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COMMERCIAL DEDUCTIONS FROM COMPARISONS OF GASOLINE AND ALCOHOL TESTS ON INTERNAL-COMBUSTION ENGINES

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By Robert M. Strong.

INTRODUCTION.

The following report is a summary of the commercial results which were obtained from 2,000 tests conducted by the technologic branch of the United States Geological Survey at St. Louis, Mo., and Norfolk, Va., in 1907 and 1908, under the technical supervision of R. H. Fernald, engineer in charge of the producer-gas section. The tests dealt primarily with gasoline, forming part of the investigation of mineral fuels provided for by acts of Congress. To determine the relative economy and efficiency of gasoline it was compared with denatured alcohol. The tests, many of which were undertaken in connection with work for the Navy Department, supplemented, to a certain extent, the work of previous investigations, but only so far as was necessary to emphasize some of the more important points and to lead up to the defining of conditions required for the economical use of gasoline and alcohol.

In order to determine and eliminate the affecting engine conditions as far as possible, the investigation was commenced by making comparative gasoline and alcohol tests on the same engines. These tests were repeated on other engines of approximately the same size and speed, having different degrees of compression, different methods of governing, and different carburetors. The final report will include much material that may be of use in engine design, but that side of the investigation was not pursued any further than was necessary to obtain the best possible results for alcohol and for gasoline with the engines at hand, and to prove that the minimum fuel-consumption rate for each could be obtained in approximately the same manner. The effects of engine and of operating conditions both have a bearing on the commercial deductions but will be discussed only in a general way at this time.

DIFFERENCES IN ENGINES.

GENERAL STATEMENT.

Gasoline and alcohol engines are built and operated on exactly the same principles, and the action of the two fuels is relatively the same. Explosive mixtures of the vapors of gasoline and of alcohol with air are formed in the same manner, and the subsequent burning of these explosive mixtures in the engine cylinder takes place in a similar way and with similar results.

GASOLINE ENGINES RUN WITH ALCOHOL.

Almost any gasoline engine with a well-designed carburetor will run as well with alcohol as with gasoline, from the standpoint of operation, except for a difference in ease of starting and in certainty of operation at low speeds. Under conditions requiring widely varying speeds the engine is less certain to operate satisfactorily at very low speed when alcohol is used, unless some special adjustment is made. The only change required for the use of alcohol in a gasoline engine, if any, is in the size of the fuel passageways. The fuel needle valve must be capable of being opened twice as wide for alcohol as is required for gasoline, and the spray nozzle must not be restricted to just the size that is required to supply the needed quantity of gasoline. The fuel passageways in a carburetor can usually be easily drilled out, and so far as producing power at constant speed is concerned the engine will be just as serviceable with either fuel. This change need not be such as to affect the consumption of gasoline, but with this change alone the consumption of alcohol will be from one and a half times to twice as much as the consumption of gasoline for the same power.

SPECIAL ENGINES FOR ALCOHOL.

By using alcohol in an alcohol engine with a high degree of compression (about 180 pounds per square inch above atmospheric pressure—much higher than can be used for gasoline on account of preignition from the high temperatures produced by compression), the fuel-consumption rate in gallons per horsepower per hour can be reduced to practically the same as the rate of consumption of gasoline for a gasoline engine of the same size and speed. The indications are that this possible 1 to 1 fuel-consumption ratio by volume for gasoline and alcohol engines will hold true for any size or speed, if the cylinder dimensions and revolutions per minute of the two engines are the same.

An alcohol engine is as adaptable to commercial requirements as a gasoline engine, except that with the present types of carburetors the same increased difficulty in starting and in operating at very low speeds is experienced as for a gasoline engine when alcohol fuel is used. The adaptability of alcohol is such, however, that this difference, which is due to ineffective vaporization, is not necessarily permanent.

When alcohol is used in a gasoline engine with the maximum degree of compression for gasoline, the available horsepower of the engine is increased about 10 per cent. An alcohol engine with the maximum degree of compression for alcohol will have an available horsepower 30 per cent greater than a gasoline engine of the same cylinder size, stroke, and speed. Owing to the higher explosion pressures, however, an alcohol engine should be built heavier than a gasoline engine, but the weight per horsepower may be less.

ALTERATION OF GASOLINE ENGINES.

Some gasoline engines may be so changed that a sufficiently high compression pressure is secured to make it possible to reduce the consumption of alcohol in gallons per horsepower per hour to an equality with that for gasoline before the engine was changed; the change, however, precludes the further use of gasoline, as it can not be used satisfactorily with compression pressures much in excess of 70 to 75 pounds per square inch above atmospheric.

The degree of compression may be most easily changed by lengthening the connecting rod, which changes the position of the piston at the extreme end of the compression stroke. This can only be done, however, in an engine which is not counterbored and in which the shape of the clearance space is such that the piston will not strike the cylinder head or valves. The type of connecting rod usually used for stationary engines can be lengthened very easily by putting liners between the crank-pin end of the connecting rod and the crank brasses. This makes it possible to adjust the degree of compression to whatever fuel it is desired to use with but little trouble.

If the cylinder is counterbored, or if there is not sufficient room at the head of the cylinder to allow the piston to travel back far enough to increase the compression pressure to the amount desired, a new cylinder head should be cast with smaller clearance space. Attaching plates to the piston or cylinder head is seldom, if ever, satisfactory. The arrangement of the valve-actuating mechanism often determines the position of the valves, which may be such that a small enough clearance space can not be secured without almost an entire redesign of the engine. Furthermore, with the increased compression pressure required for the economical use of alcohol, the maximum pressure from explosions or combustion will increase and will be as high as 600 or 700 pounds per square inch for maximum load when the compression is raised to 180 or 200 pounds per square inch above atmospheric pressure. The ordinary stationary engine, especially the horizontal type, is not usually built heavy enough to withstand such pressures continuously; hence, while it may be quite possible to raise the compression of a gasoline engine sufficiently to convert it into an economical alcohol engine, it is not always advisable to do so. This is especially true if the difference in cost of fuel is a comparatively small consideration, as is often the case.

EFFECTS OF FUEL QUALITY.

MIXTURES OF GASOLINE AND ALCOHOL.

The increased difficulty of starting an engine with alcohol and the increased uncertainty of operation under variable speed conditions has suggested the use of gasoline and alcohol in a double carburetor, which mixes the vapors or sprays of the two fuels with air in the usual manner. Tests on two similar engines having different degrees of compression were made with such mixtures. For the two engines 26 and 21 tests were required to obtain the best time of ignition and best mixture quality (as regulated by the fuel needle valve and auxiliary air valve) for 7 different proportions of gasoline and alcohol. The results obtained are not as conclusive for the tests with the higher degree of compression as might be wished on account of affecting engine conditions which were known and recorded but not eliminated. The results of these tests, which will be given in full in the final report, indicate, if rightly interpreted, that the maximum thermal efficiency for mixtures of gasoline and alcohol will vary from that for alcohol alone to that for gasoline alone, when the best degree of compression is used in each case; and that the total fuel consumption will not be less than the minimum for either fuel alone and will depend on the limiting degree of compression for each different proportion. If this be true, there is no advantage in using gasoline and alcohol together except for starting and operating under conditions of variable speed; and these advantages should be obtainable through some other means, such as more suitable design of induction passageways and carburetor. Moreover, the use of gasoline in any appreciable quantity does away with many of the advantages that are obtained from the use of alcohol alone, such as safety and absence of disagreeable odors.

GASOLINE WITH A SPRAY OR JET OF WATER.

The fact that the limiting compression pressure for gasoline and alcohol used together was always greater than for gasoline alone suggested that possibly by substituting water for alcohol and so increasing the limit of compression a corresponding increase in thermal efficiency for gasoline could be obtained. Following this suggestion, tests were first made on a gasoline engine with various proportions of gasoline and water. So far as possible the best results were obtained for each given proportion, from all gasoline to as much water as gasoline, but no change in the thermal efficiency or rate of consumption of gasoline could be made; this result showing that the effect of the water, if any, was balanced. Since higher compressions could be used, depending on the proportion of water, a similar set of experiments was made with one of the alcohol engines in which the compression pressure was about 130 pounds per square inch. Again the thermal efficiency could not be increased or the consumption rate decreased to values better than the best obtained for gasoline alone in a gasoline engine. For the two engines 28 and 23 tests were required to determine the best possible results for each percentage of water used; but the results are not conclusive, for there is a question whether the particular engine used for the latter tests, with the higher degree of compression, was free from conditions of construction that affected the best results obtainable. Details of these tests, which have been worked up in full, are to be given in the final report and will afford much information to anyone interested in carrying the investigation further.

In general, the introduction of a small quantity of water with the fuel will prevent preignition from too high compression or overheated parts in the clearance space. The heavy explosion pound often obtained in a gasoline engine operating under maximum load may be entirely eliminated and the running of the engine made much quieter and smoother by using a small quantity of water. The shock and wear of moving parts is thus obviously reduced. If the water contains any grit, however, the cylinder and piston will soon become scored; hence ordinarily it is not advisable to use a spray of water continuously with the air or fuel. The amount of cooling water required to keep the cylinder walls at a given temperature is diminished very noticeably when as much water as gasoline is taken into the cylinder, and the effect of smaller quantities of water is proportional.

ALCOHOL OF DIFFERENT STRENGTHS.

We are not limited to the use of denatured alcohol, which is about 90 per cent ethyl alcohol, so far as the engine is concerned. Even 50 per cent alcohol can be used, though not very satisfactorily. With this grade an engine is hard to start and is uncertain in operation; that is, the operating conditions are limited. The thermal efficiency decreases rapidly with increased dilution. The rate of decrease of the thermal efficiency with decrease in percentage of alcohol, however, is not constant, but is more and more rapid as the alcohol becomes more dilute. From 94 per cent to 80 per cent alcohol, however, the consumption of pure alcohol is about the same, and the total consumption is almost directly proportional to the increase in percentage of water.

The maximum power of the engine also decreases as the alcohol is diluted, but, as is the case with the thermal efficiency, the percentage of decrease with dilutions between 94 and 80 per cent is negligible. When 50 per cent alcohol is used, however, the maximum horsepower of the engine is only 72 per cent of that for 94 per cent alcohol. Less cooling water is required for the engine cylinders with alcohol than with gasoline, and when the alcohol is diluted with water a further reduction is made in the required quantity of cooling water, the effect being similar to that produced when water spray is taken into the cylinder with the mixture of gasoline vapors and air. When 50 per cent alcohol is used, scarcely any cooling water is required.

Full details of the tests from which the above results were obtained are to be given in the final report. Some of the data are very interesting, including indicator diagrams from two sets of experiments with different carburetors. One set of 15 tests was made with a double carburetor, with which the sprays of water and alcohol were mixed. For the other set of 31 tests previously diluted alcohol was used in a special carburetor. The best results for 5 and 6 different percentages of dilution, respectively, were determined. These tests were made on a gasoline engine with a considerably lower degree of compression than that found best for 94 per cent alcohol. No attempts to use higher degrees of compression for the more dilute alcohol were made. The results are conclusive as far as they go. They probably would not be different had a higher degree of compression been used; but, be that as it may, the commercial significance of the results as obtained lies in the fact that if 80 per cent alcohol can be manufactured for 15 per cent less per gallon than 90 per cent alcohol it becomes a commercial advantage to use the lower grade, provided the difference in cost of handling the greater bulk does not offset the gain in cost of manufacture. It is even possible that the use of 70 per cent alcohol or lower grades will prove to be cheaper; but the use of these more dilute alcohols is limited to a certain extent by the difficulty of starting an engine using them and by the increased uncertainty of operation, especially under conditions of variable speed. Adaptability must be taken into account when comparing fuels.

RELATIVE ADAPTABILITY OF GASOLINE AND ALCOHOL.

Different properties limit the availability or determine the adaptability of liquid gasoline and alcohol and their combinations for use in internal-combustion engines of existing types. Gasoline is more volatile than alcohol, and the heat of combustion of a pound of gasoline is considerably greater than that of a pound of alcohol. The weight of air theoretically necessary for complete combustion of a pound of gasoline is different from that for alcohol, but the theoretical heating values of a cubic foot of gasoline vapor and air and a cubic foot of alcohol vapor and air, with just sufficient air for complete combustion in each case is very nearly the same—about 80 British thermal units. Further than this but little is positively known about the properties of the working mixtures of alcohol or gasoline vapors and air, except that the pressure to which differently proportioned explosive mixtures of air and vapors of either fuel can be compressed without preigniting in the engine varies, and that an explosive mixture of alcohol vapor and air can be compressed to over twice as high a pressure as an explosive mixture of gasoline and air before self-igniting (preigniting in the engine).

Mixtures of air and fuel vapors, or sprayed fuel, are delivered to the cylinder of an engine, mixed with the remaining hot products of combustion, and subsequently burned. Differences in the homogeneity and intimacy of this ultimate mixture, in the limit of excess of air that can be used without the mixture becoming too dilute to fire and in the rate of flame propagation, may each affect the completeness of combustion, and though the mixture quality be relatively the same alcohol may burn more completely than gasoline, or vice versa. The specific heat of the burned or burning charge may also be different for alcohol and for gasoline mixtures, thus changing the theoretical basis of comparison, and may also affect the rate of heat loss to the cylinder walls. But be all these things as they may, the ultimate effect is such that alcohol can be used a little more efficiently than gasoline, even in the same engine with the same degree of compression—that is, more efficiently with respect to the percentage of available heat that is transformed into useful work, but with equal efficiency with respect to the quantity of fuel consumed when the best degree of compression for each is used.

Considering only the heating values of gasoline and alcohol, it is obvious that, if other factors are equal, the relative consumption of alcohol and gasoline will be inversely proportional to their respective heating values. The low heating value of denatured alcohol, which corresponds very closely to 94 per cent by volume ethyl alcohol, will average about 10,500 British thermal units per pound, while the low heating value of 0.71 to 0.73 specific gravity gasoline will average about 19,100 British thermal units per pound. The comparison gives a consumption-rate ratio of 1.8 to 1 by weight for a thermal efficiency ratio of 1 to 1. In actual operation, however, where gasoline and alcohol were each used in the same medium-sized (10 to 15 horsepower) stationary gasoline engines without change of compression or speed, and the operating conditions, including load, were limited to the best possible for each fuel, a ratio of alcohol consumption to gasoline consumption in pounds per brake horsepower per hour was obtained as low as 0.98 to 0.59, equivalent to 1.66 to 1 by weight, or 1.45 to 1 by volume, with a thermal efficiency ratio of 28 to 26 per cent (based on the low heating value and indicated horsepower), or 1.1 to 1. By raising the degree of compression from that best for gasoline (about 70 pounds per square inch above atmospheric) to that best for alcohol (about 180 pounds per square inch above atmospheric) the consumption-rate ratio was further reduced and a ratio of 0.7 to 0.59 pound per brake horsepower per hour, equivalent to 1.2 to 1 by weight, or 1 to 1 by volume, was obtained with a thermal efficiency ratio of 39 to 26 per cent, or 1.5 to 1.

These figures are not the results of single tests, but are the average values obtained for a number of tests under identical conditions; furthermore, these values were duplicated on different engines and at different times on the same engine. They represent the best practical values that were obtained for each fuel and stated degree of compression with the equipment at hand. They were obtained under special test conditions, however, and are not commercial values; nor were they obtained offhand, even by skilled operators.

Likewise, a consumption rate was obtained as low as 0.58 pound per brake horsepower per hour for gasoline with a corresponding thermal efficiency of 28 per cent, but the compression pressure used was 90 pounds per square inch above atmospheric. With this degree of compression, it is necessary to use the weakest mixtures that will explode, in order to prevent preignition, and the load had to be reduced accordingly. Heavy loads could not be carried without excessive preigniting. Similarly, a fuel-consumption rate of 0.68 pound per brake horsepower per hour, with a corresponding thermal efficiency of 40 per cent, was obtained for alcohol, with a compression pressure of 200 pounds per square inch above atmospheric, but preignitions were prevented only with difficulty and by a method similar to that used with gasoline, so that the conditions under which these results were obtained were not considered practical and the values have not been used in the discussion. They do not, however, change the ratios given.

The thermal efficiencies given in this discussion were calculated from the indicated horsepower and the lower heating value of the fuel. The method employed in determining the average indicated horsepower for each load was carefully worked out and the results were very satisfactory. They are consistent throughout with the brake horsepower determinations. It is not at all impossible to obtain the average indicated horsepower with sufficient accuracy for all practical purposes, if the load is kept reasonably constant; but the indicator diagrams must be taken in a careful, systematic, and understanding manner to be of any value at all.

The difference between the brake and the indicated horsepower, or the friction loss of the engines used, was practically the same and constant. For 484 tests on the five engines the average difference was 2.3. A full description of the methods used in determining the average indicated horsepower from the indicator diagrams, with tables giving details of the tests from which the mechanical efficiency of each engine at various loads was obtained, will be given in the final report. These tables substantiate the above statements.

EFFECTS OF PRINCIPAL OPERATING CONDITIONS.

EFFECT OF DIFFERENT LOADS.

The fuel-consumption ratios given above for alcohol and gasoline (1.45 to 1 and 1 to 1 by volume) are little affected by the load when the other operating conditions are limited to the best for each load. This limitation requires continual change in the time of ignition and in the quantity of fuel supplied, as regulated by the igniter and the fuel needle valve, with a correspondingly wide difference in the numerical values obtained for the minimum fuel-consumption rates for the different loads. Thus the minimum consumption rate of gasoline and alcohol for the maximum load is about 10 per cent greater than that for the best load, which is usually about 80 to 85 per cent of the maximum load; while the minimum fuel-consumption rate for light load, say about one-third load, may be anything greater than that for best load, depending on the disturbing effect of the governor. With the engines used for this investigation, the minimum fuel-consumption rate for one-third load was approximately 50 per cent greater than that for best load.

EFFECT OF MIXTURE QUALITY.

For gasoline and alcohol alike, the ratio of air to fuel for the condition of minimum fuel consumption at maximum load was found to be approximately that for a chemical mixture, that is, theoretically just sufficient air for complete combustion in each case. This ratio for gasoline is approximately 15 parts of air to 1 of fuel by weight, and for denatured alcohol (90 per cent ethyl alcohol), approximately 8 parts of air to 1 of fuel. The minimum fuel-consumption rate at best load (about 80 per cent of maximum load) was obtained with a mixture of between 19 and 23 parts of air to 1 of gasoline by weight, and of between 9½ and 11½ parts of air to 1 of alcohol by weight, when used at the same compression pressures; that is, for the most economical use of gasoline and alcohol at the same compression the calculations show that from 25 to 50 per cent excess air was used, depending on the estimated mixture temperature.

From a series of observations of the temperatures of the fuel and air mixtures as they enter the cylinder of the engine, and from measurements of exhaust temperatures for various conditions of operation, a careful estimate was made of the temperature of the ultimate mixture in the cylinder at the beginning of the compression stroke. For the condition of minimum fuel consumption for loads from maximum load to somewhat below best load (about 75 per cent of the maximum load) these estimates show a range of ultimate mixture temperatures from not to exceed about 160° F., if no vaporization of fuel takes place in the cylinder, to not less than 60° F., if all the fuel is vaporized in the cylinder.

The average weight of fuel per charge was obtained from the fuel-consumption rate and the average number of fuel admissions per minute, from which the corresponding volume of fuel per stroke was calculated. The volume of fuel and air mixture per stroke was calculated from the piston displacement, multiplied by a factor obtained from the light spring indicator diagram of the suction and compression stroke. These diagrams, if taken carefully, show accurately the volumetric efficiency of the pump action of the engine. Such, in brief, were the data used in determining the air-to-fuel ratios stated above, and a careful study of all the conditions affecting them indicate that the actual values lie about midway between the limits given.[a]

The accuracy of the foregoing method of determining the mixture quality may be questioned, but, be that as it may, for every load there is some best mixture quality and for every mixture quality there is some best time of ignition. But the mixture quality may not be constant for any given load, because there is a disturbing effect if a hit-or-miss governor attachment is used, and the throttling method of governing complicates matters by affecting the compression. From maximum load to about 80 per cent of the maximum, with the best time of ignition, the best mixture is the weakest that will make the engine carry the load. Using such a mixture automatically eliminates the disturbing effect of the governor; or at least the effect is minimized and made constant when the mixture is such that only sufficient governor action is obtained to carry the load satisfactorily under reasonably constant conditions. At about 80 per cent of the maximum load the weakest mixture that will carry the load approaches the limit of dilution with air, beyond which it becomes nonexplosive for the conditions under which it is used in the engine; hence for the light loads the disturbing effect of the governor makes the mixture quality irregular, and may be such that the best results will be obtained with the fuel needle valve much wider open than for the heavier loads.

The extent of the irregularity of the mixing can readily be seen by inspection of series of indicator diagrams taken on the same card. If the hit-or-miss method of governing is used, the irregularities caused

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[a] A more detailed discussion of this feature of the investigation has been prepared in the final report.

by the governor action will be seen clearly in a series of diagrams taken from cut-out to cut-out, or for about the first ten explosions after cut-outs. Such a series also illustrates the fact that when the mixture is irregular the time of ignition, though regulated to give the best ultimate results, is by no means the best for each individual charge of explosive mixture. This may account in part for the fact that the minimum fuel-consumption rate is increased when irregular conditions are caused by the governor action with light loads.

EFFECT OF TIME OF IGNITION.

Ignition at or near dead center will give the best results in some cases, as for maximum load, while in others ignition as early as 35° before dead center will be found best. No general rule can be given. The best time of ignition can be judged to a certain extent by inspection of the indicator diagrams, and seems to be relatively earlier for alcohol than for gasoline.

The rate of flame propagation is different for different ratios of air to fuel vapor. A very rich explosive mixture or a very lean one burns slowly as compared with those of intermediate ratio. The rate may depend somewhat on the pressure at the time of ignition and may be different for alcohol and gasoline mixtures. The indications are that the rate of flame propagation for alcohol mixtures is slower than that for gasoline mixtures of the same relative quality compressed to the same pressure, but may be practically the same when the best compression pressure for each fuel is used.

Providing an ignition device such that the time of ignition can be varied from about zero, or dead center, to about 35° advance, is almost as important for obtaining the best results as providing a fuel needle valve so constructed that a wide range of mixture quality can be obtained; for, as previously stated, it is the best mixture quality with the best time of ignition that must be determined for different loads; and this mixture is considerably richer for maximum load than for rated or best load when the governor action is constant.

If the construction of the engine is such that the time of ignition can not readily be varied for each load to suit the best mixture quality, the point to be considered is not that for every mixture quality there is some best time of ignition, but rather that for a given time of ignition there is some best mixture quality. The fixed time of ignition affects the fuel-consumption rate of the engine by limiting the quality of mixture that can be used.

TESTS WITH VARIABLE LOAD.

The load, then, may affect the fuel-consumption rate of an engine by limiting the mixture quality that can be used and by determining the irregularity caused by the method of governing. The relation between load, mixture quality, and time of ignition is very complex. The best combination could be determined only by series of systematic tests. Such tests were made to determine the minimum consumption for each engine with each fuel, with each carburetor used, etc., and for each imposed independent condition of operation, such as speed or compression.

Thus, in obtaining the foregoing consumption rates and ratios, 14 series of tests were made to determine the minimum fuel-consumption rate for each of an average of about five loads, from maximum load to approximately one-third maximum load, on five different engines, with different carburetors, methods of governing, and degrees of compression.

Four of the 14 series of tests were made with gasoline on three different engines. Two of these were 15-horsepower Otto gasoline engines of identical size, construction, and equipment. The third, a 10-horsepower Nash gasoline engine, was totally different in method of governing and detail of carburetor construction. Two series of tests with gasoline were made on this 10-horsepower engine, but with different carburetors.

Five engines were used for the ten series of alcohol tests, of which two were made on the 15-horsepower Otto gasoline engines and a third on one of these engines after the degree of compression had been raised as much as possible by lengthening the connecting rod. The fourth, fifth, and sixth series of tests were made on a 15-horsepower Otto alcohol engine of identical size with the Otto gasoline engine, but with a different valve arrangement and method of governing. A different degree of compression was obtained for each of these series of tests by lengthening the connecting rod. The seventh and eighth series of tests were made on a 10-horsepower Nash gasoline engine with two different carburetors. The ninth and tenth series of tests were made on a 10-horsepower Nash alcohol engine, which was identical in size, construction, and equipment with the 10-horsepower Nash gasoline engine, the only difference being that a higher degree of compression was obtained by diminishing the clearance space in the cylinder head. Different carburetors were used for the two series of tests on this engine.

TESTS WITH CHANGE IN TIME OF IGNITION.

Two series of tests, consisting of nine individual tests with alcohol and nine with gasoline, were made on the 15-horsepower Otto gasoline engine to determine the effect of change in time of ignition on the fuel-consumption rate when the load and fuel needle-valve setting were kept constant. The load and needle-valve setting selected were such that a wide range of ignition timing could be used.

For the gasoline tests the load was 85 per cent of the maximum. The best results, a consumption of 0.66 pound per brake horsepower per hour, were obtained for an ignition timing of 13° before dead center. For an ignition timing of 21° before dead center the fuel-consumption rate was increased 9 per cent, and 36 per cent for an ignition timing of 15° after dead center.

For the alcohol tests the load was 79 per cent of the maximum. The best results, a consumption of 1.1 pounds per brake horsepower per hour, were obtained for an ignition timing of 25° before dead center. For an ignition timing of 30° before dead center the fuel-consumption rate was increased 4 per cent, and 6½ per cent for an ignition timing of 5° after dead center.

The time of ignition was carried to the limit both ways for each fuel, the limit being the earliest or latest ignition with which the engine would carry the load satisfactorily. The disturbing effect of the governor was thus not constant, but it was comparatively slight throughout and the irregularity was probably not appreciable.

TESTS WITH VARIABLE FUEL SUPPLY.

Four series of tests with gasoline and alcohol were made on the two 15-horsepower Otto gasoline engines. The conditions for two of these series with gasoline and alcohol respectively, were as follows:

For the tests with gasoline a brake load of 85 per cent of the maximum was applied, and the time of ignition selected (21° before dead center) was such that the widest possible range of fuel needle-valve settings for this load could be used. Starting with the minimum opening of the fuel needle valve and a corresponding rate of fuel consumption of 0.62 pound per brake horsepower per hour, the fuel needle-valve opening was increased until the engine could scarcely carry the load, as indicated by the governor action. This fuel needle-valve setting gave a consumption rate of 1.31 pounds per brake horsepower per hour, or an increase of 110 per cent.

For the tests with alcohol a brake load of 79 per cent of the maximum was applied and the time of ignition selected (17° before dead center) was such that the widest possible range of fuel needle-valve settings for this load could be used. Starting with the minimum opening of the fuel needle valve and a corresponding rate of fuel consumption of 1.1 pounds per brake horsepower per hour, the fuel needle-valve opening was increased until the maximum opening was reached. This fuel needle-valve setting gave a consumption rate of 1.6 pounds per brake horsepower per hour, or an increase of 45 per cent.

When the results of these tests were platted, showing the relation between the brake horsepower and the rate of fuel consumption, the results obtained for six intermediate fuel needle-valve settings were found to lie on a straight line between the values given above in each case. As the load was kept constant the disturbing effect of the governor was not eliminated, but probably was slight, as shown by the indicator diagrams.

The other two series of tests were made in a similar way, but with a light load, so that the disturbing effect of the governor was relatively great. In these tests, 11 each for gasoline and alcohol, the needle-valve settings were not carried to the limit either way, but only so far as was necessary to show that for light loads the minimum fuel-consumption rate is not obtained with the smallest possible fuel needle-valve setting, the best setting being rather that which gave the most nearly uniform mixtures, as shown by the regularity of the shape of the successive indicator diagrams. This was also found to be true when the best ultimate settings were determined for the light loads.

INCIDENTAL MATERIAL.

In all, 1,300 tests, including trial tests, were made to determine the foregoing deductions and figures. The detailed results of these tests afford an opportunity to study the effect of degree of compression, mixture quality, and time of ignition on the fuel-consumption rate, and include a great deal of incidental material, such as indicator cards, maximum-pressure measurements, temperature records for fuel and air mixtures entering the cylinder, and the like. The fuel-consumption rates are given in pounds, gallons, and British thermal units per brake and indicated horsepower per hour. Mechanical efficiency, indicated thermal efficiency, and thermal efficiency of the brake are also given. But these tables are too bulky and involved to present at this time. The trial tests have been prepared in condensed form for the final report, and thus present some interesting and important information, showing what difficulty was experienced in determining the best ultimate results in some cases.

LIMITS OF FUEL-CONSUMPTION RATES.

LIMITS SET BY OPERATING CONDITIONS.

So wide is the range of adaptability of alcohol and gasoline to the operating conditions governing or limiting the performance and fuel consumption of internal-combustion engines, that for engines operating under different conditions the ratio of the rates of consumption of the two fuels per unit of power may be almost anything, even the reverse of their heating values; that is, even though the two engines are in good running condition and operating perfectly to all outward appearances, are of the same size, with compression regulated to that best for their respective fuels, and carry the same percentage of maximum load, the operating conditions may be made such that the engine run with gasoline will use twice as much fuel in pounds per brake horsepower per hour as the alcohol engine. Such a ratio is quite likely to be obtained in practice from off-hand comparison of the performance of two engines; but obviously such a comparison would be meaningless.

When an engine is running at maximum load and governing for constant speed, only about 50 per cent excess alcohol can be supplied without causing the engine to slow down and stop; while at half load about two and a half times the amount needed can be supplied before the engine will show any outward change in operation, except that possibly an odor of alcohol or formalin in the exhaust will indicate to the operator that an excess of fuel is being supplied. An oversupply of alcohol does not produce an exhaust of black smoke, as does an excessive supply of gasoline; yet the percentage of excess of alcohol and gasoline that can be used without being detected outwardly is approximately the same. The maximum percentage of excess of gasoline that can be used at maximum loads is a little greater than that for alcohol. With light loads alcohol is likely to be used in greater excess, because the smoke is absent that with gasoline indicates any great oversupply.

With the stationary engines which govern for constant speed the following general rule of adjustment for minimum fuel consumption will hold in almost every case for loads from about half load to maximum load, if the engine is in good mechanical condition: Adjust the time of ignition and fuel needle valve so that the least possible amount of fuel is admitted per stroke without reducing the speed of the engine. In order to obtain the minimum fuel consumption for the gradation of loads from maximum down to about half load, a continuous reduction of fuel supply with earlier time of ignition will be necessary; that is, the smallest quantity of fuel supplied per stroke that will carry the load will give the minimum fuel consumption when the best time of ignition, which changes with the quality of the mixture, is used.

When the above rule is applied to obtain the minimum fuel-consumption rate for the maximum load that the engine is called on to carry, the fuel needle valve and igniter settings found to be the best will, in most cases, be nearly the best possible settings for all other loads down to about half load; at least the best constant setting condition that can be obtained for a varying load between those limits.

With the hit-or-miss method of governing, even though the number of fuel admissions per minute be a maximum, that is, though the number of cut-outs be only sufficient to insure certainty of operation, depending on the fluctuation of load, and though nearly every first fuel admission after cut-outs misfire on account of too weak mixture, the adjustment stated may be the most economical.

With the throttling method of governing, when the disturbing effect of the governor is minimized, the above rules will hold for all loads down to about one-quarter load and lower in some cases.

The foregoing deductions in reference to the maximum and minimum rates of fuel consumption are made from the results of 4 series of tests with gasoline and alcohol on the same engine (15-horsepower Otto gasoline engine) and subsequent incidental observations on the other engines using alcohol with the higher degrees of compression. Two previously determined series of tests on the same Otto gasoline engine, consisting of 158 and 220 single tests, respectively, were taken to obtain the minimum consumption rate of gasoline and of alcohol for seven and ten loads, respectively, between maximum load and about one-third maximum load, and two additional series, of 13 and 24 tests, respectively, were made to determine the maximum rate of gasoline and of alcohol consumption for seven loads covering the same range. Later, when tests were made with alcohol on the Otto alcohol engine and the degree of compression greatly increased, it was found that the maximum amount of alcohol that could be used with the higher degree of compression was very much less for the same percentage of maximum load; but the percentage in excess of the minimum quantity that could be used was practically the same.

Deductions relating to constant engine settings were made from 12 series of tests with an average of about four different loads for each set of fixed conditions. Four of these experiments were made with gasoline and eight with alcohol. Some of them were made with the fuel needle valve and igniter settings which gave the minimum fuel-consumption rate for the maximum load which the engine would carry, while others were made with the settings which gave the minimum fuel-consumption rate for the load with which the best results were obtained (about 85 per cent maximum load). These settings were kept constant for each experiment or series of tests.

The results of the tests with constant engine settings were used in conjunction with the results of the tests which were made to determine the minimum fuel-consumption rate for each different load, and in which the fuel needle-valve setting and time of ignition were varied accordingly. This comparison was made in order to show the relation between the constant settings and best settings for the various loads, as indicated by the ultimate results expressed in pounds of fuel consumed per brake horsepower per hour. Tables giving details of the tests, and curves illustrating the wide range of results that may be obtained between the limits of operating conditions, have been prepared for the final report.

LIMITS SET BY ENGINE DESIGN.

The limiting effect of engine conditions on the relative adaptability of gasoline and alcohol—that is, the limiting effect of the fundamental principles of engine and carburetor design and construction which are not under the control of the operator—may be eliminated to a great extent in the consideration of the comparative consumption of the two fuels. Some engines operating under varying loads may be a great deal less economical than others, owing to different methods of governing or the like, though all other conditions be equal. But the best practical engine conditions have been thoroughly worked out by many of the builders of high-grade gasoline engines, and though the average rate of consumption of either fuel may be almost anything greater than some one minimum figure which depends on both engine and operating conditions, the same approach to the minimum consumption figure for each fuel can be obtained with the same degree of skill in operating and the same care in design and construction, alike for gasoline and alcohol engines, regardless of many of the little details of design, construction, and equipment, which distinguish them and may otherwise affect the average rates of fuel consumption.

At present the skill in operating, designing, and constructing engines for the use of alcohol may not be so great as for gasoline engines. The average operator and engine builder in this country has had less experience with alcohol than with gasoline. Since this is a difference that will, however, vary with the relative use of alcohol and gasoline, and since one pint of gasoline per brake horsepower per hour may be given as a fair average consumption for an engine when operated at about rated load and under favorable conditions, a like figure can reasonably be expected for alcohol when a like understanding of its use is attained and engines as well adapted to its economical use are constructed. This conclusion is based on the results of tests on stationary engines of medium speed and size. The indications are, however, that the ratios given would remain the same, or possibly change a little in favor of alcohol, were all the engine conditions worked out to their most advantageous limit and the exact effect on the fuel consumption determined.

OTHER FACTORS AFFECTING FUEL CONSUMPTION.

SPEED OF ENGINE.

The speed, or a combination of piston speed and revolutions per minute, will affect the fuel economy and thermal efficiency, and for a limited range, at least, increased speed will decrease the fuel consumption and increase the thermal efficiency, nearly alike for both fuels if the best operating conditions are obtained for both. This is likely to hold true up to the limiting practical combination of piston speed and revolution per minute, which is governed by mechanical conditions, but the tests from which the above inference was drawn covered only a range of speeds of 200 to 290 revolutions per minute, with corresponding average piston speeds of 500 to 750 feet per minute.

Series of tests with gasoline and with alcohol, consisting of 16 and 27 tests, respectively, were made on the same engine (15-horsepower Otto gasoline engine) with the same compression. These tests were required to determined the best load, fuel needle-valve setting, and time of ignition, for each of the speeds mentioned and an intermediate one. With speeds of 200 to 300 revolutions per minute, the rate of fuel consumption, in pounds per brake horsepower per hour, varied with increasing speed from 0.68 to 0.64 for gasoline (a decrease of 6 per cent) and from 1.11 to 1.05 for alcohol (a decrease of 5.5 per cent). A change in the speed of the engine is likely to change many conditions affecting the rate of fuel consumption, such as throttling from too-high air velocity through the carburetor, air passageways, and valves, as well as by affecting the mixture quality and best time of ignition. Hence it is very difficult to eliminate all the independent variables and determine the exact effect of change in speed alone. The detailed report of these tests may, however, assist in so extending this phase of the investigation as to determine the most advantageous limits of the possible combinations of speed and cylinder dimensions.

SIZE OF ENGINE.

Similarly, the size of the engine—that is, of the engine cylinder—has a certain influence on the fuel economy and thermal efficiency. A large-cylinder engine can be operated with a higher efficiency than a small one, probably because of the difference in heat loss due to the lesser ratio of cooling surface to volume of charge or heat liberated. But the difference from this cause, which has been fairly well determined by experiment, is negligible for the difference in the size of the engines used for this work. It is small as compared to the difference caused by mechanical conditions, such as leakage and friction, which are likely to be much greater in proportion for a small engine than for a large one. For similar reasons it is also harder to maintain compression with a small engine than with a large one, and this difficulty increases with the degree of compression. Hence a small alcohol engine is likely to be less satisfactory than a small gasoline engine, this depending entirely, however, on the perfection of construction and the skill of the operator.

CARBURATION.

The construction of carburetors and induction passageways suitable to the economical use of gasoline and alcohol are details of engine design and the conditions governing carburation are, to a great extent, predetermined. In most cases but little is left for the operator to adjust aside from the quantity of the fuel or the quality and quantity of air and fuel mixture.

The principle of the ordinary carburetor is that of the simple atomizer, and any effective atomizing device will make a good carburetor if the other influencing conditions are properly taken care of. Since alcohol is less volatile than gasoline, and hence harder to vaporize, a higher velocity of air through the carburetor and a greater excess of fuel is required to obtain an explosive mixture on starting an engine with alcohol than with gasoline. This higher air velocity may be obtained by giving the engine a higher rotative speed (which will also tend to assist the vaporization of the spray carried by the air, by giving less time for the dissipation of the heat of compression to the cylinder walls), or by throttling the carburetor in such a way as further to increase the velocity of the air at the spray nozzle and reduce the pressure at which vaporization takes place. With a combination of these conditions it is not difficult to start a small alcohol engine "cold." To start a large alcohol engine, however, which can not readily be revolved rapidly by hand, some mechanical means of bringing it up to speed will be required, or if the engine is not too large this may be accomplished by priming with gasoline and starting in the usual manner. Hot passageways and cylinder walls assist in vaporizing the fuel at the start, at least, but are not necessary if the previously mentioned conditions are maintained.

Under similar operating conditions with equal air velocities more alcohol than gasoline will pass into the cylinder of the engine in the form of a spray, but unless too great an excess of fuel is used it is probably completely vaporized by the heat from the cylinder walls and hot gases left in the clearance space from the preceding explosion or by the heat developed during compression. With the ordinary piston speeds used in stationary engine practice, a velocity of the air through the carburetor at the spray nozzle sufficiently high to produce as effective vaporization or atomization of alcohol as of gasoline can be obtained without throttling the engine to any appreciable degree.

THROTTLING.

Some very interesting and instructive information on the effect of throttling as an operating condition has been obtained. It appears that for any given compression the more the charge is diluted the better will be the fuel economy and thermal efficiency of the engine, if the smallest quantity of fuel possible per charge and the best time of ignition are used. The details of the tests that show, and possibly explain, this condition of affairs are too many and complicated to take up at this time; but it is evident that if the rule is true equal volumetric efficiency of the pump action (suction and compression strokes) is one of the conditions that must be imposed on comparative tests with gasoline and alcohol, when used either in the same or in different engines. Irregularities of pump action can be eliminated only by obtaining the maximum possible compression, and consequently the minimum possible amount of throttling for the engines used. The entire amount of throttling is not, however, always under the control of the operator, for it depends on the conditions under which the engine is running, the size of the passageways and valves, and the timing of the valves.

VALVE TIMING.

The effect of the timing of the exhaust valve is comparatively small and for any reasonably well-designed and adjusted engine can be neglected. The timing of the inlet valve, however, is of considerable importance. If an automatic inlet valve is used, the spring tension and the distance the valve opens will determine the timing and the amount the charge is throttled in passing the valve. The best spring tension and lift for automatic valves differ under different conditions and no general rule for adjustment can be given. The best adjustment can usually be determined by trial, if the best combination of the spring tension and lift is that with which the engine will carry the greatest load, when the needle-valve and igniter settings are adjusted accordingly. If the engine is equipped with an indicator so that light spring diagrams of the suction and the beginning of the compression stroke can be taken, the best combination of spring tension and valve lift can readily be determined by so adjusting them that the maximum volumetric efficiency of the pump stroke is obtained, as shown by the point at which the compression line crosses the atmospheric line.

When the inlet valve is mechanically operated, its maximum lift is predetermined by the design; but where a considerable lost motion is provided for, the lift and timing of the valve can usually be changed considerably. In some engines the timing can also be changed by shifting the gears that drive the two-to-one shaft. In general, the timing of a mechanically operated inlet valve should be such that it does not completely close until about 20° to 30° after the piston has passed the dead center at the beginning of the compression stroke. No set rule, however, can be given, and the same methods should be employed as in determining the best spring tension and lift of the automatic valve. Light spring diagrams illustrating the application of this method of determining the best valve settings have been prepared for the final report.

The throttling effect of restricted induction passageways may often be greatly reduced by proper timing of the inlet valve. The air passageway through carburetors, however, is often so small as to throttle the charge beyond the possibility of recovery by timing of the inlet valve. This is not necessary and should be avoided.

JACKET TEMPERATURE.

A question asked by almost every operator is: "What effect has the temperature of the jacket or cooling water on the fuel economy and thermal efficiency of an alcohol or gasoline engine, and what is the best jacket temperature?" The only safe answer to this question is: "The best jacket temperature is that which gives the best results." Many tests tend to show that the temperature of the cooling water has little if any appreciable effect, by controlling to a greater or less extent the temperature of the cylinder walls, on the fuel economy and thermal efficiency of the engine. Jacket temperature may, however, have a great effect on the performance of the engine from its influence on other conditions than cylinder-wall temperature. It has been pretty well established that when jacket temperature affects the fuel consumption of an alcohol or gasoline engine it is more by effect on cylinder lubrication, fit of piston and valves, and carburation than by change in heat loss to the cylinder walls. A hot jacket may stop leakage by way of the piston and valves by making them tight from expansion, or it may make a tight piston stick and bind and warp valves or valve seats that are tight when the cylinder walls are kept cold. If the cylinder oil used is thick and heavy, it will flow better when the cylinder is kept hot, but thin oil is more likely to run out and leave the piston dry. If the design of the carburetor is such that efficient carburation and uniform mixtures depend on hot passageways, a hot jacket will help counteract the effect of such poor or limited design; and the ultimate effect of a hot jacket on the fuel consumption is, for this reason, likely to be greater for alcohol than for gasoline.

The temperature to which the jacket water can be raised is limited in some engines by a design such that for a high temperature of jacket water the cooling system is not effective in keeping all the parts below the temperature that will cause preignition. It is not necessary to keep the temperature of the jacket water high if the design and construction of the engine is right to begin with and suitable cylinder oil is used. A "hot jacket" may, however, be a good remedy for many ills that result from poor or limited design and construction.

When a constant load is applied to a gasoline or alcohol engine and the governor action is reasonably steady, or the disturbing effect of the governor is constant, a change in temperature of the jacket water, if it causes any increase or decrease of mechanical or thermal efficiency, will so change the action of the governor as to compensate for the more or the less economical use of the fuel. This change in the action of the governor alters its disturbing effect on the quality or the uniformity of the mixture, and the operating conditions are almost hopelessly altered so far as determining the isolated effect of change in jacket temperature is concerned. The ultimate effect of the change in jacket temperature may, however, be determined if the best combination of fuel needle-valve settings and time of ignition are used in each case and if the load is above about 50 per cent of the maximum the engine will carry, so that the disturbing effect of the governor action will be automatically reduced to a minimum.

If the hit-or-miss method of governing is used, the minimum action of the governor—that is, the minimum practical number of cut-outs per minute—will be the same, regardless of the effect of jacket temperature on the efficiency of carburation.

If the throttle method of governing is used, however, the efficiency of carburization may be affected by the position of the governor-controlled throttle valve; that is, by the amount of throttling and consequent change in the suction and the compression pressures, so that the best combination of fuel needle-valve settings and time of ignition may be different for different jacket temperatures and may complicate the effect on the rate of fuel consumption through a change in both mixture quality and compression. This is true for both gasoline and alcohol, but where the jacket temperature affects the efficiency of carburation, the resultant effect on the rate of fuel consumption will be greater for alcohol than for gasoline.

The results of the tests that were made with different jacket temperatures for each of the engines used for this work indicate that the effect of jacket temperature on the efficiency of carburation of gasoline and of alcohol can be eliminated in both cases by proper care in designing the carburetor and induction passageways. These experiments consisted of eight series of tests, three with gasoline and five with alcohol. First, the minimum gasoline consumption rate at best load for the 15-horsepower Otto gasoline engine (hit-or-miss method of governing) was determined when a low jacket temperature (about 80° F. at the outlet) was used, and the effect of raising the temperature of the jacket water to the boiling point (212° F. at the outlet) was noted. There was no apparent change in the action of the governor to indicate any change in the efficiency with which the fuel was being used, but to make certain the consumption rate was determined for nine different outlet jacket-water temperatures between 80° and 212° F.

The results of these tests show that whatever change there may have been in the temperature of the cylinder walls, as measured by the outlet temperature of the jacket water for a range of over 100° F., the change in the rate of fuel consumption was slight—a decrease of less than 0.01 pound of fuel per brake horsepower per hour, or 1.7 per cent. A similar series of nine tests was made for alcohol, with identical results.

These tests were carried a little further with the second 15-horsepower Otto gasoline engine, and the engine settings were systematically sought that would give the best results for each of five different outlet temperatures of the jacket water. Two series of tests were made, 49 with gasoline and 19 with alcohol, but with the same ultimate effect as before. After the compression pressure of this engine had been raised to about 85 pounds per square inch above atmosphere, another systematic series of search tests, 12 in all, was made with alcohol to determine the minimum fuel consumption for four different jacket temperatures (as measured by the outlet temperature of the jacket water) from 80° to 212° F., but the amount of decrease in the rate of fuel consumption was the same as that previously noted. Similar experiments on the 10-horsepower Nash gasoline engine (hit-or-miss method of governing), consisting of 5 tests with gasoline and 9 with alcohol, gave the same results, though the details of the method of governing and carburetor construction were different.

The 15-horsepower Otto alcohol engine, which was equipped with a still different carburetor, and on which the throttle method of governing was used, could not be operated satisfactorily with alcohol when the outlet temperature of the jacket water was below 100° F., except under a partially throttled condition, with a corresponding increase in the rate of fuel consumption. For outlet temperatures of the jacket water between 100° and 200° F., the best fuel needle-valve setting and corresponding best time of ignition were coincident with the minimum amount of throttling and corresponding maximum compression. There was but little gain in fuel economy—about 0.01 pound per brake horsepower per hour.

Though the results of these tests are almost entirely negative, they were necessary for establishing the best operating conditions; and the tables which give all the data that were taken in them are of vital importance to the study of the whys and wherefores. These tables will appear in the final report.

PREHEATING THE AIR.

Preheated air may be of great benefit when the carburation is ineffective, or the mixture not uniform in quality; but preheating the air is not necessary to obtain the best results with alcohol, and if carried to any great degree will materially diminish the capacity of the engine and decrease the maximum practical degree of compression.

Preheating the air to 250° F. reduced the maximum horsepower of the engine about 15 per cent for alcohol and about 14 per cent for gasoline. With an air temperature of 75° to 85° F., the temperature of the gasoline vapor or spray and air mixture, taken as it entered the cylinder through the inlet valve housing, was from 80° to 100° F. It was usually approximately the same as the air temperature. When the air was preheated to 450° F., the mixture temperature was raised only to 172° F.

With an air temperature of 72° F., the temperature of the air and alcohol mixture at the inlet valve was found to be 61° F. This mixture temperature was increased only to 96° F. when the air was preheated to 250° F., and the condition of minimum fuel consumption for maximum load was maintained in both cases, as for the tests with gasoline.

By platting the minimum fuel-consumption rates in pounds of fuel per brake horsepower per hour, and the brake load in per cent of maximum brake horsepower for the normal and preheated-air temperature tests, the results show a slight increase in the fuel-consumption rate with increased air temperature. An increase of about 0.05 pound per brake horsepower per hour, alike for gasoline and alcohol and the same for all loads, was obtained for air preheated to 250° F.

With air preheated to approximately 250° F., a series of 48 tests with alcohol was made on the 15-horsepower Otto gasoline engine, as required to determine the minimum rate of alcohol consumption for each of 4 different loads from maximum load to about one-third load, so that comparison could be made with results previously determined by a series of tests for 4 different loads when the air was not preheated. A similar experiment with gasoline consisted of 35 tests on the same 15-horsepower Otto engine for maximum load and half load when the air was preheated. A previously taken set of tests for 7 loads from maximum load to one-third load when the air was not preheated was used for comparison.

Twenty-seven additional tests with gasoline and 48 with alcohol were made in order to determine the minimum fuel consumption and mixture temperatures corresponding to intermediate temperatures of the preheated air for various loads. No beneficial effect could be obtained directly or indirectly by the use of preheated air. It should be stated, however, that in the engine used for these tests the passageway between the carburetor and inlet valve was very short, and the mixture temperatures given are the temperatures of the air mixed with atomized and partially vaporized fuel as it passed into the cylinder.

SIZE AND INTENSITY OF IGNITION SPARK.

Misfiring from ineffective ignition is, of course, detrimental to the fuel economy of an engine for either fuel alike, but the ordinary ignition appliances are apparently as effective for igniting alcohol mixtures as gasoline mixtures. No attempt was made to obtain information as to the comparative efficiency of different methods of ignition, but the question was gone into far enough to demonstrate that under operating conditions approximately best for gasoline, increasing the size or intensity of the spark (as measured by the voltage and current supplied to a make-and-break ignitor) from 4.5 watts (4.5 volts and 1 ampere, the amount necessary to ignite every charge) to 48 watts (19 volts and 4.4 amperes) had no effect on the thermal efficiency or fuel economy of the engine. The details of these tests, four in all, will be given in the final report for reference if further study is desired.

In view of the fact that this is a much disputed point, it should be said that if the method of ignition used is the jump spark in the high-tension secondary circuit of an induction coil, there will be a certain amount of building up in the coils and lag of the vibrator, causing the spark to lag. This lag may or may not be appreciable, but if changing the current or the voltage of the ignitor circuit affects this lag to any appreciable degree its effect on the fuel economy and thermal efficiency will be that of changing the time of ignition, and will coincide with any effect produced by change in the intensity and size of spark; or it may account for the entire change which is apparently due to the change in the intensity and size of spark. If the mechanically operated low-tension make-and-break method of ignition is used, as was the case in the experiments referred to, there will be no building-up effect or lag, as the spark occurs after the circuit has been closed for some little time, and is not affected by change in voltage or current.

DEGREE OF COMPRESSION.

As previously stated, the minimum fuel-consumption rates and maximum thermal efficiencies for gasoline and alcohol were obtained with the maximum degree of compression that could be used for each. Furthermore, when alcohol was used, it was found that the maximum thermal efficiencies obtained, for six different degrees of compression, each fulfilled the equation $E = 1 - \left(\frac{P_a}{P_b}\right)^{.19}$; where E equals the thermal efficiency, calculated from the indicated horsepower and lower heating value of the fuel, P_a equals atmospheric pressure in pounds per square inch absolute, and P_b equals the pressure at the end of compression stroke in pounds per square inch absolute.

Each of the above degrees of compression was the maximum for the respective clearance ratio of the engine used; they ranged from 70 to 200 pounds per square inch above atmosphere (85 to 215 pounds absolute). The maximum thermal efficiency values referred to above range from 28 per cent to 40 per cent for the range of compression pressures given, and were obtained from a preceding series of tests made to determine the variation of best fuel economy and maximum thermal efficiency with load. These series of tests were made on different engines with different clearance ratios and corresponding degrees of compression, as follows: Four series of tests on four engines, each with a different clearance ratio; three series of tests on the same engine with three different clearance ratios; and two series of tests on two different engines with the same clearance ratio.

Similarly, when gasoline was used, the best thermal efficiencies obtained for compressions of 70 pounds per square inch above atmosphere (85 pounds absolute) and 92 pounds per square inch above atmosphere (107 pounds absolute) fulfill the equation $E = 1 - \left(\frac{P_a}{P_b}\right)^{.17}$. These results were obtained from a series of tests on two gasoline engines having the same clearance ratio and compression pressure and a third engine having a smaller clearance ratio and a correspondingly higher compression pressure.

The above equations are similar to the theoretical equation for thermal efficiency when expressed in terms of pressure from the air card, or standard reference diagram, and differ only in the numerical value of the exponent. The exponent for the theoretical air card, or standard reference diagram efficiency, is 0.29.

It must be clearly understood, however, that the thermal efficiencies obtained for the different clearance ratios and corresponding degrees of compression fulfilled the equations only when the maximum thermal efficiency of the engine was obtained, which required that the engines be put in the best possible running condition and operated to the best advantage. This required that the best combination of time of ignition and fuel needle-valve setting for the best load be obtained. When the engines were in the best possible running condition, and were operated for minimum fuel consumption, the best load was coincident with the minimum disturbing effect of the method of governing and the maximum compression pressure for the clearance ratio of the engine. This latter condition is of vital importance for the comparison of thermal efficiency for different compressions; for if, for any reason at all, the engines are operated under different conditions with respect to throttling of the charge, the maximum thermal efficiencies obtainable will not fulfill the same equation. The extent of the effect of throttling on the maximum thermal efficiency obtainable for any corresponding compression pressure will be seen from the following illustration: When alcohol was used in an engine whose clearance ratio was such that the maximum compression pressure, with the minimum throttling (94 per cent of piston displacement), was 70 pounds per square inch above atmosphere (85 pounds absolute), a maximum thermal efficiency of 28 per cent was obtained. Similarly, a maximum thermal efficiency of 35.8 per cent was obtained for an engine whose clearance ratio was such that the maximum compression pressure, with minimum throttling (approximately the same as given above), was 140 pounds per square inch above atmosphere (155 pounds absolute). Both of these values fulfill the equation $E = 1 - \left(\frac{P_a}{P_b}\right)^{.19}$. But when the latter engine was throttled to such an extent that the compression pressure was reduced to 70 pounds per square inch above atmosphere (85 pounds absolute) the maximum thermal efficiency for the correspondingly reduced load was 35 per cent, or an increase of 7 in percentage over the value obtained for the engine whose maximum compression was 70 pounds per square inch above atmosphere, and does not fulfill the equation given above. The horsepower of the engine was, of course, greatly reduced (to approximately one-third maximum load). Maximum thermal efficiencies for intermediate conditions of throttling and corresponding compression pressures gave similar results, and the same was found to hold true for other engines.

No attempt to explain these results or to discuss their significance will be made at this time, as the details of the tests are necessary for a clear understanding of the deductions.

SYNOPSIS OF RESULTS AND GENERAL CONCLUSIONS.

Some of the more important results and conclusions stated in this bulletin are summarized below:

1. The low heating value of completely denatured alcohol will average 10,500 British thermal units per pound, or 71,900 British thermal units per gallon.

The low heating value of 0.71 to 0.73 specific gravity gasoline will average 19,200 British thermal units per pound, or 115,800 British thermal units per gallon.

The low heating value of a pound of alcohol is approximately six-tenths of the low heating value of a pound of gasoline.

A pound of gasoline requires approximately twice the weight of air for complete combustion as a pound of alcohol.

The heating value of a cubic foot of an explosive mixture of alcohol vapor and air having theoretically just sufficient air for complete combustion is approximately equal to that of a cubic foot of a similar explosive mixture of gasoline vapor and air—about 80 British thermal units per cubic foot.

2. Explosive mixtures of alcohol vapor and air can be compressed to much higher pressures in an engine cylinder without preigniting than can explosive mixtures of gasoline vapors and air. The maximum pressure of compression that can be used without causing preignition will in each case depend partly on the quality of the explosive mixture, on the design of the engine, and the speed at which it is operated.

For 10 to 15 horsepower four-cycle stationary engines of the usual type a compression pressure of about 70 pounds per square inch above atmospheric was found to be the maximum that could be used for gasoline mixtures, and about 180 pounds the maximum that could be used for alcohol mixtures without causing preignition.

The maximum compression pressure that could be used without causing preignition was in each case found to be the most advantageous from the standpoint of fuel economy.

3. When the degree of compression is in each case that best suited to the economical use of the fuel designated, some types of gasoline engines are better adapted to the service for which they are designed than similar alcohol engines and vice versa. The relative amount of fuel consumed being disregarded, this is also true when the degree of compression is that ordinarily used for gasoline mixtures, as when denatured alcohol is used in gasoline engines; but in general the alcohol engine is or can be so designed and constructed as to be equal to the gasoline engine in adaptability to service.

A gasoline engine having a compression pressure of 70 pounds but otherwise as well suited to the economical use of denatured alcohol as gasoline will, when using alcohol, have an available horsepower about 10 per cent greater than when using gasoline.

When the fuels for which they are designed are used to an equal advantage, the maximum available horsepower of an alcohol engine having a compression pressure of 180 pounds is about 30 per cent greater than that of a gasoline engine having a compression pressure of 70 pounds, but of the same size in respect to cylinder diameter, stroke, and speed.

When denatured alcohol is used in 10 to 15 horsepower four-cycle stationary engines having a compression pressure of approximately 180 pounds and the engines are operated at their maximum loads, the pressures during explosion or combustion reach 600 to 700 pounds. Stationary gasoline engines, in which the compression pressure in some cases can be raised to 180 pounds, are not usually built heavy enough to withstand such explosion pressures for any length of time.

4. A gasoline engine having the degree of compression ordinarily used for gasoline mixtures will in general require 50 per cent more denatured alcohol than gasoline per brake horsepower per hour.

Gasoline and alcohol engines of similar construction having degrees of compression best suited to the fuel supplied will in general require equal volumes of gasoline and denatured alcohol, respectively, per brake horsepower per hour.

Gasoline engines of the usual four-cycle stationary type will ordinarily consume about a pint of gasoline per brake horsepower per hour when operated at about rated load and with a reasonably favorable adjustment of the mixture quality and time of ignition.

When carrying light loads or carrying their maximum loads, gasoline and alcohol engines governed for constant speed require a greater quantity of fuel per brake horsepower per hour than when carrying their rated loads, if rated at about 75 to 80 per cent of their maximum loads; but unless the mixture quality and time of ignition are adjusted to suit each change of load, the rate of consumption per brake horsepower per hour will in general be least at maximum load and will increase with decrease in load.

When any of the usual methods of governing are used to control the speed of gasoline or alcohol engines, the rate of fuel consumption per brake horsepower per hour will ordinarily be about twice as great at one-third load as at maximum load. At the same time an excessive rate of consumption of gasoline or denatured alcohol at any given load, if due to the incorrect adjustment of the mixture quality and time of ignition only, may be as great as but not greater than approximately twice the minimum required before it will be noticeable from outward indications.

5. The thermal efficiency of alcohol and gasoline engines will in general increase with the pressure to which the charge is compressed when ignited.

The maximum thermal efficiency of 10 to 15 horsepower four-cycle stationary engines of the usual type when operated with a minimum amount of throttling was found to increase with the compression pressure according to the formulas $E = 1 - \left(\frac{14.7}{P}\right)^{.17}$ for gasoline and $E = 1 - \left(\frac{14.7}{P}\right)^{.19}$ for alcohol, where E = the thermal efficiency based on the indicated horsepower and low heating value of the fuel and P = the indicated pressure of the charge at the end of the compression stroke in pounds per square inch absolute.

6. A high thermal efficiency and a rate of consumption of less than a pint per brake horsepower per hour, both for gasoline and for denatured alcohol, can often be obtained when the degree of com-

pression, the load, the quality of the explosive mixture, and the time of ignition are carefully adjusted. A fair representation of the best economy values obtained, taken from the results of tests on 10 to 15 horsepower Nash and Otto stationary engines, and the corresponding thermal efficiencies are given in the following table:

Results from tests made on 10 to 15 horsepower Nash and Otto stationary engines.

Fuel.	Compression pressure (pounds).[a]	Fuel consumed per brake horsepower per hour.		Thermal efficiency (per cent).[b]
		Pound.	Gallon.	
Gasoline	70	0.60	0.100	26
	90	.58	.097	28
Alcohol	70	.96	.140	28
	180	.71	.104	39
	200	.68	.099	40

[a] Per square inch above atmosphere.
[b] Based on the indicated horsepower and the lower heating value of the fuel.

7. When by means of a double carburetor gasoline and alcohol are used simultaneously in varying proportions from practically all gasoline to practically all alcohol, the most advantageous degree of compression will vary from that found to be the best for gasoline mixtures to that found to be the best for alcohol mixtures.

Tests that were made with such an adjustment of compression indicate that the total amount of fuel (gallons of gasoline + gallons of denatured alcohol) required for any given load is practically constant for the entire range of proportions from all gasoline to all denatured alcohol.

8. When water is sprayed into an explosive mixture of gasoline vapor and air as it is being taken into the cylinder of an engine and is introduced at the most advantageous location, it may in many cases be supplied in amounts up to as much water as gasoline by weight without affecting the performance of the engine, except as noted below.

The capacity or maximum available horsepower of an engine decreases with an increase in the percentage of water, by weight, present in the explosive mixture of gasoline vapor and air.

When used in an engine having a constant degree of compression, the presence of water in an explosive mixture of gasoline vapors and air in quantities equal to or less than the weight of gasoline does not increase or decrease the amount of gasoline required to carry any given percentage of the corresponding maximum available load.

The pressure to which an explosive mixture of gasoline vapor, water, and air can be compressed in an engine cylinder without preigniting increases with an increase in the percentage of water in the mixture, and can be raised to about 140 pounds when the weights of water and gasoline are equal.

That the amount of gasoline required is not affected by an increase in the compression pressure when preignition is prevented only by the introduction of water as above stated is indicated by the results of tests made on an engine having a compression pressure of 130 pounds. These tests are limited, however, and the results are not conclusive.

9. Alcohol diluted with water in any proportion from denatured alcohol, which contains about 10 per cent of water, to mixtures containing about as much water as denatured alcohol can be used in gasoline and alcohol engines if they are properly equipped and adjusted.

When used in an engine having a constant degree of compression, the amount of pure alcohol required for any given load increases and the maximum available horsepower of the engine decreases with a diminution in the percentage of pure alcohol in the diluted alcohol supplied. The rate of increase and decrease respectively is such, however, that the use of 80 per cent alcohol instead of 90 per cent, or denatured alcohol, has but little effect on the performance of the engine; so that if 80 per cent alcohol can be had for 15 per cent less cost than 90 per cent alcohol and could be sold without tax when denatured, it would be more economical to use the 80 per cent alcohol.

When an engine is supplied with diluted alcohol, the compression pressure that can be used without causing preignition increases with an increase in the percentage of water by weight in the mixture, but no tests were made to determine the effect of increased compression pressure on the economy with which diluted denatured alcohol could be used.

10. The relative hazard involved in the storage and handling of gasoline and denatured alcohol is of particular importance in considering their use as fuels for marine and factory engines and engines to be placed in the basements of office buildings, in coast-defense fortifications, or in like places where a general fire would be likely to result from the accidental burning of the fuel stored or carried for immediate supply, or where the forming of explosive or inflammable mixtures of the fuel vapors and air in the immediate vicinity would be hazardous.

It is indicated by statistics and is also the general consensus of opinion of those experienced in handling gasoline, kerosene, and alcohol that the hazard involved in the use of denatured alcohol is very much less than in the use of gasoline and possibly less than in the use of kerosene, but as yet the relative fire risk has not been definitely established. Considerable work has been done on this phase of the investigation and a series of tests intended to be of assistance in determining the relative hazard involved in the use of these fuels was made by the technologic branch of the United States Geological Survey at the testing station in Pittsburg, Pa.

11. In regard to general cleanliness, such as absence of smoke and disagreeable odors, alcohol has many advantages over gasoline or kerosene as a fuel. The exhaust from an alcohol engine is never clouded with a black or grayish smoke, as is the exhaust of a gasoline or kerosene engine when the combustion of the fuel is incomplete, and it is seldom, if ever, clouded with a bluish smoke when a cylinder oil of two low a fire test is used or an excessive amount supplied, as is so often the case with a gasoline engine. The odors of denatured alcohol and the exhaust gases from an alcohol engine are also not likely to be as obnoxious as the odor of gasoline and its products of combustion.

12. Very few alcohol engines are being used in the United States at the present time, and little has been done toward making them as adaptable as gasoline engines to the requirements of the various classes of service. Engines for stationary, marine, and traction service, automobiles, motor trucks, and motor railway cars designed especially to use denatured alcohol have, however, been tried with considerable success.

The price of denatured alcohol is greater than the price of gasoline, and the quantity of denatured alcohol consumed by an alcohol engine as ordinarily constructed and operated is in general relatively greater than the quantity of gasoline consumed by a gasoline engine of the same type. Considerable attention is being given to the development of processes for the manufacture of alcohol from cheap raw materials which are generally available, and it seems reasonable to expect that the price of denatured alcohol will eventually become as low as or lower than the price of gasoline, especially if the price of gasoline advances. It also seems reasonable to expect a greater general improvement in alcohol engines than in gasoline engines.

When used as a fuel, denatured alcohol is not always so classed as to be exempt from restrictions placed on the use of gasoline by the rules of insurance and transportation companies or city ordinances. The restrictions that are placed on the use of denatured alcohol are, however, never greater than those placed on the use of gasoline. In some places they are such that the use of an alcohol engine is permitted where the use of a gasoline engine is prohibited. For instance, alcohol motor trucks and automobiles are admitted to many of the steamer piers in New York that are not open to gasoline machines.

Where the restrictions placed on the use of denatured alcohol are less than those placed on the use of gasoline or where safety and cleanliness are important requisites, the advantages to be gained by the use of alcohol engines in place of gasoline engines may be such as to overbalance a considerable increase in the fuel expense, especially if the cost of fuel is but a small portion of the total expense involved, as is often the case. Denatured alcohol, will, however, probably not be used for power purposes to any great extent until its price and the price of gasoline become equal and the equality of gasoline and alcohol engines in respect to adaptability to service required and quantity of fuel consumed per brake horsepower, which has been demonstrated to be possible, becomes more generally realized.

A further general development in the design and construction of engines that use kerosene, or cheaper distillates, and the crude petroleums may be reasonably expected and may delay the extensive use of denatured alcohol for some time to come, but as yet comparatively few data pertaining to this phase of the general investigation are available. Some investigations relating specifically to the extent and economy with which these cheaper oils can be used as fuels for internal-combustion engines of the types suited to various classes of service have been made at the Pittsburg testing station, now a part of the Bureau of Mines.

PUBLICATIONS ON FUEL TESTING.

The following publications, except those to which a price is affixed, can be obtained free by applying to the Director of the Bureau of Mines, Washington, D. C. The priced publications can be purchased from the Superintendent of Documents, Government Printing Office, Washington, D. C.

PUBLICATIONS OF THE BUREAU OF MINES.

BULLETIN 1. The volatile matter of coal, by H. C. Porter and F. K. Ovitz. 1910. 56 pp., 1 pl.

BULLETIN 2. North Dakota lignite as a fuel for power-plant boilers, by D. T. Randall and Henry Kreisinger. 1910. 42 pp., 1 pl.

BULLETIN 3. The coke industry of the United States as related to the foundry, by Richard Moldenke. 1910. 32 pp.

BULLETIN 4. Features of producer-gas power-plant development in Europe, by R. H. Fernald. 1910. 27 pp., 4 pls.

BULLETIN 5. Coking and washing tests of coal at Denver, Colo., July 1, 1908, to June 30, 1909, by A. W. Belden, J. W. Groves, K. M. Way, and G. R. Delamater. 1910. 62 pp.

BULLETIN 7. Essential factors in the formation of producer gas, by J. K. Clement, L. H. Adams, and C. N. Haskins. 1911. 58 pp., 1 pl.

BULLETIN 8. The flow of heat through furnace walls, by W. T. Ray and Henry Kreisinger. 1911. 32 pp.

BULLETIN 9. Recent development of the producer-gas power plant in the United States, by R. H. Fernald. 1910. 82 pp. Reprint of United States Geological Survey Bulletin 416.

BULLETIN 11. The purchase of coal by the Government under specifications, by G. S. Pope. 1910. 80 pp. Reprint of United States Geological Survey Bulletin 428.

BULLETIN 12. Apparatus and methods for the sampling and analysis of furnace gases, by J. C. W. Frazer and E. J. Hoffman. 1911. 22 pp.

BULLETIN 13. Résumé of produce-gas investigations, 1904–1910, by R. H. Fernald and C. D. Smith. 1911. 368 pp.

BULLETIN 14. Briquetting tests of lignite at Pittsburg, Pa., 1908–9, with a chapter on sulphite pitch binder, by C. L. Wright. 1911. 64 pp.

BULLETIN 28. The significance of drafts in steam-boiler practice, by W. T. Ray and Henry Kreisinger. 62 pp. Reprint of United States Geological Survey Bulletin 367.

TECHNICAL PAPER 1. The sampling of coal in the mine, by J. A. Holmes.

PUBLICATIONS OF THE UNITED STATES GEOLOGICAL SURVEY.

BULLETIN 261. Preliminary report on the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, in St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1905. 172 pp. 10 cents.

PROFESSIONAL PAPER 48. Report on the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1906. In three parts. 1492 pp., 13 pls. $1.50.

BULLETIN 290. Preliminary report on the operations of the fuel-testing plant of the United States Geological Survey at St. Louis, Mo., 1905, by J. A. Holmes. 1906. 240 pp. 20 cents.

BULLETIN 325. A study of four hundred steaming tests, made at the fuel-testing plant, St. Louis, Mo., 1904, 1905, and 1906, by L. P. Breckenridge. 1907. 196 pp. 20 cents.

BULLETIN 332. Report of the United States fuel-testing plant at St. Louis, Mo., January 1, 1906, to June 30, 1907; J. A. Holmes, in charge. 1908. 299 pp. 25 cents.

BULLETIN 334. The burning of coal without smoke in boiler plants; a preliminary report, by D. T. Randall. 1908. 26 pp. 5 cents.

BULLETIN 336. Washing and coking tests of coal and cupola tests of coke, by Richard Moldenke, A. W. Belden, and G. R. Delamater. 1908. 76 pp. 10 cents.

BULLETIN 362. Mine sampling and chemical analyses of coals tested at the United States fuel-testing plant, Norfolk, Va., in 1907, by J. S. Burrows. 1908. 23 pp. 5 cents.

BULLETIN 363. Comparative tests of run-of-mine and briquetted coal on locomotives, by W. F. M. Goss. 1908. 57 pp.

BULLETIN 368. Washing and coking tests of coal at Denver, Colo., by A. W. Belden, G. R. Delamater, and J. W. Groves. 1909. 54 pp., 2 pls. 10 cents.

BULLETIN 373. The smokeless combustion of coal in boiler plants, by D. T. Randall and H. W. Weeks. 1909. 188 pp. 20 cents.

BULLETIN 402. The utilization of fuel in locomotive practice, by W. F. M. Goss. 1909. 28 pp.

BULLETIN 403. Comparative tests of run-of-mine and briquetted coal on the torpedo boat *Biddle*, by W. T. Ray and Henry Kreisinger. 1909. 49 pp. 10 cents.

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