A CRITICAL STUDY OF VARIOUS TYPES OF EXHAUST GAS ANALYZERS FOR GASOLINE ENGINES

by

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I. INTRODUCTION

Analysis of the products of combustion is a method which has been used successfully for a number of years to determine the combustion efficiency and the optimum air-fuel ratio of steam generator furnaces. It is logical, therefore, that attempts should have been made to apply the same principles to internal combustion engines. This idea was first promulgated by Dr. Dugald Clerk, an Englishman, as early as 1907 and was rapidly adopted by others.

At the present time there are at least a dozen companies in the United States who produce some type of exhaust gas analyzer intended specifically for use in connection with gasoline engines. If reasonably dependable, these devices could be a very useful tool to the engine "tune-up" mechanic, to the automotive research engineer, and to the airplane pilot by enabling them to tell quickly and accurately when proper carburetor adjustment is secured. Obviously, if this type of equipment is inaccurate its use is not only wasteful of time and money but may result in lowered efficiency and actual damage to the engine.

The average user of these instruments lacks the technical knowledge and the laboratory facilities necessary to determine for himself the characteristics of the various types and makes and is, therefore, a likely subject for extravagant advertising claims. It was in an effort to

supply some reliable information regarding the limitations of this type of apparatus that the investigation herein described was conducted.

This thesis reviews the five important phases of the problem of determining air-fuel ratio by exhaust gas analysis: (1) the correlation between the chemical composition of the exhaust gases and the air-fuel ratio; (2) the accuracy of the theories upon which the principles of analysis by different methods are based; (3) the fidelity with which representative instruments actually indicate the true air-fuel ratio; (4) details of construction which are necessary for continued reliability under service conditions, and (5) the adaptability of the different types to various usages.

While it was, of course, impossible to investigate thoroughly in the time available all of the factors relating to the entire subject, it is believed that this thesis will be of interest to a great many of those who may have occasion to employ gasoline engine exhaust gas analysis methods.

II. REVIEW OF LITERATURE

Historical

The science of gas analysis is almost as old as chemistry itself, but it is only within the last century that attempts have been made to replace chemical methods with the simpler and faster physical principles. It is thought that the basis of the thermal conductivity method, which is the method most widely used in automotive work, was discovered in 1840 by an English physicist, Andrews, who noticed that the glow of a red-hot wire, electrically heated and stretched along the center of a cylinderical tube, was considerably reduced when the air in the tube was replaced by hydrogen (4).

Apparently the potentialities of Andrews' discovery were not realized for some years because the first known application of this principle was by Leon Somzee who, about 1880, suggested the utilization of a hot-wire instrument for measuring the thermal conductivity of gases (12). Soon thereafter various other investigators developed improved devices for determining the thermal conductivity of gases by this method.

Probably the first instrument designed to employ the thermal conductivity principle to gas analysis was made by the Vereinigte Maschinenfabrik of Augsburg, Germany, and

was patented there and in England in 1904.

The World War gave added impetus to the development of this type of instrument for the determination of the concentration of hydrogen used in balloons, and various modifications of the thermal conductivity type of analyzer were developed in rapid succession by Koepsel and by the Siemens & Halske Company in Germany, by a professor of physics named Shakespear in England, and by the Sperry Gyroscope Company and by the University of California in the United States (12).

All of the work described so far was directed toward the analysis of commercial gases, though Koepsel did suggest the possibility of the application of his instrument to the determination of the carbon dioxide concentration in flue gases. So far as is known, Dr. Dugald Clerk was the first person to suggest (in a paper presented before the Institution of Automobile Engineers in 1907) that exhaust gas analysis might be used as a guide in adjusting the carburetors of internal combustion engines (9). Another British engineer, W. Watson, furthered Dr. Clerk's idea and at a subsequent meeting of the same Institution advanced definite proposals for a study of the matter. The idea was rapidly investigated by a number of other workers in the field, both from the standpoint of improving engine efficiency and from that of limiting the carbon monoxide content of exhaust gases to a point where they would not endanger human life or health.

The early investigators in this field were hampered, however, by the lack of practicable equipment and by a dearth of information on the interrelation between air-fuel ratio and exhaust gas composition. Both of these impediments have been overcome to a considerable extent in subsequent years.

The Cambridge Instrument Company of New York claims that it developed in 1924 the "first successful and accurate instrument for the measurement of air-fuel ratio by thermal conductivity analysis of the exhaust gases of gasoline engines ..... considerably before the market was ready for it" (11).

Relation of Exhaust Analysis to Air-Fuel Ratio

Exhaust gas analysis is obviously valueless unless a definite relation exists between it and the ratio of the air and fuel supplied to the engine, and unless this relation is accurately known. Much work has been done on this fundamental phase of the problem and no treatise on the subject would be complete without a résumé of the results achieved.

Outstanding work in this field has been accomplished by the United States Bureau of Mines (3), (15), the National Advisory Committee on Aeronautics (6),(7),(18), the University of Illinois Engineering Experiment Station (8),(13),(14), the Perdue University Engineering Experiment Station (1), the Research Laboratories Division of the General Motors Corporation (5), and others.

Since it is not the purpose of this thesis to examine in detail the chemistry of combustion in gasoline engines, only a summary of this work will be given. The data of previous investigators have been thoroughly and ably examined and correlated by Graf, Gleason, and Paul in the Oregon State College Engineering Experiment Station Bulletin entitled, "Interpretation of Exhaust Gas Analyses" (9). Their conclusions are of such importance that they will be quoted verbatim:

> 1. Although very evident correlation exists between the various constituents of exhaust gas from gasoline power plants, such data as are available show marked deviations which probably result from several possible causes - namely, poor distribution, air leakage, type and condition of engine, or method of sampling gases.
> 2. By far the greater portion of complete tests as reported in literature have been conducted upon engines that were in no respect modern according to present ideas.
> 3. Many of the assumed correlations or relationships expressed in literature are only approximate and then only within a restricted range.

4. Exhaust gas analysis as a test procedure is well on the way to universal adoption.

5. Instrument manufacturers have made available various instruments that operate upon exhaust gases to indicate directly air-fuel ratios, completeness of combustion, or both.

6. More satisfactory correlations from accurate analyses are desirable to enable the construction of more accurate charts or graphs for routine testing.

7. There are still many unsolved problems connected with exhaust gas analyses, chief among which are the equilibrium considerations involved.

These authors also point out the fact that disassociation is considered to be a function of maximum combustion temperature, and that the exhaust analysis reflects the effects of disassociation. They add, however, that there has been little correlation between theory and experience regarding the effects of this phenomenon.

The work of Graf, Gleason, and Paul was followed in 1935 by somewhat similar investigations by B. A. D'Alleva and W. G. Lovell of the General Motors Research Laboratories staff (5). This research was conducted with three different sizes and types of multi-cylinder engines, both in the above-

mentioned laboratories and in those of the Ethyl Gasoline Corporation in Detroit. Air flow measurements were made with a special type of positive displacement meter and by means of an accurately calibrated orifice. Gas samples were collected over mercury, and were carefully analyzed with a Standard-Burrell (chemical) gas analysis apparatus. The analyses of the various samples formed under different conditions show a close agreement when plotted against air-fuel ratio, the maximum variation in any case being in the order of one per cent. These experimental analyses also checked fairly well with theoretical values computed by D'Alleva and Lovell.

From the evidence presented, it would seem that a reasonably well defined relationship does exist between the air-fuel ratio supplied to an engine and the chemical composition of the exhaust gases resulting therefrom. This fact, then, provides a sound theoretical basis for mixture ratio determination by exhaust gas analysis, provided great accuracy is not expected.

Methods of Analysis

A generous supply of literature, ranging from the highly technical to the patently commercial, is available on the several types of instruments used for automotive exhaust gas analysis. All of the reliable information, however,

carefully avoids mention of the degree of accuracy which may be expected of the various instruments commercially available. It is in hopes of partly alleviating this deficiency that this thesis is being written.

An unusually comprehensive treatise on gas analysis by the thermal conductivity method was written by Palmer and Weaver of the National Bureau of Standards in 1924. While this report (12) is not very up-to-date, and hardly mentions the subject of internal combustion engine exhaust analysis, it does give a thorough discussion of the principles and problems involved. Two statements made by these scientists are of especial significance as regards this thesis, namely, (1) that reasonable variations in pressure (about one atmosphere) do not appreciably affect the thermal conductivity of a gas and (2) that this type of instrument is relatively insensitive to small variations in the rate of flow. As will be shown later, experimental data obtained by the author would indicate that such is not the case. A paper entitled "Pressure Error in Gas Analysis by the Thermal Conductivity Method" by Dr. J. G. M. Bullowa (2) also offers certain evidence to the contrary. It is also pertinent to note that several manufacturers of this type of apparatus specifically mention the fact that their particular instruments are so designed as not to be affected by variations in pressure and rate of flow (4),(16).

The hot-wire catalytic and the relative density principles of gas analysis are much less frequently employed in instruments intended for automotive work than the thermal conductivity method, and correspondingly less has been written about them. Very good descriptions of the catalytic type are given by Miller Reese Hutchison (10) and by L. T. White (17), however, and certain commercial bulletins (4), (16) contain good comparisons of the different methods if due allowance be made for the prejudice of the companies publishing them.

III. EXPERIMENTAL

Purpose

The ultimate object of this investigation was to determine the limits of accuracy of the several types of exhaust gas analyzers used in automotive work under various conditions likely to be encountered in ordinary service, and to suggest ways in which these instruments might be made to render greater satisfaction.

Plan of Investigation

The fundamental aim stated above may be broken down into several more-or-less basic problems which served as a guide for the following steps in the investigation:

1. A review of the relations which have been found to exist between the ratio of air and fuel supplied to an engine to the chemical composition of the resulting products of combustion. This was necessary in order to determine the dependableness of the underlying principle upon which each type of instrument is based.

2. A study of the operating principles of each of the several types of instruments in an attempt to establish their inherent limitations and applicability to the problem involved.

3. An investigation as to the feasibility of applying the underlying theoretical principles to the construction of commercial instruments without sacrificing accuracy or durability.

4. Actual tests of one or more of each type of instrument under carefully controlled conditions in order to determine their range, accuracy, and general operating characteristics under various conditions normally encountered in service.

Scope

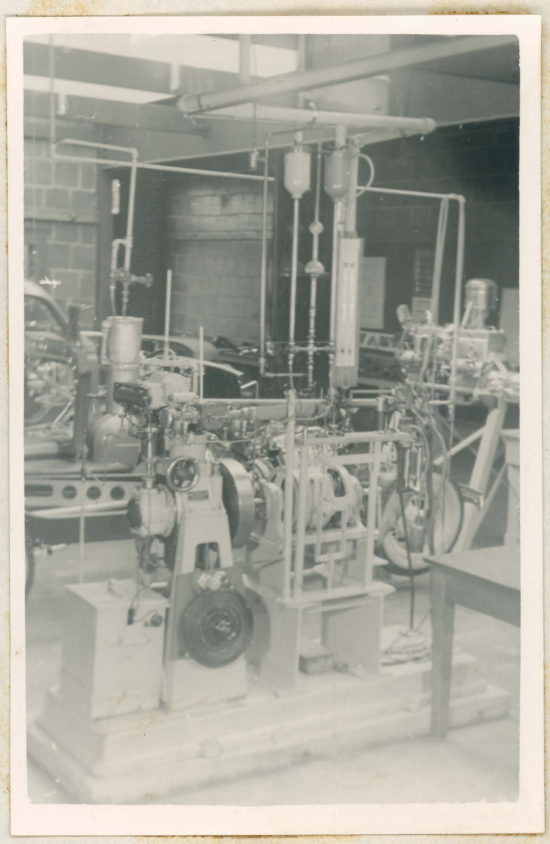
Six instruments, representing five different manufacturers and four different operating principles, were tested. Two of the instruments utilized the thermal conductivity method, one the hot-wire catalytic principle, one the relative density principle, and two were of the Orsat (selective absorption) type. Detailed descriptions and explanations of these several pieces of apparatus are given in a later section of this thesis under "Apparatus" (page 21).

It should be pointed out at this time, however, that there are eight or ten makes of thermal conductivity exhaust gas analyzers on the American market today and that the particular makes tested were of the low and medium price classes and presumably were not representative of the best that can be obtained. This statement does not apply to the other types under discussion.

As regards the scope of the actual tests performed on this equipment, both time and material facilities available limited the investigation to the most important phases only. Tests were confined to one (single-cylinder) engine, to one speed, to one compression ratio, to one brand of gasoline, and to a single engine temperature, mixture temperature, and exhaust temperature. All runs were made at full throttle only, and no effort was made to regulate the humidity of the air consumed by the engine. However, as wide a range of mixture ratios as possible were employed and the effect of spark advance and of exhaust pressure were investigated rather thoroughly. It was judged from the results thus obtained that the small variations in readings which might possibly have been secured under other conditions would not have been detectable, so large was the range of error of the instruments.

Apparatus - General

Figure 1(a) (next page) shows two views of the equipment used in these tests. It consisted essentially of a test engine direct-connected to an electric dynamometer and provided with the necessary accessories and control apparatus. The fuel burette and controls can be seen on the panel above the dynamometer, just to the right of the engine. It will be noted that the air intake of the right-hand carburetor is connected to a large surge chamber located above the fuel



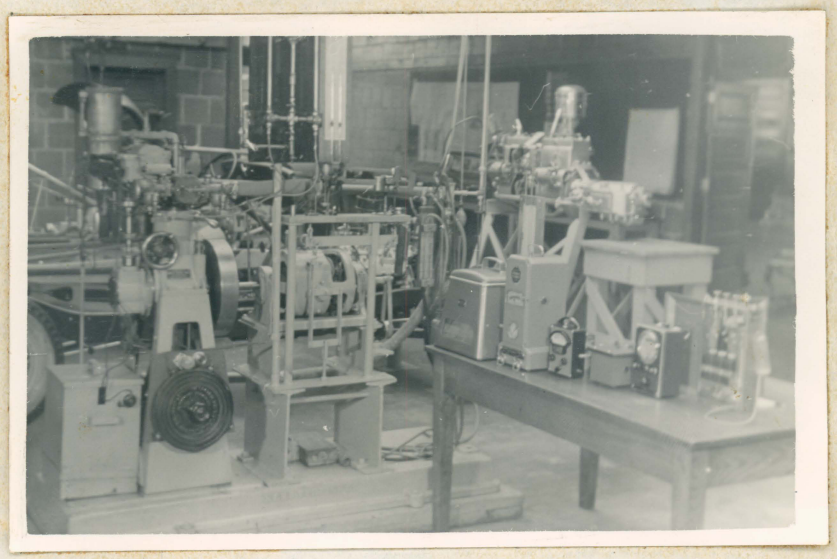


Fig. 1(a) - VIEW OF EXPERIMENTAL EQUIPMENT

control panel. From the surge tank a pipe led to the gas meter (not shown) placed at the right end of the dynamometer. The function of the surge chamber was, of course, to suppress the pulsations in the intake air, thus insuring operation of the meter under conditions the same as existed when the device was calibrated.

The exhaust pipe is connected to the rear of the engine cylinder and extends parallel to, and behind, the dynamometer. Near the end of the exhaust pipe may be seen the nipples to which the analyzer hoses were connected. A length of three-eights-inch water pipe was run inside of the exhaust pipe to permit regulation of the temperature of the exhaust gases. The thermometer used to measure this temperature (not shown) was inserted in the exhaust pipe near the sampling nipples, and the exhaust pressure manometer was connected in the same vicinity.

The rheostat used for adjusting the mixture heater may be seen on the front of the engine stand. The inlet manifold vacuum was indicated by the U-tube manometer to the right of the fuel burette, and the mixture temperature was measured by the thermometer inserted in the intake pipe just in front of the cylinder.

The small tank above and to the left of the engine is the jacket water condenser, and valves for controlling both cooling and make-up water may be seen just above it.

Apparatus - Accessory Equipment

Engine

Make: Christie Variable Compression Engine; Mfd. by the Christie Machine Works, San Francisco, Cal.

Type: Vertical, single-cylinder, water-cooled, valve-in-head, four-stroke-cycle gasoline engine with cylinder and head movable axially as a unit to permit varying compression ratio.

Bore: 3-1/16 in.

Stroke: 4-1/2 in.

Carburetion: Two Schebler Model DXL 87 single-venturi compensating jet type with adjustable needle valve in main jet and one in idling jet. Carburetors connected to intake pipe by means of a three-way valve permitting use of only one carburetor at a time. Intake pipe electrically heated.

Ignition: Conventional jump-spark battery system with manual spark advance, Auto-Lite single-arm breaker geared to camshaft, and dual-secondary ignition coil. One secondary winding of coil connected to spark advance indicator dial. Breaker point gap 0.022 in., spark plug gap 0.025 in.

Valves: Poppet type, one inlet and one exhaust, set vertically in top of cylindrical combustion chamber.
Tappet clearance (cold) - Exhaust 0.012 in.
- Inlet 0.010 in.

Valve Gear: Single overhead camshaft driven through gear train and vertical splined shaft (to permit movement of cylinder head); rocker arms with ball bearing cam followers and adjustable cams.

Valve Timing:

Exhaust closes	0 deg.	t.d.c.
Exhaust opens	35 deg.	b.b.d.c.
Inlet opens	5 deg.	b.t.d.c.
Inlet closes	30 deg.	a.b.d.c.

Cooling System: Water-jacketed cylinder barrel and head; forced circulation; evaporative type with water-cooled condenser.

Dynamometer: Four horsepower d.c. electric cradle-type, manufactured by Diehl Electric Co., equiped with Fairbanks beam balance and necessary control equipment.

Gas Meter: (Used for measuring air flow), positive displacement type, manufactured by John J. Griffin & Co., Philadelphia, Pa. Type 30A, Serial No. 922380, Roanoke Gas Co. meter No. 2923.

Calibration: (By Roanoke Gas Co. on National Bureau of Standards certified gasometer)

Before test	0.4% error at rated capacity
	-0.4% error at 180 cu.ft./hr.
After test	1.0% error at rated capacity
	1.4% error at 180 cu.ft./hr.

Fuel Burette: Conventional fuel measuring type with 50 and 150 c.c. bulbs; individually calibrated.

Tachometer: (Panel) Electric tachometer manufactured by the Weston Electric Instrument Co., for the Bristol Co., Waterbury, Conn.
Indicator Model 18252, Serial No. 436
Magneto Model 44, Type A, Serial No. 6501.

Tachometer: (Hand) Multi-range centrifugal type manufactured by The Foxboro Co., Foxboro, Mass.,
Model S 7/6 30000, Serial No. 155901.

Thermometers:

Exhaust: 0 - 400°F. standard etched glass stem, total immersion type, mercury and nitrogen filled, graduated to two degrees.

Mixture: 0 - 300°F., same as above.

Water Outlet: 0 - 220°F., same as above.

Thermometers:
(Cont'd)

Water Inlet: 0 - 240°F. industrial type, mercury filled, 6 in., graduated to two degrees.

Atmosphere: Part of Tycos hygrometer, practically same as water inlet thermometer.

Fuel: Esso gasoline (regular grade), produced by the Standard Oil Co. of N. J.; specific gravity 0.730 at 80 °F.

Lubricant: Engine crankcase oil Esselube SAE 30, produced by the Standard Oil Co. of N. J.

Stop Watch: Manufactured by the R. J. Moylan Co.; graduated to one-tenth second.

Apparatus - Analyzers

Instrument "A":

Name: Mixture Master Combustion Indicator

Mfd. by: Electro Products Co., New York, N. Y.

Type: Thermal conductivity

Serial No. E3652

Range: 10 to 16 air-fuel ratio
53 to 100% combustion efficiency

Index: Adjust current 13 a.f.r.
Balance meter 10 a.f.r.

Instrument "B":

Name: Allen Combustion Analyzer

Mfd. by: Allen Electric & Equipment Co., Kalamazoo, Mich.

Type: Thermal conductivity

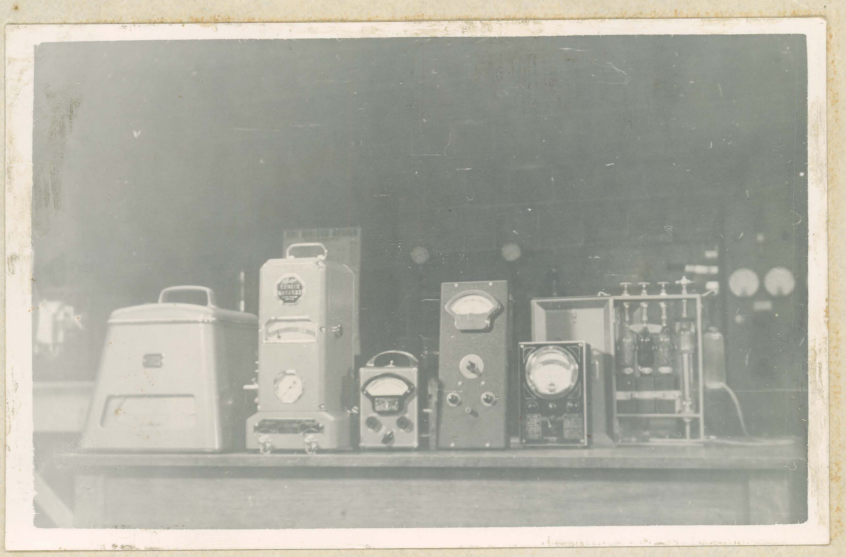


Fig. 1(b) - VIEW OF EXHAUST GAS ANALYZERS

From left to right:-
Instrument "F" (Hays Orsatomat)
Instrument "D" (Ranarex)
Instrument "C" (Stromberg)
Instrument "B" (Allen)
Instrument "A" (Mixture Master)
Instrument "E" (Hays Orsat)

Instrument "B"
(Cont'd)

Model: G32

Serial No.168299

Range: 10.7 to 16 air-fuel ratio
60 to 100% combustion efficiency

Index: Adjust current 16+ (off scale)
Balance meter 12.8

Instrument "C"

Name: Stromberg Precision Exhaust Gas Analyst

Mfd. by: E. A. Stromberg Co., Chicago, Ill.

Type: Hot-wire catalytic

Model: EP1

Serial No.1436

Range: 9.5 to 15 air-fuel ratio
50 to 100% combustion efficiency

Index: Adjust current 9.5
Balance meter 13.1

Instrument "D"

Name: Ranarex

Mfd. by: Ranarex Instrument Div. of The Permutit Co.,
New York, N. Y.

Type: Relative density

Model: Bendix Ranarex

Serial No.P-1517

Range: 8 to 17 air-fuel ratio
50 to 100% combustion efficiency

Index: Air-check 11.5

Instrument "E"

Name: Hays Improved Gas Analyzer

Mfd. by: The Hays Corp., Michigan City, Ind.

Type: Orsat (selective chemical absorption)

Model: 3-unit "Engineers' Model"

Serial No. 462980-1

Capacity: 50 c.c. gas sample

Least Reading: 0.2%

Reagents: Hays Cardisorber (for CO_2)
Hays $SeesO_2$ (for O_2)
Hays cuprous chloride (for CO)

Instrument "F"

Name: Hays Orsatomat

Mfd. by: The Hays Corp., Michigan City, Ind:

Type: Automatic Orsat, for CO_2 and O_2

Model: Catalog No. 6007

Serial No. 908850 L 7

Range: 0 to 20% (CO_2 + O_2)

Least Reading: 0.5%

Reagents: Hays Cardisorber (for CO_2)
Hays $SeesO_2$ (for O_2)

Apparatus - Operation

The operation of the thermal conductivity type of exhaust gas analyzer is based upon the fact that all elementary gases have a slightly different coefficient of thermal conductivity. The thermal conductivity coefficient of a mixture of gases thus varies with the composition (both qualitative and quantitative) of the mixture.

It has been found that the composition of the gases resulting from the combustion of gasoline in an engine cylinder is accurately governed by the amount of air supplied to burn a unit of fuel. Since this is true, it would seem logical that the thermal conductivity of the exhaust gases should also bear some definite relation to the air-fuel ratio, and such has been found to be the case.

Ordinarily, exhaust gas analyzers of the type under discussion do not actually measure the thermal conductivity of the exhaust gas but compare it with the thermal conductivity of some reference gas, generally air. It is thus possible to calibrate the instrument in such a manner that the readings are directly in terms of air-fuel ratio, percentage of completeness of combustion, or both.

Basically, the operation of the instrument is as follows: An electrical circuit comprised of four resistances, a galvanometer, and a battery is arranged in the form of the well-known Wheatstone bridge. Referring to Figure 2, it can

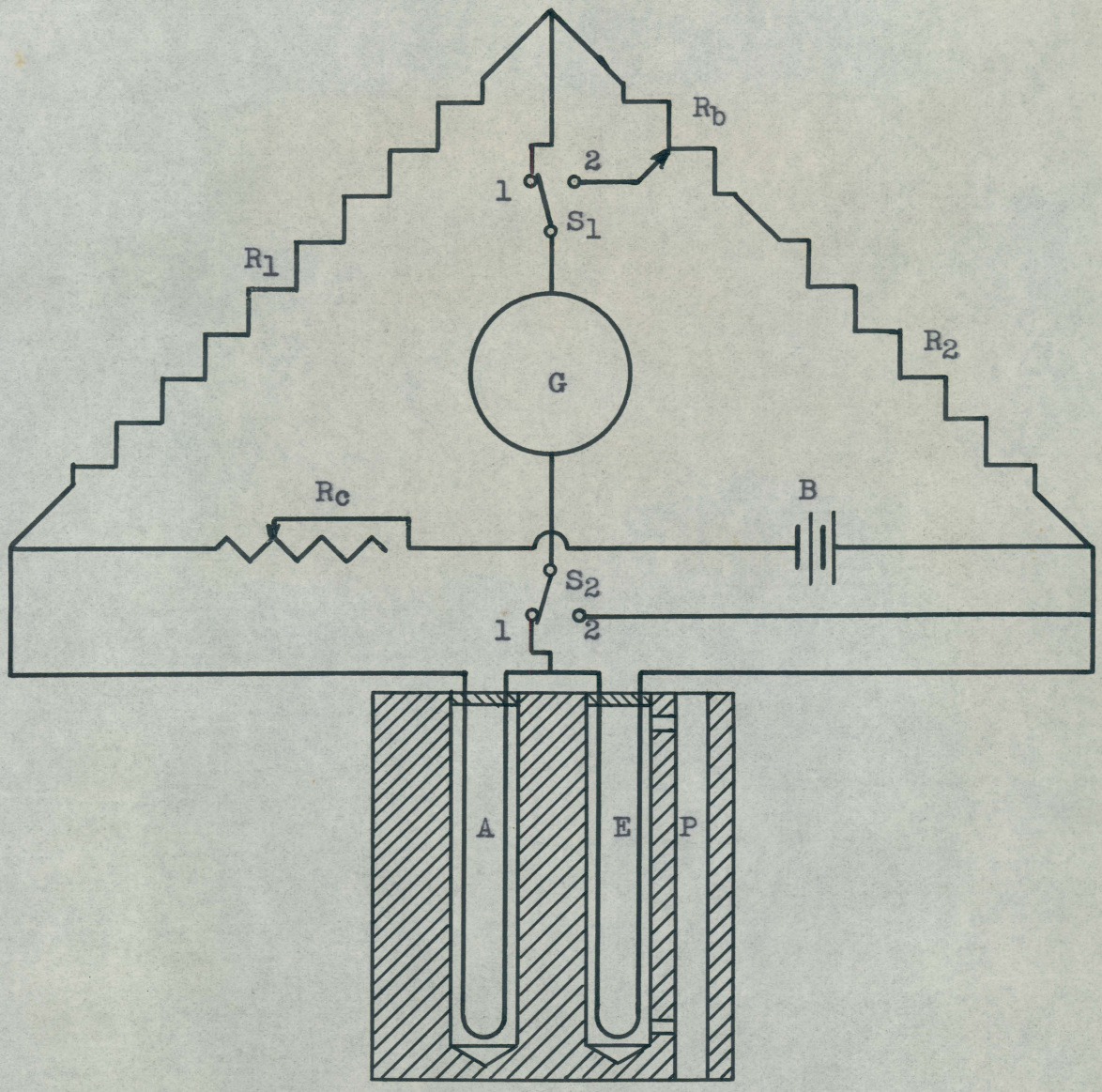


Fig. 2 - CIRCUIT DIAGRAM FOR THERMAL CONDUCTIVITY AND CATALYTIC TYPES OF EXHAUST GAS ANALYZERS

be seen that two of the arms of the bridge are encased in holes A and E in the metal cell block. Cell A is filled with the reference gas (air) while the gas to be analyzed is allowed to diffuse through cell E from gas passage P. The other two resistances, R_1 and R_2, are fixed resistances and may or may not be enclosed in the cell block. When the proper switches are closed and the necessary adjustments made, R_1, R_2, R_A, and R_E will all have the same resistance and current from the battery will be evenly divided between the two sides of the bridge, resulting in no deflection of the galvanometer. The flow of current through coils R_A and R_E will cause them to heat up (generally to about 100 ^{o}C.) and their resistance will thus be increased appreciably because they are made of platinum, nickel, or other metal having a high temperature coefficient of resistance. There will still be no current passing through the galvanometer, however, if the temperatures of both coils are the same.

If, as is often the case, the thermal conductivity of the gas in cell E is different from that of the air in A, then the two wires will not attain the same temperature (because one will be cooled by the surrounding gas more rapidly than the other) and thus will not have identical resistances. This inequality in resistance between R_A and R_E will unbalance the bridge (R_1 and R_2 are still at the same temperatures as they are both exposed to air), thus causing a

deflection of the galvanometer. The movement of the needle will be proportional to the difference between the thermal conductivity of the reference gas and that of the sample being tested, and since this was shown to be a function of mixture ratio, the scale on the instrument can be graduated in terms of the latter.

In order for the readings of the analyzer to be consistent, the circuit must be balanced and the current flowing through it must always be the same. These adjustments are achieved by means of two rheostats, R_b and R_c. First, the current is adjusted to a fixed value by moving switch S_1 to position 1 (as shown), and placing the other switch, S_2, in position 2. (Both switches are generally made as a single unit to simplify this procedure). The galvanometer is now in parallel with fixed resistance ($R_2 + R_b$) and acts as a millivoltmeter to measure the "RI drop" across this resistance. The deflection of the pointer is thus proportional to the current flowing through R_2, and this current can be regulated by means of rheostat R_c. On all instruments there is an index on the galvanometer scale to which the pointer is brought to adjust the current to the correct value. When the current is thus adjusted, it will not change except as the battery voltage decreases through use, provided the temperature of R_2 remains substantially constant and equal to that of R_1 (as is usually the case). However, this

adjustment should be checked at fairly frequent intervals when the instrument is in use, especially if the batteries are small or if they are nearly "run down".

When the current is properly adjusted, the bridge may be balanced after first reversing the position of the switches (moving S_1 to point 2 and S_2 to point 1) and blowing fresh air into gas cell, E. These conditions having been met, rheostat R_b is adjusted until the deflection of the galvanometer is zero. This point is indicated on the scale by another special index mark. After this adjustment the instrument is ready for operation and the bridge should remain in balance as long as the temperatures of resistances R_1, R_2, and R_A are equal. Frequently, however, (especially in the cheaper instruments) R_1 and R_2 are not mounted in the cell block and therefore will not attain as high a temperature as R_A. For this reason, the balance of the bridge, as well as the current adjustment, should be checked frequently, at least until the apparatus has thoroughly warmed up.

In construction and operation, the hot-wire catalytic type of instrument is almost identical to the thermal conductivity type just described. The only difference lies in the fact that in the catalytic type the resistances are so designed that coils R_A and R_E operate at red heat instead of at relatively low temperatures. Platinum, the material of which these wires are generally made, has the property of assisting or causing combustion which would not occur if no

catalyst were present. Therefore, when exhaust gas containing combustible constituents such as hydrogen, carbon monoxide, or methane is mixed with a small amount of air and passes over the glowing platinum wire, combustion ensues on the surface of the wire, thus raising its temperature considerably. The resistance of coil R_g is thereby greatly increased and the bridge becomes unbalanced, the deflection of the galvanometer indicating the relative quantity of the unburned gases in the exhaust. These quantities, like thermal conductivity, bear a certain relation to the air-fuel ratio supplied to the engine and hence the scale can be graduated in terms of air-fuel ratio and completeness of combustion as before.

It is apparent that the catalytic method is also affected by the thermal conductivity of the gases to some extent. The effects of variations of this property have a negligible effect on the temperature of the hot wire, however, as compared with the temperature rise caused by combustion.

It is equally obvious that this type of instrument is of no value whatsoever for analyzing gases which contain no combustible constituents. The significance of this limitation in connection with engine exhaust analysis is discussed in detail in a later section of this thesis.

A third type of analyzer utilizes the density of the exhaust gases as an indication of air-fuel ratio. The computed relation between density and mixture ratio is shown

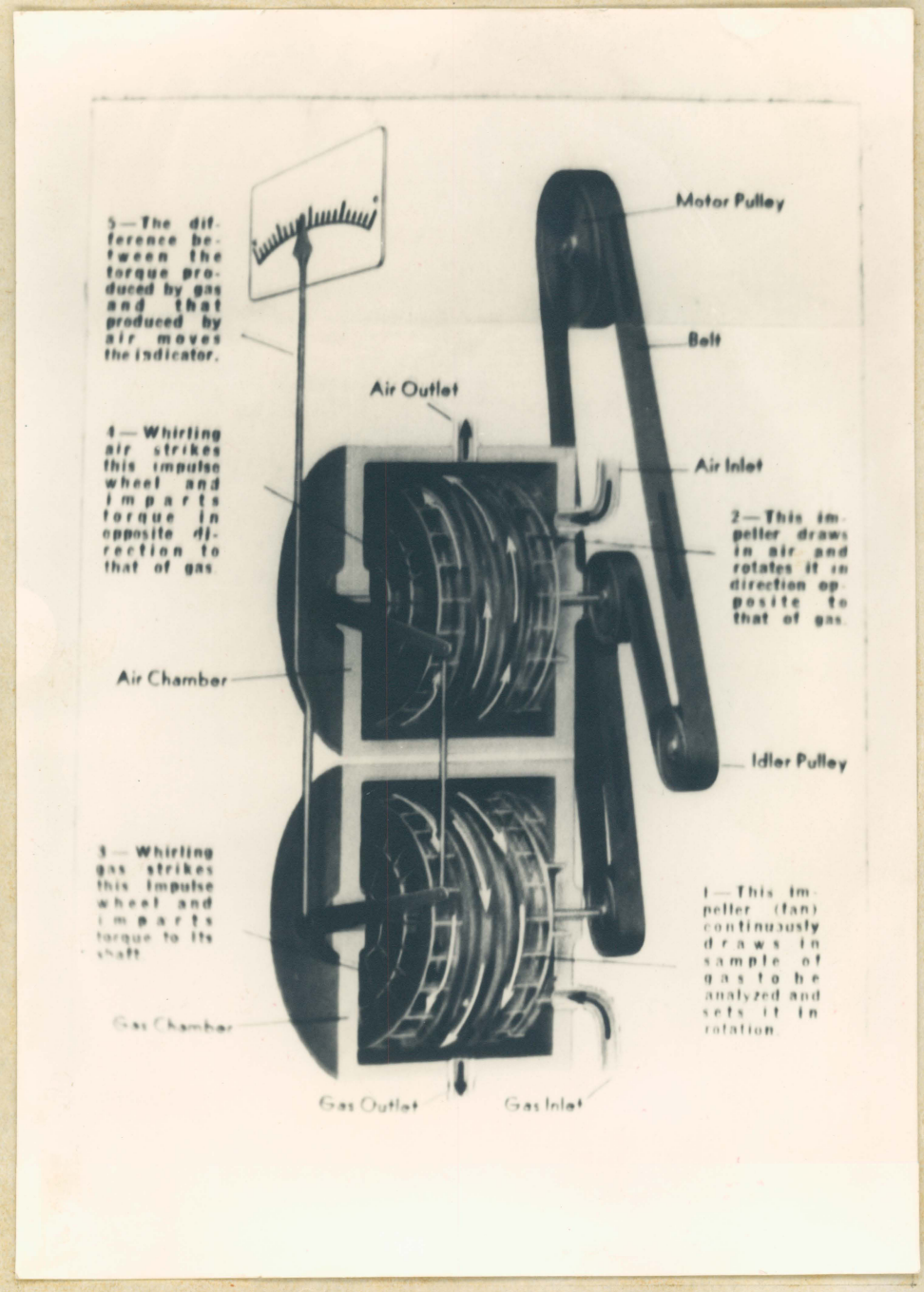


Fig. 3 - ILLUSTRATION OF OPERATING PRINCIPLE OF CENTRIFUGAL TYPE OF RELATIVE DENSITY EXHAUST GAS ANALYZER

in Figure 4 on page 47. Thus, if the density of the gases can be accurately determined, the air-fuel ratio can likewise be found, provided it is not greater than 14.7 to 1.

The principles of operation and the essential construction features of the Ranarex analyzer (the only American-made instrument employing this method for engine exhaust gas analysis) are shown in the cut on the preceding page. The instrument consists of two cylindrical chambers, each containing a set of two impellers. One impeller of each pair rotates at constant speed, driven by an electric motor. The second wheel in each set is free to rotate except as constrained by the linkage outside of the housings which connect these wheels to each other and to the pointer of the instrument. The two rotating fans, which turn in opposite directions, impart a whirling motion to the gases surrounding them. This motion of the gas exerts a torque on the opposite impellers. Because the torques on the two inter-connected wheels are in opposite directions, however, they will rotate only until an equilibrium point is reached, this point depending on the density of the gas in each rotor casing and also on the design of the linkage connecting the two stator wheels. Once the lay-out of the linkage is properly fixed, the device becomes an instrument for measuring the density of one gas as compared with another. This principle is applied to the problem of gas analysis simply by drawing air

into one chamber and the gas to be analyzed into the other. Both are presumably at the same temperature and pressure (approximately atmospheric), and both are saturated with moisture by means of humidifiers incorporated in the instrument; therefore the relative density should always give an indication of the air-fuel ratio, regardless of slight changes in surrounding conditions.

Of course, the oldest and most reliable way of analyzing gases of any kind is by one of the established chemical methods. The Orsat apparatus was used periodically in this investigation as a check on the other instruments, but since chemical analysis is not within the scope of this work, it will not be discussed in any detail. The Hays Orsatomat, which was used in some of these tests, is simply a modification of one of the several forms of automatic instruments operating on the Orsat principle which are to be found in most steam generating plants.

Procedure

The procedure followed in this experimental work was quite simple. Basically, it consisted of maintaining constant every factor possible during a given run and varying only the air-fuel ratio.

These various elements might be itemized more specifically as follows:

1. Factors maintained as nearly constant as possible:
   a. Engine compression ratio (6.0 to 1)
   b. Engine speed (1400 ± 10 r.p.m.)
   c. Engine jacket water temperature (195 ± 5 °F.)
   d. Mixture temperature (140 ± 5 °F.)
   e. Exhaust temperature (130 ± 10 °F.)
   f. Exhaust pressure, except where intentionally varied
   g. Throttle opening (full)
   h. Spark advance, except where intentionally varied
   i. Brand and grade of fuel used
   j. Quantity of fuel used per run (150 c.c.)
2. Factors beyond control, but presumably fairly constant:
   a. Barometric pressure
   b. Room temperature
   c. Humidity of intake air
3. Factors automatically varied by changine air-fuel ratio:
   a. Specific fuel consumption
   b. Power developed by engine

The "standard" runs were made with a spark advance of 25 crankshaft degrees before top dead center (approximately the spark setting for maximum power) and an exhaust pressure (measured at the analyzer taps on the exhaust pipe) of about 0.9 inches of mercury above atmosphere. Three separate runs were made at different times under these identical conditions in order to give a thorough check on the observations and results. Three other series of runs were made under conditions the same as before except with a spark advance of 15°, 35° and 40°, respectively. Another series of four runs was made with a spark advance of 25° but with an exhaust pressure of approximately 0.25 inches of mercury instead of 0.9 inches. In each of these series one basic run was made in which the mixture ratio was varied from the leanest on which the engine would run without missing excessively, to the richest, in the smallest possible increments (approximately 0.02 turns of the carburetor needle valve). In the check runs, larger steps were used, and in some cases not so wide a range was covered.

In all of the series of runs so far described the gas analyzers were attached to nipples on the exhaust pipe by means of hose supplied by the manufacturers, and no attempt was made to regulate the pressure of the gas at the instruments, nor its rate of flow, other than by maintaining a constant pressure at the source as previously mentioned. A final series of observations were made, however, in which the

pressure of the gas was regulated separately at each instrument, and this pressure was varied through the total available range in order to determine more accurately the effect of the rate of flow on the accuracy of the instruments.

No provision was made for drying or filtering the gases before they entered the analyzers because it was desired to simulate actual service conditions as closely as possible. Care was taken, however, to prevent the accumulation of appreciable quantities of water in the hoses leading to the instruments. After about half of the tests were completed (at end of Run No. 618), instruments "A", "B" and "C" were flushed with alcohol to clean the gas cells (as instructed by one manufacturer) and a check run was made to determine the effect of this cleaning. No change could be observed so the procedure was not repeated.

In all cases, the manufacturers' instructions were followed explicitly in the manipulation of the gas analyzers, and every precaution was observed to see that these instruments were handled properly. Prior to making any reading, all of the analyzers were disconnected from the gas source, thoroughly aspirated with air, and balanced or otherwise adjusted as specified. Immediately after the readings were taken, the instruments were again disconnected, cleared of exhaust gases, and rechecked for balance. Readings were taken of all analyzers as nearly simultaneously as possible,

but only after the indication became steady. These observations were re-checked after approximately one minute had elapsed.

Air and fuel consumption were measured for practically the same period of time so as to obtain corresponding values, and the duration of the measuring period was sufficient to insure obtaining average values. One hundred fifty cubic centimeters of gasoline and 35 cubic feet of air were consumed during each test period, the time required for each of these quantities to be used being measured independently with stop watches. The time required averaged about five minutes. Exhaust gas samples for analysis were obtained at approximately the middle of this period, sufficient time having elapsed since conditions were last changed to insure the presence of "fresh" gases in the exhaust pipe.

Data and Results

Although it is believed that the tables and curves which appear on the succeeding pages are for the most part self-explanatory, it may be well to make a few comments regarding them.

The following key to the system of run numbers used in identifying the various observations might be helpful: The first digit of the number is an indication of the date on which the run was made. The second numeral identifies the series or group of runs, and the third (and fourth, if any) figure(s) is simply the observation or run number.

It will be noticed that the tables are organized so that each contains the data secured under certain similar conditions, though possibly in different series of runs. The tests shown in Table 1(c) were conducted under practically the same conditions as the tests of Table 1(a), but are not included in the latter because they were check runs made near the end of the investigation to determine whether the results obtained earlier could be duplicated.

The term "needle valve setting" which appears in several of the tables refers to the carburetor adjustment by means of which the air-fuel ratio was changed. It is useful chiefly for purposes of comparison, and may be considered purely as a relative number.

Air-fuel ratio is, of course, expressed in pounds of air per pound of fuel at room conditions.

Table I(a)

DATA AND RESULTS BY EXHAUST GAS ANALYZERS

Spark Advance 25° Exhaust Pres. 0.8 "Hg

Run No.	Needle Valve Setting	Air-Fuel Ratio	Instrument Read., air-fuel ratio			
			"A"	"B"	"C"	"D"
111	9	15.8	14.8	13.6	13.6	13.6
112	9	17.7	14.7	13.4	13.7	13.6
113	10	15.7	15.0	13.7	13.9	13.7
114	11	14.3	15.1	13.8	13.9	13.8
115	12	13.2	13.8	13.0	13.4	13.1
116	13	12.3	12.3	12.3	12.6	12.8
117	14	11.5	11.5	11.5	11.5	12.5
118	15	10.9	10.6	11.3	10.9	12.0
119	16	10.4	----	11.0	10.1	11.5
1110	17	9.8	----	----	----	11.2
1111	20	8.6	----	----	----	9.6
1112	23	6.5	----	----	----	8.5
211	9	16.9	14.9	13.6	13.7	12.8
212	10	15.6	15.2	13.7	13.9	13.1
213	11	14.4	15.3	13.7	13.7	13.2
214	12	13.3	13.8	13.2	13.3	13.0
215	13	12.5	12.7	12.5	12.5	12.2
216	14	11.7	11.5	11.9	11.7	11.5
217	15	10.9	10.3	11.2	10.7	11.0
218	16	10.4	----	11.0	10.1	10.7
219	17	9.9	----	10.5	----	10.1
2110	22	8.3	----	----	----	8.8

Constant Data

Engine Speed 1400 r.p.m.
Compression Ratio 6 to 1
Esso Gasoline (regular)

Ave. Water Temp. 198 °F.
Mixture Temp. 140 °F.
Exhaust Temp. 130 °F.

Table I(b)

DATA AND RESULTS BY EXHAUST GAS ANALYZERS

Run No.	Needle Valve Setting	Air-Fuel Ratio	Instrument Read., air-fuel ratio "A"	"B"	"C"	"D"
Spark Advance 15°					Exhaust Pres. 0.8 "Hg	
131	9	17.4	14.6	13.4	13.5	13.3
132	11	14.4	15.2	13.7	13.8	13.3
231	9	17.3	14.8	13.5	13.6	13.4
232	10	15.8	14.9	13.6	13.8	13.5
233	11	14.6	15.0	13.8	13.7	13.3
234	12	13.4	13.8	13.2	13.3	13.0
235	13	12.5	12.4	12.4	12.4	12.1
236	15	10.9	10.3	11.2	10.5	10.9
Spark Advance 35°					Exhaust Pres. 0.8 "Hg	
121	9	17.0	14.8	13.4	13.8	13.3
122	9	17.0	14.8	13.4	13.5	12.9
123	11	14.4	15.3	13.8	14.0	13.2
124	13	12.4	12.9	12.6	12.6	11.9
125	15	10.9	10.8	11.4	11.2	11.8
126	17	9.9	----	10.8	9.7	10.2
Spark Advance 40°					Exhaust Pres. 1.0 "Hg	
311	8	19.0	14.7	13.7	13.7	13.1
312	9	16.5	14.8	13.9	13.8	13.3
313	10	15.2	15.3	14.0	14.0	13.5
314	11	14.2	15.0	13.9	13.8	13.7
315	12	13.0	13.8	13.2	13.0	12.7
316	13	12.5	12.6	12.8	12.6	12.0
317	14	11.5	11.25	11.8	11.8	11.4
318	15	10.8	10.3	11.3	10.9	10.9
319	16	10.4	----	11.0	10.3	10.5
3110	17	9.8	----	10.9	9.7	10.1
3112	19	9.0	----	----	----	9.2

Constant data on preceeding page

Table I(c)

DATA AND RESULTS BY EXHAUST GAS ANALYZERS

(Final Check Run)

Spark Advance 25° Exhaust Pres. 1.2 "Hg

Run No.	Needle Valve Setting	Air-Fuel Ratio	Instrument Read., air-fuel ratio			
			"A"	"B"	"C"	"D"
811	10	18.8	14.7	13.7	13.4	13.8
812	12	15.0	15.3	14.0	13.7	14.0
813	14	12.8	12.8	12.8	12.5	12.5
814	16	11.1	10.8	11.5	10.8	11.2
815	18	10.2	----	11.0	----	10.1

Constant Data

Engine Speed 1400 r.p.m.
Compression Ratio 6 to 1
Esso Gasoline (regular)

Ave. Water Temp. 197 °F.
Mixture Temp. 140 °F.
Exhaust Temp. 160 °F.

Table II

DATA AND RESULTS BY EXHAUST GAS ANALYZERS

Spark Advance 25° Exhaust Pres. 0.2 "Hg

Run No.	Needle Valve Setting	Air-Fuel Ratio	Instrument Read., air-fuel ratio			
			"A"	"B"	"C"	"D"
511	9	18.7	13.2	12.5	13.3	13.0
512	10	16.7	14.2	12.4	13.5	13.1
513	11	15.4	14.3	12.5	13.7	13.4
514	12	14.5	13.7	12.5	13.6	13.6
515	13	13.6	13.7	12.5	13.3	13.1
516	14	12.5	12.7	12.4	12.8	12.4
517	15	11.7	11.8	12.3	12.4	11.9
518	16	11.2	11.0	12.3	11.8	11.5
519	17	10.6	10.2	12.2	11.4	11.1
5110	18	10.2	----	12.2	10.9	10.8
611	9	19.9	13.2	12.4	13.2	12.9
612	10	18.1	13.2	12.4	13.4	13.1
613	12	15.0	13.4	12.4	13.5	13.6
614	14	13.1	13.0	12.4	12.9	12.7
615	16	11.7	12.4	12.3	11.9	11.6
616	18	10.5	11.9	12.1	11.4	11.0
617	19	10.0	11.7	12.1	10.6	10.6
618	20	9.8	11.3	12.1	10.4	10.4
711	10	18.5	13.3	12.3	13.3	13.1
712	12	15.7	13.4	12.4	13.6	13.6
713	14	13.4	13.2	12.4	13.0	12.9
714	16	11.9	12.4	12.3	11.9	11.6
715	18	10.6	11.9	12.2	11.0	11.1
716	20	9.8	11.4	12.1	10.1	10.5
717	22	9.1	10.8	11.9	----	10.1
721	10	18.7	13.3	12.5	13.3	13.1
722	15	12.6	12.8	12.3	12.5	12.1

Constant Data

Engine Speed 1400 r.p.m.
Compression Ratio 6 to 1
Esso Gasoline (regular)

Ave. Water Temp. 197 °F.
Mixture Temp. 140 °F.
Exhaust Temp. 130 °F.

Table III

DATA AND RESULTS BY EXHAUST GAS ANALYSIS

Spark Advance 25° Exhaust Pres. Varied

Run No.	Air-Fuel Ratio	Exhaust Pres., "H_2O	Instrument Read., air-fuel ratio			
			"A"	"B"	"C"	"D"
Needle Valve Setting 11						
731	17.0	0.75	14.1	13.1	13.7	13.8
732	17.3	1.5	14.8	13.1	14.0	13.9
733	17.8	3.0	15.0	14.6	14.1	14.0
Needle Valve Setting 10						
821	18.2	0.5	14.3	13.2	13.8	13.9
822	18.4	1.5	15.0	13.2	14.0	13.7
823	18.1	3.0	15.1	14.2	14.1	13.6
824	18.1	5.0	15.0	14.2	14.1	13.5
Needle Valve Setting 14						
831	12.8	0.5	13.3	13.2	12.9	12.7
832	12.8	1.5	13.2	13.2	13.2	12.6
833	12.7	3.0	13.3	13.1	12.9	12.4
834	12.8	5.0	13.2	13.2	13.1	12.5

Constant Data

Engine Speed 1400 r.p.m.
Compression Ratio 6 to 1
Esso Gasoline (regular)

Ave. Water Temp. 197 °F.
Mixture Temp. 140 °F.
Exhaust Temp. 150 °F.

Note:- Exhaust pressures shown in this Table are different from those in Tables I and II in that the above pressures were measured at the instrument instead of at the exhaust pipe.

Table IV(a)

DATA AND RESULTS BY CHEMICAL ANALYSIS OF EXHAUST GASES

Spark Advance 25° Exhaust Pres. 0.8 "Hg

Run No.	Air-Fuel Ratio	Analysis, % by volume on dry basis				
		Orsat			Orsatomat	
		CO_2	O_2	CO	CO_2	O_2
111	15.8	10.6	4.2	1.2	11.5	1.5
112	17.7	10.4	4.6	1.2	11.4	3.1
113	15.7	12.0	3.0	1.0	13.0	1.0
114	14.3	13.0	1.6	0.8	13.0	-1.4
115	13.2	11.4	1.6	1.8	12.2	-1.0
116	12.3	10.6	1.0	2.6	11.2	-1.0
117	11.5	10.0	0.7	2.3	10.0	-1.4
118	10.9	7.8	1.0	4.4	9.1	-1.2
119	10.4	7.6	0.8	4.6	8.0	-0.5
1110	9.8	6.6	1.4	5.0	6.5	-1.0
1111	8.6	4.4	1.6	7.0	5.1	-0.7
1112	6.5	3.8	1.2	7.4	4.6	-0.6
211	16.9	12.4	4.0	0.2	13.0	-1.3
212	15.6	13.4	1.7	0.0	13.1	-1.1
213	14.4	13.2	1.6	0.0	14.7	-2.5
214	13.3	12.0	1.4	1.2	12.7	-0.8
215	12.5	----	---	---	11.7	-1.7
216	11.7	10.2	1.2	3.6	10.5	-1.6
217	10.9	----	---	---	9.1	-1.4
218	10.4	8.2	0.8	5.4	8.2	-1.3
219	9.9	6.2	1.0	6.8	7.2	-1.0
2110	8.3	4.2	1.4	8.0	4.5	-0.7

Constant Data

Engine Speed 1400 r.p.m.
Compression Ratio 6 to 1
Esso Gasoline (Regular)

Ave. Water Temp. 198 °F.
Mixture Temp. 140 °F.
Exhaust Temp. 130 °F.

Note:- These analyses correspond to data shown in Table I(a).

Table IV(b)

DATA AND RESULTS BY CHEMICAL ANALYSIS OF EXHAUST GASES

Run No.	Air-Fuel Ratio	Analysis, % by volume on dry basis				
		Orsat			Orsatomat	
		CO_2	O_2	CO	CO_2	O_2
Spark Advance 15°					**Exhaust Pres. 0.8 "Hg**	
131	17.4	11.0	4.4	0.4	12.2	1.5
132	14.4	13.4	1.6	0.2	15.0	-3.1
231	17.3	11.8	4.2	0.0	11.0	3.2
232	15.8	----	---	---	12.8	-0.3
233	14.6	14.4	0.4	0.0	13.8	-1.0
234	13.4	13.2	0.0	0.9	12.5	-1.0
235	12.5	12.0	0.0	2.4	11.3	-1.3
236	10.9	9.1	0.5	4.8	8.9	-1.1
Spark Advance 35°					**Exhaust Pres. 0.8 "Hg**	
121	17.0	10.4	3.6	1.8	10.4	3.1
122	17.0	11.2	5.0	0.0	11.8	3.5
123	14.4	13.4	1.4	0.0	14.8	-1.4
124	12.4	11.2	0.9	2.0	12.0	-0.5
125	10.9	9.0	0.8	3.4	10.2	-1.7
126	9.9	7.0	0.8	4.9	7.3	-0.7
Spark Advance 40°					**Exhaust Pres. 1.0 "Hg**	
311	19.0	10.4	6.0	0.4	10.7	5.7
312	16.5	12.2	3.4	0.2	12.4	2.4
313	15.2	13.6	1.2	0.0	13.8	0.5
314	14.2	14.3	0.7	0.4	14.8	-1.7
315	13.0	12.8	0.0	1.4	12.5	-1.2
316	12.5	11.4	0.4	2.5	11.4	-1.2
317	11.5	10.4	0.6	3.7	10.0	-1.2
318	10.8	9.2	0.0	4.2	8 .7	-1.2
319	10.4	8.2	0.0	5.4	8.0	-2.0
3110	9.8	7.8	0.4	6.3	6.8	-1.1
3111	9.2	6.7	0.5	10.4	6.2	-1.0
3112	9.0	5.8	0.0	12.0	---	---

Constant data on preceeding page

Note:- These analyses correspond to data shown in Table I(b).

Table V

COMPUTED VALUES OF THERMAL CONDUCTIVITY AND DENSITY OF EXHAUST GAS AT VARIOUS AIR-FUEL RATIOS

Air-Fuel Ratio	Analysis, % by volume on dry basis					Density, lb./ft.^{3}	Thermal Conductivity
	CO_2	O_2	CO	H_2	CH_4		
Computed Theoretical Analyses							
8.0	3.8	0.2	17.3	11.5	0.4	0.0712	0.01336
9.0	5.4	0.2	14.8	8.9	0.4	0.0736	0.01309
10.0	7.0	0.2	12.0	6.4	0.4	0.0764	0.01283
11.0	8.6	0.2	9.3	4.3	0.4	0.0785	0.01263
12.0	10.2	0.2	6.8	2.7	0.3	0.0805	0.01241
13.0	11.9	0.2	4.2	1.4	0.3	0.0822	0.01227
14.0	13.5	0.2	1.7	0.6	0.3	0.0835	0.01212
14.7	14.7	0.2	0.2	0.2	0.3	0.0842	0.01203
15.0	14.4	0.5	0.2	0.2	0.3	0.0842	0.01205
16.0	13.4	1.8	0.1	0.1	0.2	0.0840	0.01212
17.0	12.6	2.9	0.1	0.0	0.2	0.0839	0.01218
18.0	11.9	3.9	0.0	0.0	0.2	0.0837	0.01224
19.0	11.3	4.8	0.0	0.0	0.2	0.0835	0.01228
Experimental Analyses							
11.0	8.7	0.2	8.6	4.0	0.4	0.0787	0.01259
11.0	8.7	0.3	8.9	3.7	0.3	0.0790	0.01257
11.0	9.0	0.2	8.8	3.4	0.4	0.0793	0.01256
14.6	13.6	0.4	0.8	0.0	0.4	0.0838	0.01211
14.6	14.0	0.7	0.5	0.0	0.1	0.0843	0.01209

Notes:-

(1) All exhaust gas analyses by D'Alleva and Lovell

(2) Thermal conductivity values of component gases from "International Critical Tables"

(3) Thermal conductivity in B.t.u./sq.ft./ft./hr./°F.

(4) Thermal conductivity and density computed for gas at 32°F. and 14.7 lb./sq.in. abs.

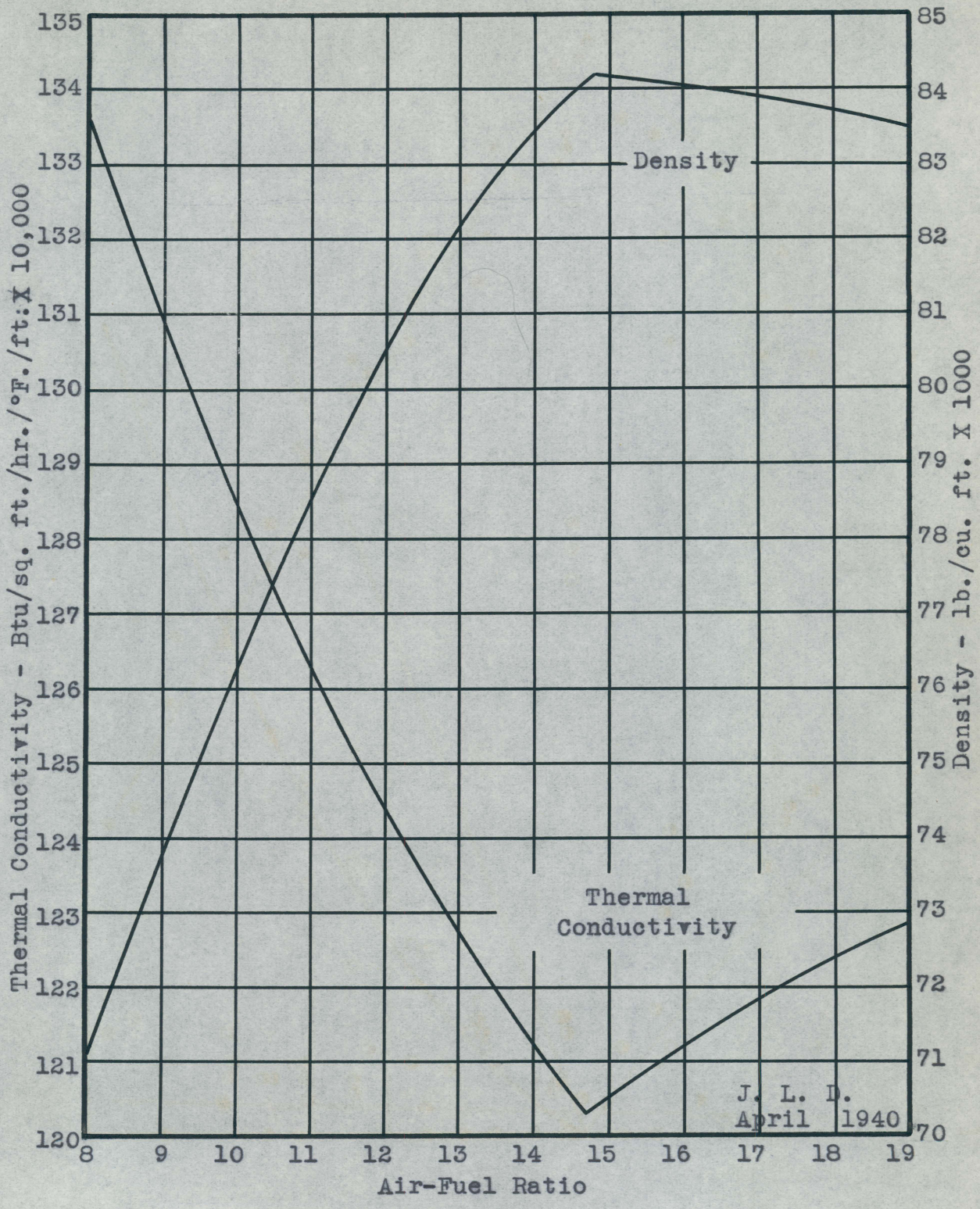


Fig. 4 - COMPUTED THERMAL CONDUCTIVITY AND DENSITY OF EXHAUST GASES AT VARIOUS AIR-FUEL RATIOS

Based on theoretical exhaust gas analysis as determined by D'Alleva and Lovell; thermal conductivity values from International Critical Tables; all data for gases at 32° F. and 14.7 lb./sq.in. absolute

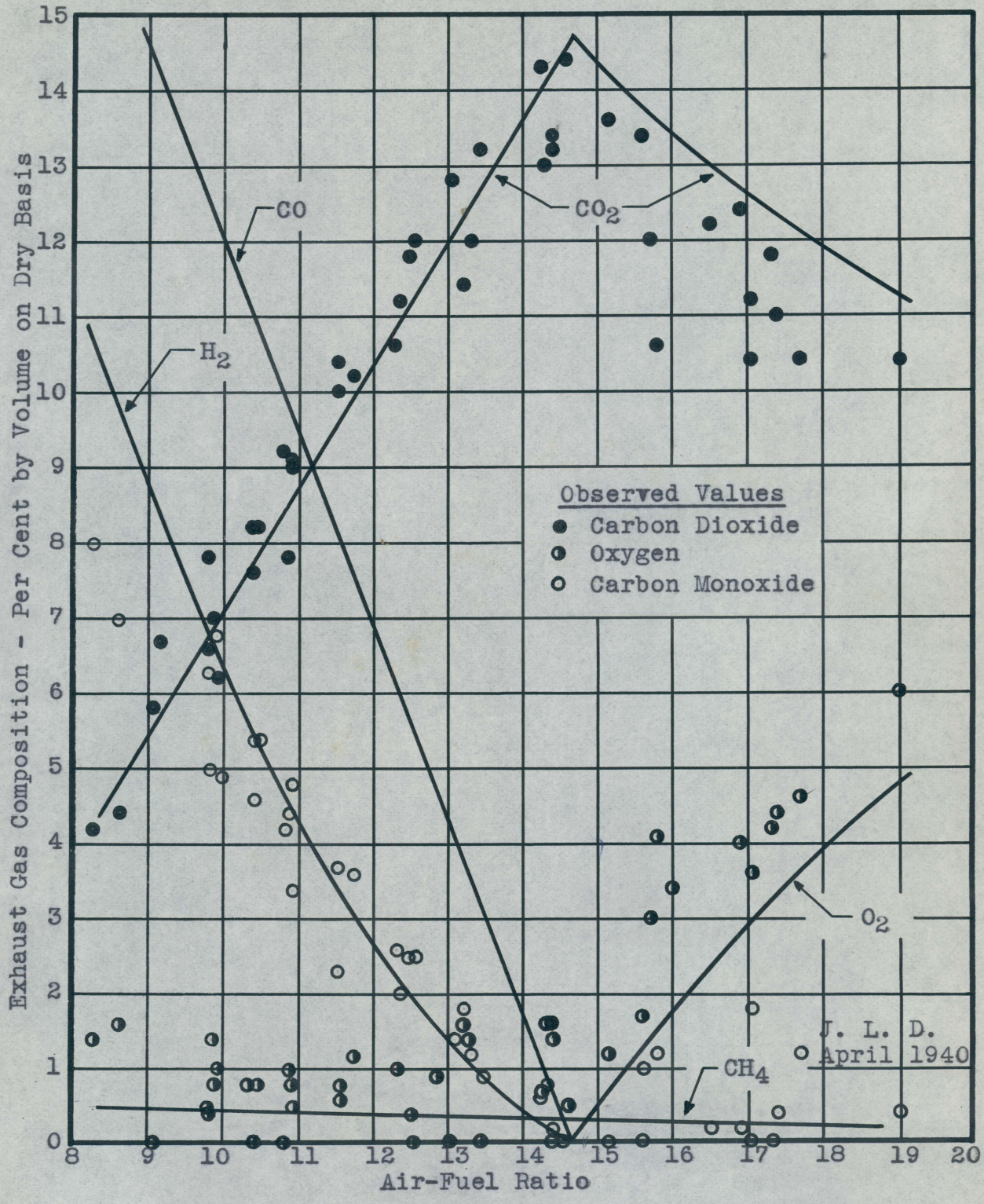


Fig. 5 - ORSAT ANALYSES OF VARIOUS EXHAUST GAS SAMPLES COMPARED WITH COMPUTED VALUES

Plotted points indicate experimental values; curves represent theoretical analyses (as determined by D'Alleva and Lovell)

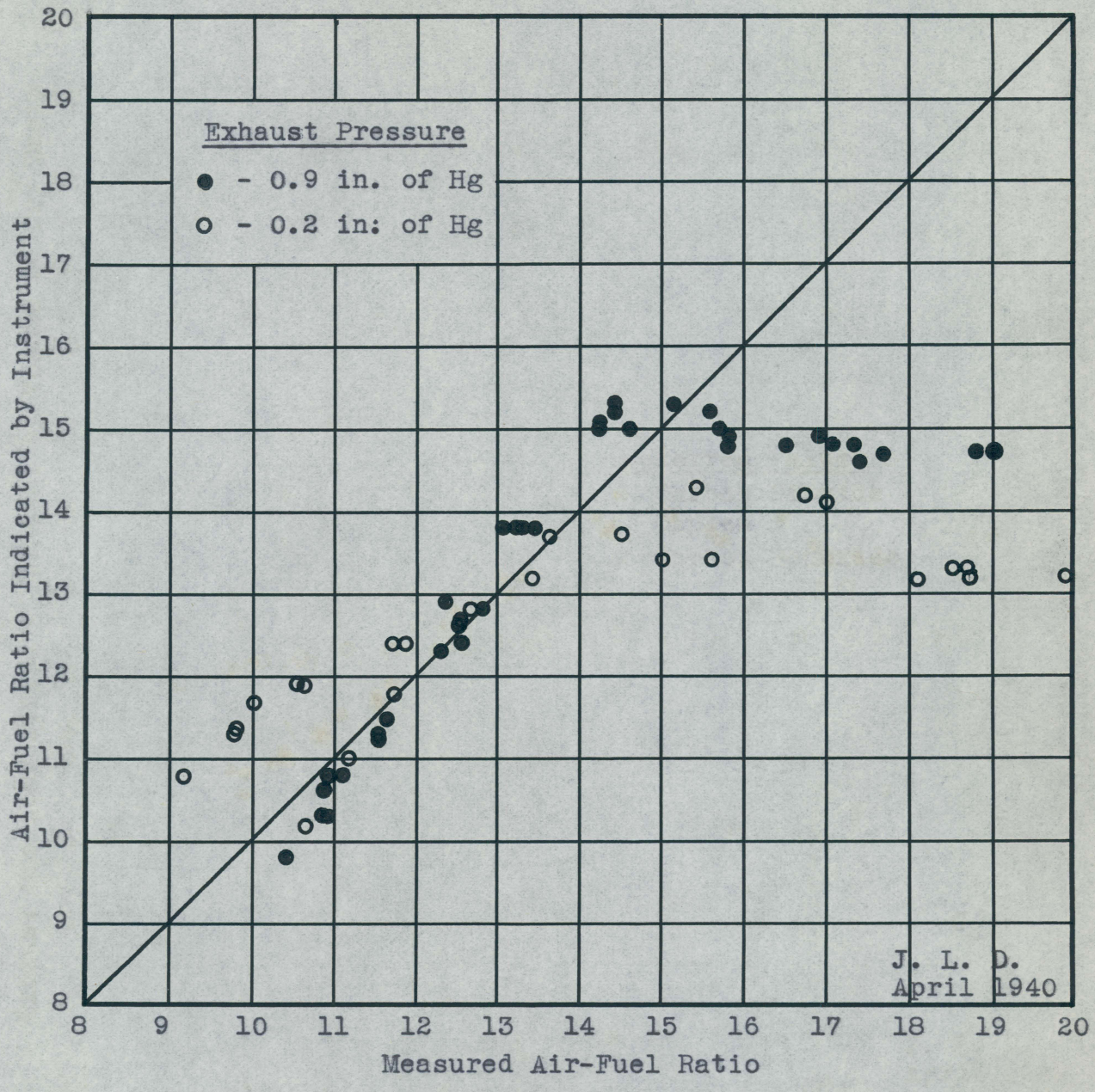


Fig. 6 - CALIBRATION CURVE OF INSTRUMENT "A"

Thermal conductivity type of exhaust gas analyzer; engine speed 1400 r.p.m., compression ratio 6.0:1, mixture temperature 140°F., exhaust temp. 130°F., spark advance varied from 15° to 40° b.t.d.c.; Esso gasoline

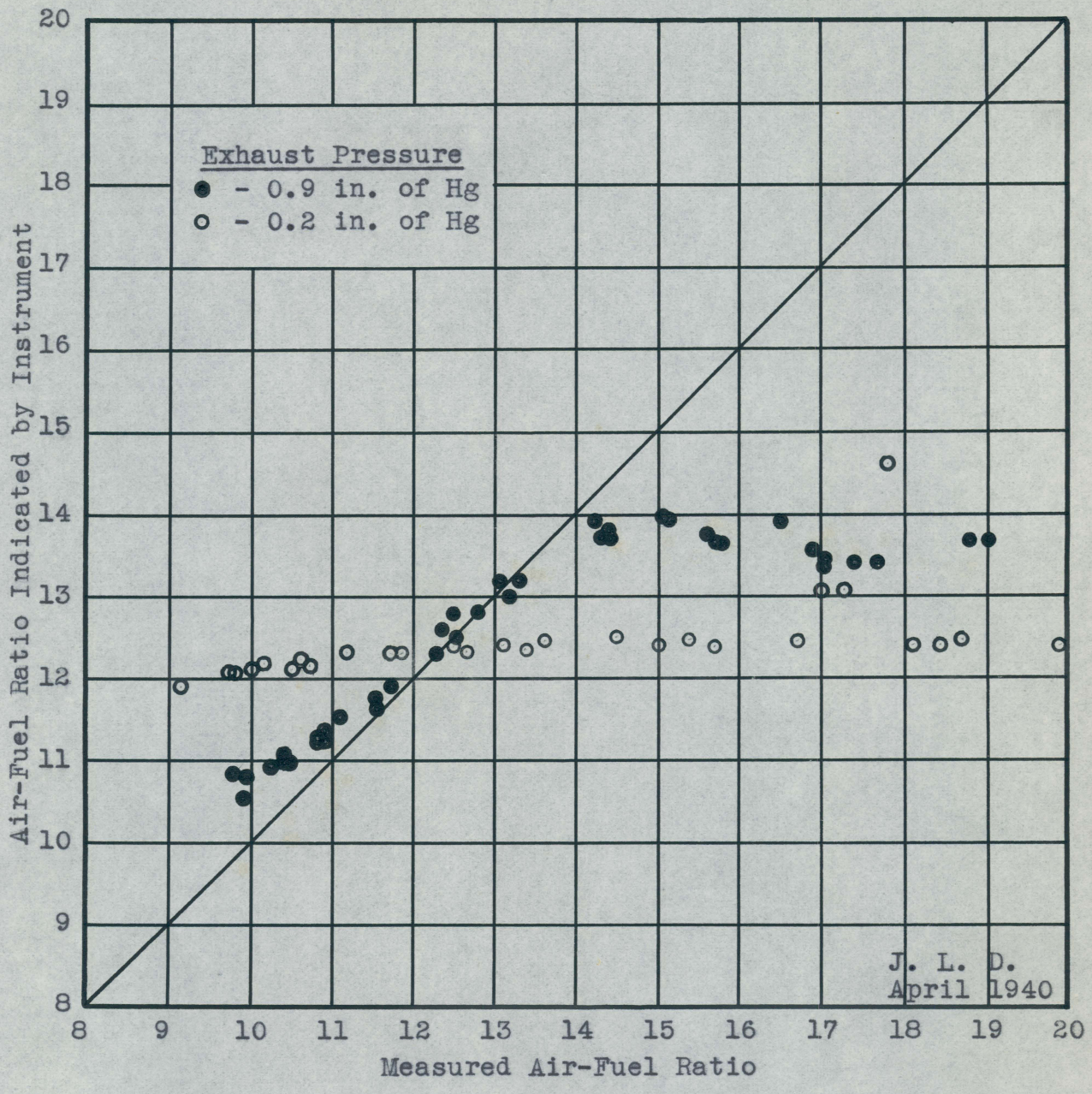


Fig. 7 - CALIBRATION CURVE OF INSTRUMENT "B"

Thermal conductivity type of exhaust gas analyzer; engine speed 1400 r.p.m., compression ratio 6.0:1, mixture temperature 140°F., exhaust temp. 130°F., spark advance varied from 15° to 40° b.t.d.c.; Esso gasoline

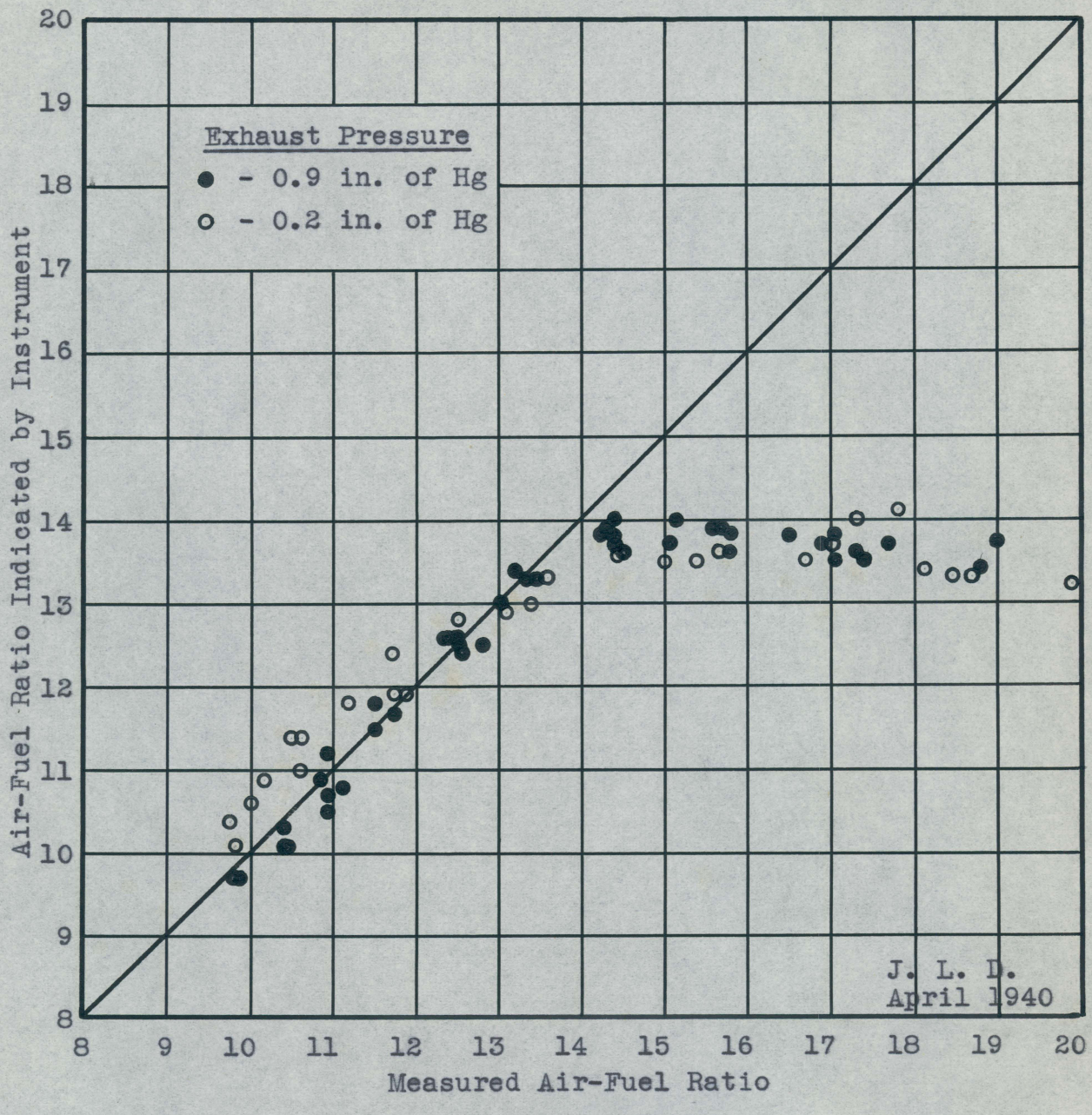


Fig. 8 - CALIBRATION CURVE OF INSTRUMENT "C"

Hot-wire catalyst type of exhaust gas analyzer; engine speed 1400 r.p.m., compression ratio 6.0:1, mixture temperature 140°F., exhaust temp. 130°F., spark advance varied from 15° to 40° b.t.d.c.; Esso gasoline

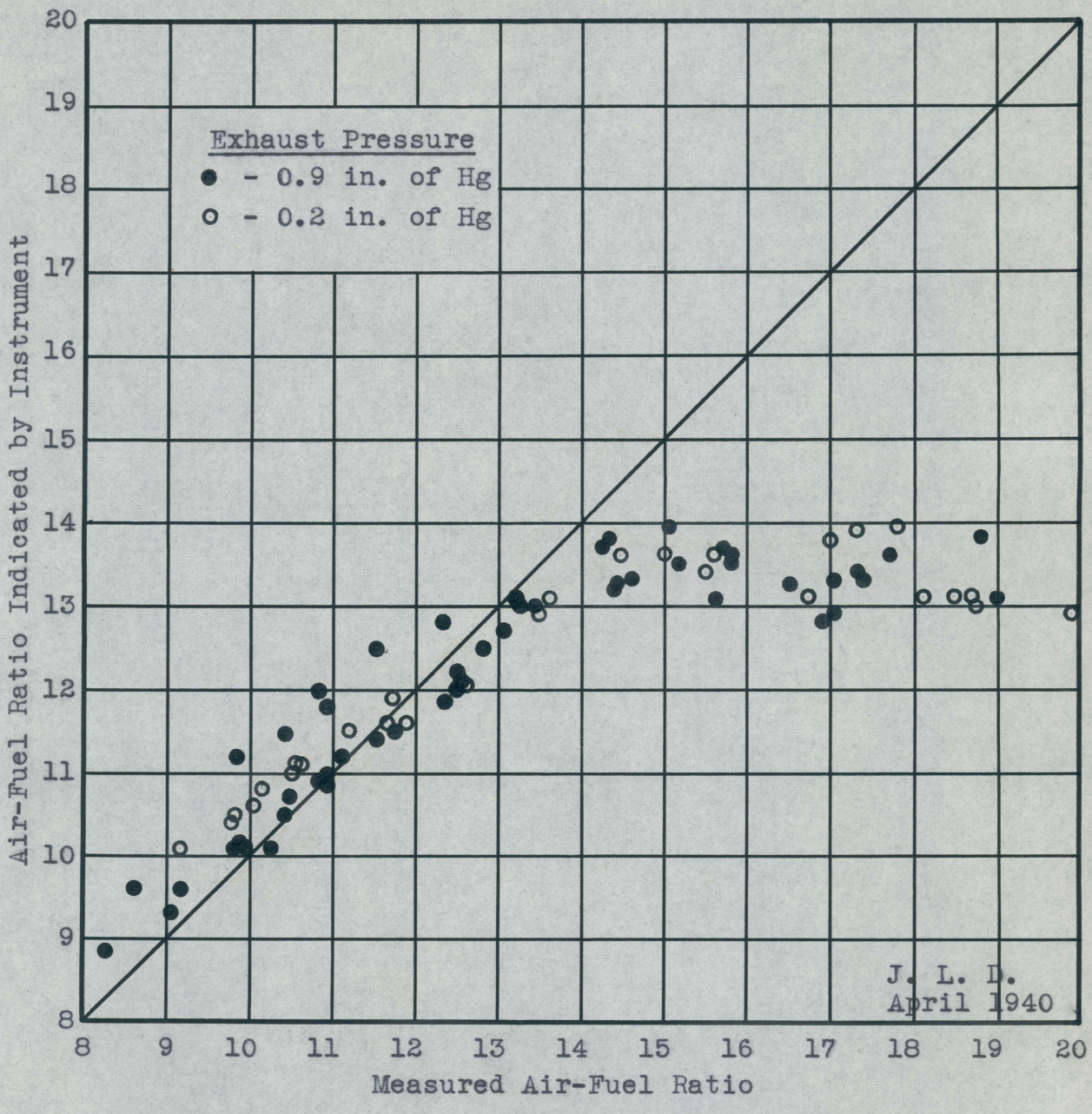


Fig. 9 - CALIBRATION CURVE OF INSTRUMENT "D"

Relative density type of exhaust gas analyzer;
engine speed 1400 r.p.m., compression ratio 6.0:1,
mixture temperature 140°F., exhaust temperature 130°F.,
spark advance varied from 15° to 40° b.t.d.c.;
Esso Gasoline

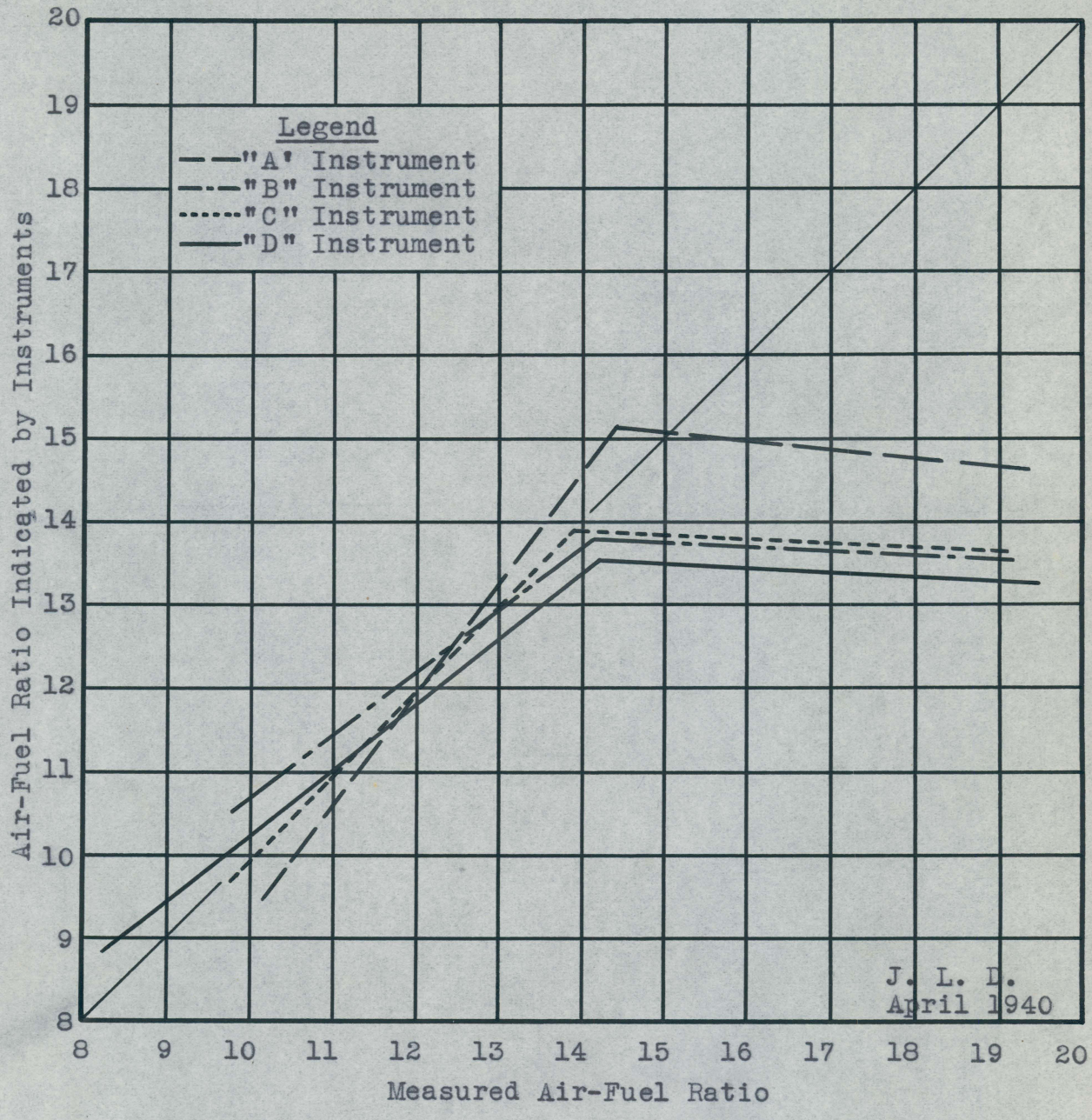


Fig. 10 - CONSOLIDATED CALIBRATION CURVES FOR ALL INSTRUMENTS

These curves represent the mean values taken from Figures 6 through 9, inclusive, for observations made with 0.9 in. of Hg exhaust pressure, only

General Observations

Instrument "A"

Under certain conditions this instrument gave a very unsteady reading, the pointer fluctuating through a range of about five-tenths of one air-fuel ratio. It was also exceptionally hard to keep adjusted and balanced, frequently returning to a point one-half of one air-fuel ratio from the "balanced meter" index after one minute's use. If sufficient time were allowed, however, this error would generally decrease.

Instrument "B"

This analyzer maintained its adjustment very well, required balancing very seldom, and would generally return to the balance index immediately after aspiration with fresh air.

Instrument "C"

The catalytic analyzer would remain in adjustment for long periods, but required considerable time to return to the balanced state after use. Under certain conditions, it was rather unsteady, the pointer slowly fluctuating over a range of several tenths of one air-fuel ratio. It also required a longer warm-up period than either of the thermal conductivity meters.

Instrument "D"

This apparatus was more sluggish in action than any of the other types previously discussed, but gave a steady reading when the proper indication was reached. It was likewise slow in returning to the "air check" point after being disconnected from the gas supply. It would return to this point unerringly when warm, but required about an hour's operation to attain normal conditions. It was also subject to flooding with water from the humidifiers if the gas pressure much exceeded atmospheric.

Instrument "F"

The automatic Orsat analyzer performed very poorly in these tests. The oxygen determination was generally badly in error, the action of the apparatus was considerably slower than that of any of the other types, and the indication never became entirely steady. This instrument is also adversely affected to a considerable extent by slight jars or vibration. It is believed, however, that this particular unit was improperly adjusted at the factory.

IV. DISCUSSION OF RESULTS

Method

Although the scope of this investigation, and the methods employed in conducting it, gave a considerable quantity of reliable data of importance, the writer feels that there is still much additional work which might be done in this field.

Perhaps the greatest shortcoming of the work as a whole is that only a limited number of makes of instruments were tested. Furthermore, it was impossible to obtain a Cambridge analyzer, which is generally conceded to be the best instrument of its type on the American market. Undoubtedly, information secured as to the performance of medium and low-priced instruments cannot be applied in full to the better makes without danger of refutation.

Experimental methods and apparatus used in these tests were sufficiently accurate and reliable for the work in hand, but as the tests progressed a number of small items were observed which might be refined or improved. The more important changes which might be incorporated in future tests of this nature are as follows: (a) Provide better speed regulation of engine by loading with an alternating current generator; (b) Employ means of heating the mixture which would permit faster and closer regulation and give a wider

temperature range; (c) Provide better means of controlling exhaust temperature (automatically, if possible); (d) Provide a means of controlling and measuring the rate of flow of gas through the instruments without changing exhaust pressure at the engine; (e) Eliminate pulsations in exhaust gas supplied to instruments; (f) Provide means of washing and/or filtering exhaust gas supplied to analyzers; (g) Control humidity of exhaust to analyzers; (h) Accurately analyze gas chemically for all five major components; (i) Pack engine inlet valve stems and throttle-valve shaft to insure against air leakage.

As regards increasing the scope of the investigation, the following suggestions are offered: (a) Test a wider variety of instruments; (b) Conduct tests on several different engines, both single- and multi-cylinder types; (c) Use a wide variety of fuels; (d) Conduct tests under a wider range of operating conditions as regards temperatures, speed, compression ratio, throttle opening, etc.; (e) Employ a wider range of temperature, pressure, and rate of flow of gas through analyzers.

To carry out all of the above recommendations in a satisfactory manner would, of course, entail the expenditure of a considerable sum of money and an immense amount of time without any guarantee of a commensurate return in the form of useful information. If the instruments as used under

service conditions are so inaccurate as not to be noticably affected by minor influences (as seems likely), highly refined test procedure would be a waste of time. This uncertainty can only be settled, however, by careful tests.

Results

It appears obvious upon examination of Figure 4 (page 47) that the usefulness of both the thermal conductivity and the relative density types of analyzers is limited to the range of air-fuel ratios below the chemically correct one. For instance, the theoretical thermal conductivity of the exhaust resulting from a mixture ratio of 14 to 1 is exactly the same as that resulting from a 16 to 1 mixture ratio, and there is no way in which the instrument can possibly distinguish between the two. The same characteristic is likewise inherent in an instrument actuated by the density of the gases. As was noted above in the description of the catalytic type of analyzer (page 29), it also is limited to air-fuel ratios below the chemically correct one. Above this value there is little or no combustible material in the exhaust (if all cylinders are firing properly) and therefore the instrument necessarily becomes inoperative.

In regard to the plot of thermal conductivity vs. air-fuel ratio, the writer has seen similar relations computed by others. The shape of the curve in Figure 4 is, for

instance, quite similar to one determined by a member of the staff of the Research Laboratories Division of the General Motors Corporation. The chief difference lies in the slope of the curve for mixture ratios richer than 14.7 to 1. This slope was somewhat less in the General Motors curve than in the one shown herein, but the same effect was manifest. Such differences as exist are probably attributable to the use of slightly different gas analyses and basic thermal conductivity values.

The experimental results obtained in these tests bear out the theoretical limitations just discussed to a remarkable degree, as can readily be seen by inspection of Figures 6 to 10, inclusive. It will be noticed, however, that most of the instruments become valueless at a mixture ratio of about 14 to 1 instead of the theoretical 14.7 to 1.

The fact that all of the physical methods of engine exhaust gas analysis so far developed become inoperative for lean mixtures does not mean that such instruments are useless. As a matter of fact, the mixture ratios generally desired in automobile or aircraft engines range from 14 to 1 to about 18 to 1. Mixtures leaner than 14 to 1 contribute little, if anything, to economy, and are liable to cause serious overheating of the exhaust valves.

Herein lies the danger of incorrect exhaust analysis, however. It is quite conceivable that a mechanic

attempting to obtain an economy mixture ratio of 14 to 1, say, would be misled by the analyzer reading (which presumably would not greatly exceed this value, regardless of the actual lean-ness of the mixture) and might adjust the carburetor to supply an air-fuel ratio so lean that serious damage to the valves would result.

This potential danger on the part of exhaust gas analyzers could be minimized by the manufacturers of these instruments if they would notify their users of this limitation and if they would not graduate the scales of the instruments above the point of reasonable accuracy - say 14 to 1. This latter precaution is observed by certain companies but others, apparently fearing that an admission of any limitation on the part of their product will discourage sales, provide a scale range up to 16 or 17 to 1, thereby inferring that the instrument will operate up to that limit. Reference to the specifications of the instruments tested (pages 21-23) will bear out this point.

Figures 6 through 9 give a general idea as to the accuracy of each type of instrument in the usable range. It may be said that none of the instruments can be depended on for an accuracy greater than one-half of one air-fuel ratio, and that there is little difference among the several types and makes as regards accuracy.

The points on the charts mentioned above indicated

by heavy dots were all obtained with a fairly high exhaust pressure and those indicated by circles were all obtained at a low exhaust pressure. It is clear from an inspection of these figures that none of the analyzers were at all reliable under the latter condition, though some were affected to a much greater extent than others by decreasing the rate of gas flow. The reason for this is not altogether clear if the statement made by Palmer and Weaver (page 12) is correct because they maintained that reasonable variations in pressure and rate of flow did not affect the readings of thermal conductivity analyzers. There are two possible explanations for this phenomenon: In the first place, it is quite likely that the variation in the rate of flow attained in these tests was greater than what Palmer and Weaver term "reasonable". Secondly, it is possible that with low rates of flow considerable quantities of moisture might collect in the analyzer cell instead of being blown on through, thereby causing the meter to partly measure the thermal conductivity of water instead of that of gas.

This last argument could not apply to the Kanarex instrument, however, because it was provided with a device for saturating the gas with water vapor under all conditions, thus eliminating the effect of moisture condensing from the exhaust. On the other hand, this instrument was only slightly affected by the variations in exhaust pressure.

This might be expected, not only for the reason just mentioned, but also because this analyzer employed a fan which draws gas into the instrument at a fairly constant rate, regardless of fluctuations in external conditions.

Whatever may be the cause, it seems evident that all of these analyzers except the Ranarex are subject to serious error when the exhaust pressure reaches a low value. This fact is of especial significance under service conditions because then the sampling tube is generally inserted into the exhaust pipe in such a manner that the only motivating force tending to cause gas flow through the analyzer is the velocity head of the exhaust as it is directed up the sampling tube. Furthermore, the velocity of the gas passing through the instrument will vary many-fold, depending on the speed and throttle opening of the engine. Some manufacturers attempt to remedy this difficulty by providing a sampling tube with a baffle or other arrangement which completely restricts the exhaust pipe. A spring-loaded by-pass valve in the baffle permits the excess gases to escape and allegedly maintains a constant pressure in the sampling tube, regardless of the rate of flow of exhaust from the engine. Most analyzers also employ a cell block in which the gas supposedly diffuses through the gas cell (see Figure 2, page 26) in such a manner that the rate of flow of exhaust through the main gas passage will have no effet on the circulation of

gas through the analyzing cell proper. The ineffectiveness of this design feature seems apparent from a study of the results achieved, however.

In this connection, it is interesting to note that obstructing the outlet of the analyzers would often cause the pointer to swing violently, sometimes entirely off the scale. The Allen analyzer (Instrument "B") was so sensitive to the effect of back pressure that an error of approximately one air-fuel ratio could be caused simply by connecting a two-foot length of 1/4 inch i.d. drain hose (supplied with the instrument to carry off moisture exhausted from the gas cell) to the gas outlet. The manufacturer specifies that this drain hose be connected to the instrument at all times, but it was found that under the conditions of this test its use caused considerable error at the higher exhaust pressures. However, the fact that it was not used may partially account for the excessive error of this device at the lower pressures.

One group of runs was made for the express purpose of determining the effect of small changes in gas pressure on the instrument reading, and the results are those shown in Table III. Apparently, small variations in pressure and rate of flow did not appreciably affect the readings. It should be noted, however, that the maximum pressure range obtainable in this particular series of runs was less than one-half an inch of mercury, compared with approximately

seven-tenths of an inch difference secured at other times.

While this subject of the effect of pressure on instrument performance demands a lot more investigation before definite conclusions can be drawn, it seems that large pressure variations do unquestionably affect the operation of the thermal conductivity and catalytic types of analyzers. The reason for this, however, was not definitely established.

The various points shown on the calibration curves of the several instruments were obtained with the engine operating with a wide range of spark advance. A preliminary plot of the various runs, each with a different spark advance, showed no correlation whatsoever between the runs; hence it was concluded that the effect of spark advance on gas analysis, if any, was not measurable. No attempt was made, therefore, to separate these points on the graphs shown here.

It should be mentioned that the top row of points shown in Figure 9 for Instrument "D" are the result of a single series of runs (Runs No. 111 - 1112). Apparently, some unknown error (such as moisture in the impeller chambers) existed in this particular run, and it would seem advisable to disregard these points. They were plotted only because no sound justification could be found for omitting them entirely.

Figure 10 represents an attempt to show the comparative average accuracy of the several analyzers. It should

be borne in mind that these curves are approximate only, and give no indication of the deviation from the average reading which might be expected from a given instrument under various circumstances. It is significant to note, however, that these curves could be properly aligned by accurate calibration of the resistances and the scale of the analyzers. Instrument "C", for example, seemed to be in almost perfect adjustment.

Definite data regarding such factors as responsiveness and constancy of adjustment would be extremely difficult to obtain, and hence they are included only as General Observations. It is thought that some explanation can be given regarding these characteristics, however. In the first place, it is believed that the trouble experienced with the Ranarex analyzer when direct-connected to the exhaust pipe resulted from the high gas velocity blowing water from the humidifier into the impeller chamber. This theory was pretty well proved by the fact that the trouble could be removed by drying the instrument for an hour or so on a hot radiator. Also, no further difficulty was experienced after a loose connection was made between the sampling hose and the exhaust pipe, thus decreasing the gas pressure on the instrument.

It is also noted that continual adjustment of the Ranarex instrument was required until it had been in operation for at least an hour. It seems likely that this might

have been caused by the fact that the exhaust gas chamber warmed up faster than the air chamber because the exhaust was, of course, somewhat warmer than the air. The whole instrument eventually attained a uniform temperature as a result of the heat conducted from the motor.

The other types of analyzers also required a certain warm-up period, though not so long a one as the Ranarex. This was manifest by need of more frequent adjustment at the beginning of the operating period.

Quite a difference existed between the several instruments as regards their ability to return to a balanced condition after use, followed by aspiration with fresh air. Instrument "B" would usually balance immediately, instrument "C" required somewhat longer, and instrument "D", the catalytic type, invariably required a much greater period than any of the others. This factor is very likely a function of the thermal capacity and operating temperature of the cell block. An instrument in which all of the four arms of the Wheatstone bridge are encased in the cell block presumably would not experience any lag in reaching an equilibrium temperature. This feature is rather important because unless an operator was familiar with this characteristic of his instrument he might adjust the current and balance the bridge when the temperatures within the apparatus were not stable, thereby imposing a false calibration on the circuit.

The ability of an instrument to remain in balance over a period of time is probably dependent upon the ratio of the current consumption to the capacity of the batteries installed. A very small change in battery voltage is sufficient to throw such a sensitive circuit out of balance, and obviously a given current drain will decrease the voltage of a No. 6 dry cell less rapidly than that of several relatively small flashlight cells. The latter type of battery is often utilized, however, to make the instrument smaller and lighter.

Figure 5 shows actual gas analyses made at different intervals throughout the test by the Orsat method compared with the theoretical analyses computed by D'Alleva and Lovell (5). It should be emphasized that these Orsat analyses are probably not very accurate and not too much dependence should be placed upon them. It is unfortunate that this is the case, but circumstances made it necessary for this rather delicate operation to be performed by relatively inexperienced personnel. The carbon dioxide analyses are probably fairly reliable, however, and they compare favorably with actual analyses obtained by D'Alleva and Lovell (not shown). It should be noticed that the points representing carbon monoxide follow quite closely the theoretical curve for hydrogen at rich mixtures, and at no time greatly exceeds one-half of the computed value. This is probably the

result of allowing insufficient time for the complete absorption of this constituent.

It would be interesting to compute the thermal conductivity, density, and heating value of each sample of exhaust gas and plot the values thus obtained against the corresponding readings of the respective instruments. This procedure would give some idea as to whether the errors in the analyzer readings were caused by inherent inaccuracy of the analyzers themselves or by deviations of the gas analyses from the theoretical. Such a procedure was of course impossible with the incomplete analyses obtained with the Orsat apparatus, even if there were reasonable assurance that these analyses were correct.

Since the idea outlined above could not be executed, another plan along similar lines was used. Several actual analyses obtained by D'Alleva and Lovell were selected at identical air-fuel ratios; the values chosen representing the widest variations in gas composition obtained at each of the chosen mixture ratios. The thermal conductivity and density of each of these gas samples were computed and the results are shown in Table V. It will be noticed that the maximum difference in either conductivity or density at any given mixture ratio amounts to little more than one-tenth of the average change resulting from varying the mixture by one air-fuel ratio. In other words, it would appear that the

greatest error in analyzer readings which might be caused by deviation of the composition of the exhaust gas from the average would not greatly exceed one-tenth of one air-fuel ratio. It is, of course, impossible to say definitely that this conclusion would apply with equal accuracy to the results of this test because it could be that the gas analyses secured from this engine varied more than did those obtained by D'Alleva and Lovell. This appears unlikely, though, when it is remembered that the work of those scientists was performed on three different engines.

Little mention has been made thus far of the Hays Orsatomat. This apparent omission is caused by the fact that this instrument is not well adapted to automotive exhaust gas analysis and therefore its inclusion in this investigation was incidental.

Tables IV(a) and IV(b) give the data secured with this instrument and compare it with the Orsat analyses taken at the same time. As can be seen from the data presented, the carbon dioxide determination by the Orsatomat appeared to be reasonably satisfactory. The oxygen readings, however, were frequently in error, even being negative in a number of instances. There is no apparent reason why an instrument of this type could not be made to give fairly reliable results, and it is believed that the partial failure of this particular unit is attributable to improper adjustment rather than

to any inherent defect. Unfortunately, time did not permit returning the apparatus to the manufacturer for correction prior to continuation of the tests.

The reasons this type of instrument is not considered particularly suited to automotive work are several: In the first place, it is neither continuous nor automatic in operation. Secondly, its care and operation require slightly more skill and entail more time and expense (for recharging with fresh chemicals) than do the other types. Thirdly, the instrument reads in per cent carbon dioxide and per cent carbon dioxide plus oxygen, thus necessitating the use of a chart to convert the readings into terms of air-fuel ratio. Finally, the apparatus is not adapted to road testing of vehicles nor to aircraft because it is very sensitive to vibration and change of position and is also rather large and cumbersome.

In a way, the greatest objection to the Orsatomat is the fact that the pointers never come entirely to rest, thus making it difficult to tell just when to take the readings. Complete absorption of the gases takes over a minute, and after a much longer period of time the pointers begin to recede gradually towards the zero mark.

One outstanding advantage of this type of analyzer, however, is that it works equally well for both rich and lean mixtures. Certain models have a carbon dioxide absorption

unit only, and of course they suffer the same limitations in this respect as do the other types.

Much has been written about the effect of unequal distribution, mis-firing, and similar irregularities upon the behavior of exhaust analyzers. It is considered advisable, however, to emphasize the fact that no type of exhaust gas analyzer can be expected to give results of any value whatsoever when used on an engine which is not operating properly.

V. CONCLUSIONS

The results of this investigation, while not as thoroughly conclusive in some respects as might be desired, seem to indicate the following facts with a considerable degree of certainty:

1. The data of previous investigators show that the relation between the air-fuel ratio supplied to a gasoline engine and the analysis of the resulting products of combustion is sufficiently definite to serve as a basis for determining, with a fair degree of accuracy, the air-fuel ratio by exhaust gas analysis.

2. Of the three physical methods commonly employed for measuring air-fuel ratio by exhaust gas analysis, no one of them seems definitely superior, either theoretically or practically. The thermal conductivity principle, however, is by far the most commonly used.

3. All of these three types of instruments are limited to the measurement of air-fuel ratios of about 14 to 1 or less, their readings having absolutely no meaning when the mixture ratio is leaner than that.

4. The users of these instruments should be aware of this limitation so that carburetors will not be

inadvertently adjusted to give mixture ratios sufficiently lean to burn the engine exhaust valves.

5. None of the instruments tested can be relied upon to give results closer than one-half of one air-fuel ratio under ordinary service conditions.

6. All of the exhaust analyzers tested are subject to considerable error if the exhaust pressure varies a great deal from normal unless a satisfactory means of compensating for this effect is provided.

7. Exceptional care must be exercised to see that any type of gas analyzer is properly adjusted and balanced at all times.

8. Prospective users of this kind of apparatus should bear in mind the following points:

a. Some instruments may be subject to error caused by incorrect calibration at the factory.

b. Slide-wire rheostats used as fixed resistances in the Wheatstone bridge circuit are subject to contact corrosion which may appreciably alter the calibration of the circuit.

c. Thermal conductivity and catalytic types of analyzers are likely to become increasingly inaccurate through use if oil and dirt are allowed

to enter the gas cell, where they may form an insulating film on the heating coil.

d. An exhaust gas analyzer should be suitable for use in moving vehicles and should, therefore, be capable of withstanding vibration, jolting, and change of position.

VI. SUMMARY

It is quite common practice in automotive and aircraft engine maintainence, operation, and research to employ any one of several types of instruments now on the market for determining the air-fuel ratio by exhaust gas analysis. It was the purpose of this investigation to determine the most important operating characteristics, especially range and accuracy, of each of these types of instruments.

The theory underlying the operation of this kind of apparatus was studied critically, and certain tests were performed on representative makes in order to observe the operation of each type under service conditions. These tests consisted essentially of connecting the analyzers to the exhaust pipe of a single-cylinder engine and comparing the analyzer readings with the true air-fuel ratio determined by accurately measuring the air and fuel supplied to the engine while the instruments were being observed. This procedure was repeated for a number of different carburetor settings, all other factors being kept as nearly constant as possible during a given series of runs. The effect of variations in engine spark advance and the pressure of the gas supplied to the instruments was also investigated.

The test revealed several interesting facts. Study of the operating principles of the several instruments

indicated that they were limited to air-fuel ratios below about 14 to 1, and this has been conclusively proved by these experiments. This limitation applies to thermal conductivity, hot-wire catalytic, and relative density types. While the most expensive makes of instruments were not tested, it was found that, in general, the limit of accuracy is not greater than one-half of one air-fuel ratio, regardless of the operating principle employed. Large variations in the pressure and rate of flow of the exhaust supplied to the analyzers were found to cause considerable deviations in those instruments which did not employ some kind of device to insure a steady and uniform supply.

Certain features of design and construction which affect the reliability of the various types of exhaust gas analyzers are also reviewed in this thesis, and some of the more important chemical methods of analysis are treated briefly.

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