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DETONATION AND AUTOIGNITION

SOME CONSIDERATIONS ON METHODS OF DETERMINATION

By G. D. Boerlage

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SUMMARY

For the purpose of measuring the knock rating of a
fuel, the choice of a method is of less importance than
the suitable adaptation of a particular method, the impor-
tant consideration being that this method be universally
recognized and imposed. For the purpose of scientific in-
vestigation, however, such a unique method is not suffi-
cient, and various methods and engines must be employed.

I have been asked to present a critical analysis of
the methods of determination of the tendency to detonation.
Considering the large number of methods and numerous re-
sults already published, it appeared to me that such a
presentation should first of all concern itself with bring-
ing out the essential nature of the problems involved in
the measurement of the detonation. No attempt has there-
fore been made to describe in detail the different fuels
and the different methods proposed. The work is based
chiefly on the data obtained in the author's laboratory,
and the opportunity is here taken of thanking the large
number of collaborators.

Measurements and Limits

In general, the rating of fuels requires the conduc-
tion of measurements and leads to the prescription of lim-
its - the latter only reluctantly decided upon, since it
is recognized that on account of the great diversity of
fuels, engines, and operating conditions, these limits can-
not be valid for all cases. It is known to designers of

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engines that whereas in certain cases it is necessary to
remain within the prescribed limits, in other cases it is
permissible to go considerably beyond these limits. En-
gine buyers, the government, and other authorities, how-
ever, demand clearly prescribed limits, so that in cases
where in practice no differences could be ascertained, the
legal specifications nevertheless require these differ-
ences to be measured, and with great precision too. For
relatively simple physical and chemical properties this
does not involve too great difficulties. In certain cases,
however, and particularly in the case of problems of deto-
nation, the differences to be measured involve an array of
factors that demand complicated methods, difficult to carry
out because of the necessity of measuring separately the
effects of each of these factors.

Object to be Attained

Before such measurements are begun it is necessary to
see clearly the object which it is proposed to attain and
to check whether the measurements made correspond to this
desired object. It may be objected that this is quite ev-
ident but we shall see farther on that it is very useful
to bear this clearly in mind when we find ourselves in the
midst of a confusion of problems where it is not easy to
recognize the method to be approached.

The example of detonation brings out the following
difficulty: We all are acquainted with detonation as a
suspicious noise in the engine – which noise we all con-
sider more or less as a nuisance and whose intensity we
are agreed should be measured. On reflecting, however, we
see that it is not the intensities themselves that we should
be concerned in measuring, but rather the harm that is done
by the detonation or, more properly, we should concern our-
selves with the determination of the cause of this harm.
If it is shown that this cause bears a direct relation to
the intensity of the noise, then we may confine ourselves
to the measurement of these intensities if such measurement
is simple. Before having ascertained such a relation, how-
ever, the measurement of the intensities is, to say the
least, rather premature.

The fact that we do not as yet know how to measure
the cause of the harm produced by the detonation and that,
moreover, we are not so certain of the nature of this harm,

leads us to conclude that we are not yet in a position to know the object to be attained. Meanwhile, we are content simply with recording and computing as best we may, the phenomena observed. It is therefore wrong to entertain too many illusions as to the actual value of a critical exposition of the methods of measurement of detonation. As long as an acceptable analysis of the phenomena is lacking any presentation will remain subject to caution.

We shall nevertheless present an analysis which at the present time appears to us acceptable, and we shall make a critical exposition of the methods of measuring based on this analysis. This presentation will constitute nothing more than an attempt, however, and we are far from pretending that the views here presented are to be regarded as definitive. Some of our conclusions, naturally, will not be novel, and we ask to be pardoned for not mentioning the names of all the pioneers in the field.

I. CONSIDERATIONS ON THE PROCESS OF COMBUSTION

Our views on combustion and detonation previous to the tests on the "engine with window." Octane and cetene numbers.

For the purpose of studying the combustion phenomena, we constructed a special engine provided with quartz windows. Before proceeding to the results which we have obtained with this engine, we shall summarize the views previously held by us on combustion and detonation.

Knocking in the Diesel engine is generally the more intense the greater the ignition lag. From the very high compression temperatures attained in the Diesel (up to about 1,000° C.), we have deduced the fact that the auto-ignition which is developed at one or more particularly favorable centers (nuclear flames) should be chiefly an effect of destructive combustion disrupting the molecules thermally with the more or less effective assistance of contact with the oxygen. In our opinion it was the gas which was ignited, not the droplets, and the large quantity of the gas was due precisely to the effect of the first inflammation. We introduced the cetene number as a measure of the quality of the inflammation in the engine.

The tendency to detonation in the gasoline or spark-ignition engine, measured by the octane number, showed a number of points common with the tendency to knocking as measured in the Diesel engine. The cetene number expressed the tendency to autoignition, whereas the octane number, on the contrary, the resistance to autoignition. We found a linear relation between the two (fig. 1), the octane number being more or less the opposite of the cetene number. We are familiar with the method of Dumanois, who utilizes this property to determine the cetene numbers of a gas oil in a gasoline engine simply by determining the reduction in octane number produced by the addition of a small quantity of gas oil in the gasoline. We have also done the reverse — that is, determined the octane number in a Diesel engine, obtaining similar results. Autoignition tests in the C.F.R. engine with compression up to the point where the electric ignition could be disconnected, have shown us that this method of determining the tendency to autoignition of gasolines could be used to determine the octane numbers of these fuels, the results showing good agreement (fig. 2). In these tests the time factor played a dominant part, the autoignition requiring more rigorous conditions the shorter the time available. The good correlation between the octane number and the tendency to autoignition thus measured under moderate as well as severe conditions in the same engine, appears to indicate that we are confronted with practically the same process developing under very different temperatures, pressures, and times.

On the other hand, the good correlation between the octane and cetene numbers measured in engines of quite different types, appeared to indicate that again it was a question of the same process in a Diesel engine. The problem of detonation in a gasoline engine thus appeared to be reduced to a problem of autoignition of the type known in the Diesel engine, and thus a bridge seemed to have been thrown between the "knocking" of the Diesel and the detonation in the gasoline engine. Figure 6 shows how the existence of "Diesel" conditions can be represented in a spark-ignition engine. It may be seen that the "endgas" (a term which will be used to denote the portion of the still unburned charge which is compressed by the portion that is under combustion), undergoes a primary compression due to the piston, and a secondary compression due to the effect of the combustion released by the electric spark. The total compression of the "endgas" therefore, is of the order of magnitude of the compressions in the Diesel. Any difference between autoignition in the Diesel and the gaso-

line or spark-ignition engines was to be ascribed primarily to the fact that the mixture in the Diesel, contrary to conditions in the case of the gasoline engine, is very poor and far from being homogeneous. The more explosive detonation in the gasoline engine was attributed to the more "simultaneous" (not "instantaneous") ignition of the "endgas." Detonation diagrams that have been shown us presenting "local pressures" double those recorded in the combustion chamber, appeared to confirm the picture we had formed of the process and served to explain the explosive detonation.

Tests on the Engine with Windows

Let us now consider the results recently obtained in our laboratory tests on the engine with windows.

Figures 3 and 4 show the arrangement of the combustion chamber and some combustion diagrams obtained with a rotating mirror. It may be seen that we have followed more or less the method of the French pioneer in the field, Duchene, and of the General Motors. In our test engine the conditions for detonation appear to be ideal. A well-scavenged cylindrical chamber assures a rectilinear propagation of the flame. The possibility of changing the position of the electric spark and of producing two sparks at desired instants at each end of the combustion chamber, permits the flame fronts to be varied and enables very close study of the accompanying light phenomena. In many respects the pictures obtained will be seen to resemble those of Duchene. Besides observing the phenomena in the rotating mirror by the naked eye, a special photographic apparatus was added that permits sufficiently clear photographs to be obtained of the accompanying light phenomena during a single combustion and the simultaneous recording of the pressure (fig. 5). For this purpose we have adapted a high-speed indicator (piezo-electric indicator constructed in our laboratory) that enables the relation to be found between the light phenomena and the pressure. The possibility of employing detonation indicators such as the "bouncing pin," "thermoelectric spark plug," etc., enables the relation to be investigated between the results obtained with these indicators and the light phenomena and pressure. Following are some of the data on the engine that may help fix our ideas: Engine is single-cylinder, four-stroke-cycle, of about 3 horsepower, bore 73 millimeters, stroke 89 millimeters, number of revolutions per minute 1,000. Combustion chamber is in

the form of a vertical cylinder of about 25 millimeters di-
ameter and 80 millimeters height; height of quartz windows,
70 millimeters. utilizable width 4 millimeters. Compres-
sion ratio 8:1. Engine may be supercharged.

Without speaking of the other possibilities offered
by the test engine, I wish to point out the following fact,
namely, that whereas in the normal engine everything pos-
sible is done to suppress detonation, in the case of the
quartz-window test engine, every effort has been made to
maintain the natural character of the detonation.

Results Obtained with the Quartz-Window Engine

Autoignition a Relatively Slow Phenomenon

We shall now analyze the results obtained and shall
see in what respect they furnish us with new ideas on the
phenomena of detonation.

The combustion in our test engine clearly presents
the character of a detonating combustion. First of all
the noise is quite comparable to that of the C.F.R. en-
gines, for example. The bouncing pin and the thermoelectric
spark plug also give us comparable indications. Finally,
the piezoelectric indicator clearly indicates the detonat-
ing character of the combustion.

The first clear results showed that the detonation
(knock) coincided with the appearance of a second ignition
center - an autoignition at the opposite end of the primary
ignition center; that is, the spark. It would seem as if
this autoignition "fears" the proximity of the primary
flame. The "endgas" or portion of the fuel still unburned,
particularly in this engine, is not sufficiently homogene-
ous to produce a "simultaneous" combustion. This is, more-
over, what we should expect since, even assuming perfect
homogeneity of the mixture as far as richness is concerned,
there is no reason for assuming a thermal homogeneity of
this mixture in a combustion chamber of such elongated form.

In the case of figure 5, at the instant of appearance
of the "secondary" flame front, the pressure is of the or-
der of 30 kilograms. The temperature of the "endgas" at
this instant may be estimated to be 550° C., but it is ev-
ident that the temperature may be locally much higher. It
thus appears that the autoignition, which causes detona-

tion in this case, occurs under conditions of pressure and temperature of the order of those encountered in the auto-ignition of Diesel engines. This confirms the opinion we had already expressed on this subject and would explain the linear relation (fig. 1) which we had found between the octane number and the cetene number.

In order to compare a Diesel-engine diagram with a spark-ignition or gasoline-engine diagram, it is evidently necessary to begin by creating comparable conditions. It is necessary, in particular, to take account of the effects of the time factor and of the quality of the mixture, which are different in the two types of engines and which have a great effect on the tendency to autoignition. For this purpose we have compared the diagram of a Diesel engine fed with a fuel of about 50 cetene with the diagram of our quartz-window engine operating on a gasoline of about 25 ce-tene. Figure 6 shows schematically that the two types of engines under the given conditions have the same level of autoignition. What surprised us, however, in the results obtained with the test engine, was the relatively slow character of the combustion due to autoignition. The de-velopment of the second center of ignition was at all points similar to the progression of the primary flame due to the spark.

The "simultaneous" combustion of the "endgas" which we have believed responsible for the knock, thus seems to be reduced to the rather calm development of a secondary cen-ter of ignition. Farther on, in speaking of "knock" and "pink" we shall return to this "calm" character of the det-onating combustion.

We have avoided considering here the chemical charac-ter of the detonation. It was sufficient for us to know the physical character, which we would describe today as the effect of the formation - earlier or later in the cy-cle - of a center of autoignition corresponding to a still relatively slow combustion of the "endgas," but more or less accelerated, according to the character of the fuel. A slight detonation is normal in engines with full charge.

Speed of Propagation of the Flame Fronts

In order to facilitate the explanation, we shall speak of "primary" and "secondary" flame fronts. A computation

of the speeds of propagation permits us to reduce the ap-
parent speed of the fronts to the actual speed of inflam-
mation. It will readily be understood that the upper
flame front, which is supported on the fixed bottom of the
chamber, is propagated with an apparent speed greater than
the lower flame front which is supported on the burned gas
covering the piston head. It will also be seen that in a
simple case the flame front is propagated with an apparent
speed greater than the real speed (speed of inflammation)
because of the expansion of the burned gases behind the
flame front, in much the same way as a boat descends a river
at full power and is simultaneously carried downstream by
the river current.

This is what our analysis shows in figure 5, on which
may be seen how the secondary combustion due to the auto-
ignition thrusts back the primary flame front due to the
spark. This analysis brings out the fact - which is rather
surprising at first, but after all readily understood -
that the velocity of the secondary flame front is practic-
ally equal at each instant to that of the primary flame
front.

We have never been able to make out any speed equal
to the speed of sound, but at most, speeds of 150 meters
per second, and these only in the case of excessive detona-
tion. In the case of slight detonation the speeds do not
attain even half this figure. At the start the primary
flame front is propagated at a speed no greater than 20 me-
ters per second. It would appear that preliminary reac-
tions take place ahead of the primary flame front - reac-
tions the result of which is autoignition. The speeds of
the primary and secondary flame fronts, which are sensibly
equal, increase only very slowly. It appears, however,
that the speeds increase as the reactions become stronger.
Turbulence accelerates the apparent speed in the gaseous
mass but in no way changes the phenomenon which we have
just described.

Nomenclature

We propose to distinguish between "normal" and "abnor-
mal" ignition. "Normal" ignition includes the formation
of the primary and secondary flames and everything that may
be considered as unavoidable in the "normal" operation of
the engine. The "abnormal" ignition includes all the avoid-
able causes in the normal operation of the engine. The "ab-

normal" ignition includes all the avoidable causes in the
normal operation of the engine - for example, preignition
by hot spots.

In exceptional cases, abnormal (avoidable) ignition
may be produced after the spark ignition and the autoig-
nition before the spark ignition. It is for this reason
that we prefer the name "abnormal ignition" for all avoid-
able ignitions. The term "preignition" therefore remains
reserved for all normal and abnormal ignition produced be-
fore the ignition by spark.

With semi-Diesel engines we have even met with cases
of ignition before injection. The diagram shows in this
case, before the injection, a pressure rise caused evi-
dently by a final combustion of the products previously
incompletely burned. This is still another case of "preig-
nition." It is possible for autoignition the become pre-
ignition - that is, abnormal ignition, and conversely.

Practically, the following two cases may be distin-
guished:

A - The fuel does not show any preliminary reaction
     and the speed of the flame fronts remains con-
     stant (fig. 7).

B - The fuel shows a preliminary reaction and the
     speed of the flame fronts finally increases
     considerably.

Actually, case A does show some increase in speed but
always less than case B.

Two stages may be distinguished for the "endgas":

Primary "endgas" behind the primary front, before
    autoignition occurs.

Secondary "endgas," namely, that compressed by the
    primary and secondary flame fronts. This term
    may also be applied to the case of a new auto-
    ignition at one or several points.

Finally, it is possible that the secondary "endgas"
undergoes an apparently simultaneous combustion but our
tests with the window engine appear to indicate that the
secondary "endgas" is burned before attaining this extreme
stage.

Review of some of the special terms for which it is useful to use commonly accepted meanings:

Normal ignition:

Ignition by spark.
Advance (retard) of ignition.
Autoignition.

Abnormal ignition: for example, preignition by hot spots or by autoignition.

Preignition: every ignition before the electric spark or before injection.

Primary and secondary flame fronts.

Real speed of flame front: speed of inflammation.

Apparent speed: speed observed by the eye.

Primary and secondary "endgas."

"Restgas": burned gas not scavenged.

Bouncing pin.

Temperature plug.

Pink.

Knock.

Bumpy running.

Reproducible results: identical results for identical tests.

Problems in Connection with the Indicator

The pressure increases more rapidly than would be expected from the speed of the flame front. This is partly explained by the fact that the number of calories per unit of volume of the "endgas" increases as the pressure increases. At the instant when the primary flame front appears, there may be seen a progressive pressure rise which becomes even more intense at the instant the second flame

front appears. Thus, the "endgas" is progressively burned and more and more rapidly until the last portion disappears — that is, until the instant when the two fronts reunite.

The pressure diagrams show only moderate pressure rises, and this is still another indirect proof of the fact that the speeds of the flames are relatively low and remain much below the speed of sound.

We have not succeeded in demonstrating the existence of extreme local pressures. Invariably when they were recorded on a diagram, we have been able to show that the indicator was at fault. This is an important fact concerning which we should like to obtain some exact information from other experimenters.

Every sudden variation in the pressure rise may cause vibrations of the walls of the chamber and of the charge. In the same manner certain parts of an insufficiently rapid indicator may start to vibrate. Finally, the entire engine and indicator may have received a shock causing seismic vibrations. It is therefore necessary to distinguish at least four types of vibrations: vibrations of the charge, of the walls, of parts of the indicator, and seismic vibrations. The ideal indicator would evidently not show vibrations of the charge. It is very difficult to eliminate the seismic vibrations and those of parts of the indicator. By "choking" the diagram they can be made to disappear, but there is then the danger of "juggling away" the essential vibrations of the gas.

"Knock" and "Pink" — Luminous Waves

We have not observed large luminous effects or large pressure rises at the instant the secondary flame front appeared. There was evidently produced at this instant a rather sharp change in the pressure rise, as occurred somewhat later, when the "endgas" was completely burned. These discontinuities also showed up exactly in the images of the flame. Often, particularly under severe conditions, the first discontinuity — that is, the appearance of the secondary flame front (autoignition) — corresponds to the appearance of luminous waves. When these luminous waves appear, they show up only very vaguely at first, then more clearly as the conditions become more severe.

These luminous waves correspond to pressure waves as our indicator shows (fig. 9). It seems probable that these pressure waves, which are at most three, in our engine, correspond to the noise of "pinking" — quite distinct from the noise of "knocking," which appears to correspond to a vibration of certain parts of the engine. It is difficult — perhaps, even impossible — to distinguish the pinking noise in the engine with windows. If this noise appears at all, it is masked by the knocking noise. The same is true, for that matter, in the case of the C.F.R. engine. The sudden pressure variation would already be sufficient to explain these vibrations. The possibility, nevertheless, should not be excluded that the appearance of autoignition really corresponds to some explosive chemical reaction, since the appearance of the pressure waves is rather pronounced. However, at least in the case of our engine, this explosive reaction would only correspond to a very feeble development of energy.

Besides these very rapid vibrations, it is still necessary to take account of the possibility of slower vibrations. The bumpy running, for example, would correspond rather to torsional vibrations of the crankshaft and of solid members.

It may still be asked how the rough operation caused, for example, by excessive turbulence or by the use of an abnormal fuel, such as hydrogen, may be interpreted. The pressure rise in this case does not show well-pronounced discontinuities except at the end of combustion — a fact which leads us to suppose that there is no preliminary reaction. Apart from the effect of the shock which is to be expected from such a rapid combustion, no detonation properly so-called is observed except perhaps in extreme cases. Figure 10 gives a sketch summarizing what has been discussed.

II. CONSIDERATIONS ON THE METHODS OF DETERMINATION OF

THE RESISTANCE TO AUTOIGNITION

We have attempted to give an analysis of the phenomena of combustion and detonation. We do not claim that it is new or complete, but it does appear to us at present to be somewhat better founded. We may ask whether this analysis will serve as a basis for discovering and passing upon methods of measurements. We shall first speak of methods applying to the automobile.

American C.F.R. Methods - Adjustment of the Methods

On the C.F.R. engine the so-called "research" method
has been used, which consists of first establishing a com-
pression ratio which assures a strong detonation and then
comparing this result with those obtained with the stand-
ard or reference fuels.

In order to check the value of this method for the
automobile, some large-scale road tests were conducted at
Union Town in 1935. In principle, it was a question, in
these tests, of adjusting the method to practice. Two well-
adjusted different methods often give better agreement in
results than two different adjustments of the same method.
The conclusion from the tests at Union Town was that for
automobiles the "research" method was not sufficiently rig-
orous. It was adjusted by adopting the so-called "motor
method"; the r.p.m. was raised from 600 to 900 and the tem-
perature of the mixture, from the ambient temperature to
150° C. Here it was not a question of a new method but
really of a better adjustment to practice of the same meth-
od. It seems that it would have been of advantage to ap-
proach practice more closely still; for example, by fur-
ther increasing the r.p.m. and raising the mixture temper-
ature to a lesser degree.

The Ricardo E.35 Method

We must first present our due respects to the E.35 en-
gine of Ricardo - the classical engine with variable com-
pression ratio. This engine is still in operation and it
must be admitted that this classic method remains one of
the best. It seeks to determine the highest useful com-
pression ratio that a gasoline can advantageously support.
The test conditions are quite acceptable, the measurements
being carried out under a moderate intensity of detonation
and at a reasonable number of revolutions per minute
(1,500 r.p.m.). The principal objection to the method is
not on scientific grounds but on excessive cost. The
large bore of 114 millimeters, possesses advantages in
certain cases, unfortunately not possessed by the modern
small C.F.R. engine. Thus the E.35 engine is still today
the one we prefer at times for attacking the problems of
the large truck engines and airplane engines without com-
pressor.

Method S.30 (Series 30)

The small Ethyl Gasoline Corporation S.30 engine, hav-
ing a compression ratio of 8, and which has almost been
abandoned at present, was quite practical. The method was
not bad. The throttle valve was opened until a normal de-
gree of detonation was obtained — the degree being fixed
with the aid of the bouncing pin. The mixture of standard
fuels was then sought which gave the same results. The
method was simple and reliable.

Standard Fuels

The introduction of standard fuels was certainly a
step in advance. It was Ricardo who introduced them in
1919, in determining his values in toluol. Today the use
of standard iso-octane-normal heptane mixtures has become
general. These products have a slight disadvantage, name-
ly, their sensitiveness to such factors as the temperature
is somewhat different from that of most gasolines. It is as
if measurements were made with a scale which changes its
length with the temperature. Fortunately, the difference
is not great, being at most several octane points. Gener-
ally these standard fuels give entire satisfaction.

Other Methods

What shall be said of the numerous other methods which
have lived through a few years only? They all appear to
have been sufficiently satisfactory, and the question is,
Why did they disappear? The analysis we have made will
help us to find the answer.

We understand, in fact, that detonation occurs in
all engines and any engine will permit us to obtain octane
numbers that may be utilized. Any method for starting the
detonation may be applied: throttle, ignition advance,
cooling temperature, revolutions per minute, or richness
of the mixture. The intensity of the detonation could be
regulated by adding dopes to the fuel. Comparisons could
be made by ear, or by using the bouncing pin or some pres-
sure indicator, or a "temperature plug," or the tempera-
ture of cooling water. The H.U.C.R. (highest useful com-
pression ratio) may be sought, or the maximum power, or

the minimum fuel consumption under certain conditions, or the minimum temperatures of the exhaust under predetermined conditions, etc. Any of these methods may equally well be used.

Factors that Influence the Detonation

We may here add the great diversity of factors that affect the phenomenon of detonation and which must be taken into account. On the part of the engine there is above all, the effect of the temperature of the walls and of the gases, the effect of the pressure, and the effect of the time factor. It may be attempted to separate these effects but it is rather difficult to do so. There is the effect of the catalyzer, for example, of the walls of different temperature and material covered more or less by half-burned products. There is the effect of turbulence, the preponderant effect of the richness of the mixture, and the effect of remaining burned gases. On the part of the fuel are to be considered all the mysterious properties that control the tendency to detonation (including the dopes), all of which react differently under different con-ditions of temperature, pressure, and time. We mention only the effects most in evidence. None of these effects gives us a unique point on a diagram but a series of lines.

It is also necessary to take into account the fact that the condition of the engine is quite variable. A dirty engine, for example, will detonate with a fuel of 80 octane at full charge while the same engine if well cleaned, will give complete satisfaction at full throttle with a fuel of 50 octane. From 80 to 50 is quite a difference — which we would do well to recall when, perhaps, we discuss some day, the chances of increasing the octane value from 64 to 66, for example.

In short, there is no cause for surprise that any single method which provides but a single figure to indi-cate the tendency to detonation, could ever be satisfac-tory for all requirements. On the contrary, it is more surprising that, amidst all this chaos, sufficiently suc-cessful compromises may still be found.

The Object and the Complications Involved

To extricate ourselves from the difficulty, there is
only one way, namely, to begin by making clear to ourselves
the object that is to be attained in these measurements.
The object, evidently, is to measure that which is objec-
tionable in the detonation. The driver of a de luxe auto-
mobile who complains of the detonation in his engine at
full speed, does not, however, have the same object as the
driver of an omnibus who complains of detonation during
acceleration. Theoretically, it would be necessary to ap-
ply different methods for all the different operating con-
ditions of the engine. This, evidently, is impossible.

The Restricted Object Should Be a Compromise

Attainment of the object which we seek being an impos-
sibility, it is necessary to reduce our requirements. We
must make concessions and must compromise. The object then
should be a compromise which appears acceptable to a suffi-
ciently homogeneous group of interests; for example, auto-
mobile builders or other specialists in connection with au-
tomobiles. Therefore, we require a method that approaches
practical conditions and which may easily be adjusted - a
simple, inexpensive and, above all, rapid method that gives
results which may readily be repeated and which, for legal
specifications, even allows decimals to be distinguished
where in practice, only differences in units could be ob-
served. We require above all a unique method, since it will
be necessary to cut short the innumerable objections and
demands to which all compromises are unfortunately subject.
There should be at most two or three methods for two or
three groups of interests whose objects will be too differ-
ent for them to be reduced to a single group. It is then
no longer a question of discussing whether this or the other
known method is better, since no "better" exists; but of
adopting a unique universally applied method, as we have just
pointed out.

It is these conditions that the so-called C.F.R. motor
method, universally recognized for the automobile, should
satisfy. Other variants, no doubt, will be proposed.
There is, for example, a difference between conditions at
full continuous load and conditions of acceleration, often
interrupted and followed by periods of average or zero load.

A better design for the bouncing pin would certainly be welcome. These variants would be of no great importance, however, and we shall not discuss them here.

The "Object" in the Case of Airplane Engines

Aviation yields quite a distinct group of interests. It would therefore be necessary to require these interests to agree as to what they consider an acceptable compromise. They, no doubt, would prefer an engine of about 150 millimeters (6 inches) diameter; air-cooled in a stream of about 200 kilometers per hour (124 miles per hour); supercharged to produce about 10 kilograms (22.05 pounds) mean effective pressure. When they come to consider the actual operation cost of some 250,000 francs a year, they will probably seek to reduce the requirements and end up, for example, by adopting an installation that costs some 25,000 francs a year. The 250,000 francs installation could serve to determine the conditions in practice - supply a standard to which the 25,000 francs installation must conform. Under these conditions it would still be desirable to use a universal engine, like the C.F.R., using a measuring procedure adapted to the requirements of aviation.

The C.F.R. "Aviation" Method (A.B. Ratio Method)

We believe we have succeeded rather well in developing with the C.F.R. engine, a method which we have designated the "A.B. ratio" (allowable boost ratio - that is, amount of supercharge admissible). What, in fact, are the requirements of aviation engines? A high mean effective pressure, a moderate compression ratio, maximum supercharge, high r.p.m., a moderate inlet temperature, and an extremely severe regulation of the richness of the mixture. The automobile is developing in the direction of maximum compression ratios; that is, maximum temperatures and pressures, whereas aviation is developing in the direction of maximum mean effective pressure - i.e., of maximum supercharge. The pilot has before him his manometers, which indicate to him each moment the mean pressure that he could attain. The value in octane determined according to the C.F.R. "aviation" method, will tell him approximately whether his fuel will permit that pressure.

Figure 11 gives the relations between the various factors considered. It is interesting to note that the theoretical mixture is even leaner than the mixture defined by "lean adjustment" (which in practice is called lean mixture). The figure shows the great importance which would be attached to the use of mixtures even leaner than the theoretical, since it would at the same time permit an increase in the power and a lowering of the temperature.

The C.F.R. motor method is very satisfactory up to about 80 octane; beyond that the precision of the readings diminishes and there is less correlation with practice. This method, moreover, does not bring out the erroneous gain in power (up to 50 percent) which can be obtained by supercharging the engine with fuels of 100 octane and more (fig. 12).

An analysis of the causes of this defect would lead us too far from our subject. It is sufficient to say that a series of very complete tests has shown that by employing supercharge in the tests on the C.F.R. engine the exceptional advantages which may be obtained with fuels of 100 octane, may easily be utilized.

We have already said that four other methods could give similar results, the choice of any one being immaterial. Whoever has an engine at his disposal may propose a new method provided he has been able to "adjust" it sufficiently to practical requirements. We repeat that it is a compromise we need — a unique method.

Figure 13 brings out the effect of the factors considered on the fuel consumption. Figure 14 shows the effect of the detonation on the temperature. Figures 11, 13, and 14 particularly, bring out the danger of insufficient control of the richness of the mixture. In approaching a very lean mixture, the temperature and intensity of detonation simultaneously reach a maximum and this condition, evidently, must be avoided.

Practical experience has clearly shown us that for a sufficiently short time the engine perfectly resists the very severe detonations. It is only after some time that the temperature of the cylinder head reaches a dangerous value for the metal and the lubricating oil. The engine would, perhaps, resist even better if the autoignition did not begin to occur earlier as the temperature kept rising. Finally, preignition occurs. Preignition, under these

conditions, is quite a different thing from detonation, and is absolutely disastrous. It leads to pressures and temperatures that simply "demolish" the engine. It is true that the loss in power avoids some of the danger, but in a multicylinder engine this may be ignored when only one or two cylinders are at fault.

Research and Routine

Having indicated what conditions a good method must satisfy for determining the antidetonating values of fuels, it is once more necessary to return to the fundamental question of what is the object to be attained.

Questions may evidently arise with regard to detonation that would require special tests to answer. Let us suppose, for example, that it is required to find the effect of the pressure, or the temperature, or the time on the detonation. It would be misunderstanding us to suppose that the methods we have just described might be used for these purposes. It is necessary to make a distinction between research and routine. For the purpose of research, it is necessary to use different engines and to apply different methods, according to the object which it is proposed to attain. The results may perhaps serve to correct the adjustment of the C.F.R. methods described.

For routine purposes, it is necessary to make use of a definite engine and apply a definite method.

III. COMBUSTION IN DIESEL ENGINES

Although the development of the Diesel engine for aviation purposes is still passing through a difficult period, the problem of weight per horsepower playing a preponderant part, we do not wish to pass over this engine without adding a few remarks.

The problem of combustion in Diesel engines is, above all, a problem of autoignition and distribution. The tendency to autoignition is very well expressed in terms of a cetene number. This number is determined for any engine by ascertaining what mixture of standard fuels gives the same ignition lags as the fuel examined. The differences

in cetene for two different engines are technically neg-
ligible and of less importance than the differences in oc-
tane number that are found with different spark-ignition
engines. The fact should nevertheless be taken into ac-
count that certain engines, like those with separate cham-
ber, are not very sensitive to the quality of ignition,
and hence not suitable as test engines.

If it is true that a high octane number contains a
promise of increased performance of a spark-ignition en-
gine, the same is not true of the cetene number for Diesel
engines. On the contrary, while an increased cetene num-
ber permits easy starting and gives quiet operation, it
generally prevents the attainment of maximum power and best
fuel consumption at full load. We have been able, in fact,
to show that the mixture remained imperfect where too easy
ignition formed a kind of "fire barrage" for the rest of
the fuel during the injection. An increased specific power
evidently requires that a maximum portion of the air charge
shall take part in the combustion, but the fire barrage
prevents good distribution. The increased power is accom-
panied by higher pressures but the fouling of the engine
is reduced. In this case, too, a compromise is imposed.
Recourse to higher cetene numbers, unlike higher octane
numbers, would certainly not lead to an improvement of the
situation.

The quality of ignition of Diesel fuels is measured by
the ignition lag during the normal operation of the engine.
Methods based on a minimum compression ratio or on a mini-
mum starting temperature have shown themselves to be less
suitable in giving repeatable results. It is necessary that
the engine remain clean during the tests.

As in the case of spark-ignition engines, it is prefer-
able to employ mixtures of standard fuels.

As for the distribution, it may be said that it is
mainly controlled by certain factors in the engine design.
Viscosity does not play a part here except in extreme cases,
the ignition quality and the volatility being preponderant
factors. Nevertheless, it is necessary to take into account
the fact that different engines react differently to these
two latter characteristics.

For "research" tests on Diesel engines, it is there-
fore necessary to take different engines and to employ dif-
ferent methods, as we have pointed out for spark-ignition
engines.

In order to pass uniformly on the quality of ignition of a fuel, however, that is, its tendency to autoignition in the Diesel engine, it will be necessary to standardize a single engine and a single method as was done for the spark-ignition engine.

The same arguments we have given in the case of the spark-ignition engine will here also be found. Many methods present themselves that may be utilized in practice, particularly if they approach normal conditions. It is useless to seek any one method that is better than the others. It is necessary to find a compromise. The difficulties lie more in the "adjustment" of the method and in the perfecting of the measuring instruments than in the choice of engine and method. Here again the greatest difficulty is the psychological one of sacrificing something in order to reach a compromise.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.
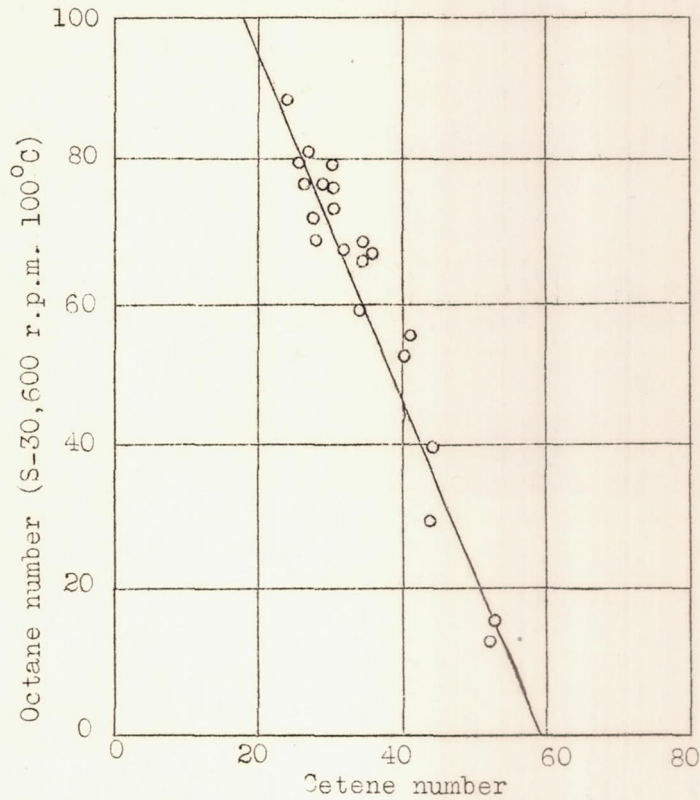
Figure 1.- Relation between octane and cetene numbers.
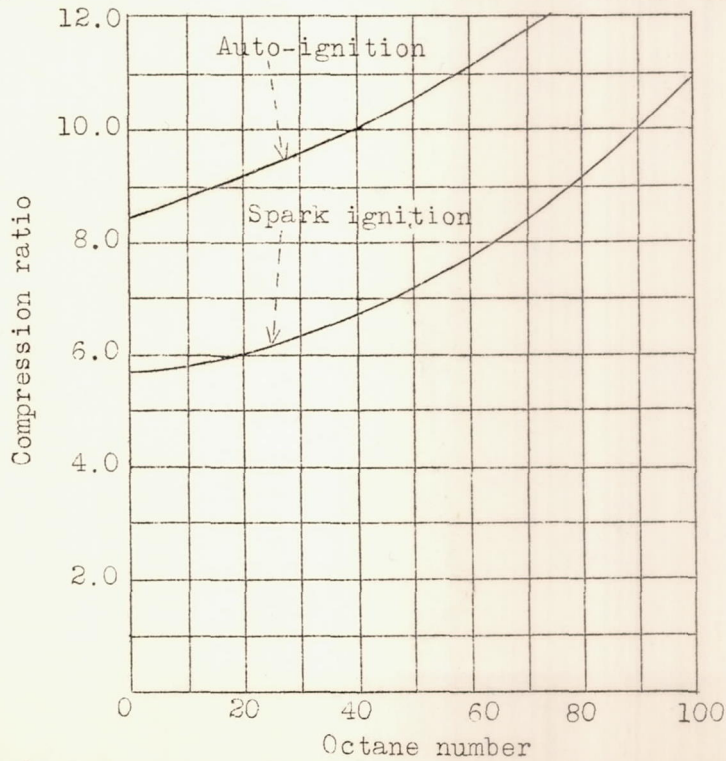
Figure 2.- Ignition with and without spark in a spark-ignition engine.
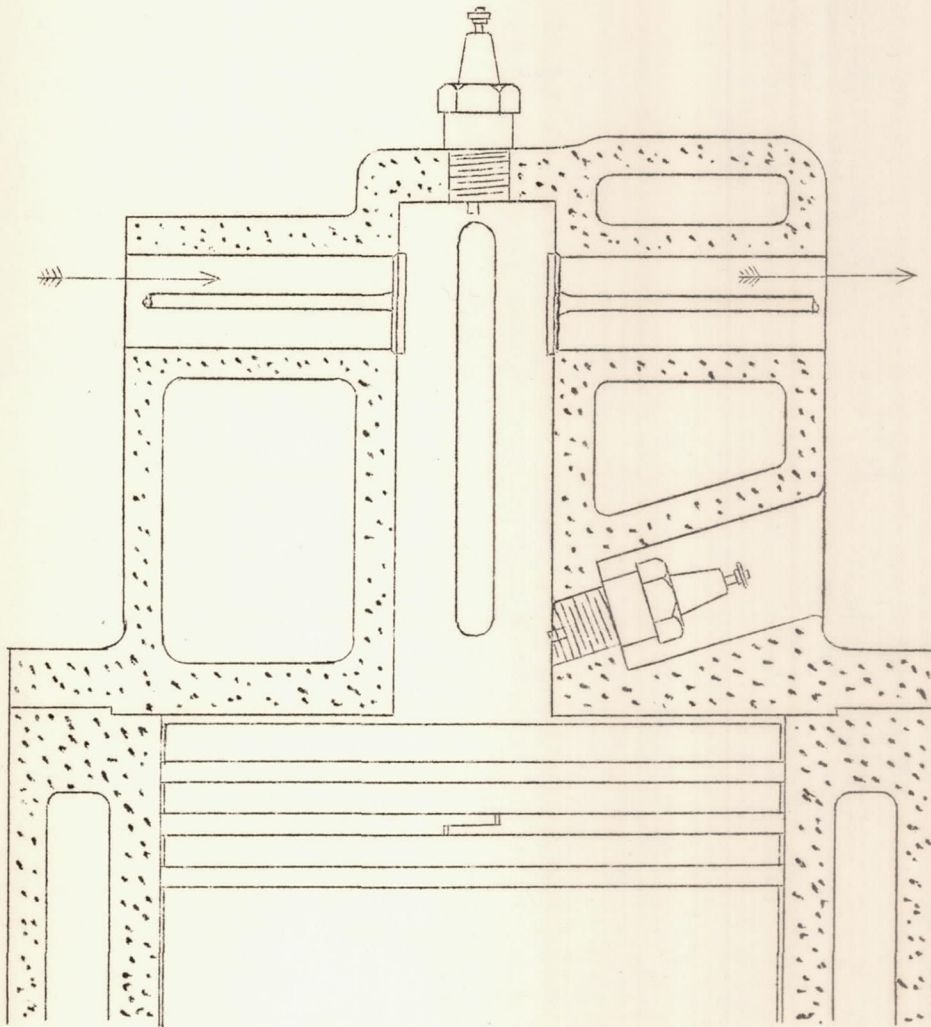
Figure 3.- Combustion chamber of engine with windows.
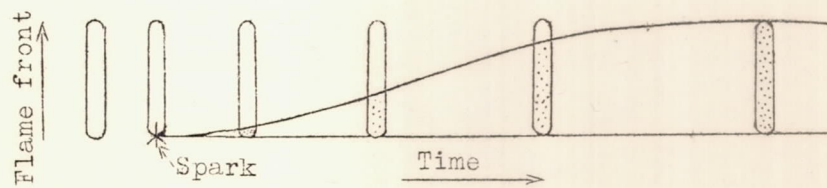
Figure 4.- Flame front travel.
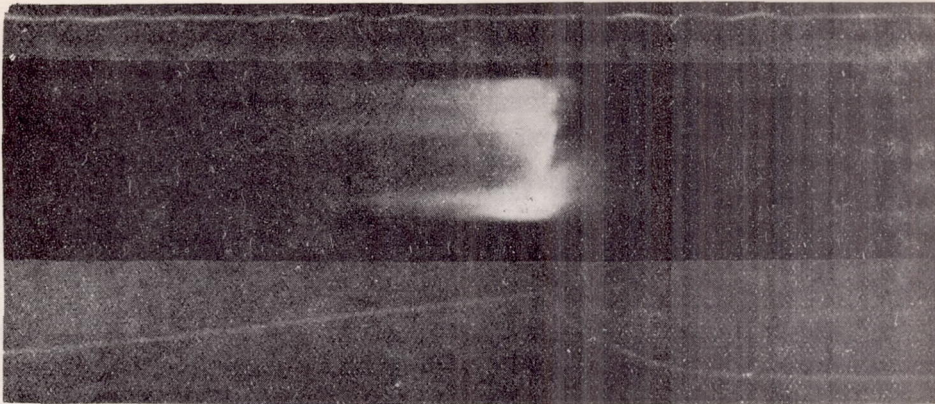
Figure 5.- Detonating combustion and simultaneous pressure variation recorded in the engine provided with windows.
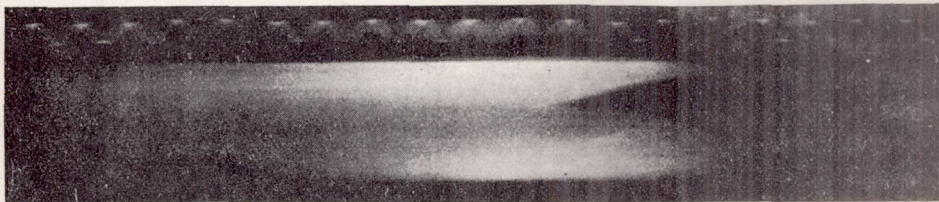
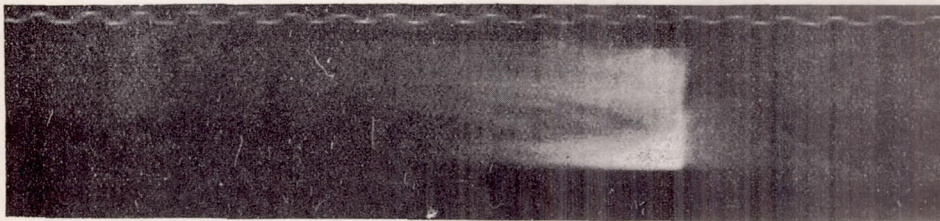Figure 7.- Non-detonating combustion with two flame fronts ignited by sparks.
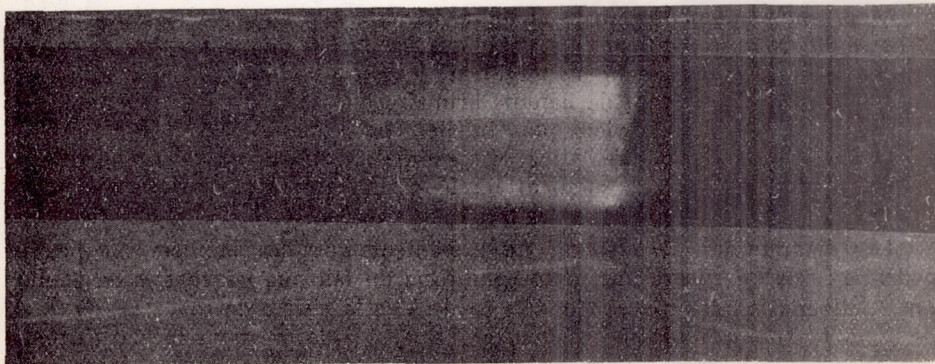
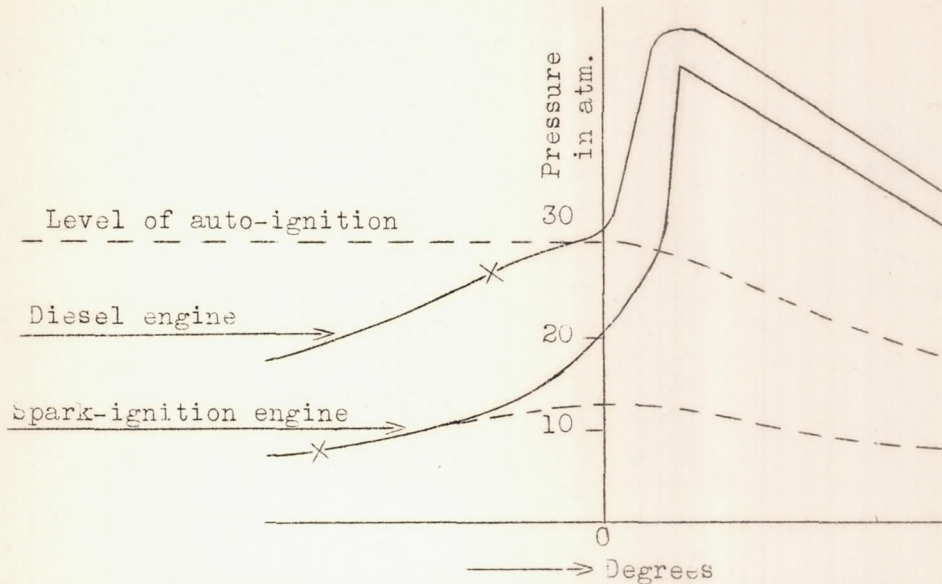Figure 8.- Detonating combustion.

Figure 9.- Luminous waves and pressure waves in a detonating engine.

Figure 6.- Diagrams of a detonating combustion in the engine with
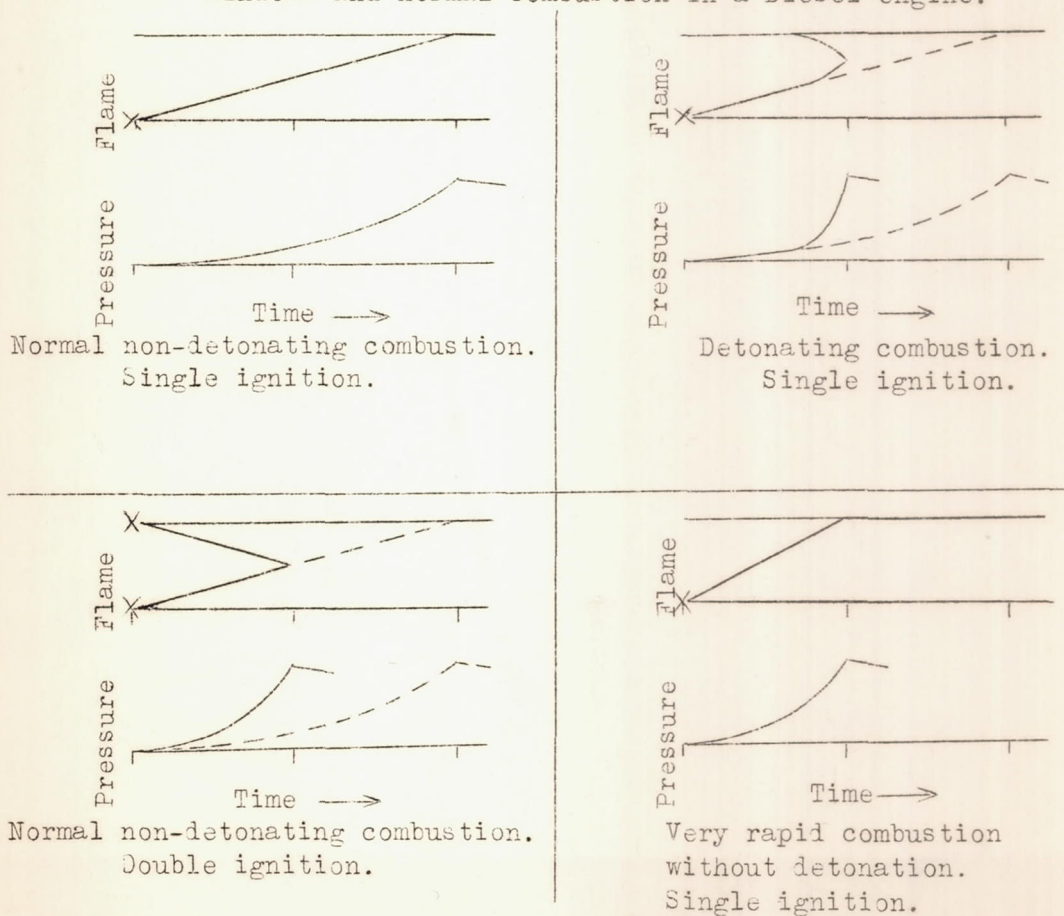windows and normal combustion in a Diesel engine.

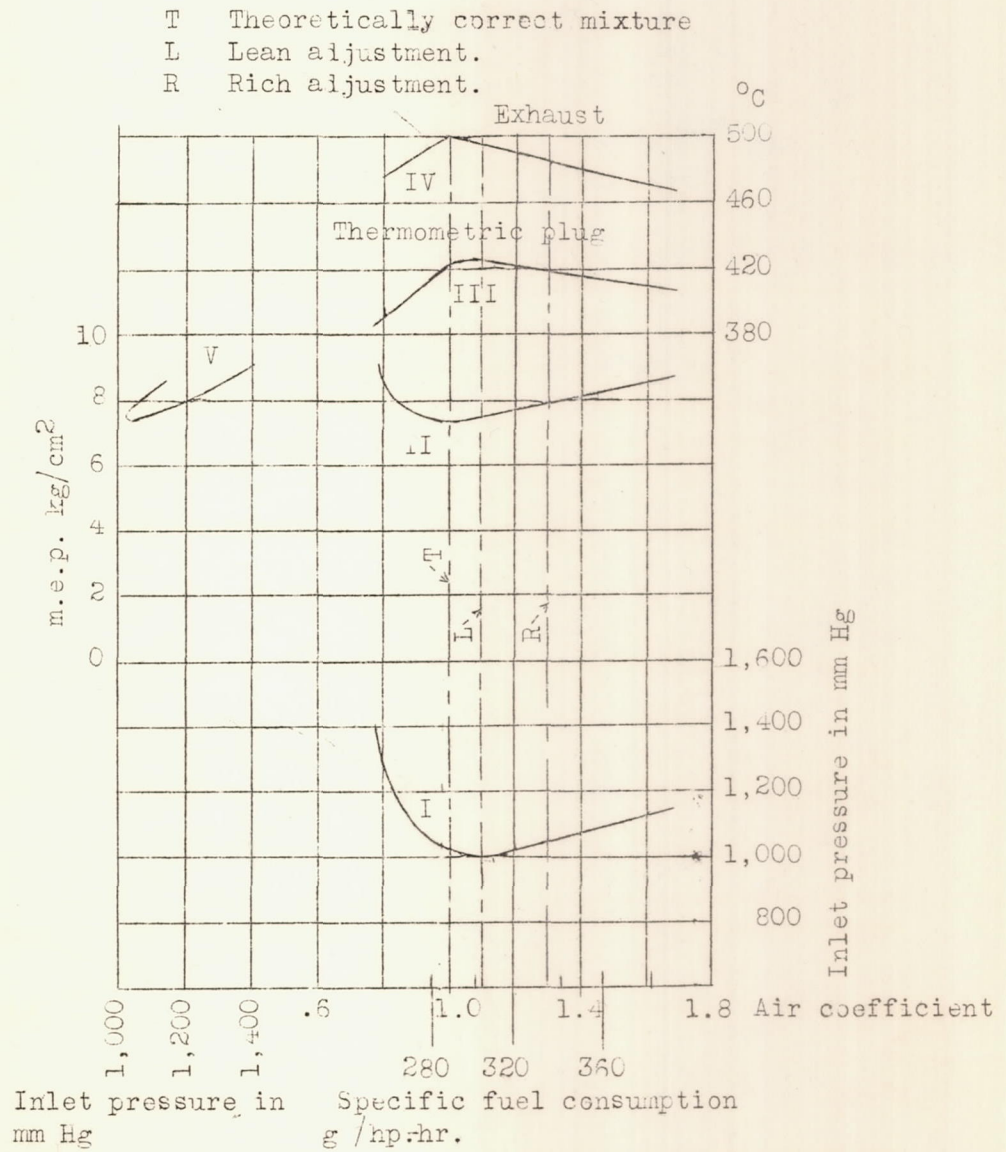Figure 10.- Different forms of combustion with corresponding
pressures.

T   Theoretically correct mixture
L   Lean adjustment.
R   Rich adjustment.

Figure 11.- Relation between the power, richness of mixture, degree
            of supercharge, and temperatures at equal intensity
of detonation.

(Air coefficient = $\dfrac{\text{Weight of air theoretically required}}{\text{Weight of air at disposal}}$
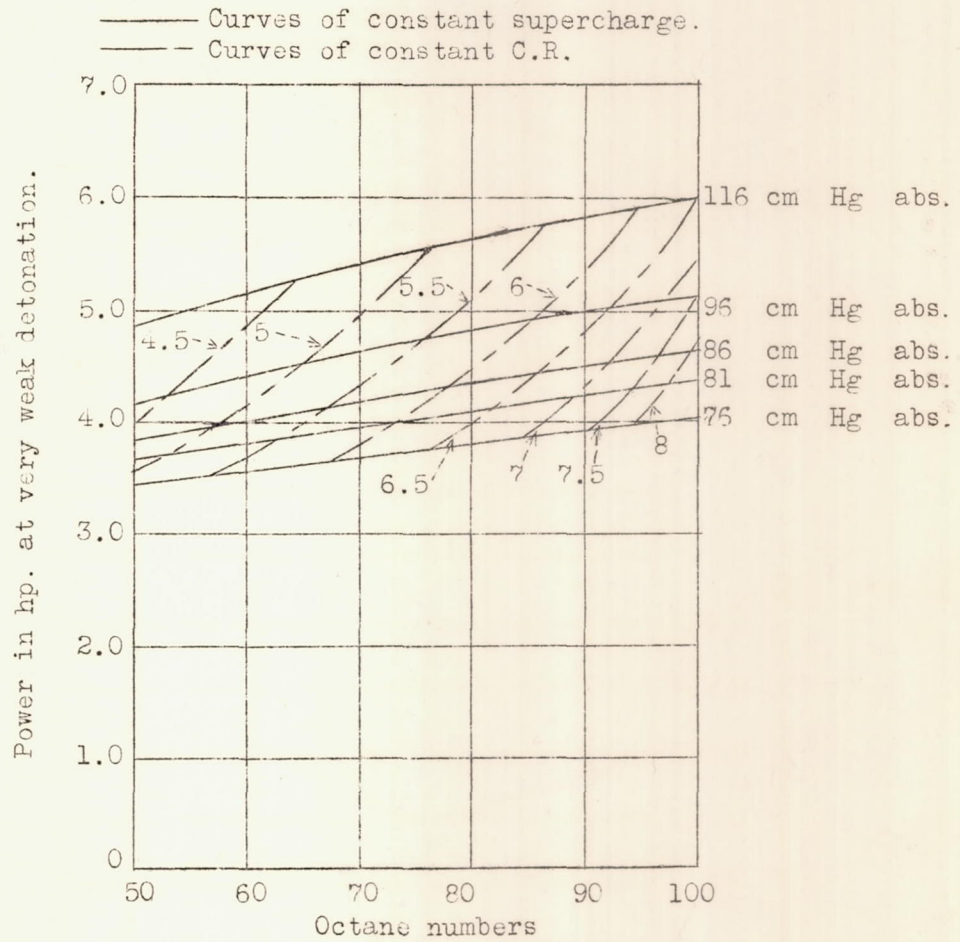
Figure 12.- Relation between octane number, compression
              ratio, degree of supercharge and power for
    the C.F.R. engine.

Curve of light detonation.

— — — Curves of constant inlet pressure.

X   Indicates start of detonation.

Figure 13.- Airplane engine. Relation between fuel
             consumption, mean effective pressure,
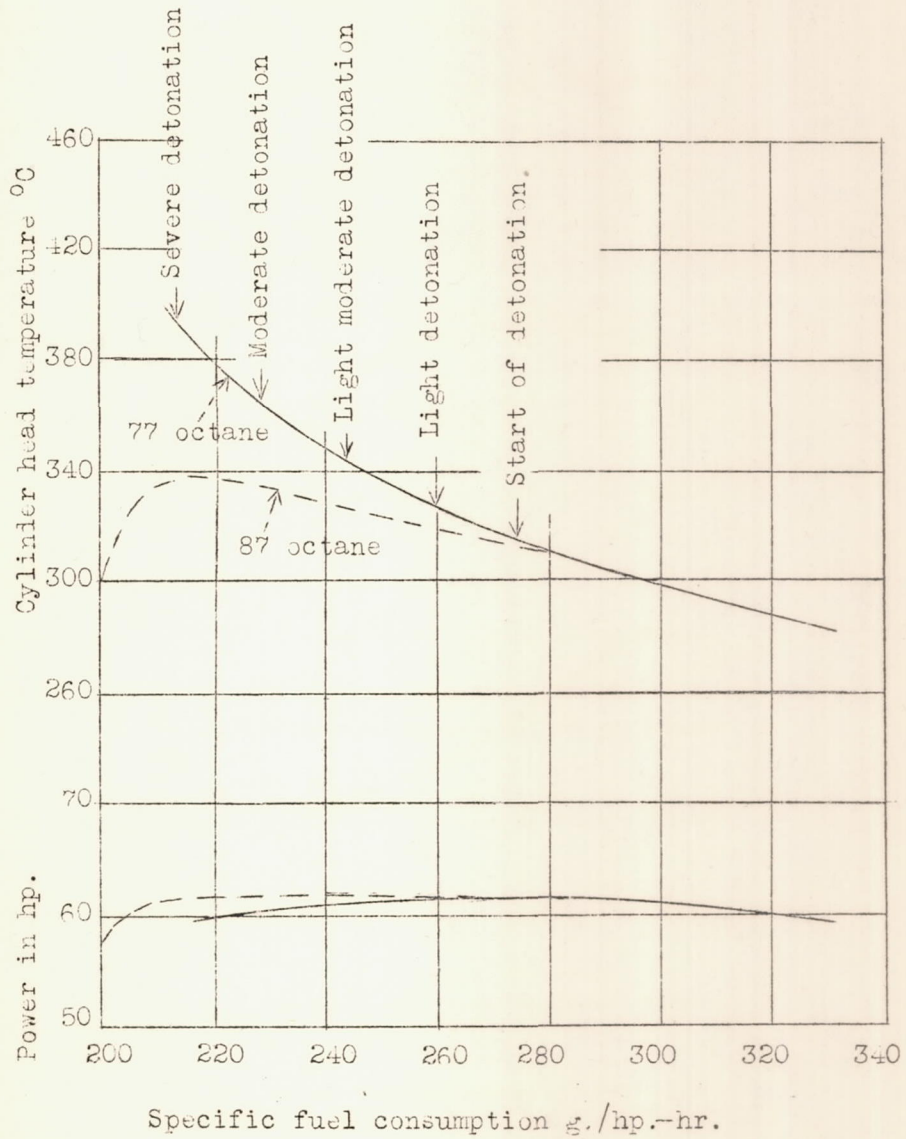and temperature for different degrees of super-
charge.

Figure 14.- Airplane engine. Effect of detonation on the temperature.