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# HIGH SPEED ENGINE PRESSURE INDICATORS

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## INDEX

# HIGH-SPEED ENGINE PRESSURE INDICATORS



(Prepared by Ford L. Prescott, Matériel Divison, Air Corps, Wright Field, Dayton, Ohio, February 27, 1933)

## OBJECT

The object of this study was to investigate the available types of indicators and to determine their limitations for various kinds of aircraft engine research.

## CONCLUSIONS

From the tests so far conducted, it appears that the sampling or averaging type of indicator, and the electric or instantaneous type each has a field of usefulness not covered by the other. For transient and qualitative work, such as combustion study, the electric indicator will still provide the most satisfactory device, while for engine development, valve timing studies, supercharging, etc., the sampling device is probably the most useful. One type is strictly a laboratory instrument, while the other is a most convenient tool for the use of the engine research man, comparing in usefulness to the steam engine indicator, as related to steam engine development.

## METHOD OF TEST

Many types of indicators were available for examination and test. These included the Midgeley optical indicator, the Maeder microindicator, the R.A.E. or Farnboro electric indicator, and the Bureau of Standards indicator. A total of three telemeter electric pressure units were procured and tested and a DeJuhasz indicator, with all accessories, was also procured. The Midgeley and Maeder indicators were not tested, since examination disclosed many of the shortcomings of these instruments. The R.A.E. and Bureau of Standards indicators were set up on a Liberty single-cylinder test engine and many records were taken in the effort to secure good cards with these instruments. The telemeter indicator was set up, using a Westinghouse oscillograph as the recording mechanism. This was found to be unsatisfactory, due to the low current sensitivity of the oscillograph. A special oscillograph was constructed, having the desired sensitivity, and was so constructed that P-V or P-T diagrams could be viewed on a screen or photographed with a built-in camera. With this indicator many cards were taken under various conditions. The DeJuhasz indicator was set up on the Liberty single-cylinder engine and a large number of cards taken. These included cylinder cards, both high pressure and weak spring, and also some intake pipe cards.

After determining the operating characteristics of these indicators, the electric and sampling types seemed to possess inherent advantages worth developing. The electric type gave records of the complete engine cycle, while the DeJuhasz sampling type gave records of the average cycle. Due to leaking difficulties with the DeJuhasz, it was decided that a better sampling valve should be devised. A poppet-type sampling valve was designed and after considerable development brought to a useful state and gave the best sampling valve or average cards obtained with any of the indicators. This indicator, as developed, was applied to the study of valve timing on the SV-1570 engine and also on a supercharged single-cylinder test engine using an R-1340 cylinder and piston.

In both cases the B.M.E.P. of the engines was improved as a result of the information obtained, and it was felt that the indicator had proved its usefulness. This indicator was then installed on an R-1340 engine, using the Chandler fuel-metering system. The telemeter electric indicator was used to study oil pressure fluctuation in the V-1570 engine, due to register of oil grooves, and also to a study of the pressure cycle of the fuel injection system of the Chandler device.

## RECORD OF TEST

Preliminary study led to discarding as unsuited to the purpose in view, the microindicators, and the small high-speed indicators of the conventional type. The reasons for this were inertia of pencil mechanism and of the recording drum, and also the small size of records obtained. These indicators are not adapted to taking weak spring cards, which is essential to a study of pumping loops.

### *Optical indicators*

Indicators of the optical type employing moving parts of appreciable mass (such as the Midgeley) were discarded because of inertia effects and difficulty of installing on an engine. The Midgeley indicator, however, has one obvious advantage over some previous optical indicators in that the piston is located within the combustion space, preferably flush with the wall. Thus, any question of pressure lag or surge in a connecting passage is eliminated. A moving piston exposed to the hot gases eventually sticks by reason of accumulated carbon and thus becomes unreliable. It does not, therefore, appear that this type of indicator is suited to research work. The jagged pressure record on detonation, once supposed to represent detonation waves, is believed to be due to the natural frequency of the indicator mechanism.

*Balanced pressure indicators*

Progressing to the balanced pressure type of indicator, there are the R.A.E. and the Bureau of Standards indicators. Both of these operate on the principle of balancing an externally controlled pressure against the instantaneous cylinder pressure. Both require an external source of pressure and vacuum exceeding those to be measured. At the instant of balance, an electrical contact is made or broken. This contact point is, in the case of the R.A.E. indicator, in the form of a light valve, seating on either side, and with a travel of 0.005 to 0.010 inch from one seat to the other. Upon leaving either seat contact is broken and the primary current of an induction coil interrupted. A spark passes from the pressure-actuated stylus and punctures a hole in a paper on a drum revolving at engine or half-engine speed. By this means, a pressure-time diagram is obtained. It has been found that the shape of the pressure peak varies from one cycle to another, and for this reason the high-pressure portion of the record obtained with the R.A.E. indicator is composed of a mass of widely scattered points, through which a line is drawn at one's own discretion. It appears to be impossible to eliminate this defect, hence the record loses value. There is also a measurable time required for the disk valve to pass from one seat to the other. Time is also required to build up sufficient flux in the induction coil core to cause a spark to pass. This imposes a definite speed limit beyond which only the rising side of the pressure record is obtained. With this indicator, low scale or weak spring cards may be readily obtained. Some lag due to pressure required to actuate the moving stylus undoubtedly occurs, which renders such low-pressure cards of little value unless very slowly taken.

The Bureau of Standards indicator is without doubt the most precise of those tested during development. A light steel diaphragm is supported between two perforated disks, and touches an insulated electrode at approximately zero pressure (atmospheric). A timer is driven at half engine speed, and closes contact during a brief instant (about 2° rotation of crank shaft). If, during this instant, the cylinder pressure is higher than the external pressure, contact is closed and a click heard in a telephone receiver. If the external pressure is higher, no click is heard. At the point where clicks cease, the external pressure equals the cylinder pressure during the short period of contact. Thus, a series of points is obtained and plotted against crank angle, or piston position, giving a pressure-time or pressure-volume card. During the high-pressure portion of the card, it is necessary to estimate approximately 50 percent clicks, for a mean value, or to secure 0 and 100 percent clicks for maximum and minimum pressures at the crank angle in question.

In working in the same room with an engine, the clicks could not be heard. A circuit was devised, including an induction coil having a neon lamp in the secondary circuit. The flash could readily be observed and this made it possible to take cards with the ears protected from the deafening exhaust of the engine. Two operators can take a card by reading every 10° of crank-shaft rotation in about 10 minutes. This consumption of time and lack of permanent record, other than a table of observed angles and pressures, constitute a major objection to the indicator. For lower loop diagrams, there is a shift of the zero position of the diaphragm with temperature which may amount to 1½ pounds per square inch. This may constitute an error of 100 percent if pressures are measured within this amount. It is impossible without introducing a cock and a considerable length of connecting pipe to be sure of the atmospheric line. Hence, on lower loop diagrams some doubt exists as to where the zero line should be drawn. The same applies to the boost line on supercharged engines. This error is insignificant on the high-pressure card. Very close checks have been obtained on single-cylinder engines between the I.M.E.P. obtained from the card, and the sum of brake and friction M.E.P.

An attempt was made to combine the Bureau of Standards diaphragm element with the R.A.E. recording mechanism, by constructing a relay which opened a primary circuit whether the diaphragm contact opened or closed. Thus, a single contact on the side of the diaphragm not exposed to the products of combustion would cause a spark on the "make" as well as the "break" of contact. This worked beautifully at low speed, but at the higher speeds the electromagnetic lag was so great that complete failure of the record occurred. Double contacts on the diaphragm were unsuccessful, due to the rapid accumulation of carbon and moisture on the under side of the diaphragm. Water cooling of the diaphragm element at times caused condensation of moisture on the diaphragm and support, causing them to stick together, with failure to record. The chief objection to the Bureau of Standards indicator is the time required to take data and plot it. Besides great accuracy, it has the advantage of simple application to an engine, since only a tube and a wire are connected to the pressure element and recording may be done at a remote point.

In connection with an unsuccessful attempt to indicate a Diesel engine with the R.A.E. indicator, where maximum pressures of 1,000 to 1,200 pounds per square inch were expected, a $CO_2$ bottle was placed in a bath of warm water and a pressure of 1,200 pounds per square inch obtained. Upon attempting to take a card, the warm vapor condensed in the piping and valves and when the pressure was blown off the entire system froze up with $CO_2$ snow. No cards were obtained. On a previous occasion, a bottle of oxygen was used with the R.A.E. indicator, with the result that a cylinder head was blown off. Nitrogen or helium should be ideally suited to the purpose, but neither of these gases was available. The necessity of an external supply of high-pressure gas constitutes an objection to the balanced-pressure type of indicator.

*Electrical indicators*

Two types of indicators which produce an electric current varying with pressure have been quite successful for certain types of indicator work. These are the carbon-pile, or telemeter type, as developed by Martin and Caris of General Motors Research Corporation, and the condenser transmitter type, developed in Germany and reported in the 1930 year book of the D.V.L. Both of these indicators use an oscillograph as the recording mechanism.

The condenser transmitter type utilizes the principle of semiresonance between an oscillating circuit and a second oscillatory circuit connected to the grid of a tube biased for detection. The detector circuit is detuned slightly, so as to operate normally on the steep side of the resonance curve. The condenser transmitter shunts the tuning condenser of this circuit, and since its capacity changes with pressure, the oscillatory circuit is tuned or detuned by the action of pressure on the transmitter. The plate current of the detector tube is passed through an oscillograph and a pressure record thus obtained. Formerly the transmitter condenser was so constructed that pressure moved the plates closer together. This gave low sensitivity to pressures near atmospheric, and increasing sensitivity with higher pressures. A vacuum would produce the lowest sensitivity of all. In the D.V.L. indicator, a small diaphragm is exposed to the pressure, and a strut transmits movements from this to the condenser diaphragm. The latter is mounted on the side of an insulated plate remote from the pressure source. Thus, pressure tends to separate the condenser plates, giving a zero position such that the plates are normally very close together. Thus high sensitivity is obtained on pressures near atmospheric and decreasing sensitivity at high pressures, with no danger of shorting the condenser by causing the plates to touch.

The telemeter type makes use of the principle of the varying conductivity with pressure of a pile of carbon disks. In order to secure a straight-line response, two stacks are opposed and connected to a diaphragm in such a manner that increase of pressure on one stack accompanies decrease of pressure on the other. The stacks have resistances of approximately 45 ohms each and are connected as two legs of a Wheatstone bridge. The "galvanometer" current of the bridge circuit is passed through a sensitive oscillograph. Figure 3 shows three of these pressure elements with cover plates removed to show the carbon stacks. A 3-wire cable and a tube to conduct cooling air are all the connections required, and the diaphragm is mounted preferably flush with the inner surface of the combustion chamber. For recording, a special oscillograph (figs. 8 and 9) is required, due to the small current available from the pressure element. The oscillograph incorporates two fixed resistors of 40 ohms, as the other two legs of the Wheatstone bridge, a 10-ohm potentiometer with ends connected to the 40-ohm resistors, the center movable contact furnishing, with the center tap of the two carbon piles, the two "galvanometer" connections of the bridge. These are connected directly to the terminals of the permanent magnet oscillograph element employed to record the pressure changes. A rheostat and ammeter are employed to adjust the bridge current, and a milliammeter is included, which may be cut in or out of the galvanometer circuit. This is for calibration and zero adjustment.

The optical system employs a carbon arc lamp with its condensing lens, a vertical slit shutter of the cylindrical type, an auxiliary slit to trim the haze from the sides of the light beam, a permanent magnet oscillograph element, a reflecting mirror to double the optical path, a cylindric condensing lens, and a rotating or oscillating mirror to reflect the light to its focus on the curved screen. A shield is provided so that the image may be viewed in daylight, and a camera so built in that it may be slid into the place occupied by the screen and the record photographed. When using the P-V mechanism, shown in figure 7, the light spot is continuously in sight on the screen and every cycle may be observed. Figure 6 shows the rotating mirror assembly for taking P-T records. The mirror is of fused quartz with four optically plane surfaces accurately at right angles to each other and parallel to the axis of rotation. It is driven at $\frac{1}{20}$-crank-shaft speed by a 20:1 worm reduction. By this means every fifth revolution is shown on the screen and two consecutive faces of the mirror reproduce one complete cycle. The length of screen or film is a little longer than one revolution of the crank shaft as recorded on the film. The two mirror units are interchangeable without affecting the focus of the cylindric condensing lens, since the mirror surfaces at midposition have the same relation to the lens and screen.

Figure 5 shows the operating mechanism of the oscillating mirror assembly. A small crank shaft is fitted with a miniature connecting rod, having an $\frac{L}{R}$ ratio of 4:1. A small error in phase occurs when other $\frac{L}{R}$ ratios are used. For example, with $\frac{L}{R}=3.2$, the maximum error in position of light beam is 1.6 percent. Since the curves are relatively flat near the center, and the error becomes zero at either extreme, the error in area of card is probably less than 0.8 percent. The mirror is oscillated by a crank on the end of the mirror shaft, the free end of which mounts a lever having two equal arms of the same length as the crank. The lower end of the lever is mounted on a horizontal vibrating link, and the upper end has true straight-line motion and thus is adapted to guide the small end of the connecting rod. The maximum error in angular displacement of the mirror, referred to linear motion of the straight-line mechanism, is about 0.6 percent. Hence for all practical purposes the inherent errors in the mechanism are less than other experimental errors. The width of line drawn by the moving light spot is in excess of one sixteenth inch. Hence a larger error is possible in interpretation of the card.

The special oscillograph as described has an optical arm of about 35 inches, and a high sensitivity galvanometer is used, giving a deflection of about 0.6 inch per milliampere. Thus a bridge current from a 6- to 12-volt source of only 100 to 400 milliamperes gives cards of satisfactory size. The film used is 3¼ by 5½, and with maximum sensitivity the lower, or pumping, loop may readily be studied. The scale under these conditions is probably about 50 pounds per inch.

The instrument is not a precision indicator, by reason, first of all, of the varying conductivity of carbon with temperature. The electrical characteristics are also altered by the intensity of pressure, and the dynamic calibration does not check the static calibration. Compressed air must be blown through the pressure element to cool the diaphragm and carbon stacks. The pressure element is affected by vibration and shock, and when inserted in the conventional aircraft engine cylinder, a very ragged line (see fig. 12) is drawn, due to the shocks transmitted to the carbon stacks. The frequency of this vibration, as recorded, appears to be that of the steel tongue which transmits pressure to the stacks. When used in a cast-iron cylinder, the records are free from this defect. The electrical connections are fragile and do not last long where vibration is severe. There is no means of obtaining a zero line under the actual test conditions.

There are, however, some problems where this type of indicator offers the only available solution. It does produce a record of one continuous pressure wave, either recurrent or transient, and shows all the variations that occur, since each cycle may be observed. It has been used to good advantage to record the pressure variations in an engine oiling system due to register of oil grooves, and teeth in the gear pump (see fig. 11). Performance of fuel-injection nozzles has also been studied (fig. 11) and the effect of length and diameter of tubing for fuel injection determined. Detonation pressures are recorded (fig. 12) showing the very high, if not actually instantaneous, rate of pressure rise when detonation occurs. Even with a very steadily operating single-cylinder test engine it has shown a great variation, from cycle to cycle, in the time of maximum pressure, or the time detonation occurs. All things considered, this indicator, while useful for certain special problems, cannot be considered satisfactory for ordinary engine research. The cost is prohibitive, as the special oscillograph required for satisfactory operation is necessarily expensive, and not well adapted for general use as an oscillograph.

Much the same criticisms would apply to the condenser-transmitter type of indicator previously mentioned. Some of the records reproduced in the D.V.L. year book show the effect of vibration just as found in the case of the carbon stack indicator. In addition to an oscillograph as required for the latter, the condenser-transmitter type requires the electrical apparatus incidental to the tuned semiresonant circuits, such as vacuum tubes, variable condensers, A, B, and C batteries, and meters for adjusting the circuits. These introduce new variables and increase the difficulty of calibration. The conclusion thus far reached, regarding the electrical type of indicator, is that for qualitative work, such as combustion research, development of fuel-injection systems, and allied special problems, it is the best device available. The exact magnitude of the pressures as recorded cannot be relied upon, but the character of the pressure phenomenon is probably correctly recorded.

*Sampling valve indicators*

There remains to be considered one more method of indicating high-speed engines, which has much to recommend it. This is the so-called "sampling" or point-by-point method. A valve is interposed between the combustion space and an ordinary low-speed indicator. A phase gear is employed to drive the sampling valve at cam-shaft speed. This phase gear is so constructed that the phase or point in the cycle at which the valve opens for a brief instant, is adjustable manually. As this period of opening is moved through the cycle, the drum of the low-speed indicator is moved a proportionate amount. Continuous records are thus made of points taken from 1,000 or more cycles of the engine. The phase gear may be driven automatically at a low speed or operated manually by means of a crank. The latter is preferable, since the rate of change of phase should be inversely proportional to the rate of change of pressure. The indicator should therefore be moved very slowly where the pressure is changing rapidly, and can be moved quite rapidly on the flat portions of the curve. Greater accuracy results, together with a saving in time. A complete card can be taken in two or three minutes, including change of indicator springs to secure both high-pressure and low-scale cards.

The best commercial example of this type is probably the DeJuhasz, shown in figure 13. The valve of this indicator consists of a small piston surrounded by a sleeve, working in an air-cooled cylinder. A port through the piston registers with a port through the sleeve twice each revolution of the indicator crank shaft. At the same instant a port through the cylinder registers to give a free port area through the entire unit. The action of the port is rapid, due to the piston and sleeve moving in opposite directions, even though the indicator is driven at one fourth engine speed. A tube connects the valve with the combustion space. This tube is about one eighth inch inside diameter and the length varies from about 4 inches as a minimum up to about 12 inches as a maximum. The tube requires water cooling either with a wet rag or by soldering a second tube to it, and flowing water through the latter.

It may be thought that tube resonance effects would produce a very ragged card, but in practice it is found that any pressure surges present are lost in the average card, due to the fact that the pressure surges have no definite time relation to the cycle. Shifting of pressure peaks due to irregularities in combustion is much more serious and may be taken care of by throttling the indicator cock, thus making the card conform to the average cycle instead of attempting to follow the individual cycles. The time lag due to a connecting tube 11 inches long is of the order of 0.001 second, based on transmission of pressure at the velocity of sound. Cards have been taken with this indicator, using tubes longer than 12 inches, at an engine speed of 1,700 r.p.m. Cards have been taken with varying lengths of connecting tubes and little or no difference is observable in the cards until a length of a foot is exceeded. Based on velocity of sound, the entire card would be expected to shift later by the time lag of 0.001 second where a tube 11 inches long is used. If the engine is operating at 1,800 r.p.m., or 30 revolutions per second, the delay should be $\frac{30}{1000}\ 360=10.8°$ crank travel. It is entirely possible that this delay does occur, but there is the possibility that pressure may be transmitted at a velocity greater than 1,100 feet per second.

This indicator uses a standard outside spring Maihak indicator for the recording mechanism and the phase gear provides a crank and slider mechanism with adjustable $\frac{L}{R}$ ratio, with which P-B cards are taken. Offset, or 90° cards provide a means of studying the peak of the pressure diagram substantially in P-T form.

It is very difficult to maintain the piston valve tight enough for the correct register of the high-pressure portion of the card. The port area is large, and the indicator stylus attempts to follow the variations of pressure from cycle to cycle. Hence, the pressure peak is very ragged. Pressures up to 150 pounds per square inch are held without difficulty, but higher pressures blow the oil seal from the piston valve and the record appears to be consistently low. In one case where the pressure peak was known to have a value of about 475 pounds per square inch, the record showed only 350 pounds per square inch. The results were somewhat better when castor oil was flooded over the valve just before taking the high-pressure portion of the card.

The use of a connecting tube appears to be a necessity, and this entails an unknown phase shift, as previously pointed out, which may be objected to. The phase gear and valve are in one unit. Hence, some installations are not as convenient as would be the case were the valve a separate unit. However, the weak spring or lower loop diagrams are excellent, and for valve timing and inlet manifold development are most useful.

The multiple element sampling valve or "direct pressure indicator", figure 14, of Commercial Laboratories, is another interesting example of this type of indicator. It is made with as many as 12 pressure sampling valves, located at the wall of each combustion chamber, each actuated by an electromagnet, and so timed as to operate in the firing order of the engine. Simultaneous pressure records are made in phase on a wide sheet of paper. The phase gear and electrical timer are driven by a flexible cable from the engine crank shaft. The phase gear may be engaged or disengaged, and the valve electromagnets may also be cut in or out. A special storage battery is used to actuate the valves, and, on account of the heavy drain, the valves cannot well be operated simultaneously. A circuit has been devised whereby the phasing may be checked with a neon lamp. The mechanical drive of the phase gear is open to some objection, since if slow enough for the pressure peaks it is too slow for the rest of the card. Flexible shafts must be looked upon with suspicion, and the magnetic lag of an electromagnet is proportional to the speed. The latter is compensated for by increasing the voltage applied to the electromagnets. The pressure recorders are inverted and filled with heavy oil above the pistons, and are of the outside spring type. Springs may be changed to secure weak spring cards if desired. The most obvious use of such an indicator is to study distribution, manifolds, and ignition, not attempting to analyze the cards. For this work the indicator has given good results.

Recognizing the good points of this method of indicating high-speed engines, the Materiel Division has developed a highly satisfactory indicator, which has given excellent service in engine development work. The requirements laid down for this indicator were as follows:

1. Complete elimination of connecting passage by locating the valve in the combustion chamber wall.
2. Positive mechanical drive.
3. Minimum duration of valve opening period.
4. Elimination of leaks in the valve and recording system.
5. Minimum backlash in the phase gear mechanism.

These requirements were most fully met by a poppet valve in a unit which is adapted to be screwed directly into the combustion chamber wall. This unit is driven through a light shaft and universal joints by a simple phase adjusting gear which in turn is mechanically driven from the engine or dynamometer shaft. A special form of balanced valve relieves the valve spring of load due to pressure trapped in the recording system. Gas-tight packing is used with pressure lubrication from the engine oiling system, making the valve remain tight for long periods of time. As a further precaution, a cooling passage is provided for water circulation in the valve body.

The phase gear is fitted with a grooved drum, adapted to pull the drum cord of a conventional low-speed indicator. Thus, P-T diagrams are obtained, one revolution of the indicator drum representing one crank shaft rotation. A simple mechanism can also be fitted to move the drum so as to secure P-V diagrams. However, the P-T diagram spreads out the events at top center, both firing and exhaust strokes, so as to enable study of valve timing. After all, little importance attaches to the P-V diagram, except for checking I.M.E.P., while the study of valve events by means of weak spring P-T diagrams is of direct importance in engine research. The P-V mechanism can readily be added to enable taking records of this type if desired.

The sampling valve method has the advantage over the balanced pressure type of simplicity, not requiring pressure tanks nor vacuum pumps, and it takes a permanent record of satisfactory size, on ordinary indicator paper. The recently developed wax-sensitized paper is in some respects better for this purpose. It requires very light stylus pressure and has less pencil friction than the metallic sensitized paper. It does not, however, stand handling well, and oil darkens the wax coating. The cost of this paper is very moderate, and it has proven quite satisfactory for most purposes.

The Matériel Division sampling valve was directly compared with the Bureau of Standards balanced diaphragm indicator by taking readings of pressure and phase angle, using the same gages and manometer as are used on the Bureau of Standards indicator. This was done on a Liberty single-cylinder test engine. The pressure diagrams were almost identical when plotted. Hence it was concluded that the sampling type is inherently as precise as any other known method. The greatest care must be exercised to insure no leaking of pressure on the recording side of the system. The chief disadvantage is that it is not simple to secure a good installation, due to the mechanical drive required. For single-cylinder research work, the drive for the phase gear may be built in and a tapped hole conveniently located for the valve. Figure 10 shows the set-sup of the Matériel Division indicator on the single-cylinder test engine.

### DISCUSSION OF PRESSURE RECORDS

Cards (*a*) and (*b*), shown in Figure 11, were taken at the oil-pressure gage connection on a 12-cylinder aircraft engine. Card (*a*) was taken at a speed of about 600 r.p.m., and shows the effect of oil groove register. Card (*b*) shows this effect to a small degree and also what appears to be pulsations due to the teeth of the gear type oil pump used. Card (*c*) shows the pressure cycle of a fuel injection system at low speed, while (*d*) shows the pressure cycle at high speed. The waves present in both records appear to be pressure waves in the fuel, since they change radically with tube length and diameter. On cards (*c*) and (*d*), time is from right to left, due to the direction of rotation of the mirror unit.

Figure 12 shows typical records of cylinder pressure on aircraft engines when using the carbon-pile type of indicator. In (*a*), (*c*), and (*d*) the effects of vibration of the pressure element are evident. These oscillations are so bad as to render the cards of little value. Card (*b*) was taken on a test engine having a cast iron cylinder. The very poor record is due to use of an alternating current arc, since direct current was not available. The form of a detonation pressure peak may be observed, as well as the great variation in shape and time of pressure peak. This card was made with the P-V mechanism offset 90°. In both (*a*) and (*b*), time is from right to left.

Cards (*c*) and (*d*) are typical of the records obtained on aircraft engine cylinders, using the P-V mechanism. The effect of vibration obscures the form of the record, making its interpretation difficult.

Figure 2 shows typical records obtained with the Matériel Division sampling valve indicator. Cards (*a*), (*b*), and (*c*) were taken on a 12-cylinder Vee engine at 2,400 r.p.m. In (*a*) the engine was operating unsupercharged, while in (*b*) a small boost was used, which is evident in the weak spring card. The sharp peaks at maximum pressure were due to incipient detonation, this being the only way detonation is shown by this indicator. In (*c*) an exhaust manifold was used at two back pressures, and the effect of cylinder interference and back pressure are plainly visible.

Cards (*d*) and (*h*) show records on a single-cylinder test engine with poor valve timing (*d*) and improved timing (*h*). In the latter case, an error evidently was made in the scale of the high-pressure card. The scale should have been 300 pounds per inch instead of 180 pounds per inch, as shown. The peak pressure would then be 425 pounds per square inch instead of 245, as indicated. The relatively fat card is due to the 5:1 compression ratio used, and the engine was supercharged, as shown by the low-pressure card.

Cards (*e*), (*f*), and (*g*) were taken in the intake pipe close to the intake valve. They show typical pressure surges due to resonance and gas inertia. Card (*g*) was taken at a boost of 13.1 inches of mercury.

Figure 1 shows some interesting cards taken on a supercharged single-cylinder test engine. At (*a*) is shown the compression curve. The compression ratio is 4:1, and the indicator was phased by setting to the peak pressure, as indicated. The phase index was marked and thereafter a T.C. mark was made on the cards at this point, as shown in (*b*), (*c*), and (*d*). Card (*b*) was taken at a boost of 20 inches of mercury, while (*c*) shows unsupercharged, 10-inch boost, and 10-inch boost with 10-inch back pressure. Here, too early exhaust closing is shown by the pressure peak at end of exhaust stroke. In (*d*) the boost was 20 inches, but the peak pressure was low, due to late ignition. Cards (*e*) and (*f*) are P-V cards, taken at 16- and 30-inch boost pressure. The B.M.E.P. in (*f*) is 219 pounds per square inch. The source of supercharge was an air compressor, and the boost pressure acting on the intake stroke should have been sufficient to operate the engine; hence, the "mechanical efficiency" of 100 percent which this card shows by its I.M.E.P. of 216 pounds per square inch. On another occasion, a test engine with a 39-inch boost refused to stop when the ignition and fuel were cut off. Its "mechanical efficiency" was evidently above 100 percent, since the dynamometer caused a considerable drag due to the residual field and windage.

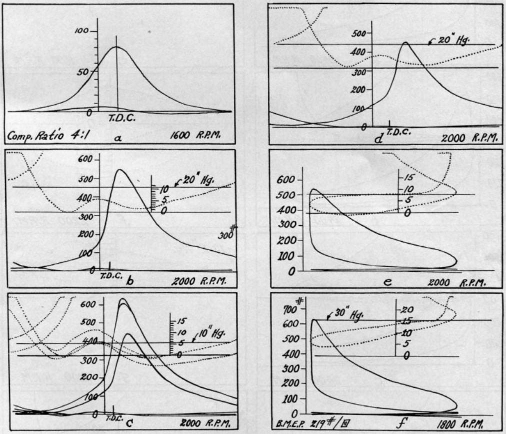


FIGURE 1.—P-T and P-V Cards on Single-cylinder Supercharged Test Engine

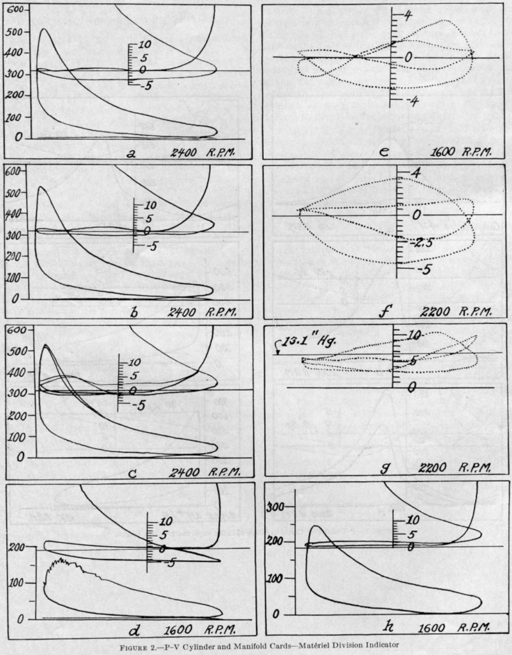


FIGURE 2.—P-V Cylinder and Manifold Cards—Matériel Division Indicator

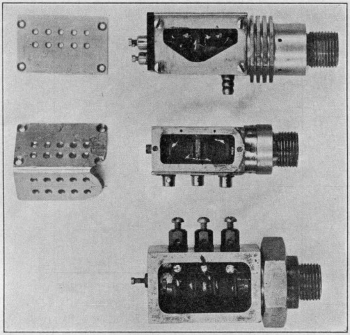

FIGURE 3.—Telemeter or Carbon-pile Pressure Elements

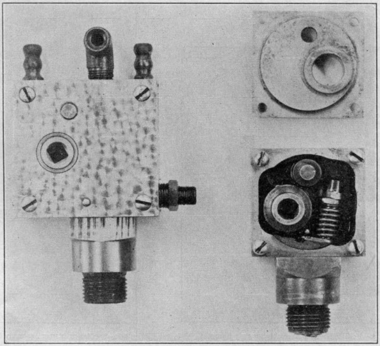

FIGURE 4.—Sampling Valve—Matériel Division Indicator

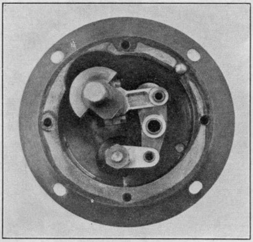

FIGURE 5.—Operating Mechanism for Oscillating Mirror Assembly

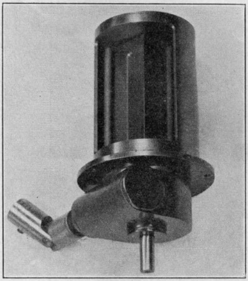

FIGURE 6.—Rotating Mirror Assembly for P–T Records

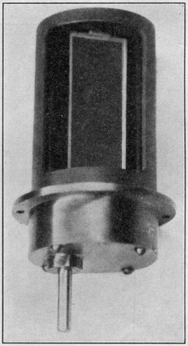

FIGURE 7.—Oscillating Mirror Assembly for P–V Records

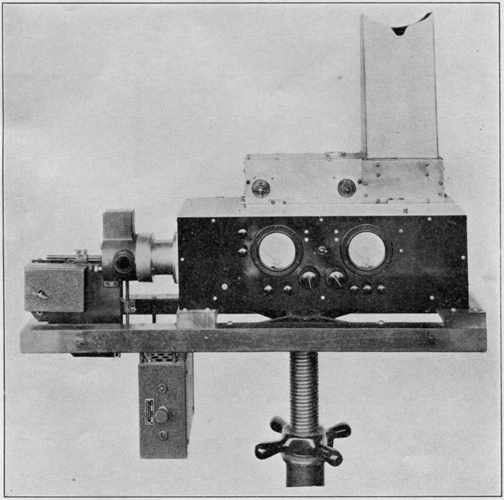

FIGURE 8.—Special Electric Indicator Oscillograph

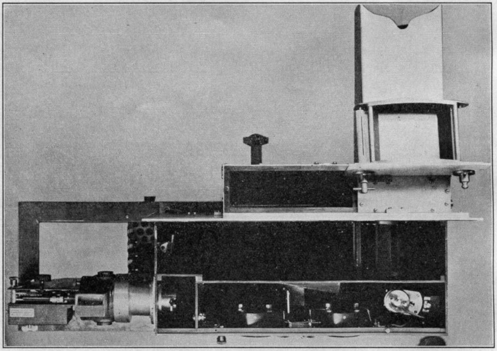

FIGURE 9.—Top View—Special Electric Indicator Oscillograph

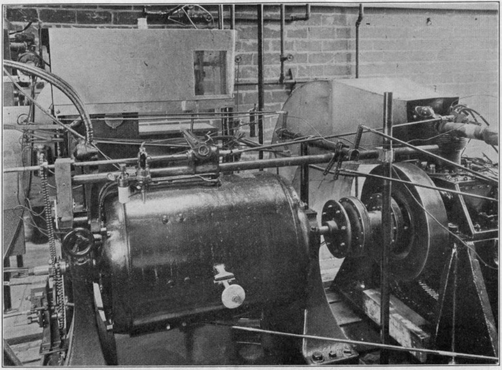

FIGURE 10.—Set-up of Matériel Division Indicator on Single-cylinder Test Engine.

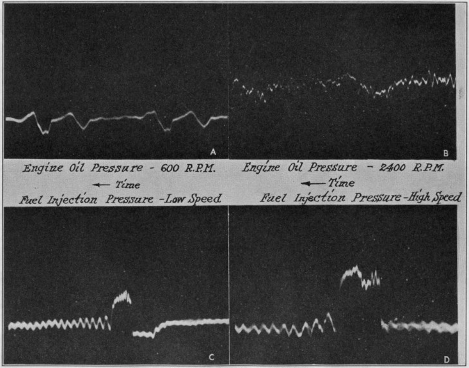


FIGURE 11.—P-T Records of Engine Oil Pressure and Fuel Injection Pressure.

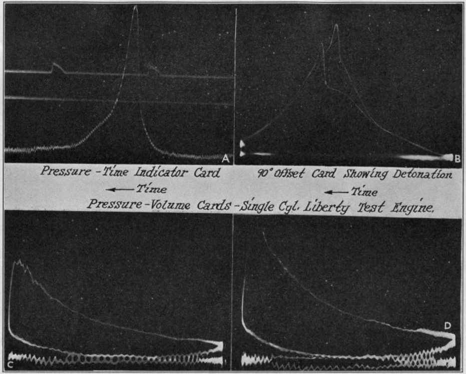


FIGURE 12.—P-T, Offset P-V, and P-V Records of Engine Cylinder Pressure.

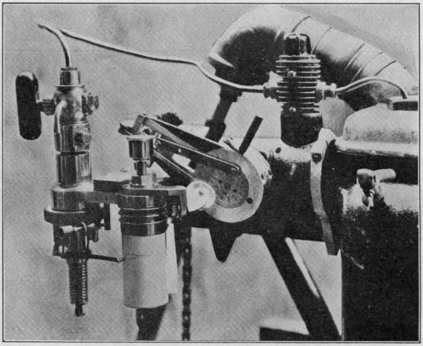

FIGURE 13.—DeJuhasz Indicator Mounted on Automobile Engine.

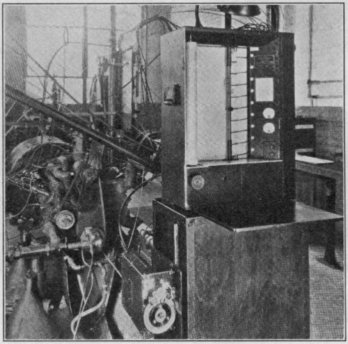

FIGURE 14.—Commercial Engineering Laboratories Indicator Mounted on an Automobile Engine.

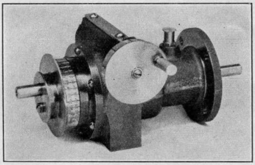

FIGURE 15—Phase Gear—Matériel Division Indicator.