THE KNOCK RATING OF MOTOR FUELS

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The knock rating of a fuel is essentially a direct comparison of the intensity of the knock produced by it with that of a standard fuel, these intensities being measured according to a specified procedure. Other methods, such as chemical analysis or bomb explosions, have been found to be inadequate for predicting the knock characteristics of a fuel when in actual service.

The fuels used as a standard of comparison are normal heptane and isoöctane (2,2,4-trimethylpentane), first proposed by Graham Edgar (6). These fuels are pure hydrocarbons and thus can always be duplicated; they are similar to each other and to gasolines in their physical and chemical properties, and when blended can duplicate the range of antiknock qualities of gasolines likely to be used for motor cars, since isoöctane is considerably better and normal heptane poorer in this respect than ordinary motor fuels. Thus blends of these substances establish a standard scale for comparison of any motor gasoline.

In order that the results of different laboratories may correlate, not only is a standard reference fuel necessary, but the engine and the operating procedure must be standardized, because operating conditions affect the relative knock intensities of fuels. Therefore the Coöperative Fuel Research, single-cylinder, variable compression, vapor-cooled engine was designed specifically for this purpose. In order to obtain the knock rating of a fuel this engine is operated at 900 R.P.M. with a mixture temperature of 300°F. and the knock intensity of the fuel measured (1). The blend of normal heptane and isoöctane which matches the fuel in knock intensity under the same operating conditions is then determined, and the fuel is said to have an octane number which is the percentage of isoöctane in the isoöctane–heptane mixture which it matched.

A specified knock intensity is used which is obtained by varying the compression ratio and is measured by means of a bouncing pin. Secondary reference fuels which have been suitably calibrated against normal heptane and isoöctane blends are generally used instead of the expensive primary reference fuels. This method was developed by the Coöperative

Fuel Research Committee, on which are represented the Automotive Industry, the Petroleum Industry, and the National Bureau of Standards, and is the result of a great deal of coöperative work done by individual laboratories throughout the world.

In 1932 the Committee had developed the octane number scale, the knock-testing engine, and a procedure. The procedure at that time differed from the present procedure in that the engine was operated at 600 R.P.M. instead of 900 R.P.M. and the mixture temperature was approximately room temperature instead of 300°F. Also the spark timing was retarded 3.5 degrees with respect to that now in use. This method, now called the C. F. R. research method, was modified because results obtained with it did not correlate with results obtained in service.

ROAD RATINGS

In order to determine what effect actual service conditions have on the knocking characteristics of representative fuels, the C. F. R. Committee conducted in 1932 and again in 1934 comprehensive coöperative road tests at Uniontown, Pennsylvania (11, 10). A method of rating fuels on the road was developed which consists essentially in comparing the maximum knock intensity obtained with the fuel under test to the maximum knock intensity of reference fuel blends, irrespective of the speeds at which they occur. This method differs from that used in the laboratory in that the comparison of knock intensity is not made at any predetermined speed and the intensity is measured by ear rather than by instrument.

These road tests definitely established the fact that the variations in design of different makes of engine or even differences in adjustments in cars of the same make and model were sufficient to cause considerable differences in the relative knock intensities of fuels of different types. It was found that a cracked fuel, when run in one car, might knock with an intensity which was equal to that obtained with a reference fuel blend differing by 8 octane numbers from the blend it equalled when run in another car. Such differences were found even in two cars of the same make and model, showing that major variations in design were not necessarily the cause of these differences.

The knock intensity of any fuel varies with engine speed, but this characteristic is not the same for different fuels in the same engine or for the same fuel when used in different engines. With one fuel it may decrease continuously with increasing speeds, with another it may reach a maximum value at relatively high speeds or it may reach a maximum at two speeds.

Campbell, Lovell, and Boyd have obtained data which clearly illustrate these differences in knocking characteristics and which are reproduced in figures 1 and 2 (5). They ran a 100 per cent cracked fuel and blends of straight-run reference fuels in a 1934 production car, having an ell-head engine with standard spark timing. These data are represented in figure 1, which shows that the reference fuels knocked throughout the speed range, the maximum intensity occurring at about 25 miles per hour and again at 50 miles per hour. The cracked fuel produced the maximum knock intensity at 50 miles per hour, but none at all below 35 miles per hour. The maximum knock equalled that of a 66 octane number reference fuel.

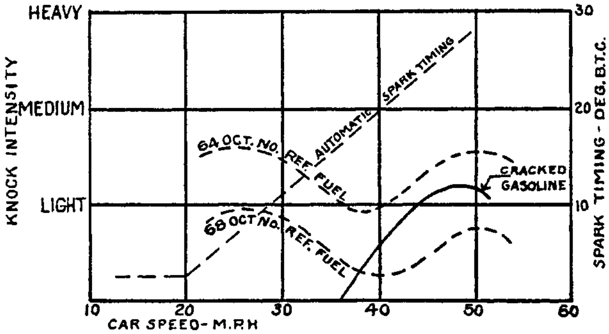

FIG. 1. Knocking characteristics of two types of fuels in a 1934 car (Campbell Lovell, and Boyd (5)).

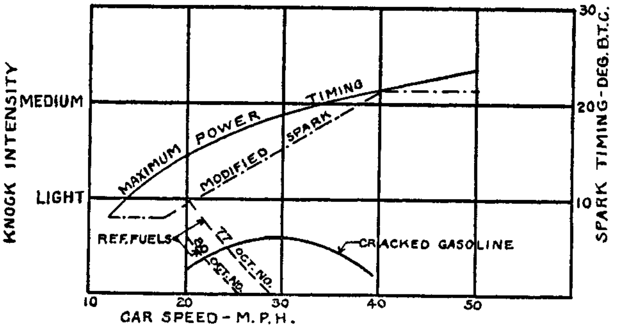

FIG. 2. Knocking characteristics of car represented in figure 1 with modified automatic spark timing (Campbell, Lovell, and Boyd (5)).

The automatic spark advance was then modified by advancing it 6° at low speeds and retarding it at high speeds with the results shown in figure 2. With this change, maximum knock with the cracked fuel occurred at between 25 and 30 miles per hour instead of at 50 miles per hour, and the intensity was decreased slightly. The reference fuels gave a continuous and rapid decrease of knock intensity with increasing speeds, but a 77 octane number blend now knocked with an intensity which equalled that previously obtained with a 68 octane number blend. The cracked fuel equalled in intensity of knock approximately an 80 octane number blend, whereas with the standard spark adjustment it equalled a 66 octane number reference fuel blend. Thus this modification in spark timing in this particular engine caused the fuels to knock at lower speeds; it had but little effect on the knock intensity of the cracked fuel and considerably increased the knock intensity of the straight-run reference fuels, thus increasing the road knock rating of the former from 66 to 80 octane number. Therefore, the road rating of this fuel was changed by approximately 14 octane units because of the comparatively large effect on the reference fuels.

This example clearly illustrates the effect a change in adjustment of an engine may have on fuels of different types. In table 1 are tabulated some of the data obtained at Uniontown showing the effect of different representative engines (11). Column 3 gives the octane number of the straight-run reference fuels which were required for knock-free operation above 15 miles per hour. Column 4 gives the knock intensity obtained with a 100 per cent experimental cracked fuel when used in the same cars. Column 5 gives the knock intensity obtained with a commercial fuel, and columns 6 and 7 give the road ratings of these fuels in each car in terms of octane number of the reference fuel blends which they matched.

TABLE 1

Data obtained with different engines

CAR NO.	TYPE OF ENGINE	OCTANE REQUIREMENT (REFERENCE FUELS)	KNOCK INTENSITY		ROAD RATING	
			Experimental cracked fuel	Commercial fuel	Experimental cracked fuel	Commercial fuel
1	Overhead valve	76–78	Trace	Trace	75	76
2	Ell-head	76–78	Trace	Trace	77	76
3	Ell-head	76–78	Heavy	Trace	64	76
4	Ell-head	76–78	Heavy		64	
5	Ell-head	66–68	Heavy		55	

A study of this table shows that the reference fuels knocked with the same intensity in cars 1, 2, 3, and 4, but the cracked fuel knocked considerably more in cars 3 and 4 than in 1 and 2. Therefore its rating was reduced from about 76 to 64, when run in the two latter cars. When run in car 5 this same cracked fuel knocked with approximately the same intensity as it did in cars 3 and 4. However, the reference fuels knocked considerably less in car 5. Thus the rating was still further reduced to 55, because in this case the reference fuel was affected but not the cracked fuel.

The data in column 3 indicate that cars 1, 2, 3, and 4 require a better fuel than does car 5 if the fuel is of the same type as the reference fuel. However, if the cracked fuel is used, car 5 requires a better fuel than do cars 1 and 2.

The examples cited above are extreme cases illustrating how different conditions affect the relative knock characteristics of fuels of different types. Such large differences are not common. The maximum differences observed during the Uniontown tests with typical commercial fuels were the equivalent of 5 to 8 octane numbers.

Since two fuels which are alike when run in one engine may vary considerably in another, it is obvious that no single laboratory procedure can be made to give results which correlate exactly with results obtained under the variety of conditions to which any motor fuel is subjected in service. Therefore the average of the road ratings obtained on each fuel during the Uniontown tests was considered the road rating of that fuel, and the laboratory method was made to result in ratings which correlated with these average road ratings.

It was found that the laboratory procedure in use prior to 1933 gave results which were generally higher than the average road ratings (11). With commercial fuels this discrepancy amounted to the equivalent of about 3 octane numbers, the maximum being 5 octane numbers. In the case of a 100 per cent experimental cracked fuel it was 9 octane numbers. By changing some of the laboratory engine operating conditions very good correlation with average road ratings was brought about, the principal changes being an increase in speed from 600 R.P.M. to 900 R.P.M., an increase in mixture temperature from approximately room temperature to 300°F., and an advance in spark timing of 3.5 degrees. These changes resulted in the present A.S.T.M. Tentative Method of Test for Knock Characteristics of Motor Fuels (Designation D 357–36T), sometimes called the motor method.

FUEL "SENSITIVITY"

Although the old procedure, now known as the research method, was displaced as a means for obtaining knock ratings for commercial purposes, it was retained for research purposes. By rating a fuel by both methods the susceptibility of that fuel to the changes in operating conditions introduced, as compared to that of the reference fuels, can be determined. For example, if a fuel has the same rating by both methods its knock intensity changed the same as did that of the reference fuel; if its rating differs, then the operating variables have affected its knock intensity more or less than they did the reference fuel. The difference between the ratings of a fuel obtained by the research method and the motor method has been called the "sensitivity" of that fuel (10, 2). The data obtained in the Uniontown tests show that those fuels having the greatest "sensitivity" as measured by the difference between the research method rating and the A.S.T.M. rating also gave the greatest differences when rated on the road. This indicates that the changes introduced in the laboratory engine operating conditions have an effect which is similar to the changes encountered in service.

Although a change in operating conditions changes the rating of a fuel, whether in the laboratory or on the road, this does not necessarily mean that the fuel is sensitive to that change in regard to knock, for it may be the reference fuel which is sensitive. For example, from the data obtained by Campbell, Lovell, and Boyd (5) (figures 1 and 2), it appears that the change in spark timing caused no appreciable difference in the knock intensity of the cracked fuel but did considerably increase the knock intensity of the reference fuel. Therefore, in this particular case a considerable change in rating was caused by an engine variable because the reference fuel was sensitive to this variable in regard to intensity of knock,

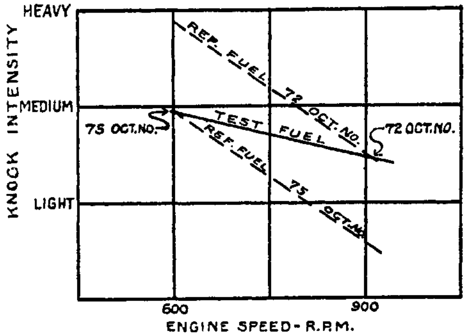

FIG. 3. Effect of speed on knock intensity

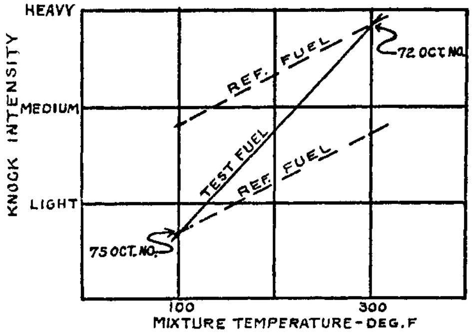

FIG. 4. Effect of mixture temperature on knock intensity

whereas the fuel under test was comparatively insensitive. To determine whether, in general, the differences obtained in rating fuels on the road are due largely to the susceptibility of the reference fuels or of the fuels under test to the changes in operating conditions requires further investigation.

The "sensitivity" of a fuel, as defined by the difference between the research method of rating and the motor method, is determined principally by changing the engine speed and the mixture temperature of the knock-testing engine. The effect of each of these variables is shown diagrammatically in figures 3 and 4. As shown in figure 3, increasing the speed of the C. F. R. engine usually reduces the knock intensity of fuels. If a given increase in speed reduces the knock intensity of a fuel less than it does that of the reference fuel, then the rating of that fuel will be less at the higher speed than at the lower.

As indicated in figure 4, increasing the mixture temperature increases the knock intensity of fuels. Therefore if a given increase in temperature produces a greater increase in the knock intensity of a fuel than it does in that of the reference fuel, the rating of the fuel will be less at the higher temperature. Therefore a fuel which rates lower by the motor method than it does by the research method may do so because it is comparatively sensitive to a change in mixture temperature and/or insensitive to a change in speed. Thus "sensitivity," as determined by the difference between the research method of rating and the A.S.T.M. or motor method, is a measure of the *relative* susceptibility of a fuel to changes in operating conditions, but is not necessarily a measure of the degree to which a fuel responds in knock intensity to such changes.

FACTORS AFFECTING LABORATORY KNOCK RATING

Since an essential factor in insuring the continued validity of the method of knock rating is the maintenance of correlation with service conditions, and since the present method was designed to correlate with the average performance in service of motor fuels in 1932 model cars, modifications in the method may be necessary from time to time because of changes occurring in motor fuels and engine designs. The road tests conducted by the C. F. R. Committee in 1934 showed that the changes made since 1932, when the method was developed, were not sufficient to warrant any modification (10). However, preliminary tests with present-day automobiles indicate that some modification in laboratory procedure is now necessary in order that knock ratings may correlate with average current service conditions. It therefore is pertinent to discuss some of the factors which might readily be changed in the laboratory procedure to produce a change in ratings.

It is well known that there are many variables which affect the knock intensity of a fuel when burnt in an engine. Some of these are differences in design, such as combustion chamber shape or material, compression ratio, and spark plug location; others are variations in operating conditions, such as engine speed, carbon accumulation, atmospheric conditions, mixture temperature, spark advance, and mixture ratios. If these factors had the same effect on the knock intensity of all types of fuels, then they would have no effect on knock ratings. However, these factors change the knock intensity of different types of fuels in varying degrees and therefore anything which affects the detonation of a fuel may affect its rating.

Two of these factors, namely, engine speed and mixture temperature, have already been briefly discussed. Some specific data showing the effect of mixture temperature on ratings were obtained by the C. F. R. Committee (8). The fifteen fuels used in the 1934 Uniontown road tests were rated by twenty laboratories at mixture temperatures of 300°F., 275°F., 250°F., and 200°F. In all other respects the procedure used was the motor method. It was found that antiknock values increase directly with decrease in manifold temperatures and that the mean antiknock value of all the fuels tested rose 2 octane numbers for each 100°F. drop in manifold temperature.

TABLE 2

Fuel ratings by two methods and effect of decrease in manifold temperature on octane number

FUEL	MOTOR METHOD	RESEARCH METHOD	MOTOR METHOD − RESEARCH METHOD (COLUMN 3 − COLUMN 2)	INCREASE IN OCTANE NUMBER PER 100°F. DECREASE IN MANIFOLD TEMPERATURE
1. 100 per cent cracked	70.7	79.9	9.2	2.9
2. California straight-run	71.9	73.0	1.1	0.5
3. Cracked gasoline + tetraethyl lead	74.3	78.8	4.5	2.7
4. Cracked + straight-run + lead tetraethyl	70.8	74.9	4.1	2.5
5. Cracked + straight-run	64.3	67.6	3.3	1.9

In table 2 are listed for five of the fuels tested approximately the difference between the research and the motor method ratings and the increase in octane number occasioned by a decrease of 100°F. in the manifold temperature. The maximum increase was 2.9 octane numbers for a 100°F. decrease in temperature and occurred with a 100 per cent cracked fuel which was also the most "sensitive" of all the fuels tested, as determined by the difference between the research and motor method ratings. However, the next most "sensitive" fuel gave very nearly the same decrease, although the difference between the research method and motor method ratings was only slightly over one-half that of the other fuel. This perhaps indicates that the comparatively large difference between the research and motor method ratings of the first fuel was caused largely by the change in engine speed, and serves to illustrate further that the difference obtained by the two methods of rating is not necessarily indicative of the response of a fuel to a change in operating conditions.

It is a well-known fact that spark advance affects detonation, and, since the effect is dissimilar on different types of fuel, knock ratings may vary with spark timing. Figure 5 shows the effect of spark timing on the knock intensity of three fuels. These data were obtained by Campbell, Lovell, and Boyd, using a single-cylinder engine running at 600 R.P.M. (4). It can be seen that at a 40-degree spark advance fuels 2 and 3 are alike, whereas with the spark retarded to 20 degrees before top center fuels 1 and 2 are alike. Therefore the ratings of these fuels would depend on the spark timing used.

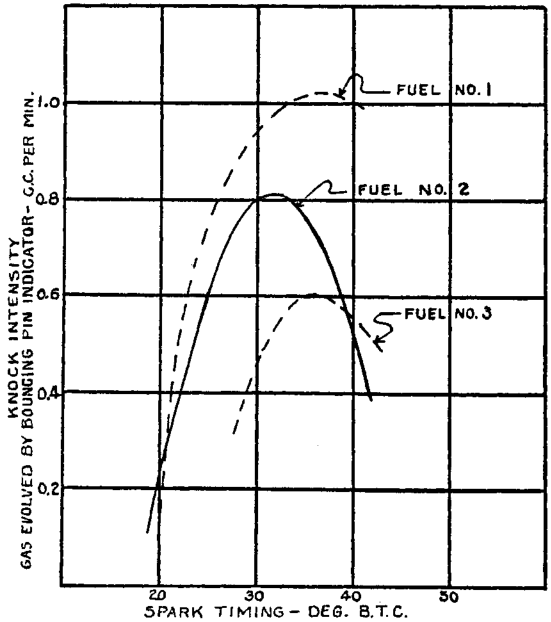

FIG. 5. Effect of spark timing on knock intensity (Campbell, Lovell and Boyd (5)).

The A.S.T.M. procedure specifies a spark timing of 26 degrees before top center when the compression ratio is 5 to 1. This timing is automatically changed with compression ratio by means of a suitable linkage. The effect of changes in this timing and its relation to maximum power and maximum knock intensity at different compression ratios is now being studied by the C. F. R. Committee.

There are many other variables which affect knock and therefore might be used to change knock ratings appreciably. However, the three discussed above, namely, engine speed, mixture temperature, and spark timing, are easily controlled and can be readily varied without necessitating any radical change in engine design or procedure. They can again be used, either singly or in combination, to effect a modification in procedure in order to obtain better correlation with average present-day road ratings. However, as pointed out above, they cannot produce exact correlation with all service conditions nor do they take care of all of the factors involved such as, for instance, the volatility and distribution effects.

Campbell, Lovell, and Boyd have presented evidence that in certain cases volatility, as well as chemical composition, may affect the knocking characteristics of a fuel (5). Because the fuel entering the cylinders of an automobile engine is only partially vaporized, the quality of the mixture delivered to different cylinders or even to any one cylinder during successive cycles is not uniform. Since the average mixture delivered by the carburetor is generally richer than that producing maximum knock intensity, it is likely that most of the knock occurring in an engine originates from the leaner charges, which are probably richer in the more volatile constituents than the original fuel. If the fuel contains a comparatively large proportion of a relatively volatile fuel which is a knock suppressor, such as benzene, then the knock from these lean charges will be reduced, thus diminishing the knock produced by the engine.

In order to confirm this theory, two fuels were prepared which had the same knock rating by the A.S.T.M. method. One of these fuels was a blend of benzene and a straight-run fuel, the other was a blend of ethyl ether and a straight-run fuel. Both benzene and ethyl ether are of high volatility, and the former is a knock suppressor whereas the latter is a knock inducer. As was expected, when these fuels were compared in a car on the road, the ethyl ether blend produced a knock of light to medium intensity, whereas the benzene blend produced no knock at all, although they gave the same knock intensity when run in the single-cylinder laboratory engine where the distribution effects were not present.

FACTORS AFFECTING PRECISION OF RATINGS

There are also variables which at present are not controlled or perhaps not sufficiently so, which may affect the reproducibility of ratings. In order to determine the precision of knock ratings, a group of twenty laboratories, called the exchange group, was formed by the C. F. R. Committee. Three fuels are sent every month to each of these laboratories to be rated. D. B. Brooks, of the National Bureau of Standards, has analyzed 1882 tests on 95 fuels made by this group for the C. F. R. Committee (3). He found the probable error of knock rating to be 0.465 octane unit. Of these 1882 tests, 86.9 per cent showed deviations from the average of less than 1 octane unit, 11.9 per cent between 1.0 and 1.9 units, 1.1 per cent between 2.0 and 2.9 units, and 0.1 per cent over 2.9 units. The types of fuels used were as follows: straight-run fuel with and without lead tetraethyl; aviation fuel with and without lead tetraethyl; straight-run fuel plus cracked fuel; straight-run fuel plus cracked fuel with lead tetraethyl; 100 per cent cracked fuel; two benzene blends; two reference fuels. Of these the 100 per cent cracked fuel showed a distinctly larger error than the others.

The two reference fuels were sent out as test fuels and so were rated against themselves without the knowledge of the operator. Therefore any errors obtained with these fuels were due to experimental errors rather than variations in conditions. If the ratings of these two fuels are assumed to be representative, then perfect technique would reduce the probable error from 0.465 to about 0.25 octane unit.

TABLE 3

Change in octane number for carbon accumulation due to 100-hour operation

FUEL	AVERAGE CHANGE	GREATEST CHANGE	
Straight-run (plus lead tetraethyl)	+0.05	+2.0	−0.8
Straight-run (plus cracked)	−0.3	+0.1	−1.2
Straight-run cracked + lead tetraethyl	−0.8	+1.1	−1.2
100 per cent cracked	−1.2	+0.1	−2.6

The factors, other than experimental error, to which these deviations were attributed, were humidity, knock intensity, and carbon accumulation.

The effect of carbon accumulation as determined by these tests is presented in table 3. These data indicate that fuels containing cracked gasoline respond to carbon accumulation, showing a lower octane number on engines run over one hundred hours without cleaning than do the other types of fuel.

It is well known that humidity affects detonation, increasing humidity decreasing the knock. Its effect on knock ratings is being studied by the C. F. R. Committee, and the results of some tests to determine this effect have been reported by J. R. MacGregor (9). He found that the reduction in knock intensity for a given increase in humidity was approximately the same for a straight-run, secondary reference fuel blend, a benzene blend, and a cracked fuel, all of about 68 octane number. Thus a change in humidity would not affect the rating of these fuels when matched against the secondary reference fuels. However, the effect on knock intensity of an increase in humidity was considerably less with a blend of 67.5 per cent octane and 32.5 per cent heptane and considerably more with a straight-run secondary reference fuel blend containing 2.2 cc. of lead tetraethyl. Thus, if octane–heptane blends were used as reference fuels, the ratings of all the other fuels would be affected. An increase in humidity from 0.002 to 0.023 lb. of water per pound of dry air was estimated to affect the leaded reference fuel approximately 5.7 octane units when matched against octane–heptane blends, and 3.6 octane units when matched against the unleaded secondary reference fuels.

In order to determine whether more rigid specifications regarding the knock intensity at which to rate fuels would result in improved precision, the C. F. R. Committee is also investigating this factor. At present, this is specified in the procedure by prescribing that a rating should be made at one compression ratio higher than that producing incipient knock, which should result in a knock intensity equivalent to that obtained by a 65 per cent blend of isoöctane in 35 per cent normal heptane with the engine set at 5.3 to 1 compression ratio at a barometric pressure of 29.92 in. of mercury (1). Since it is difficult to determine incipient detonation exactly, particularly where other noises are present, and its reproducibility is open to question, the more definite secondary specification has in practice largely superseded the one based on incipient knock.

The results of some tests conducted by the C. F. R. Committee on the effect of knock intensity on ratings were reported by Neil MacCoull (7). For these tests the following fuels were used: a blend of benzene in reference fuel C-9, a commercial gasoline containing at least 0.7 cc. of lead tetraethyl per gallon, and two stabilized, highly cracked gasolines from different sources. These four fuels were rated by the nineteen member laboratories of the exchange group at two compression ratios, one 0.2 of a ratio higher than standard and one 0.2 of a ratio lower than standard. Otherwise, the method used was identical with the A.S.T.M. procedure. The results obtained indicated that increasing the compression ratio increases the knock rating, but, as might be expected, the amount of increase varies with the type of fuel. Thus the maximum increase of the average ratings of all the laboratories occurred with the benzene blend and equalled 2.2 octane numbers. The minimum increase was 0.3 octane number with the commercial fuel. The two cracked fuels gave a difference of 1.1 and 1.2 octane numbers. These differences are not very great, considering that the difference in knock intensity used was appreciable, namely, that produced by a difference in compression ratio of 0.4, whereas the standard knock intensity is such that a reduction of 1 in the compression ratio would reduce the intensity to zero.

In conclusion it may be said that, through the coöperative efforts of members of both the petroleum and automotive industries, a great deal of work, of which only a small part could be taken up within the limits of this paper, has been and still is being done towards establishing a precise means of evaluating the knock characteristics of motor fuels. It is to be hoped that the many factors regarding detonation brought out as a result of this work will also aid in shedding more light on this complex phenomenon of combustion.

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DISCUSSION[1,2]

Bernard Lewis and Guenther von Elbe: It should be possible to interpret the experience in the road service tests mentioned by Mr. Best by a consideration of the ignition regions and ignition lag periods of various types of fuels.

Knocking is avoided if the flame travels throughout the combustion space of the engine in a time which is shorter than the ignition lag time of the last part of the charge to burn. The ignition lag of a given fuel-air mixture is, among other factors, a function of temperature and pressure. The lower part of the accompanying figure contains typical curves of equal ignition lags in a temperature-pressure diagram (Townend). The actual

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[2] Received September 25, 1937.

position of these curves is influenced by engine design, but some such set will be valid for a given engine. Keeping the spark timing constant and assuming constant intake pressure and mixture composition, we shall confine ourselves mainly to the variation of the temperature of the compressed unburned charge with engine speed. This relation depends on design factors. It will be assumed that the temperature increases somewhat with engine speed, as shown in the upper part of the figure. Measurements on a C. F. R. engine have shown that the temperature goes through a maximum (Seeber: Dissertation, Breslau, 1932; see also Philippovich: Z. Elektrochem. **42,** 472 (1936)). While we have no further knowledge of this relation, the assumed dependence in the upper part of the figure will suffice to illustrate the possibilities of explaining the observed relationships between engine speed and knock.

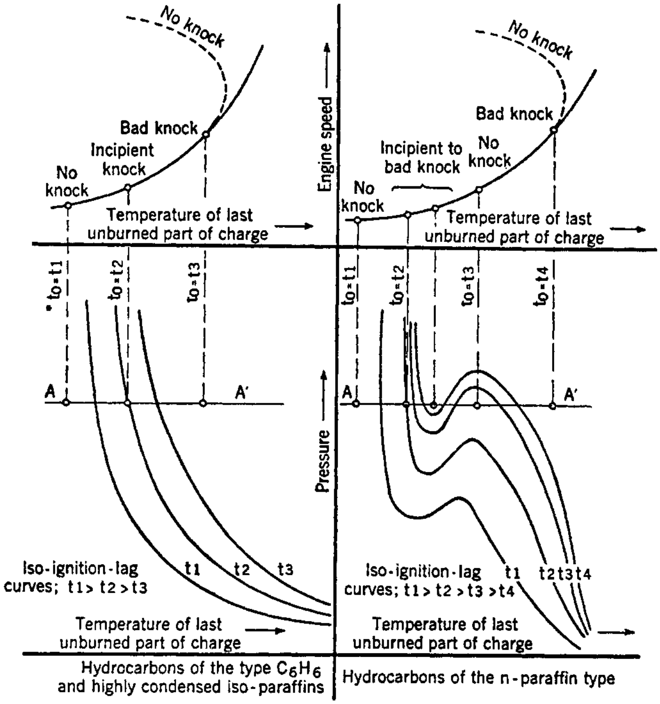

FIG. 1. Relation between knock, fuel, and engine speed. t_0 = time required for normal combustion.

Let us, for example, take the experience of service tests that a cracked fuel showed one region of knock at high speeds and a straight-run fuel two regions of knock, one at low and the other at high speeds. The behavior of the cracked fuel may be understood from the left-hand side of the figure.

Let us assume that a pressure corresponding to the line AA' is reached in the last part of the charge. As the engine speed increases the temperature increases and the time, t_0, required for normal combustion decreases (probably mainly owing to turbulence). Three iso-ignition-lag curves are shown with lag periods corresponding to $t_1 > t_2 > t_3$. If $t_0 = t_1$ at the temperature shown, the flame will travel throughout the combustion space in a time shorter than the ignition lag and no knock will result. When, on increasing the engine speed, $t_0 = t_2$ at the temperature shown, there will be incipient knock, since the time of flame travel is just equal to the ignition lag. On further increase of the engine speed, the time required for normal combustion becomes longer than the ignition lag, the discrepancy increasing with engine speed, resulting in an increase in the severity of the knock. If the temperature–engine speed curve goes through a maximum, the knock will decrease again in severity and finally disappear. By the same procedure, it is easily seen that straight-run fuels which have the peculiar peninsula-shaped iso-ignition-lag curves shown in the right side of the figure should exhibit two knocking regions, one at low and the other at high speed.

Changes in spark timing shift the line AA' to other positions and change the position of knock with respect to engine speed accordingly, spark advance increasing the knocking tendency and spark retard decreasing it.

Although the foregoing outline is admittedly crude, it nevertheless is suggestive of the direction in which future research might move in order to find improved methods of rating fuels. The crux of the problem is the separation of pure fuel factors and engine factors. Although the present analysis is partly hypothetical, it is not impossible that it accomplishes this separation to a satisfactory degree. It need only be assumed that the iso-ignition-lag curves are not very different in engines of the same type. This is a matter for experimental test. If this is so, then the lower part of the figure represents essentially fuel characteristics and the upper part engine characteristics. Fuel rating would then consist, in principle, in the determination of iso-ignition-lag curves. The sets of curves for two given fuels may actually cross each other. Since that fuel is better whose ignition lag curves lie farthest to the right in the figure, it is evident that fuel A may be superior to fuel B under one set of engine conditions, and inferior under another set of engine conditions. Having established the engine characteristics as is shown, for example, in the upper part of the figure, it should become possible to predict the better fuel under various service conditions.

F. L. GASTON (Shell Petroleum Corporation, St. Louis, Missouri):[3] Mr. Best makes the statement that the sensitivity of a fuel does not neces-

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[3] Received September 18, 1937.

sarily indicate the response in knock intensity to any variable. One of the difficulties of engine research is that a change in one variable frequently causes an unavoidable change in another, and hence the various factors involved often cannot be studied one at a time.

The research method minus motor method sensitivity involves sensitivity to air intake temperature, to jacket temperature, and to speed. In some experiments which we made some time ago, the sensitivity to jacket temperature was found to be nearly twice as great as the sensitivity to intake temperature. However, raising the intake temperature reduces the weight of air drawn into the cylinder on each stroke and hence the tendency to detonation. When the results were corrected to the same volumetric efficiency, it was found that intake temperature was more effective in reducing the knock rating of temperature-sensitive fuels than a similar increase in jacket temperature, as one would expect.