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THE N.A.C.A. OPTICAL ENGINE INDICATOR

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SUMMARY

An optically recording engine-pressure indicator of simple and rugged construction has been developed for use in high-pressure and high-temperature combustion research. This instrument is of the diaphragm type and has a natural frequency of about 10,000 cycles per second.

INTRODUCTION

Development of an optical indicator was started by the N.A.C.A. in 1930 for use with a research test engine. This engine was of the high-speed, high-compression-ratio type and was designed to fire on only one revolution (reference 1) and to allow the investigation of nearly all the variables of engine operation over the practical range. The scope of the tests and the conditions under which data were to be observed fixed several requirements that had to be met by the pressure recorder. The most important of these requirements were:

1. Accurate recording of pressure.
2. Fixed or known calibration.
3. Minimum attendant apparatus.
4. Simplicity and ruggedness.
5. Recording of a single explosion.

A survey of the indicators available showed none that satisfactorily met all the requirements. It was found, however, that an indicator having the desired characteristics could be made by the development of a diaphragm type with optical magnification. A design was worked out following suggestions made by Dr. Theodore Theodorsen of the Laboratory staff and, after some development, has proved satisfactory.

DESIGN

In order that a diaphragm-type indicator may faithfully record very high rates of change of pressure, its natural frequency must be high. It was found from indicator data for a test engine that rates of pressure change of the order of 10^6 pounds per square inch per second were to be expected in the range of "normal" operation, as well as what may be considered the infinite rate accompanying knocking performance. For this design a frequency of 10,000 cycles per second was chosen as the highest practical value and was shown by calculation to be satisfactory for all rates except severe knocking, which cannot be faithfully recorded with this type of indicator. Figure 1 shows the maximum calculated error of a 10,000-cycle diaphragm for increments of pressure of 300 pounds per square inch in the time (t) plotted as the abscissa. The pressure was assumed to vary as kt^2, which approximates the applied pressure phenomena. A calculation with almost exactly the same derivation has been published in reference 2.

The design of the combustion chamber of the test engine allowed the use of an unusually large diaphragm (1-3/8 inches diameter), which was flush with the inner wall of the combustion space. The large diameter made it possible to obtain a larger deflection and to use correspondingly less magnification; this condition simplified the problem and increased the reliability of the indicator. The flush mounting eliminated all pocket and tube effects that would interfere with engine operation or pressure indication.

The possible magnification is limited by the length of the optical lever and the smallest practicable distance between the pivots that produce the rotation of the mirror. With the dimensions chosen for this instrument, the maximum value of the magnification is about 300 times. When the frequency and the diameter of the diaphragm are fixed at the values given, the thickness is fixed thereby and the maximum stress allowable fixes the maximum pressure for the diaphragm. It is therefore not always possible to make a record as large as is desirable.

The diaphragm most frequently used in the test engine has a thickness of 0.054 inch and is ordinarily used for pressures to about 1,200 to 1,500 pounds per square inch. The resulting high stress requires a steel of a very high yield point. Experience has shown a nondeforming die steel to be satisfactory under these conditions up to a diaphragm temperature of about 300° C. Some "hysteresis" error is observed at these high stresses, but it ordinarily amounts to less than 25 pounds per square inch at the maximum width of the loop.

DESCRIPTION OF THE INDICATOR

The indicator is composed of three parts (fig. 2): the diaphragm unit, the camera, and the film drum. The film drum is a modification of the N.A.C.A. standard drum, which has a pin-actuated shutter opened only when the drum is on the camera. Ten inches of film 2-7/16 inches wide is carried on a cylindrical drum rotated at a speed of 10 revolutions per second by a small synchronous motor, which drives the drum through a coupling that slips into place when the drum is installed.

The camera unit, made of welded steel sheets, acts both as a light shield and as a support for the lamp and film drum. Since the oscillating mirror cannot be perfectly alined in its holder, the camera was made adjustable so that it could be warped several degrees in any direction to set the zero or to bring the image of the filament to the slit of the film drum. The camera is screwed to the diaphragm unit by a fine-pitch thread to allow the adjustment of the focal distance of the optical assembly and also the removal of the camera to facilitate installation of the diaphragm unit.

The diaphragm unit is similar in principle to the high-temperature unit shown in figure 3, except that the diaphragm and part of the heavy side walls were attached by a clamping nut to the body of the indicator to facilitate replacement of the diaphragms. In the center of the diaphragm is machined a boss into which is screwed the center bearing of the magnification system. This bearing has a V-grooved seat for the knife-edge bearing of the mirror staff. Opposite the center bearing are two other V-grooved bearings on a part which is movable to allow adjustment by means of an eccentric. (See fig. 3, section B-B.) After the mirror staff is inserted, the adjustable bearings are moved up to a firm contact and the clamping wedges, shown in section A-A, are tightened to lock the assembly.

Any deflection of the diaphragm rotates the mirror staff and the mirror projects the magnified motion onto the moving film. The lens focuses the image of a 15-candlepower lamp at the surface of the film but, since the film drum has a slit aperture, only a point is exposed. Practically this same principle of magnification has been used by the U.S. Bureau of Mines in their modification of the Illinois manometer (reference 3).

The engine revolutions at top center and 90° after top center are marked on the film by light from a spark jumping a gap provided on the camera. The spark is caused by an auxiliary spark mechanism driven by the engine on its one cycle of combustion.

A modification of this indicator (fig. 3) has been made for use on a special high-temperature bomb; the modified indicator has the special property of operating while the whole lower assembly is at a red heat (600° C.).

All parts of the modified indicator were constructed of a special high-tungsten alloy steel for which the manufacturer claimed a yield point after heat treatment of 120,000 pounds per square inch at 600° C. The diaphragm was accordingly designed for a maximum pressure of 3,000 pounds per square inch and a frequency higher than 10,000 cycles per second at 600° C. It was found that, in order to avoid appreciable drift of the indication during a static calibration lasting several minutes, the pressure had to be limited to 2,500 and 2,000 pounds per square inch at 500° C. and 600° C., respectively. At lower temperatures, the whole range of 3,000 pounds per square inch could be employed. As the drift occurring at high temperatures and pressures increased with the time of deflection, these limiting static pressures could be exceeded by a quickly applied and released load, such as an explosion, without any deleterious effects. Some of the records show a vibration frequency of about 10,000 cycles per second but, since the primary mode of vibration of the combustion chamber was also of this order, it is uncertain whether this frequency is that of the diaphragm or of the chamber.

The mirror and the lens of this assembly were made of fused quartz, and the mirror was platinized. Thermal insulation is provided between the diaphragm unit and the camera, except along the light path, and the camera is cooled by a water coil soldered to it.

LABORATORY TESTS

Calibrations.- The calibration of the indicator was established by applying static pressure to the diaphragm by a dead-weight gage tester and recording the deflection on the film. Points were taken with both increasing and decreasing pressures to evaluate the total of the frictional (believed very small) and lag errors. For ordinary usage, the pressure error at the widest part of the loop was about 1 or 2 percent of the maximum pressure.

Temperature effect.- The temperature dependency of the indicator calibration was evaluated by heating the lower assembly of the indicator in a bath. Calibrations were made at 50° C. intervals of temperature to about 300° C. after the temperature had been held constant long enough to become stabilized. The dependency of some diaphragms varied from the mean value, but the magnitude was generally about 5 percent increase in sensitivity for 100° C., owing to the decrease of the elastic modulus. No zero shift was observed.

The effect of transient heating was tested by moving a flame over the surface of the diaphragm. The deflection due to unequal heating was about 2 percent of full scale. The diaphragms used were so thick (0.054 inch to 0.065 inch) that the change of diaphragm temperature during the single firing cycle was very small. Provisions for cooling the diaphragm were made but have not been necessary.

Frequency determinations.- The frequency of the diaphragm and its magnification system was determined by jacking up the diaphragm with a pin and then jerking out the pin. The measured frequencies were about 9,600 cycles per second and varied from 9,000 to 10,000 cycles for the most frequently used (0.054 inch) diaphragm, which was for a maximum pressure of 1,200 pounds per square inch. Variation of the magnification ratio in the diaphragm unit changes the effective mass of the parts and consequently the frequency.

Comparison with other indicators.- The optical indicator was tested in conjunction with a modified Farnboro type of indicator on an N.A.C.A. universal test engine; the agreement obtained was as good as could be expected under the conditions of the test. The large size of the diaphragm made it necessary to use an adapter having a tube length of several inches. With low rates of change of pressure, the average diagrams checked within the variations of individual cycles. Figure 4 shows the effect of introducing a connecting passage about 3 inches long and 1/2 inch in diameter between the indicator and the combustion space. The superposed pressure vibration is caused by the low frequency of the connecting passage.

More recently the indicator has been checked against a piezoelectric indicator and the results were in good agreement.

USE IN RESEARCH

Numerous research programs have been completed in which the indicator was used to record the effect of systematic changes of the many variables of engine operation. Results of several of these research programs have been published by the N.A.C.A. Records taken during a knock investigation are shown in figure 5.

When used for this sort of work, the indicator has the advantage of simplicity, ruggedness, and comparative accuracy even under very severe service, but it has the disadvantage that the diaphragm is too large to use on a regular test engine without an adapter. The instrument also served as a very sensitive indicator of the presence of knock and, unless the knock is very severe, the pressure card can be evaluated inasmuch as the natural frequency of the diaphragm is generally several times the frequency of the waves in the gas column of the combustion space.

The original model has also been extensively used with a constant-volume combustion bomb (reference 4). This program was limited by the maximum temperature at which the indicator would function properly (300° C.); therefore, the design was changed, as previously outlined, to make an indicator that would operate to 600° C. with a frequency of greater than 10,000 cycles per second at that temperature. Results of some of these tests are given in reference 5.

An unusual type of failure observed during the bomb tests has not been eliminated. When the instrument is in use on a test engine, two types of failure occur (diaphragm failure and pivot wear), but a third type appears that seems to be due to a characteristic of bomb combustion. Under certain conditions, an explosion occurs that is clearly audible and has a frequency characteristic of the combustion space and temperature. This explosion records as a wave of increasing amplitude imposed on the pressure rise with harmonics appearing at maximum pressure, followed after some time by a wave of decreasing amplitude. In most cases, the effect on the indicator is to bend the mirror staff enough to make readjustment or replacement necessary; this bending of the mirror staff is probably due to harmonics of the diaphragm that tend to move the center post in directions other than along its center line.

The indicator has been used for other tests when a very high-frequency pressure recorder has been necessary. One of these tests was the recording of the pressure produced in a hydraulic system subject to shock loading. Another test, two records of which are shown in figure 6, was for the purpose of recording the pressure in a high-pressure fuel-injection line, which operated with a variable amount of residual pressure. Although the large diameter of the diaphragm was a handicap, it was the best method available at the time and good records were obtained.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., January 8, 1938.

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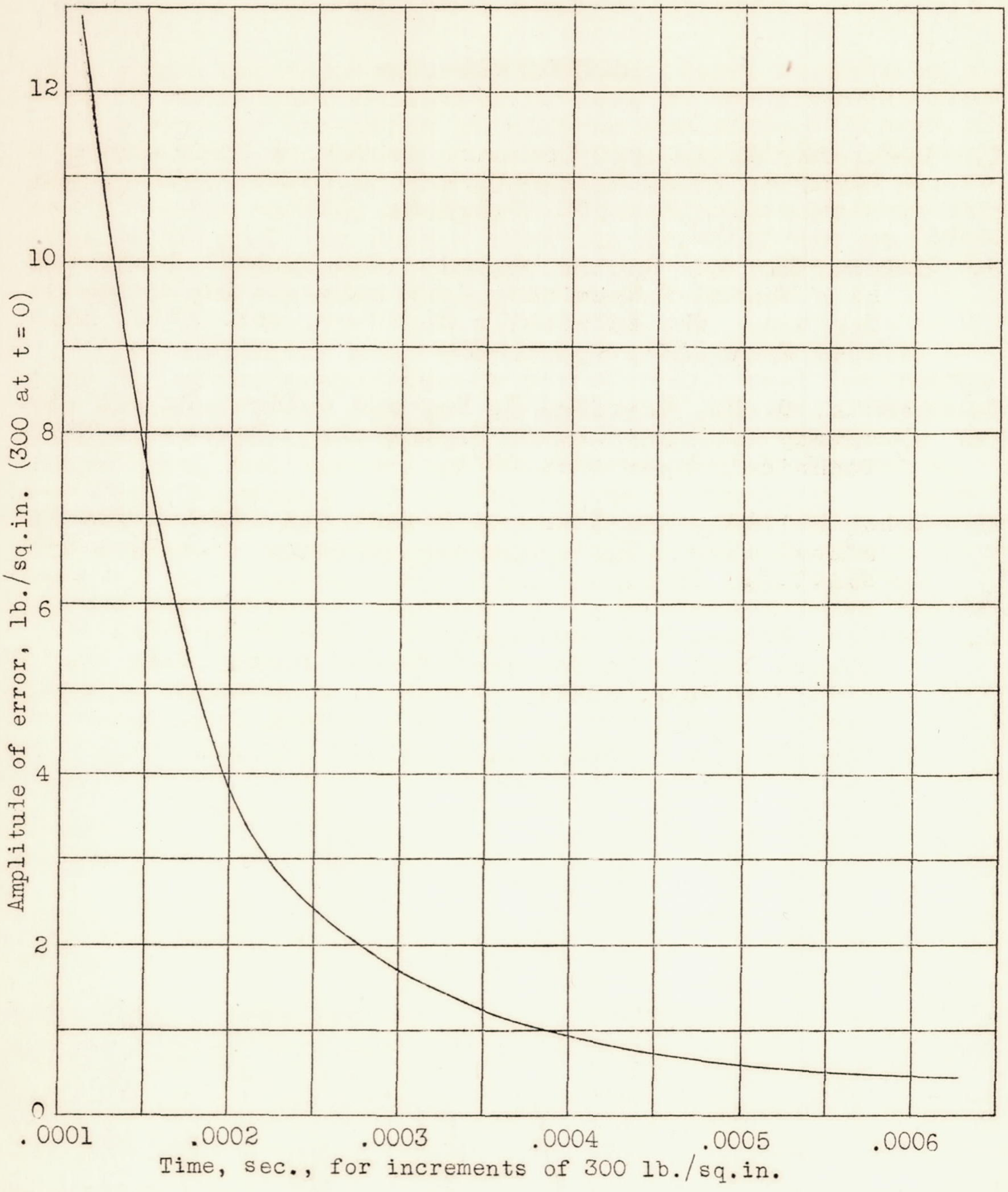


Figure 1.- Calculated amplitude of pressure error. Frequency, 10,000 cycles per second. ($\Delta P = kt^2$)

$$(p_i - p_r) = \frac{-2wk}{Sg}\left[\sin t\sqrt{\frac{Sg}{w}} - 1\right]$$

$$f = \frac{1}{2\pi}\sqrt{\frac{Sg}{w}}$$

$p_i = kt^2$ = imposed pressure

p_r = recorded pressure

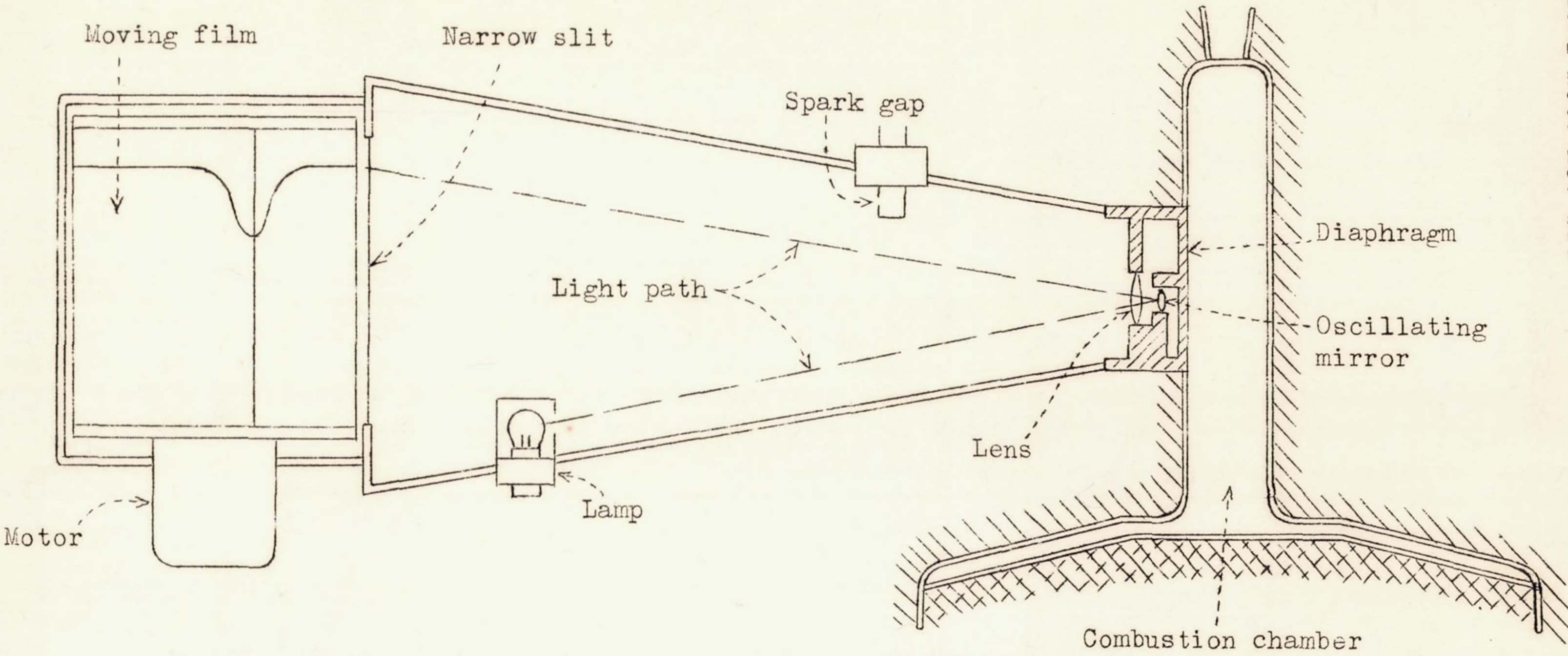


Figure 2.- Schematic diagram of the optical indicator.

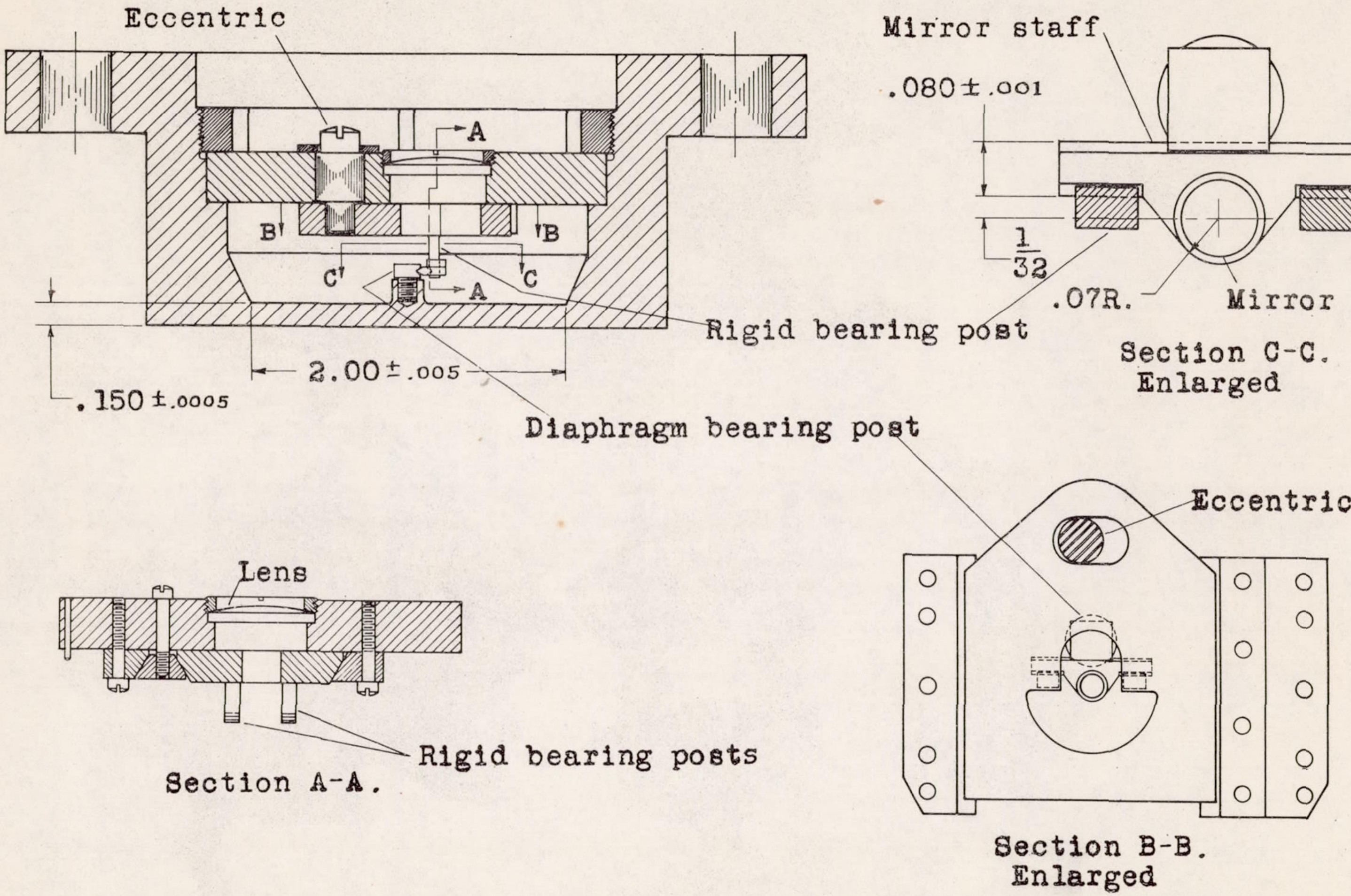
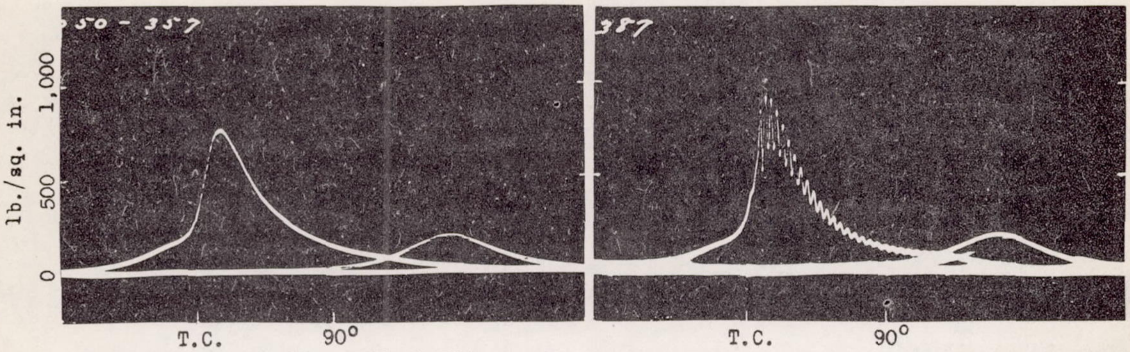
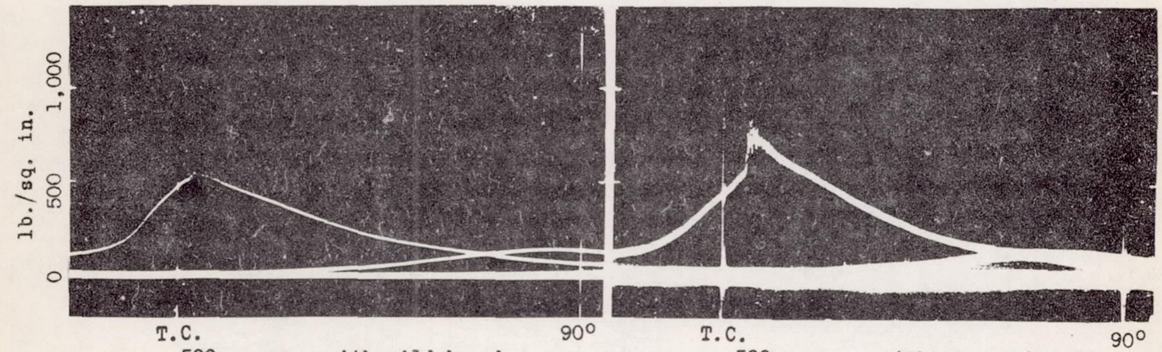


Figure 3. – Details of high-temperature diaphragm unit.



Indicator at cylinder wall; 1,500 r.p.m. Similar conditions, with 3-inch tube length.

Figure 4.- Effect of a connecting passage on the recorded pressure.



500 r.p.m., with mild knock. 500 r.p.m., with severe knock.

Figure 5.- Cylinder pressure records.

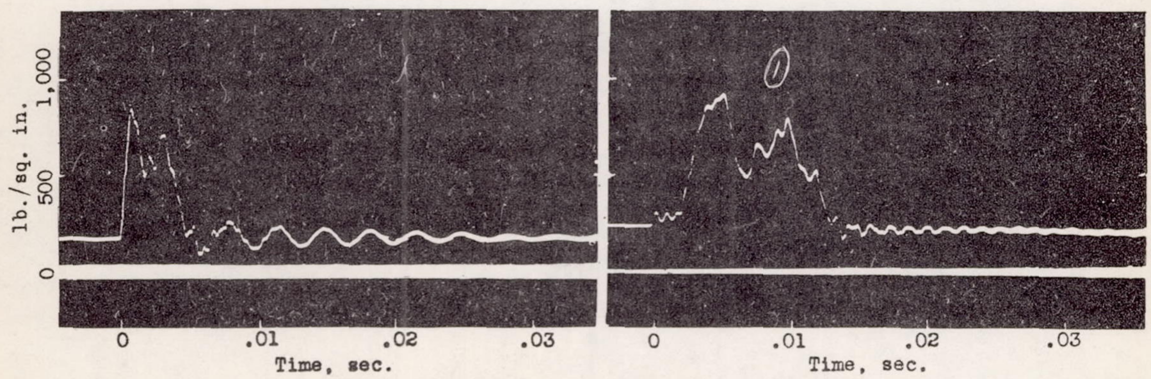


Figure 6.- Pressure in fuel-injection line.