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TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 930

EXPERIMENTAL CONTRIBUTION TO THE STUDY OF COMBUSTION IN COMPRESSION-IGNITION ENGINES

By R. Duchêne

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THE STUDY OF COMBUSTION IN AN ENGINE

The many research workers who for a certain number of years have studied the combustion in engines, utilized either the pressure rise, the record of the flame-front motion, or, at times, the two combined. Other means for exploring the mechanism accompanying combustion were chemical analysis and spectroscopic analysis.

The steady progress in the application of these various means has gradually increased our knowledge on this complex question of combustion in engine cylinder. For instance, the improvements made on indicators have gradually freed the diagrams from the inertia effects of the components of the instrument.

In a very important report, published in 1936, M. Labarthe has described the evolution of the manograph from the first indicators for slow machines to the most modern versions, whose indications are totally free from inertia effects notwithstanding the extremely rapid pressure changes of modern engines.

OBJECT OF RESEARCH

It is purposed to explain the differences in thermodynamic qualities of two oils and to try to make this differentiation clear enough so that it can be applied to two oils extremely alike, as, for instance, a given oil and the same oil to which a small amount of some other substance has been added.

*"Contribution expérimentale à l'Étude de la Combustion dans les Moteurs à Injection." Publications scientifiques et Techniques du Ministère de l'Air. No. 149, 1939.

However, the following conditionsmust be met: The engines must be capable of adapting themselves in the same way to different oils, and variations in the shape of chamber or method of injection must not be such as to produce a radical change in the opinion formed up until then about the respective values of these oils. Now, if hot-bulb or spark-ignition engines (with oil and not with gasoline) are exempted, it seems well established that the qualities looked for are the same for all oil engines.

The comparison of injection oils by their behavior in a given engine is moreover current practice in the testing stations of the various oil firms, where the oils are classified according to the results obtained in a typical engine. The most generally used test engines are known by the names of: Thomassen, Gardner, Ricardo, and C. F. R. engines.

It is not our intention to suggest a new test engine but merely to give the various results obtained in the laboratory rather than on the test stand, with a set-up somewhat different from that of a real engine since it permits but one explosion during a test. Ten years and more have passed since our first experiments on the combustion in gasoline engines with an apparatus of this kind, and whatever results we have been able to achieve have prompted us to remain true to this apparatus for the study of combustion by injection.

The principal advantages of this engine with a single explosion are:

1) The possibility of controlling the test conditions as accurately as desired (temperature, quantity of injection, elimination of all burned gas);

2) The minimum amount of fuel needed for a test, which permits examination of numerous substances;

3) The absence of deleterious vibrations during the explosion, particularly during the most interesting phase of the cycle: namely, the portion around top center.

Experimental Arrangement

The experimental layout, illustrated in figure 1, includes:

The cylinder with piston, connecting rod, flywheel, camshaft operating the values, and the injector, compressed-air starter;

Device for recording the flame movement in the explosion chamber (figured for 90°);

A Labarthe type manograph;

A number of contacts on the flywheel for determining the curve of angular speed of the flywheel during the explosion.

Cylinder.-

Bore: 80 mm   Displacement: 1035 cm^3

Stroke: 207 mm   Maximum compression ratio: 13.5

Cylindrical explosion chamber: d = 33 mm, l = 100 mm

The explosion chamber has a heavy glass window for photographing the flame; the valves are arranged on the other side of the chamber. At the top of the chamber a diaphragm of chromium-plated steel serves as a mirror for the indicator.

The injector, located at the end of the chamber comprises a plunger piston and a spring-loaded needle valve which rises under the effect of the pressure. Spray orifice: 0.03 mm - 1 mm movement of the plunger corresponds to the injection of 19.5 mm^3 of fuel into the cylinder.

The cylinder can be raised to any desired temperature by means of an electric heater, the temperature is taken at the inside of the cylinder.

Starting.- The piston being at bottom center (left in fig. 1) and the auxiliary starter meshed with the flywheel, the compressed-air tank is charged to a little more than 12 kilograms. When everything is ready, the manometer is set to exactly 12 kilograms and the starting handle pressed down. The piston is driven toward the right, compressing the charge, the piston valve being regulated so that the escape of the starting air takes place at the end of the stroke. The speed obtained by this method of starting corresponds at dead center to that of an actual engine rotating at 300 revolutions per minute.

Photographic recording.- This apparatus has been so often described that it suffices to state that the drum carrying the film is driven from a synchronous motor assuring constant speed; drums with different diameters can, of course, be used for different tangential speeds. The tests were made at a speed of 12.50 meters per second. We have also made tests at 25 meters per second, but the accuracy does not justify this modification.

Easy mounting of the film and its perfect application over the drum are assured by means of a ratchet locking mechanism. Other than the movement of the flame front, the film also records the instant of the break of the contacts on the circumference of the flywheel.

The Labarthe indicator.- This instantaneous pressure recorder is also so well-known that we shall only describe its adaptation to our installation.

A beam of light from an intense light source is thrown on the chromium-plated steel membrane subjected on the cylinder side to the pressure existing in the chamber. The great sensitivity of the method permits the use of a heavy membrane which raises its natural vibration frequency and protests against parasitic indications mingled in the observations. The reflected beam is thrown on a screen where it must form a spot of uniform luminous intensity. There is a hole smaller than the luminous spot in the screen and the part of the beam passing through this hole is thrown on a photoelectric vacuum cell. The changes in the curvature of the membrane caused by pressure variations produce diffusion of the reflected beam and the luminous intensity in the cell changes. Labarthe has proved proportionality between the pressure in the capsule and the deflections of the spot of the oscillograph to which the voltage of the photoelectric cell is applied.

If a voltage which varies proportinally to the movements of the piston is applied to the second pair of deflecting plates of the oscillograph, the spot describes a pressure-volume diagram corresponding to the cycle of the engine. This second voltage was obtained by using a carbon resistance between the ends of which a constant voltage was maintained. On this resistance a sliding contact controlled by a second connecting rod pivoted to the flywheel of the engine, served to provide a voltage between this slider and one end of the resistance substantially proportional to the piston movements.

Instead of the voltage on the second pair of plates, the conventional chronographic method based on the time of charge of a condenser, the sudden discharge returning the spot to its initial point quasi-instantaneously, can be used. We used both.

Change of Angular Speed of the Flywheel under the Effect of the Explosion

The engine with a single stroke together with its light flywheel offers another possibility to differentiate combustions and, consequently, fuels.

The combustion energy is transmitted in the form of kinetic energy to the flywheel and two combustions which develop different energies must give, everything else being equal, different accelerations to the flywheel. It was for the purpose of studying these differences in speed that the set of contacts C (fig. 1) was mounted on the periphery of the flywheel. Having previously indicated that the instant of break of these contacts was recorded on the revolving film, we shall now show how with such an instrument the curve of the angular velocities of the flywheel can be obtained in function of its angle of rotation.

Along a circumference and concentric with the circumference of the flywheel are tapped holes, 10° apart, to accomodate finger d. The contacts C themselves are also spaced 10°.

Suppose the first contact C_1 should be opened by finger d at the instant the piston passes top center, contacts C_2, C_3, C_4 are successively released during the expansion for the angles of rotation of the flywheel at 10°, 20°, 30° after dead center. During each test, four points are marked on the film and it will be easy to deduce from their spacing the time corresponding to equal rotations. Shifting finger d 20° gives a new schedule of time which overlaps the first by a third; the overlap constitutes a resection. It is thus possible to plot by degrees for a given oil the curve $t = f(\theta)$ for a rotation θ of the flywheel as stretched out as desired. One such curve is illustrated in figure 2 for flywheel rotation between dead center and 140°. The desired curve $\omega = f_1(\theta)$ is readily deduced from the curve $t = f(\theta)$, if it is remembered that $\omega = \frac{d\theta}{dt}$. Figure 2 gives this curve which corresponds to the integral curve obtained experimentally.

Other Information Obtainable with the Installation

The installation can also furnish the information indicated in the appended table. Besides the three records given in the tabulation, it can also give information on the ignitability of the different fuels. For oils with high ignition point it merely requires successive tests by starting from a high enough temperature in the cylinder (100°, for instance) and gradually lower this temperature with the heating rheostat until no ignition occurs. For easily ignitable oils and those which are ignited by the compression when the cylinder is initially at ambient temperature, it suffices to lower the compression ratio by degrees. It thus is possible to allot to each oil an ignition temperature T_0 computed by the following formula

$$T_1 = T_0 \, r^{\gamma-1}$$

where r is the compression ratio and

T_0, the absolute temperature in the cylinder when the ignition starts.

Record	Possible determination	Characteristics
1) Flame record	Combustion Start of ignition	With or without vibration Progressive or violent
2) Pressure record	Rise Combustion Maximum pressure	More or les inclined Vibrations
3) Record of curve $t = f(\epsilon)$	The curve $\omega = f_1(\theta)$ angular speed in function of angle of flywheel	Curve $\omega = f_1(\theta)$ informs about the variations to be attained from the use of one fuel in place of another and also of the role of accelerators.

Flame Records

We forego an analysis of the flame records, which already has been published in bulletin no. 94, and confine ourselves to those which served to establish the curves $t = f(\theta)$.

These photographs, reproduced in figures 6, 7, and 8, are for different methods of combustion. Figure 7 indicates a fairly progressive flame development starting from a point, those of figures 6 and 8 disclose a very rapid spread of flame throughout the length of the chamber. The first correspond to progressive, the second to violent, combustion. The records of the violent combustions manifest streaks perpendicular to the border of the film as well as sinusoidal lines of the same period as that of the streaks. These peculiar features result from pressure waves, as the sound waves, which originate in the explosion chamber under tho influence of the combustion. It should be noted, moreover, that a violent combustion can be clearly distinguished from a gradual combustion, the noise accompanying the combustion being much shorter in the first case.

The photographs on figure 7 disclose under a magnifying glass the path of the ignited particles of gas oil launched by the injector, they are projected from left to right and the film moving downward, the slope of these paths permits the measurement of the speed of the particles in the chamber. The records on figure 6 show the difference in lag at ignition between the combustion of gas oil and those where the gas oil is blended with an accelerator such as methyl nitrate. The advance adduced by this substance is of tho order of 10° flywheel angle. This measurement can also be achieved very accurately from the records.

Pressure Cards

Bulletin no. 94 of the Air Ministry contained various records obtained with a manograph which ceased to give deviations proportional to the pressure as soon as $\frac{dp}{dt}$ reached a certain value. So, when passing from a gradual combustion to another more violent the diagram, which for the first carried a round maximum, would indicate for the seconda peak so accentuated that the record went beyond the borders of the negative. We pointed out, when presenting the photographs for violent combustion, that it certainly involves an over-travel under the influence of an impulse and that the amplitude of the deviation no longer recorded the real pressure.

And this opinion was confirmed by the Labarthe indicator, which also served for a comparative study of normal gas oil and gas oil blends.

This study was made at:

29° injection advance;

55° initial temperature in the cylinder;

1 gram of oil to 17 liters of air, mixture ratio;

The horizontal shift of the spot of the oscillograph is controlled by a rod set at 180° to the master rod (fig. 1);

The terminal voltage of the graphite resistance was 30 volts, which is the maximum voltage applied to the two plates of the oscillograph which give the movement as abscissas.

These test conditions were modified in several ways during the tests in order to bring out certain interesting features.

Figures 11a, 11b, and 11c, which are true copies of the records make it possible to check the following:

Figure 11a - The records nos. 15 and 22 refer to normal gas oil;

Nos. 16 and 17 to gas oil + 5 percent of ethyl nitrate;

No. 20 to kerosene.

The plots should be studied counter-clockwise, the spot being at 0 at the start of the test: i.e., at the moment of incipient compression.

The pressure rise is fairly continuous as far as the arrow, this period corresponds to compression of the air in the cycle. If no ignition took place, the diagram indicated a maximum soon after this arrow and formed a kind of bell-shape curve as indicated in no. 15.

But the combustion defines an angular point and the ordinates continue to increase to a maximum soon after top center. The part of the diagram corresponding to the start of combustion is only faintly marked, which indicates a quick passage of the spot and consequently an abrupt pressure rise.

The comparison of plots 15 and 16 shows that the angular point is produced much earlier with the gas oil - nitrate blend so that, on superimposing the records, the curve representing the combustion falls more to the left for the normal gas oil. Figure 11a shows this superposition of plots 15 and 16 and of 15 and 17. The difference in the ordinates of the arrows measures the advance resulting from the ethyl nitrate.

During a test, the flywheel making several revolutions, while producing only one explosion, made it necessary to use a shutter in order to prevent the record from being superimposed by useless dashes, which explains the more or less truncated aspect of the diagrams during expansion. Since the rise in pressure was the most interesting factor, this suppression of part of the diagram was deemed secondary.

If l is the abscissa from the point of origin, the slope $\frac{dp}{dt}$ of the curve of the pressure rise from the arrow is an indication of the rapidity of the combustion. The evaluation of this criterion should prove very interesting, but unfortunately the spread of the diagram along the abscissas is of little significance; in fact, it is difficult to learn whether the pressure maxima are simultaneous or otherwise.

The comparison of records 20 and 22, obtained successively, shows that the pressure for gas oil and refined petroleum develops substantially the same.

Figure 11b - Changes made in the previous test conditions:

In order to obtain greater spread along the abscissas, the terminal voltage of the graphite resistance was boosted from 30 to 60 volts.

Figure 11b - (cont'd.) The injection was advanced to 45° to assure more violent combustion. This, of course, increased the amount of the injected gas oil (1 gram per 14 liters of air).

Figure 11b gives some records obtained under these conditions:

Nos. 10 and 11 are for straight-run gas oil.

Nos. 8 and 9 for gas oil blended with 5 percent ethyl nitrate.

Records nos. 10 and 11 are very largely superposable, thus permitting one to attribute the differences observed between two records of different fuels to different properties of these fuels. It may happen, however, that for some reason, the combustion is abnormal, in which case, the comparison of the records yields incorrect results. So, in order to forestall this, it is always expedient to run several tests with the same fuel and to compare only those records which are reproduced identically.

The combustions here are more violent than under the conditions of figure 11a, as may be judged from the slope of $\frac{dp}{dt}$ of the curve during combustion: the record is almost vertical and the rapidity of combustion is such that the line is scarcely marked on the paper during part of the combustion (record between the two arrows). Conceivably such an impulse is of a nature as to create a number of compression waves in the explosion chamber.

The superposition of records nos. 9 and 10 and 8 and 11 shows again that methyl nitrate advances the ignition point and that the curve for blended gas oil passes to the right of the curve for straight-run gas oil. The maxima of pressure are a little lower for nitrated gas oil, but they are produced a little sooner after dead center. The quasi-instantaneous part of the pressure rise seems to be a little shorter for the nitrated carburant.

Figure 11c - Here a time base was substituted in the potentiometric device in order to assure uniform sweep along the abscissas in place of sweep reproducing the piston movement. This time base is controllable.

1) Relatively slow sweep (fig. 11c):

> Records nos. 28 and 29 are for gas oil blended with 5 percent ethyl nitrate; record No. 31 is for straight-run gas oil.

A comparison of these records reveals nothing new; they confirm what had been stated previously.

2) Rapid sweep (fig. 11c):

> Record no. 26 is for straight-run gas oil; nos. 24 and 25 are for gas oil blended with 5 percent ethyl nitrate.

This time the results achieved previously are more definitely presented: advance of ignition - rise in pressure sudden, less for nitrated gas oil - pressure maximum a little lower.

A new factor comes into evidence: the presence of pressure vibrations after the sudden rise. It is difficult to determine the frequency of these vibrations exactly, but it appears to be near the frequencies registered on the flame records.

3) Very rapid sweep (fig. $11c_3$):

> Record no. 20 is for 5 percent nitrated gas oil; records nos. 22 and 23 for straight-run gas oil.

The spread along the abscissas is more pronounced, the effect of which is to separate the curves more in the part corresponding to the combustion. The superposition of Nos. 20 and 22 shows that the maxima of the curves seem to lie along adjacent abscissas. Note the vibrations as in the preceding test series.

The measure of the rate of the sweep is given by the record of the variation in the luminous intensity of a lamp fed by a 50-cycle circuit. Two periods of this record represent 1/50 second. (The luminous intensity is independent of the direction of current, it merely depends upon its absolute value.) From this scale, the pressure rise in its most abrupt part may be appraised at the rate of 20 kilometers in 1/2000 second.

MECHANISM OF COMBUSTION IN COMPRESSION-IGNITION ENGINES

The records of the flame and of the pressure furnish a certain amount of information:

1) Starting from ignition, a quasi-instantaneous pressure rise is produced, which is succeeded by a more gradual rise in pressure.

2) When the flame records present streaks or sinusoids, characteristics of a violent combustion, these invariably are formed from the start of the ignition; on the pressure records the vibrations arrive immediately after the vertical rise in pressure.

3) The presence of certain oxidized substances, such as ethyl or methyl nitrate, decreases the ignition lag, these substances acting as oxidation catalyzers with respect to gas oil.

4) Unless the injection advance is abnormal, these accelerators have a moderating effect on the combustion: disappearance of vibrations on the flame records and attenuation of the quasi-instantaneous rise of pressure on the manograph records.

During the time which elapses between the start of injection and the ignition (ignition lag), there is stored in the cylinder charge a certain amount of latent energy resulting from the presence of a combustible mist and the oxygen of the air. When the ignition temperature is attained at a point, the flame appears and, the other points of the charge being of necessity at a temperature approaching it, the flame immediately spreads over the entire fuel injected up to that time (during the lag) in such a manner as to cause a quasi-instantaneous release of the latent energy. This liberation of energy can be so sudden that it may cause pressure waves which spread throughout the cylinder charge.

The injected gas oil is accordingly ignited and continues to burn progressively like a gas burner, so long as there is enough oxygen or gas oil to insure combustion.

One particular result of this process is that any reduction in lag, reducing the importance of the quasi-instantaneous combustion, attenuates the violence of combustion and vice versa.

Now, an advance in injection necessarily increases the ignition lag since the first particles of the injected oil arrive sooner in the air of the cylinder charge, with the result that for substantial injection advances, the effect of accelerators, such as ethyl nitrate, must be substantially less than for more moderate ignition advances.

ENERGY PRODUCED BY THE EXPLOSION

One characteristic of an injection oil which seems particularly interesting is the energy developed during the cycle or, more simply, the change in energy obtained from a change of fuel. None of the records gives any explicit information in that respect.

In fact, a difference in maximum pressure shown on the manograph does not necessarily indicate a difference in power, that is, the mean pressure which it is necessary to know. Now, to evaluate the mean pressure, the pressure curve during the cycle and the manograph records which must be integrated lend themselves poorly to a correct determination of this kind. In order to remedy this lack of information on the energy omitted by the combustion, we attempted to measure the variations in angular velocity of the flywheel which are associated with the energy through the known equation

$$\frac{1}{2} I \left(\omega^2 - \omega^2{}_0\right) = \Delta T$$

where ω_0 is angular speed of flywheel at an instant t_0;

ω_1, angular speed of flywheel at an instant t_1;

ΔT, energy produced by the combustion between instant t_0 and t_1;

I, moment of inertia of the moving parts.

And the most suitable means for obtaining this information consisted in the previously described contacts mounted on the flywheel. However, before giving the results obtained by this method, it was believed to be of no less interest to give the results achieved previously by different methods.

1. Method of spaced signals.- The combustion taking

place largely before dead center according to the flame and the pressure records, we believed that, if the combustibles, to be compared, give different powers, a different time interval between the instant of injection and the instant when the piston reaches dead center should elapse for each one. With this in mind, two contacts were made to open at these instants and the breaks to generate, by means of coils, sparks which were recorded on the rotating film intended for the flame records. The break was controlled by cams mounted on the control shaft of the injector (see bulletin no. 94), but subsequently changed to a finger mounted on the circumference of the flywheel.

This arrangement was used to study very close combustions of 30 fractions obtained by vacuum distillation of Iraq gas oil.

Figures 13 and 14 of the first 14 fractions give the records of the flame and of the sparks at break. Those sparking records are not, as will be noted, at the place where they should be on the film in relation to the flame. The exact positions at the start of injection and of the dead center are marked by light dashes on the records. The surprising fact, on examining these records, is the constancy of the interval between two sparks, the slight differences observable for certain fractions being, we believe, of experimental magnitude.

As to the flames, they present greater differences and particularly the fractions 11 to 14 indicate a greater ignition lag than the preceding fractions.

The first modification consisted in adding a third signal for determining a spark 25° after top center. Figure 14 shows the records for fractions 15 to 19 with the three signals. The time lapse between start of injection and top center is always fairly constant, while the ignition lag verified for the fractions 11 to 14 subsides for fraction 15, then is ameliorated in the subsequent fractions. As to the time corresponding to the interval (top center) - (+25°), it appears to be augmented somewhat, but very little.

A second modification consisted in placing the third spark signal 100° after dead center. The results prove slightly less constant, which is not surprising in view of the fact that changing passive resistances intervene more.

2. Plunger method.- In the presence of the slight variations in effect from one fuel to the next, we tried to improve the sensitivity of the method by introducing, with the centrifugal force, the square of the angular speed. Since the radial component of the centrifugal force was proportional to ω^2, we believed that by mounting a small gear with radial movement on the flywheel the record of its motion would afford some interesting changes between one fuel and the next. Hence, the equipment shown in figure 15. It consists of a steel bar 40 centimeters long mounted on the flywheel axle. Toward one end of the bar is an opening for a slide with four rollers. The slide is pulled toward the center by two helical springs. A stylus is mounted perpendicular to the plane of the rollers. As the flywheel turns, it engages the bar and the slide and the stylus describes a circumference whose plan is parallel to that of the flywheel, on a sheet of white paper backed by carbon paper. When the speed of rotation of the flywheel is high enough to overcome the tension of the spring holding the slide, it moves and the stylus leaves the circumference to describe a sort of spiral.

By playing with the tension of the springs, we were able to achieve the starting of the slide soon after dead center and so to obtain a certain trajectory resulting from the centrifugal force developed. Unfortunately, the records frequently varied from one test to the next in the same proportions as with a change of fuel, while the record itself was quite confused since the flywheel made numerous revolutions for each test. The last-cited drawback was readily remedied by an arresting device (fig. 15).

The other drawback, more difficult to remove, was probably due to the fact that the speed of the flywheel was not constant and the acceleration rather than radial was along the resultant of a centrifugal acceleration equal to $m\omega^2R$ and a tangential acceleration equal to $mR\frac{d\omega}{dt}$. The result of this is that the force which acts on the slide, by reason of its rotation, slopes toward the radius of an angle, so that

$\tan\alpha = \frac{1}{\omega^2}\frac{d\omega}{dt}$. Thus the slide is not free along the rails but rubs against one side.

Since ω and $\frac{d\omega}{dt}$ change constantly, the best that could be done was to fix an approximate angle at which the slide did not rub against the rails. To determine this angle, recourse was had to the curves of figure 2, which permit recording $\frac{d\omega}{dt}$, and from which α can then be deduced.

The appended table gives the sequence of the different records and calculations.

Angle θ (A.T.C.)	dw (mm)	dw (C.G.S.)	dt (mm)	dt (mm/s)	w (mm)	w (C.G.S.)	w^2	tan α	x
3°	7.5	3.5	20	3.2	75	35.4	1250	0.88	
10°	13	6.1	18	2.9	85	40.2	1620	1.3	
16°	11	5.2	15	2.4	97	45.8	2100	1.03	45°
23°	9	4.2	13.5	2.2	107	50.4	2540	.775	38°
30°	7.5	3.5	13	2.1	115	54.2	2940	.578	30°
36°	6.5	3.1	12	1.9	121	57	3250	.492	26°
(40°)									(23°)
43°	5.5	2.6	12	1.9	127	60	3600	.375	
50°	5	2.4	11	1.8	132	62.2	3880	.345	19°
56°	3.5	1.6	11	1.8	136	64.2	4130	.227	13°
63°	1	.5	10.5	1.7	138	65	4240	.066	4°
70°	.7	.3	10	1.6	140	66	4370	.047	3°

According to this table, the experimental conditions under which the curves of figure 2 had been obtained are readily realized, by inclining the bar 23° toward the radius, whence the slide is not subjected to the reaction of the rails although the flywheel has passed the top center of 40°.

Figure 16 illustrates the set-up for the 23° inclination, and figure 17 is the record obtained with it for normal gas oil superimposed on peanut oil and gas oil blended with 10 percent ethyl nitrate.

The only part to be considered is obviously the curve of passage of the inner to the outer circle. The more rapid this passage is, the greater the force which it defines and hence, the more the fuel supplies energy. According to this, figure 17 indicates for the gas-oil - ethyl-nitrate blend a power output a little less than for normal gas oil, peanut oil gives definitely less power, but it should be borne in mind that this oil, more viscous than gas oil, must without a doubt be employed with an injector of much greater diameter.

We further tested in comparison with gas oil:

Petroleum, which seems to give a slightly inferior power;

Primary alcohol in C°, which gives an equal power;

Vaseline oil, which gives a little less power, but, as with peanut oil, the viscosity should play a part in this reduction;

Gas oil with 5 percent ethyl nitrate, which gives a little less power, but more than the 10 percent nitrate blend;

Lastly, we compared the two extreme fractions nos. 2 and 29; the latter giving a little more power than the first.

To sum up, it was found that all these power outputs are much alike as pointed out previously and the difficulty of the problem of differentiation resides precisely in this fact. The device described is simple to use and permits a reliable comparison.

If the final result of the combustion is substantially the same for the different fuels, their pressure records have proved that the evolution of the combustion was quite different.

<u>3. Method of closely related signals.</u>- We recall the contacts arranged over the circumference of the flywheel

and the recording of the break on the film revolving at constant speed; we also indicated how to deduce from this record the curve $\omega = f_1(\theta)$.

The appended graphs illustrate the results obtainable by this method for comparing oils with blends of the same oils.

The curves of figure 3 show the effect of ethyl nitrate blended with Iraq gas oil, of methyl nitrate and isopropyl oxide. The curves $t = f(\theta)$ are simple transcriptions of the records and the curves $\omega = f_1(\theta)$ were graphically deduced from these integral curves.

Under the experimental conditions described and, in particular, with the 45° injection advance, the accelerators indicate the lowering of the speed at top center.

From 40° A.T.C. (+40°) on, the curves are confused, thus indicating that the method of distribution of power may change without the general result's being affected.

Figure 5 illustrates for -20° to +30°, and 45° injection advance the combustion curves of gas oil and a gas-oil - methyl-propyl-ketone mixture. It is seen that from dead center on this accelerator has an effect similar to ethyl nitrate, i.e., that with the advance cited it causes the drop in angular velocity at dead center.

It will be noted that the flame records indicate only that this substance reduces the lag. These records are also much furrowed by streaks and vibrations, which are signs of very violent combustion.

Figure 4 establishes the comparison between normal gas oil and nitrated gas oil at 30° injection advance. The decrease in speed before dead center is greater for the blend (up to within -10°), then, up to dead center it is greater for normal gas. This time the nitrate plays the part of regulator by attenuating the decrease in speed at dead center. Besides, this slowing up at dead center has not as a consequence a reduction in speed during the expansion, the curve for normal gas oil passes again a little above that for gas oil and nitrate. It is evident from these curves that the effect of a catalyst of oxidation varies with the injection advance. When, for a moderate advance (30°) the decrease in lag, effected by the catalyst, regularizes the angular velocity, the opposite is produced at great injection advance (45°). A glance at the flame records of figures 3 and 5 discloses that these records correspond to very violent combustions.

This result does not seem to have been completely explained by the combustion method described above, but it nullifies it in nothing.

The comparison of fractions 1 and 23 are recorded on figure 18. The records obtained in view of the construction of the curves $t = f(\theta)$ are so close that it is quite difficult to represent the two curves separately in a graph. We attempted to give these records which could be easily verified on figures 18 and 19.

Angle of flywheel θ	Time, as ordinates (mm)	
	Fraction 1	Fraction 23
-20°	0	0
-10°	49	50
0°	118	119
+10°	180	180
+20°	226	227
+30°	266	267
+40°	300	300
+50°	331	332
+60°	361	362
+70°	390	392

This table shows the smallest difference between two corresponding coordinates.

A similar comparison made by the method of the moving slide disclosed a slight but still sensible difference between one fraction at the head and a fraction at the end.

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

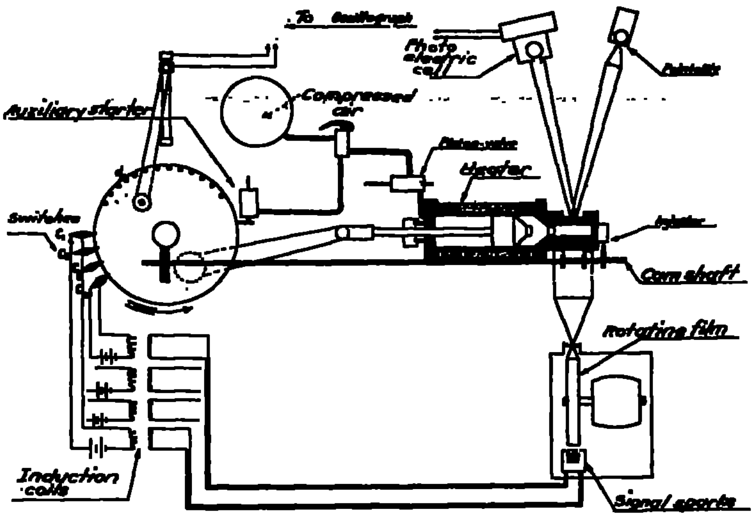


Figure 1.- Experimental set up.

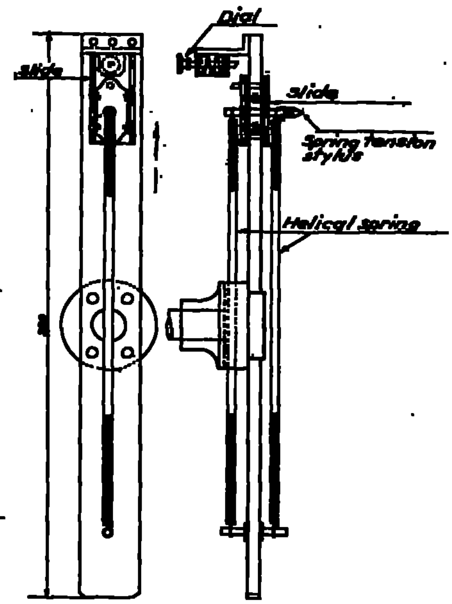


Figure 15.

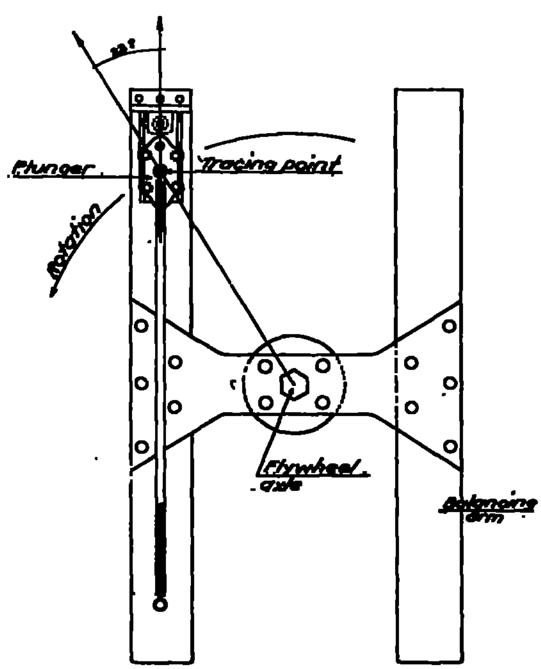


Figure 16.

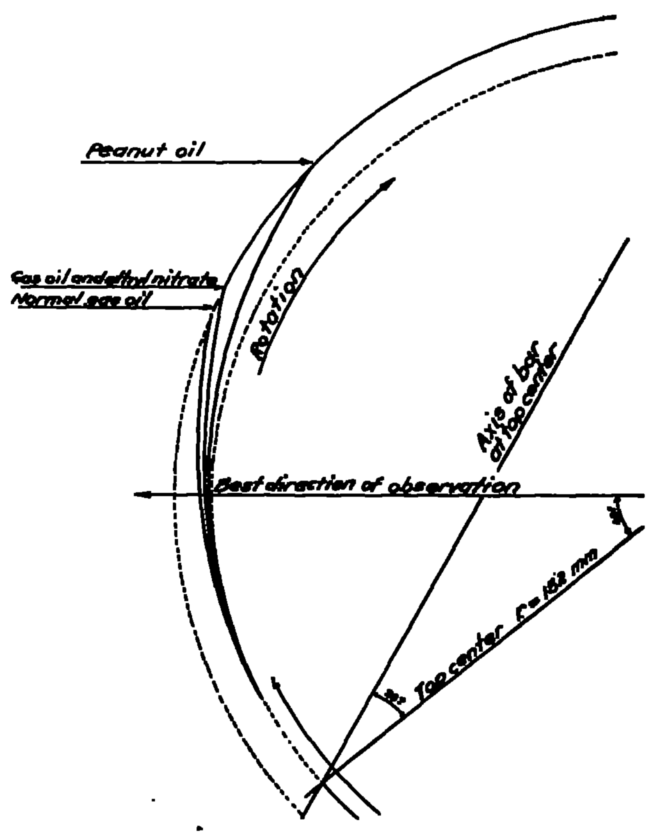


Figure 17.

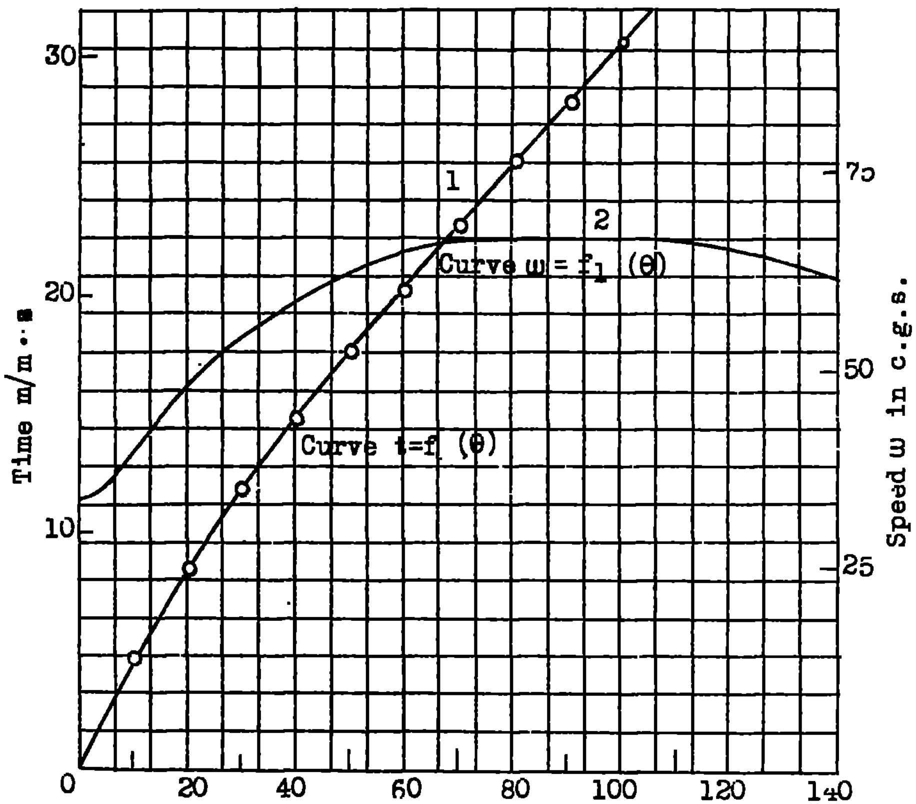
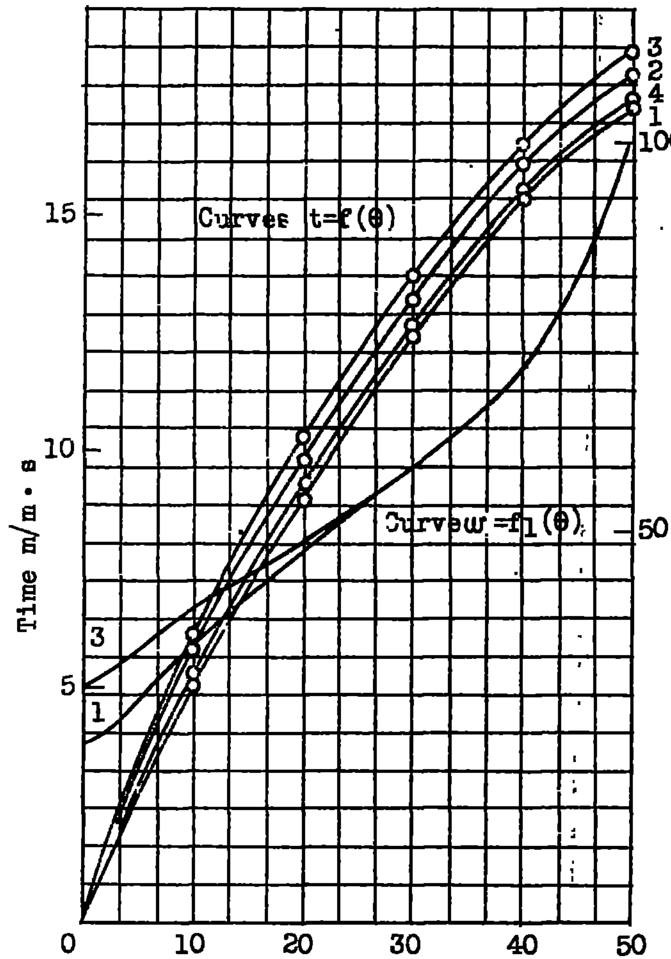
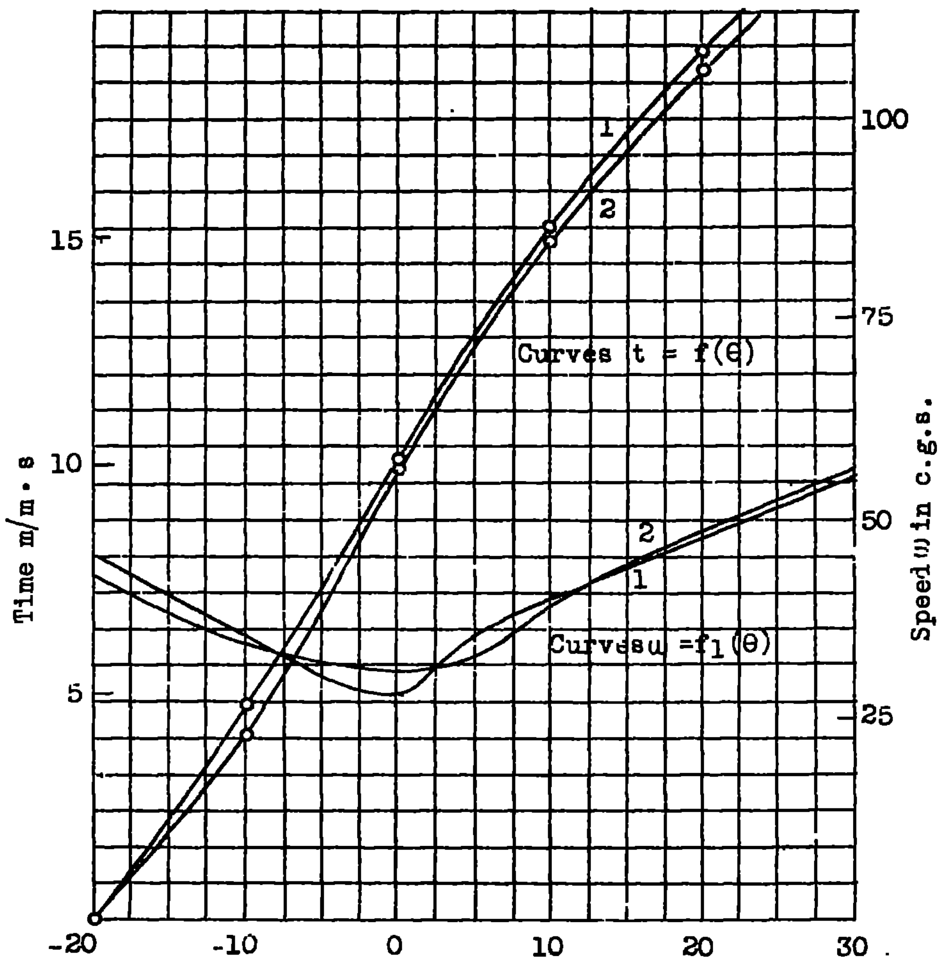


Figure 2.- Irak gas oil. Temperature: 55°; advance: 29°



1.-Normal gas oil
2.-Gas oil + 5% ethyl nitrate
3.- " + 5% methyl "
4.- " + 5% isopropyl oxide
Temperature: 85°; advance: 45°

Figure 3.



Angle of rotation of fly wheel, θ.
2.- Gas oil
1.- Gas oil + 2% ethyl nitrate
Temperature: 57°; advance: 30°; mixture ratio: 1 c^3 for 18 l of air
Figure 4.

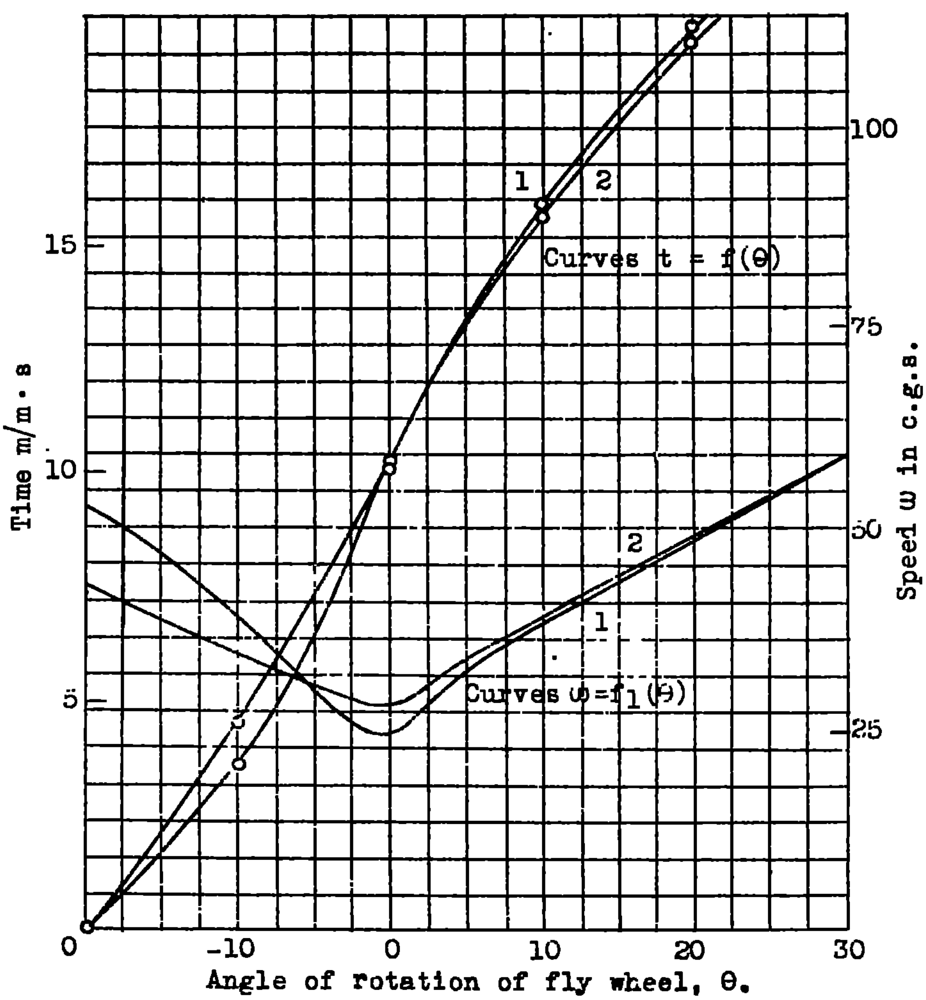


Figure 2.- Gas oil
Figure 1.- Gas oil + 5% of methyl propyl ketone
Temperature: 76°; advance: 45°
Figure 5.

1. Gas oil
2. Gas oil + 5% methyl nitrate

Figure 6.

1. Gas oil + 5% ethyl nitrate
2. Gas oil + 5% isopropyl oxide
3. kerosene

Figure 7.

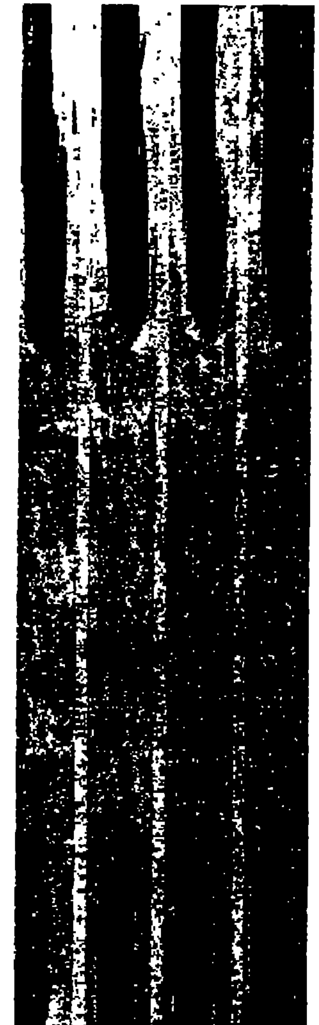


Figure 8.- Normal gas oil.

Figure 9.- Gas oil + 2% ethyl nitrate.

1 Gas oil 2.Gas oil + 5% methyl-propyl-ketone.

Figure 10.

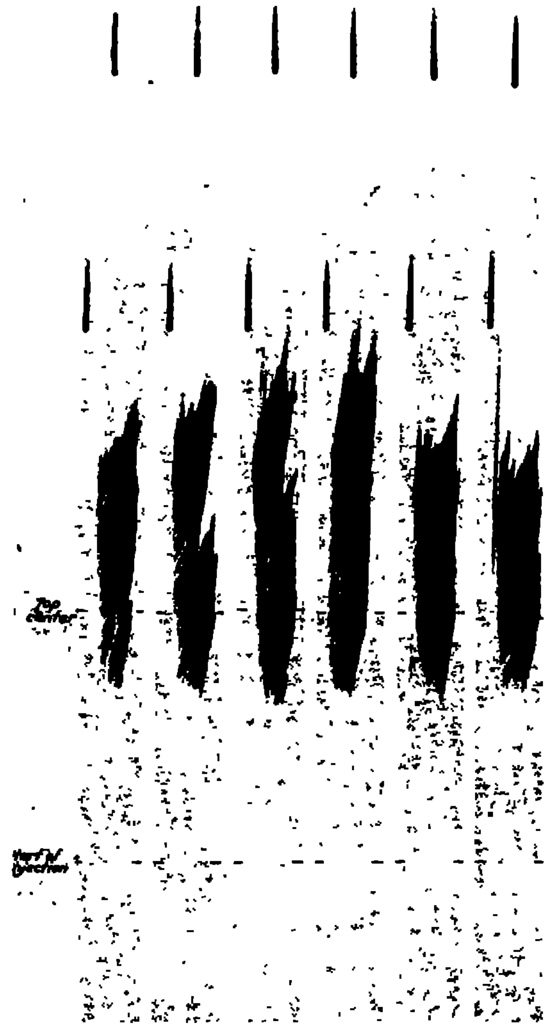
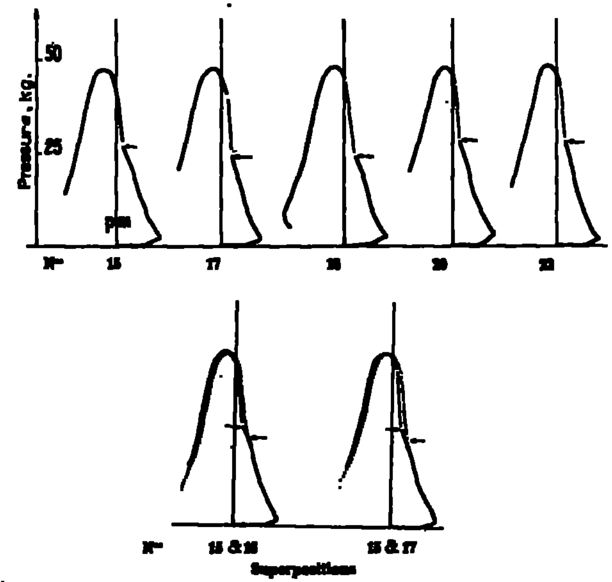


Figure 12.- Comparison of fractions 1 to 7 of distillation of a type of gas oil (two signals).

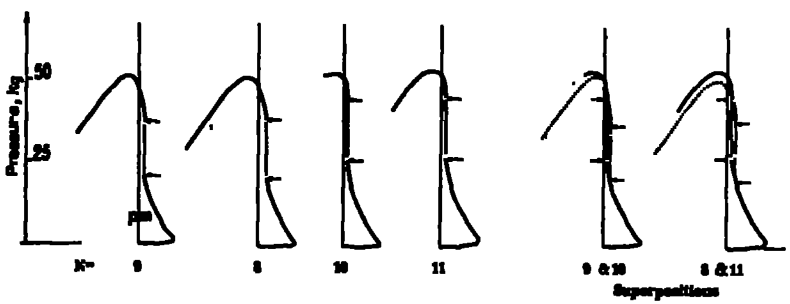
Figure 13.- Comparison of fractions 9 to 14 (two signals).



15 & 22. Normal gas oil. 16 & 17. Gas oil + 5% nitrate. 20. Kerosene

Figure 11a.

No. 20
" 24 & 25 } Gas oil + 5% ethyl nitrate.
" 28 & 29
" 22 & 23
" 26 } Normal gas oil
" 31



10 & 11. Normal gas oil.

8 & 9. Gas oil + 5% nitrate.

Figure 11b.

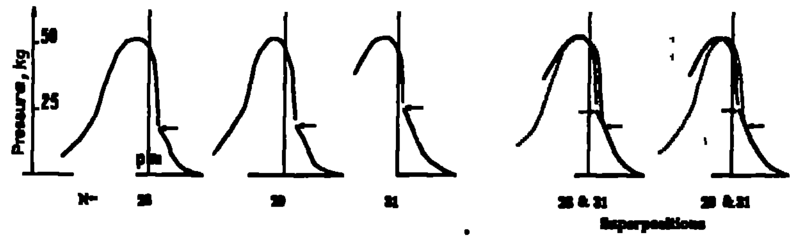


Figure 11 c_1

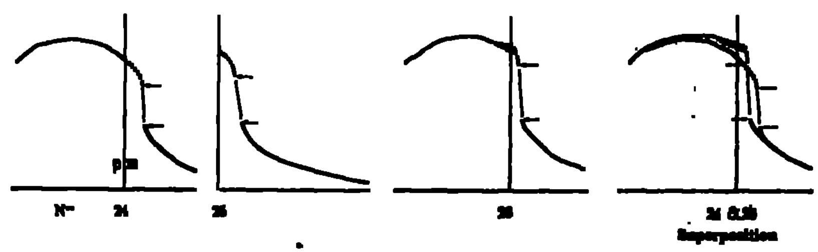


Figure 11 c_2

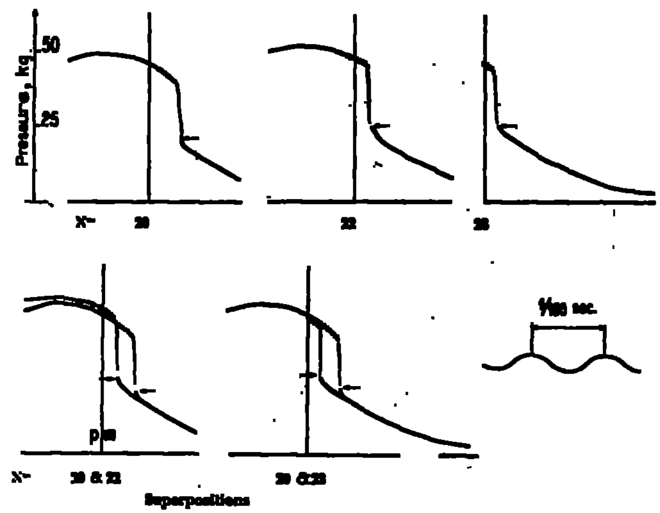


Figure 11 c_3

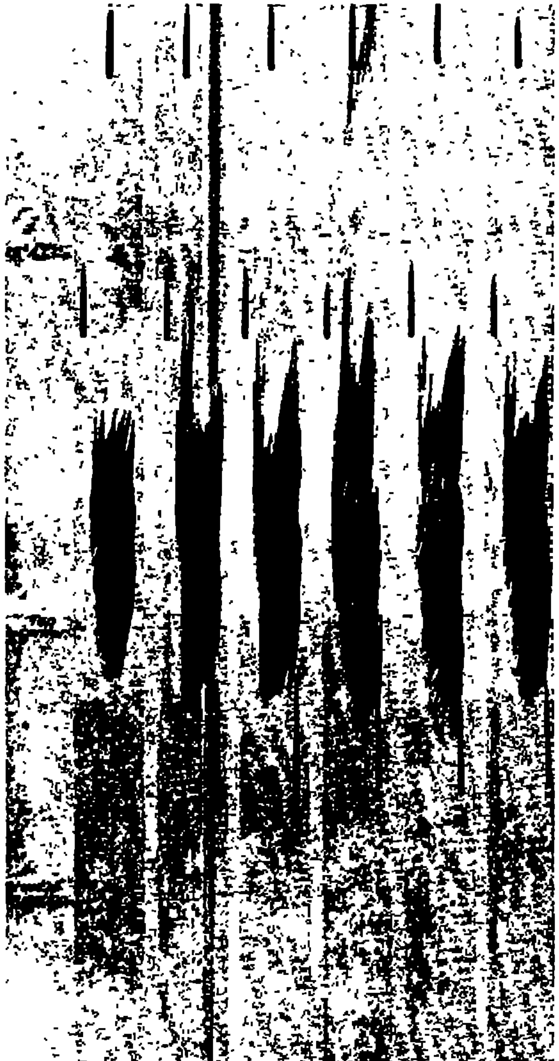


Figure 14.- Comparison of fractions 15 to 19 (three signals).

Figure 18.- Fraction 1 of distilled gas oil.

Figure 19.- Fraction 23 of distilled gas oil.