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The extremely transient nature of the engine combustion process requires that special instrumentation be used to study the associated phenomena.

The methods which have been used to study flame propagation and cylinder pressure are described and the limitations of the present instrumentation are pointed out.

A new type engine indicator developed in the laboratories of the Standard Oil Company of California employing the magnetostriction principle is described. This engine indicator consists essentially of a magnetostrictive nickel alloy rod surrounded by two coils of wire and held firmly against a diaphragm which is exposed to the cylinder pressure. To one coil a voltage is applied from a flashlight battery. The second coil is connected through a low gain amplifier to the vertical plates of a cathode ray oscillograph. The cylinder pressure is transmitted to the rod and the longitudinal stress resulting changes the magnetic permeability so that a voltage is generated in the second coil which is directly proportional to rate of pressure change within the engine cylinder.

Oscillograms are presented showing rate of pressure change vs. time diagrams of the combustion process in a high speed Diesel engine. Other measurements made on both Diesel and gasoline engines with the magnetostriction engine indicator are given.

In addition to the engine indicator several other electronic devices used in studying engine combustion are described and illustrated by photographs.

The recent work of the General Motors Research Corporation correlating flame propagation as observed by photographing engine combustion at 5000 pictures per second with the cylinder pressures measured simultaneously has made it possible to study flame propagation without the need of a costly quartz window equipped engine. The only requirement is that the pressure indicator be substantially inertialess and accurately reproduce the cylinder pressure even at high speeds and with severe detonation.

The data presented indicate that the magnetostriction engine indicator fulfills these requirements and in addition is convenient to operate and is low in cost.
ELECTRONIC INSTRUMENTATION FOR MEASURING DETONATION IN SPARK AND COMPRESSION IGNITION ENGINES

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TABLE OF CONTENTS

I. Introduction .................................................. 1-3
II. Methods Used to Study the Combustion Process .. 4-10
III. Development of the Magneto-Striction Indicator. 11-25
IV. Calibration of the Magneto-Striction Indicator. 26-29
V. Typical Measurements Made with the Magneto-

    Striction Indicator ...................................... 30-37
VI. Other Electronic Instrumentation Used to

    Study Combustion ......................................... 38-47
VII. Conclusions .................................................. 48-49
VIII. Bibliography .................................................. 50-52

FIGURES

Fig. 1. Circuit Used with Magneto-Striction Indicator.. 15
Fig. 2. Magneto-Striction Cylinder Pressure Unit ..... 15
Fig. 3. Magneto-Striction Injection Line Pressure Unit 15
Fig. 4. First Magneto-Striction Pressure Unit .......... 17
Fig. 5. Improved Magneto-Striction Pressure Indicator. 18
Fig. 6. Circuit Diagram 5" Cathode Ray Oscillograph... 20
Fig. 7. Supercharged Army Air Corps Gasoline Engine... 21
Fig. 8. Moving Picture Viewer ................................. 24
Fig. 9. Balanced Pressure Unit ................................. 27
Fig. 10. Fairbanks-Morse Diesel Engine .................... 31
Fig. 11. Oscillograms Showing Effect of Changes in Load 32
Fig. 12. Oscillograms Showing Effect of Changes in Cetane Number ............................................. 32
Fig. 13. Waukesha Conversion Diesel Engine ............. 39
Fig. 14. Miscellaneous Electronic Equipment Used in Studying Engine Combustion .......................... 41
ELECTRONIC INSTRUMENTATION FOR MEASURING DETONATION IN SPARK AND COMPRESSION IGNITION ENGINES

I. INTRODUCTION

Ever since the early work of Midgely, Boyd and Ricardo in which the phenomenon of detonation in spark ignition engines was demonstrated, the design of engines and the development of fuels of high anti-knock value to minimize this objectional phase of combustion have been important considerations. More recently detonation in high-speed Diesel engines has been recognized as a problem retarding the development of engines of high specific output for use in mobile equipment.

In common with most engineering problems the solution is largely a matter of sufficient interest and the development of suitable instrumentation to allow a study of the fundamentals involved. The design of instrumentation for studying engine detonation is largely a matter of making use of the electronic devices which have been developed within the past few years for radio, communications and other electrical services. The greatest single development has been the improved types of vacuum tubes which are adaptable to many uses.

As an example of the developments in this field the oscillograph is typical. Five years ago the oscillographs commercially available cost several
thousand dollars and were large, cumbersome and inconvenient to use, and very limited in frequency response. Although cathode ray oscillographs have been in use for over ten years it has been only within the past five years that small portable oscillographs with high sensitivity and wide frequency range have been commercially available for less than $100.

These recent developments in the field of electronics have been brought about not by their application to the study of engine combustion, to be described in the following sections, but by the vast amount of research work in connection with the development of the modern radio. The low cost of the electronic equipment is the result of the mass production methods required to manufacture radios at present prices. Electronic devices for measuring the physical, chemical and mechanical processes associated with engine combustion have not been adequately investigated due largely to the lack of understanding of the function and application of such equipment and the reticence on the part of the average mechanical engineer to trust measurements made with vacuum tubes.

The following description of the application of electronic equipment to the measurement of detonation and other combustion phenomena illustrates a number of cases in which the solution of the problem could not have been
obtained by any known mechanical measuring methods.
II. METHODS USED TO STUDY THE COMBUSTION PROCESS

A wide variety of methods have been employed to study the combustion process within the engine cylinder. These are divided into two general classes; measurement of flame propagation, and the measurement of pressure changes within the engine cylinder.

Measurement of Flame Propagation

Among the methods which have been used to investigate the propagation of flame are the following: Sodium line reversal method of measuring temperature (20, 4, 11, 13), spectroscopic analysis of radiation (6, 35), Schlieren photography showing the flame movement by difference in refraction of gases of different densities (8, 25), instantaneous sampling (29, 39), ionization gaps indicating presence and location of flame (27, 3, 14), radiometric measurement of flame temperature (9, 19), photoelectric detection of flame travel (22), and high-speed flame photography (12, 5, 23, 24).

Measurement of Cylinder Pressures

These indirect methods of determining the progress of combustion have all yielded valuable information, but since the primary object of the combustion of fuel in the cylinder is to develop pressure which may be converted to useful work on the engine piston, the more
direct measurement of cylinder pressure would normally be preferred, except that in the past instrumentation has not been available to indicate the extremely rapid pressure changes which occur. Cylinder pressure changes at frequencies as high as 20,000 per second are known to exist, and the entire combustion process is completed in a few micro-seconds thus rendering the problem of measurement exceedingly difficult. Because of the need of an accurate and inertialess pressure indicator, many attempts have been made to develop such an instrument. The following brief summary includes descriptions of the more important and better-known types:

**Mechanical Types**

The earliest attempts at indicating cylinder pressures all consisted of transmitting the pressure through a diaphragm or piston to some form of pencil or stylus bearing on a rotating drum. These mechanical indicators have been found unsatisfactory for indicating cylinder pressures in engines operating at high speed, although the Mairak, Mader and Cambridge micro mechanical indicators have been found reasonably satisfactory at low engine speeds.

The De Juhasz sampling valve indicator is another mechanical type which has been used with some success on high-speed engines. With this unit the usual mechanical
indicator is connected to the engine through a rotary valve which is operated by the engine. The valve is opened during a small portion of each cycle and the pressure in the indicator cylinder increases until it equals the average pressure in the engine cylinder during the time the valve is open.

The National Advisory Committee for Aeronautics, the Royal Aircraft Establishment and the National Bureau of Standards balanced pressure indicators are all similar in principle but are somewhat different in design. In these units gas from a high pressure cylinder is conducted to one side of a diaphragm which has the other side exposed to cylinder pressure. When the cylinder pressure exceeds the balancing pressure, the diaphragm is deflected, closing the contacts. The closure is indicated either by means of a neon light or earphones. By slowly varying the balanced pressure, the cylinder pressure which exists at any point in the cycle can be determined. However, to obtain a complete card requires several minutes and an average diagram only can be obtained. Variations from cycle to cycle and the rapid pressure changes due to detonation are not indicated.

**Optical Type**

Several optical type indicators have been developed,
but the two best known are the Midgely and more recently the N.A.C.A. indicator. The Midgely indicator is an improvement over the previously known mechanical types, but is influenced by inertia effects and cannot be used at high engine speeds. The N.A.C.A. optical indicator was developed in an attempt to overcome these difficulties. A large diaphragm is employed which is built into the combustion chamber and an optical amplification of approximately 300 is employed. However, with all of the refinements contained in this instrument it has been stated that it is not useable with heavy detonation because of the inertia effect.

Electrical Type

Several types of engine indicators employing electrical means for converting the pressure changes to electrical changes have been designed. Probably the best known is the General Motors Telemeter. In this indicator the change in pressure exerted on a series of carbon discs causes a change in electrical resistance which can be measured and indicated on an oscillograph. The following disadvantages were found with this indicator: Vibration effects seriously interfered with the diagram obtained, it was necessary to calibrate at frequent intervals, and an extreme temperature effect was found.
The Capacitance type developed by J. Obata and Y. Yosida made use of the change in capacitance with change in cylinder pressure of two plates, one of which was exposed to the cylinder pressure and the other of which remained stationary. With this indicator, extremely slight variations in output with change in cylinder pressure were obtained so that a high degree of electrical amplification was necessary. The impedance was high, requiring the use of special materials and complete shielding to eliminate stray currents. In addition it was necessary to use a radio-frequency oscillator which added considerable complication.

Two types of indicator employing the principle of electromagnetic inductance have been developed. In the first type a permanent electromagnet is spaced by an air gap from a diaphragm subjected to cylinder pressure. The change in magnetic reluctance due to the motion of the diaphragm develops a current in the winding proportional to the rate of change of pressure. Although this unit has the advantage of a very slight inertia effect which is limited to that of the diaphragm itself, the electrical output varies in a non-linear relationship with rate of change of pressure, since the magnetic reluctance is a logarithmic function of the spacing between the diaphragm and the magnet. This can be par-
tially overcome by using a large initial spacing so that the output approaches linearity. However, this has the disadvantage of decreasing the output very materially.

Another inductive type indicator unit was developed at the Massachusetts Institute of Technology. In this unit a small coil of wire is rigidly mounted to a diaphragm and is positioned in a magnetic field so that movements of the diaphragm causes the conductors to cut lines of force. This type has the advantage of providing linear output with change in rate of pressure rise, but had the disadvantage of adding weight to the diaphragm and thereby increasing the inertia effect.

The Piezoelectric type is probably the most successful high-speed engine indicator available on the market. In this indicator the current generated at the surfaces of certain crystals such as quartz, with changes in pressure, are amplified and indicated on an oscillograph. This unit has very few of the disadvantages previously described and has the added advantage of being substantially inertialess, as the only motion involved is that due to the compression of the quartz crystals. This indicator does, however, have the following disadvantages: The impedance is high and the output is low, increasing the difficulty of properly coupling this pressure unit to the oscillograph, amplification of the order of 100,000
to 1 is required, and because of this fact and the high impedance of the unit shielding from stray currents is extremely difficult.

In the writer's laboratory the Midgely optical indicator, the N.A.C.A. balanced pressure indicator, and an electromagnetic type indicator developed by the Anglo Aranian Oil Company and known as the Standard Sunbury indicator have been used for some time. In addition, observations and tests on an R.C.A. Piezoelectric type indicator were made. None of these indicators were considered entirely satisfactory, although in the R.C.A. Piezoelectric indicator most of the difficulties with earlier indicators of this type appear to have been eliminated. This indicator was found to be subject somewhat to vibration, stray currents, and had the disadvantage of being high in price, the entire unit costing over $1,000.

In an attempt to develop an indicator which would have as many of the advantages of the well-known indicators as possible and a minimum of disadvantages, work was initiated in January, 1937, on the construction of a new type cylinder pressure unit.
III. DEVELOPMENT OF THE MAGNETO-STRICCTION INDICATOR

The principle of magnetostriction, or change in magnetic properties of certain materials with pressure, has been known for many years (8). The particular phase of magnetostriction of interest in connection with the design of an engine indicator is the change in magnetic permeability with change in longitudinal stress, and was first discovered by Matteucci in 1847. The effect was first noted in iron and later in other materials such as nickel and alloys of nickel. In the years that followed the early discovery of the magneto-strictive effect, but little practical application of the phenomenon was made. However, numerous investigations were conducted to determine the effect of the many variables involved. Most of these tests were made with all-sided or hydraulic pressures and most of the tests were made on the converse effect, of interest in connection with engine indicators. In this case an oscillating current is applied to a magneto-strictive rod which then elongates and contracts in phase with the changes in voltage. In this manner vibrations may be set up at any desired frequency even in the ultrasonic range.

Since a very thorough search of the literature and patent files disclosed little or no quantitative data on
the many variables involved in the change in magnetic permeability with change in longitudinal stress, it was necessary to undertake a considerable amount of research work before attempting the design of an indicator using this principle. Two methods of making use of the magnetostriction principle were immediately apparent. By the first method two coils of wire are wound on a magnetostrictive material such as invar. To one coil is connected a battery, the voltage of which is adjusted so that the optimum number of ampere turns is obtained. A voltage change proportional to the rate of change of pressure should then be developed in the second coil. In this type indicator, rate of change of pressure rather than pressure is indicated. By the second method an alternating current is connected to the energizing coil and the output of the second coil should then be proportional to pressure rather than rate of change of pressure. Since detonation frequencies as high as 20,000 per second are known to exist, the alternating current impressed upon the energizing coil would of necessity have to be several times the highest frequency to be measured, or approximately 100,000 cycles per second. This would require the use of a radio-frequency oscillator which entails a considerable amount of additional complications.
Of the two types, the rate of change of pressure indicator using direct current on the energizing coil would obviously be the least complicated and was therefore investigated first. It was first necessary to know the relationship between the length, diameter, composition, and heat treatment of the magneto-strictive material and the change in electrical output with change in pressure. Also, it was necessary to determine the optimum number of turns in the energizing and indicator coil, the frequency response, temperature effects and maximum allowable stress. As a result of an extended series of tests, it was found that the electrical output is directly proportional to the length, inversely proportional to the cross-sectional area, directly proportional to the number of turns in the indicator coil, and that annealed nickel alloys were somewhat better than heat-treated materials. A wide variation was found in the output with change in percentage of iron and nickel in the magneto-strictive rods. The optimum percentage of iron in nickel was found to be 50%.

The electrical output was found to vary directly as the number of turns in the indicator coil. It was expected that an excessively large number of turns in this coil would effect the high frequency response because of the higher distributed capacitance. However,
a test in which two 10,000-turn windings were used first singly and then in series showed that doubling the number of turns doubled the output and had no appreciable effect on the frequency response when observing detonation at a frequency of 20,000 cycles per second.

It was found that for each change in dimension of the magnetostrictive material, there was an optimum number of ampere turns for maximum output which could be obtained by either the proper choice of size of wire and number of turns or a change in battery voltage with any given energizing coil.

The maximum allowable stress in the magnetostrictive rod for linear change in voltage with change in pressure was found to be 20,000 pounds per square inch which was also the elastic limit of the nickel alloy used.

After these preliminary data were obtained, an indicator was built and connected as shown diagrammatically in Figure 1. The magnetostrictive rod, 1, is pressed against the diaphragm which is exposed to cylinder pressure on one side and atmospheric pressure on the other side by the adjustable back-up plug, 2, with a slight initial tension. Surrounding the rod are two coils, 3 and 5. Coil 3 has connected to it a 1-1/2
FIG-1 ELECTRICAL CIRCUIT USED WITH MAGNETOSTRICTION ENGINE INDICATOR

FIG-2
MAGNETOSTRICTION CYLINDER PRESSURE UNIT

FIG-3
MAGNETOSTRICTION INJECTION LINE PRESSURE UNIT
volt flashlight cell which is sufficient to produce the optimum flux density. Coil 5 is connected through the low-gain amplifier, 6, in the cathode ray oscillograph to the cathode ray tube, 7. Because of the very high output obtained and the low resistance of the indicator coil, the coupling of the indicator to the cathode ray tube presents no problem. With the low amplification used no difficulty from stray ignition currents is experienced. Figure 4 is a photograph of the first magnetostriction engine indicator unit. With this indicator, useable oscillograms were obtained. However, considerable vibration was apparent and an improved unit of smaller size was designed. The details of this pressure unit are shown in Figures 2 and 5. A number of designs were tried to obtain the maximum output with minimum vibration effect and with a minimum size before the unit shown in Figure 5 was finally developed. An important consideration in the design of an indicator to be universally applicable is the size of the unit. With several of the well-known experimental engines such as the C.F.R. knock testing engine, the surrounding mechanisms limit the size of unit which can be used. In several service engines the large indicator shown in Figure 4 could not be used because of interference with some of the engine accessories. Also, the large size
FIG. 4 FIRST MAGNETOSTRICTION PRESSURE UNIT.
FIG-5 IMPROVED MAGNETOSTRICTION PRESSURE INDICATOR.
contributes to the vibration difficulties.

The present magnetostriction indicator has been used continuously for several months in a supercharged engine at a jacket temperature of 365°F., an intake temperature of 300°F. and at supercharge pressures as high as 60 inches of mercury without appreciable temperature effect or deterioration.

The earlier electrical type indicators used as an indicating means some form of oscillograph. In most cases this consisted of the magnetic type which had many disadvantages as previously described. The development of the cathode ray tube has made available a very satisfactory oscillograph at prices ranging from $50 to $100. A two-inch oscillograph is shown in Figure 14, and in Figure 7 a three-inch and a five-inch unit are shown. The electrical circuit used with the five-inch oscillograph is shown in Figure 6.

For fuel work the rate of change of pressure diagram is much more valuable than the pressure diagram as the effects due to changes in fuel quality are more readily apparent. For engine design purposes the pressure time or pressure volume diagrams are of more use. For those studies in which pressure was desired instead of rate of change of pressure, it was necessary to design an electrical integrating circuit which would convert the rate of pressure indication to pressure. In this same
FIG. 7 SUPERCHARGED ARMY AIR CORPS GASOLINE ENGINE
unit an electrical differentiator was built so that with this unit interposed between the cylinder pressure unit and the oscillograph it is possible to obtain pressure, rate of change of pressure, or the second differential of pressure diagrams. The integrator and differentiator are shown in Figure 14.

When observing detonation with the pressure diagram, a barely perceptible irregularity on the expansion curve is apparent. With the rate diagram this same detonation appears as an irregularity of very high amplitude and is readily distinguishable. The oscillating portion is super-imposed on the normal firing diagram, and even though the amplitude is great, interpretation is somewhat difficult because of this fact. On the rate of rate or second differential of pressure diagram only the detonation is apparent as a high amplitude oscillating trace occurring on the base line, and the detection and measurement of detonation is simplified considerably.

In order to make a permanent record of the diagram traced on the oscillograph screen, several methods of photographing were tried. The most successful found to date has been the use of a 16 millimeter moving picture camera with an f 1.5 lens, and a variable speed shutter which can be set to synchronize approximately with the
engine speed. The camera used is shown in Figure 7. By this means it is possible to obtain oscillograms of successive cycles from which an average diagram can be selected, since the combustion varies from cycle to cycle.

Filing and storing of the oscillograms is simplified by the large number of individual photographs included in the usual 100 feet of 16 millimeter film. There are approximately 4,000 frames on each roll, and therefore by photographing ten successive cycles per test, some 400 tests per 100-foot roll of film can be recorded.

In order to view the oscillograms without the necessity of making photographic prints, the viewing arrangement showed in Figure 8 was devised. A binocular type microscope with an eight power lens is mounted at the proper distance from the film which is projected against the microscope lens by means of a "toy" moving picture projector of the type used to project animated cartoon black and white 16 millimeter films. The film itself is viewed directly and the detail and magnification possible are limited only by the size of grain of the film. With this arrangement, details on the oscillograms which are too indistinct to allow printing are
FIG-8 MOVING PICTURE FILM VIEWER
readily distinguishable. The projector is provided with two cranks which are geared at different ratios so that the oscillograms may be viewed as a moving picture, or one frame at a time.
IV. CALIBRATION OF THE MAGNETO STRICTION INDICATOR

For calibrating the pressure time diagram which is obtained by electrically integrating the rate of pressure rise, the balanced pressure indicator shown in Figure 9 is used. By comparing the two measurements over a wide range of compression ratios with non-detonating combustion it is possible to obtain a calibration of oscillogram screen height versus cylinder pressure, although considerable time is required. The calibration thus obtained remains substantially constant, provided the amplifier gain is accurately adjusted. Therefore, a calibration is required only at infrequent intervals.

The calibration of the rate diagram is more difficult and must be done by indirect means. One method used was to calculate the rate of pressure rise without firing at a number of different crank angles from the known engine dimensions and an assumed compression exponent and the usual polytropic equation \( P_2 = P_1 \left( \frac{V_1}{V_2} \right)^n \).

It was first necessary to obtain an expression for the cylinder volume in terms of crank angle and substitute in the above equation, differentiate, and then solve for \( \frac{dP}{dT} \) at several crank angles. The latter calculation could not be found in any text or handbook available, so the following equations were developed to obtain the desired rate of pressure rise values:
FIG.-9 BALANCED PRESSURE UNIT
\[ X = r(1 - \cos \phi + \frac{r}{2\ell} \sin^2 \phi) \]

Where:

- \( X \) = distance from piston (at crank angle \( \phi \)) to end of stroke
- \( r \) = length of crank arm
- \( \ell \) = length of connecting rod

\[
P_2 = 2P_1 \left( \frac{(1 + k)}{2(1 + k) - (1 - \cos \phi - \frac{r}{2\ell} \sin^2 \phi)} \right)^n
\]

Where:

- \( P_2 \) = pressure at any crank angle \( \phi \)
- \( P_1 \) = cylinder pressure at bottom center
- \( k \) = equivalent height of clearance space with diameter equal to piston diameter:
  \[
k = \frac{1}{\text{compression ratio} - 1}
\]

Differentiating:

\[
\frac{dP_2}{d\phi} = \frac{2nP_1 (1 + k)^n (\sin \phi - \frac{r}{2\ell} \sin 2\phi)}{\left[2(1 + k) - (1 - \cos \phi - \frac{r}{2\ell} \sin^2 \phi)\right]^{n+1}}
\]
Sample calculation:

\[ \phi = 160^\circ \text{ from B.D.C. or } 20^\circ \text{ from T.D.C.} \]

Compression ratio = 15

\[ n = 1.3 \]

\[ P_1 = 13 \]

\[ \frac{dP_2}{d\phi} = \frac{2 \times 1.3 \times 13 (1 + 0.0715)^{1.5} (\sin 160^\circ - 0.1 \sin 2 \phi)}{2 (1 + 0.0715) - (1 - \cos \phi - 0.1 \sin^2 \phi)^{2.3}} \]

\[ = 315 \text{ pounds per square inch per radian} \]

\[ = 5.49 \text{ pounds per square inch per degree} \]

By comparing the observed and calculated rate diagrams for a wide range of compression ratios, the rate scale on the oscillograph was evaluated. Since the vertical rate scale on the oscillograph is linear, an extrapolation to include the much higher rates resulting from detonation was then made. Although this method is somewhat inexact, the main use of the rate diagram is for comparative purposes, the determination of incipient detonation or the magnitude of detonation, the timing of the various events in the cycle, and the frequency of detonation. For all such measurements the absolute calibration of the rate scale is unimportant.
V. **TYPICAL MEASUREMENTS MADE WITH THE MAGNETO-STRICION INDICATOR**

To illustrate the use of the magnetostriction indicator, the following two typical problems have been selected:

1. Study of combustion in a high-speed Diesel engine with changes in load.
2. A determination of the frequency of detonation inside and also outside the cylinder in a spark ignition and a compression ignition engine.

The oscillograms shown in Figure 11 indicate the effect of changes in load on the delay period, the rate of pressure rise, and knocking. A Fairbanks-Morse 10 horsepower, single-cylinder, high-speed Diesel engine shown in Figure 10 was used. It will be noted that the delay decreases continuously with increase in load. This would be expected since temperatures are higher, thereby accelerating the combustion process. The delay varied from 7-3/4° at idle to 5-1/2° at full load. Also, it will be noted that as judged by the maximum rate of pressure rise and also the amplitude of changes in pressure on the expansion curve, the maximum knocking occurred at the intermediate load. This is explained by the fact that although at light load the delay period is longer,
FIG. 10—FAIRBANKS MORSE DIESEL ENGINE
FIG-11
OSCILLOGRAMS SHOWING EFFECT OF CHANGES IN LOAD.

FIG-12
OSCILLOGRAMS SHOWING EFFECT OF CHANGES IN CETANE NUMBER
the amount of fuel injected is less and therefore at the instant of combustion even with a long delay period, a smaller amount of fuel is present to burn without the control of the injection pump. At full load, although a larger quantity of fuel is injected, the delay period is much shorter because of the increased temperature and therefore at the instant of combustion something less than the maximum amount of fuel is present to detonate. In this engine at approximately one-third load, the delay and quantity of fuel injected combine to provide the largest amount of fuel present at the time of initial combustion and therefore the greatest knock. The oscillograms shown in Figures 11 and 12 were obtained using the original magnetostriction pressure unit illustrated in Figure 4. The effect of engine vibration is evident on the baseline. However, the improved design of cylinder pressure unit shown in Figure 5 eliminated all trace of vibration even in rough running engines with heavy detonation.

In Figure 12 the effect of raising the cetane number on knocking is clearly shown. The oscillograms of Figure 12 were taken under the same engine conditions as the oscillogram shown in Figure 11 at 3 kilowatt load with 40 cetane fuel.
In Figure 7 the equipment used to determine knock frequency is shown. The rate of rise of cylinder pressure was observed on the oscillograph screen on which was also super-imposed a sine wave of variable and controllable frequency generated by the oscillator shown. The frequency of the oscillator was varied until the cylinder knock frequency and the oscillator knock frequency coincided, and from the calibration of the oscillator the frequency of gas vibration determined. The knock apparent to the ear was measured by observing the output of the dynamic microphone, also shown in Figure 7, and comparing with the frequency generated by the oscillator in the same manner as previously described.

Measurements made in the Army Air Corps engine shown in Figure 7 indicated that at a 5 to 1 compression ratio with 40 octane fuel the cylinder knock frequency was 7,750 cycles per second and the knock outside of the cylinder was 1,520 cycles. At 7.5 compression ratio with 75 octane fuel and the same degree of knocking as obtained in the first test, the cylinder knock frequency was found to be 12,050 cycles and the knock outside the cylinder 1,540. In the Fairbanks-Morse diesel engine shown in Figure 10 the cylinder knock frequency was found to be 2,050 and the knock outside the cylinder 910.
Knock frequencies within the cylinders of the C.F.R. engine have been quoted in the literature to vary from 6,000 to 20,000 cycles per second. One investigator has indicated that the frequencies measured inside the cylinder coincide with that measured outside the cylinder.(7) In most cases no mention has been made of the effect of changes in compression ratio on the cylinder knock frequency, the assumption being that each particular engine had a fixed cylinder frequency during detonation. Also, the effect of location of the pressure measuring unit within the cylinder is usually neglected. In the supercharged engine tests it was shown that the cylinder frequency varied with compression ratio as would be expected because of the change in cylinder combustion chamber dimensions. However, the knock frequencies measured outside the engine cylinder were found to be unaffected by the changes in the cylinder frequencies caused by the change in compression ratio.

In the Fairbanks-Morse engine the cylinder knock frequency and the frequency measured in the room were also different, but both were considerably lower than the frequencies measured in the supercharged engine. The audible knock frequency is probably determined by the natural period of some part of the engine structure. Since the Army Air Corps engine has only a 2-5/8 inch
cylinder bore compared to 4-1/2 inches for the Fairbanks-Morse engine and is considerably more rigid, the audible knock frequency would be expected to be somewhat higher in the Army engine. The smaller cylinder dimension of the Army cylinder also explains the higher cylinder knock measured in this engine.

Because of the non-symmetrical shape of the combustion chamber it is entirely possible that gas frequency measurements made in different parts of the cylinder would be quite different. Therefore, a general statement that a given engine has a fixed cylinder gas frequency is probably not correct. In addition, the location of the pressure measuring unit, the compression ratio used, and the crank angle at which the detonation occurs must be specified. There was some evidence in the test described that the frequency changes throughout the detonating period as the piston moves, although the duration of detonation is so short that exact evaluation of this effect has not yet been found possible. This could be investigated, however, by covering a wide range of ignition timing.

Electrically differentiating the wave form obtained from either the microphone or the cylinder pressure units was found to be a decided help in eliminating extraneous effects such as engine vibration or engine background
noise. However, differentiating is of value only when the frequencies observed are considerably higher than the extraneous frequencies.
VI. OTHER ELECTRONIC INSTRUMENTATION USED TO STUDY COMBUSTION

There are many other applications of electronic instrumentation to the measurement of the combustion process besides those previously mentioned. A few of the more important uses will be described.

In Figure 13 is shown a Waukesha C.F.R. engine which has been converted to Diesel operation by substituting a Bosch injection pump and nozzle in the place of the electrical equipment used with the gasoline engine. This engine is used to test the ignition qualities in terms of cetane numbers under stated conditions. By this method of test, the engine is motored at a compression ratio below that required for ignition of the Diesel fuels being tested. The compression ratio is then raised by increments until first firing is obtained. The compression ratio at which ignition occurs is a measure of the startability of the fuel.

The method as originally proposed was later discarded because of the difficulty of ascertaining with certainty the point of firing. Also, the fuel which either failed to fire or fired erratically soon gummed up the interior of the engine. However, by the application of electronic instrumentation a very convenient test
FIG-13 WAUKESHA CONVERSION DIESEL ENGINE
method was developed by which cetane numbers could be measured and reproduced within one-half cetane number.

An electrical timer shown on the right side of the engine crankcase was geared to the crankshaft and connected electrically to the solenoid shown at the front of the engine attached to the injection pump rack. With this equipment injection was timed to occur twice in succession and the injection pump was then cut off for 28 successive cycles, thus clearing the engine of unburned fuel. In order to determine the incidence of combustion more accurately than was possible with the previous exhaust listening method, two electrodes were fitted into the combustion chamber through an insulated bushing. These electrodes were then connected to the ionic gap amplifier shown mounted on the engine panel. The ionization of the gas in the combustion chamber caused by the presence of flame changes the electrical resistance of the gas between the two electrodes. This change is then amplified and indicated by the illumination of the neon light mounted on the crankshaft at the front of the engine. With this equipment, the incidence of combustion as well as the timing and duration of combustion are readily determined.

Several other electronic devices are shown in Figure 14. The peak voltmeter shown on the top shelf is
FIG-14 MISCELLANEOUS ELECTRONIC EQUIPMENT USED IN STUDYING ENGINE COMBUSTION.
used to measure quantitatively the rate of pressure rise caused by detonation. Either the maximum rate or the average rate can be determined and indicated on the meter. This instrument is provided with a gain control, a meter zeroing circuit, an electrical damping arrangement and a means of checking the voltage of the A and B batteries on the output meter. The peak voltmeter is used in conjunction with either the magnetostriction indicators or the microphone shown in Figure 7. The peak voltmeter in conjunction with a special vibration pick-up unit has been successfully used to rate Diesel fuels in terms of cetane numbers and gasoline in terms of octane numbers in both multi- and single-cylinder engines. In one series of tests it was found possible to measure changes in the ignition quality of Diesel fuels of the order of one-half cetane number in a multi-cylinder tractor Diesel engine.

The Thyatron relay also shown on the top shelf has a number of uses. As a relay it will trip on voltages as low as 0.002 volts and as low as 0.00001 amperes. The output of the relay is either 300 volts at one-tenth ampere or 5,000 volts at two-tenths ampere. The latter output is applied to either a neon light rotating on the flywheel or the stroboscope neon light shown on the lower shelf in Figure 14. The input to the Thyatron relay may be connected to a magnetic injection indicator, such as
the one shown on the lower shelf, a photo tube exposed to the combustion chamber illumination through a window also shown on the lower shelf, or to the balanced pressure indicator shown in Figure 14, or to the magnetostriction pressure unit. By the use of a Thyatron relay in conjunction with a rotating neon light on the flywheel, the timing of fuel injection, the timing of firing, the duration of firing, and cylinder pressure at any crank angle may be determined.

In addition to the above uses as an ultra-sensitive relay with substantially zero time lag, the Thyatron unit may be used as a self-contained stroboscope. In this case the Thyatron is caused to alternately conduct and fail to conduct by the periodic charging and discharging of a condenser through a variable resistor. By varying the resistor the frequency of the tripping may be controlled. The output of the Thyatron is then connected to the stroboscope light shown in Figure 14. This stroboscope has been found useful in studying cyclic motion such as valve and valve spring performance, flow of lubricants and the displacement of injection nozzle parts.

When using the Thyatron or magnetostriction indicator in certain applications where the actuating force is very slight, an additional amplifier is sometimes required. The 100,000 to 1 gain amplifier shown in
Figure 14 is then used. With this amplifier and a magnetostriction pressure unit using alternating current on the energizing coil, it was found possible to measure the pressure exerted by the hand through a one-inch steel block. The design of a high gain amplifier presents many problems not present in the usual amplifier. The vacuum tubes used must be carefully selected to minimize microphonic tube noises and all circuits and leads must be completely shielded.

The synchronizer unit shown in Figure 14 is used to measure the time interval between events on the oscillograph screen and also to lock the pattern stationary even though engine speed varies somewhat. This unit consists of two magnetos mounted on a common shaft. One magneto can be phased by moving the permanent magnets around the armature by means of the dial shown on the front of the unit. The impulses on the oscillograph screen is moved along the time axis by rotating this dial until the synchronizer impulse and the event being studied coincide. The crank angle at which the event occurs is then read directly off of the synchronizer dial. The second magneto generates six electrical impulses per revolution and the magnets surrounding the armature can be phased through 60°. Therefore, an impulse can be
generated at any crank angle. This is then applied to the locking circuit of the oscillograph for the purpose of maintaining the pattern stationary on the oscillograph screen and starting the trace at any desired crank angle.

The spark advance indicator shown in Figure 14 was developed in the laboratory of the Standard Oil Company of California, as no such equipment was available on the market. Measurement of spark timing at the instant the knock observations are made on the road has been found to be extremely important since on the average the octane requirement of cars varies approximately three octane numbers per one degree change in spark timing. Even though the spark advance characteristics of a particular distributor may be measured on a rotating head type stroboscope, tests with the above-mentioned spark advance indicator have shown that this same distributor installed in the car and subject to vibration and misalignment will not reproduce the same timing through the speed and load range of the car as found in the bench test.

In this spark advance indicator, current is started in the meter circuit through a series of vacuum tubes by spark plug current. The meter current is stopped at top center by an electrical impulse generated by a bolt on the flywheel passing a magnetic unit. A compensating
means is provided so that the interval measured in crankshaft degrees between the incidence of spark and top dead center is independent of engine speed except as the engine speed actually changes the spark advance through the speed and load control on the distributor. The spark timing is indicated continuously while the car is in motion on the meter shown alongside of the spark advance indicator. A range switch is included on the meter so that the size of the scale may be doubled for extreme accuracy in the low range. The spark can be timed to one-half degree with this device.

The magnetostriction injection line pressure indicator shown in Figures 3 and 14 utilizes the same principle and is similar in construction to the cylinder pressure unit. With this device variations in Diesel engine injection line pressures can be measured and observed on the oscillograph screen for the purpose of studying the hydraulic phenomena associated with fuel injection. Using this equipment, the effect of compressibility of the Diesel fuel has been studied to determine the relationship between fuel type and injection line lag. In one series of tests made at injection pressure as high as 50,000 pounds per square inch, certain Diesel fuels were found to solidify and failed to inject even though the ambient temperature was approximately 80°F. At these
High pressures the fuel properties and the hydraulic phenomena were found to be entirely different than at the more normal injection pressures in the range 1,000 to 2,000 pounds.
VII. CONCLUSIONS

In the foregoing account of the uses of electronic instrumentation for studying the combustion process, it was not intended to give the details of the construction of the equipment or delve into the many ramifications of the test results obtained. The purpose was to demonstrate the usefulness of such instrumentation and the necessity for more precise measuring methods when studying the transient phenomena associated with combustion.

The measurement of cylinder pressure has added significance since the recent work of Rassweiler and Withrow of the General Motors Research Corporation, published in the May, 1938, Society of Automotive Engineers Journal, correlating rate of flame propagation and cylinder pressure changes.

After several years of research on combustion in which flame propagation was studied by photographing the combustion chamber of a running engine through quartz windows at the rate of 5,000 pictures per second, a very close correlation was found to exist between cylinder pressure and flame propagation.

Among the important findings was the equations developed from which the mass rate of fuel combustion can be calculated from the pressure-time oscillograms with a correction applied for changes in cylinder volume.
as the piston moves through the expansion stroke.

By the use of a suitable high-speed engine indicator and the equations developed by Rasweiler and Withrow, it is now possible to follow combustion in the engine without the need of direct observation of the flame. The engine indicator, therefore, provides a means of "seeing" into any engine without the need of combustion chamber windows which can be used only in engines especially designed for their use at an almost prohibitive cost.
VIII. BIBLIOGRAPHY


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