A METHOD FOR DETECTING DETONATION WAVES IN THE INTERNAL COMBUSTION ENGINE

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I. OBJECT

The general object of this investigation was to examine certain phenomena which accompany detonation in the internal combustion engine. Attention was particularly directed toward mechanical disturbances of cylinder gases and engine parts which are characteristic of the detonation process.

The specific phase of the work which is to be considered in the present report is the development of satisfactory methods and apparatus.

It is hoped that these instruments may be applied to a thorough investigation of the processes under examination in a succeeding years work.

II. FOREWORD TO EXAMINATION OF LITERATURE ON DETONATION.

Development of modern engines of high output has naturally brought strongly to the fore, the process of detonation which limits so seriously the practical efficiency of carburetor engine operation.

There is a quite widely extended list of articles on detonation in the literature, with new papers appearing at short intervals. The following brief resume' of detonation articles is not presented as being complete. The object being rather to roughly outline the better known methods of investigation, experimental facts and hypotheses concerning detonation.

The term "theory" loosely applied in the following discussion to statements of ideas which amount at best to rather weak hypotheses. This misuse of the word "theory" is carried thru the discussion in accord with common practice in the literature of detonation.

NOTE

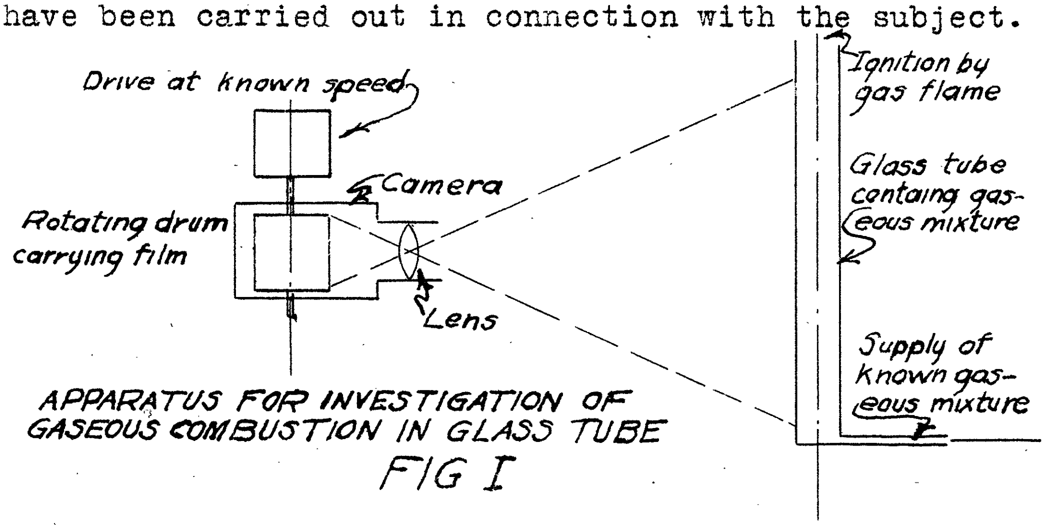
The numbers occurring hereafter in the text refer to the bibliography at the end of the report.

III. THEORIES OF DETONATION.

Before taking up the study of theories of detonation it is desirable to examine the phenomenon itself in order that the facts to be explained may be summarized.

The term "detonation" is applied to describe a process whose most obvious manifestation is a sharp metallic sound. The noise, of course, is but one evidence of a very complex process which takes place with great rapidity under conditions which render effective investigation rather difficult. A description of detonation would only be complete if all possible angles of the process were considered.

In order to clearly understand certain ideas which occur in the detonation theories, it is helpful to make a short examination of certain experiments which have been carried out in connection with the subject.



APPARATUS FOR INVESTIGATION OF GASEOUS COMBUSTION IN GLASS TUBE

FIG I

The progress of the combustion in the tube may be analysed from the photographic record.

This type of experiment has been known and carried out over a considerable number of years. A large part of this type of work has been carried out in Europe.

Bone, Fraser and Witt[*22] in England recently conducted some work on flame propagation in tubes. From previous work on the subject, the behaviour of a flame traveling along open or closed tubes is summarized.

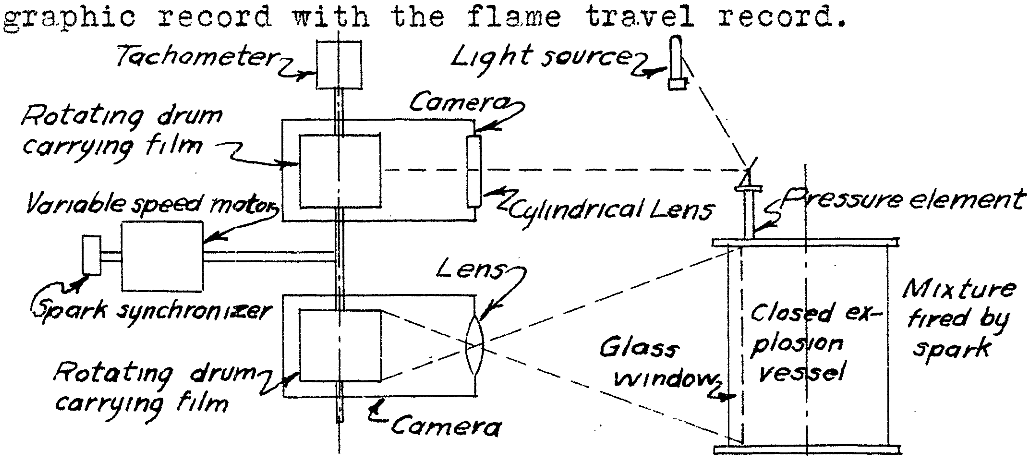
In the open tube (open at both ends) method, at first the flame proceeded along the tube at a uniformly slow velocity, this uniform velocity was succeeded by an "oscillatory" period, the flame swinging back and forth with increasing amplitude and finally either dying out entirely or giving rise to detonation. When any mixture was ignited near the closed end of a tube, the flame was continuously accelerated until "detonation" was set up.

The term "detonation" as applied to this case in general, refers to a disturbance propagated at a high uniform speed. There seems to be fairly good agreement that the speed of the detonation wave is very close to that of sound in the mixture thru which it travels.

*Note- Numbers apply to bibliography references, page 148.

In general, these gaseous explosions carried out in tubes are affected by a large number of factors such as tube diameter, material, wall texture, etc.

A second type of experiment aside from actual engine tests, that is performed on gaseous explosions, is typified by the work of Woodbury, Lewis and Canby[41] of the Du Pont Company. These experimenters used a closed bomb fitted with a longitudinal window thru which a gaseous explosion flame could be photographed on a moving film. The bomb was also fitted with a high speed recording pressure element which gave a simultaneous photographic record with the flame travel record.



APPARATUS OF WOODBURY, LEWIS and CANBY

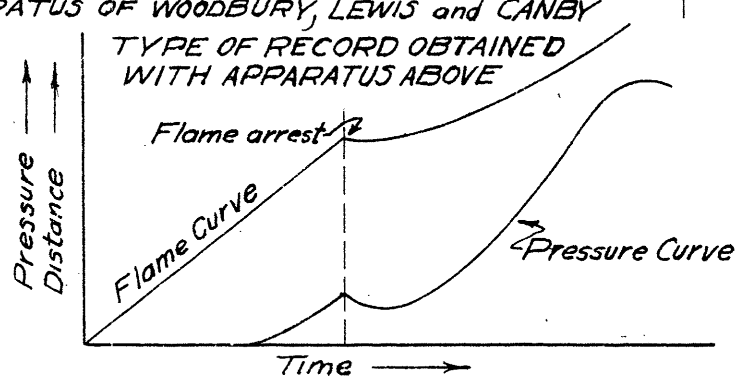


FIG. II

A similar type of apparatus was used by Brown and Watkins[5] in their work on the rate of rise of pressure of various fuel mixtures.

There is general agreement among those working in the field of internal cumbustion engine reactions, that actual work on the engine is necessary if the results are to be counted as reliable.

The following diagram is intended as an aid in summarizing the experimental facts concerning detonation: (See next page)

A list of the phenomena commonly accepted as accompanying detonation is given below:

(1) A very sharp metallic noise.

(2) A bright yellow flame within the cylinder.

(3) Increase in heat rejected to the cylinder jackets over that rejected during normal operation.

(4) Decrease in power.

(5) High instantaneous pressures.

This fact is apparent from records taken with the high speed indicator[28]. The cards for normal operation and for detonation are distinctly different.

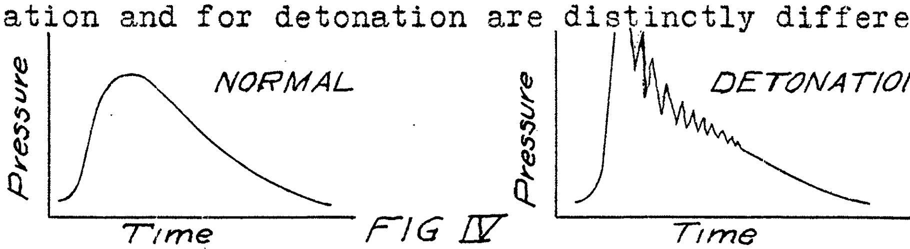


FIG IV

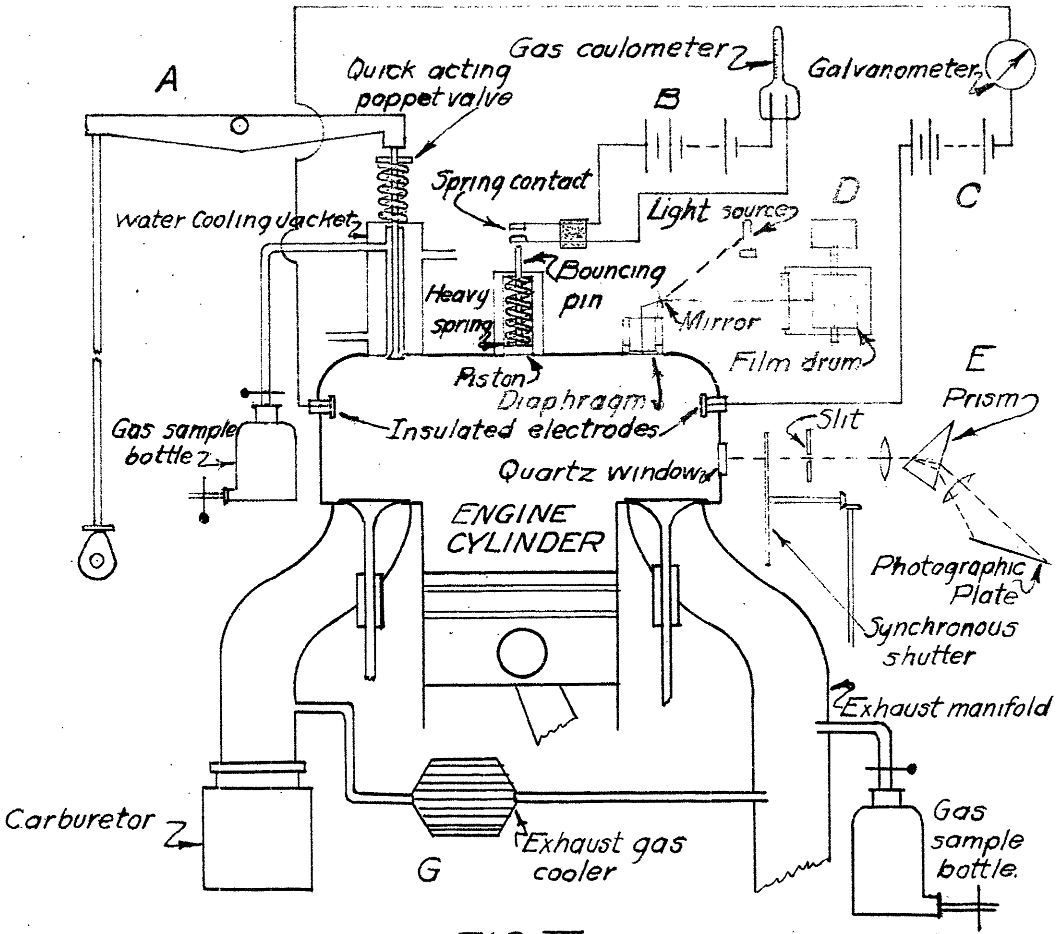


FIG. III

DIAGRAM INDICATING METHODS USED IN ENGINE RESEARCH

(A) Instantaneous sampling valve.

(B) Bouncing pin detonation indicator.

(C) Gas conductivity apparatus.

(D) High speed optical indicator.

(E) Flame spectroscopy apparatus.

(F) Exhaust gas analysis.

(G) Exhaust gases supplied to intake system.

The bouncing pin[23,26(a)] apparatus is widely used for detonation measurements. It depends upon the use of a piston indicator with a spring so heavy that it may not move under ordinary combustion but will give a sharp blow to a pin resting on the piston if detonation occurs. The strength of the bounce of the pin is measured in various ways and is taken as an indication of the degree of detonation.

(6) Destructive mechanical effects[30] such as breakage of spark plug porcelains, rupture of pistons or other damage to the motor structure.

(7) Black smoke issuing from the exhaust.[30,35]

(8) Preignition in most cases if detonation is allowed to continue.[30,32(a)]

(9) Electrical conductivity of gases within the cylinder increases in detonation over that found for normal combustion.[8] This phase of the process was examined experimentally by Charch, Mack and Boord who placed two insulated electrodes in an engine cylinder and observed galvanometer deflections due to a fixed voltage in the circuit. Results indicated a direct relationship between intensity of detonation and electrical conductivity.

(10) The emission of radiation[10] from the cylinder reaction is greatly increased in the first quarter of

the stroke for detonation as compared with normal combustion. Emission is weaker in the last three quarters for detonation than for normal combustion.

This fact was found experimentally by Clark and Henne working on a single cylinder engine fitted with a quartz window. A synchronized shutter was used to isolate the four quarters of the stroke. The radiation was estimated with the aid of a spectrograph.

(11) The wavelength of the emitted radiation is shifted toward the short wave end (the ultra-violet) end of the spectrum during detonation as compared with the spectrum of normal combustion.

This conclusion was also reached by Clark and Henne in their spectrographic work.

(12) The gaseous reaction starts sooner and reaches its final state faster for detonation than for normal combustion.

The work of Lovell, Boyd and Coleman [21(a)(b)] in the General Motors Research laboratory brought out this fact experimentally.

The effect is shown in the accompanying curves;

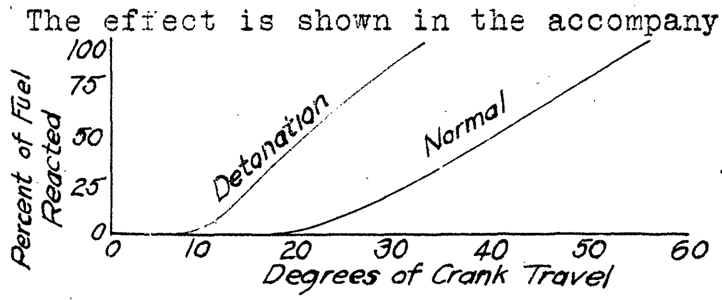


FIG V

The apparatus consisted of a small poppet valve arranged to sample the gaseous products in the cylinder in a range of about 2 degrees of crank travel.
The sample taken from the cylinder was immediately cooled by expansion and contact with a water-cooled jacket around the valve. This cooling served to stop the reaction very quickly and allow examination of the cylinder reaction at various points in its course.

(13) The exhaust gas analysis is different for detonation and normal combustion.

For normal combustion $K = \frac{(H_2O)\ (CO)}{(H_2)\ (CO_2)} = 3.3 - 3.4$

For detonation $K = 3.8 - 4.0$

The next matter to be considered is that of the factors which control detonation. The following summarized list is taken from a progress report of the Society of Automotive Engineers subcommittee on detonation.

(1) Detonation is increased by increasing the temperature and pressure of the charge during the time of explosion.

(2) The presence of localized hot spots or an increase of length of flame travel tend to increase detonation.

(3) Detonation varies greatly with mixture ratio, generally passing thru a maximum between the point of maximum power and that of maximum economy.

(4) Probably the greatest single factor which influences detonation is the chemical composition of the fuel but even here there are apparently few generalizations.

(5) Paraffins vary among themselves.

(6) A great many elements and compounds have the quality of affecting detonation profoundly. It appears in general that the anti-knock property is fundamentally a property of the individual element, although it is modified to a certain extent by the compounds in which the element occurs. Many, not all, Nitrogen compounds have a moderate anti-knock effect, practically all the volatile compounds of I_2, Se, Fe, Ni, Co, Sn, Pb have marked anti-knock effects, some of them being effective when present in small quantities.

We come now to the consideration of detonation theories themselves. The foregoing very brief outline of facts to be considered in formulating a comprehensive theory of detonation makes the difficulties of the task obvious. The number of factors to be investigated is too great for a few workers to obtain all the necessary data within a reasonable time. On this account, we find experiments carried out by a widely varied group of investigators both as to geographical location and as to previous training. This fact inevitably brings with it a wide diversity of conclusions which must be harmonized and coordinated before the final result is in an acceptable form. The whole matter at present is in such a state of flux that in attributing a given theory to an investigator, to be fair, the date of theory must also be given, since opinions must often be altered to fit new experimental facts.

(1) The Mechanical Theory.[25,20]

The mechanical knock theory holds that the sound results from an actual impact between parts of the engine due to gas pressure as apart from the inertia forces of the engine. It does not attempt to explain the origin of these pressures.

(2) The "Pressure-Auto-ignition" Theory.

This is the theory usually in the past identified with the name of Ricardo. Ricardo stated this theory in the "Automobile Engineer" in 1921 as follows:

"The phenomenon of detonation appears to be substantially as follows: 32(a) when a mixture of hydro-carbon vapor and air is compressed to a high pressure and to a temperature below that of its self-ignition temperature and then ignited from any one point, the flame at first spreads by the normal process of burning. When the rise in temperature of the unburnt portion due to compression by the burning gases, exceeds the rate of heat dissipated by a certain margin; spontaneous ignition of the former takes place and an explosive wave is set up which strikes the walls of the cylinder with a hammer-like blow, thus causing the familiar metallic ring known as "pinking" or detonation.----If detonation is allowed to persist it will, unless it be very slight, increase in severity and ultimately raise the temperature of the igniter points to such a degree as to cause pre-ignition ----before the spark has passed; this is a quite distinct phenomenon and should not be confused with detonation."

In this article, Ricardo defines his "highest useful compression ratio"; "This point, namely, the compression at which detonation first becomes audible with certain definite temperature conditions, and with both ignition and mixture strength adjusted to give maximum efficiency, is taken hereafter as representing the highest useful compression ratio for any fuel. It is not the highest compression ratio that can be employed, but the highest that it is worth while to employ.

Young, Holloway and Huebotter[43] at Purdue University, state a theory very similar to that outlined above.

"The following theory seems to offer a reasonable explanation of this-----phenomenon. The charge is ignited by the spark and burns at the normal rate of flame propagation during the early stages of the reaction. The unburned gas, which has been heated during the compression stroke, is compressed still further by expansion of the products of combustion behind the flame cap.---- Unless the heat due to this latter compression is transferred to the combustion chamber walls as rapidly as it is generated, the temperature of the entire mass of gas rises to the ignition point and explodes instantaneously, producing a hammerlike blow effect both in shock and sound. In support of this hypothesis, is the experimental evidence that the knock ceases when certain suspected high temperature areas are subjected to additional cooling. The absorption of heat from the combustible charge is thereby facilitated and auto-ignition is prevented."

(3) "Maximum Flame Temperature" Theory.

This theory as put forward by Tizard was reported by Ricardo in the S.A.E. Journal in 1922.[33,1]

The following points are noted;

(a) Detonation depends primarily upon the rate of burning of the part of the charge first ignited.

(b) The rate of burning increases very rapidly with increase of flame temperature and whether it will prove sufficiently rapid to produce detonation depends upon the ratio between the rate of evolution of heat by the burning portion of the charge and the rate of loss of heat.

(c) The chance that the rate of burning of any portion of the mixture will become so high as to cause detonation, depends but little so far as practical engine conditions are concerned, upon the temperature or pressure of compression but rather upon the maximum flame temperature.

(d) For any given mixture strength, the maximum flame temperature depends primarily upon the proportion of diluent or exhaust products present. It depends also of course upon the compression temperature but the effect of this is small compared to the effect of the proportion of residual exhaust products.

Experimental results showed:

(a) If the residual exhaust products are cleared away by scavenging with air, it was found that detonation became severe at once, even with very low compression pressures.

(b) Addition of cooled exhaust products thru the carburetor, permitted the compression ratio to be increased to almost any degree depending upon the quantity admitted.

"The effectiveness of such inert gases appears to be closely proportional to their specific heats, that is to their direct influence upon flame temperature."

"Broadly speaking, two factors determine whether or not a fuel will detonate; (a) the self-ignition of the fuel-air mixture, (b) the rate of acceleration of burning as the ignition temperature is exceeded."

(4) The "Detonation Wave" Theory.[11,20]

This theory holds that when the mixture is ignited, the wave of combustion spreads out from the ignition point at a relatively slow but increasing rate. Under certain conditions, before the flame has filled the combustion space, its rate of motion accelerates to what is known as "detonation" velocity, a velocity so high as to constitute practically the simultaneous burning assumed by Ricardo.

This theory in substance assumes that the process occuring in the cylinder of an internal combustion engine is analagous to that taking place in open tube experiments like those previously mentioned when the reaction velocity reaches the "detonation" stage.

Ricardo's theory as outlined above assumes that the cylinder pressures are true pressures produced by a sudden increase of pressure throughout the cylinder, while the "Detonation Wave" theory includes the assumption that the high pressures may be localized impacts of the detonation wave. This means that the maximum pressures may not be the same at different points within the combustion space.

Dickinson[20] of the Bureau of Standards comments on the detonation wave theory as follows;

A light steel rod was placed on top of a Liberty engine cylinder during detonation. Observations of the velocities of this rod show that the velocity of distortion of the cylinder head is comparable to that of a high pitch tuning fork.

From certain other work Dickinson concludes;

(a) The sound produced by the fuel knock can be adequately accounted for by the distortion of parts of the cylinder, without assuming any mechanical impacts.

(b) The maximum pressures seem to exceed those which could be produced by the normal explosion of the charge. This indicates that some phenomenon such as detonation must be assumed in order to account for the pressures observed.

(c) The rate of increase of pressure found by experiments are such as to require some such disturbance as detonation as an adequate explanation.

(5) Midgley's "Critical Pressure" Theory. Midgley and Janeway[28] using the results of Woodbury, Lewis and Canby[41] from their work on bomb explosions of gaseous fuels, set up an equation for the difference between the pressure before the flame front in an explosion and the pressure behind the same flame front. The derivation is based on the experimental results from the bomb experiments amplified by relations taken from physical chemistry. The final equation as derived is:

$$P_1 - P_2 = MP_1^{Q} \quad P_2$$

Where M and Q are symbols for rather complicated expressions depending on absolute temperatures, densities, reaction constants, etc.

Plotting the relation between $P_1 - P_2$ and P_2 givesa curve of the shape indicated;

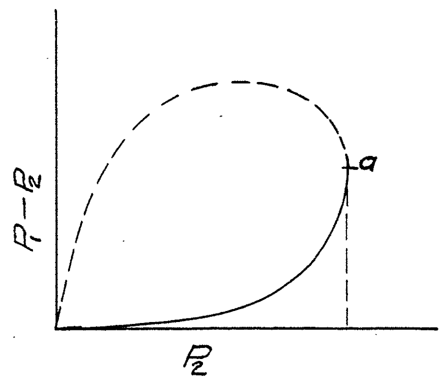


FIG. VI

Midgley and Janeway make the following comment:

"It is quite obvious that in the actual phenomenon of combustion, P_2 cannot reduce from the point a, but must increase as combustion goes on. What actually takes place at this point is a sudden enormous increase in reaction velocity and hence in the pressure differential. The extent of this increase is governed by some limiting factor or factors other than those already taken into account and are irrelevant for this paper. ----Probably the major factor is the limiting of the flame travel to the velocity of sound which the rate of transmission of molecular activity cannot exceed."

The following points are presented in support of the idea that gaseous detonation within the cylinder is the cause of knocking;

(a) a high-pressure, high velocity, detonation wave should distort it and thereby produce the metallic noise called a "knock".

(b) The luminosity that is observed during gaseous detonation in an explosion tube is also present in the flame within the cylinder when the engine knocks.

(c) Anti-knock materials such as diethyl selenide and lead tetraethyl could scarcely affect the auto-ignition temperature when present in such small quantities. Apparently the only way to account for their action is that they affect the constant of reaction velocity for gaseous detonation. Furthermore, these materials will suppress the detonation occuring in explosion tubes to the same degree and in the same manner that they suppress the knock in an engine.

(6) Ricardo's modified theory as set forth in "Engines of High Output".[35]

"When a combustible mixture of fuel and air is ignited, a nucleus of flame builds up with a rapid acceleration outwards from the point of ignition; when its rate of development exceeds a certain critical speed, depending upon a large number of factors, a detonation wave will be set up. This wave will pass thru the mixture at such a velocity that the pressure in the wave front will be excessively high, perhaps nearly double that of the average maximum pressure. On striking the cylinder walls, the impact of this wave will compress anew the already burned products, will still further raise their temperature and that of any isolated or partially insulated objects in their vicinity--------- until they cause preignition."

"From experimental results, Tizard has shown that detonation will be set up when the rate of evolution of heat by the burning gases exceeds the rate at which it can be disposed of to the cylinder walls, etc., by a certain margin, depending upon the nature of the fuel, the size of the containing vessel, etc."

It will be noticed that both Midgley and Ricardo in the last two theories are putting forward statements that are equivalent to those of the "Detonation Wave" theory.

(7) Brown and Watkins' "Rate of Pressur Rise-Auto-ignition Temperature" Theory.

Brown and Watkins[5] of the Chemical Engineering Department at the University of Michigan, carried out a series of experiments on bomb explosions of gaseous mixtures over a period of several years. They conclude that the detonation wave as it is recognized in progressive homogeneous reactions is not the cause of detonation in internal combustion engines.

"The data presented in this paper indicate that the rate of rise of pressure as measured in non-detonating theoretical explosive mixtures varies directly as the tendency of a fuel to initiate the detonation wave in a progressive homogeneous reaction as described. But it is well known that the aromatic hydrocarbons have much less tendency to knock in the internal combustion engine than normal paraffin hydrocarbons having similar rates of rise of pressure. The relative tendency of the normal paraffin and aromatic hydrocarbons to initiate the detonation wave is entirely different from the relative tendency of the same fuels to knock in the internal combustion engine. Therefore, the detonation wave, as it is recognized in progressive homogeneous reactions is not the cause of detonation in internal combustion engines."

It is shown that if the maximum rate of rise of pressure for a given set of fuels is divided by the auto-ignition temperature for these same fuels, a series of numbers is obtained which are in the same order as the knocking tendency of these fuels in the internal combustion engine.

The knocking tendency varies inversely as the "highest useful compression ratio" so it is possible to arrange these same fuels in the order of their "H.U.C.R2"s.

Such a comparison for an actual set of runs shows fairly good agreement with the data given by Ricardo for the same fuels.

Brown and Watkins summarize their work as follows:

"In brief, Midgley and Tizard have overlooked the fact that an increase in initial temperature decreases the rate of rise of pressure of a homogeneous gaseous explosion and have assumed the opposite to be true. This led Midgley to disregard the importance of the auto-ignition temperature and Tizard to disregard the importance of the rate of rise of pressure. The facts summarized in this paper indicate that both the rate of rise of pressure and the auto-ignition must be considered in estimating the tendency of a fuel to knock in an internal combustion engine, and suggest autoignition of the unburned part of the charge caused by adiabatic compression against heated surfaces as the mechanism of combustion causing engine knock. The rate of flame travel and the rate of rise of pressure in the explosions may approach the rates accompanying the detonation wave, but the mechanism of autoignition is so radically different from the mechanism initiating the detonation wave that a precise distinction should be made."

(8) Radiation Theory.

This theory is stated by Thee[39]; "As soon as the fuel is ignited and starts to burn around the electrodes of the spark plug, a portion of the mass of the mixture which is unburned is activated by radiations sent ahead by the flame.-----It will be recalled that radiant heat can press thru part of the mixture without raising its temperature. The more dense the mixture vapors are, the less easily the radiant heat will pass thru and the more of it will be absorbed by them. This absorption of the radiations tends to decompose the hydro-carbons constituting the vapor. This decomposition produces carbon, lighter hydro-carbons and possibly hydrogen. The last two immediately ignite and burn with abnormal rapidity. The knock may be produced by a pressure wave resulting from this sudden combustion."

Spectroscopic data show that detonation is accompanied by radically different radiation from that found to occur when the engine is running normally. The greatest intensity wave lengths are shifted toward the ultraviolet. The addition of anti-knock compounds return the emitted radiation to normal.

(9) Electron Theory.

Wendt and Grimm[40] put forward a tentative theory "---that the explosive flame is propagated by emission of electrons from the reacting molecules in that the advance of electrons before the flame front ionizes and activates the unburned molecules, causing detonation at high temperatures and pressures."

By this theory, the function of an anti-knock is to absorb electrons and promote recombination of ions previous to combustion, thus reducing the normal acceleration of combustion rate.

Clark, Brugman and Thee[9] at M.I.T. performed a series of experiments on the effect of knock inducers and suppressors on gaseous ionization. Their conclusion was; "The experiments indicate that the theory of electron wave fronts in explosions and the absorption of electrons by knock suppressors is not sufficient to explain the practical operation of such chemical substances in the control of detonation----."

Lind and Bardwell, working on the slow oxidation of methane under the ionizing influence of alpha radiation does not indicate any retardation by the anti-knock compound but rather some acceleration. Lind and Bardwell question the role played by ionization in explosive reactions. It is not a primary action.

(10) Organic Peroxide Theory.

Callender[6] holds that detonation in paraffin fuels and ether is due to the accumulation of organic peroxides in the liquid during rapid compression. The amount of peroxides formed is not sufficient to cause the observed detonation but acts as a primer in causing the simultaneous ignition of the fuel.

Peroxides are experimentally shown to be present in detonation combustion products. Other evidence seems to substantiate the theory.

(11) Theory suggested by A. H. Denison[14]

Cites evidence from the indicator card taken during detonation.

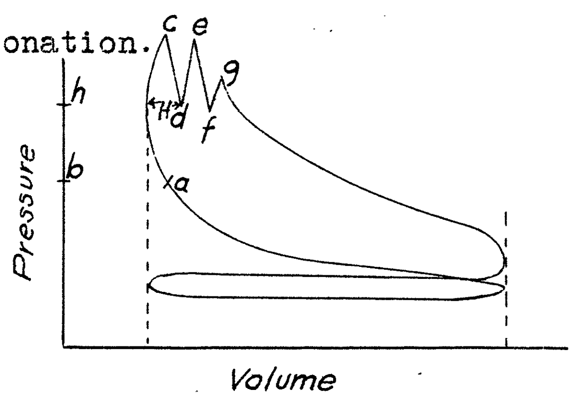


FIG VII

From a to c enough mixture burns to develop high pressures at c---rapid drop shows that the evolution of heat had stopped and cooling was rapidly reducing the temperature of the whole mixture. At d flame propagation again started. A condition capable of supporting a high rate of flame propagation was present and a heat evolution cycle independent of ignition was set up.

The theory holds that

(a) Further physical mixing of fuel and air by pressure waves and flame waves was set up during the first burning period, together with the effect of the first changes in volume, resulting in better mixing giving the oxygen a better chance at the fuel. This either completes the combustion of the charge or allows another heat evolution cycle.

or (b) the first evolution of heat and pressure had changed the proportions of H and C in the molecules of unburned fuel which apparently required the time H for its completion.

(12) Theory suggested by Charch, Mack and Boord[8], together with their "Pyrophoric Particle" theory of anti-knock action.

These investigators state their theory of detonation as follows: "The view held here is that detonation is a sudden disruption of the molecules and this depends to a large degree upon the stability of the molecule toward heat."

A similar theory is expressed by Sokol[36] who believes that detonation is caused by decomposition of large fuel molecules.

Charch, Mack and Boord[8] hold that the anti-knock action of lead tetraethyl etc., is due to the thermal decomposition of the anti-knock compound into small "pyrophoric" particles which become hot by rapid oxidation and act as a set of small auxiliary spark plugs in that they set up combustion at many points in the mixture and thru this action prevent detonation.

Olin, Read and Gow[29] conducted some experiments on the effect of metallic colloids on detonation. These particles did not have a measurable effect in suppressing detonation. From this, the conclusion is drawn that the "pyrophoric particle" theory of anti-knock action is not correct.

(13) Gasin and German Theory of Detonation.

The detonation produced by a fuel increases as its electrical conductivity decreases.

German contends that a non-conducting fuel becomes charged with electricity generated by friction in the fuel line when the air gas mixture is sharply sucked into the engine. The presence of the electric charge causes combustion to take place too quickly after the jumping of the spark and the detonation knock appears. If, on the contrary, the fuel is a conductor, it does not become charged, the combustion follows the spark normally and no knock is heard.

(14) Suggestion of Prof. L. C. Lichty[13] (Sheffield Scientific School).

The abnormally high pressures during detonation in the internal combustion engine seems to be due to one or all of the following;

(a) A momentary liberation of energy in excess of what is anticipated.

(b) An increase of volume larger than the reaction equation of the fuel would indicate.

(c) The formation of an unstable compound with a specific heat much lower than the products of combustion ordinarily formed.

In addition to the theories noted above, four more will be mentioned. These theories are taken from the article summarizing detonation theories by Clark and Thee[11].

(15) Dissociation Theory.

"One of the first theories proposed was that of dissociation of the products of combustion. The amount of dissociation of carbon dioxide and water at the temperature and pressure reached in the ordinary internal combustion engine is small, probably not more than five percent. Furthermore, while this theory might account for some of the phenomena that take place, it cannot very well account for most of the knock in the cylinder, nor the vibration in the cylinder head. The dissociation of these compounds, while producing a slight increase in volume of the gases, does not proceed with any great violence. As the temperature and pressure are lowered by the piston moving on the expansion stroke, these dissociated elements reunite, but scarcely with the violence often attributed to them."

(16) The Free Hydrogen Theory.

The theory holds that the knock is caused by the excessively rapid combustion of free hydrogen.

It is an experimental fact that certain constituents of gasoline will liberate free hydrogen when heated in air. In addition to the liberation of hydrogen certain other hydrocarbons may be formed such as acetylene..

It is characteristic of hydrogen or acetylene to burn at a very high rate. If they are actually present in the cylinder, they would tend to accelerate the rate of combustion of all the gases present to the detonation point.

"The principal reason for believing that free hydrogen is the basis of the detonating difficulties is that addition of any substance which will combine readily with hydrogen and at the same rate vaporize under the same conditions, will eliminate the knock. Iodine will meet all these requirements and actually does stop detonation when about 2% is added to gasoline."

(17) Absolute Density Theory.

Lind states that absolute density may be the controlling factor for the cause or elimination of detonation. In seeking to explain this, he points out the similarity of the case to that of the velocity of interaction of hydrogen and oxygen under the influence of alpha particles, whose departure from the equvalent mixture in the direction of excess hydrogen (lower density or 'stopping power' for radiation) while excess of oxygen (higher density or "stopping power") increases the velocity."

(18) Molecular Collision Theory.

"According to this theory, undecomposed hydrocarbon fuel molecules immediately in the front of an explosion wave will be bombarded by swiftly moving molecules of carbon, hydrogen, oxygen, carbon monoxide, etc., from the explosion wave itself. The controlling reaction will therefore depend upon the relative numbers of these bombarding molecules. This theory has had a remarkable test in the experiments of Garner and Saunders on the spectra of acetylene explosions (really detonations). They explain the appearance and disappearance of the Swan and cyanogen bands as due first to the formation of carbon from the collision of the molecules with C_2H_2 to form 2C and H_2, then a preponderance of the collision reaction $C_2H_2 + O_2 = 2\,CO + H_2$."

IV. PRELIMINARY DISCUSSION

The foregoing discussion indicates that a rather wide range of ideas has been considered in the attempt to explain internal combustion engine detonation. Certain of the hypotheses appear to be quite reasonable and offer worthwhile aid in considering the fundamental problem, while others have little practical value.

With the matter in its present state of flux, it appears to the writer that more progress is likely to result from energy spent in experimental examination of the phenomena than if the same time were applied to a more extended examination of the literature.

In the various hypotheses which attempt to explain detonation, there is a constant recurrence of the idea that engine detonation processes are analogous to the processes found in examination of gaseous combustion in open tubes.

It seems fair to suggest that at present, the "detonation wave" type of hypothesis may be included among the more reasonable ideas concerning the detonatiom process. The desirable type of engine combustion is considered as analogous to the initial period of slow uniform flame propagation, while the undesirable type corresponds to the high velocity "detonation wave".

If a"detonation wave" is actually involved in the cylinder process of detonation, it follows that there is probably a certain critical distance from the spark plug points inside of which combustion is normal, while at greater distances the detonation wave appears. A knowledge of this critical distance for known compression ratios, fuels etc, might furnish more or less valuable design data with regard to cylinder size and spark plug location for a given compression ratio.

The primary object of the present experimental work was to develop, if possible, a method and instruments which might permit practical experimental work on the problem mentioned above.

The primary characteristic of such a device must be its ability to respond with negligible time lag to very rapid fluctuations of pressure.

It is also necessary that the device be of such a nature that it might be satisfactorily held inside the cylinder at known positions with respect to the spark plug supplying ignition.

In general, the available openings found in the ordinary experimental engine cylinder are designed to take a spark plug. For this reason, a limit of one half inch external diameter was imposed on the size of the sensitive element before the work was started. This dimension for the unit allowed something over one sixteenth of an inch between the sensitive element and the inside diameter of a metric spark plug hole. This allowance seemed to be sufficient for the necessary spark plug hole bushing.

The next matter for consideration was the type of sensitive element to the developed. The usual high speed optical indicator might possibly be adapted to the purposes of the present work, but the necessary accessory mechanism for controlling the mirror would probably give considerable difficulty due to the necessity of keeping the photographic mechanism outside the cylinders while the sensitive diaphragm itself might be some inches distant inside the cylinder. Such a unit would probably be developed if necessary, but another type of system seemed to offer more immediate promise for present purposes.

In considering the range of apparatus which might be used in connection with the problem, the oscillograph, as developed for use in electrical work, seemed to offer an instrument particularly well suited to take care of the short time intervals to be encountered in detonation experiments. On this account, it was decided to make an attempt to utilize the oscillograph in the present investigation. This, of course carried with it, the necessity of so constructing the sensitive element that it would produce a variation of inductance, capacity or resistance in an electrical circuit.

Of necessity, some portion of the sensitive element must be exposed to the pressure existing in the cylinder, so that in addition to its sensitivity, it must be able to successfully withstand the temperatures and pressures encountered.

In addition to the two requirements mentioned above, the free vibration period of the element should be much higher than the period of any disturbance likely to be encountered. A diaphragm type of element seemed to offer most promise in this connection and was accordingly adopted as the type to be developed.

In regard to the mechanical action of a diaphragm, it is noted here that there must always be some lag in the displacement of any mechanical system by gas pressure. The writer has spent some time in study of the mathematical treatment of vibrating systems and hopes to be able to include in a future report a more or less complete discussion of the dynamics of high speed pressure indicating devices. The present report will consider only the practical experimental possibilities as they have worked out, refinements of method being left for future consideration.

Having decided on the diaphragm as a suitable element for detecting gas pressures and passing the indication along to the recording system, the next step was to settle on the method to be used in utilizing diaphragm deflections to alter conditions in an electrical circuit. The writer is indebted for useful suggestions in regard to this matter to Professors Lyon and Hudson of the Electrical Engineering Department as well as to Professor Taylor of the Aeronautical Engineering Department under whose supervision the work has been carried out.

Three possible methods of transferring diaphragm displacements into electrical indications presented themselves; (1) the motion of the diaphragm might be made to alter the reluctance of a magnetic circuit linking an electrical circuit after the manner of a magnetic "pick-up" used for phonographic sound reproduction; (2) the movement of the diaphragm might be made to alter the capacity of a small condenser by a method similar to that used for the "capacitative" phonograph "pick-up"; (3) some sort of resistance element might be developed that would alter its electrical resistance in proportion to the diaphragm displacement.

Of these types of electrical systems, the first two would require some sort of vacuum tube amplifying device which could undoubtedly be developed but which would offer a complication to be avoided if possible.

The magnetic type of unit would be under the decided disadvantage that it would give an indication only during the motion of the diaphragm as pressures were changing in the cylinder i.e. when flux linking the electrical coil undergoes a change. This characteristic, coupled with the necessity of using the vacuum tube system, seemed to make the magnetic type of unit least desirable of any of the types noted.

The capacitative type of pressure indicator has been successfully used by Juichi Obata[44]. A description of his apparatus will not be included here except to note that in all his arrangements, some sort of vacuum tube circuit was used. The capacitative type of unit indicates magnitudes as well as changes of pressure. However, it was felt that some simpler scheme should be tried out before taking up the development of such a device.

If a sensitive element could be constructed whose resistance between contacts decreases as pressure is applied to the diaphragm, an ideal type of instrument would be at hand. A simple series circuit could be used between the oscillograph vibrator and the unit, which would not only offer a minimum of complication but would be as free as possible from lag effects due to capacity and inductance in the electrical circuit. For these reasons, it was decided to investigate the possibility of developing a resistance type of sensitive element.

It is perhaps in order to consider here the necessary general characteristics of the elements of a satisfactory pressure indicating unit of the resistance type.

In the first place, the diaphragm itself should be of such a nature that the resulting deflections are proportional to the pressures existing within the cylinder, i.e.

$$Z = k_1 P$$

Z = deflection of the center point of the diaphragm from the equilibrium position.

k_1 = constant.

P = pressure existing within the cylinder.

Secondly, this displacement of the diaphragm should be made to react on some sort of variable resistance element in such a manner that:

$$\frac{1}{R} = k_2 Z$$

R = electrical resistance of the element

k_2= constant

By use of a constant electro-motive force V in a series circuit with the unit and an oscillograph:

$$I = \frac{V}{R} = Vk_2 Z = Vk_1 k_2 P = K\ P$$

It follows from this that current flowing in the series circuit will be proportional to the pressures existing in the cylinder.

In general for small deflections, the oscillograph vibrator may be assumed to have a law deflection;

$$d = k_3\ I$$

d = deflection in length units of the light spot on the recording film.

In summary then:

$$d = k_3\ \ I = k_3\ K\ P = C\ P$$

Hence, if the conditions noted above are fulfilled, the deflection noted on the oscillograph film is proportional to the pressure existing in the cylinder at any instant (neglecting the mechanical lag).

Having decided on the method of attack to be used in the problem, the next step was to carry out experimental work with a view of determining the practicability of diaphragm units of the necessary rather small size.

For this preliminary work on diaphragms, in order to keep the apparatus as simple as possible, a plain steel contact was used to give an electrical make and break in response to cylinder pressures. This experimental unit and the results obtained by its use will be described later in the report.

During the progress of the mechanical work on the diaphragm unit, a study was made of cylinder head distortions under operating conditions. This work was carried out with the aid of a special type of vibration recorder or accelerometer developed by F. H. Norton of the Physics Department at M. I. T. This instrument had been successfully applied to the study of mechanical vibrations by Professor L. H. Young also of the Physics Department. Professor Young very kindly spent considerable time with the writer in applying the vibration recorder to the particular problem at hand.

V. ENGINE CONDITIONS FOR PRELIMINARY WORK

In general it has been the object to apply the instruments to the examination detonation contrasted with normal operation. Since development of apparatus was the primary object, no nicities of detail as regards engine conditions were attempted. For conditions of normal operation, a relatively light load and reasonable spark advance was used. For detonation a heavy load with excessive spark advance coupled with the use of a lean mixture, resulted in a very bad condition of detonation. The compression ratio used was about 5.3: 1. The fuel used was ordinary gasoline.

Three conditions of operation will be noted in the following discussion (a) normal operation, (b) slight detonation, and (c) bad detonation.

The engine conditions for these three cases are noted below:

Operation	Throttle	Spark Advance	Speed in r.p.m.	Load in h.p.
normal	half	20°	1000	15-16
slight detonation	half	20°	1000	19-20
bad detonation	full	35°	1000	20-21

The engine used in all tests was the N.A.C.A single cylinder adjustable test engine in the Aeronautical Engine Laboratory. The load was supplied by a 45 horse power electric dynamometer.

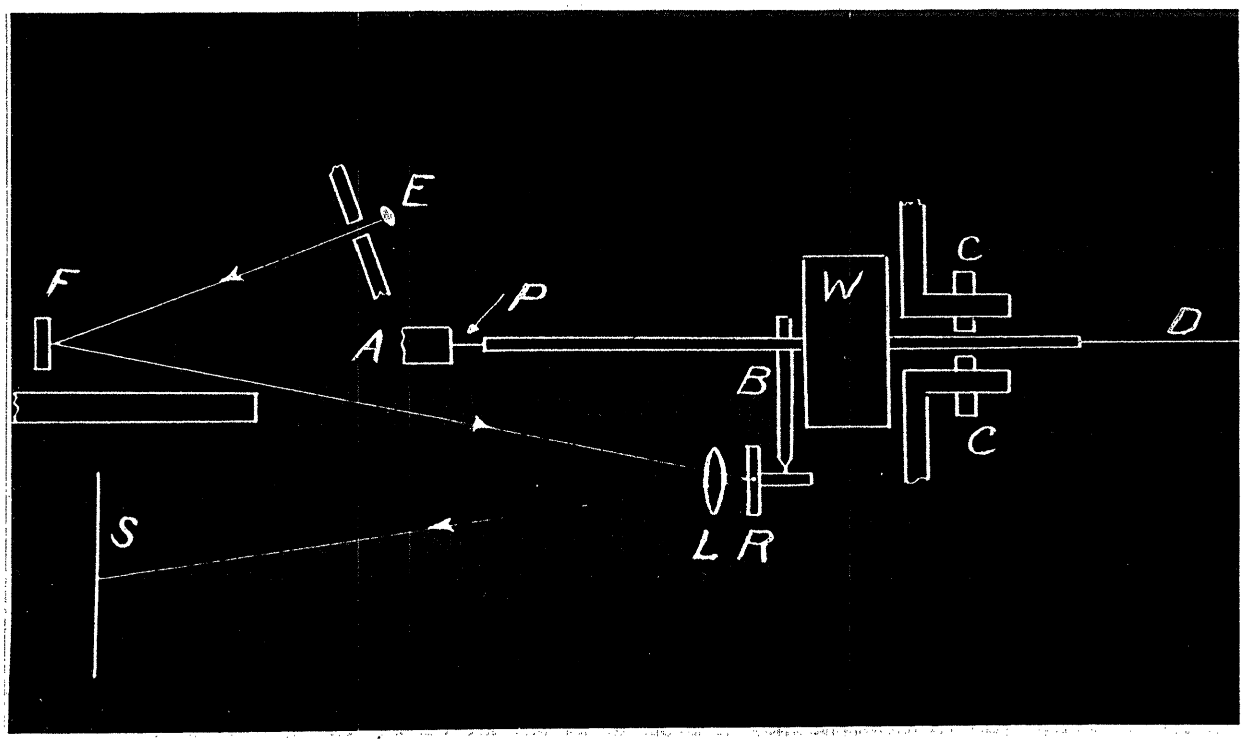
This engine has a stroke of 5 inches and a stroke of 7 inches. Ignition is accomplished by means of two independantly operated breakers and coils. The carburetor is a Stromberg aircraft type for a 2.5 inch manifold.

VI. STUDY OF CYLINDER HEAD DISTORTIONS UNDER DETONATION CONDITIONS

The essentials of the vibration recorder are indicated below in Figure 1.

A and C are parts of the frame of the instrument being rigidly connected together. The frame is made fast to the object whose vibration it is desired to study.

P is a flat phosphor bronze spring supporting the relatively large mass W. This spring is made up of two thin strips in such a manner that motion of the weight W with respect to the frame is permitted in one plane only.



A

The stops at C limit the amount of motion between W and the frame. In operation the weight is balanced between the stops and does not touch either side.

D is a flat vane for damping the motion between W and the frame.

The adjustable screw B is connected to the rigid arm carrying W and bears on a projection from the back of a pivoted mirror R. The mass of R is made small and the arm is held against B by means of a coiled hair spring.

L is a lens mounted in front of the mirror T.

A source of light consisting of a flashlight bulb with straight filament is placed at D.

A section of the straight portion of this filament is reflected by the fixed mirror F thru the lens L on to the mirror R. The light is reflected from R thru L and falls on the narrow slit S.

Mounted behind S (not shown in the diagram) is a drum carrying a photographic film. This drum is rotated at a known uniform speed by means of a small ratchet type motor operated with impulses from a vibrating spring contact.

Actually the drum itself does not carry the film but instead serves to accurately locate the sensitive surface in the right plane as the film is wound from one small spool to another. One spool is geared directly to the drum which in turn is driven by the motor. Motion picture size film is used in the instrument.

Observations were made with the accelerometer in both the vertical and horizontal planes.

In obtaining results for the vertical plane, the weight of the mass W was compensated for by means of a long spiral spring attached to the frame of the instrument.

In use, the accelerometer was rigidly clamped to a heavy brass plate held to the head of the engine cylinder thru a stud screwed into a spark plug hole.

Certain experimental difficulties were encountered in using the instrument mounted on such a violently accelerated base. For this reason, the number of satisfactory records taken is limited, but includes one each of normal operation and detonation in both horizontal and vertical planes.

In previous use, the instrument had been adapted to vibrations of much lower frequency than those found in the present case. On account of this fact, the records are not spread out as much as might be desirable, but the indication of the relative amplitudes of vibration is fairly satisfactory. The film speed of the instrument may be easily increased by a modification of the driving motor in case it might be deemed desirable to take further records of this type.

The records are shown below:

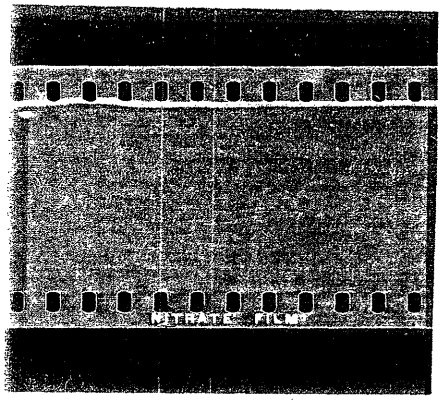


Fig. I.

Vibration in vertical plane.

Record for normal operation.

Magnification-----40.

Amplitude of cylinder head vibration------ 0.00063 in.

The record shows that the vibration for normal operation is quite even and uniform.

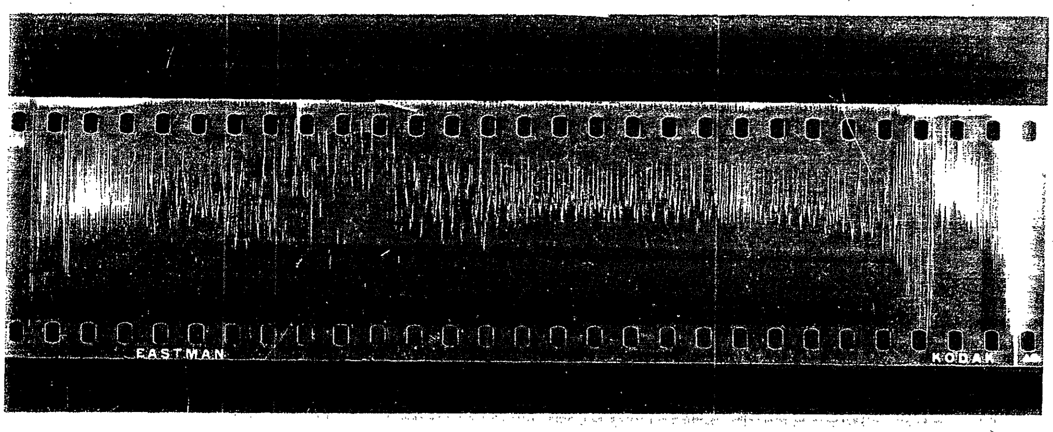


Fig. II.

Vibration in vertical plane. Record for bad detonation. Magnification----40. Amplitude of cylinder head vibration----0.0073 inch. (value calculated from mean of ten measurements)

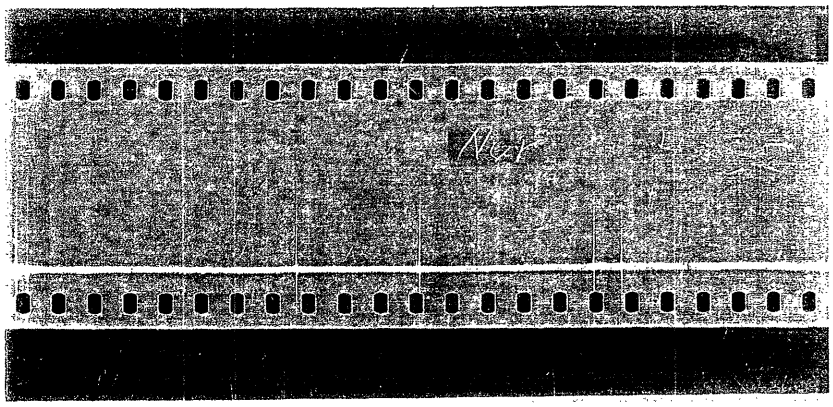


PLATE IV.

Vibration in horizontal plane. Record for normal operation. Magnification----90. Amplitude of vibration----.00037 in.

As in the case of the vertical plane record, the vibration is apparently of a uniform nature.

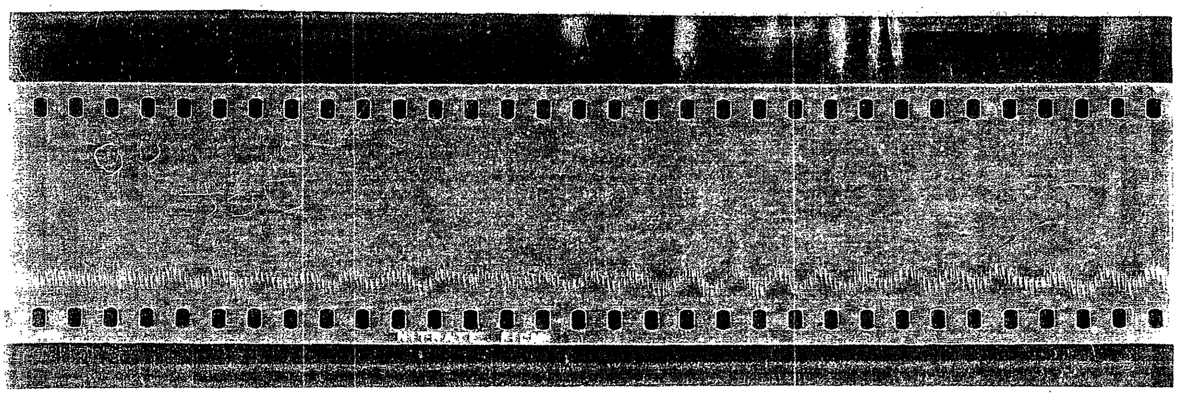


PLATE V.

Vibration in horizontal plane. Record for bad detonation. Magnification 90. Amplitude of vibration .0019 in.

No attempt has been made to make an exhaustive analysis of the data which might be derived from the records shown above by enlargement. Time available for the present years work has prevented any continuation of this line of experiment.

Whatever might be the final results of a careful examination of the records, the plates exhibited above, certainly bring out the marked difference which exist between normal operation and detonation as far as the forces which are exerted on the cylinder head are concerned. Considering only the amplitudes of the resulting vibrations, detonation brings with it an increased motion in a vertical direction some ten times that found for normal operation. Similarly in the horizontal plane, detonation conditions an increase of amplitude of some five times the normal operation value.

As concerns the increase in vertical displacement of the cylinder head, the explanation appears to lie in an actual bending out of the head itself. The head construction for the particular engine used in the test is very heavy, so it must follow that the instantaneous values of the force which produces the distortion are relatively high.

Examination of the detonation record for horizontal displacements shows in addition to the small oscillations recorded from the engine, a much slower vibration of a sinusoidal nature. The slow frequency recorded by the instrument is probably due to the weight system itself which is constantly subjected to heavy accelerations in a plane perpendicular to the motion permitted ordinarily by its construction.

The horizontal plane record shows that the high amplitude vibrations are followed in each case by a line of shorter length. It seems reasonable to suppose that the large amplitude lines are those resulting from the detonation of the power stroke while the shorter lines record the displacement resulting from the ordinary inertia forces for the other strokes of the cycle.

There can, of course, be no tendency of the gas pressures directly to move the middle of the top of the cylinder head in a horizontal plane. On this account it must follow, that the increased amplitude in the horizontal direction of the top of the cylinder head, is due to the reaction of the cylinder barrel to the sideways pressure exerted by the piston, under the influence of a heavy shock from the detonation process in the cylinder.

A more extended discussion of this matter will not be included here, the object of the report being primarily to indicate the nature of results which might be obtained by use of the vibration recorder rather than to formulate any final conclusions.

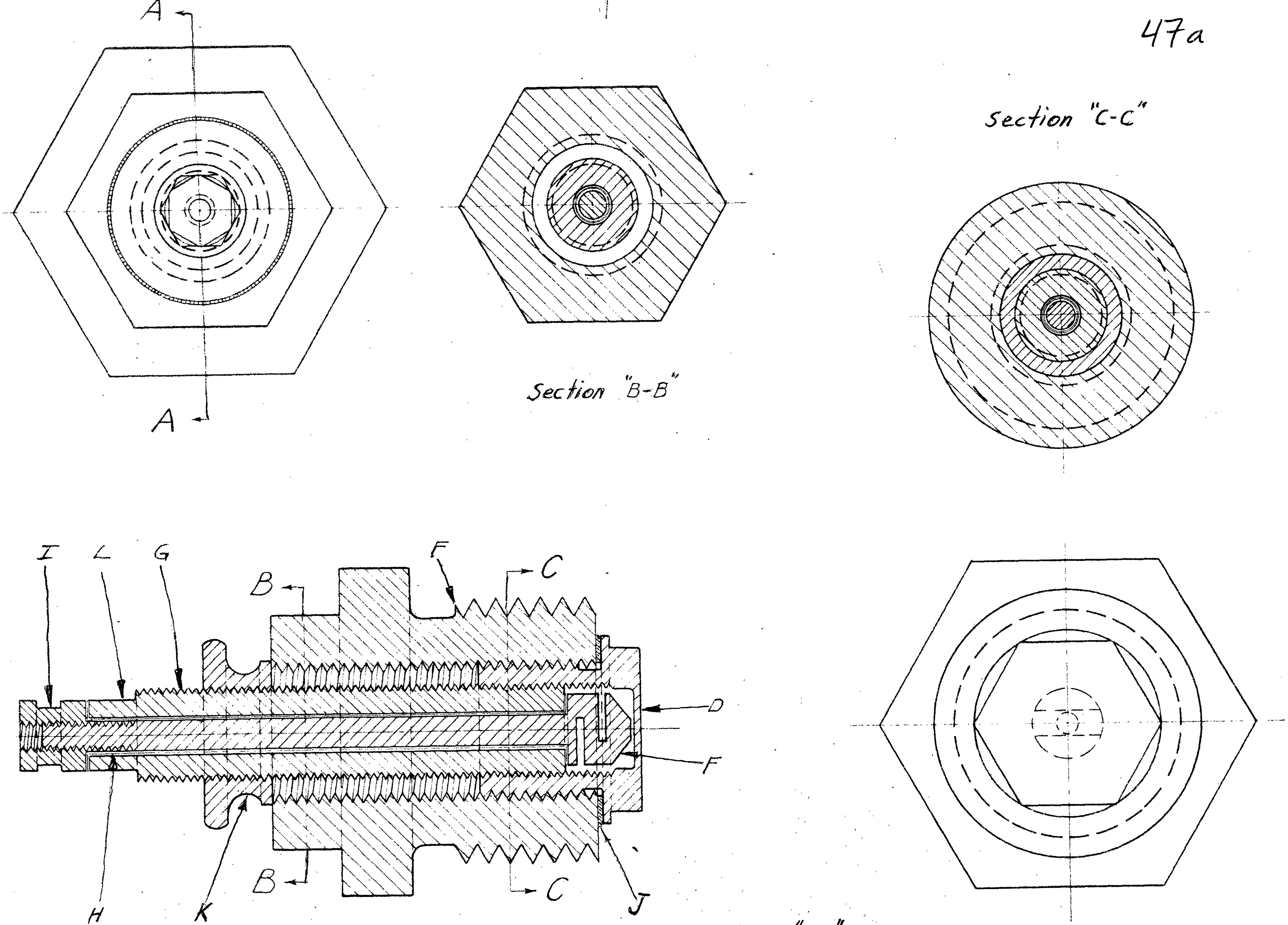
VII. DEVELOPMENT AND TESTS OF DIAPHRAGM UNIT

The actual experimental development of a diaphragm unit was undertaken after several preliminary designs had been laid out on paper. All of this phase of the work was carried out under the supervision of Professor C. F. Taylor of the Aeronautical Engineering Department.

In the preliminary work many helpful suggestions were made by Professor Hudson. The writer is also particularly indebted to Professor D. C. Stockbarger of the Electro-chemical Engineering Department for the use of his bench lathe and tools in addition to aid given in the form of suggestions. The actual mechanical work was greatly facilitated thru the use of a room in the Physics Department made available by the kind interest of Professor H. M. Goodwin.

Thanks are due to John Rosen of the Physics Department Shop for advice on mechanical details in addition to some very nice machine work on the unit. The actual testing of the units was carried out in the Aeronautical Engine Laboratory with the cooperation of Mr. E. S. Taylor who was in charge of the laboratory.

A number of units of different forms were made up before a satisfactory type was finally completed. The unit as finally used for test purposes on diaphragms of different thicknesses, is shown in the following blue print.



Section "B-B"

Section "C-C"

Section "A-A"

Scale - 4" = 1"

As used up to the present time, the unit consists of a diaphragm D, somewhat less than a quarter of an inch in diameter. The thin sensitive point of the unit is formed from a piece of solid steel stock bored to the proper depth with a flat bottoming tool. The resulting hole is tapped with a quarter inch thread, 50 threads to the inch. The exposed side of the diaphragm is turned flat in a lathe and a hexagon formed near the end for holding a wrench for making the unit tight in the spark plug bushing E. The insulated contact F, is carried in a hollow piece G, threaded to fit the hole tapped in the diaphragm section of the instrument. Insulation is accomplished by use of thin sheet mica shown at H, the internal contact being made solid by tightening the small unit I to which is soldered an electrical lead. The diaphragm unit is made tight in the bushing by means of a copper gasket J. A jam nut K serves to keep the insulated contact solid in position for purposes of adjustment. Adjustment is accomplished by use of a small wrench on the hexagon portion of the piece G. In order to prevent the diaphragm D from damage in case of a too severe distortion, the contact F, is slotted near its end in order to permit a slight spring action but at the same time keep the contact stiff enough to cause it always to return to the same position after bending. The material of all parts of the unit was cold rolled steel.

Tests made in a pressure bomb constructed for the purpose, showed that with pressures ranging from 200 to 600 pounds per square inch, a diaphragm 0.020 inches thick would distort sufficiently to close the contact between F and D. The unit was then screwed into a spark plug hole in an actual engine. A telephone receiver was used as the sensitive element in a series circuit with a dry cell and the diaphragm unit.

With the telephone receiver,it was found that the unit could be adjusted to give regular clicks under the influence of cylinder pressures in the operating engine. Detonation conditions in the engine caused the clicks to disappear.

For purposes of further investigation, a series of diaphragms of varying thicknesses were made up. The thicknesses used were 0.009 inch, 0.015 inch, 0.020 inch and 0.029 inch.

Further tests were conducted with these units, using the N.A.C.A. test engine, with a millivoltmeter as the sensitive element. A single dry cell connected across a 400 ohm potentio-meter was used as the source of e.m.f.

Runs made with this arrangement showed that under conditions of normal operation, the needle of the milli-voltmeter oscillated about a position of equilibrium somewhat lower than the short circuit reading (found by short-circuiting out the diaphragm unit). The effect of increasing load on the engine was relatively slight, the tendency being to shift the equilibrium up scale (this may have been due to reduced speed since no particular effort was made to keep this factor constant). The effect of detonation was to markedly shift the equilibrium position to a lower scale reading.

In general in these tests, detonation was induced by leaning out the mixture and advancing the spark under heavy load. It was found that on retarding the spark to normal after a period of detonating operation, the pointer returned to its former equilibrium position. This phenomenon was observed to be independent of diaphragm thickness since it was uniform in action for the four diaphragms available. In general, it was found that the difficulty of adjustment increased with the thickness of the diaphragm used.

It was hoped that the nature of the action might be cleared up by substitution of an oscillograph for the well damped volt-meter.

At the suggestion of Professor Hudson,of the Electrical Engineering Department,an oscillograph was obtained thru the kind permission of Professor C. E. Tucker and H. M. Lane of the same department.

The instrument was a Siemans-Halske three vibrator type fitted with visual and photographic attachments. The photographic attachment consisted of a drum which could be rotated at any desired speed by a direct current motor. A shutter operated by an electrical relay serves to make an exposure during the period of one revolution of the drum. The film carried by the drum is 8.5 inches in length and 3.25 inches in width.

Messrs McQuillan, McClintic and Oser of the Electrical Engineering Department assisted in carrying out the experimental work.

In general, the work was directed toward the primary object of examining the action of the diaphragm unit rather than forming any conclusions with regard to the engine phenomena.

One of the oscillograph vibrators was connected thru the proper resistance to the alternating current lighting circuit for the purpose of obtaining a reference time line.

A low resistance drop wire was connected in series with the primary of the engine ignition circuit. One side of the second oscillograph vibrator was connected to one end of this drop wire, the other side being connected to a sliding contact on the drop wire. By this arrangement, a voltage sufficient to operate the second vibrator was obtained from the primary circuit of the ignition system. An attempt was made to utilize the voltage across the spark plug itself to operate the vibrator, thru the surge of current in a low capacity condenser connected between the plug terminal and ground. This attempt showed that it would probably be necessary to use some sort of thermionic tube amplifier in order to obtain the necessary current. Since the oscillograph was available for a limited time only, the attempt was abandoned in favor of the simpler primary circuit connection, the lag of the spark after the primary circuit break, being disregarded.

Since but three drums were available for the oscillograph and the dark room was some distance from the motor installation, the runs were made in groups of three.

The first three exposures were made with the 0.020 inch diaphragm with the object of testing the effect of detonation of the diaphragm unit contact. The spark vibrator was not used for these runs.

The records are shown below:

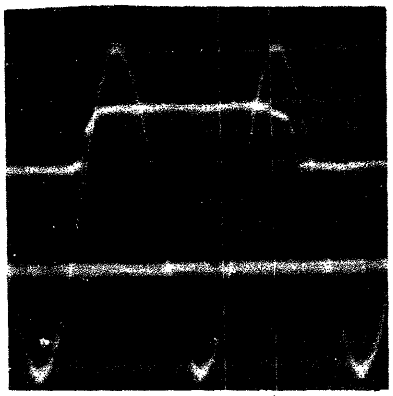


PLATE VI

Diaphragm............0.020 inch

Operation...........normal

Contact closed 0.023 second

The sine curve line is the record from the vibrator connected to the alternating current circuit.

The upper line showing the break is the make and break of the diaphragm unit.

The lower line is the third vibrator which was later used for the spark record.

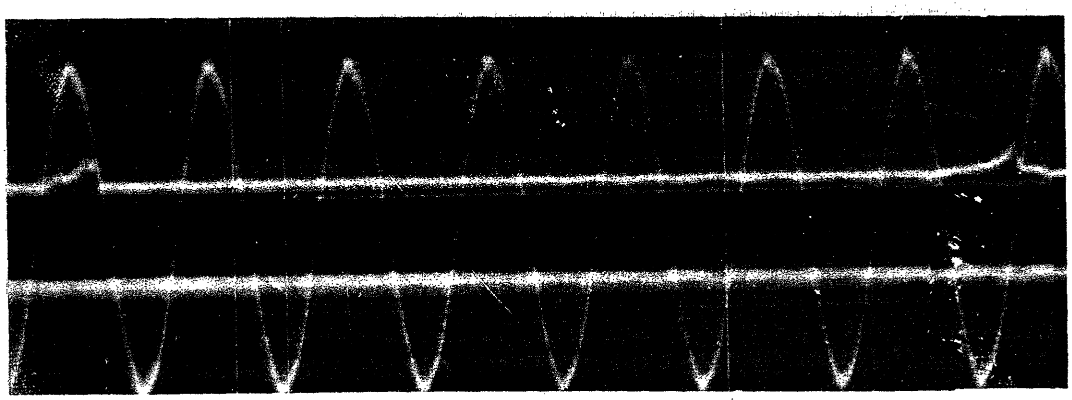


PLATE VII

Data on PLATE VII:

Diaphragm......................0.020 inch

Operation......................Bad detonation

Record to right................0.0032 second

Contact closed-record to left...0.0069 second

Note irregular line as current in diaphragm circuit drops off from its maximum value. Note that the maximum value is less than in the record for normal operation. The adjustment of the contact was the same in this record as in the previous record for normal operation.

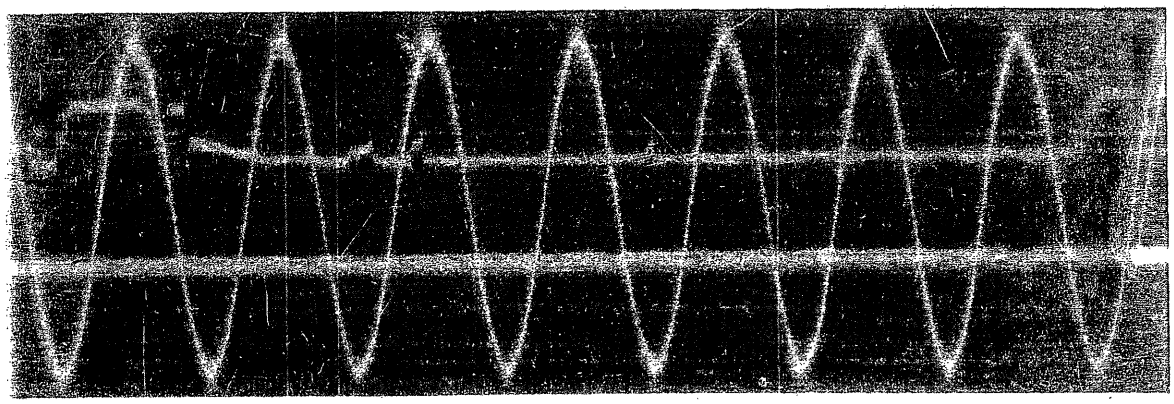


PLATE VIII

Diaphragm...........0.020 inch

Operation...........Bad detonation

Contact adjusted to a smaller gap than for the two previous records. Note the irregular nature of the contact as the current drops off from its maximum value. Note that the maximum value of current is equal to the value obtained in normal operation.

These three plates show that it is possible to obtain a record with the diaphragm unit which indicates the time interval during which the pressure in the cylinder exceeds a certain minimum value.

The effect of detenation appears to be that of reducing the time that the diaphragm is deflected a fixed distance to touch the insulated contact. The nature of the contact is altered by detonation from the apparently steady deflection found in normal operation to an unsteady contact which might well be caused by a rapid vibration of the diaphragm.

With regard to the growth and decay lines of the current in the diaphragm circuit, it may be mentioned here, that after a diaphragm had been used in the engine under heavy load conditions, inspection showed that a coating of oxide was formed on the inside of the diaphragm. This coating varied in color from a bright blue corresponding to a temperature of 550° F. in the thinnest unit to no perceptible color in the 0.029 inch unit. This coating of oxide made it possible to vary the resistance of the contact between the diaphragm and the insulated member by adjusting the pressure with the fine screw thread shown in the blue print.

In the second set of three records, the same diaphragm was used. The spark circuit was connected to its vibrator so that the occurrence of the spark was included in the record.

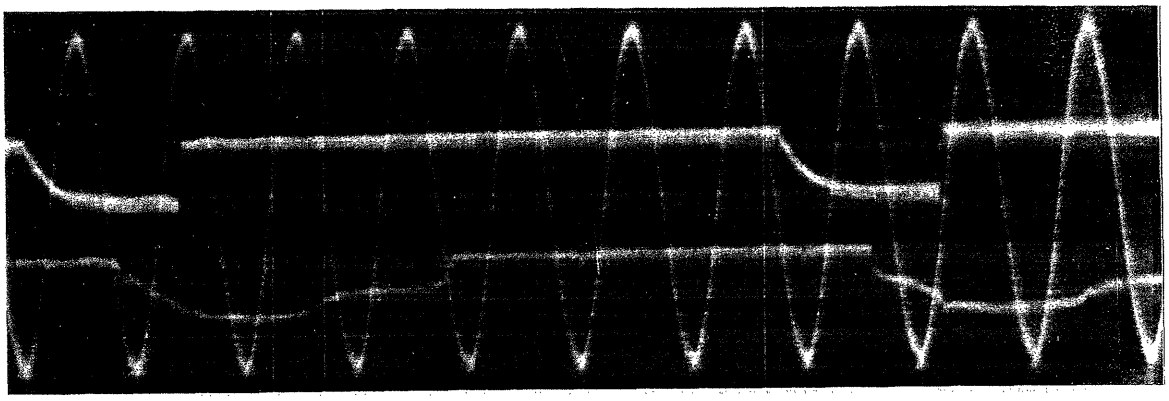
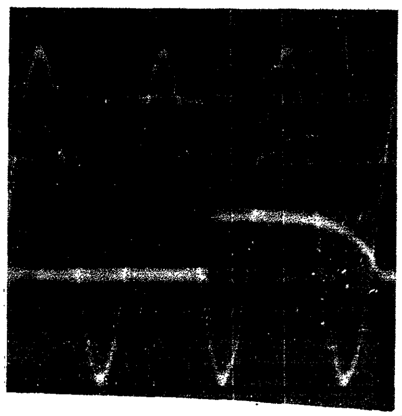


PLATE IX

Diaphragm.....0.020; Close gap; Normal apera-tion.

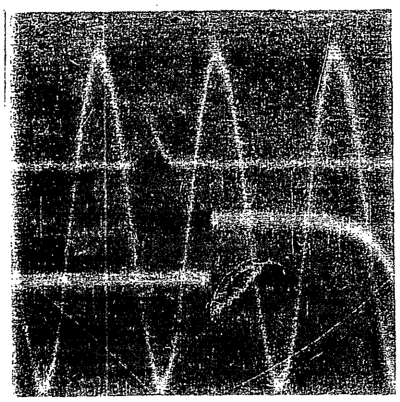
Note that the contact closed the circuit before the spark occurred. Contacts remain closed 0.042 second after the spark jumps.

PLATE X



Diaphragm...........0.220 inch
Adjustment same as in PLATE IX
Operation.....Slight detonation
Contact closed 0.017 second
Note sharp make of diaphragm circuit with no appreciable lag after spark. Note gradual decay of current with little indication of vibration.

PLATE XI



Diaphragm ..0.020 inch
Bad detonation; contact adjusted to give minimum satisfactory contact.
Contact lag after spark record to....0.0059 second;
Contact remains closed..... record...........0.0056 second. Note the gradual growth of current with the characteristic vibratory nature of the decay line.

The interesting point brought out by these last three records is that there is apparently some maximum pressure which builds up in the cylinder after the spark occurs, in a time interval which is too short to show up on a record moving at the film speed used up to the present. The last record shows that for detonation at least, a certain time interval around 0.006 second must elapse before the peak of the cylinder pressure occurs (assuming that the diaphragm follows the pressure variation without too great a lag).

The record obtained from the spark vibrator presents no feature of note. The record shows that the current in the primary circuit builds up gradually when the breaker contacts close. The sharp dropping off of the primary current line indicates the instant when the spark occurred. Plate X seems to indicate that the lag between the break of the primary circuit and the occurrence of the spark is not serious as far as the purposes of the present work are concerned.

The procedure outlined above for the 0.020 inch diaphragm was repeated with the 0.015 inch diaphragm and the three following records obtained.

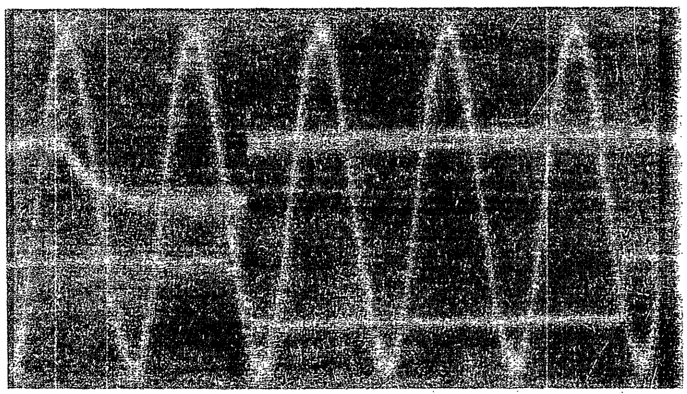


PLATE XII

Diaphragm............0.015 inch

Operation............Normal

Small gap

Contact closed.......0.049 second

Note that the contact closes before the spark occurs but that the contact improves at the spark.

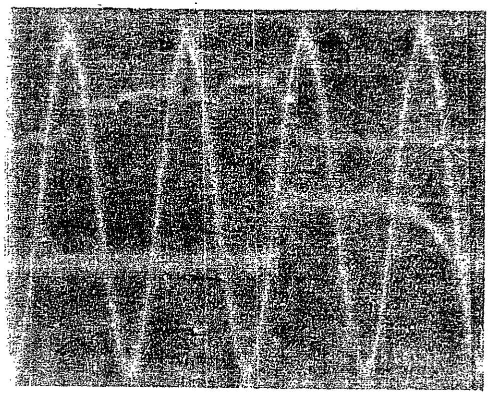


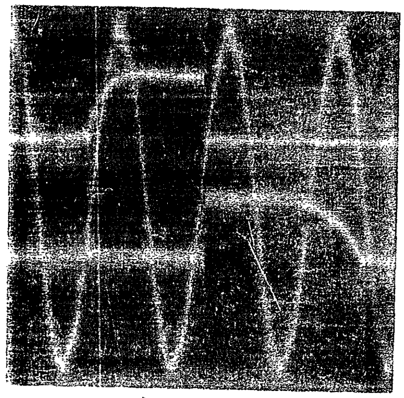
PLATE XIII

Diaphragm.....0.015 inch

Operation.....Slight detonation.

Contact adjusted to small gap. Note that contact closes before spark but that contact improves at instant spark occurs. Note irregular nature of contact.

PLATE XIV



Diaphragm.....0.015 inch

Operation...Bad detonation.

Contact adjusted to give good record. Note that there is no appreciable time lag after spark occurs before pressure closes contacts in unit. Note irregular decay line for diaphragm unit current.

The last three records serve to indicate that the unit may be made to operate with different thicknesses of diaphragm. The particular point brought out is the closing of the unit contacts with no discernible lag after the spark occurs. If the effect were confined to the cases where a close adjustment of the contact caused the

the circuit to close before the spark jumped, it might be held that the sudden improvement in the unit contact is due to an induced voltage from the ignition system which served to break down a thin remaining insulating film of oxide. Consideration of the last record where the diaphragm current builds up suddenly from zero to its maximum value appears to suggest that the effect is due to some rapid increase of pressure in the cylinder.

The next set of runs was made with the 0.029 inch diaphragm in the unit.

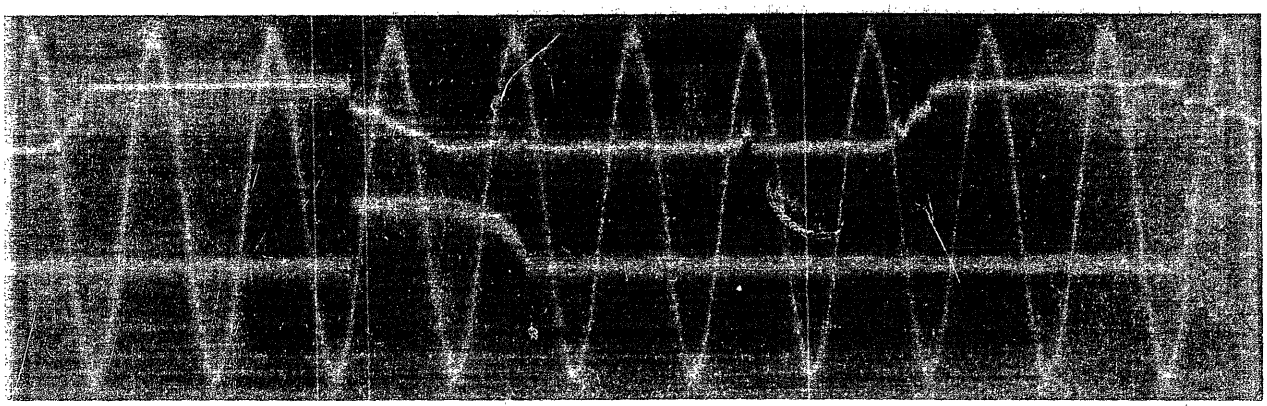


PLATE XV

Diaphragm...........0.029 inch

Operation...........Normal

Time of contact..Record on right..0.041 sec.

Record on left...0.042 sec.

Note that in both cases the contacts started to close before the spark occurred but that the contact suddenly improved with the occurrence of the spark.

In general it was found very difficult to adjust the unit with this diaphragm in place. An angular motion of one or two degrees served to make the difference between full break and full contact. The difficulties in this connection were increased by the fact that it was necessary for one worker to adjust the contact on signals from another experimenter who observed the effects of the adjustment in the oscillograph hood.

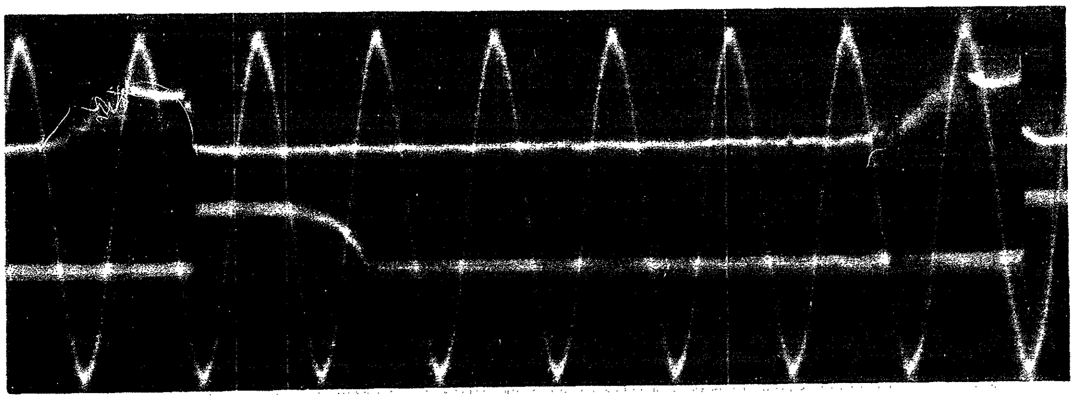


PLATE XVI

Diaphragm.................0.029

Operation..............Bad detonation

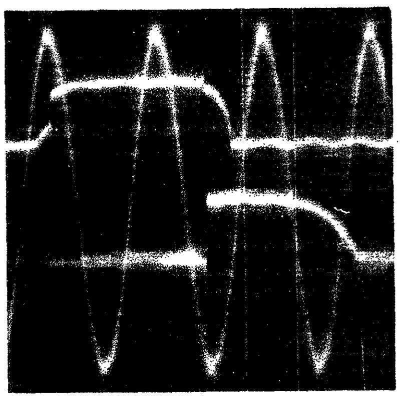
Time of contact..record to right..0.021 sec.

record to left...0.020 sec.

This last record shows plainly the sudden increase offer the spark, the current building up immediately to its maximum value. Apparently for the first part of the time interval after the contact closed, cylinder pressures were similar to those encountered in normal operation. For the last part of the record pressure interval, the irregular vibratory line characteristic of detonation showed that the nature of the pressure on the diaphragm had altered considerably.

The next step in the procedure was to exchange the 0.029 inch diaphragm for the 0.009 inch diaphragm, a series of three records being taken with the thin unit in place. For this case, the object was to ascertain the nature of the records which might be obtained if the best possible contact adjustment were used.

PLATE XVII



Diaphragm..........0.009 inch

Operation..........Normal

Time of contact..0.026 second

Adjustment.........Small gap

Note that contact occurs before spark jumped. Note sudden improvement in contact at moment of spark.

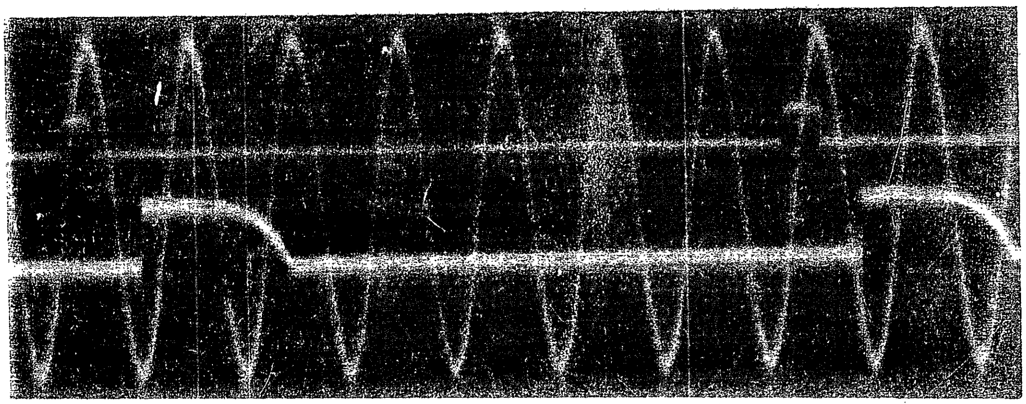


PLATE XVIII

Diaphragm......................... .0.009

Operation.........................Normal

Adjustment...........gap made as large as possi-
for satisfactory contact.

Time of lag between jump of spark and make of
diaphragm contact

Record on right.................0.0067

Record on left..................0.0080

Time of contact..Record on right.0.0061 second

Record on left..0.0043 second

This last plate shows that the time lag in building up the peak cylinder pressure exists in normal operation as well as detonation

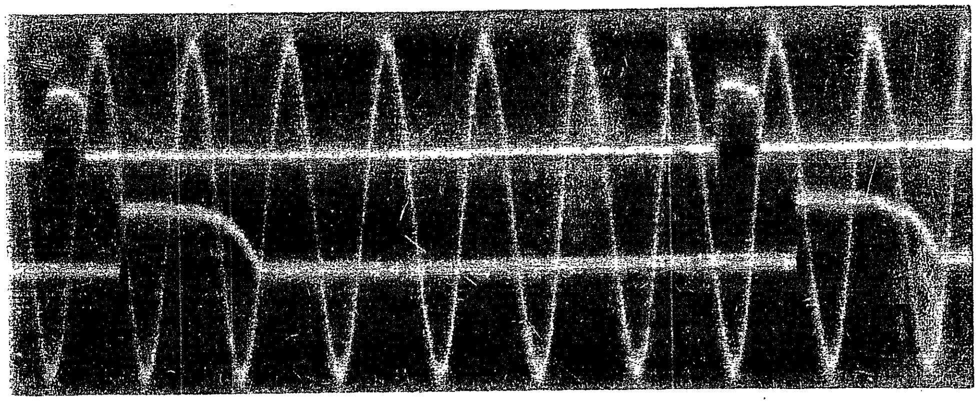


PLATE XIX

Diaphragm. ....0.009 inch

Operation......................Bad detonation

Adujustment..........Gap made as large as possible for satisfactory operation (actually this gap was somewhat smaller than for normal operation).

Lag time between jump of spark and make of diaphragm contact: record on right....0.0060 second
record on left.....0.0060 second.

Time of contact: record on right...0.008 second
record on left....0.0073 second

Note irregular appearance of rise and decay lines of diaphragm contact as contrasted with the record for normal operation.

The set of records exhibited in plates VI to XIX seemed to show that the method of attack might be developed to give satisfactory results on the type of work at hand. The records show that the 0.009 inch diaphragm is decidedly the most satisfactory as far as adjustment and resulting records are concerned.

One of the principal defects of the apparatus as used in these experiments is the impossibility of checking on any definite scale, the adjustment of the gap with which a record is taken.

In an unexpected manner, the oscillograph was made available for a day longer than the original loan. This extended time was used in taking records with an increased drum speed. Speeding up the drum naturally brought with it the probability that the chance opening of the shutter would not occur at the right instant to give a record of spark occurrence and diaphragm action. The problem became one of synchronizing the opening of the shutter to take place just before the break of the primary ignition circuit.

The experimental engine is fitted with two sets of breaker points for ignition. During the course of the work, the engine was operated by a single plug situated in the cylinder wall directly opposite the hole used for the pressure unit. The other breaker was disconnected from the ignition system and placed in series with the circuit which tripped the shutter on the oscillograph. The breaker cam was loosened and set to make slightly before the ignition cam caused the break of the ignition primary circuit. By this arrangement it was possible to locate the record on the photographic film at the desired position.

The first three records were taken under conditions of bad detonation. In these cases, the shutter did not work properly so that the resulting record extended but a short distance on the film. By good fortune, the portion of the film which was exposed recorded what was evidently the break of the diaphragm contact. In taking these last high speed records, the connections to the diaphragm unit vibrator were reversed so that a displacement of the upper line toward the bottom of the record indicates a current flowing in the diaphragm circuit.

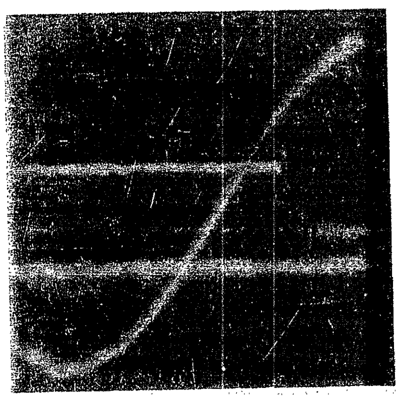


PLATE XX

Diaphragm............0.009 inch

Operation.........Bad detonation

Frequency of
vibration....3,850 per second

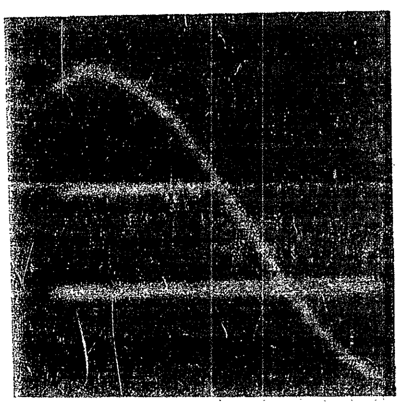


PLATE XXI

Diaphragm............0.009 inch

Operation..........Bad detonation

Frequency of
vibration....3,950 per second

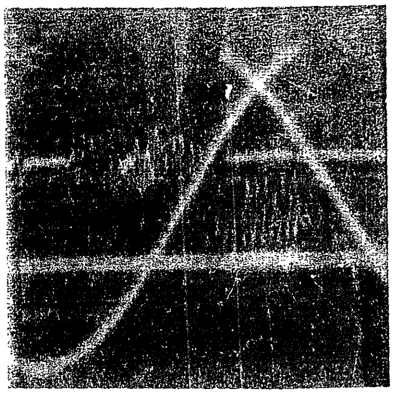


PLATE XXII

Diaphragm............0.009 inch

Operation.........Bad detonation

Frequency of
vibration.......3,940 per second

PLATE XXIV

Diaphragm..............................0.009 inch

Operation ....Normal

Contacts remain closed................0.016 second

Frequency of vibration of spark vibrator as shown by the quickly damped oscillation as the spark vibrator returns to its zero position...3,060 vds.sec.

Note that the diaphragm contact appears to start to make immediately at the jump of the spark.

Note that the well defined vibration shown in the three previous plates is entirely absent.

Even though the first three records were defective, the four plates shown above serve to indicate clearly the nature of the difference in diaphragm contact found for detonation and normal operation. Detonation appears to condition a well defined vibratory movement of the oscillograph vibrator of a frequency around 3,900 per second. Normal operation apparently gives a relatively stable non vibrating type of contact.

Before any valid opinion can be formed of the meaning of the vibratory contact found in detonation, the exact source of the phenomenon must be carefully examined. Three possible causes of this action presented themselves

(1) The vibration might be due to the response of the diaphragm to pressure fluctuations in the cylinder of the same frequency.

(2) The vibration might be due to the natural period of the oscillograph vibrator set in motion by impulses of some higher frequency from the diaphragm.

(3) The vibration might be due to the natural period of the diaphragm itself or of the contact spring.

In order to check the possibility that the natural period of the oscillograph vibrator is the essential factor, the period of the vibrator connected to the spark circuit was estimated from all the records in which it was measurable. It is to be noted that the records show that this period is about 3,000 vibrations per second which is of the order of magnitude of the frequency determined from the detonation records. From this it seems possible that the recorded frequency might have been determined by the oscillograph vibrator itself.

In order to test the effect of the sensitive diaphragm on the frequency of the detonation record, the 0.009 inch diaphragm was replaced by the 0.029 inch diaphragm. The records obtained are shown below.

PLATE XXV

Diaphragm....................0.029

Operation....................Normal

Contacts closed..............0.016 second

Spark vibratory frequency..3,060 per sec.

No time lag after spark.

PLATE XXVI

Diaphragm..................0.029 inch

Operation..............Bad detoantion

Frequency of diaphragm unit
vibration........3,600.vds per second

These last two records seem to indicate that the phenomena as recorded by the oscillograph are relatively independent of the thickness of the diaphragm used. The recorded frequencies for different diaphragms check fairly well but not to entirely satisfactory values. The responsibility for the definite frequency observed in detonation records seems to lie either in the spring contact of the unit or in the vibrator of the oscillograph.

The record shown below is an example of the type which mith be considered as satisfactory from a make and break type of unit.

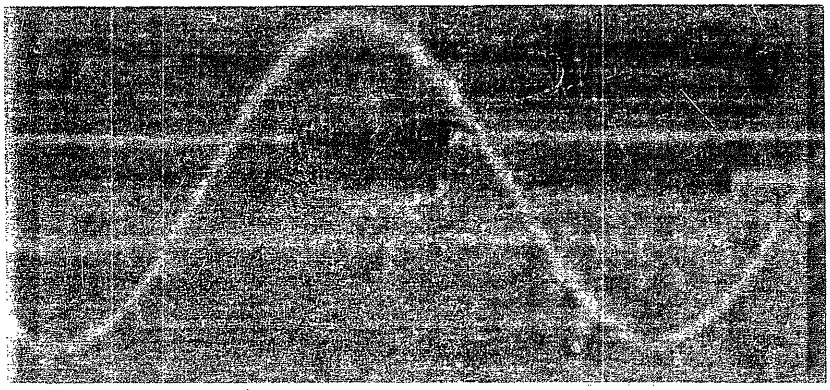


PLATE XXVII

Diaphragm.................. .....0.009 inch

Operation..................Bad.detonation

Time for pressure to close contacts after spark.............0.0018 second

Contacts remain closed...........0043 second

Frequency of diaphragm record..3,980 per second

Frequency of spark record......3,200 per second

VIII. RESULTS OF TESTS ON DIAPHRAGM UNITS.

The foregoing group of records indicates clearly that steel diaphragm units of one half inch external diameter may be made which will satisfactorily withstand any operating conditions likely to be encountered in test work on detonation. A single unit was often left in the engine for over an hour under severe operating conditions without a single failure occurring.

Using a diaphragm of one quarter inch internal diameter, a range of thicknesses from than 0.010 inch to about 0.030 inch, gave sufficient deflection under cylinder pressures to close the electrical contacts of the unit.

In regard to the matter of cooling, all the diaphragms used in the preliminary work were satisfactory. The 0.030 inch thickness diaphragm showed no signs of oxide color even after prolonged use under severe engine conditions. The 0.009 inch diaphragm showed a bright blue oxide color corresponding to a temperature of 550° C.

Cooling for the unit was by conduction thru the metal of the spark plug bushing, no special means being employed in any case. It seems reasonable to expect that satisfactory cooling may be accomplished on a unit designed to hold the sensitive element inside the cylinder under conditions of operation.

The final form of the diaphragm element of the sensitive unit as indicated on the blue print seemed to be practical to such a degree that further work on the diaphragm itself was suspended.

The tests run with diaphragms of different thicknesses showed that a diaphragm of about 0.010 inch thickness gave the most satisfactory results.

The records all show a distinct difference between detonation and normal operation, normal operation in general gives a smooth line on the record, while in all cases, detonation conditioned an unmistakable vibratory motion of some part of the contact system in the sensitive unit.

The preliminary work indicated that if the vibratory motion shown in the detonation records is not due directly to pressure waves in the cylinder gases, the responsible part of the recording system is either the spring contact in the sensitive unit or the oscillograph vibrator itself.

The empirical results show that it is possible to get an oscillographic record showing:

(1) The time interval between occurrence of the spark and the building up of a certain minimum pressure inside the cylinder which is able to deflect the diaphragm and close the contacts.

(2) The time interval during which the cylinder pressure exceeded that necessary to close the contacts.

(3) The character of operation whether normal or detonating.

IX. OUTLINE OF SPECIFIC EXPERIMENTAL PROBLEMS

The preliminary work brought out a number of problems to be solved before the form of the apparatus could be considered satisfactory for the proposed method of investigation.

I. As a primary requirement for carrying on the work, an oscillograph had to be made available for use at any time it might be required. It was necessary that the apparatus include the following features:

(a) A high speed vibrator element suitable for use in series with the sensitive unit.

(b) Some means for recording photographically on the moving film the occurence of the ignition spark in the engine cylinder.

(c) A device for marking down time intervals on the moving photographic film.

(d) A mechanism designed to make sure that the spark and vibrator records occur during the time interval over which the shutter of the oscillograph was open.

II. The sensitive element for detecting pressure waves in the cylinder as used in the preliminary work was obviously in a rather crude form so far as operation was concerned. It was held that further work on the diaphragm should consider the following matters:

(a) The actual magnitude of diaphragm deflections under operation conditions.

(b) The part of the mechanism which conditioned the characteristic frequency noted in the detonation recores.

(c) The possibility of calibrating the sensitive unit to determine the cylinder pressure existing at the moment of contact.

(d) The probable time lag of diaphragm deflection after the occurrence of a given cylinder pressure.

(e) The possibility of making up a unit whose resistance between terminals would be inversely proportional to diaphragm deflections.

(f) The possibility of selecting a diaphragm whose deflections would be directly proportional to cylinder pressures but whose free period would be much higher than any frequencies likely to be encountered under operating conditions.

(g) The possibility of constructing an entire unit whose resistance between terminals would be inversely proportional to cylinder pressures.

III. Assuming that a suitable sensitive unit were developed, it would next become necessary to attack the problem of a device for fixing the unit at different positions inside the cylinder. The design of such an arrangement consider:

(a) The necessity of using a spark plug hole as the opening for placing the unit inside thecylinder.

(b) The necessitiy of cooling the arrangement to a reasonable temperature under operating conditions.

(c) The desirability of easily making known changes in the position of the sensitive unit.

(d) The necessity of making the device so rugged as to resist engine operation successfully.

IV. Having settled the details of the apparatus, the next matter to be examined should be the type of record given by the apparatus for normal engine operation and for detonation. For the method to be of any value, some pronounced and easily identified difference in the records must consistently appear between normal operation and detonation. In the examination of this point, a series of runs was proposed with the following conditions of operation:

(I) Starting with detonation at full throttle and straight gasoline for fuel.

(a) Detonation checked by use of a doped fuel.

(b) Detonation checked by increasing richness of fuel mixture.

(c) Detonation checked by reducing throttle opening

(2) Starting with normal operation on straight gasoline at reduced throttle.

(a) Detonation induced by advanced spark.

(3) Starting with normal operation on doped fuel.

(a) Detonation induced by increased compression ratio.

The list of problems outlined above obviously represents more work than it was possible for the writer to carry out in a single term. The progress as outlined also represented considerable time and money to be expended if the results were problematical to a too great extent. For these reasons, the writer undertook only those portions of the work which seemed likely to offer the quickest answer as to the value of the proposed method. This idea of proving the practicability or worthlessness of the method prompted the experimental work which is described below rather than any attempt to go thru the entire problem systematically and completely.

X. OSCILLOGRAPH APPARATUS WITH ACCESSORIES

The primary requisite for setting up this part of the apparatus was an oscillograph unit. A single vibrator oscillograph with visual and photographic attachments was made available thru the courtesy of Mr. M. F. Gardner of the Electrical Engineering Laboratory. This unit was one of several constructed at M. I. T. for use in electrical research problems.

The oscillograph consisted of a standard General Electric vibratory unit with a field excited from a six volt storage battery.
The moving element was immersed in a bath of transparent oil (Nujol) which served to damp the motion of the vibrator. The front of the oil bath vessel was in the form of a glass lens.

A small arc operated from direct current was used as the light source. An optical system composed of a condensing lens, an adjustable slit, an adjustable prism, the oil bath lens and a cylindrical lens mounted with its axis parallel to the sensitive film, served to focus a spot of light from the vibrator mirror on the surface of the film drum. Angular motion of the oscillograph caused a displacement of the spot of light on the photographic film.

For visually inspecting the motion of the oscillograph vibrator, a mirror was arranged so that it might be set in the path of the light spot behind the cylindrical lens. This mirror was set on a shaft with pivots and a spring so that tripping a trigger caused the mirror to be moved out of the path of the vibrator beam.

A four sided rotatable mirror was arranged at the proper distance from the first mirror to catch the focussed spot of light from the vibrator mirror. The four sided mirror was mounted on a shaft so that it could be rotated by a small hand crank. Thus by setting the first mirror and turning the hand crank, the motion of the oscillograph vibrator could be visually inspected as a continuous curve spread out on a time axis.

The photographic attachment consisted of a cylindrical drum enclosed in a light proof housing unit. The drum was mounted on a shaft with bearings in the ends of the housing. One end of the housing was made removable for loading purposes. A small gear was fitted to the end of the shaft outside of the removable end of the housing. The front of the housing was made of a flat plate having a slit parallel to the axis of the drum. This slit was fitted with a rotatable slotted shutter which served to make the unit light tight when desired.

In use, the slide on the drum housing fitted into grooves on the back of the viewing attachment box of the oscillograph in such a manner that with the housing unit shutter open, the light spot from the vibrator would fall on the sensitive film surface. The gear on the drum shaft fitted into mesh with a gear on the viewing attachment box so that the drum might be rotated by means of the hand crank.

The viewing box contained a shutter mechanism so arranged that the shutter would remain open during one revolution of the drum only. The shutter became operative only when tripped by the trigger on the stationary viewing mirror. The details of the shutter mechanism will not be described here except to indicate that the arrangement consisted of a lug which passed thru slots in a rotating cylinder to open and close the shutter.

The writer is indebted to Mr. H. E. Edgerton of the Electrical Engineering Research Division for help and advice in operation of the oscillograph.

The oscillograph having been set up and put in operating condition, the next problem to be considered was that of indicating time intervals on the photographic record. The oscillograph incorporated a device for recording a timing wave from a mechanically sounded tuning fork. This tuning fork arrangement was tried out and found to be unsatisfactory for the problem at hand. This fact being settled, Mr. Edgerton suggested a shutter mechanism placed in the light beam from the arc and rotating at a known speed as probably the most satisfactory timing device.

A small synchronous motor running at 1800 R.P.M. was kindly loaned to the writer by Professor D. C. Stockbarger.

A brass disc six inches in diameter was carefully made up and fitted to the shaft of the motor. This disc was three eighths of an inch thickness and carried six holes tapped 10-32 machine screw thread perpendicular to the axis of the motor shaft. These holes were spaced equally around the periphery of the disc.

Two brass rods one quarter inch in diameter were made tight with lock nuts in two holes diametrically opposite on the disc. These rods were three inches in length.

By suitably placing the motor with respect to the slit in the optical system, the two brass rods acted as a shutter cutting off light from the instrument for a short time interval sixty times a second. In order to prevent accidents, the motor and oscillograph were both fastened securely with screws to a board carried on the supporting table. The rotating disc was protected with a sheet metal guard.

The next problem in order was the construction of a mechanism for tripping the oscillograph shutter at the proper time in the engine cycle.

A second ignition breaker mechanism on the engine was available for furnishing an electrical make or break at any desired point in the cycle. This breaker was connected in series with two dry cells and an electromagnet which operated a trigger arrangement. This trigger was so designed that the make of the circuit permitted a spring to immediately pull down the oscillograph trigger which in turn tripped the shutter mechanism.

A difficulty was introduced by the construction of the shutter mechanism. The arrangement was so designed that a lag variation was possible from zero to over one full revolution of the film drum. This feature of the shutter meant that even if the mirror was tripped at the proper time by the breaker mechanism, the actual opening of the shutter would be erratic as far as the engine cycle was concerned. To remedy this difficulty, a small rotating contact of the plunger type was designed to run over a series of insulated contact segments arranged in a circle on a piece of bakelite panel. This rotating contact was fixed to the slotted cylinder of the shutter mechanism.

By connecting the rotating contact and the proper segment of this device in series with the engine breaker and the electromagnetic trigger, it was necessary that both the shutter mechanism and the engine contacts be in the proper position before the oscillograph shutter would open. By allowing the proper amount of lead to take care of the various lags inherent in the device, a satisfactorily operating arrangement was attained.

The remaining problem was that of recording on the moving film, the occurrence of the ignition spark. To accomplish this end, a spark gap unit was made up of bakelite. This unit was connected in series with the engine spark plug thru suitable wire insulated for high tension work.

The external gap was rigidly held by a clamp in the proper place with regard to a lens system for the image of the spark to be focussed on the sensitive film. It was found in practice that this arrangement gave a satisfactory spark record.

The following photographs indicate the various features of the apparatus as it was used in the latter part of the work

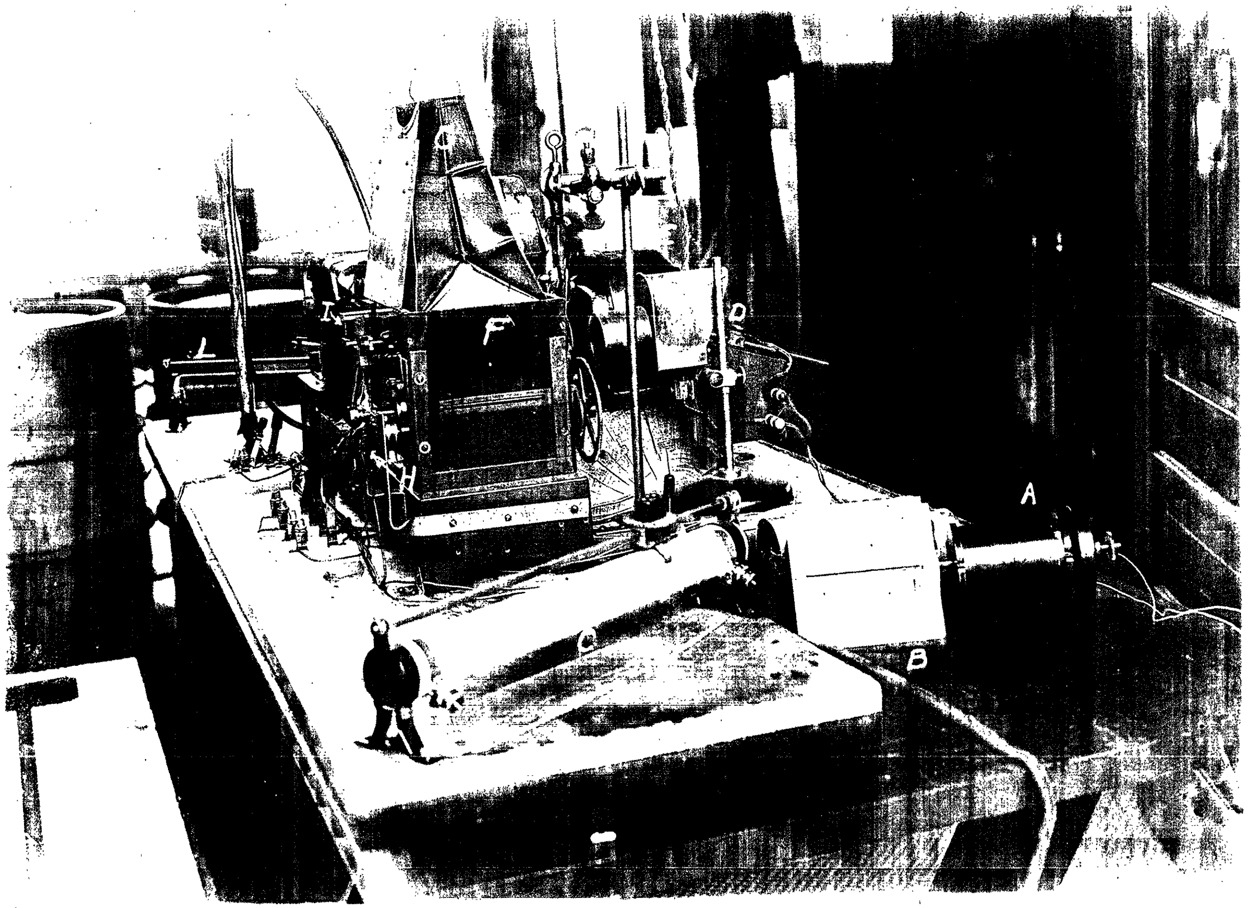


PLATE XXVIII

Oscillograph Assembly.

A. Film drum.

B. Film drum housing showing slide and shutter.

C. Rheostat for controlling arc.

D. Arc lamp.

E. Synchronous motor with disc shutter.

F. Back of viewing box showing grooves for film drum housing and shutter mechanism.

G. Viewing hood.

H. Shutter synchronizing unit.

I. Electromagnetic synchronizing trigger.

J. Controlling switches.

K. Cable for series spark gap.

L. High resistance for A. C. test circuit.

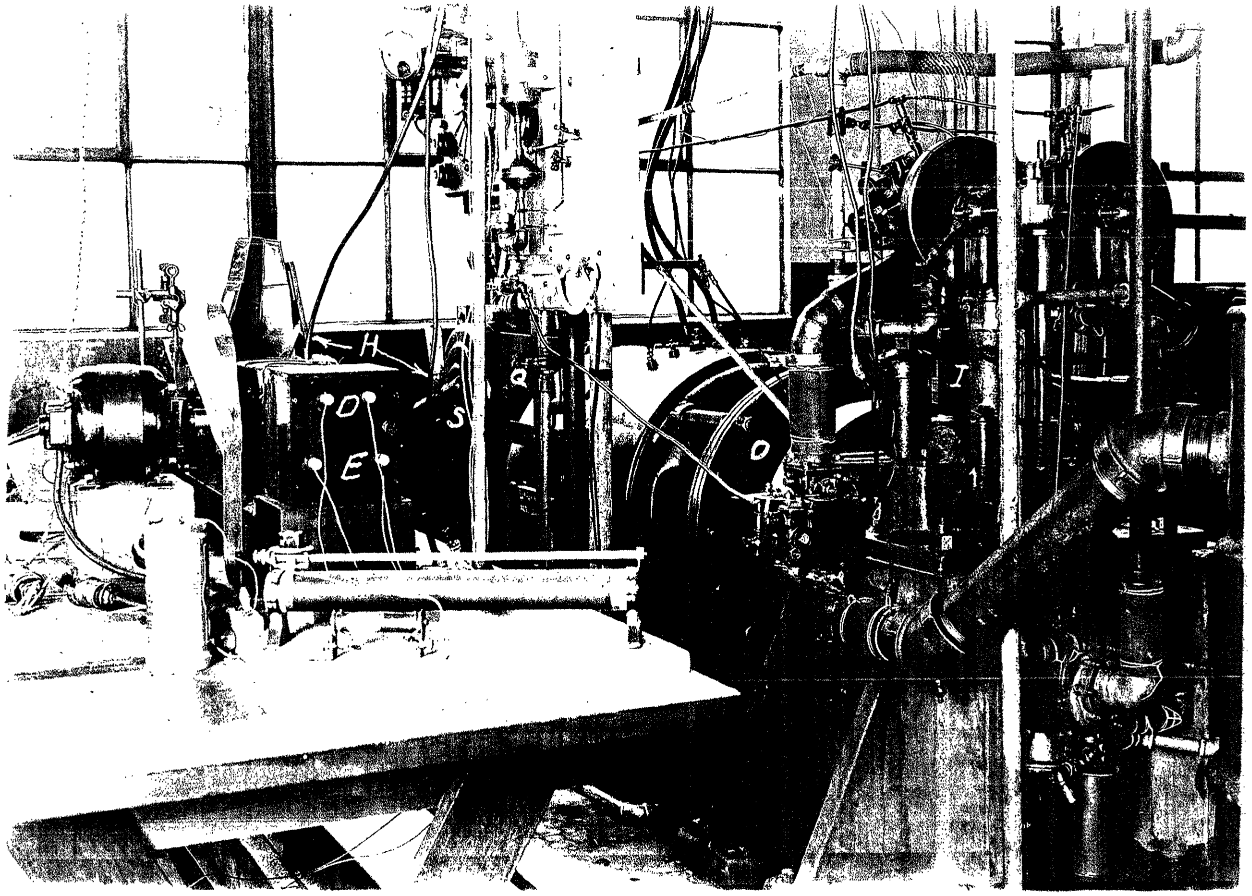


PLATE XXIX

General View of Apparatus.

A. High resistance for A.C. test circuit.

B. Dry cell supplying cement to sensitive unit.

C. Potentiometer.

D. Vibrator connections.

E. Vibrator field terminals.

F. Synchronous motor with shutter.

G. Guard for shutter.

H. Series spark gap connection.

I. N.A.C.A. Universal test engine.

J. Spark control.

K. Throttle.

L. Cooling water control.

M. Exhaust water valve.

N. Fuel meter.

O. Water Brake.

P. Dynometer unit.

Q. Water brake control valve.

R. Tachometer.

S. Dynamometer field rheostat.

T. Dynamometer control panel.

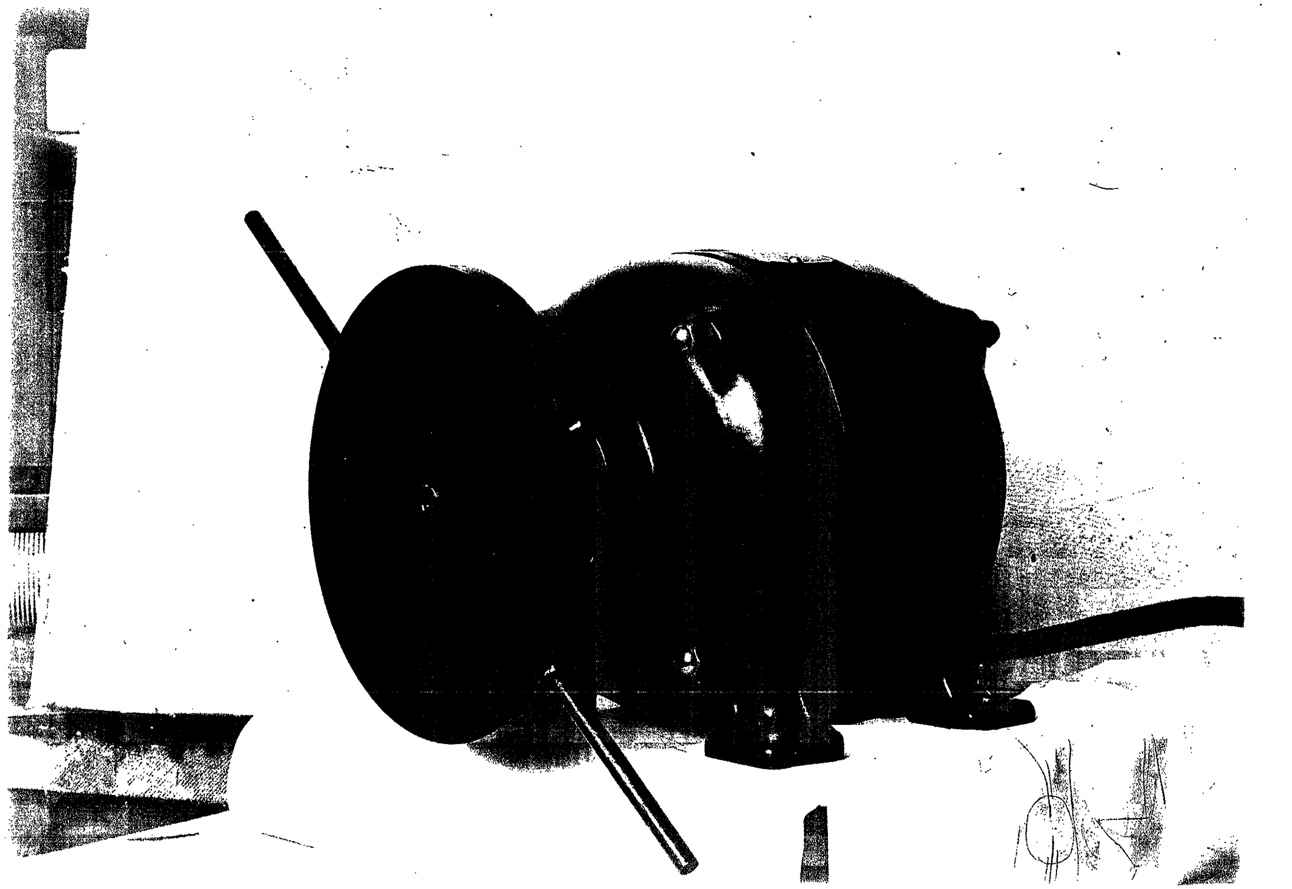


PLATE XXX

The plate above shows the details of the synchronous motor shutter unit.

XI. WORK ON THE SENSITIVE UNIT.

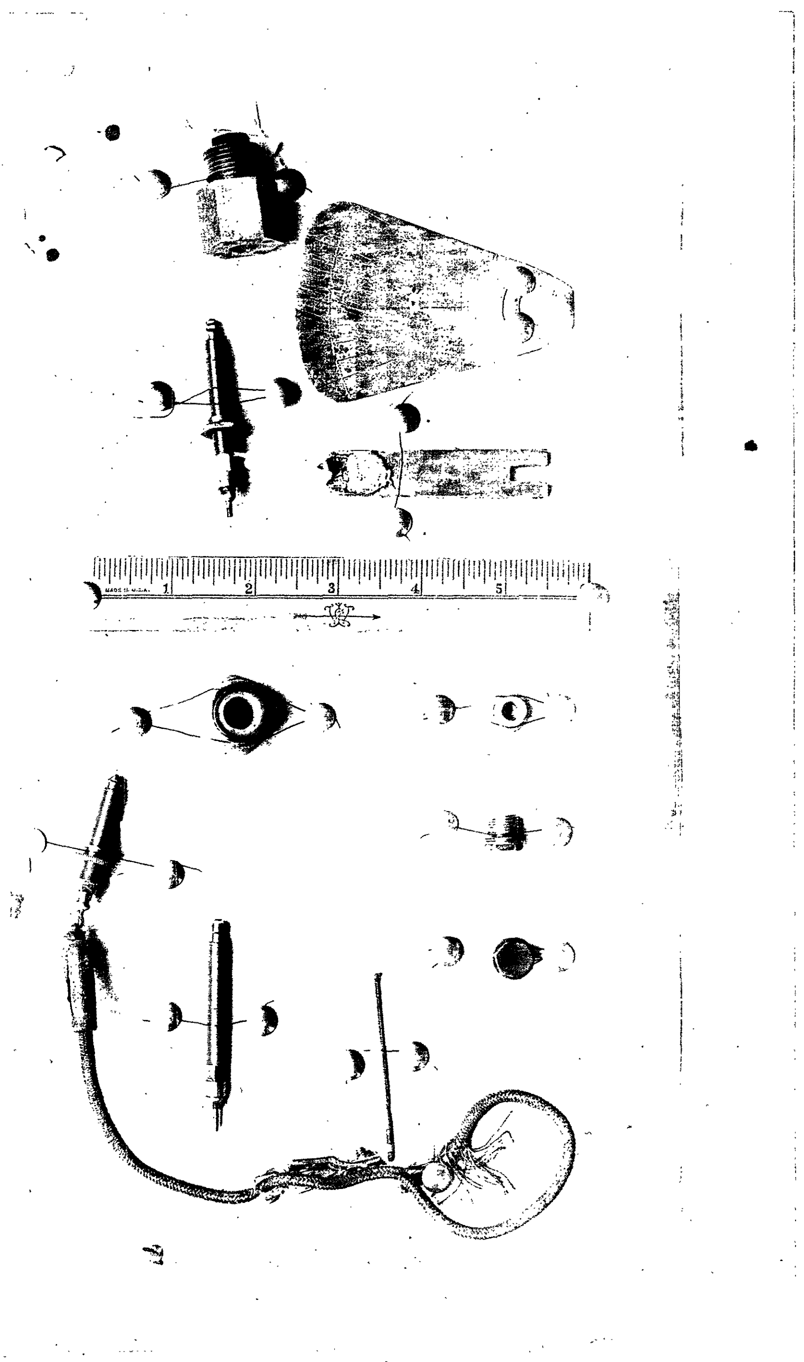


PLATE XXXI

The above photograph indicates the appearance of the parts of the sensitive units used in the experimental work.

A. Spark plug bushing with diaphragm in place.

B. Sheet metal plate with scale marked in degrees.

C. Wrench for adjusting unit carrying pointer for scale reading.

D. Plug carrying insulated contact.

   a. Insulated contact tipped with copper and slotted to give spring action.

   b. Quarter inch diameter plug threaded fifty threads per inch and drilled to take reduced diameter portion of insulated contact with mica insulation.

   c. Hexagon lock nut.

   d. Square portion of plug for taking wrench c.

   e. Nut for holding insulated contact firm in plug.

E. End view of spark plug bushing.

F. Insulated contact and plug used in preliminary experimental work.

G. Insulated contact and plug designed to give continuous pressure record.

H. Insulated contact element with flat face used for continuous recording unit experiments.

I. End view of diaphragm element showing hexagon.

J. Side view of diaphragm element.

K. End view of diaphragm element showing thread tapped fifty to the inch.

The diagram of connections used in the arrangement of apparatus is shown on the next page.

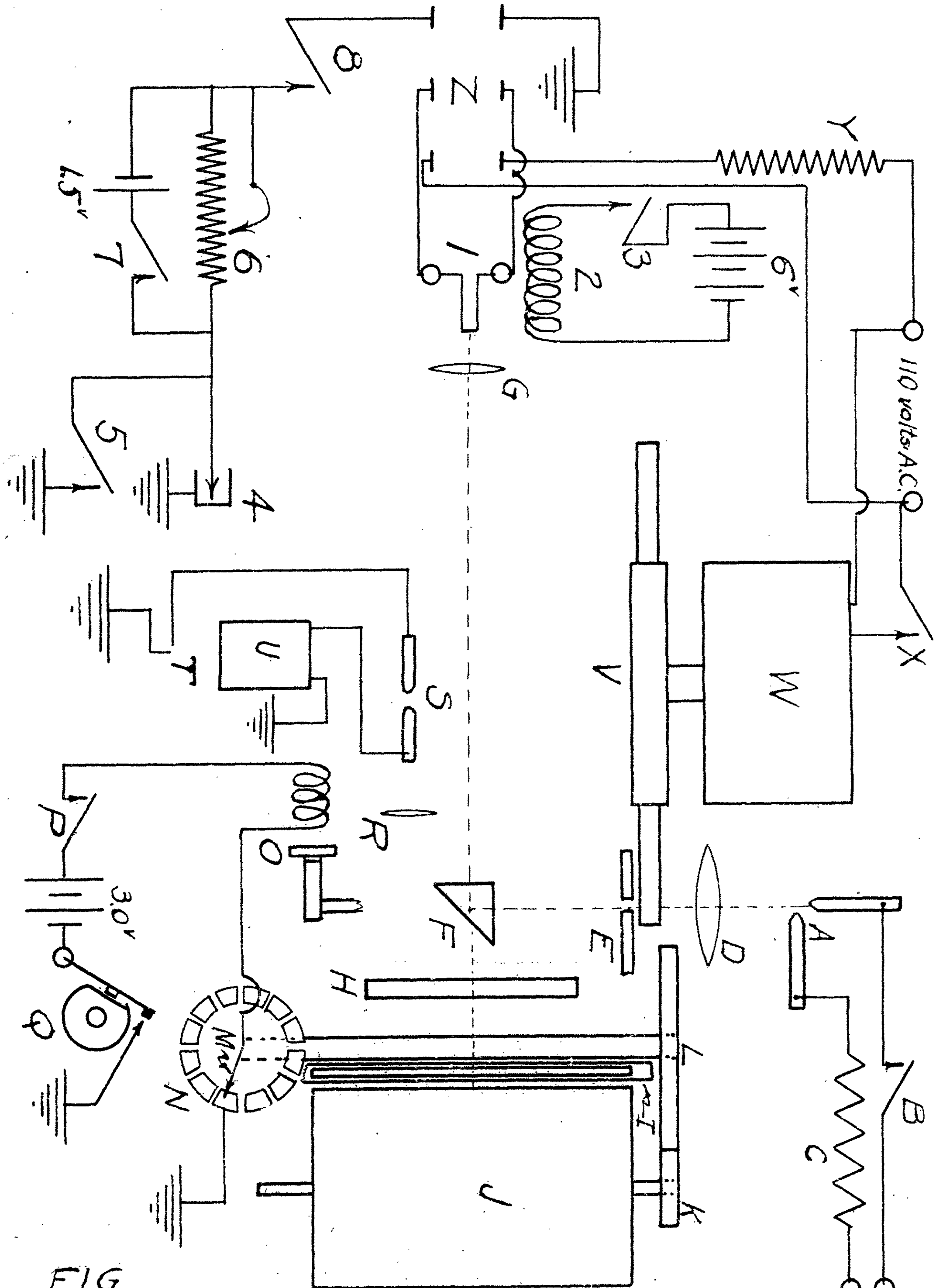


FIG.

DIAGRAM OF APPARATUS

A Carbon arc lamp

B Arc lamp switch

C Arc series resistance

D Condensing lens

E Slit

F Reflecting prism

G Oil bath lens

H Cylindrical lens

I Cylindrical slotted shutter

J Film drum

K Gear on film drum shaft

L Gear on shutter timing shaft

M Rotating synchronizing contact

N Stationary synchronizing contact segments

O Magnetic synchronizing trigger

P Trigger swith

Q Breaker mechanism on engine

R Lens to focus spark on film

S External spark gap

T Spark plug

U Ignition coil

V Timing shutter disc

W Synchronous motor

X Timing motor swith

Y Resistance of 5000 ohms

Z	Double pole, double throw switch
1	Oscillograph vibrator
2	Oscillograph field
3	Field switch
4	Sensitive unit in cylinder
5	Switch to short circuit unit for test purposes
6	Potentiometer of 400 ohms resistance
7	Potentiometer switch
8	Switch to close sensitive unit circuit

The plate below indicates the type of record which was consistently obtained with the apparatus in its final form.

The same diaphragm (0.013) inch in thickness was used for all the following records.

The engine operation conditions for the records are tabulated by number in appendix A.

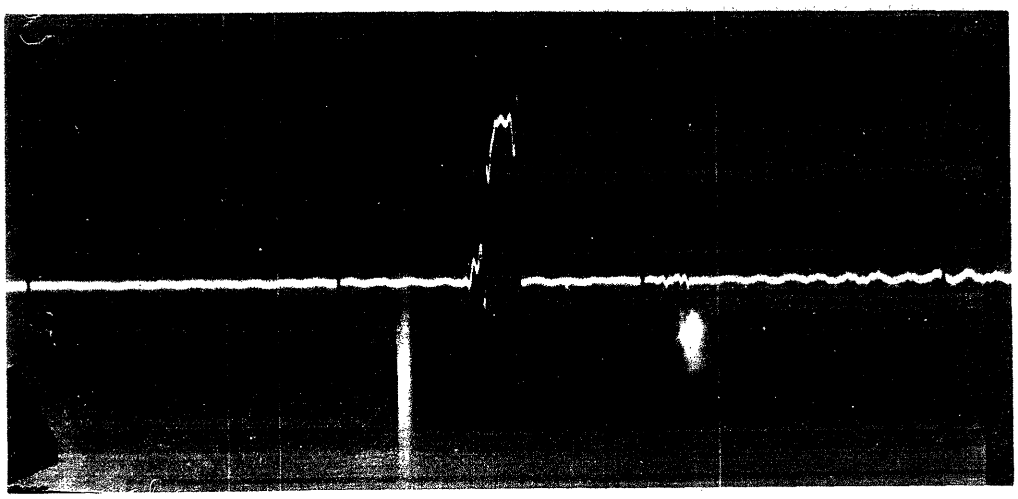


PLATE XXXII

Record......................3

Lag of contact after spark....0.0093 second

Contacts remain closed........0.0029 second

The record shows a number of interesting points.

The continuous white line on the dark background is the path traced by the spot of light from the oscillograph vibrator mirror.

The distinct black spaces in the vibrator record are due to the shutter on the synchronous motor.

The distance between the breaks in the white line represents the motion of the drum during one sixtieth part of a second.

Measurement of the distance between two of the breaks in the oscillograph line immediately establishes a time scale which may be used in estimating time intervals between events on the record.

In all cases the film was moving in such a direction that events to the right on the records as they are mounted, occurred before events to the left.

The white spot below the oscillograph record in the impression left by the light from the spark. It is interesting in this connection to note that in every case with one exception (Record 2c) a slight break in the oscillograph line occurred immediately over the middle intense line which passes thru the white spark record spot. This single exception occurred when the vibrator line was very unsteady for some reason and may or may not be of importance in considering the general effect.

The conclusion is obvious that the vibrator line break is due to a surge of current induced in the vibrator circuit by the spark discharge current in the ignition cable. In arrangement of apparatus, all wires running from the engine to the oscillograph were supported parallel to each other on a single upright so there was undoubtedly the possibility of interaction between the two circuits.

The writer is in some doubt as to the exact mechanism causing this break in the vibrator line. The current which flows might be due to an induced voltage which is sufficient to momentarily break down the resistance between contacts in the sensitive unit. On the other hand, the current surge might be due to a purely capacitative effect between the vibrator leads and the ignition cable.

Whatever the cause of the phenomenon may be, it seemed to exhibit enough consistency in the course of the work to be depended upon for recording the jump of the ignition spark without the necessity of using the auxiliary gap with its lens system.

The action of the sensitive unit in closing and opening its contacts is made clear by the break in the vibrator line near the middle of the record. The record shows that the vibrator was under-damped in its action since it "over-shot" both on the sudden make and the sudden complete break. This matter could probably have been remedied by changes in the viscosity of the damping oil and the tension on the oscillograph vibrator suspension, but on account of the limited time available for the work, no attempt was made to adjust the apparatus to the point of critical damping.

In summary, the record permits the following data to be determined:

(1) The time interval elapsing between the spark occurrence and closing of the sensitive unit contacts.

(2) The time interval over which the resistance between contacts is lower than for the open position.

(3) The period of any vibratory disturbance which might be introduced in the record by the action of the apparatus.

(a) Estimation of Diaphragm Deflections.

The procedure in determining diaphragm deflections was to note the range in degrees over which the adjusting wrench had to be moved to change the oscillograph indication from continuous contact to no contact.

This procedure was carried out for full throttle and reduced throttle normal operation and for detonation at full throttle.

The results of these tests are summarized in the following table:

Diaphragm Thickness .013 inch.

Throttle	Detonation	Range of Motion	
		Degrees motion of Wrench.	Linear motion of contact(inches)
Full	None	6	0.00033
Full	Heavy	6	0.00033
Half	None	5	0.00028

TABLE A

For detonation at full throttle no indication appeared on the oscillograph vibrator until after the contact plug had been turned about one degree past the position at which deflections appeared for full throttle normal operation. For the case of detonation, the vibrator indicated disturbances of the sensitive unit contact until after the plug of the sensitive unit had been turned about one degree past the position giving constant contact for both cases of normal operation.

The tests as outlined above are obviously very rough. The aim was to estimate approximately the magnitude of the deflection to be dealt with in the design of continuously recording units.

The data tends to show that the maximum effective amplitude of diaphragm motion is somewhat less for detonation than for normal operation. On the other hand there is apparently some action which tends to displace the diaphragm away from its equillibrium position toward the inside of the cylinder. This action is probably connected with the effects of heavy pressure waves within the cylinder. The vibrations communicated to the diaphragm by the waves might tend to cause an unsteadiness in the contact of the diaphragm with the insulated plug.

Further work is necessary to verify the effect and to study its exact nature before conclusions of any value may be reached.

(b) Inquiry Into The Cause of Vibration Shown By Detonation Records.

The preliminary work indicated tentatively that the vibratory record characteristic of detonating operation was not greatly affected by an increase of three times in diaphragm thickness. This fact tends to suggest that the vibration shown by the records is not a characteristic frequency of the diaphragm element of the sensitive unit.

In order to test out the effect of the heavy spring holding the insulated contact, an entirely new plug and contact was made up. In this second unit, care was taken to alter the distance apart of the spring slots. In both the first and the second units, the slots for the spring were made by hand with a hack saw, so that the possibility that the spring in both units would have the same period was very remote.

The oscillograph vibrator was entirely different for the two cases. The suspension of the vibrator used in the latter part of the work was drawn as tight as possible without danger of breakage. On the whole it seems highly improbable that the free periods of the Siemens-Halske and the M. I. T. oscillographs should be the same.

A number of detonation records were taken with the new arrangement.

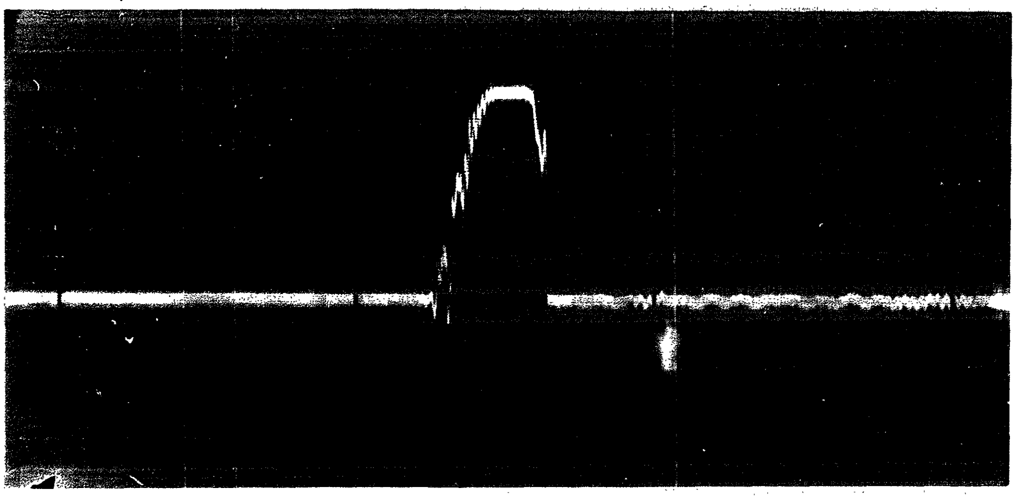


PLATE XXXIII

Record...................3b

Lag of contact after spark-0.0067 second

Contacts remain closed.....0.0064 second

Vibration frequency- 3,900 vds per second

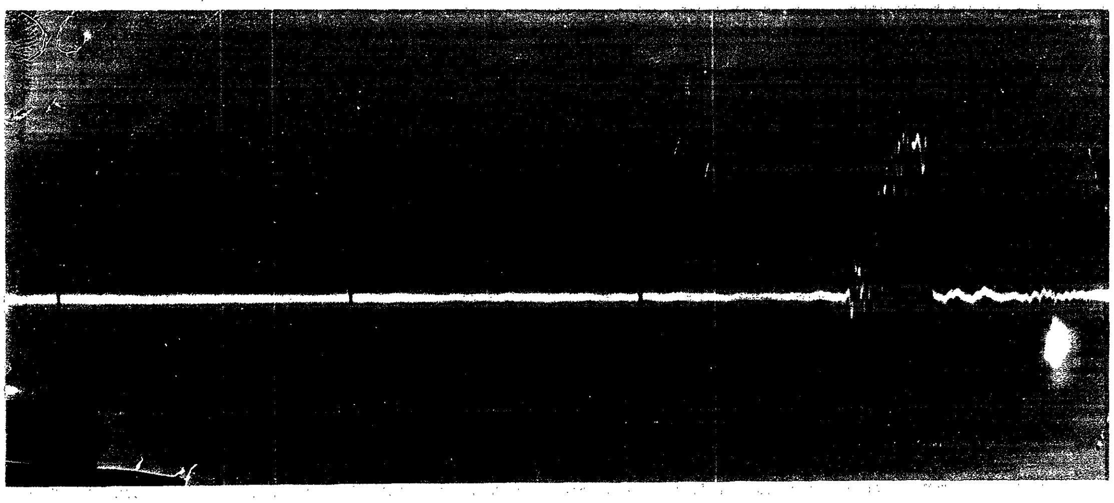


PLATE XXXIV

Record...................2c

Lag of contacts after spark-0.0069 second

Contacts remain closed......0.0064 second

Vibration frequency-3,800 vds per second

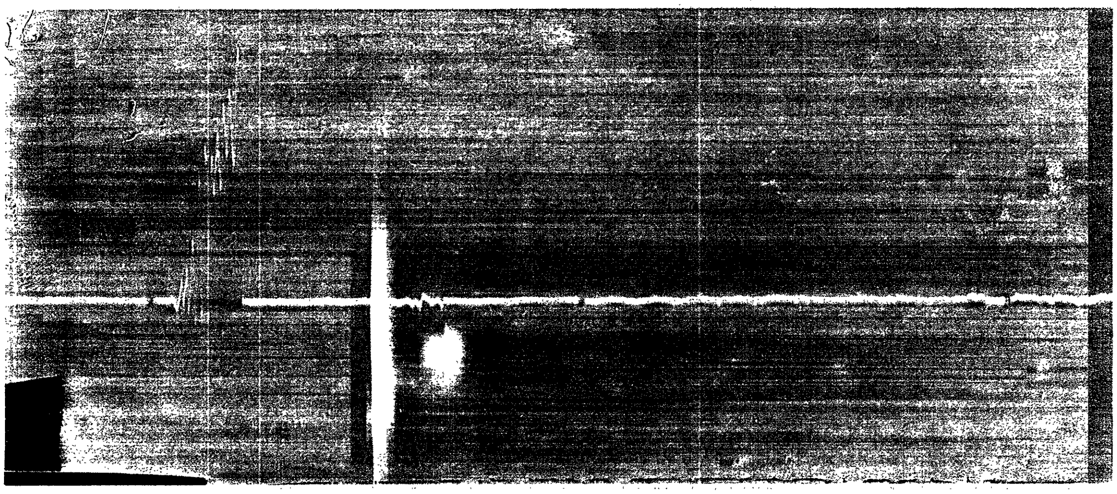


PLATE XXXV

Record...............2d

Lag of contact after spark......0.008 second

Contacts remain closed..........0.0026 second

Vibration frequency......4000 vds per second

For the last two plates the engine was operating under conditions of heavy detonation induced by using a compression ratio of 5.5 with gasoline having 5 cc. of lead tetraethyl per gallon.

The contact in the sensitive unit was adjusted to a somewhat wider gap for Plate XXXV than for Plate XXXIV.

In making these detonation records, an effort was made to turn the drum by hand at the highest practical speed. It was found that certain difficulties were experienced with the shutter and its timing devices at higher speeds. For a given angle of lead on the synchronizing contact segments, the proper operation seemed to be dependent upon keeping the speed of the hand crank within a rather small range. Since the apparatus included no means for checking the drum speed, a rather large percentage of films having no record of the action occurred in taking the detonation records.

As the engine was operating at a constant speed, the drum speed might have been checked by using as the crank speed that necessary to hold the record still in the visual inspection field (i.e. when the rotating mirror was turning at a speed which brought a face of the mirror always in the same position when the contacts were closed in the sensitive unit). It was found that the first of these synchronous speeds did not spread the record out enough while the next higher was too fast for satisfactory shutter operation. A speed below this synchronous speed was hard to duplicate without more skill than was developed in the time available. For this reason, the number of successful high speed detonation records was limited.

The three detonation records exhibited above are in fair agreement that the characteristic frequency exhibited by detonation records is in the range between 3,800 and 4,000 cycles per second. It is to be noted that this range of frequency is about the same shown by detonation records in the preliminary work.

The following table summarizes the data on detonation vibration frequency as collected from all the records taken in the work.

All Records Tabulated Below Were Taken Under Conditions of Detonation.

Record or Plate.	Oscillograph.	Diaphragm Thickness In Inches.	Vibration Frequency Shown by Record.
XX	Siemens-Halske	0.009	3900
XXI		0.009	4000
XXV		0.009	3900
XXVI		0.029	3600
XXVII		0.009	4000
XXXIII	M. I. T. Single Vibrator.	0.013	3900
XXXIV		0.013	3800
XXXV		0.013	4000
XXXVIII		0.013	3700

TABLE B

Summary of Data on Frequency Exhibited by Records Taken During Detonation.

The natural free period of the oscillograph unit would obviously be an important point to consider in connection with this matter of vibration in detonation records.

Inspection of the oscillograph records both in the preliminary and final phases of the work showed that on a sudden break or make in the electrical circuit, the vibrator unit tended to over run the equillibrium position and returned to its normal place only after two or three rapidly damped vibrations.

When these damped vibrations are in process of execution, the vibrator is apparently acting under the influence of its own inertia alone. For this reason, it is very probable that the period of these damped vibrations corresponds closely to the natural period of the oscillograph vibrator.

With the fact mentioned above in mind, the period of these damped vibrations was roughly determined for those records in which this was possible. The table below summarizes the results of this procedure.

PLATE	OSCILLOGRAPH	FREQUENCY OF DAMPED VIBRATION CYCLES PER SECOND
XXIV		3,100
XXV	Siemans-Halske	3,100
XXVII		3,200
XLI	M. I. T.	2,400
XLII	Single Vibrator	2,400
XLIII		2,000

TABLE C

The results as recorded in this table seem to indicate that the free vibration frequency of the Siemans-Halske instrument was about 3,100 cycles per second, while the free period of the single vibrator instrument used in the later work was near 2,300 cycles per second.

In any case, these results show that the increased tension used with the M. I. T. vibrator was not effective in increasing its frequency beyond that of the Siemans-Halske instrument.

Considerations of the results from detonation records as summarized in Table A, shows that with one exception of a low frequency of 3,600 found with the diaphragm 0.029 inch thick, the results in the frequency column might well be within the range of experimental error if the active cause of vibration in the records were a heavy pressure wave within the cylinder of about 3,900 cycles per second.

It is to be regretted that no other records were taken with the thick diaphragm, however, the change of 0.004 inch in the thickness of a 0.009 inch diaphragm represents a thickness variation of over 30%. If the diaphragm itself were the essential element in conditioning the recorded frequency, it would seem reasonable that such a relatively great alteration in thickness should show up strongly on the records. No such effect is apparent, so it may be concluded that the diaphragm is not the element governing the observed vibration in detonation records.

As concerns the spring holding the insulated contact, Plate XXXI shows photographically the different types of elements which were used in taking the records. No exact measurement will be given, but comparison of the contact tips of parts D and F on the photograph, shows plainly that a considerable difference existed between the slotted spring of the contact used in taking the preliminary and final records. Part F is the contact plug used for the preliminary records, while part D is the plug used in the final runs.

Since the use of distinctly different contact springs did not alter the observed frequency, it may be concluded that the detonation frequency is not a function of the spring behind the contact tip.

The remaining element in the circuit of the sensitive unit which might be responsible for the vibratory character of detonation records is the oscillograph vibrator. Table C indicates that the vibrator used in the preliminary work, probably had a natural frequency around 3,100 cycles per second, while the instrument used in the later runs appeared to have a natural period corresponding to about 2,300 cycles per second.

Even though the method used in estimation of these frequencies may give no more than a very rough estimate of the actual period it is desired to determine, it seems reasonable to conclude that the natural periods of the two oscillographs used in the experimental work were distinctly different. In both cases also, the natural frequency of the vibrator element seems to have been markedly less than the frequency shown in the detonation records.

Change of the oscillograph vibrator did not appreciably change the recorded frequency as recorded, so that the responsibility for the detonation frequency can not be laid to the vibrator element.

The one remaining explanation of the observed vibration for detonation records, is that the diaphragm was actually moving in forced vibrations due to a series of strong pressure waves in the cylinder gases which appeared only during detonation. The frequency of this wave appears to be in the neighborhood of 3,900 cycles per second.

As an interesting point in this connection, detonation for the preliminary work was induced by spark advance at full throttle, using straight gasoline with a compression ratio of 5.3 : 1. Plate XXXII of the final runs was made with a compression ratio of 4.5 using straight gasoline, while the three remaining runs were made with ethyl gasoline using a compression ratio of 5.5. The data tabulated in Table B shows that the observed frequency is independent of the way in which detonation is induced as far as the present records extend.

It would make a very interesting addition to data on this subject if records could be taken using different test engines in order to determine whether or not the observed frequency is a function of the particular engine.

This matter of the connection between detonation and the vibratory oscillograph records will be considered further in a future report on the subject.

(c) Calibration of Sensitive Unit.

No experimental work was actually carried out in regard to cylinder pressures existing at the instant of contact in the sensitive unit.

It would be very desirable to carry out any calibration under actual cylinder conditions. If a stage in development of the sensitive unit should be reached where calibration becomes desirable, it is proposed to use the "balanced pressure" type of engine indicator as developed by the Bureau of Standards as the standard for calibration.

Data from the "balanced pressure" instrument could be used to plot cylinder pressures over the range in which the sensitive unit starts to operate. This plot would show cylinder pressures existing at different points in the cycle. The instant of spark would be marked on the oscillograph record with a time scale. The instant of spark occurrence is also known for the engine from the spark advance setting. These data would permit correlation of oscillograph deflections with cylinder pressures.

In work such as that suggested above, it would of course, be necessary to take a number of oscillograph records and establish an "average record" before the pressure calibration would be of any very great value.

(e) Work on an Element with Resistance inversely proportional to Diaphragm Deflection.

The conditions which must be fulfilled in order that a sensitive unit might give a line record with displacement proportional to diaphragm deflections, have already been discussed. The next step in order is to consider methods by means of which the theoretical apparatus might be realized practically.

If some type of element could be developed whose resistance between contacts would be inversely proportional to the pressure to which it is subjected, the problem might be solved. In addition to its resistance characteristic, the element would have to be able to withstand operating temperatures and shocks in addition to being of such a size that it might satisfactorily fit into the small space available in the sensitive unit.

The preliminary work indicated that after a thin diaphragm had been used in the engine long enough to acquire a fairly heavy oxide film, the records in certain cases showed a gradual growth and decay of the current. Certain other records showed a very clean and rapid break in the vibrator line due to the action of the sensitive unit. This latter observation proved that the gradual changes of current in the circuit could not have been due to reactance effects in the circuit itself. The only other explanation seemed to be that the oxide film itself possessed an insulating power depending upon the pressure to which it was subjected.

This suggestion of an oxide film as a variable pressure element, was the basis for a rough investigation of the resistance properties of metallic oxide and sulfide films.

Small pieces of sheet stock of various metals were obtained from the chemical supply room. The metals were copper, iron, zinc, aluminum and nickel.

Small discs were made up from each of the metals. Two discs of each metal were oxidized by heating for some time in the oxidizing flame of blast lamp. In a similar manner two discs of each metal were given a coating of sulfide by heating in a mass of burning sulfur.

The resistance characteristic of each coating for each metal was tested out separately. One of the pair of discs to be tested was laid on a flat steel block with the other disc of the pair placed on top.

One side of a series circuit containing a single dry cell and a milliammeter, was connected to the steel block. The other side of the circuit was connected to a steel rod surfaced on one end. The surfaced end of the rod was used to subject the discs to pressure by hand. The action of the milliammeter was noted as pressure was gradually applied and released.

These preliminary tests indicated that a number of the discs showed a decided increase in resistance due to the chemical coating. Likewise, there seemed to be a slight resistance change due to pressure variation in most of the cases. The resistance effect was most pronounced for the cases of iron sulfide and copper oxide. Of these two, the copper oxide coating appeared to give the best action. For this reason later work was confined to this type of element.

The next step in the work was to make up a unit containing copper oxide discs and actually test its action under engine conditions. This unit contained a stack of seven copper oxide discs insulated at the sides by a cylinder of mica. One end of the stack of discs laid directly on the inside of the diaphragm surface, while the other end of the stack was directly against the surfaced end of a short rod serving as the insulated contact.

It was found that the resistance of this first unit was so high that engine operation conditioned no detectible change in resistance.

The obvious thing to do was to reduce the number of oxide coatings in series. The next unit consisted of a single oxide coated copper disc between the diaphragm and a solid insulated rod contact with surfaced end.

This second type of element was tried out in the engine and found to be an improvement on the larger number of discs, but the results were quite erratic. The disc was made by hand and fitted inside a cylinder of mica also fashioned by hand. The work was hurriedly done and quite rough so the disc fitted somewhat loosely in the unit. It was found in order that the disc might be held firmly in its place in the unit, so great a pressure had to be used that the readings were unsatisfactory.

The principal difficulty with the single disc type of element seemed to be in its tendency to give erratic results with light pressures from the insulated contact. With this in mind a third type of element was made up.

The modification introduced in this unit was in the insulated contact itself. The contact was made with a slotted spring in a manner similar to the unit used in the preliminary work. The steel spring was tipped with a thin layer of copper held in place by a small screw thread and made firm with silver solder. The contact surface of the copper was carefully squared off on a razor hone. This smooth surface was coated with oxide in the blast lamp flame.

A record taken with the unit is shown below.

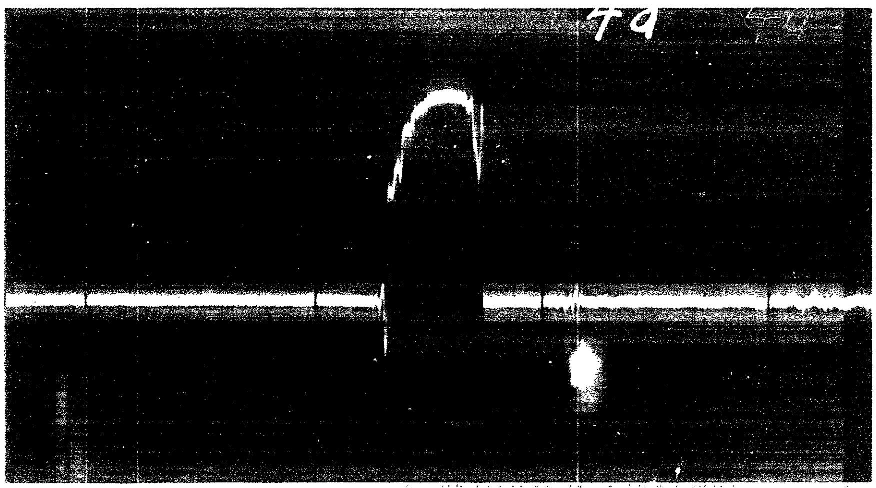


Plate XXXVI

Record....................4 d

Lag of contact after spark....0.0074 second

Contacts remain closed........0.0070 second

This record, taken with the engine operating under conditions of slight detonation, shows that as far as the make or break of the contact is concerned, the use of copper oxide has no effect on the first or last parts of the record. However, the upper portion of the record, although somewhat unsteady, takes on a form which might well be fairly close to the form of the peak of the cylinder pressure. The range of pressure over which the desired action occurs is small but the record seemed to offer a certain amount of encouragement.

Inspection of the contact point and diaphragm after dismantling the unit, showed that the copper oxide film was almost completely worn away over the area which was concerned in the actual contact.

Considering the results of the last experiment, two points seemed to present themselves:

(1) The oxide film should be protected from abrasion by rubbing.

(2) The pressure on the resistance film should be adjusted to a value such that the film is kept under the influence of diaphragm displacements throughout the duration of cylinder pressures which it might be desirable to examine, i.e. the sensitive film should be constantly under a greater or less pressure from the diaphragm without the circuit being entirely broken at any time.

A fourth modification of the unit was constructed. In this case the end of the slotted spring contact was turned out in the shape of a shallow cup with straight sides and a carefully made flat bottom. The slotted spring was more carefully made than in previous instances, the slots being cut on a milling machine with a cutter one sixty fourth of an inch in thickness. The distance between slots was made less than for previous units and the cuts were made somewhat deeper, the aim being to obtain a more flexible spring to carry the force exerted by the diaphragm on the oxide film. The material of the spring was drill rod properly tempered in oil.

In assembling the unit,a thin piece of sheet copper was oxidized on both sides and placed flat on the bottom of the cup in the end of the spring. A cylinder of mica was placed around the sides of the cup and a small copper plug with slightly tapered ends was fitted snugly into the mica. This tapered plug of copper served as the actual contact element between the insulated slotted spring and the diaphragm. It was hoped that the spring would be sufficiently flexible to permit the copper plug to be kept always in contact with the diaphragm, while pressures on the oxide film would be kept within the proper range by the stiffness of the spring.

Due to the short time available for this phase of the work, but one record was taken with this unit. The record is shown below.

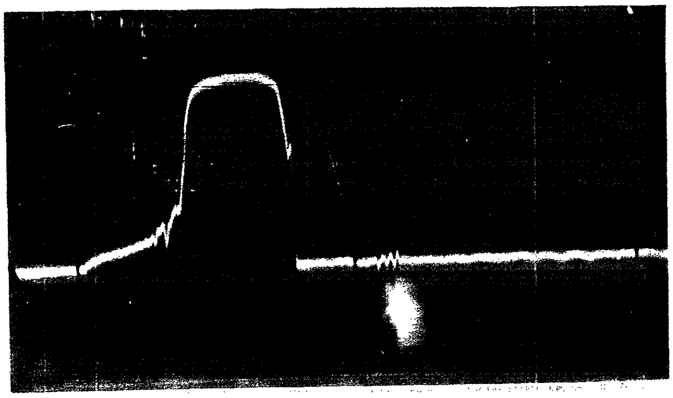


Plate XXXVII

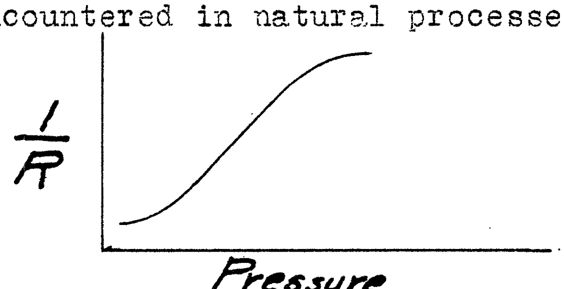
Record.................... R

Lag of contact after spark.....0.0060 second

Contacts closed for...........0.014 second

At 1000 R.P.M. one stroke of the engine requires 0.030 second for its completion. It follows that the unit used for the record above was at some resistance lower than its normal value for a time corresponding to about half of the power stroke. The plate also shows that the record begins to take on the rough outlines of a portion of the indicator card. The flat top of the record probably means that for the higher pressures inside the cylinder, the pressure on the oxide film reached a point where its resistance became very low and showed but little further change with varying pressures. The results seem to indicate that progress was being made toward the desired goal of an apparatus which would give displacements of the oscillograph spot following cylinder pressures more or less closely. At this point the work was cut short by the lack of further time.

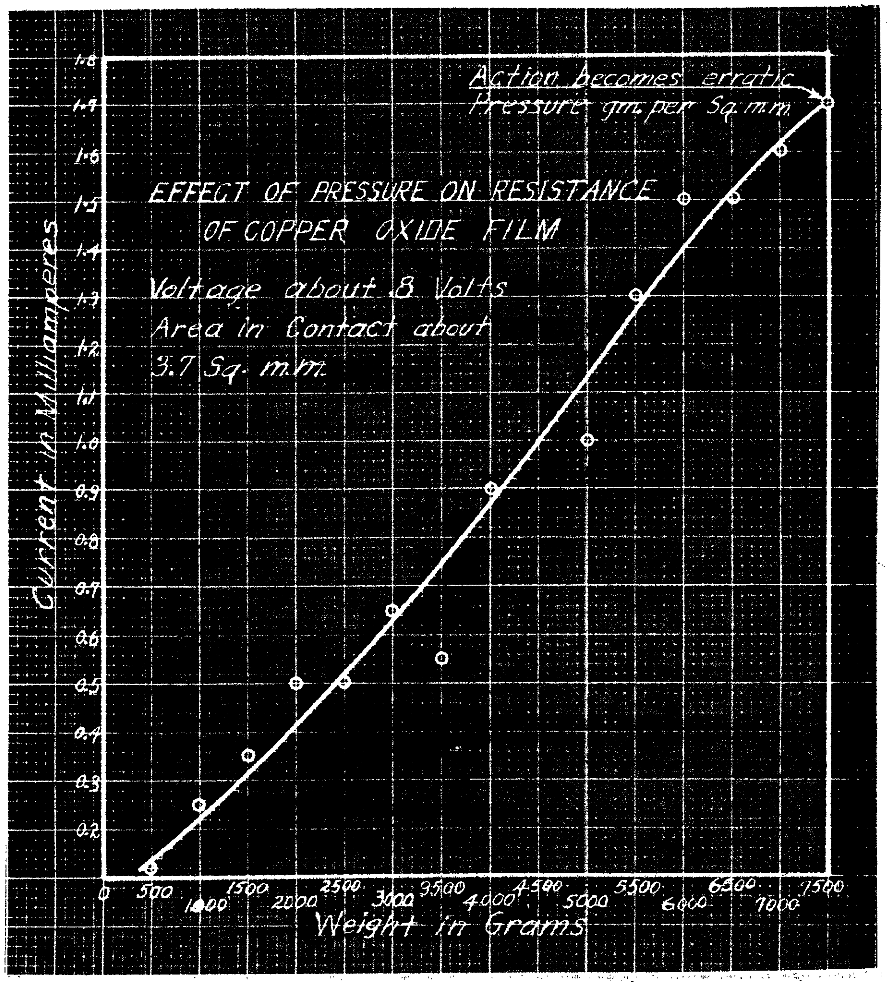
Considering the problem of the resistance element in general, it is probable that any resistance element of the type desired, would present a response curve of a type often encountered in natural processes.



The curve indicates that for very low pressures, there is a range in which changes in pressure condition very small changes in resistance. For an intermediate range of pressures, the change in resistance is closely proportional to pressure changes, while for very high pressures, the film would change its resistance very little with pressure and would probably break down entirely.

With the idea of testing this hypothesis, an apparatus was made up by means of which known weights could be applied to a known area of oxide film. This apparatus as constructed was of a very crude nature.

The following plot is enclosed to illustrate the type of data which it was intended to obtain by this method.



The curve is not plotted in specific units as the writer is too uncertain of the numerical validity of the results to submit any definite conclusions on that phase of the matter.

The experimental data is quite erratic. A large part of this variation is probably due to imperfections

in the apparatus thru which the angle of application of the force varied slightly from time to time. This action made the actual area of oxide rather uncertain in addition to introduce a more or less serious abrading action. In estimating the area to be noted in connection with the curve, the irregular spot on the face of the resistance disc, which showed the glaze due to pressure, was taken as the actual area of contact rather than the total area of the end of the contact rod itself.
In addition to the uncertainty of contact area, there was a binding effect on the shaft carrying the weights which undoubtedly introduced uncertainties in the force applied to the film area.

Despite the imperfections in the apparatus, the curve shows that the increase of current for pressure increase is fairly uniform up to a pressure of about 2 Kg. per square millimeter. At pressures exceeding this value, the film seemed to lose its insulating power almost completely. It was noted also that a film which had once been subjected to a high pressure took on a glazed appearance and either attained a constant high resistance or broke down entirely.

The tentative conclusion to be drawn from this very rough experimental work is that a copper oxide film appears to change its resistance with pressure in a more or less linear manner up to a pressure somewhat below 2 Kg. per square millimeter. Pressures in excess of this value apparently cause the film to become erratic as regards resistance.

It was found experimentally that the extent to which the oxidation process was carried influenced the nature of the results. The oxide film did not become very effective as a resistance until it had reached a fairly dark brown color. A dark brown film formed by moderate oxidation appeared to give best results. If the oxidation was carried too far, the film tended to scale off badly and become useless.

Another factor which seemed to enter into the problem was the nature of the copper surface before oxidation was carried out. A smooth surface apparently did not work as satisfactorily as a roughened surface. It may well be that some systematic roughening up of the surface before oxidation would improve the action of the element.

So many variables are involved in the problem that no satisfactory final conclusion can be attempted at this time. Apparently the best summary that may be expressed here, is that up to the present the copper oxide coating seems to offer some promise of supplying the desired type of resistance element and has not as yet been definitely proven to be impractical for this purpose.

(f) Variation of Diaphragm Deflection with Pressure.

One of the experimental problems worked out above was the approximate magnitude of diaphragm deflections under the worst conditions of operation. It was found that for full throttle operation, the maximum amplitude of diaphragm deflections was something under 0.00035 inch, using a diaphragm 0.013 inch in thickness.

The diameter of the diaphragm was approximately .250 inch. This means that maximum diaphragm deflection was something less than $\frac{1}{700}$ part of the diaphragm diameter.

The question to be answered in this connection was whether or not the deflections of a steel diaphragm are proportional to pressures exerted on the diaphragm if the maximum deflection is $\frac{1}{700}$ of the diameter.

Professor Barss of the Physics Department was kind enough to consider the matter. He advanced the tentative conclusion that for such a range of deflection, it is probable that deflections would be closely proportional to pressures on the diaphragm.

Professor A.E.Kennelly[45] in his book on "Electrical Vibration Instruments" cites some curves plotted from experimental work on telephone diaphragms.

These curves show that for this case, deflections are closely proportional to distorting forces up to a deflection equal to about $\frac{1}{600}$ of the diaphragm diameter.

The matter cannot be considered as definitely settled, but the tentative conclusion seems justified that deflections in a diaphragm 0.013 thick of o.25 inch diameter should be closely proportional to pressures exerted on the diaphragm over the range of pressures encountered in carburetor engine operation.

For practical purposes, the natural free period of the diaphragm used in the present type of work should be greatly different from any frequency which it might be desired to measure. This particular part of the problem has been given no direct attention either experimentally or analytically. It seems quite probable that a steel diaphragm of the dimensions used in the experimental work should have a very high natural period.

As regards both the law of deflection and the natural free period, it is obvious that both are under control within rather wide limits by variation of diaphragm thicknesses.

The matter of diaphragm action will be taken up more at length analytically and practically in the continuation of the general problem.

(g) Procedure in Construction of a Sensitive Unit Whose Resistance Would Vary Directly With Cylinder Pressure.

The problems to be solved in the development of a satisfactory pressure recording device have already been considered individually. There remains only the necessity of working out the method of fitting these various parts together into a practical unit.

If the variable resistance element of the unit may be made to work satisfactorily with a range of deflections up to 0.0004 inch, it seems probable that the diaphragm element of the unit in its present form will be satisfactory.

The copper oxide type of variable resistance element is not suitable in the stage of development to which it was carried in the present work. However, if the copper oxide or some other type of resistance element could be developed, the general problem would be greatly simplified.

Assuming that a resistance element may be brought to a form where a plot of the reciprocal of its resistance variation with applied pressures gives a straight line relation, the next step of the development is clear. The range of pressures over which the resistance plot maintains the straight line relation would be determined by experiment.

A spring of some form would be designed to face against one surface of the resistance element, the other side of the element facing against a small plug which in turn made contact with the sensitive diaphragm.

The effective area of the resistance element might be controlled by adjusting the contact surface of the small plug to the desired size. Knowing this area and having the empirical curve plotted as indicated above, the range of force on the resistance film for satisfactory operation could be selected.

With the range of forces to be exerted by the contact spring at hand, the contact spring could be designed to cover that range of force during a deflection of the contact end over a distance of 0.0004 inch.

A unit designed as indicated above should give a satisfactory law of resistance change with cylinder pressures. There would remain the problem of making the arrangement rugged enough to withstand operating conditions but it is probable that this feature of the problem would give little trouble on account of the small size of the parts involved.

A point to be kept in mind in considerations of this sort is that a contact plug which is kept under an initial compression in contact with the diaphragm might so alter the period of the diaphragm that the primary purpose of recording rapid pressure fluctuations would be defeated.

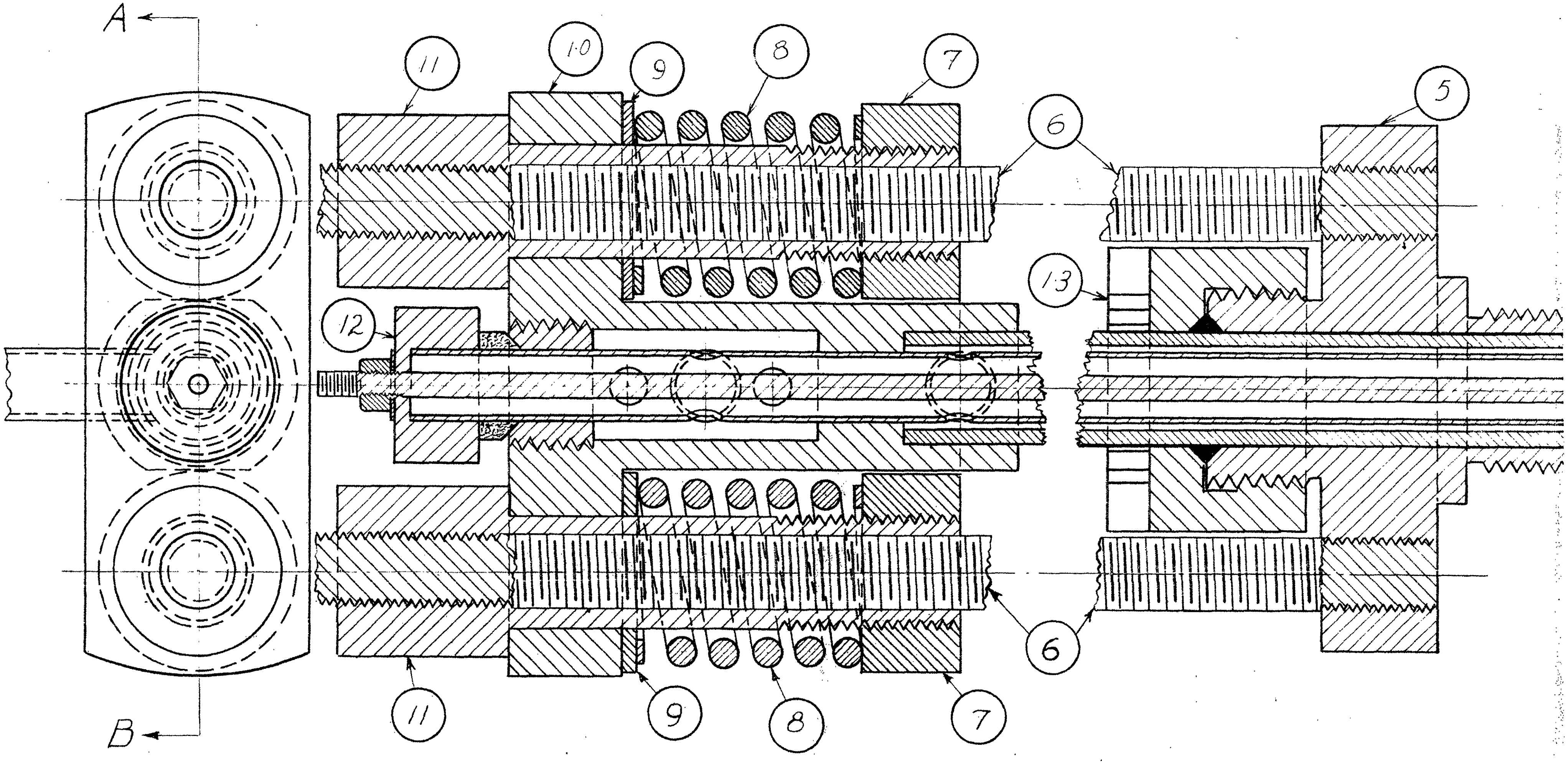
This is obviously a long way to go from the sensitive units used in the present work to a unit possessing the ideal characteristics, however, the writer feels that with the aid of good fortune a satisfactory unit might be developed.

III. Device for Holding the Sensitive Unit at Different Positions Inside the Engine Cylinder.

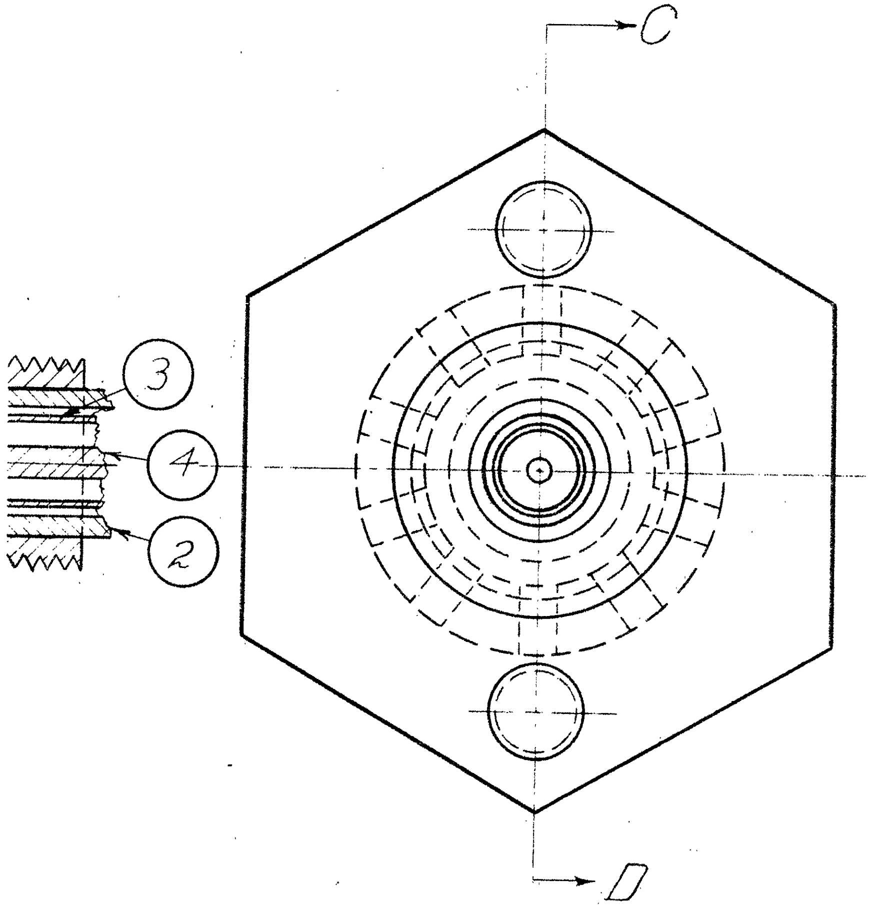
In the design of the element for inserting the sensitive unit into the cylinder volume, the writer is greatly indebted to Professor C. F. Taylor for suggestions and criticisms. Valuable aid was also given by Mr. E. S. Taylor in the form of practical suggestions.

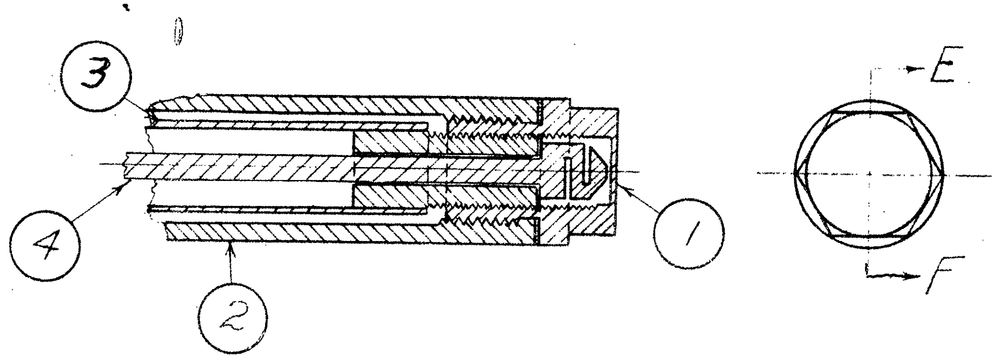
An assembly drawing of the insertion unit is enclosed in the form of the following blue print.
A number of minor changes were introduced in the arrangement as finally constructed but the general form of the device is indicated in the drawing.

The sensitive unit is carried on the end of the tube (2) which fits thru the bushing (5). The bushing is designed to be screwed into a metric size spark plug hole. The lead screws (6) serve to hold the unit in any desired position along its path of travel. Inside the tube (2) is the tube (3) which carries a supply of cooling water to the end of the larger tube and serves also as a means of adjusting the sensitive unit. The rod (4) insulated with special insulating varnish, furnishes the electrical connection to the insulated contact in the sensitive unit.



Section "A-B"   Section "C-D"





Section E-F

Scale - 2" = 1"

The assembly shown at (7), (8), (9), (10) and (11) showes the arrangement employed for holding the tubes and supplying cooling water.

Cooling water is supplied to the annular space surrounding the smaller tube near the outer end of the part (10). Water is retained in the annular space on one side by a snug fitting bushing fitted with a rubber band and on the other side by the shoulder holding the larger outer tube (2).

In operation, water flows from the large annular space in (10) thru holes into the passage between the tube (3) and the rod (4). The water leaves the inner tube thru a number of small holes near the sensitive unit and enters the annular passage between tubes (2) and (3). By this arrangement a continual supply of cold water is forced along the inside of the outer tube (2) which is in external contact with the hot cylinder gases. An exit for the cooling water is supplied in the piece (10) near the shoulder holding the tube (2).

A set of detail drawings was made up by the writer and the unit was constructed by John Rosen of the Physics Department Shop.

Plate XXXVIII shows the appearance of the completed unit.

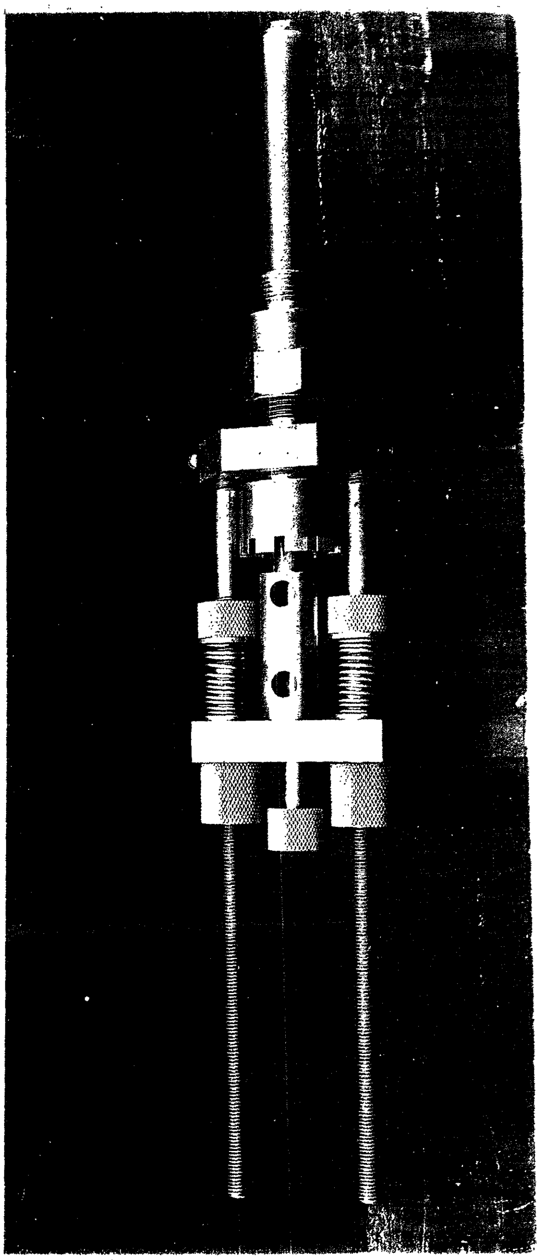


PLATE XXXVIII

Device to Hold Sensitive Unit at Different Positions iside the Engine Cylinder.

The photograph shows an adapter in place on the spark plug thread of the bushing. This adapter was made necessary by the fact that the spark plug hole in the N.A.C.A. test engine is counterbored with a hole diameter of one inch to a depth of something over half an inch. By making up another such adapter, the unit could be immediately fitted into either a metric of $\frac{7}{8}$ inch spark plug hole as future work on different engines might require.

The device discussed above was not brought to the stage of actual trial as it was considered a better policy to complete the work on the sensitive unit before any accessories depending upon the unit were developed. However, most of the machine work is completed and the apparatus is ready for immediate trial in case the sensitive unit is brought to a fair degree of perfection.

It is appreciated by the writer that the problem which is attacked in this phase of the work will be quite difficult experimentally. Difficulty is to be expected in keeping the sensitive unit sufficiently cool and at the same time prevent moisture from interfering with its operation. The matter of insulating the long rod (4) from the water stream in which it is immersed will also probably give trouble but it is hoped that some coating such as bakelite varnish or rubber will solve this part of the problem. The work will undoubtedly bring out a number of imperfections that are not apparent from preliminary considerations. The degree of success which will be attained in work with the insertion unit is at present a matter for conjecture that may be settled only by empirical trials.

IV. Final Test Runs.

In making the records which have been previously exhibited in this report, attention was directed toward the individual record rather than to a set of records intended to correlate engine operation with oscillograph records. In order to discover any uniformities which records from the plain contact type of unit might possess with respect to engine operation, a final set of records was taken with the same adjustment of the insulated contact in the sensitive unit. This set was composed of six records including the conditions of operation which have already been mentioned under "Outline of Specific Problems". This outline is repeated below.

(1) Starting with detonation at full throttle using straight gasoline for fuel.

(a) Detonation checked by use of doped fuel.

(b) Detonation checked by increasing richness of fuel mixture.

(c) Detonation checked by reducing throttle opening.

(2) Starting with normal operation on straight gasoline at reduced throttle.

(a) Detonation induced by advancing spark.

(3) Starting with normal operation on doped fuel.

(a) Detonation induced by increasing compression ratio.

These runs were carried out in the laboratory with the assistance of E. S. Taylor and R. L. McLane of the laboratory staff.

Before starting the actual runs, the insulated contact in the sensitive unit was carefully adjusted to a position which permitted records to be taken over the entire range of proposed operating conditions. The diaphragm thickness was 0.013 inch and the copper tipped contact was used.

The engine was brought up to the required operating conditions and allowed to steady down before the oscillograph record was taken for any case. Table D summarizes the results of the test.

There was but one film drum for the oscillograph available, so that a period of several minutes was necessary between single records.

Visual inspection of the action of the sensitive unit by means of the rotating mirror showed plainly a

TABLE - D

Run	Gasoline	Comp. Ratio	Spark Adv.	Throttle	B.H.P.	B.M.E.P.	S.F.C. lbs. per B.H.P.	Detonation
3	Straight	4.5	30°	Full	20.5	118	0.653	Erratic
5	Straight	4.5	45°	Part	18.0	104	0.618	Slight Det.
2c	5cc $Pb(C_2H_5)_4$	5.5	30°	Full	22.75	131	0.599	Heavy
2d	5cc. $Pb(C_2H_5)_4$	5.5	30°	Full	23.25	134	0.584	Heavy
4d	Straight	4.5	30°	Part	18.0	104	0.608	Very slight
3b	Straight	4.5	30°	Full	20.63	119	0.640	Heavy
I_a	5cc $Pb(C_2H_5)_4$	5.5	30°	Full	23.5	135	0.577	Heavy Reg.
II_c	5cc $Pb(C_2H_5)_4$	4.5	30°	Full	22.63	130	0.583	None
III	Straight	4.5	30°	Full	22.5	130	0.593	Sharp Interm.
IV	Straight	4.5	30°	Part	17.0	98	0.653	None
V	Straight	4.5	55°	Part	17.63	102	0.632	Sharp Reg.
VI	Straight	4.5	30°	Full	21.5	124	0.815	None

Considerable difference between records from successive explosions. This fact considerably reduces the value of single records taken in the manner of the present tests. However, it was hoped that the single records would show certain characteristic differences between normal operation and detonation which might give an indication of the results which might be expected from future work along the present lines.

The records are arranged below in the order in which the runs were noted under the outline.

(1) Full throttle detonation on straight gasoline. (Compression Ratio 4.5).

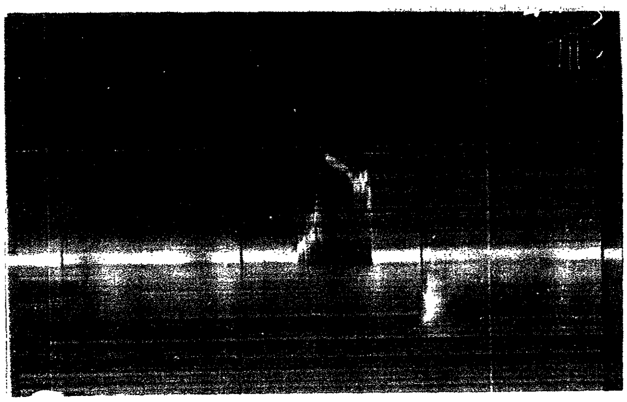


PLATE XXXIX

Record.....................III

Lag of contact after spark....0.0052 second

Contact closed................0.0070 second

(a) Detonation checked by use of 5 cc. of lead tetraethyl per gallon in straight gasoline.

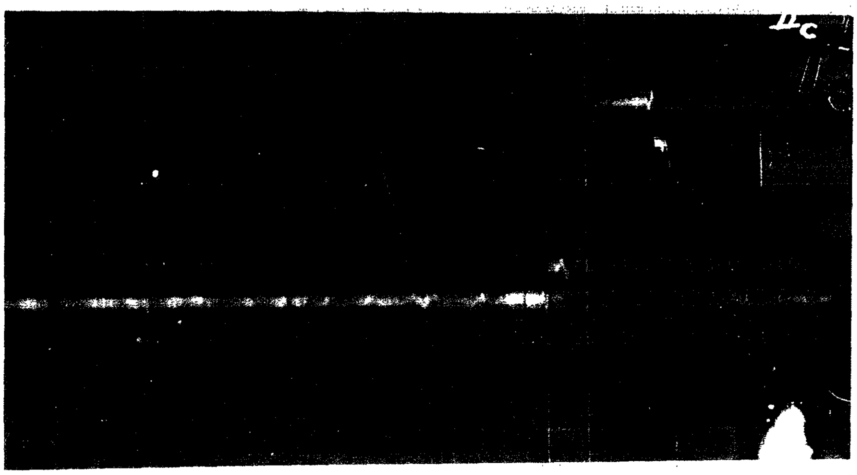


PLATE XL

Record.......................IIc

Lag of contact after spark...0.0064 second

Contacts closed..............0.0093 second (?)

(b) Detonation checked by increasing richness of fuel mixture.

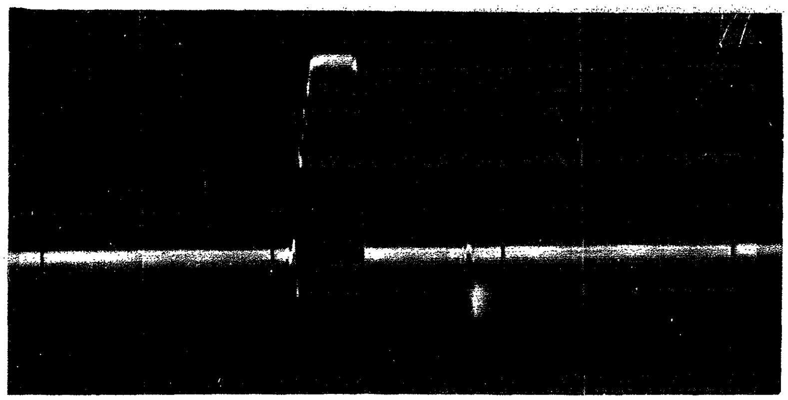


PLATE XLI

Record VI
Lag of contact after spark...0.0081 second
Contact closed..............0.0049 second

(c) Detonation checked by reducing throttle opening.

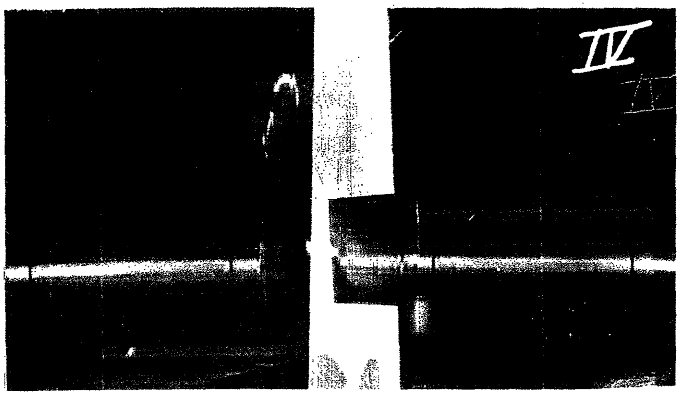


PLATE XLII

Record.....................IV

Lag of contact after spark....0.0066 second

Contacts closed...............0.0063 second

(2) See Plate XLI for normal operation at reduced throttle.

(a) Detonation induced by advancing spark with reduced throttle.

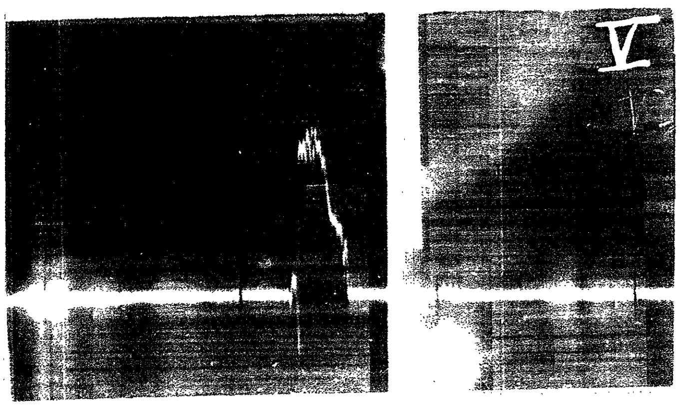


PLATE XLIII

Record.......................V
Lag of contact after spark....0.0085 second
Contacts closed...............0.0046 second
Vibration frequency about.....
3,500 cycles per second

(3) See Plate XXXIX for normal operation with doped fuel.

(a) Detonation induced with doped fuel by increasing the compression ratio. (Compression Ratio 5.5)

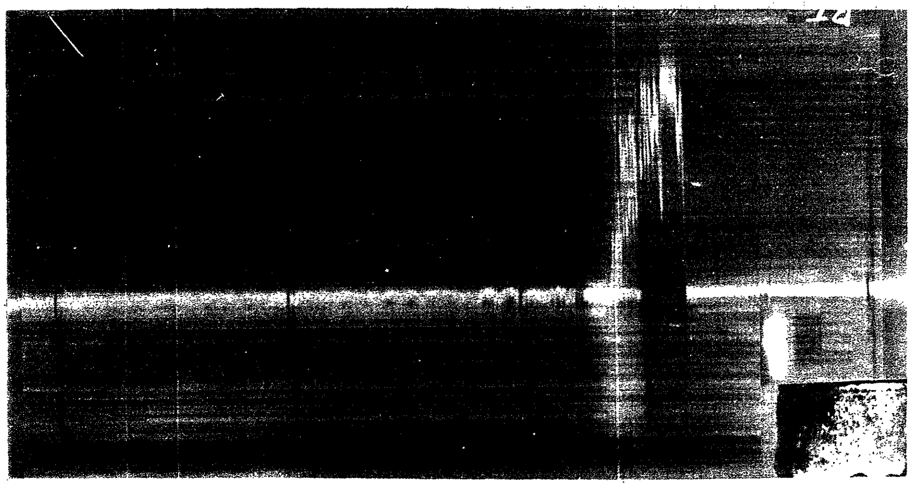


PLATE XLIV

Record.....................Ia
Lag of contact after spark....0.0066 second
Contacts closed..............0.0057 second
Vibration frequency..3,700 cycles per second

Plate XXXVIII shows the record for full throttle detonation with straight gasoline. The record shows the pronounced vibratory characteristic uniformly found in all the detonation records made during the experimental work. It is unfortunate that the drum speed for this record was not high enough to permit a satisfactory frequency determination. Record 3b exhibited under the section of detonation frequency was taken under almost the same conditions (see Table D) and shows the characteristic frequency of 3,900 cycles per second.

Plate XXXIX shows the effect on the record if normal operation is restored by use of a doped gasoline under the same engine conditions. As it happens the record is a rather poor one, apparently occurring at the instant the shutter mechanism of the oscillograph was operating. The measurement of lag in the contact closing after the spark is probably correct but the interval over which the contacts remained closed is uncertain. However, the record shows plainly a marked difference for normal operation over detonation, the top of the displaced portion of the normal record is flat, indicating a steady contact, while the contact of the detonation record is of a decidedly vibratory nature.

It is to be noted that the time lag of contact closing after the spark, is increased from 0.0052 second for the detonation record to 0.0064 second for the normal operation record.

Plate XL shows a record obtained with the detonation of Plate XXXIII checked by adjustment of the carburetor to give a rich mixture. Again the flat top of the record is apparent indicating a steady contact in the sensitive unit.

The difference in time lag of contact in the unit for the two cases, is interesting. For normal operation with a rich mixture, 0.0081 second is required for cylinder pressure to close the contact,while for detonation the contacts closed 0.0052 second after the spark. This is the action to be expected from our knowledge of the comparatively slow burning found with rich gasoline mixtures.

For normal operation with the rich mixture, the cylinder pressure kept the contacts closed only 0.0049 second as compared with 0.0070 second for the detonation record. Table D shows a B. M. E. P. of 130 pounds per square inch for detonation a B. M. E. P. of 124 pounds per square inch for normal operation with the rich mixture. This last fact indicates a comparatively slight change in B.M.E.P. While according to the oscillograph records, the rich mixture gave high cylinder pressures for a much shorter time than the lean detonating mixture. It may be concluded from these facts that the detonating mixture produced a pronounced period of high pressures in the first part of the power stroke, while the rich mixture gave a more even distribution of pressure throughout the stroke with a shorter period of high pressures.

Plate XLI shows the effect on the oscillograph record of checking detonation by reduction in throttle opening. The record which is shown, unfortunately occurred just at the break in the film. The two ends of the film were carefully pieced together before printing.

The measurements by which time intervals were estimated were checked over on the film itself and the results as recorded in this case should be as accurate as those for any of the other cases.

The reduced throttle record does not exhibit the characteristic flat top noted in the full throttle normal operation records. The record is of the type to be expected if the cylinder pressures were not high enough to push the diaphragm against the copper contact hard enough to break thru the thin copper oxide film on the tip. The record shows a somewhat unsteady contact, but the characteristic forced vibrations of detonation records is lacking.

Time lag of contact closing after spark occurrence, is 0.0066 second as compared to 0.0052 for the case of detonation. The contacts remained closed under the influence of cylinder pressures about the same time interval as for the full throttle detonation case.

Summarizing the results for full throttle detonation checked by the different methods brings out the following tentative conclusions.

(1) Detonation records show a characteristic vibration of a frequency apparently definite at about 3,900 cycles per second.

(2) Normal operation records seem to be entirely lacking in this definite characteristic vibration.

(3) The time lag necessary for cylinder pressures to close the contacts of the sensitive unit appears to be somewhat less for detonation than for normal operation.

(4) A rich mixture seems to definitely require a longer time for cylinder pressures to deflect the diaphragm, than is the case for leaner mixtures.

(5) No obvious conclusion is apparent with respect to the length of time the sensitive unit contacts are closed.

Plate XLII shows a record obtained with the engine detonating on reduced throttle at an excessive spark advance. (see Table D)

In this case, the building up of pressure seems to have been somewhat uncertain at first but this phase was succeeded by a sudden pressure rise which forced the contacts together suddenly. After the sudden pressure rise, the high frequency vibration characteristic of detonation appeared immediately.

As regards time lag, the detonation record shows a longer lag by about 0.0020 second than occurred in the case of the normal operation record. The contacts remained closed a period about 0.0020 second less for the case of detonation than for normal operation.

Plate XLIII shows a record made with heavy detonation induced by using a compression ratio of 5.5 when operating on ethyl gasoline.

The record apparently starts out in a manner similar to the normal operation records but soon takes on the pronounced vibratory nature characteristic of detonation. As taken from this record, the detonation frequency is about 3,700 cycles per second.

The time lag after the spark for the closure of the contacts, is almost identical with the lag found for normal operation on ethyl gasoline at 4.5 compression ratio.

The time over which the contacts permit current to flow is over 0.0030 second less for detonation than for normal operation.

XII. SUMMARY OF TEST RUN RESULTS

(1) Records taken under conditions of detonation uniformly show an apparently definite characteristic frequency which does not occur in records made for normal operation.

(2) There probably exist characteristic differences in the time lag for cylinder pressure to reach a value high enough to close the sensitive unit contacts. However, further work will be required before the nature of any such differences may be made apparent.

(3) The case of the time interval over which cylinder pressures hold the sensitive unit contacts closed is analogous to the time of lag in closing the contacts. Further work may or may not disclose valuable characteristics of this time interval.

XIII. GENERAL SUMMARY OF RESULTS

The experimental work described in this report covers what might well be thought of as the preliminary work of the original problem of the investigation.

An apparently satisfactory form has been evolved for a steel diaphragm of such a size that it may easily pass through a metric spark plug hole.

A more or less satisfactory method of converting diaphragm deflections into electrical indications has been worked out. A program of development for this element of the apparatus has been stated and will be followed in the continuation of the work.

Preliminary work has been done on a method of photographically recording the electrical indications of the sensitive unit. The requirements of this part of the apparatus are known and a specially constructed oscillograph unit will be made up for use in future work on the subject.

A device has been designed and constructed which it is hoped will permit the sensitive element to be fixed at definite positions inside the cylinder of an operating test engine.

A characteristic difference has been found between the oscillograph records for normal operation and similar records for detonation.

This difference is in the nature of a characteristic frequency of about 3,900 cycles per second, found only in detonation records. This frequency may or may not be a function of the engine in which the sensitive unit is placed when the record is taken and may or may not vary over a certain range with operating conditions.

It has been found possible to measure the time lag after spark occurrence before the sensitive unit contacts are closed by cylinder pressures. The data available at present are too few to permit conclusions to be drawn regarding the variation of this time lag with engine conditions.

In a manner similar to that used for time lag in the contact of the sensitive unit, it has been possible to measure the time interval over which cylinder pressures are able to keep the diaphragm deflected to the point of contact.

Work with a special type of continuously recording accelerometer, has shown that under conditions of heavy detonation, the cylinder head of the N.A.C.A. test engine is actually displaced vertically over an amplitude which is about ten times larger than the amplitude for normal operation.

The accelerometer showed that cylinder head displacements in a horzontal plane are not markedly larger for detonation than for normal operation.

XIV. GENERAL DISCUSSION

The foregoing report indicates that up to the present time, experimental work has been rather sketchy in nature. No attempt has been made to make final definite conclusions concerning any of the problems which have been considered.

The number of photographic prints which have been included is perhaps larger than the strict necessities of the case justify. It was intended to lay the actual results of the experimental work before the reader rather than to formulate concise conclusions.

Of the interesting points which have presented themselves, one in particular may be mentioned here. The vibration recording accelerometer indicates with certainty that the amplitude of the cylinder head motion increases to a very pronounced extent for detonation over normal operation. On the other hand the mean effective position of the maximum diaphragm deflection seems to be distinctly closer to the zero pressure position for detonation than for normal operation at the same throttle setting. This fact appears to indicate that over the part of the card which is considered, instantaneous average pressures (distinct from the vibratory changes in pressure) which exist in detonation, are actually lower than the average pressure found in normal operation. This effect is probably due to some peculiarity in the action of the contacts in the sensitive unit.

A final decision on the problem will have to await further experimental investigation.

The original object of the experimental work was to develop a sensitive unit which might be fixed at positions inside the cylinder volume and which would be able to give records discriminating between volumes in which detonation exists and volumes in which normal combustion is in progress.

The sensitive unit in its present form is obviously a rather crude device, but the writer feels that if violent detonation is used in the experimental work, the oscillograph records from the present type of unit should make it possible to determine whether the type of pressure variation applied to the sensitive surface of the unit is that of normal combustion or of detonation.

A considerable number of experimental difficulties will undoubtedly arise in the course of the work, but the writer feels that a sufficient effort put in on the problem will eventually be repaid with more or less valuable results.

The primary problem to be solved in future work is undoubtedly the construction of a satisfactory sensitive unit. Development of this part of the apparatus will follow the line previously laid down in this report.

The lack of uniformity in the oscillograph indications for succeeding power strokes of the engine is another problem which must be met in the future. A part of this variation is very likely due to non-uniformity in the mixture delivered by the carburetor to the engine over a number of strokes. It is suggested that this source of irregularity may be minimized by use of illuminating gas as a fuel in connection with a mixing valve.

With the variation between records due to the engine made as small as possible, there remain probable irregularities in the operation of the unit which will in turn be corrected as far as possible before data are taken to form the basis of final conclusions.

In any case, it seems very desirable if not absolutely necessary to develop a means of taking a number of records from successive power strokes of the engine. With the present form of the oscillograph apparatus, it is necessary to keep the engine in operation over a period of from five to ten minutes in order to obtain a single record which obviously can not give a true picture of average cylinder processes. The film used for this single record is rectangular $3\frac{1}{4}$ inches in width by $9\frac{1}{2}$ inches long, while as the prints show the record itself never occupies any very great proportion of this space.

It is entirely possible to use motion picture film in an oscillographic apparatus. Professor Hardy[46] of the Physics Department at M. I. T. has summed up the matter as follows: "It would seem that a more efficient apparatus might be constructed on a much smaller scale which would then permit the trace to be recorded on motion picture film, using either negative or positive film depending upon the amount of light available........ There is a saving in film not only because of the decrease in its width but because the speed of the film will be decreased proportionately also. Thus the area of film required is about proportional to the square of the deflection. These advantages usually more than compensate for the necessity of enlarging the records."

The use of motion picture film in a modified form of the oscillograph would have a number of advantages. A considerable number of successive records could be taken in a minimum of time. All of the records would be made with the same film speed. The wastage of film would be reduced to a minimum and the apparatus could be arranged so that it might be stopped after any desired amount of film had been exposed. The film would be easily handled in development by standard methods at a minimum of expense.

After development, the motion picture film might easily be placed in a projection unit with which it could be enlarged to any reasonable size. The enlarged record might either be traced on paper with a pencil or some light sensitive paper might be used for a chemical print. By throwing successive records on the screen with the projector and tracing with a pencil, it would be very easy to rapidly superimpose the records and estimate an average record from the assembled tracings.

The records obtained in the latter part of the work are considerably reduced in value by the different drum speeds with which they were taken. It would also be very desirable to use film speeds much higher than any which have been attained in the work up to the present. These last two problems should be easily solved by use of a variable speed direct circuit current motor to operate the mechanism for moving the film.

This higher film speed should produce interesting results when applied to the accurate measurement of the vibration frequency found in detonation records.

The synchronous shutter arrangement seems to the writer to be a very satisfactory method of indicating time intervals on the oscillograph record. For this reason, any new oscillograph apparatus will incorporate the synchronous motor and shutter.

The direct photographic record from a series gap is a simple and certain method for recording the ignition spark occurrence and will be included in the new arrangement. It is probable that the use of a quartz lens system instead of the glass lenses used in the present form of the instrument will improve the photographic record by allowing a larger portion of ultra-violet wavelengths to reach the film than would be possible if glass were used.

It is probable that the use of an optical system entirely of quartz in connection with a high intensity incandescent lamp, may permit satisfactory oscillograph records with very high film speeds.

In general the preliminary work seems to promise that valid experimental results may be expected from future work on the "point of incipient detonation" in the cylinder combustion process. Just what these results are likely to be is a matter that can only be settled by data taken with apparatus meeting the requirements of the problem.

As another suggestion for future work, the oscillograph might be applied to the study of instantaneous gaseous conductivities at different points in the cylinder. It is well known that gaseous conductivity undergoes a marked increase at the instant of passage of a flame front thru a gaseous mixture. This type of investigation may offer some information on the problem of flame motion involved in the cylinder combustion process.

It is hoped that a future report may be able to state more definite conclusions to the problems which have presented themselves during the course of the preliminary work.

APPENDIX A

TABLE I

Plate	Diaphragm	Condition	Lag After Spark	Contact Closed	Frequency
	Preliminary Records				
VI	0.020	Normal		0.023	
VII	0.020	Bad Det.		0.0032 0.0069	
IX	0.020	Normal		0.042	
X	0.020	Slight Det.		0.017	
XI	0.020	Bad Det.		0.0056	
XII	0.015	Normal		0.049	
XV	0.029	Normal		0.041 0.042	
XVI	0.029	Bad Det		0.021 0.020	
XVII	0.009	Normal		0.026	
XVIII	0.009	Normal	0.0067 0.0080	0.0061 0.0043	
XIX	0.009	Bad Det.	0.0060 0.0060	0.008 0.0073	
XX	0.009	Bad Det			3900
XXI	0.009	Bad Det.			4000
XXII	0.009	Bad Det.			3900
XXIV	0.009	Normal		0.016	
XXV	0.029	Normal		0.016	
XXVI	0.029	Bad Det.			3600

TABLE-I (Contd.)

Plate	Diaphraam Thickness inch	Condition of Operation	Lag After Spark second	Contact Closed second	Frequency of Det. Vibration Yds/sec
XXVII	0.009	Bad Det.	0.0018	0.0043	4000
		FINAL RECORDS			
XXXII (3)	0.013	Erratic Det.	0.0093	0.0029	
XXXIII (3b)	0.013	Heavy Det.	0.0067	0.0064	3900
XXXIV (2c)	0.013	Heavy Det.	0.0069	0.0064	3800
XXXV (2d)	0.013	Heavy Det.	0.008	0.0026	4000
XXXVI (4d)	0.013	Slight Det	0.0074	0.0070	
XXXVII R-Unit	0.013	Normal	0.0060	0.014	
XXXVIII III	0.013	Sharp Intermittent Det.	0.0052	0.0070	
XXXIX IIc	0.013	Normal	0.0064	0.0093	
XL VI	0.013	Normal	0.0081	0.0049	
XLI IV	0.013	Normal	0.0066	0.0063	
XLII V	0.013	Sharp Regular Det.	0.0085	0.0046	
XLIII Ia	0.013	Heavy Det.	0.0066	0.0057	3700

BIBLIOGRAPHY

1 Alcock ....Auto. Eng. 14, 165 (1924)

2 Bone, Fraser and Winter....Proc. Roy. Soc. A, Vol. 114, (1927)

3 Boyd...........Ind. Eng. Chem. 16, 893-5 (1924)

4 Brooks.........J.S.A.E., 16, 445 ff. (1926)

5 Brown and Watkins...Ind. Eng. Chem. (a) 17, 4, 397 (1925) (b) 19, 2, (1927) (c) 19, 3, 363 (1927) (d) 19, 3, 366 (1927)

6 Callender......Engineering, 123, 182-4 (1927) (b) 123, 210-2, (1927)

7 Campbell and Woodhead...J. Chem. Soc. 3010 (1926)

8 Charch, Mack and Boord...Ind. Eng. Chem. 18, 334-40 (1926)

9 Clark, Brugman and Thee...Ind. Eng. Chem. 17, 12, 1226 (1925)

10 Clark and Henne... J. S. A. E. 20, 2, 264 (1927)

11 Clark and Thee.... Ind. Eng. Chem. 17, 12, 1219 (1925)

12 Clark and Thee.... Ind. Eng. Chem. 18, 5, 528 (1926)

13 Cummings.......... J. S. A. E. (a) 20, 2, 183-7 (1927); (b) 20, 5, 599 (1927)

14 Denison........... J. S. A. E. 17, 273 (1925)

15 Dickinson......... (a) J. S. A. E. 8, 5, 482 (1921); (b) 20, 5, 645 (1927)

16 Edgar.............J. S. A. E. 20, 2, 245 (1927)

17 Farragher and Hubner... J. S. A. E. 20, 3, 405 (1927)

BIBLIOGRAPHY (cont'd)

18 German and Gasin....Nat'l Petr. News Dec. 29, page 21 (1926)

19 Horning.............J.S. A. E. (a) 13, 2, 144 (1923) (b) 14, 142 (1924)

20 James..........J. S. A. E. 8, 6, 542 (1921)

21 Lovell, Coleman and Boyd...Ind. Eng. Chem. (a) 19, 3, 376 (1927); (b) 19, 3, 373 (1927)

22 Lind and Bardwell... Ind. Eng. Chem. 19, 2, 231 (1927)

23 Marley, Stevens,and Gruse... J. S. A. E. 20, 2, 215 (1927)

24 Midgley........J. S. A. E. 10, 5, 357 (1922)

25 Midgley and Boyd... Ind. Eng. Chem. (a) 14, 10, 894 (1922)

26 Midgley and Boyd... J. S. A. E. (a) 10, 1, 7 (1922); (b) 10, 6, 45 (1922)

27 Midgley and Gilkey... J. S. A. E. 10, 218 ff., (1922)

28 Midgley and Janeway... J. S. A. E. 12, 4, 367 (1923)

29 Olin, Read and Gow.... Ind. Eng. Chem. 18, 12, 1326 (1926)

30 Report of subcommittee... J. S. A. E. 20, 3, 327 (1927)

31 Reiman..............Ind. Eng. Chem. 19, 9,(1927)

32 Ricardo........Auto Eng. (a) 2, 92, (1921); (b) 2, 130 (1921)

33 Ricardo........J. S. A. E. 10, 5, 305 (1922)

34 Rosecrans......Univ. of Ill. Eng. Expt. Sta. Bull. No. 157 (1926)

BIBLIOGRAPHY (cont'd)

35 Ricardo....... Engines of High Output pg. 54 ff.

36 Sokol......... J. Soc. Chem. Ind. (Japan) 43, 273-4 (1924); Cf. Chem. Absts. 18, 3475 (1924)

37 Stevens and Marby...Ind. Eng. Chem. 19, 2, 228 (1927)

38 Tanaka.........J. Soc. Chem. Ind. 29, 266-72 (1926); Cf. Chem. Absts. 28, 487 (1925)

39 Thee...........J. S. A. E. 20, 5, 566 (1927)

40 Wendt and Gwinn... Ind. Eng. Chem. 16, 890-3 (1924)

41 Woodbury, Lewis and Canby... J. S. A. E. 8, 209 (1921)

42 Young and Holloway....J. S. A. E. 14, 3, 273(1925)

43 Young, Holloway and Huebotter....J. S. A. E. 12, 1, 110 (1923)

44 Juichi Obata....Engineering pg. 253 (Aug.19,1927)

45 A. E. Kennelly....Electrical Vibration Instruments Pg. 39

46 A.C. Hardy........Jour., Optical Soc. of Am. and Review of Scientific Instruments, Pg. 510, Vol. 14, No. 6 (June 1927)