, inlet	55°
lead of opening, exhaust	57°
delay of closing, exhaust	0°
valve lift	15 mm
clearance of exhaust tappets	0.4 mm
clearance of intake tappets	0.3 mm
rated speed	1250 r.p.m.

This engine can be fitted with antiturbulent cylinder head (figs. 6 and 7), semiturbulent cylinder head (fig. 8), or turbulent cylinder head (fig. 9).

Accessories Installation

The accessories (described in detail in bulletin No. 77 of this same series) included:

- a generator and a precision tachometer;
- an air conditioning system aspirated by the engine;
- a constant temperature, water, and oiling system;
- a neon tube marking system of the spark advance;
- a bulbed tube for measuring the consumption;
- an exhaust gas sampler with Lacondamine analyzer.

Manograph

The tests were checked with the low inertia optical manograph described in the author's thesis, and with which some very accurate diagrams have been registered, as illustrated at the end of the article. With the employed installation the upper limit of errors corresponding to the registration is 0.25° crankshaft angle, for the abscissas, 0.1 to 0.2 kg/cm^2 for the ordinates, (original dimensions 110 x 720 mm). The natural vibration frequency of the employed capsule is about 15,000/sec. (test figures).

Test Procedure

The primary object of the study was to determine the ttemperature of the hot spot capable of producing an ignition in the engine, and to study the variations of this temperature with the physical and constructive factors of the engine.

However, the value of this temperature is not an absolute constant for the engine, for, in spite of the number of factors kept constant there are still others which escape. To illustrate: It is impossible, when the engine has been running for some time, to ascertain the state of the inside of the walls between two tests separated by a certain time interval (carbon deposit) and it is scarcely possible to assess this factor numerically.

Moreover, the exact temperature need not be absolutely known as the different types of engines themselves are not comparable. The order of magnitude of this temperature alone is of importance.

On the contrary, for tests run successively on the same day, experience shows that the results are comparable under these conditions; the recorded temperature changes, even if one of the factors is modified, can be considered good. Inasmuch as this change must be accurately known, it is important that each test series is run without interruption.

The normal test procedure is as follows:

Establish a stable* engine regime; after speed, carbu-

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*I.e., when each measurable factor of the engine leaves no measurable variation at the end of 20 minutes.

retion, load, spark advance, cooling-water temperature, oil temperature, etc., have reached the chosen values, measure the horsepower, fuel consumption, composition of gas, if necessary, etc., as in routine testing.

When the engine seems to run steady, produce the intermittent, stated misfire, as described above, then adjust the engine speed to 1250 r.p.m. As the hot spot is not heated, there is no autoignition.

Then gradually increase the heating, noting the temperature level at which the first autoignition is produced. Then let the hot spot cool a little to verify if, at a lower temperature, no autoignition occurs. By successive trials then note the minimum temperature T_1 below which no autoignition occurs. At this temperature, termed the <u>minimum temperature of autoignition appearance</u>, autoignition is produced at properly spaced intervals. Raising the temperature of the hot spot again up to a value T_2, the autoignition becomes regular, the misfiring disappears completely. This temperature T_2 is termed the "regulation temperature of autoignition."

The two critical temperatures T_1 and T_2 were deemed sufficient to characterize the phenomenon.

Owing to the cyclic irregularity of combustion, the values of T_1 and T_2 vary a little from one test to the next, amounting to the order of magnitude of 10° at times. Each test point is measured several times, thus eliminating the doubtful values.

PART II

EFFECT OF RUNNING CONDITIONS AND ENGINE CHARACTERISTICS ON THE CRITICAL TEMPERATURES T_1, T_2

A. RUNNING CONDITIONS

1. Oil and Water Temperatures

The water-temperature tests ranged between 60° to 90°, and oil temperatures between 25 to 50°. No distinct difference was noted for the antiturbulent head (figs. 6 and 7), which served as normal head in the tests concerning the influence of running conditions. (With this head the effect of one factor, such as angular speed, can be studied without involving too important correlative turbulence variations.)

For these secondary factors (water and oil temperature) no correction needs to be made if accidently changes of $\pm 1^\circ$ C. or even several degrees are not exceeded.

2. Effect of Ignition Advance

One series of tests was run at normal timing (1250 r.p.m., 760 mm intake pressure, 30° oil temperature, 80 percent humidity, 55°-65° water temperature, while varying the ignition advance from 0° to optimum value. The critical temperatures remain constant. The timing therefore has no effect on the value of the findings.

This finding simplifies the experiments because, the normally used compression ratio being a little too high, the violent combustion produced after the misfirings induces detonations of very strong intensity if the optimum spark advance of the rated speed is maintained.

3. Effect of Air Characteristics

Effect of Pressure

Test Conditions

Air . . . . . .
- temperature . . . . . $30^\circ \pm 1^\circ$
- humidity. . . . . . . 79% ± 2%
- pressure. . . . . . . variable

Water . . . . .
- inlet temperature . . $52^\circ \pm 2^\circ$
- outlet temperature. . $59^\circ \pm 2^\circ$

Oil . . . . . .
- inlet temperature . . $40^\circ \pm 2^\circ$
- outlet temperature. . $49^\circ \pm 2^\circ$

Speed	Pressure	Horsepower	Hot-Spot Temperature		
			T_1	T_2	$T_2 - T_1$
r.p.m.	mm Hg		°C.	°C.	°C.
1250	700	5.65	930	960	30
1250	760	6.35	930	950	20
1250	878	8.75	925	940	15

Considering the imperfection of the measurements, the first critical temperature appears insensitive to atmospheric pressure changes in the explored range.

This result does not quite conform to what might be expected, but it may be characteristic for the employed cylinder head. On the other hand, when the intake pressure increases, the proportion of burned gas contained in the charge decreases and consequently its mean temperature as well, which probably neutralizes the drop in the critical temperatures of autoignition, which it should appear obliged to introduce.

T_2, however, decreases when the pressure increases although the difference is slight (20^o for 100 mm mercury, (fig. 10)).

Effect of Air Temperature

a) Antiturbulent head

Test Conditions

Inlet air . . . . { pressure . . . . . . .760 ± 1 mm Hg; humidity . . . . . . 78 ± 2% }

Water . . . . . . { inlet temperature. . 54° ± 1°; outlet temperature . 60° ± 1° }

Oil . . . . { inlet temperature. . 40° ± 2°; outlet temperature . 48° ± 2° }

r.p.m.	Air temperature °C.	hp.	Advance deg.	Hot-spot temperature T_1 °C.	T_2 °C.	$T_2 - T_1$ °C.
1250	21	6.92	5	947-952	974-980	27.5
1250	30.5	6.57	5	947	974	27
1250	29	6.33	5	952-947	985	33-38

With this antiturbulent head the critical temperatures do not seem to be much affected by the intake air temperature (fig. 11).

b) Turbulent head (fig. 9)

This second test series complements the preceding one in an interesting manner to the extent that with antiturbulent head it may be admitted that the measured temperature differences are due to differencesresulting from the heterogeneity of the carbureted mixture. This objection does not exist on the turbulent head and still the differences are greater (fig. 12).

Air	pressure	760 ± 2 mm Hg
	temperature.	variable
	humidity	variable (weight)
Water	inlet temperature. .	$54^{\circ} \pm 2^{\circ}$
	outlet temperature .	$58^{\circ} \pm 2^{\circ}$
Oil	inlet temperature. .	$41^{\circ} \pm 2^{\circ}$
	outlet temperature .	$48^{\circ} \pm 2^{\circ}$

r.p.m.	Air temperature °C.	Humidity percent	Advance deg.	hp.	Consumption g/hp.-h	Hot-spot temperature		
						T_1 °C.	T_2 °C.	$T_2 - T_1$ °C.
1250	15	90	6	7.42	280	910	932	22
1250	39.5	81	8	7.22	289	927	948	21
1250	60	70	11	6.78	293	932	947	15
1250	81	60	12	6.50	306	939	956	17
1250	89	50	12	6.38	306	937	948	11

The rise of the critical temperatures with the air temperature inducted by the engine is even more marked with this head than with the preceding one. This may be due to the fact that the carbureted mixture is more homogeneous when the inlet temperature is higher. (A slightly homogeneous mixture containing portions of varying richness should, in principle, ignite quicker on contact with a hot spot than a homogeneous mixture of definite richness.)

Effect of Air Humidity

Test Conditions

Inlet air	pressure	.760 ± 1 mm Hg
	temperature.	31° ± 1°
Water	inlet temperature. .	55° ± 1°
	outlet temperature .	61° ± 1°
Oil	inlet temperature. .	44° ± 1°
	outlet temperature .	50° ± 1°

r.p.m.	Humidity	Optimum advance	hp.	Hot-spot temperature		
				T_1	T_2	$T_2 - T_1$
	percent	deg.		°C.	°C.	°C.
1250	46	9	7.03	953	975	22
1250	60	9	7.03	953	975	22
1250	67.5	9	6.98	953	980	27
1250	72	10	6.92	950	975	25
1250	90	10	6.92	943	959	16
1250	98	10	6.87	932	953	21

The results of the measurements are appended in figure 13.

It is seen that increasing humidity seems to produce a reduction of the critical temperatures. This is in accord with the catalytic power of water vapor in the igniting of combustible gas mixtures. At any rate the variation is slight.

Summing, it is seen that the characteristics of the air inducted by the engine have a fairly small although measurable effect on the critical temperatures of autoignition. The sense of these variations is the same as that of the critical temperatures corresponding to the detonation so that it can be deduced from diagrams, except maybe in the case of humidity.

4. Effect of Mixture Richness

Semiturbulent cylinder head (fig. 14)

Test Conditions

Inlet air . . . . . pressure. . . . . . 760 ± 2 mm Hg; temperature . . . . $30^\circ \pm 2^\circ$; humidity. . . . . 80% ± 2%

Water . . . . inlet temperature . $55^\circ \pm 2^\circ$; outlet temperature. $60^\circ \pm 2^\circ$

Oil . . . . inlet temperature . $45^\circ \pm 2^\circ$; outlet temperature. $51^\circ \pm 2^\circ$

N = 1250

Richness of mixture	Spark advance	hp.	Consumption	Critical temperatures		
				T_1	T_2	$T_2 - T_1$
cm^3/s	deg.		g/hp.-h	°C.	°C.	°C.
0.604	22	5.83	258	917	939	22
.669	17	6.33	278	911	928	17
.789	16	6.37	314	939	949	10
.841	14	6.40	341	947	980	33
.947	17	6.46	380	970	998	28
1.021	15	6.33	417	970	998	28

The critical temperatures increase for both the lean and the rich mixture whenever a certain value which corresponds to a mixture slightly richer than the theoretical is departed from.

The difference amounts to 70° when the richness varies in the ratio of $\frac{0.949}{0.669} = 1.40$ starting with a mixture giving the lowest critical temperature. This fact explains why the autoignition occurs most of the time in practice after an accidental leanness in carbureted mixture. The effect of this leanness is lower critical temperature and higher temperature in the hottest parts of the walls (exhaust valves).

5. Effect of fuel

a) Effect of Fuel of Constant Octane Number

For this test series three different fuel samples were prepared. To prevent any potential perturbation arising from more or less complete vaporization of fuel in the carburetor, we operated with fairly high inlet air temperature, so that all the fuel inducted was vaporized.

On the other hand, with a view to still more perfect comparability of the tests, the carburetor setting followed the exhaust gas analysis, with a content of CO constant (2 percent).

Fuel Characteristics

Fuel A

Gasoline, 69 octane rating: 55.2 octane rating - 63.6 percent. Benzine 36.4 percent.

Density at 15° 0.7945

Removable through SO_4H_2 98 percent . . . . . 55.6 percent

Density after sulphonation at 15°C. 0.717

T.C.D. after sulphonation 62.6°

Distillation:

Start	55° C.
5 percent	72°
10 "	76°
20 "	79°
30 "	82°
40 "	84°
50 "	86.5° C.
60 "	91° C.
70 "	98°
80 "	119°
90 "	147°
95 "	163°

End point	181.5° C.
Condensation	98 cc
Residue, percent	0.8
Barometric pressure	743 mm
Calorific power per kg	10.688
Calorific power per liter	8.491
Carbon, percent	85.3
Hydrogen, percent	14.7

Fuel B

Gasoline, 69 octane rating: pure gasoline 55.2 octane - 85 percent. Alcohol 15 percent.

Density at 15° 0.7507

Distillation:

Start	48° C.
5 percent	60.5° C.
10 "	63° C.
20 "	66.5° C.

30 percent	69° C.
40 "	71° C.
50 "	87° C.
60 "	110° C.
70 "	123.5° C.
80 "	138.5° C.
90 "	153° C.
95 "	166° C.
End point	184.5° C.
Condensation	98 cc
Residue, percent	0.8
Alcohol, percent	14
Alcohol separated:	
Density at 15° C. after alcohol separation . .	0.7432
Removable with SO_4 H_2 98 percent	24.5%
Density at 15° after sulphonation	0.7152
T.C.D. after sulphonation	64°
Calorific power (kg)	10.495
Calorific power (liter)	7.878
Carbon, percent	83.4
Hydrogen, percent	11.6
Oxygen, percent	5

Fuel C

Gasoline, 69 octane: pure gasoline 55.2 octane + 0.65 cm^3 ethyl fluid per liter of mixture.

Density at 15°	0.7429
Removable with SO_4 H_2 98 percent	24.2%
Density after sulphonation at 15° C.	0.7145
T.C.D. after sulphonation	63.8°

Distillation:

Start	42° C.
5 percent	66° C.
10 "	73° C.
20 "	83° C.
30 "	90.5° C.
40 "	98° C.
50 "	107° C.
60 "	117.5° C.
70 "	130° C.
80 "	142° C.
90 "	156° C.
95 "	168° C.
End point	186° C.
Condensation	98 cc
Residue, percent	0.9
Barometric pressure	749 mm
Calorific power (kg)	11.090
Calorific power (liters)	8.239
Carbon, percent	85.4
Hydrogen, percent	14.6

All these tests were made with the turbulence head, which gives the most uniform results.

Test Conditions

Characteristics

Inlet air	temperature	$133^\circ \pm 2^\circ$
Water	inlet temperature	$70^\circ \pm 1^\circ$
	outlet temperature	$80^\circ \pm 1^\circ$
Oil	inlet temperature	$47^\circ \pm 2^\circ$
	outlet temperature	$52^\circ \pm 2^\circ$

Gasoline	r.p.m.	Advance deg.	hp.	Consumption g/hp.-h	Inlet pressure mm Hg	Critical temperatures T_1 °C	T_2 °C	T_2-T_1 °C	Exhaust gas CO_2 %	O_2 %	CO %
A	1250	6.5	5.96	292	746	885	916	21	12.1	0	3.2
B	1250	6.5	6.33	340	762	894	921	27	10.5	0.2	3.3
C	1250	6.5	5.99	312	752	900	910	10	11.2	0.2	3.1

It is seen that for a given octane rating, the temperature at auto-ignition is very little affected by the chemical composition of the fuel itself. But, on the other hand, we shall see the marked dependence of the auto-ignition temperature on the octane rating itself, as pointed out by P. Dumanois in 1926 (Comptes Rendus des Séances de l'Académie des Sciences, vol. 181, 1926, p. 1526, and vol. 196, 1928, p. 292).

b) Effect of Octane Rating of Fuel

In order to effect a change in the octane rating without considerably modifying the mean composition and the physical characteristics, we added ethyl nitrate (knock producer) or tetraethyl lead (antiknock) to the same gasoline base.

Characteristics

Inlet air	pressure	760 :: + 2 mm Hg
	temperature	30° ± 2°
	humidity	78% ± 2%
Water	inlet temperature	55° ± 1°
	outlet temperature	60° ± 1°
Oil	inlet temperature	45° ± 2°
	outlet temperature	50° ± 2°

r.p.m.	Gasoline	Temperatures of hot spot			Octane rating
		T_1 °C	T_2 °C	$T_2 - T_1$ °C	
1250	ordinary	965	976	11	59
1250	ordinary + 0.15 percent of nitrate	900	948	48	21
1250	ordinary + 1/1000 ethyl fluid	1026	1057	31	75

A proper addition of ethyl fluid raises the auto-ignition temperature by more than 75°, while ethyl nitrate lowers it close to 50°.

These variations in the critical temperature of ignition resemble those deduced from the measurements of the critical temperature of detonation. They seem, however, of much lower order of magnitude. It takes two hours after completion of a test before the effects of the added product disappear. It should also be noted that 1/1000 "dose" of ethyl fluid produces no measurable variation of critical temperature of auto-ignition.

B. ENGINE CHARACTERISTICS

1. Effect of Compression Ratio

In this test series it was attempted to realize an experimental arrangement in which the variation in compression ratio produced the least possible change in the conditions of the other factors, particularly in turbulence. An antiturbulent head was therefore used. (The hot spot is placed above the inlet valve as in the preceding tests.)

Test Conditions

Characteristics

Air inlet	pressure	750 ± 1 mm Hg
	temperature	$28^\circ \pm 1^\circ$
	humidity	80% ± 2%
Water	inlet temperature	$52^\circ \pm 1^\circ$
	outlet temperature	$62^\circ \pm 1^\circ$
Oil	inlet temperature	$37^\circ \pm 2^\circ$
	outlet temperature	$42^\circ \pm 2^\circ$

The measurements were made at 1,250 r.p.m. and optimum setting; that is, with the advance which gives the best horsepower for each head.

The compression ratio is changed by placing one thickness of a metallic joint in each case. The highest value of the compression ratio obtained exceeds that of the rated value. So, in order to avoid detonation it was necessary in this particular case to reduce the ignition advance considerably - which, however, as stated above, does not alter the measured critical temperature.

These measurements are summarized in the following table and figure 15. They vary fairly little from the average indicated in the different tests.

r.p.m.	Compression ratio	Optimum of advance deg.	hp.	Specific fuel consumption g/hp.-h	Temperatures of hot spot		
					T_1 °C	T_2 °C	$T_2 - T_1$ °C
1250	4.58	20	5.2	414	1000	1020	20
1250	5.54	12	7.25	282	990	1000	10
1250	6.52	3	7.50	272	955	975	20

The increased power, the lowered consumption, the lower optimum advance with increased compression ratio are too well known to require explanation.

For a rise of two points in compression ratio, the critical T_1 of the hot spot drops by about 45°. The change in T_2 is substantially the same; the difference between T_2 and T_1 is about 20°.*

But it was also found that the critical temperature varies in the inverse sense of the pressure.

2. Effect of Hot-Spot Location

a) Antiturbulent Head

The results of the measurements are given in the following table.

r.p.m.	Advance deg.	hp.	Consumption g/hp.-h	Location of hot spot	Temperature of hot spot T_1 °C	T_2 °C	T_2-T_1 °C
1250	7	6.87	285	above inlet	947	974	27
1250	7	6.87	283	above exhaust	952	970	18
1250	7	6.87	283	above cylinder	962	989	27

It is seen that for the hot spot located above the cylinder, the temperature must be about 30° higher than when located above the intake valve to produce autoignition. This is undoubtedly due to the fact that the gas, having already advanced near to the valves, is much easier ignited than the rest of the gaseous charge.

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*This result states precisely what was already known from the necessity of using very cold spark plugs on highly compressed engines; in fact, it is seen that it is necessary not only to permit these spark plugs to evacuate a greater amount of heat as higher temperatures are reached, but to effect this heat removal for a less high temperature of the spark-plug components.

b) Head of Medium Turbulence

r.p.m.	Ignition advance deg.	hp.	Specific consumption g/hp.-h	Location of hot spot	Hot-spot temperature T_1 °C	mean °C	T_2 °C	mean °C	T_2-T_1 °C
1250	16	7.08	286	on exhaust valve	990 1000	995	1016 1013	1015	20
1250	16	7.08	288	on inlet valve	970 960 975	968	985 970 1000	985	17
1250	16	7.08	286	on cylinder	967 966 966 966	966	998 998 1000 998	999	33

From the tabulated data, it can be inferred that:

1. Located on the exhaust side, the gases can support a much higher hot-spot temperature without igniting. This temperature is 30° higher than that for the other positions.

2. The location on the inlet valve and on the cylinder are equivalent as far as temperature T_1 is concerned. But the difference in temperature between the first appearance of auto-ignition and the regular auto-ignition region is sensibly double for the location on the cylinder.

It was also observed for the position over the cylinder that, when the temperature of the hot spot reaches around 1075° C., the auto-ignition is so violent that the engine sticks. The auto-ignition in this case seems to be produced with a considerable advance not encountered for the other hot-spot positions.

c) Strongly Turbulent Head
(5.87/1 compression ratio)

r.p.m.	Advance deg.	hp.	Consumption g/hp.-h	Location of hot spot	Hot-spot temperatures				
					T_1 °C	mean °C	T_2 °C	mean °C	$T_2 - T_1$ °C
1250	9	7.24	280	on inlet valve	927 932	929.5	948 943	945.5	16
1250	9	7.24	280	on exhaust valve	938 932	935	948 948	948	13
1250	9	7.24	280	on cylinder axis	938 932	935	943 938	940.5	5.5

Within the precision of the measurements, it is seen that the three locations are substantially equivalent - as is readily understood - the turbulence being sufficient to homogenize the carbureted mixture and probably having almost the same intensity at the three positions.

The difference between T_1 and T_2 is much less than for the other cylinder heads.

3. Effect of Cylinder-Head Design

The comparison of the three preceding tests indicate that the critical temperatures of auto-ignition increase substantially with the turbulence. (It is necessary, in effect, to take into consideration the fact that the turbulent head has a much greater volumetric compression than the medium turbulence head.) Unfortunately, it is very difficult to express the intensity of turbulence by actual figures; it is no less interesting to find that the effect of it can change the critical temperatures of auto-ignition by about 50°.

This rise in critical temperature is probably the result of the reduced duration of exhaust gases which are not in contact with the hot spot as long when the turbulence is strong as when it is weak.

4. Effect of Distance from the Surface of the Cylinder Head

The distance of the hot spot from the inner wall of the head was regulated by means of wedges as already indicated in the description of the metallic hot spot.

Cast-Iron Turbulence Head; 1:5.85 compression ratio.

Characteristics

Inlet air	pressure	760 ± 1 mm Hg
	temperature	$30^{\circ} \pm 1^{\circ}$
	humidity	100%
Water	inlet temperature	$55^{\circ} \pm 2^{\circ}$
	outlet temperature	$60^{\circ} \pm 2^{\circ}$
Oil	inlet temperature	$45^{\circ} \pm 2^{\circ}$
	outlet temperature	$50^{\circ} \pm 2^{\circ}$

r.p.m.	Advance deg.	hp.	Consumption g/hp.-h	Hot spot	Hot-spot temperature T_1 °C	T_2 °C	T_2-T_1 °C
1250	90	7.2	281	projects 5 mm	957	968	11
1250	90	7.2	281	0	936	949	13
1250	90	7.2	281	retracts 5 mm	906	927	21

These results are summarized in figure 16.

The more the hot spot is retracted the easier the auto-ignition is produced. The critical temperature difference reaches 40° to 50° in extreme cases, which appears to confirm that for this factor as for the preceding one, it is the variation in the rate of displacement of the gases in contact with the hot spot which is active.

The significance of this conclusion is immediately understood from the point of view of spark-plug design, for which a protruding position of the central electrode is already expedient from other viewpoints.

5. Effect of Engine Charge on the Temperature of the Hot Spot Which Produces Auto-ignition

The engine charge is changed by carburetor throttling. This manner of regulating the power of the engine differs from the intake under variable pressure to the extent that the pressure and temperature of the gases at the end of compression as well as the burned-gas content is changed.

In this series of tests two types of heads were used: one with strong turbulence, the other with weak turbulence. The speed was again 1,250 r.p.m., the inlet-air temperature 30°, the pressure 760 mm Hg, and the humidity 80 percent.

The results plotted in figure 17 are as follows:

a) For the Semiturbulent Head

r.p.m.	Advance deg.	Engine charge percent	Hot-spot temperature T_1 °C	T_2 °C	$T_2 - T_1$ °C
1250	6	100	928	939	11
1250	6	80	917	939	22
1250	6	60	939	949	10
1250	6	40	939	955	16
1250	6	20	949	971	22

The critical temperature rises as the engine charge is decreased. For this particular head, the increase is relatively small (about 25°).

b) For Turbulence Head

The test conditions are the same as before.

Characteristics

Inlet air	pressure	760 ± 2 mm Hg
	temperature	$30^\circ \pm 1^\circ$
	humidity	80% ± 2%
Water	inlet temperature	$54^\circ \pm 2^\circ$
	outlet temperature	$62^\circ \pm 2^\circ$
Oil	inlet temperature	$41^\circ \pm 1^\circ$
	outlet temperature	$49^\circ \pm 1^\circ$

r.p.m.	Charge percent	Advance deg.	Hot-spot temperature T_1 °C	T_2 °C	$T_2 - T_1$ °C
1250	100	8	950	965	15
1250	75	8	988	1004	16
1250	50	8	1000	1021	21
1250	25	8	1031	1064	33

The results have been plotted in figure 18.

With this head the critical temperatures of ignition by hot spot manifest a marked increase if the engine charge decreases. It increases from 950° to 1,031°, or by 81° when the charge varies between 100 and 25 percent.

This decrease in auto-ignition temperature with increasing engine charge is similar to that indicated regarding the effect of inlet pressure, but here the decrease in burned-gas content which corresponds to an increase in charge, actually aids the pressure effect, which accentuates the amplitude of variations of the critical temperature.

6. Effect of Rotative Speed of the Engine

The rate of rotation of the engine has a direct effect on the state of turbulence of the gases. The results should therefore be dependent on the created turbulence. We have, for this reason, tested the three heads already mentioned, whose inside form was so designed as to produce a more or less pronounced turbulence. Their characteristics are as follows:

Designation	Form	Figure	Compression ratio
Antiturbulent head	wedge-shaped	6 - 7	6.06
Semiturbulent "	flat	8	4.90
Turbulent "	special	9 and 19	5.85

a) Cast-iron Antiturbulent Head

Test Conditions

Characteristics

Inlet air	pressure	760 ± 1 mm Hg
	temperature	30° ± 1°
	humidity	79% ± 2%
Water	inlet temperature	54° ± 2°
	outlet temperature	60° ± 3°
Oil	inlet temperature	44° ± 3°
	outlet temperature	50° ± 2°

r.p.m.	Optimum advance deg.	hp.	Consumption g/hp.-h	Hot-spot temperature T_1 °C	T_2 °C	T_2-T_1 °C	Remarks
520	6	2.84	292	903	923	20	Engine knocks a little
1000	5	5.73	286	913	930	17	Auto-ignition has caused detonation
1250	6.5	7.16	282	903	914	11	
1500	8	8.65	272	904	925	21	

These results are summarized in figure 19.

In this case the critical temperatures change little with the speed.

b) Semiturbulent Head

Characteristics

Inlet air	pressure	760 ± 1 mm Hg
	temperature	$30^\circ \pm 1^\circ$
	humidity	80% ± 2%

r.p.m.	Advance deg.	hp.	Consumption g/hp.-h	Hot-spot temperature		
				T_1 °C	T_2 °C	T_2-T_1 °C
2000	18	8.25	344	969	989	20
1500	17	7.75	303	970	1000	30
1250	16	6.77	298	969	989	20
1000	13.5	5.27	309	916	932	16
500	10	2.50	326 (unstable)	905	916	11

These results are plotted in figure 20.

The critical temperatures of auto-ignition manifest a drop of almost 70° when the speed changes from 2,000 to 500 r.p.m.

c) Turbulence Head

Characteristics

Inlet air	pressure	760 ± 2 mm Hg
	temperature	$30^\circ \pm 2^\circ$
	humidity	100%
Water	inlet temperature	$53^\circ \pm 2^\circ$
	outlet temperature	$63^\circ \pm 2^\circ$
Oil	inlet temperature	$45^\circ \pm 2^\circ$
	outlet temperature	$50^\circ \pm 2^\circ$

r.p.m.	Advance deg.	hp.	Consumption g/hp.-h	Hot-spot temperature		
				T_1 °C	T_2 °C	T_2-T_1 °C
1500	11	8.5	969	969	980	11
1250	9	7.2	281	948	959	11
1000	7	5.6	288	904	915	11
510	5	2.61	322	860	872	12
280	5	0.95	413	795	806	11

These results are plotted in figure 21.

The variation in critical temperature of auto-ignition reaches here about 110° between 500 and 2,000 r.p.m., and approximately 175° between 280 and 2,000 r.p.m. It is evident that the turbulence (which increases with the speed) lowers the tendency to auto-ignition considerably.

It was also found that it regularizes the phenomenon very clearly, as proved by the slight difference between the measured critical temperatures T_1 and T_2.

PART III

EFFECT OF THE HOT-SPOT TEMPERATURE ON THE COURSE OF THE PRESSURE DIAGRAM

In order to give a proper account of the character of the previously defined critical temperatures, a series of tests was made with full-scale diagrams with the help of a low-inertia optical manograph.

The tests were carried out with the medium turbulence head whose low compression permits tests otherwise ticklish or too dangerous at a higher compression. The manograph was fitted above the intake valve. The ignition was effected by a spark plug located between the valves. The test conditions were the same as before:

Air: $t = 30^{\circ}$, $p = 760$ mm, $h = 80$ percent

Water: $55-65^{\circ}$

Oil: $45-51^{\circ}$

The plot (1) of figure 22 corresponds to a normal speed with optimum ignition advance, which is at the same time the advance corresponding to the limit of detonation. The hot spot, not electrically heated, has a temperature of only about 530° C.

The plot (2) of figure 23 corresponds to the same settings but with zero advance. The lower diagram corresponds to a hot-spot temperature of about 500°; the upper one to about 970°, for which the irregularities of misfire have ceased to exist.

It will be noted that in this diagram the pressure does not go down again after the piston has passed T.C., as it does in the lower diagram - probably as a result of the heating of the gases in contact with the hot spot without ignition and, perhaps, even of the slow reaction of a small portion of the carbureted mixture.

The diagram (3) at the bottom of figure 24 corresponds to a critical temperature $T_1 = 1{,}015^{\circ}$ C.

In this case, auto-ignition probably induces a combustion substantially the same as that by normal ignition.

Diagram (4) at the top of figure 24 corresponds to critical temperature $T_2 = 1,045^\circ$ C. The action of the hot spot produces auto-ignition with an advance superior to 0°. At times the auto-ignition is accompanied by detonation; the combustion is very irregular.

Lastly, diagram (5) of figure 25 corresponds to a hot-spot temperature distinctly superior to the critical values, reaching, in fact, $1,190^\circ$.

The auto-ignition is advanced so that combustion terminates under a very low pressure. Then follows the compression of the burned gases. (The power output of the engine is very low or zero, and electricity must be resorted to, to maintain the speed.)

The interesting fact here is that detonation disappears in the case of materially advanced auto-ignition as already pointed out by the author several years ago.

SUMMARY

The working up of the different diagrams discloses the following:

1. At minimum temperature on appearance of auto-ignition the combustion produced by hot spot proceeds along a regime substantially the same as with electric ignition at zero advance.

2. At the temperature of regularization of auto-ignition the combustion released by it is more advanced than the normal combustion, which may induce the detonation and tend to further increase the temperature of the hot spot.

3. An increase of less than 200° in hot-spot temperature ushers in a regime for which auto-ignition is practically indistinguishable from a regime of zero horsepower.

Information Supplied by the Diagrams Regarding the Phenomena of Dissociation of Carbureted Mixture at High Temperatures

An analysis of diagrams (1) and (4) has revealed, among other things, some particularly interesting information. On transforming these diagrams into p v axes (figs. 26 and 27), we find that the mean polytropic coefficient of expansion (between 0.05 and 0.75 of the stroke) is:

1.25 if no auto-ignition exists, and

1.26 for very advanced auto-ignition (diagram 4).

The mean polytropic coefficient of compression is, in the latter case, only 0.96. This seems to point to release of heat during expansion, even for very advanced auto-ignition.

Owing to the abnormally small value of mean polytropic coefficient of compression, it cannot be admitted that this release of heat is due to a simple phenomenon of late burning when there is auto-ignition. The specific heat changes of the gases with temperature are no longer of sufficient order of magnitude to allow for the result obtained. It seems very likely that the products of the advanced combustion due to the auto-ignition are subject during compression to a very material dissociation followed by an equally very intense recombination during expansion.

It is difficult to directly verify the proper base of this conclusion with the few diagrams, by reason of the relatively great importance of the wall losses in the test engine and, in any case, the question is clearly beyond the scope of the present study. Even so, these facts appeared striking enough to merit particular mentioning.

CONCLUSION

From the results outlined in Parts II and III, the following conclusions can be reached.

From the theoretical point of view:

1. The critical temperatures of auto-ignition by hot spot is increased as:

a) the pressure of carburetion is decreased;

b) the period of contact between this mixture and the hot spot is increased;

c) the carburetion is farther away from a richness corresponding to 2 percent of CO at exhaust;

d) the octane number of the fuel is increased.

2. For an extremely low speed and sufficiently weak turbulence, the hot-spot temperature capable of causing auto-ignition in the engine approaches the spontaneous ignition temperature of the employed fuel.

3. Taken as a whole, the variations observed for the critical temperatures of auto-ignition, are the same as those assumed by the author regarding the spontaneous ignition temperature of fuels in his detonation theory.

However, the agreement between these variations is more qualitative than quantitative, as is easily proved either by comparing the ignition-temperature variations with the pressure, as may be deduced from figures 10, 15, or 17 with the experimental relation previously determined in the case of nuclear ignition (No. 103 of this series), or by comparing the effect of ethyl fluid with the critical temperatures of auto-ignition and with the critical temperature corresponding to the appearance of detonation.

In any case, the critical temperatures of ignition by hot spot remain, for the same ignition lag, distinctly above the critical temperatures which we have had to consider regarding the detonation, and it remains doubtful whether the difference can be attributed to a temperature difference between hot spot and gas which becomes heated on contact.

The laws governing the ignition by hot spot of carbureted mixtures, though similar in entirety to the laws governing the ignition in mass of the same mixtures, do not seem to harmonize with the latter. This, it is said, conforms to the result of applying the reaction theory "by chains" to the ignition of combustible mixtures.

4. The burned gases are subject to a very pronounced dissociation on reaching a temperature slightly above normal terminal combustion temperature (about 2,200° C.) and this dissociation is followed by a very active recombination during expansion.

From the Practical Point of View

a) The temperature of a hot spot of extent and form similar to that of a central electrode must, in general, be much higher than the spontaneous ignition temperature of the employed fuel (800° to 1,000° in place of about 650° for gasoline of 60 octane).

b) Auto-ignition is substantially delayed by the use of antiknock fuels; by higher turbulence; and by letting the hot spot protrude in relation to the wall of the engine.

The significance of these last points from the point of view of spark-plug design and general arrangement of the engine, is readily seen.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

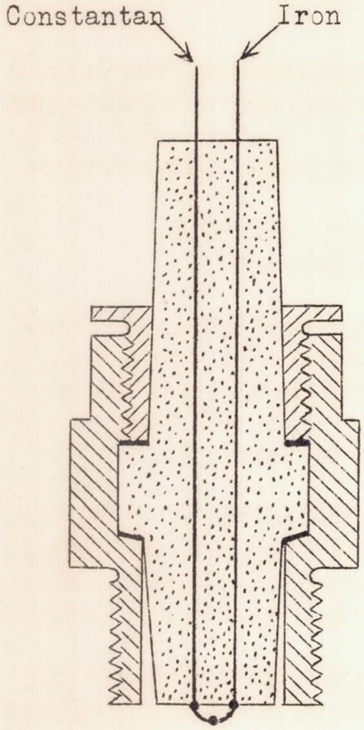

Figure 1

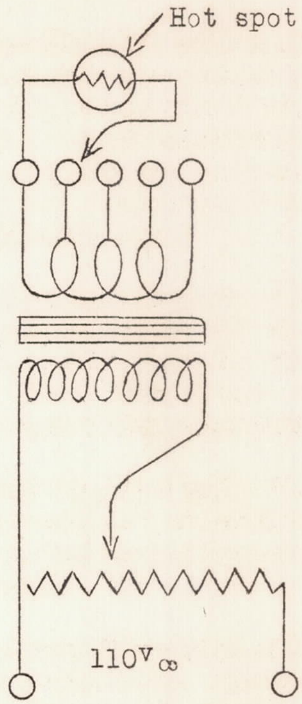

Figure 3

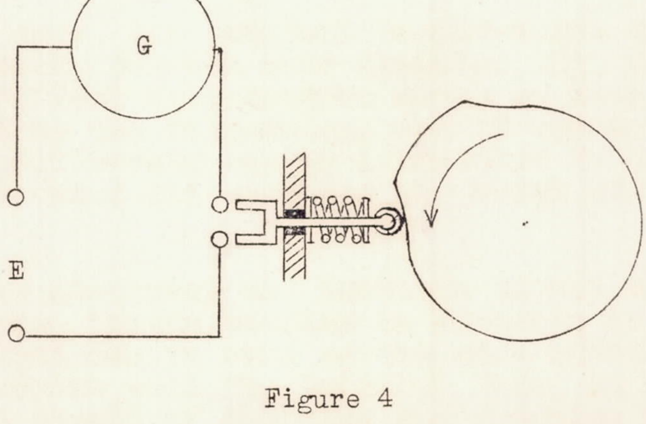

Figure 4

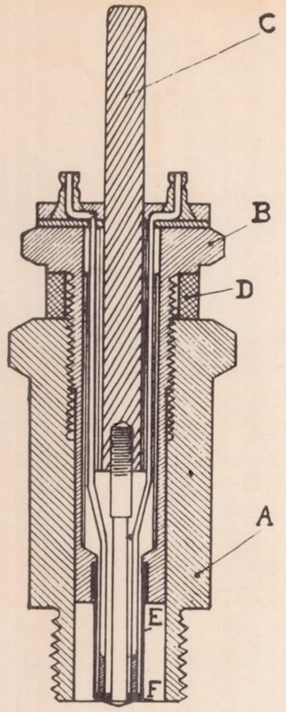

Figure 2

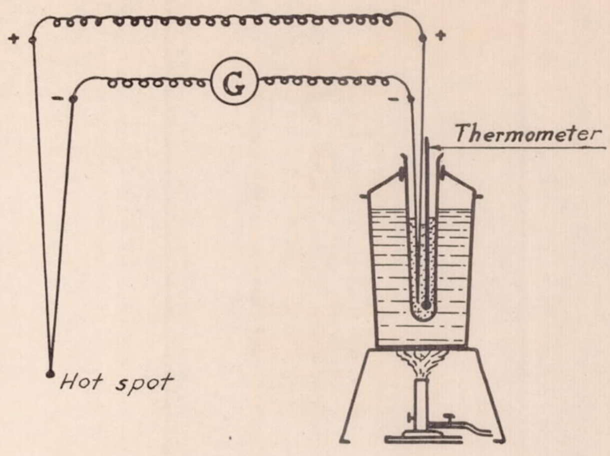

Figure 5

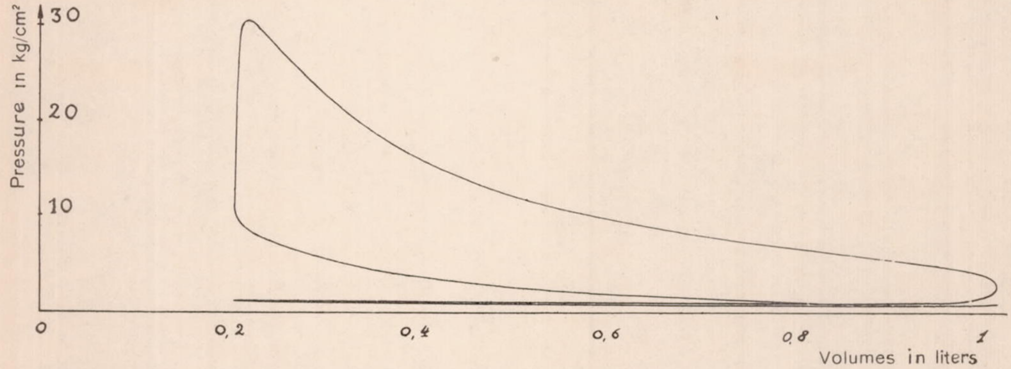

Figure 26.- Diagram No. 1 transformed in p.v. axes.

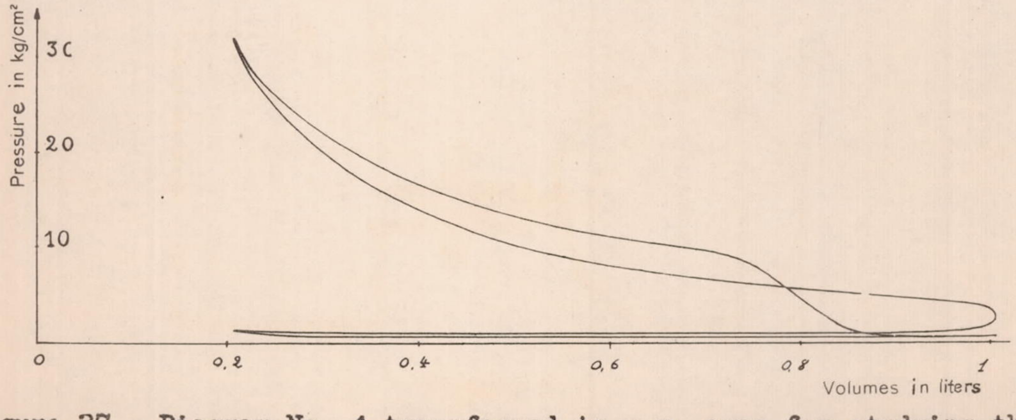

Figure 27.- Diagram No. 4 transformed in p.v. axes for studying the variations in polytropic coefficient during compression and expansion.

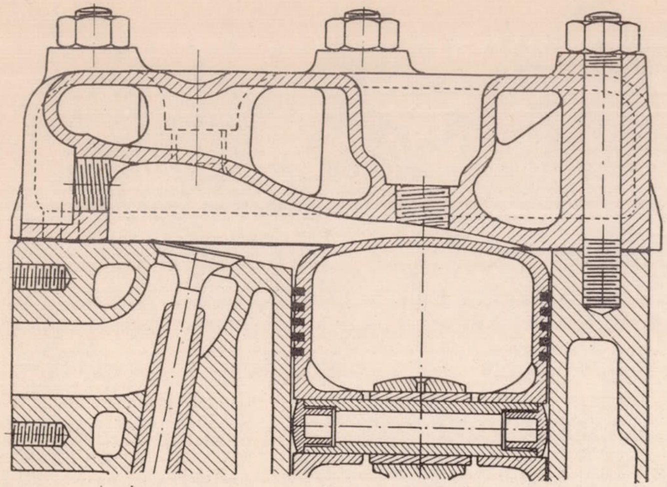

Figure 6.- Vertical section of cylinder head of form No. 4.

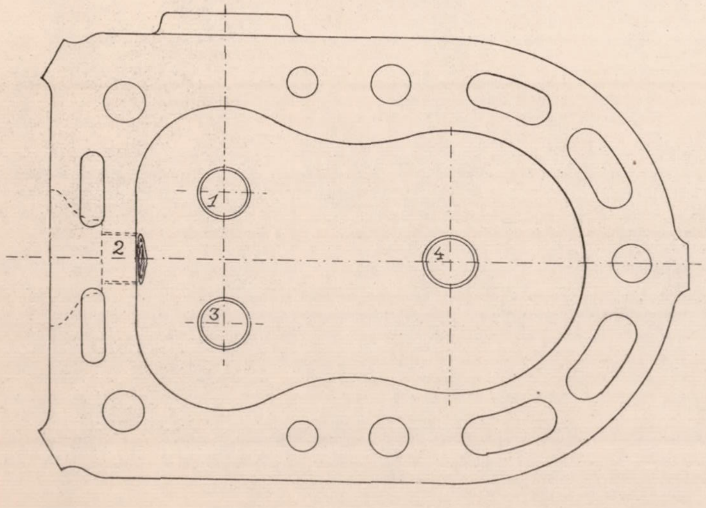

Figure 7.- Form of head Nos. 3,4 or 5 seen from below.

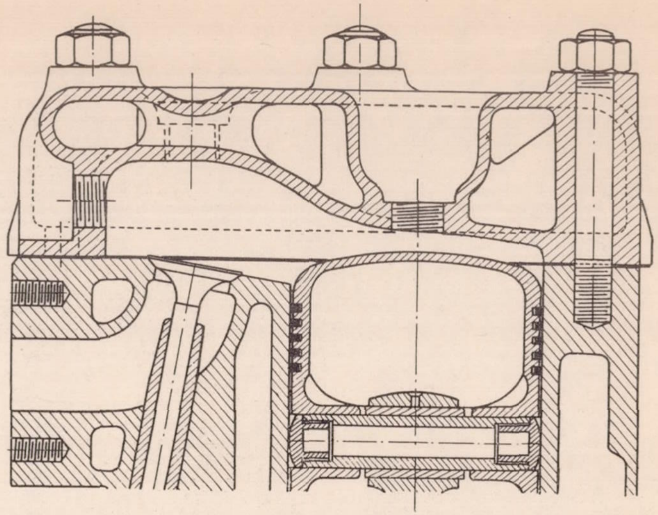

Figure 8.- Vertical section of head of form No. 3.

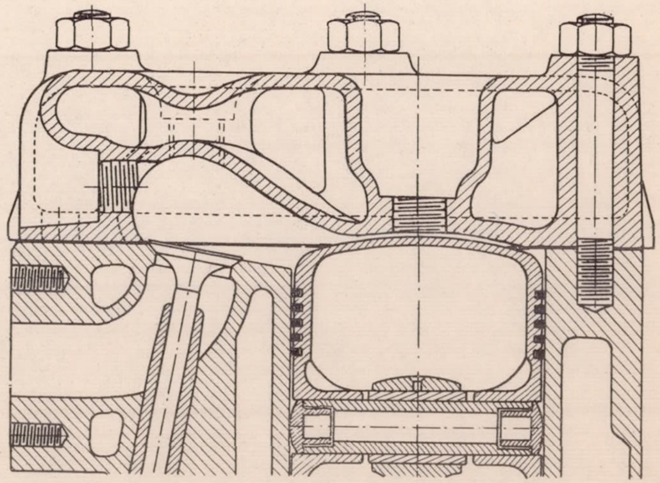

Figure 9.- Vertical section of head of form No. 5.

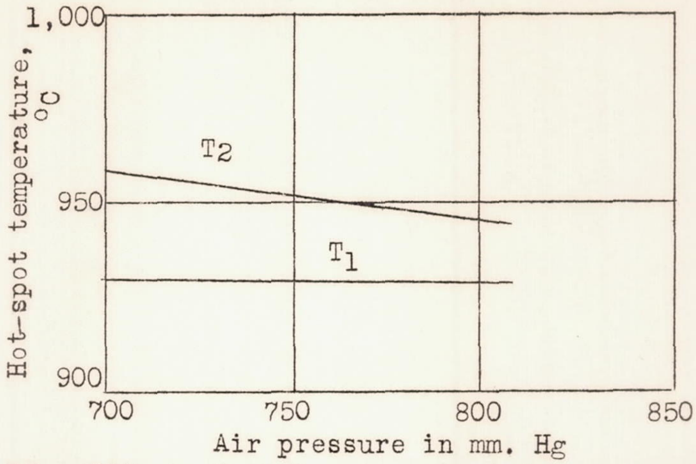

Figure 10.- Effect of carburetor air intake pressure (anti-turbulent head). N=1,250 r.p.m.

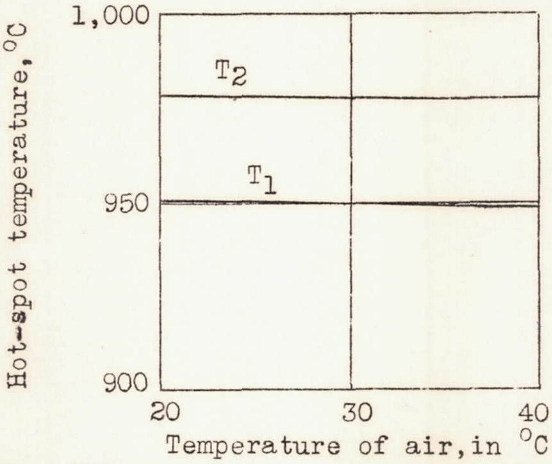

Figure 11.- Effect of air temperature at carburetor intake (anti-turbulent head) N=1,250 r.p.m. hygroscopicity constant.

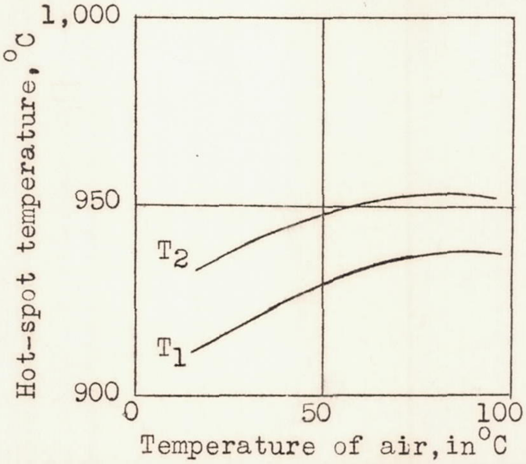

Figure 12.- Effect of air temperature at carburetor intake (turbulent head) N=1,250 r.p.m. Weight of water per liter of air constant.

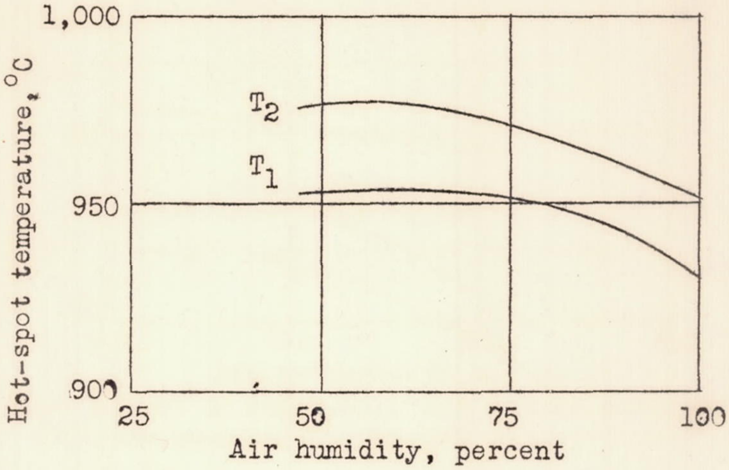

Figure 13. - Effect of inducted air humidity (anti-turbulent head) N = 1,250 r.p.m.

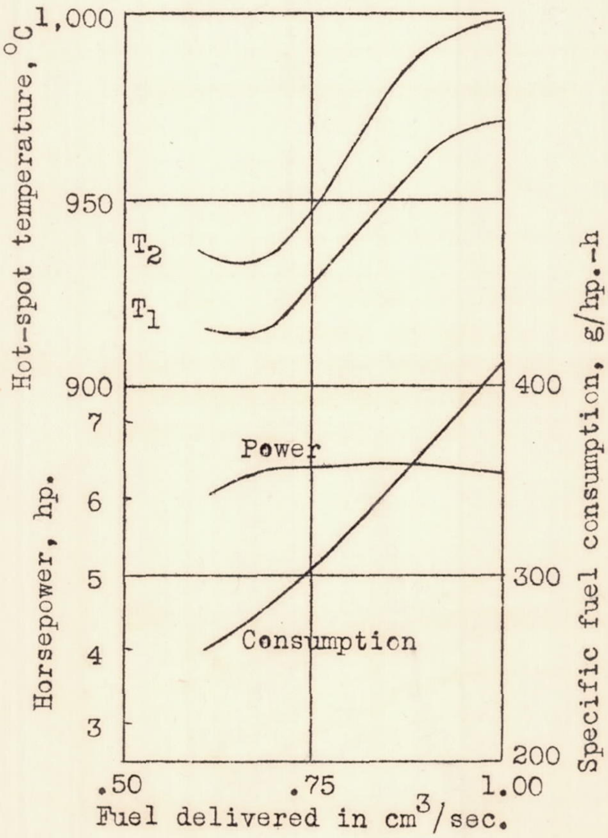

Figure 14. - Effect of richness of mixture (anti-turbulent head) N = 1,250 r.p.m.

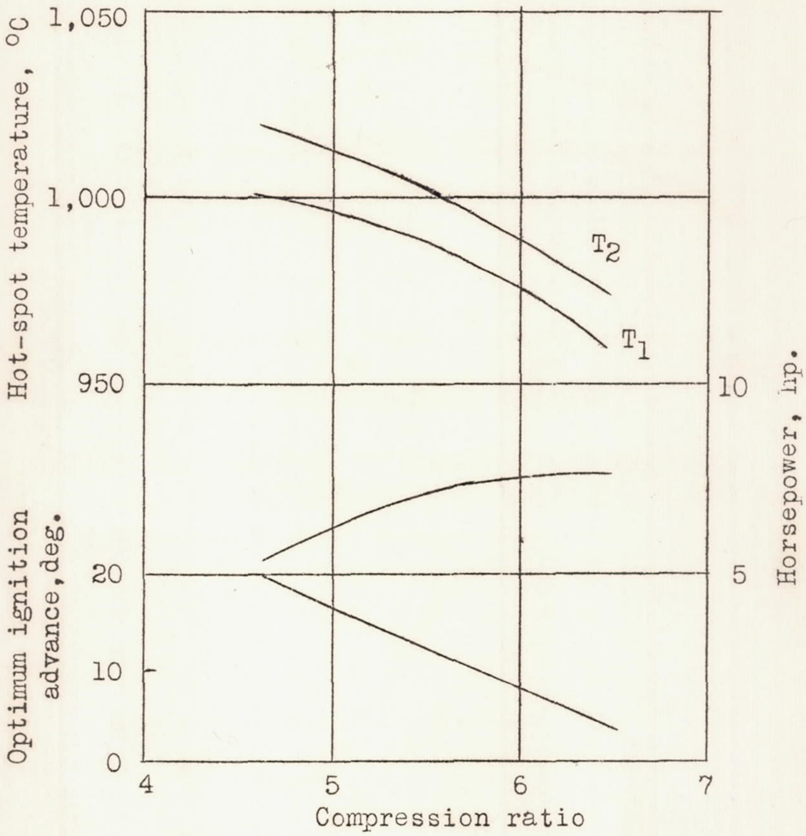

Figure 15.- Effect of compression ratio (anti-turbulent head,) N = 1,250 r.p.m.

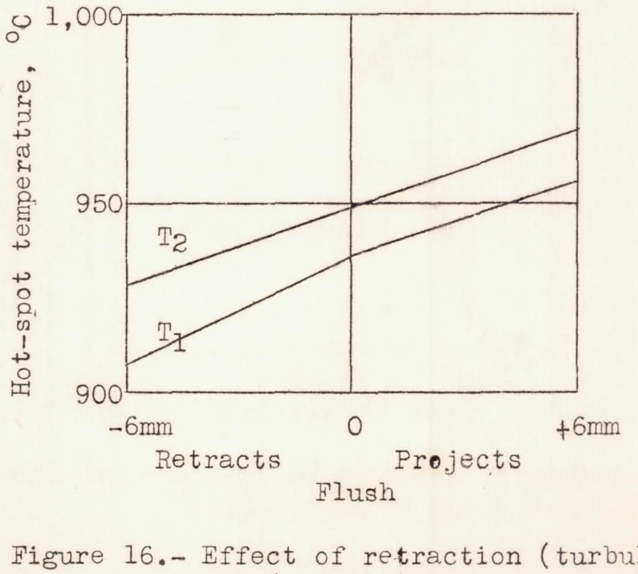

Figure 16.- Effect of retraction (turbulent head,) N = 1,250 r.p.m.

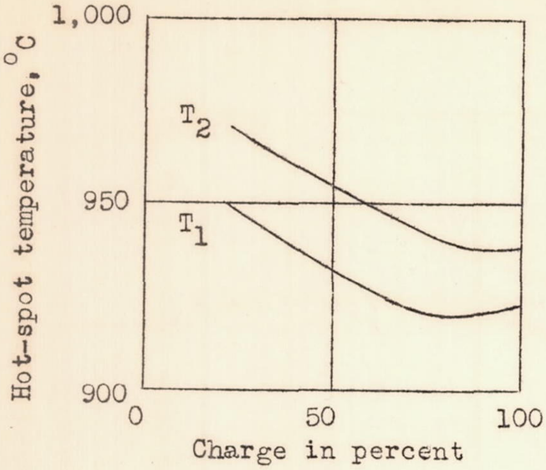

Figure 17. - Effect of engine charge
(semi-turbulent head)
N = 1,250 r.p.m.

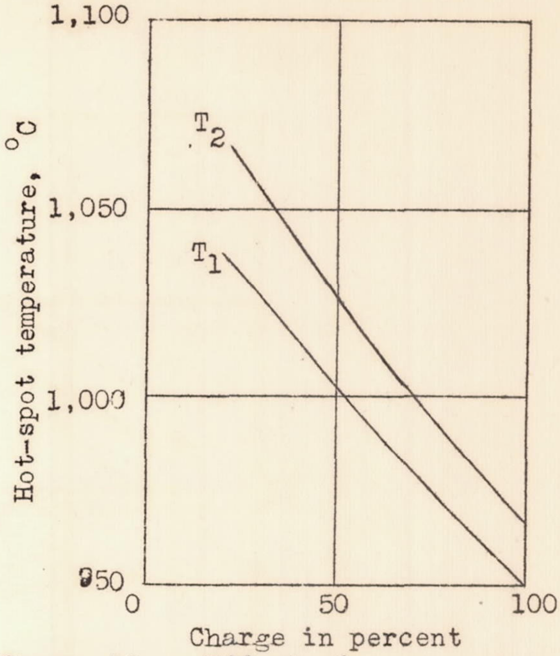

Figure 18. - Effect of engine charge
(turbulent head)
N = 1,250 r.p.m.

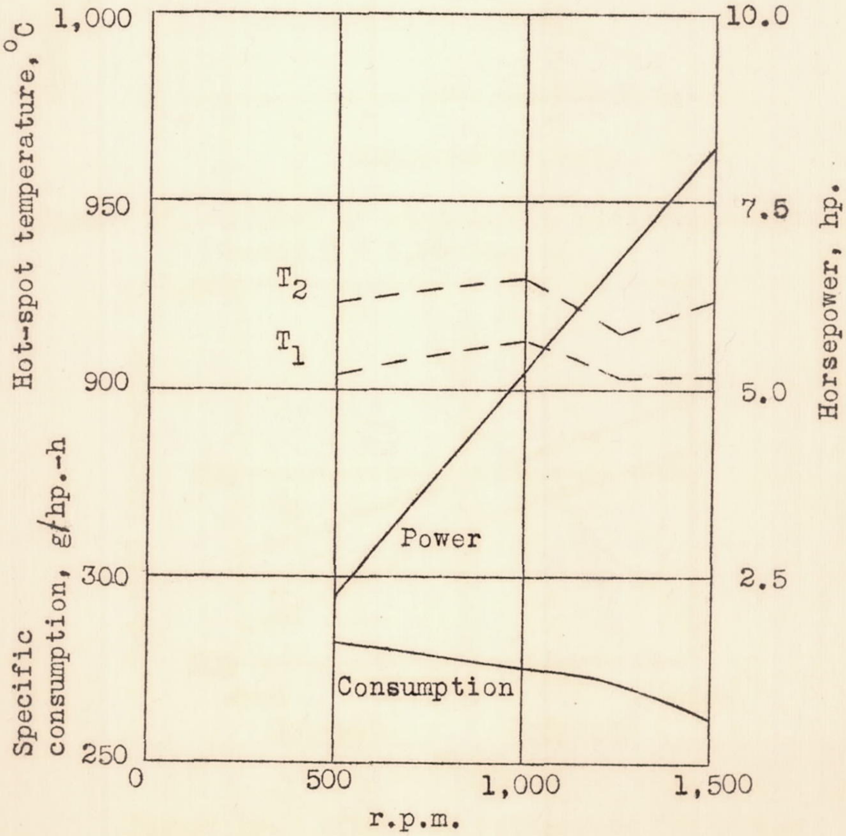

Figure 19. - Effect of r.p.m.
(anti-turbulent head)

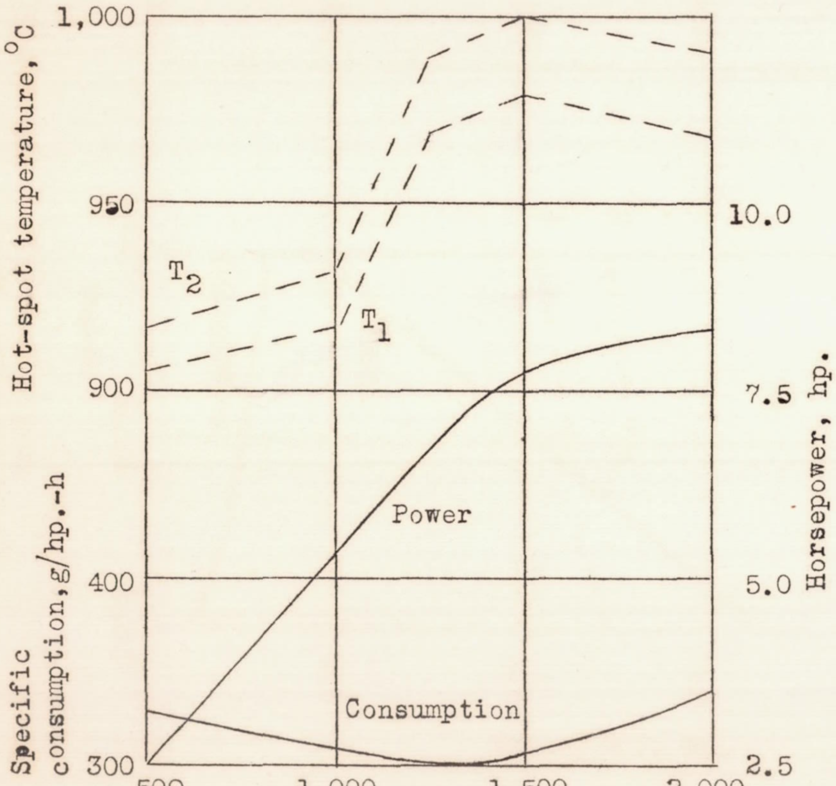

Figure 20. - Effect of r.p.m. (semi-turbulent head)

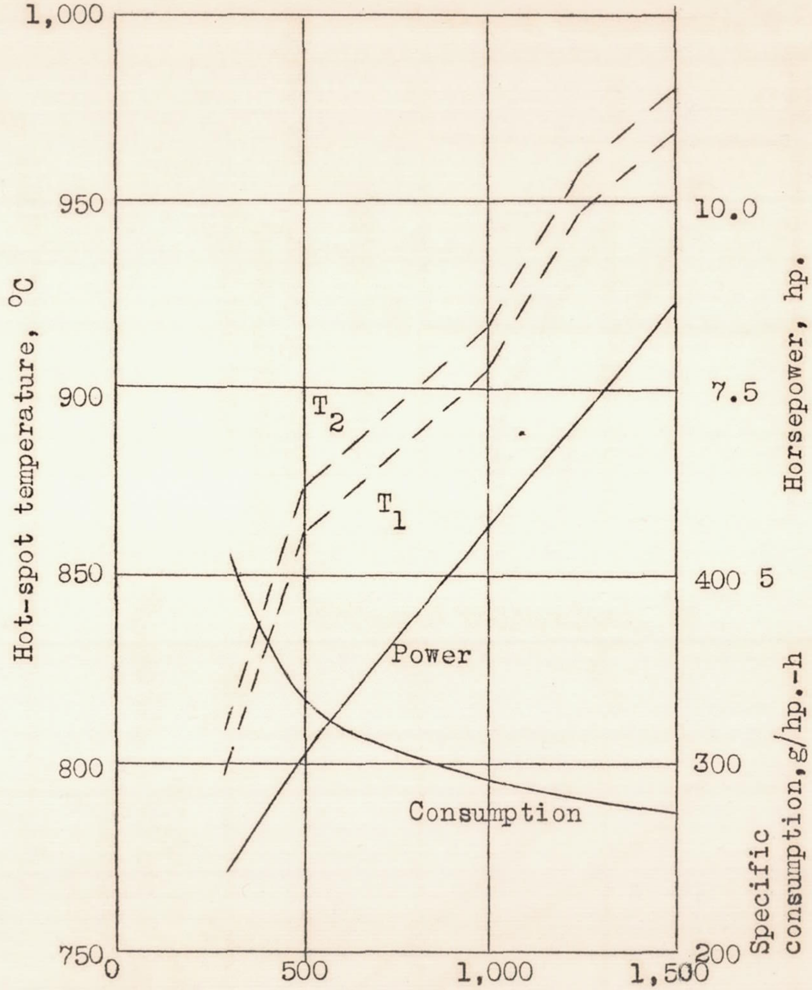

Figure 21. - Effect of r.p.m. (turbulent head)

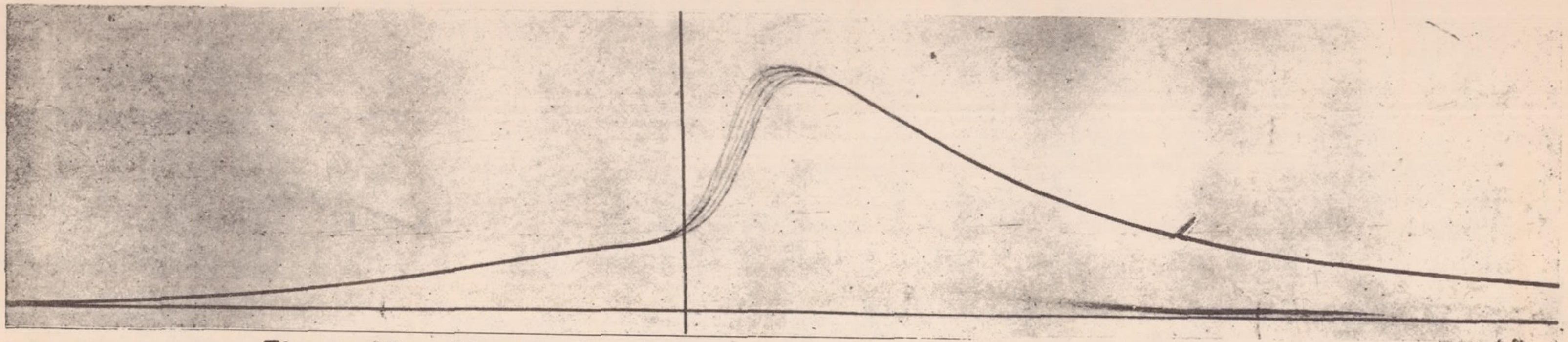

Figure 22.- Diagram 1 - optimum advance - hot spot not heated (temperature 530°).

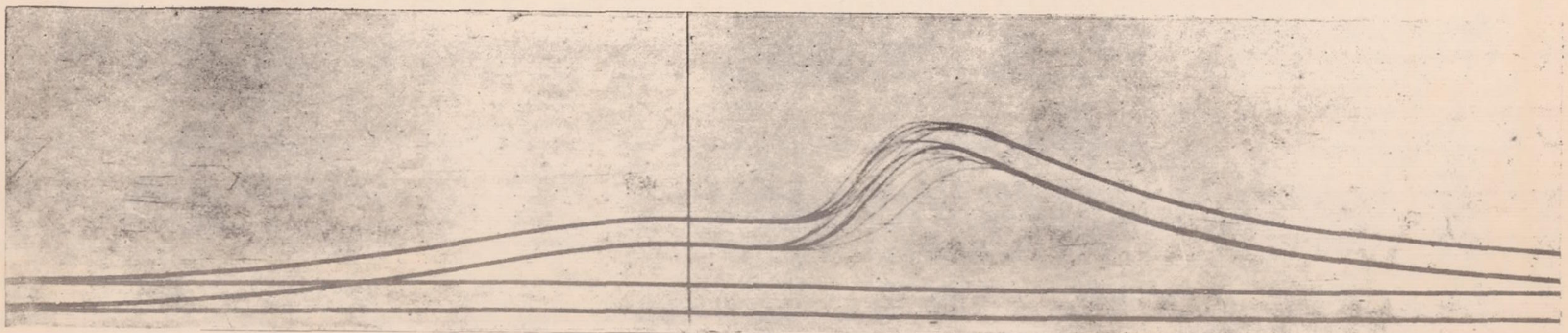

Figure 23.- Diagram 2 advance 0° - hot-spot temperature: 500° for lower, 970° for upper diagram; no auto-ignition.

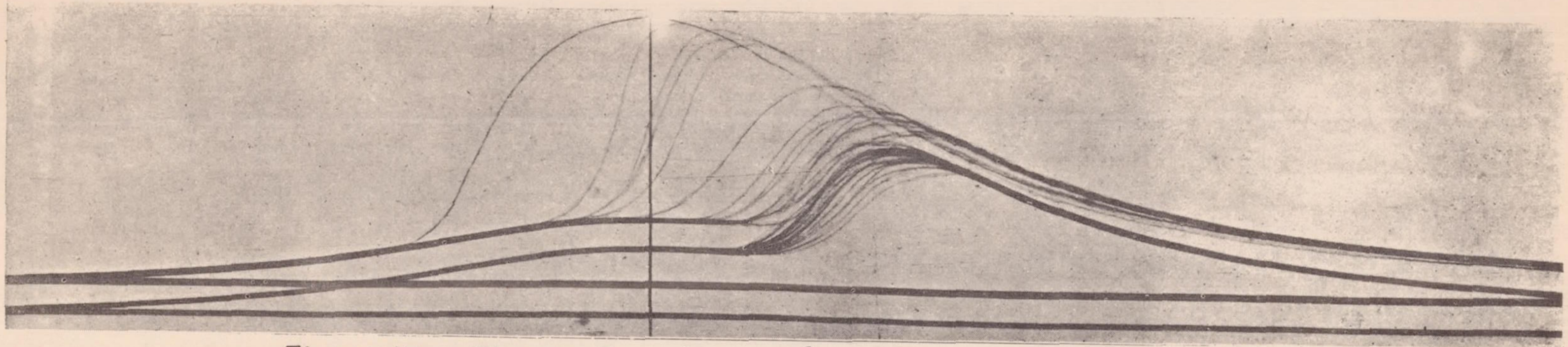

Figure 24.- Diagram 3 - advance 0°; hot-spot temperature; T_1 1015° for lower, T_2 1045° for upper diagram.

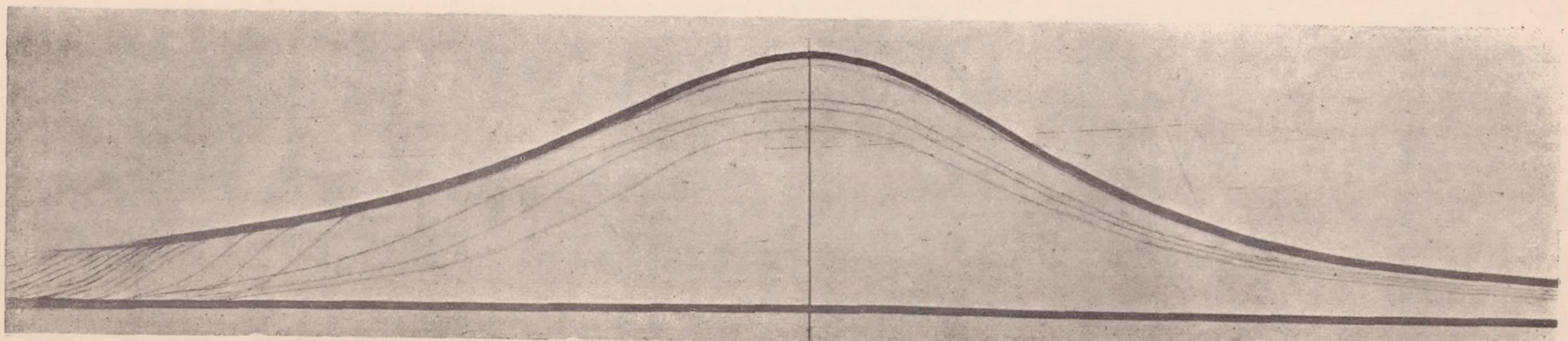

Figure 25.- Diagram 4 - advance 0°; hot-spot temperature; 1190; very advanced auto-ignition.