

A PIEZO-ELECTRIC INTERNAL COMBUSTION

ENGINE INDICATOR

by

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TABLE OF CONTENTS

	Pages
Introduction	2
Brief History of Piezo-electricity and Its Applications	3
Principle of Operation of the Piezo-electric Indicator	5
Crystallography	8
The Piezo-electric Properties of Quartz	11
Table of Electric Constants of Quartz	13
Principle of Operation of the Cathode Ray Oscillograph	14
Calculation of the Effect of Leakage Resistance and External Capacitance on the Voltage Output of the Crystal Element	20
Calculation of Voltage Output of Crystal Element	28
Design of Amplifier Circuit	29
Proposed Method of Calibration	31
Results of Experimental Tests	35
Conversion of Pressure-Time Cards into Pressure-Volume Cards	46
Bibliography	48

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INTRODUCTION

The design and construction of an accurate and reliable indicator for high-speed internal combustion engines present problems quite different from those of the slow-speed-piston-type indicator. Indicators having mechanical linkages and moving parts are unsuitable for the requirements of a high-speed indicator because the inertia of the moving parts introduces varying degrees of lag and the vibrations of the component parts produce extraneous oscillations on the indicator diagram.

Mechanical high-speed indicators, such as the balanced diaphragm type, have been used successfully; but these indicators require a number of engine revolutions to obtain a complete diagram and are subject to certain difficulties of operation. High-speed mechanical indicators in general require accurately machined parts and are costly and complicated. Electrical indicators, on the other hand, are easily operated, require less machine work than mechanical types, and are capable of producing a diagram of a single cycle of the engine. Another advantage of the electrical indicator is that the element which must be attached to the cylinder can be made small enough so as not to influence the operation of the engine.

There are several types of electrical indicators, but these differ principally in the method of converting the pressure variations into electrical impulses. Among the types of devices for converting mechanical impulses into electrical impulses may be mentioned the electrostatic, the electromagnetic, the variable-resistance, and the piezo-electric. The last two types listed require simpler auxiliary apparatus than the other two types.

BRIEF HISTORY OF PIEZO-ELECTRICITY AND ITS APPLICATIONS

The word piezo-electricity is derived from the Greek word piezen meaning to press; hence the word symbolizes electricity developed by pressure. Piezo-electric crystals thus possess the property of producing an electrical charge when subjected to external pressure and so converting mechanical energy into electrical energy. The converse of this is also true.

The quantitative piezo-electric properties of quartz were first investigated by Curie and Curie in 1880. (21) They also investigated the converse effect when an electric charge applied to the crystal would produce a change in crystal dimensions, and derived equations showing the relation between the applied pressure and the piezo-electric charge developed on the crystal faces. Voight (22) in

1895 developed theoretical formulas for the piezo-electric charge in terms of the piezo-electric constant and the elastic constants of the crystals. His calculated values checked the Curies experimental values.

Of the many uses that have been made of piezo-electric properties, the following are a few of the more widely known: pressure gages, loud speakers, earphones, microphones, under-water sound transmitters, filter circuits, and perhaps the most widespread use, the use of piezo-electric crystals as precision frequency resonators in electrical circuits.

The piezo-electric properties of tourmaline were used for obtaining the pressure diagrams of explosions by Thompson (17) in 1919 and by Keys (3) in 1921. Quartz crystals were used by Karcher (2) for the measurement of explosion pressures in guns. However, the electrical instruments available at that time for the measurement of electrical potential were in no manner comparable to the rugged electronic devices of the present day.

Apparently the first description of the use of piezo-electric crystals as an internal combustion engine indicator was an instrument described by Watanabe in 1929 (11,12). Watanabe's device measured only the pressures in the engine cylinder and no scale diagrams of either the pressure-volume or pressure-time types were obtained,

although he indicated the possibility of obtaining such diagrams. In 1930 Kluge and Linkh (10) constructed a piezo-electric type indicator in combination with an amplifier and a string galvanometer. In 1932, Watson and Keys (1) built an indicator of the piezo-electric type and used an oscillograph with a uniform time sweep to obtain pressure-time diagrams. Other types of electrical indicators requiring apparatus of a similar nature to the piezo-electric type have been described in several technical journals, (see bibliography) but the literature on the piezo-electric type of internal combustion engine indicator is rather meager. Since this thesis was started, the Carl Zeiss Company has announced the production of a piezo-electric type indicator which, however, is very expensive.

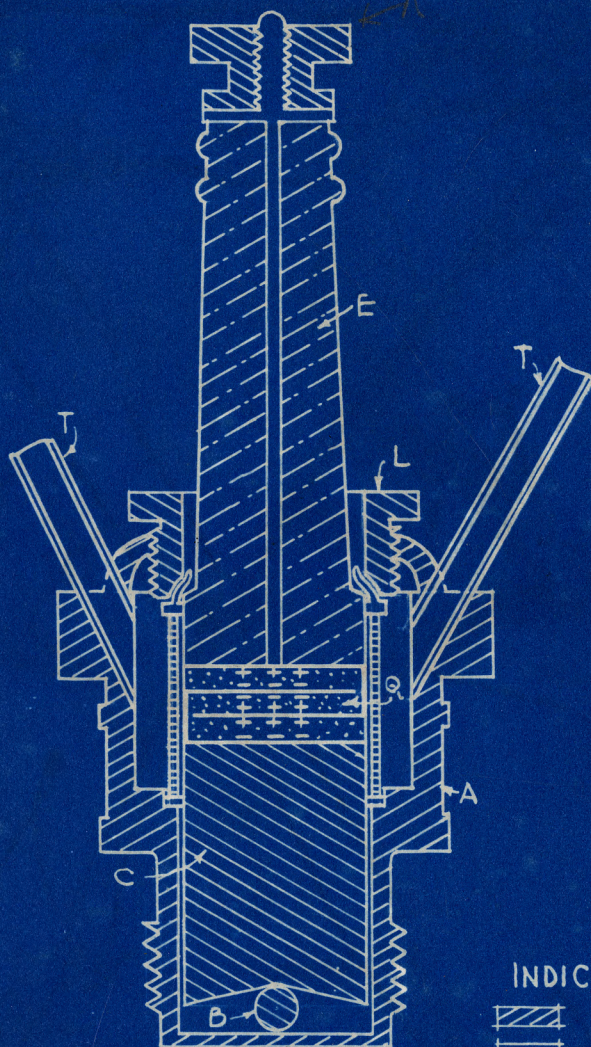
PRINCIPLE OF OPERATION OF THE PIEZO-ELECTRIC INDICATOR

Since the charge developed by certain piezo-electric crystals, such as quartz, when subjected to external pressures is directly proportional to the applied pressure, and since the time lag of these crystals is extremely small, their use for the conversion of pressure variations into corresponding electrical variations for use in a high-speed indicator appears to offer considerable promise.





Some method of applying the cylinder pressure to the piezo-electric crystals is necessary, requiring a unit which

is called a crystal element or holder in the following discussion. The following description of the writer's original design of crystal holder will assist the reader in understanding the principle of operation.

The indicator crystal holder shown in figure 1 consists of a base piece A with an integral diaphragm $1/64''$ thick, a small steel ball B, a solid steel cylinder C, three quartz crystals Q, a hollow glass cylinder G surrounding the quartz crystals, and a porcelain electrode E held in place by the nut L. The annular space between the glass cylinder and the base piece is filled with water for cooling purposes. The copper tubing T is to supply water at the proper rate to maintain the temperature of the water leaving the unit at a constant known value. By means of the nut L an initial pressure is applied to the quartz crystals in order to remove all looseness between the parts. When the crystal element is screwed into the engine cylinder the pressure variations are transmitted to the crystals through the diaphragm, the steel ball, and the cylinder. The variations in pressure on the crystals produce corresponding variations in the electric charge and potential which appears across the base piece A and the terminal R. The potential developed is too small to operate a recording device so a vacuum tube amplifier is interposed between the crystal unit and a cathode



INDICATIONS

	STEEL
	GLASS
	QUARTZ
	PORCELAIN

CRYSTAL HOLDER

FIGURE 1

ray oscillograph which is used as a recording device. The crystals are connected in parallel by means of tinfoil connected as shown. The polarities marked on the crystals illustrate the manner in which the charges that would be developed under pressure are connected in parallel.

CRYSTALLOGRAPHY

A large number of crystalline substances such as quartz, Rochelle salts, and tourmaline have excellent piezo-electric and pyro-electric* properties. All of these substances are optically double refracting and possess an asymmetric atomic structure. Alpha quartz which is piezo-electrically active has an unsymmetrical hexagonal atomic structure, while Beta quartz which exists above 573 degrees Centigrade has a regular hexagonal atomic structure and is piezo-electrically inactive. (19,33)

Of the three more commonly known piezo-electric crystals, quartz, Rochelle salt, and tourmaline, only quartz appears available for use in indicators. Rochelle salt, although exhibiting ten times the piezo-electric properties of quartz, is unreliable, hard to manufacture into suitable sizes, fragile, and difficult to handle. Tourmaline is too expensive to use commercially and it does not possess any

*Pyro-electricity denotes electricity produced by changes in temperature.

appreciably superior piezo-electric properties over quartz.* Quartz can be obtained in commercial quantities from Brazil, Madagascar, Japan, and the United States. To be of value for its piezo-electric properties the quartz must have no flaws, intergrowths, or optical twinning** which renders the crystal piezo-electrically inactive (33).

Quartz crystals in the natural state are hexagonal in shape and in true form have a pyramidal apex at each end as shown in figure 2a. The methods of mining and the process of growing cause the majority of commercial crystals to be imperfect as regards the external crystal structure. In the crystal shown in figure 2a the line Z-Z drawn between the two apexes is called the optical axis. In the section shown in figure 2b a slab of the crystal cut in a direction normal to the optical axis is illustrated with the appropriate axes drawn. The section is designated as having three X electrical axes drawn between opposite corners and three Y electrical axes drawn normal to the midpoints of the sides of the hexagonal section. If a slice is cut from the slab as shown

*It should be mentioned, however, that tourmaline will develop an electric charge when subjected to uniform hydrostatic pressure whereas quartz will not; thus tourmaline lends itself to certain pressure measurements more readily than quartz. In the present application the crystals are not exposed to the pressures in the cylinders but the pressures are transmitted to the crystals through a diaphragm.

**Optical twinning denotes a combination of quartz with both right and left hand optical rotary powers.

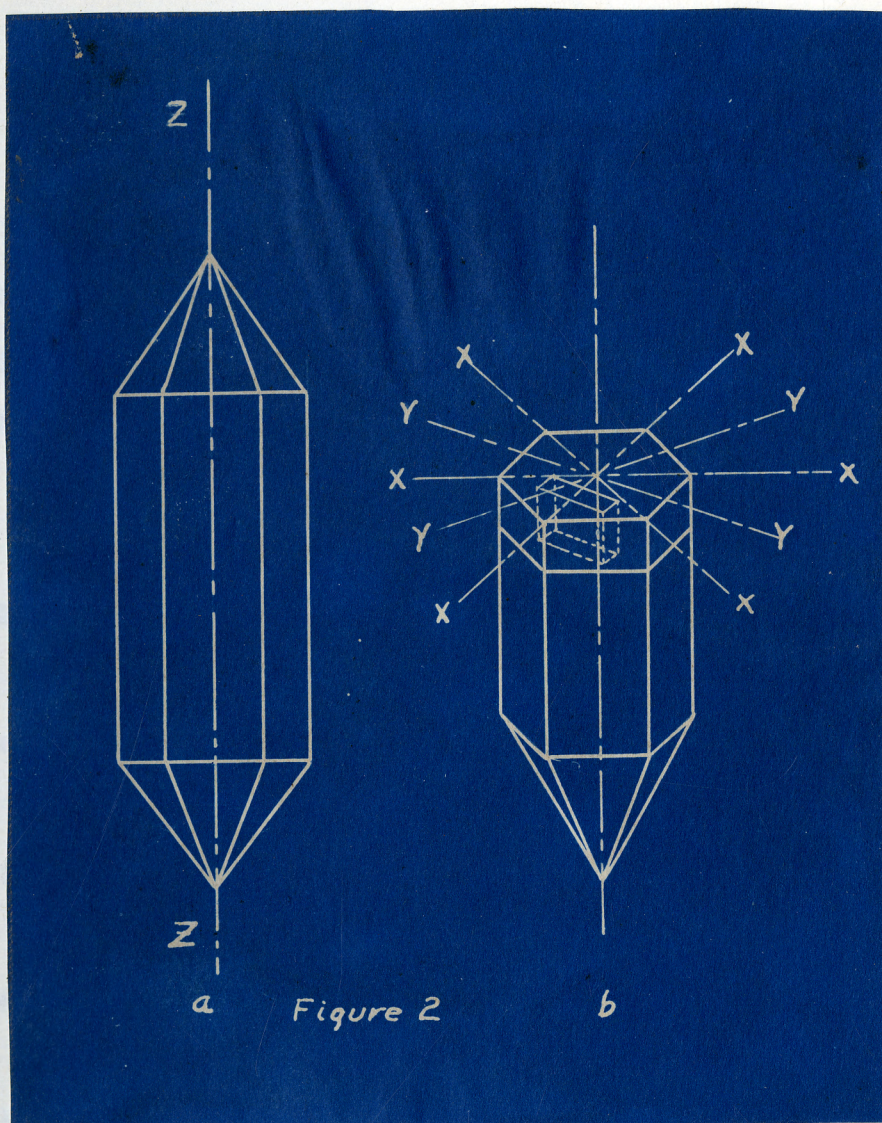


Figure 2

in the figure with its thickness in the direction of an X axis, its width in the direction of the Y axis normal to the X axis, and the depth parallel to the Z axis, a crystal called an X-cut crystal is obtained. Other cuts produce crystals having properties of a different nature, but the X-cut is the most suitable for indicator purposes because it has a maximum piezo-electric effect and because the charge developed is on the faces upon which the pressure is applied. (Pressure applied on surfaces normal to X axis.)

THE PIEZO-ELECTRIC PROPERTIES OF QUARTZ

When Curie and Curie (20,21) investigated the quantitative piezo-electric properties of quartz they found that the electric charge developed by applying pressure to the quartz was directly proportional to the pressure applied. Karcher (2) has tested quartz at pressures up to 50,000 pounds per square inch and found that the linear relationship between developed charge and applied pressure held within the .1 per cent limit of accuracy of his apparatus. He further found evidence that the value of the piezo-electric constant for pressures applied adiabatically was equal to the isothermal constant, i.e., the piezo-electric constant is independent of the rate of pressure change. When pressure is applied to opposite faces of a properly cut quartz crystal one side will become positively charged while

the other side will be negatively charged. When the direction of the pressure is reversed, i.e., when a pull is applied, the charges on the crystal likewise reverse. The time lag between the applied pressure and the developed charge is extremely small as may be shown from the use of quartz crystals as resonators at frequencies above a million cycles per second.

The value of the piezo-electric constant--the electric charge developed per unit of applied pressure--for quartz is 1.03×10^{-11} coulombs per pound at 20 degrees Centigrade. The exact value varies appreciably from crystal to crystal and over the surface of one crystal but for a given specimen the value is always the same at the same temperature and is entirely independent of the temperature variations to which the specimen has been subjected.* (40) Since the variation of the piezo-electric constant with temperature is of considerable importance in a large number of the applications of quartz crystals, investigations to determine the manner of variation have been made (40). As the temperature of the quartz is increased above room temperature the value of the constant increases to a maximum at approximately 60 degrees

*When quartz is heated above 573 degrees Centigrade and permitted to cool the piezo-electric constant does not return to its normal value for a considerable time (several hours or more), however, the time lag is negligible for small variations in temperature.

Centigrade and then decreases with increase in temperature until it becomes zero at 573 degrees Centigrade.* At room temperature the constant is about 80 per cent of its value at 60 degrees, while at 100 degrees the value is more than 90 per cent of the maximum value. From 150-300 degrees Centigrade the constant is nearly independent of the temperature. It is therefore necessary to maintain the crystals at a constant known temperature when they are to be used for quantitative measurements such as in a pressure indicator, or else calibrate the apparatus against temperature.

TABLE OF ELECTRIC CONSTANTS OF QUARTZ**

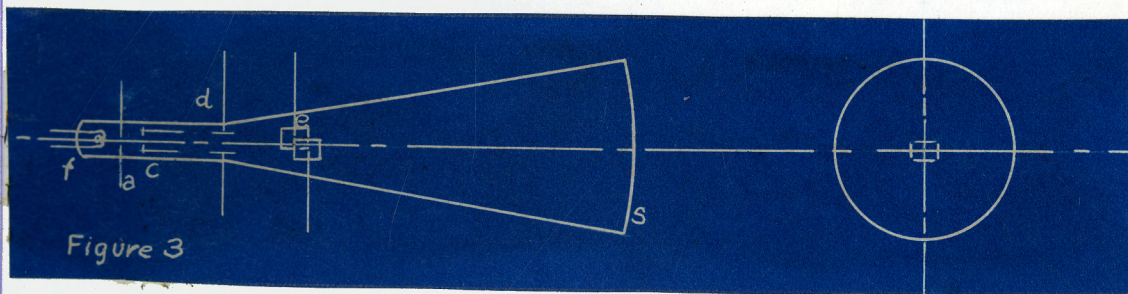
Piezo-electric constant	$6.9 \cdot 10^{-8}$ e.s.u. per dyne $1.03 \cdot 10^{-11}$ coulombs per lb.
Electric resistivity (normal to optic axis) (ohms between opposite faces of centimeter cube)	$20 \cdot 10^{15}$ ohms at 20°C
Dielectric constant	4.5

*It should be mentioned that since the temperature coefficient of the X cut crystals is opposite to that of the Y cut crystals (but of different magnitude) it is possible to obtain special cut crystals with negligible temperature coefficients over limited temperature ranges.

**From the International Critical Tables, 1926, v6, McGraw-Hill, New York.

PRINCIPLE OF OPERATION OF THE CATHODE RAY OSCILLOGRAPH

The cathode ray oscillograph has been used for recording electrical oscillations of a frequency exceeding 1,000,000 cycles per second and for the recording of transient impulses of a period of one one-hundredth of a micro-second. The cathode ray oscillograph is thus an instrument of negligible inertia and is therefore to be preferred to other types of recording devices for use with the piezo-electric crystal element. The use of a fluorescent screen permits convenient visual observation or photographic recording when desired. Other advantages of the oscillograph will become apparent as the theory of its operation is discussed.



In figure 3 is shown a sketch of the principal parts of an ordinary hot cathode type cathode ray oscillograph tube the operation of which is as follows. Electrons are drawn from the hot oxide coated filament f by the anode

a which is maintained at a high positive potential (from several hundred to several thousand volts depending on the tube and the intensity of the electron beam desired). A number of electrons pass through the hole in the anode and form a high speed electron beam which passes between the two pairs of mutually perpendicular deflecting plates d and e which are near the anode as shown and then travels until it impinges upon the fluorescent screen s making a spot of light on the screen. The focusing cylinder c, acting as an electrical lens, is biased with a negative potential in order to force the electrons into a compact beam and thus neutralize the tendency of the electrons to separate from each other and form a wide and poorly defined beam. When a potential is placed across a pair of deflecting plates the electron beam will be deflected toward the positive plate and the position of the spot of light on the fluorescent due to the beam will be displaced accordingly. For a constant anode voltage, the displacement of the beam is directly proportional to the magnitude of the voltage applied to the deflecting plates. This method of controlling the position of the spot of light on the screen is an electrostatic one and requires only a minute amount of power for operating the deflecting plates. In the electro-magnetic method the motion of the electron beam is controll-

ed by the magnetic field of suitably placed coils which require an appreciable quantity of power for operation as compared to the electrostatic method but is more advantageous when currents rather than voltages are to be measured. The voltage required to deflect the electron beam a given amount depends on the velocity of the electrons in the beam. The velocity or "stiffness" of the beam is controlled by the anode voltage used to accelerate the electrons.

When the cathode ray is used to trace out an indicator diagram variations in voltage corresponding to the variations of pressure in the engine cylinder are impressed across a pair of the deflecting plates so as to deflect the electron beam in a vertical direction while simultaneously a voltage proportional either to piston position or crank angle is impressed across the other pair of deflecting plates so as to move the beam in a horizontal path. The resultant motion of the beam traces out an indicator diagram. The wave form of a voltage proportional to the crank angle suitable for use with the oscillograph is shown in figure 4. The time interval between a and b is the same as the time for a cycle of the engine so that the pressures in the cylinder for a cycle are shown in an indicator diagram on a uniform time base (figure 5).

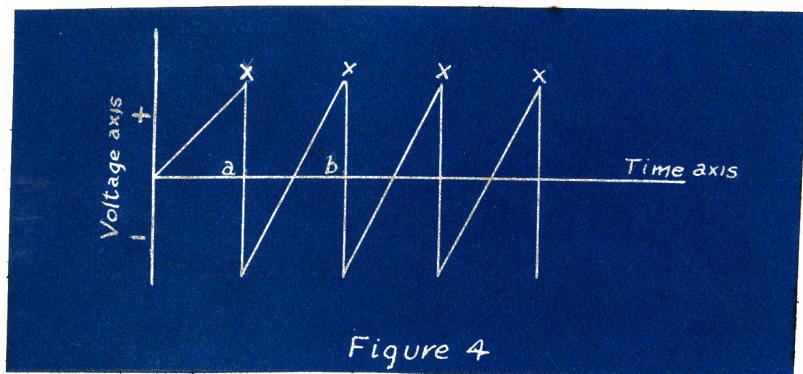


Figure 4

Time "sweep" circuits capable of producing a waveform of this nature called a "linear sweep" are incorporated in ordinary commercial cathode ray oscillographs. The "sawtooth" waveform is obtained by charging a condenser with a constant current flowing through a voltage saturated vacuum tube and then short-circuiting the condenser at the proper time by a grid controlled gas filled electron tube.* A uniform current flowing into a condenser will increase the voltage across the condenser directly proportional to the time of current flow. If the period of the linear sweep is made equal to the period of rotation of the engine a pressure time diagram such as that illustrated in figure 5 is obtained. If, however, the period of the linear sweep

*For a detailed explanation of the cathode ray oscillograph see any book on electron tubes, or the booklets describing the commercial oscillographs.

is made a sub-multiple of the engine rotation period the length of the diagram can be amplified in the manner shown in figure 6 thus permitting accurate timing of the events of the engine cycle. The time at which the condenser of the sweep circuit is short-circuited, i.e. the time at which the events x in figure 4 occur can be controlled by means of a voltage applied to the grid element of the gas filled electron tube. By employing contacts on the flywheel and and on the body of the engine a voltage may be applied to the grid of the gas filled tube at any desired and measurable point in the cycle of the engine. By this means the sweep circuit may be synchronized with the rotation of the engine and the position of the starting point 0 in figure 5 may be made to occur at any desired point in the engine cycle thus accurately timing the event with respect to the crank position.*

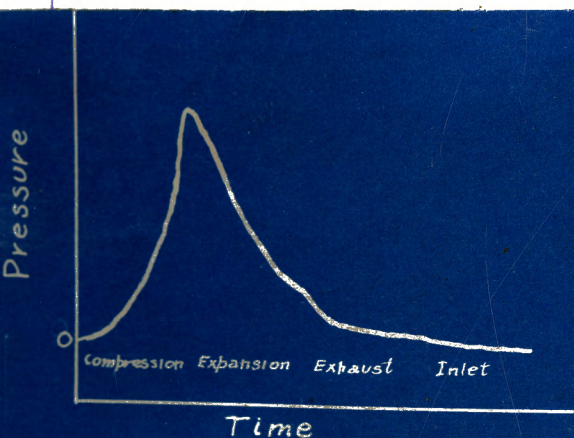


Figure 5

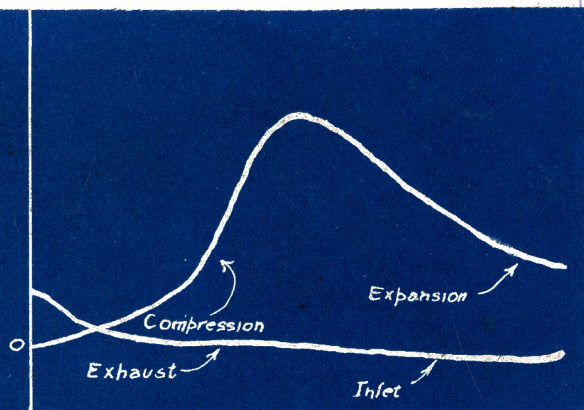


Figure 6

*See "Engineering," 140:185, August 23, 1935.

Diagrams corresponding to the "blocked spring" diagrams of the piston-type indicator may be obtained by increasing the amplification of the amplifier thus expanding the low pressure portion of the diagram. The pressure-time diagrams may be converted to pressure-volume diagrams by means of a crank angle dummy as explained under figure 18.

It is difficult to obtain a voltage which is proportional to the piston position, but such a voltage may be obtained by reciprocating a strip of high resistance metal between roller contacts by means of a connecting rod and crank adjusted to have the same connecting rod to crank ratio and the same phase as the engine under test. Current or voltage variations obtained in this manner can be applied to the cathode ray oscillograph and thus a pressure-volume diagram may be obtained. A more elaborate method using a generator with an electrically distorted output may be used.*

It should be mentioned that the cathode ray oscillograph may be used on internal combustion engines for a number of other purposes similar to the above. For example, the oscillograph may be used to demonstrate the rate of flame propagation in the cylinder after ignition by using the oscillograph to indicate the current flowing across an insu-

*See "Engineering", 140:185, August 23, 1935.

lated spark gap placed in the cylinder. The quantity of current flowing is dependent on the ionization of the air in the cylinder which in turn is dependent on the temperature of the air.

CALCULATION OF THE EFFECT OF LEAKAGE RESISTANCE AND EXTERNAL CAPACITANCE ON THE VOLTAGE OUTPUT OF THE CRYSTAL ELEMENT

Because of the manner of connecting the output of the crystal element to the associated amplifying apparatus, it is necessary to know the effect produced on the voltage developed by the crystal element by such leakage resistance and external capacitance as may exist. The net external resistance, R_x , will depend on the insulation resistance of the circuit and the input impedance of the amplifier. The external capacitance, C_x , is determined by the capacity of the shielded lead used and the input capacitance of the amplifier. The crystal capacity, C_c , is fixed by the area and thickness of the crystals. The approximate circuit diagram of figure 8 has been used as a basis for the design of crystal elements, but this circuit neglects the impedance of the source of voltage which is properly shown in figure 7. However, in this particular case the difference between the solutions based on the different diagrams is negligible.

The following analysis is based on the equivalent circuit diagram of figure 7.

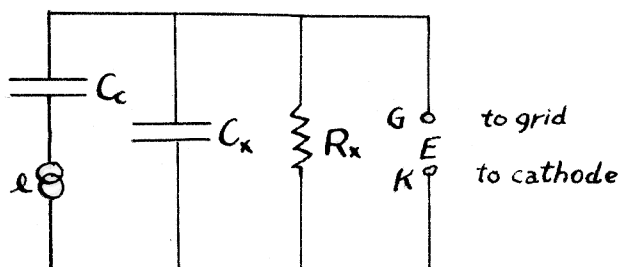


Figure 7. Equivalent Circuit Diagram.

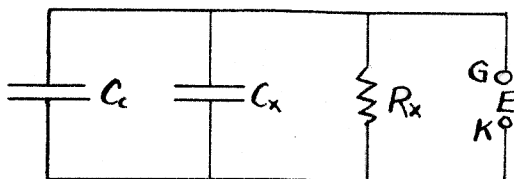


Figure 8. Approximate Circuit Diagram.

R_x - net external resistance in ohms.

C_x - net external capacitance in farads.

C_c - internal capacity of crystals.

e - voltage generated by crystals due to pressure.

E - voltage appearing at grid of amplifier (from G to K).

t - time in seconds.

i_r - current flowing through resistance, R_x .

i_x - current flowing through condenser, C_x .

i_c - current flowing through condenser, C_c .

q_c - charge on condenser C_c .

q_x - charge on condenser C_x .

f - frequency (cycles per second) $= \frac{R.P.M.}{60}$

w - $2\pi f$.

q - charge on condenser C_c due to pressure.

$$(1) \quad e = \frac{q_c}{C_c} + i_r R_x = \frac{q_c}{C_c} + E$$

Differentiating (1) with respect to time.

$$(2) \quad \frac{de}{dt} = \frac{1}{C_c} \frac{dq_c}{dt} + \frac{dE}{dt} = \frac{i_c}{C_c} + \frac{dE}{dt}$$

$$(3) \quad e = \frac{q}{C_c} \quad \text{by definition.}$$

The pressure on the crystals is a function of the time only, and hence the charge, q , developed being directly proportional to the pressure is a function of time, $F(t)$.

Substituting $q = F(t)$ in (3) and combining with (2)

gives

$$(4) \quad \frac{de}{dt} = \frac{F'(t)}{C_c} = \frac{i_x + i_r}{C_c} + \frac{dE}{dt}$$

Substituting $i_r = \frac{E}{R_x}$ and $i_x = C_x \frac{dE}{dt}$ in (4) and combining terms gives the differential equation of the circuit.

$$(5) \quad \frac{dE}{dt} + \frac{E}{R_x (C_c + C_x)} = \frac{F'(t)}{C_c + C_x} \quad \text{where } F'(t) = \frac{dF(t)}{dt}$$

This is a simple linear differential equation, the solution of which is

$$(6) \quad E \ell \frac{t}{R_x (C_c + C_x)} = \frac{1}{C_x + C_c} F(t) \ell \frac{t}{R_x (C_c + C_x)} - \int \frac{F(t) \ell \frac{t}{R_x (C_c + C_x)}}{(C_c + C_x)^2 R_x} dt + k$$

$$e = 2.71828$$

$k = \text{constant of integration}$

Assume that the charge developed varies as $h \sin wt$, where h is the maximum amplitude of the charge or $F(t) = h \sin wt$. Substituting this in equation (6) and integrating gives

$$(7) \quad E = \frac{h \sin wt}{C_c + C_x} - \frac{h(\sin wt - R_x(C_c + C_x) w \cos wt)}{(C_c + C_x)(R_x^2(C_c + C_x)^2 w^2 + 1)} + k e^{-\frac{t}{R_x(C_c + C_x)}}$$

The constant of integration under the initial conditions of $E = 0$ when $t = 0$ becomes $k = -\frac{h R_x (C_c + C_x) w}{(C_c + C_x)(R_x^2(C_c + C_x)^2 w^2 + 1)}$

It should be noted that the first term in equation (7) is exactly the voltage that would be generated at G to K were there no leakage. At the steady state condition (i.e., $t \rightarrow \infty$) the exponential term in equation (7) becomes zero and the voltage that would exist were there no leakage is diminished by the term

$$(8) \quad \frac{h (\sin wt - R_x(C_c + C_x) w \cos wt)}{(C_c + C_x)(R_x^2(C_c + C_x)^2 w^2 + 1)}$$

Since the actual developed charge vs. time curve can be analyzed by Fourier series into the sum of a constant and a series of harmonic sines as follows:

$$F(t) = a_0 + a_1 \sin(wt + \alpha) + a_2 \sin(wt + \beta) + \dots$$

A summation of the E terms obtained by substituting each term of the series in place of $F(t)$ in equation (6) will give the actual voltage developed by the pressure wave. Since the amplitude of the fundamental frequency is generally the greatest and since the term (8) decreases with increase in frequency, the magnitude of the term (8) is a negligible percentage of $\frac{h}{C_c + C_x} \sin wt$ for the fundamental frequency. It will be of proportionally less significance for the higher frequency components.

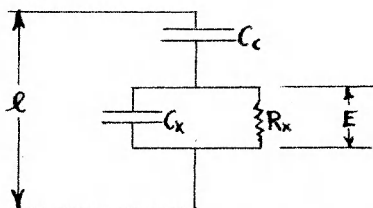
Assume for instance that the minimum speed of the engine on which the indicator is to be used is 600 R.P.M. or $w = 2\pi f = 62.8$, the external resistance, R_x , to be 10^7 ohms, the external capacitance to be $3 \cdot 10^{-8}$ farads and the internal capacitance to be 10^{-11} farads. Under these conditions

$$\begin{aligned}
 E &= \frac{h}{3 \cdot 10^{-8}} \sin wt - \frac{h}{3 \cdot 10^{-8}} \left[\frac{\sin wt - 10^7 \cdot 3 \cdot 10^{-8} \cdot 62.8 \cos wt}{(10^7 \cdot 3 \cdot 10^{-8} \cdot 62.8)^2 + 1} \right] \\
 &= \frac{h}{3 \cdot 10^{-8}} \sin wt \left[1 - \frac{1}{350+1} \right] + \frac{h \cdot 19 \cdot \cos wt}{3 \cdot 10^{-8} (350+1)} \\
 &= \frac{h}{3 \cdot 10^{-8}} \sin wt \quad \text{very nearly}
 \end{aligned}$$

Only a short time is required for the voltage due to the component represented by the constant term of the series to become negligible as can be seen from the solution of the

differential equation. The voltage output of the crystal element therefore consists of variations of voltage from the voltage of the average pressure as a base instead of an atmospheric pressure line base. Hence, the absolute pressures cannot be determined from the indicator card unless the absolute pressure at a known point of the cycle is determined. The value of the maximum pressure in the cycle may be determined by a number of methods* such as by the use of a balanced diaphragm and a pressure gage and the pressures at any other point in the cycle may be readily determined from this value and the scale of the indicator card. The average pressure during the cycle may also be determined directly from the indicator diagram since the base line upon which the card is drawn is the average pressure line.**

The steady state solution of the equivalent circuit can be obtained more easily by using conventional alternating current methods.



*See N.A.C.A. Report 294, Peak Pressure Gages, for a description of a number of peak pressure gages. See also "Engineering", 140:185, August 23, 1935, for a description of a diaphragm type of peak pressure gage.

**This average pressure is the average on a time basis and is not the mean effective pressure which is the average pressure on a volume (cylinder) basis.

$$(1) Z_x = \frac{R_x X_x}{R_x + X_x}$$

$$(2) I = \frac{e}{Z_c + Z_x}$$

$$(3) \text{ hence } I Z_x = E = \frac{e \frac{R_x X_x}{R_x + X_x}}{X_c + \frac{R_x X_x}{R_x + X_x}} = e \frac{R_x X_x}{X_c R_x + X_x X_c + R_x X_x}$$

substituting $X = \frac{1}{j\omega C}$ and reducing gives

$$(4) E = e \frac{R_x^2 \omega^2 C_c (C_c + C_x) + j R_x \omega C_c}{\omega^2 R_x^2 (C_x + C_c)^2 + 1} \quad \text{and since } e = \frac{q}{C_c}$$

$$(5) E = \frac{q}{C_c + C_x} - \frac{q(1 + j \omega R_x (C_c + C_x))}{(C_c + C_x)(\omega^2 R_x^2 (C_c + C_x)^2 + 1)}$$

This is the vector form of the steady state solution as obtained from the differential equation for a sinusoidal voltage e .

From this analysis we see that in order to make the error due to the leakage resistance insignificant, it is necessary to make the total capacitance of the circuit and the leakage resistance at least as high as the values indicated on page 24. By increasing the capacitance the voltage output of the crystal element is decreased, thus increasing the required amplification of the associated amplifier. The highest possible value of the leakage resistance is the insulation resistance of the circuit, and in a well constructed unit might be expected to be considerably greater than the

10^7 ohms used in the numerical calculation. The necessity of producing a leakage path for the charge which accumulates on the grid element of the amplifier tube to which the crystal element must be connected compels a reduction of the net leakage resistance below the desired maximum value in order to maintain the stability of the amplifier. The insulation resistance can usually be made so high that it may be neglected in comparison with the input resistance of the amplifier. In case the external capacity required to make the effect of the leakage resistance negligible reduces the voltage too much the amplifier may be compensated by the use of a load in the plate circuit having the proper characteristics to correct for the power factor distortion introduced by the leakage resistance. An inverted* vacuum tube may be used in the first stage of the amplifier and will be stable in operation even with an extremely high leakage resistance but an inverted vacuum tube has the disadvantage of having a fractional amplification factor. However, it is possible that this method of coupling the crystal unit to the amplifier may have sufficient advantages to make its use worthwhile.

If the crystals are subjected to a single transient impulse of pressure as in the case of the measurement of single

*An inverted vacuum tube is one in which the functions of the plate and grid elements are interchanged.

explosions (1,16) the above statements concerning the leakage resistance do not apply and the leakage resistance should be made as high as possible with a minimum of input capacity. (Vacuum tubes such as the FP54 with a grid input impedance of 10^{16} ohms (55) may be used to advantage in such cases.)

CALCULATION OF VOLTAGE OUTPUT OF CRYSTAL ELEMENT

Since it is desirable that the crystal holder be sufficiently small to screw into an opening no larger than a spark plug hole and at the same time not affect the operation of the engine by increasing the clearance volume, the design of holder illustrated in figure 10 was decided upon. Although the crystal holders used in the experimental tests were constructed of cold rolled steel, it would be preferable from the standpoint of heat and corrosion resistance to make the holder of stainless steel or Monel metal. Using a holder that will screw into an opening the same size as an 18 millimeter spark plug will limit the area of the diaphragm to approximately .20 square inches so that the maximum load upon the crystals is 100 pounds assuming a maximum cylinder pressure of 500 pounds per square inch. The maximum charge that will be developed by the crystals is $n \times 1.03 \times 10^{-11} \times 100$ coulombs (see table of electrical constants) where n is the number of crystals in parallel, in this case three. The minimum desirable value of capacitance in the crystal circuit

is 3×10^{-8} farads and hence the maximum value of voltage developed is charge \div capacity = .10 volts. A voltage of approximately 100 volts is required to deflect the beam of the oscillograph to be used* full scale. Hence a voltage amplification of at least 1000 will be required. So called "weak spring" indicator cards would require the use of an amplifier with a considerably higher amplification or a reduction in the external capacity in the crystal circuit.

It can be seen by considering the voltage developed and the leakage resistance calculations that (1) the size of the crystals used should be governed by convenience of handling, use, and mechanical strength.** (2) as many crystals as possible should be connected in parallel consistent with space limitations and convenience.

DESIGN OF AMPLIFIER CIRCUIT

Since it has been determined that a voltage amplification of approximately 1000 will be necessary, an amplifier must be used which is capable of amplifying the voltage de-

*An R.C.A. three-inch cathode ray oscillograph was the only one available. Larger tubes require corresponding larger voltages for deflection of the cathode ray beam, e.g. a. seven-inch tube requires more than three hundred volts for full scale deflection.

**Karcher (2) has found that the charge developed by quartz crystals is linear with pressure up to pressures as high as 50,000 pounds per square inch. Hence the area of the crystals need be considered only as affecting the crystal capacity.

veloped by the crystal element by 1000 times and at the same time have a high input impedance and a number of the characteristics of a perfect amplifier. With conventional type vacuum tubes the maximum value of grid input impedance permissible for stable operation is 10 megohms with a recommended maximum value of 1 megohm* (10^6 ohms). The frequency response of the amplifier should be linear from a minimum frequency of 10 cycles per second (600 R.P.M.) to as high a frequency as possible. Actual measurements of the amplifier using a known voltage input of various frequencies developed by a beat frequency oscillator and a vacuum tube voltmeter to measure the output of the amplifier shows that the voltage amplification is linear within 2 per cent over a frequency range of 8-8,000 cycles per second.** Other requirements of the amplifier are (1) freedom from extraneous disturbances from the power supply, (2) an output voltage of approximately 100(peak to peak variation) volts, (3) linear amplification with regard to amplitude of input, i.e., the amplifier tubes must operate on a linear portion of their characteristic curves, (4) no variable phase shifting for

*See R. C. A. Technical Bulletin No. R.G. 12 which lists the characteristics of commercial vacuum tubes used in radio work.

**Prof. L. C. Paslay of the Kansas State College Electrical Engineering department conducted this test for the author.

different frequencies, etc.

A resistance capacity coupled type amplifier was believed to be able to fulfill the requirements outlined above more readily than other types of amplifiers. Prof. L. C. Paslay designed the circuit shown in figure 9. Ample size filter condensers in the power supply prevent disturbance in the output from the alternating current power line. Large capacity coupling condensers insure the required low frequency response.

PROPOSED METHOD OF CALIBRATION

Because of the number of connected parts in the complete indicator, it is believed desirable to calibrate the assembled units instead of calibrating each unit separately. Static methods of applying pressure to the crystals are not easily adapted to calibration of the indicator because of the effect of the external leakage resistance. Since the calibration of the indicator is independent of the speed at which pressure is applied to the crystals, the indicator may be calibrated by comparing the card taken by a mechanical piston-type indicator with the card obtained simultaneously on the cathode ray oscillograph on a slow speed gasoline engine (600 R.P.M.). The peak pressures on both cards may be compared and the constant for the crystal indicator obtained

TYPE 6C6

TYPE 76

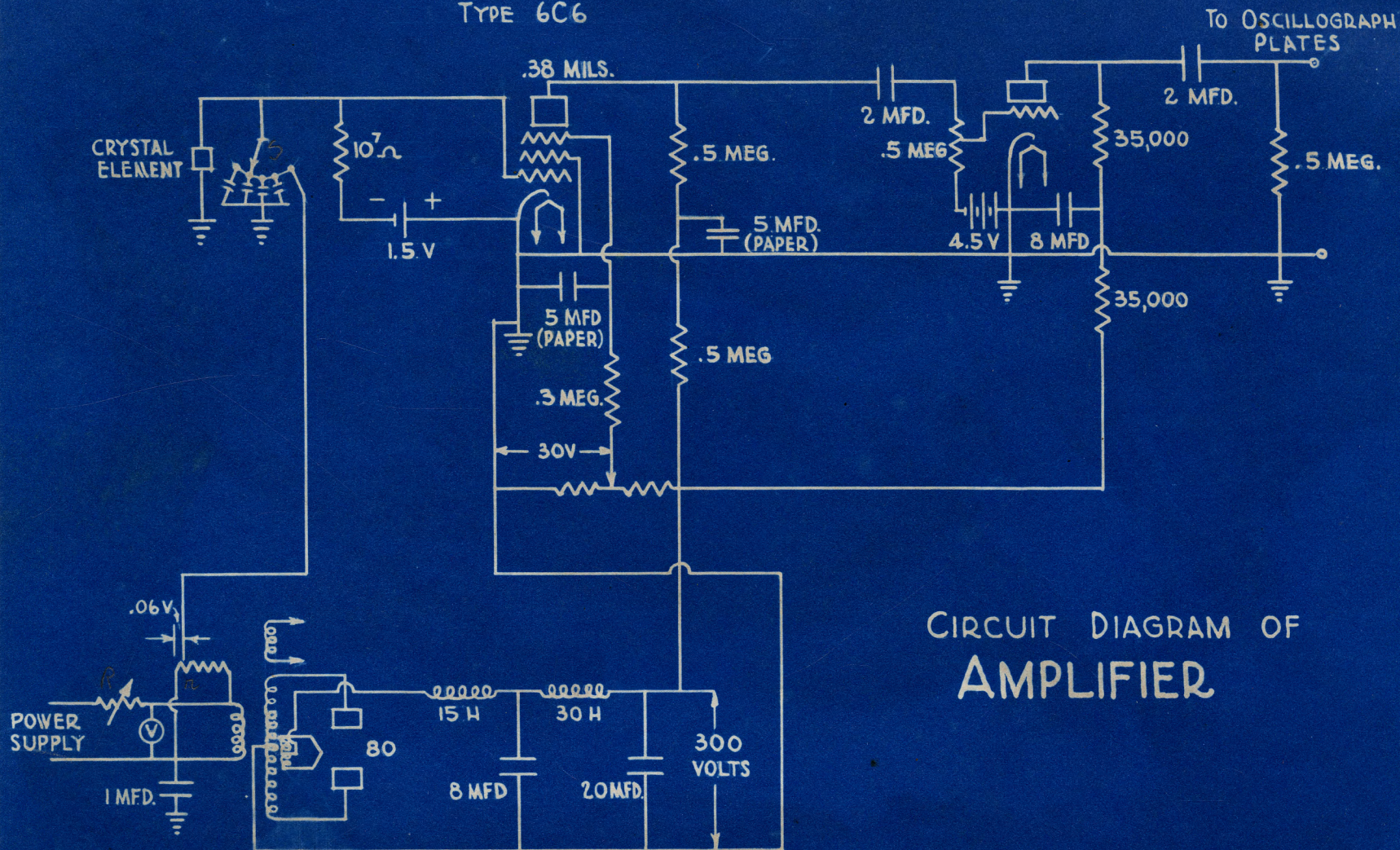
CIRCUIT DIAGRAM OF
AMPLIFIER

FIGURE 9

from the known peak pressure indicated by the mechanical piston-type indicator. Others (1,16) have used compressed air or other gases under pressure for calibration by using a poppet valve to suddenly release the gas pressure exerted on the indicator which is screwed into a closed pressure chest. However this method is subject to errors due to the effect of the leakage resistance and is more difficult to apply. Another method which could be used for calibration would be to use a peak pressure gage* instead of a mechanical indicator. Water at a known temperature should be circulated through the crystal holder for the calibration tests and when obtaining indicator cards in order to eliminate errors due to temperature differences.

The voltage amplification of the amplifier will change if the voltage used to supply power to the amplifier is changed. The amplification will also change slightly from day to day due to changes in the constants of the circuit caused by humidity changes, etc. This is also true of the voltage required to deflect the oscillograph beam. In order to eliminate errors due to this source the amplifier and oscillograph unit are calibrated before use by means of the following procedure. A rheostat R is used to maintain the

*See N. A. C. A. Report No. 294 on peak pressure gages.

voltage to the amplifier as measured by the voltmeter V constant. (See figure 9.) With the line voltage at the known constant value the alternating potential across resistance r (approximately .06 volts) is applied to the input of the amplifier by means of the multiple point switch S which is also used to change the capacity across the crystal element. The deflection of the beam of the oscillograph is then a measure of the amplification of the amplifier and the voltage required to deflect the beam of the oscillograph. The gain control of the amplifier or the oscillograph beam intensity control (anode voltage) is then adjusted until the electron beam deflection is the same (or a known proportion) when the indicator is to be used to obtain an indicator card as the deflection when the indicator was calibrated. This obviates the necessity of using amplifiers of accurately known or constant amplification factors. Since the voltage per unit of applied pressure of the quartz crystals is dependent only on the temperature and the temperature is maintained the same during use as in the calibration tests, the only inherent source of error is that due to a change in the amplification of the amplifier and changes in voltage applied to the anode of the oscillograph. This error is mitigated by the procedure described above.

RESULTS OF EXPERIMENTAL TESTS

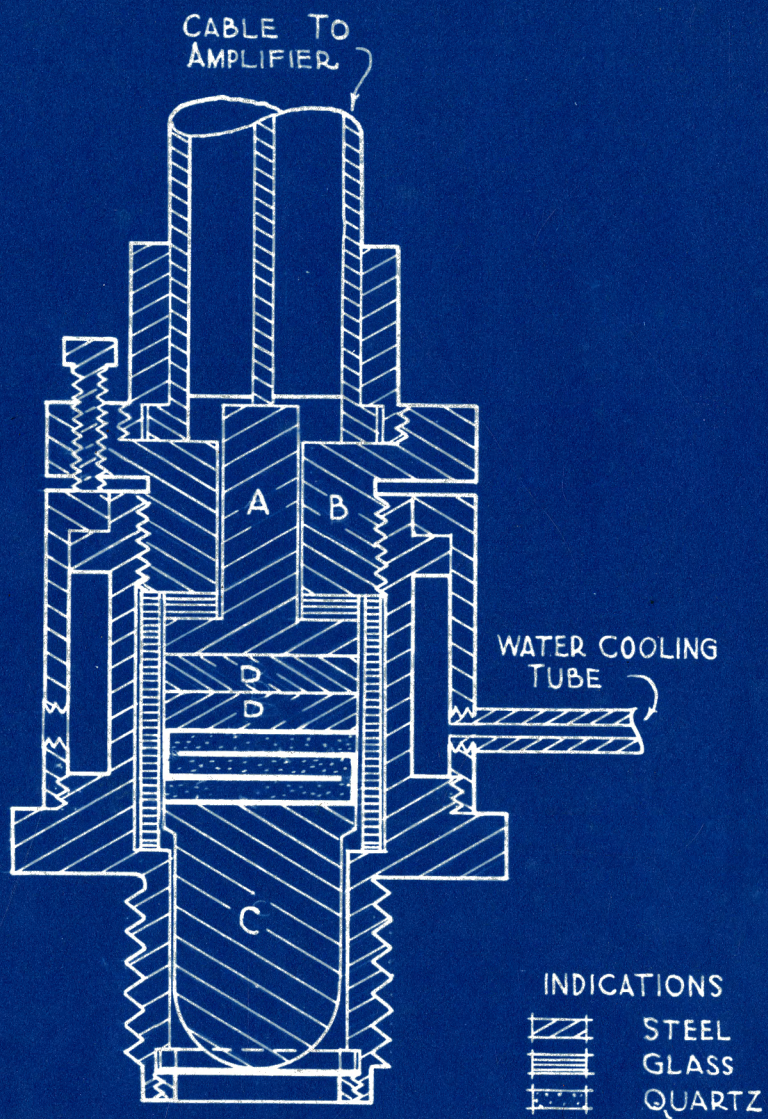
Although the piezo-electric type of engine indicator is perhaps simpler in fundamental theory than any other type of high-speed internal combustion engine indicator, there are a number of problems which prevent the application of the piezo-electric indicator from being as simple as the theory would indicate. A somewhat ambitious program of experimental work outlined at the beginning of the year was cut to a fraction of the amount intended because of difficulties encountered in the initial attempts to make the indicator function.

Using the theory outlined in the preceding pages the writer designed and constructed a crystal holder and amplifier. Figure 1 is a twice full-size section view of the original holder. This holder failed to give satisfactory results when used with the amplifier and a R. C. A. three-inch cathode ray oscillograph. A large amount of interference picked up from the ignition system which at first obscured any pressure effects was eliminated by the use of a shield around the porcelain electrode. At first it was believed that the diaphragm was too rigid to transmit the cylinder pressures but the use of a thinner diaphragm did not improve the results. The only limitation on the thickness of the diaphragm is that it be flexible compared to the re-

mainder of the crystal holder which is under stress. A considerable amount of time was spent attempting to obtain satisfactory results with this holder before it was decided to construct another holder. The completely shielded holder then constructed is shown in section in figure 10 and is twice full size in the drawing. The results obtained with this holder while better than the previous holder were not satisfactory until an additional stage of amplification was added to the amplifier increasing the voltage amplification to approximately 10,000 although calculations made according to the theory outlined on pages 28 and 29 indicate that amplification of 1000 would be sufficient. A possible reason for this discrepancy lies in the value of the piezo-electric constant used in the calculations. No tests were made to determine the actual values of the piezo-electric constant of any of the ten crystals used. It is possible that a bimorph type of crystal assembly and construction as used in crystal microphones might be used to advantage.

The photographs* shown in figures 11 to 16 are some indicator cards taken on a Mogul single cylinder six horsepower, horizontal, gasoline engine running at its rated speed of 425 R. P. M. A portion of the engine is shown in the photograph of the set-up of the apparatus in figure 17. The cards are not entirely satisfactory because of the high

*Photographs taken by F. J. Hanna, college photographer.



CRYSTAL HOLDER

FIGURE 10

percentage of spurious vibration and distortion. Figure 11 shows some cards taken using a single crystal in the holder and exposing the film for four cycles of the engine. Beyond showing the rise of pressure due to the combustion in the engine the cards are of little value and the interpretation of the right half of the card is unknown. The cards of figures 12 to 16 were obtained using three crystals in the holder and are more satisfactory in that they show results more in line with what might be expected. The speed of the engine was less than the lowest frequency for which the amplifier characteristics were linear, thus introducing an additional source of distortion in the diagrams.

A large percentage of the vibration shown on the cards was probably due to vibration of the amplifier which was so sensitive to vibration that a slight jar was sufficient to deflect the oscillograph beam full scale. This sensitivity to vibration was caused by the type 6C6 tube used in the first stage of the amplifier. It is suggested that a tube with a lower amplification factor than the type 6C6 (with greater spacing of elements and more rigid construction) be used to reduce the effect of vibration on the amplifier. An additional source of vibration on the cards is vibration of the crystal holder itself. If the pieces of the holder marked A, B, C, and D as shown in figure 10 are made light the inertia forces on the crystals due to the vibration of

the holder will be reduced.

The R. C. A. oscillograph used had a fluorescent screen of the type intended for visual observation emitting a green light which possesses poor actinic properties and requires a special type of film sensitive in this range of the spectrum for satisfactory photographic results. Oscillographs intended for photographing are provided with a fluorescent screen of a type which emits a blue light that is easily photographed even with ordinary film. The three-inch screen of the oscillograph used is too small to obtain an indicator card large enough for accurate measurements. Although the line traced on the screen by the electron beam is apparently broad when observed visually, the photograph shows a comparatively fine line.

Synchronization of the horizontal "sweep" of the electron beam of the oscillograph with the engine rotation was obtained by connecting the voltage drop across a two ohm resistor in the primary circuit of the spark coil used for ignition purposes to the synchronizing circuit of the oscillograph. On the R. C. A. oscillograph used two external binding posts are provided for external synchronization. The "sweep" of the electron beam starts with the closing of the contact or breaker points of the timer. The angular position of the closing of the timer points with respect to the piston position can be determined by turning the engine by

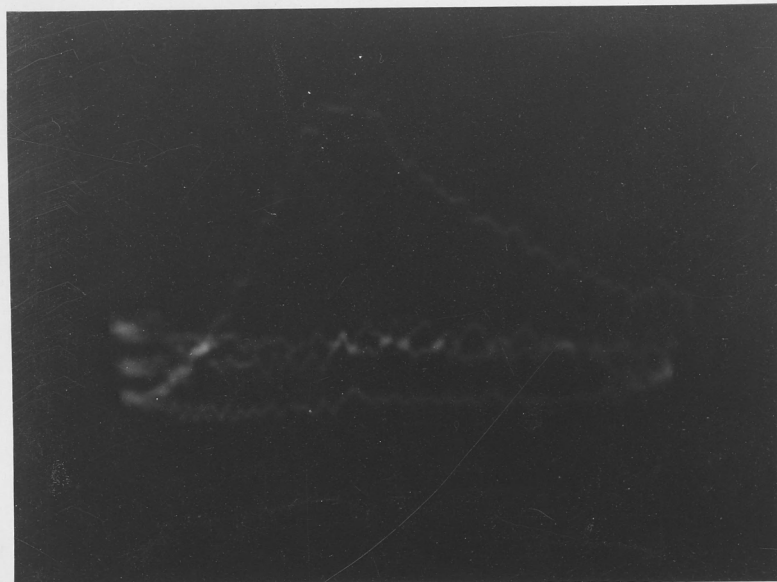
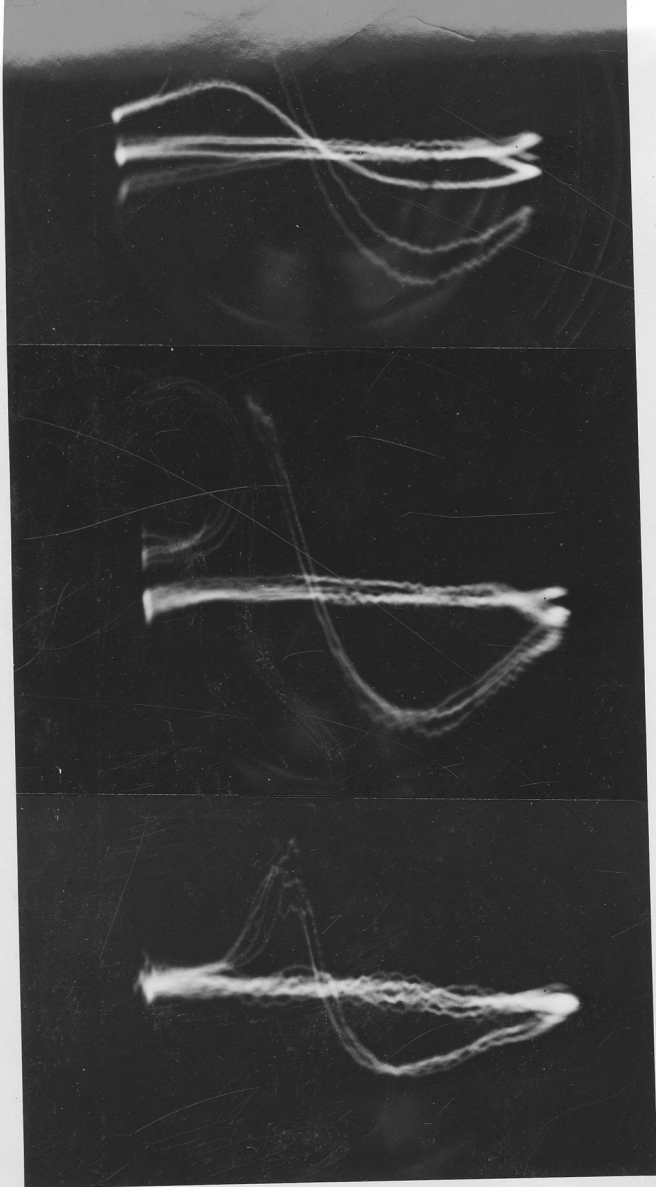
hand and noting the piston position when current begins to flow through the points. A more satisfactory method of synchronization would be obtained by placing a separate system of contacts which could be set to close or open at any desired angle on the crankshaft. Since the ignition occurs when the breaker points open the time of ignition with respect to the position of the piston can also be determined. If the high tension part of the ignition circuit is electrically coupled with the second stage* of the amplifier by means of several turns of wire wound around the high tension cable the point of ignition will show as a sharp break or discontinuity on the indicator card.

Before assembling the crystals in the holder it was necessary to determine the polarity of each of the crystals. This was done by placing each crystal in the holder by itself and noting the direction of the deflection of the electron beam of the oscillograph when the diaphragm of the crystal holder was pressed. The crystals were then assembled with all sides of the same polarity connected together by means of tinfoil. A small drop of oil was placed on each crystal to hold the tinfoil to it and assist in assembling the unit. The crystals were placed in the holder so that a pressure on the diaphragm would deflect the oscillograph beam upward.

*Coupling to the second stage is suggested because of the high input impedance of the first stage.

The experimental work was limited to a great extent because no entirely suitable engines were available. Experimental work beyond that of the present report was prevented by lack of time. However, when the simplicity and low cost* of the components composing the indicator used is considered, the results obtained while not as satisfactory as might have been expected, are sufficient to show that it is possible to construct a reliable piezo-electric type indicator for a reasonable cost.

*Cost of crystal holder and amplifier components exclusive of oscillograph was approximately \$35.00.



Left, figure 11.
Right, figure 12.

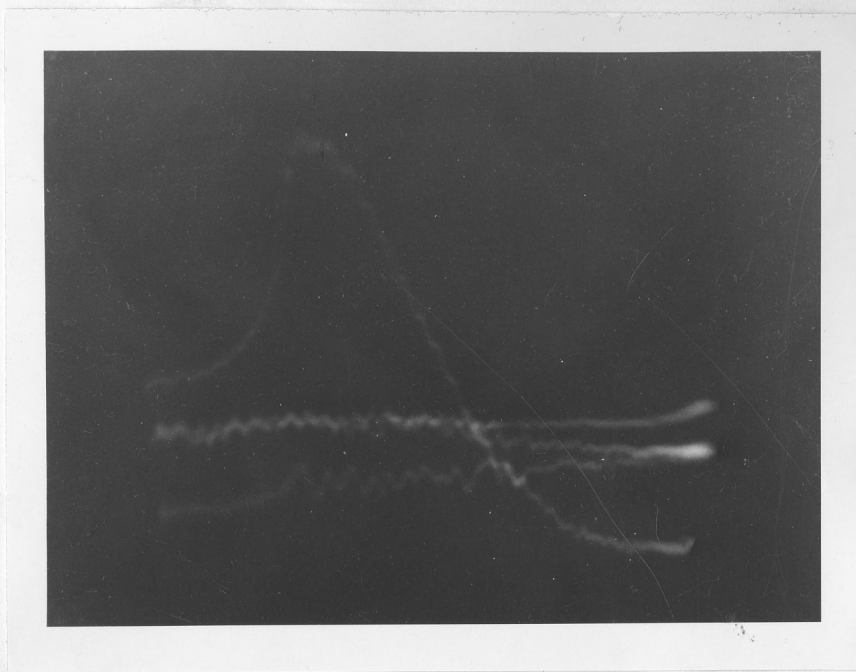


Figure 13.

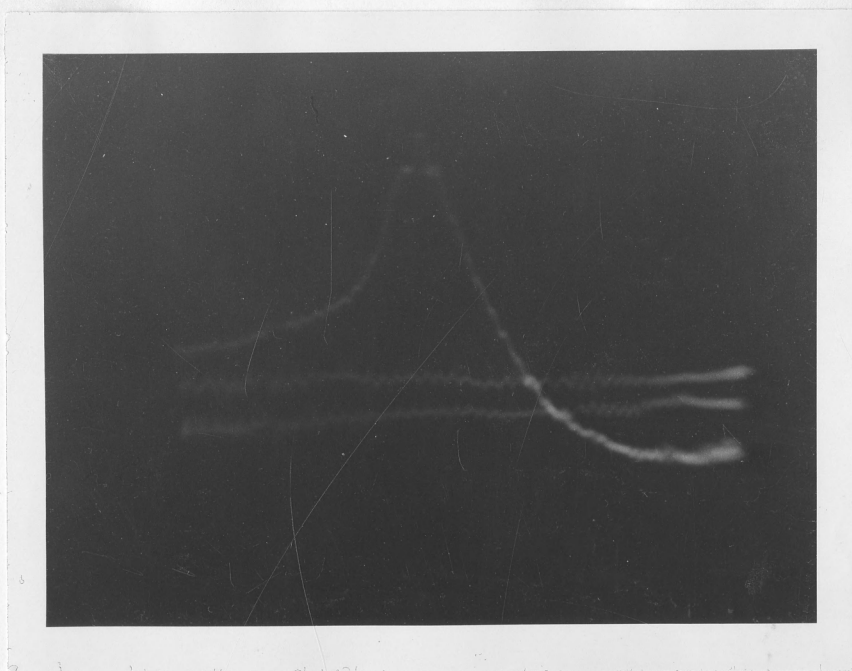


Figure 14.

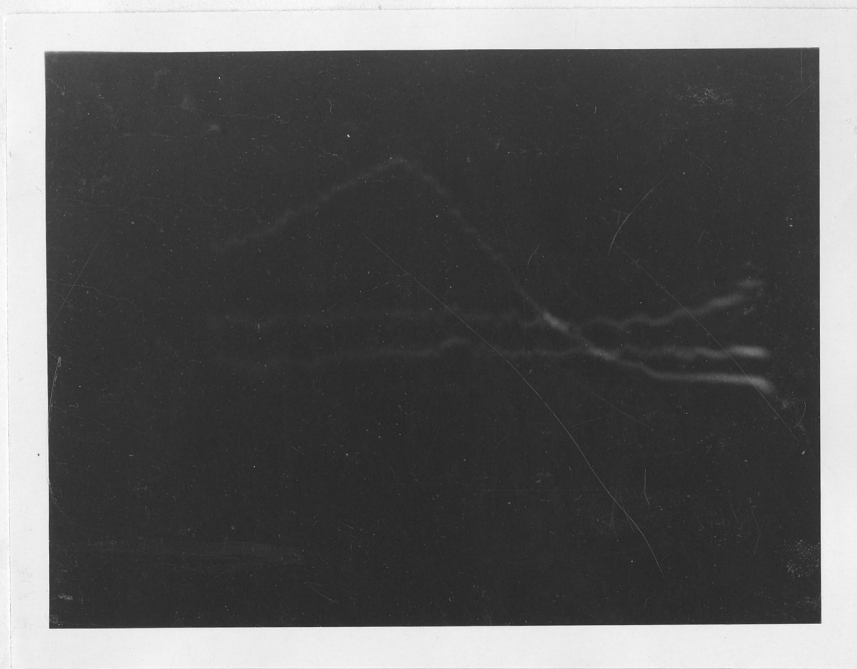


Figure 15.

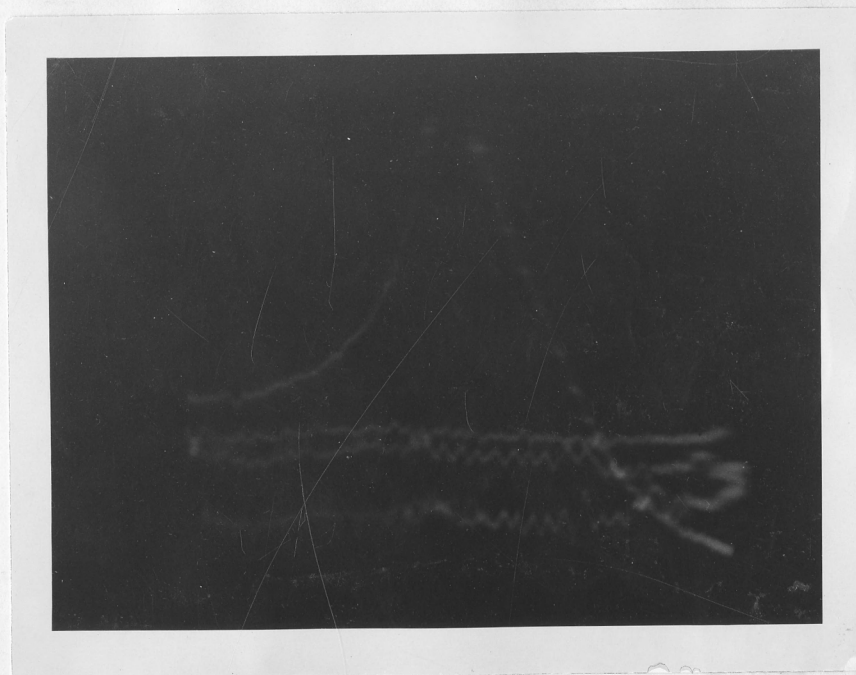


Figure 16.

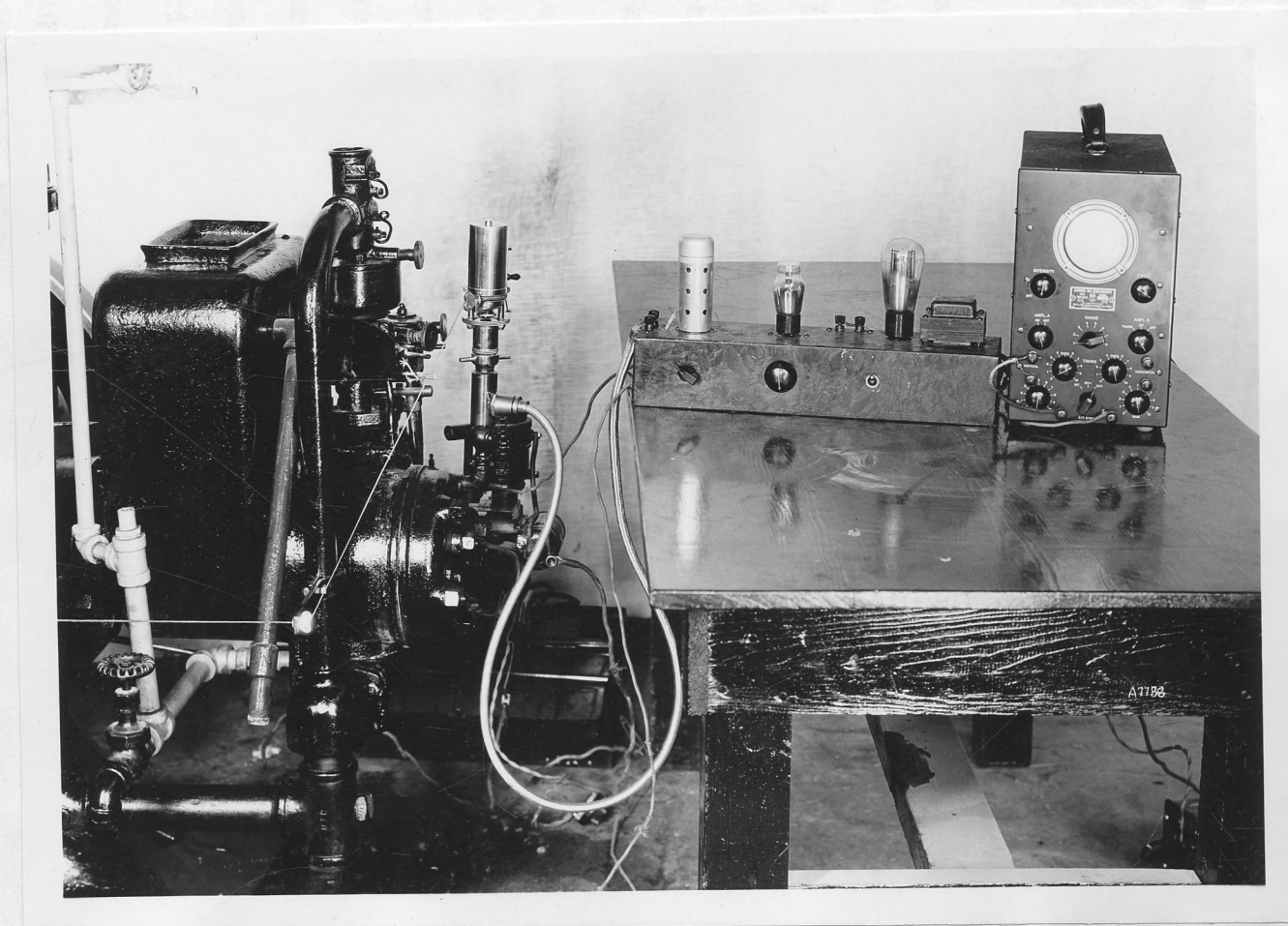


Figure 17.

CONVERSION OF PRESSURE-TIME CARDS INTO PRESSURE-VOLUME CARDS

Although pressure vs. time indicator cards are more suitable than pressure vs. volume cards for studying a number of phenomena such as rate of pressure rise, detonation, etc., the pressure vs. volume card may be used for obtaining indicated horsepower. For this reason the following graphical method of converting a pressure-time card into a pressure-volume card is included.

A crank angle vs. piston displacement diagram is constructed graphically as shown on the right half of figure 18. The ratio of $\frac{2L}{l}$ is equal to the connecting rod crank ratio, the lengths, l and L , being any convenient distances of the proper ratio. The pressure-time card is divided into equal intervals displaced by the same angle as the vertical lines on the pressure-volume chart. The dead center positions on the pressure-time card are determined from the angular position of the synchronizing contacts or from the point of ignition and spark advance angle as explained previously. Pressures at corresponding crank angle positions are then sufficient to construct a pressure volume diagram as shown in the figure 18.

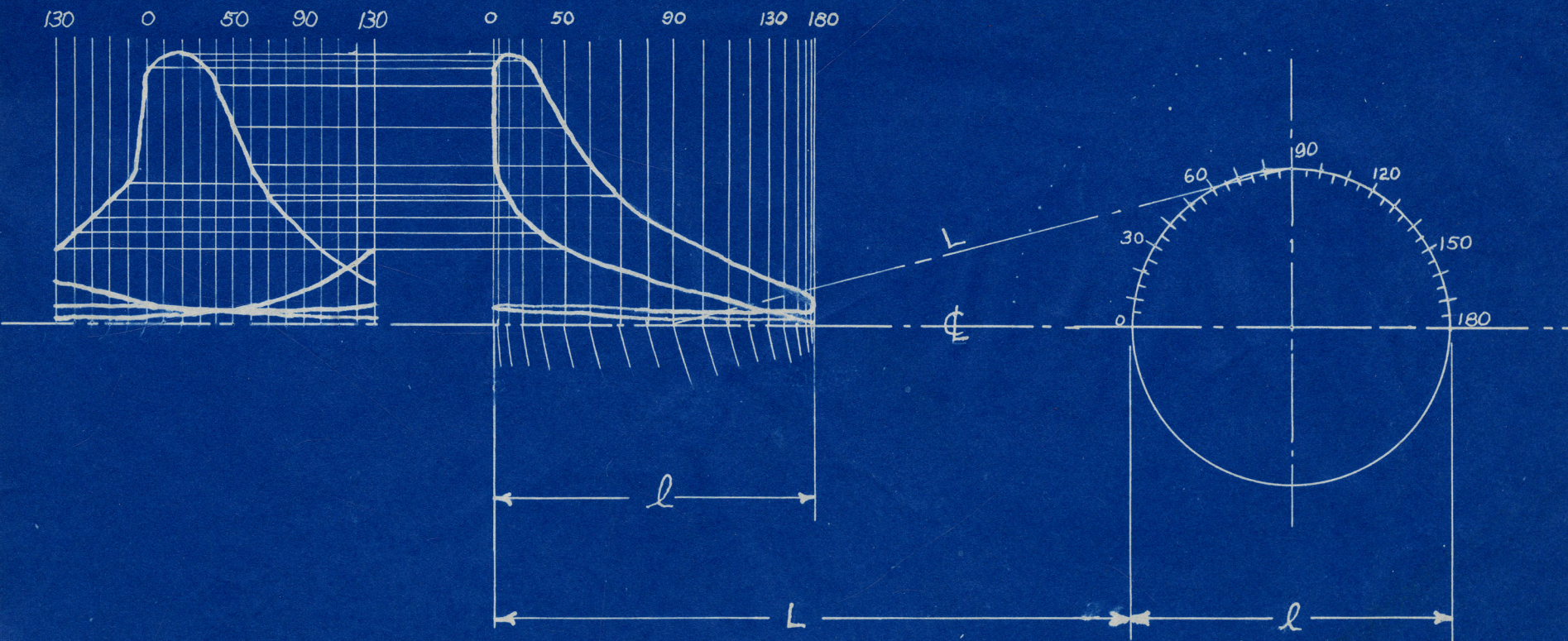


Figure 18

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