

## REPORT No. 699

### EFFECT OF FUEL-AIR RATIO, INLET TEMPERATURE, AND EXHAUST PRESSURE ON DETONATION

By E. S. TAYLOR, W. A. LEARY, and J. R. DIVER

#### SUMMARY

*An accurate determination of the end-gas condition was attempted by applying a refined method of analysis to experimental results. The results are compared with those obtained in Technical Report No. 655.*

*The experimental technique employed afforded excellent control over the engine variables and unusual cyclic reproducibility. This, in conjunction with the new analysis, made possible the determination of the state of the end-gas at any instant to a fair degree of precision.*

*Results showed that for any given maximum pressure the maximum permissible end-gas temperature increased as the fuel-air ratio was increased. The tendency to detonate was slightly reduced by an increase in residual gas content resulting from an increase in exhaust back-pressure with inlet pressure constant.*

#### INTRODUCTION

While there is a great deal of information available on the knock rating of fuels, there is little information on the relation between permissible compression ratio, fuel-air ratio, and inlet temperature. There are also few data on the effect of proportion of residual exhaust gas present. This report is an attempt to supplement existing data on these points.

The temperature and the pressure (or density) of the last part of the charge to burn (end gas) is now the center of interest in the combustion process of the internal-combustion engine as the key to a basic evaluation of the phenomenon of detonation. Serruys (reference 1) has made an approximate analysis of end-gas conditions and the work has been further advanced by Rothrock and Biermann (reference 2). Both of these analyses are characterized by simplifying assumptions, especially with regard to the combustion process. The combustion process was treated as in the conventional air cycle; that is, combustion was considered to be equivalent to the addition of heat to a perfect gas medium inside the cylinder. The equations of Rothrock and Biermann are convenient expressions that give good qualitative results for investigations at constant fuel-air ratio but, when this quantity varies, the results are

doubtful. A more accurate determination of end-gas conditions therefore seemed desirable.

An accurate determination of the end-gas condition has been attempted in the present report. An experimental technique has been developed that affords excellent control over engine variables; and due allowance has been made for the variation of specific heats and chemical equilibrium of the charge, before and after combustion, with temperature, pressure, and fuel-air ratio.

Stated briefly the object of these tests was:

1. To determine the effect of fuel-air ratio and inlet temperature on the compression ratio for incipient detonation.
2. To determine the effect of exhaust-gas dilution on the compression ratio for incipient detonation.
3. To determine the relation (if any) between maximum end-gas pressure, maximum end-gas temperature, and fuel-air ratio for incipient detonation.

#### DESCRIPTION OF APPARATUS

Figures 1, 2, and 3 show three views of the apparatus. Figure 4 is a schematic diagram of the complete installation.

#### ENGINE

The engine used was a C. F. R. single-cylinder, water-cooled, variable-compression-ratio engine of 3.25-inch bore and 4.5-inch stroke. This engine was provided with a standard shrouded inlet valve. A special cylinder head having two additional holes located as shown in figure 5 was used. The engine was fitted with a standard Bosch fuel-injection pump having a 5-millimeter plunger.

In order to avoid the variation in spark advance that occurs with the ordinary ignition system, a special breaker mechanism was constructed to operate from the dynamometer shaft, which was directly coupled to the crankshaft. This mechanism was similar to the one described by Biermann in reference 3. A 5-microfarad condenser was charged from the 110-volt d-c

line through a 750-ohm resistor and then discharged through the spark coil by the closing of the breaker

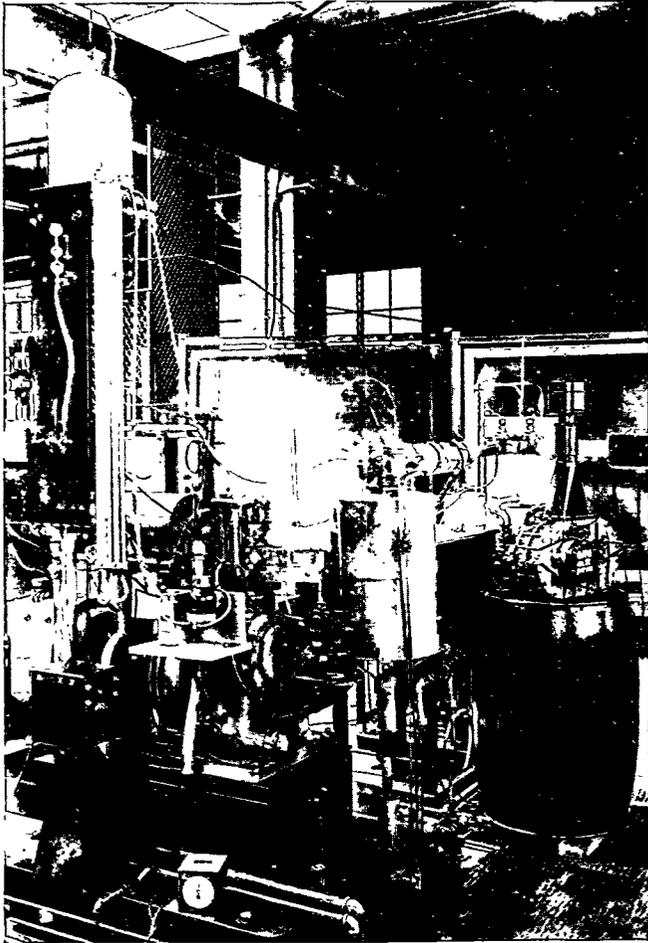


FIGURE 1.—Front view of apparatus showing Strobotac and inlet system.

points. With this system, the variation in the spark timing at 1,200 rpm was less than  $\pm \frac{1}{4}^\circ$  as observed on

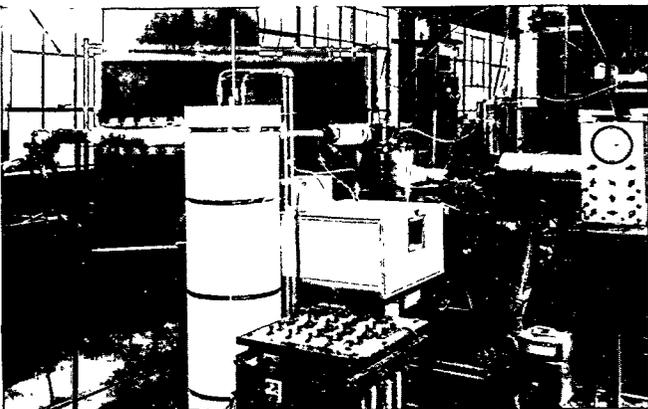


FIGURE 2.—Side view of apparatus showing drying tower, hygrometer, and visual oscillograph.

the spark protractor. A new BG3B2 spark plug was used.

#### INLET SYSTEM

Air to the engine passed in turn through a meter, a dehumidifier, a throttle valve, a heater, a surge tank, a vaporizing tank, and thence to the engine. (See fig. 4.)

An N. A. C. A. Roots-type supercharger mounted on a 50-gallon surge tank was used as an air meter. Calibration against a standard orifice box showed that the meter delivered 0.180 cubic foot per revolution over the range in which it was used in these experiments.

The dehumidifier, which used activated alumina, is described in detail in appendix A. The dew point of the air from the engine was measured by a specially constructed hygrometer, which is also described in

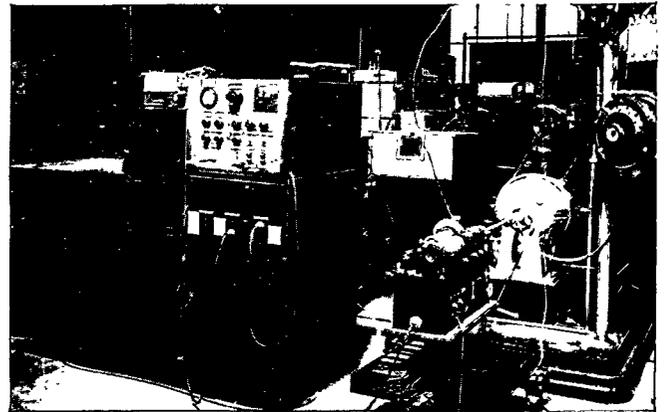


FIGURE 3.—Rear view of apparatus showing Draper recording oscillograph and M. I. T. balanced-pressure indicator.

appendix A. The weight of water vapor admitted to the engine was less than 1 percent of the weight of water vapor present in the residual gases as a product of combustion.

Pressure in the vaporizing tank was controlled by a gate valve placed in the line between the drying tower and the heater.

After leaving the drying tower, the air passed through a 1,000-watt rheostat-controlled electrical-resistance heater.

Air from the heater passed into a combined vaporizing, mixing, and surge tank. Fuel was added at the entrance to the surge tank by the Bosch injection pump through a Bosch KC 30 S1 spray nozzle discharging through a mixing orifice as shown in figure 6.

Tests made with this arrangement showed that thorough mixing was obtained without the formation of drops at the orifice edges even at extremely rich fuel-air ratios. Leak-off from the nozzle was returned to the air stream by means of a small tube, shown in figure 6, to eliminate the slight error in the fuel-air ratio due to leakage. The vaporizing tank was provided with a water jacket. In a preliminary test, the minimum allowable jacket temperature was determined by running the engine at a rich mixture and gradually cooling the tank walls. A small wad of cotton on the end of a rod

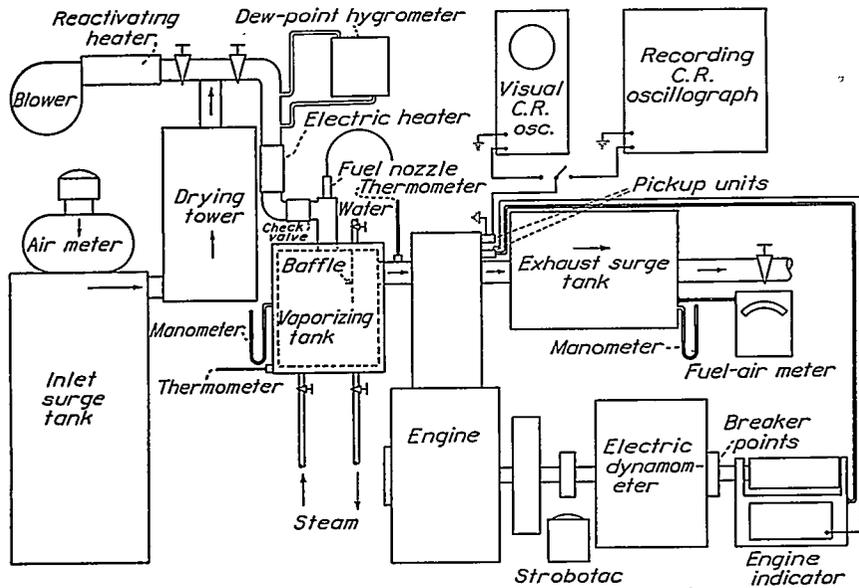


FIGURE 4.—Schematic layout of apparatus.

was inserted through a capped opening from time to time and brought into contact with the walls and bottom of the tank. By this means, the presence of condensate could be detected.

It was found that an iso-octane-air mixture, richer than any used in the actual tests, condensed when the jacket temperature was about 80° F and the pressure of the mixture was 29.9 inches of mercury. The water

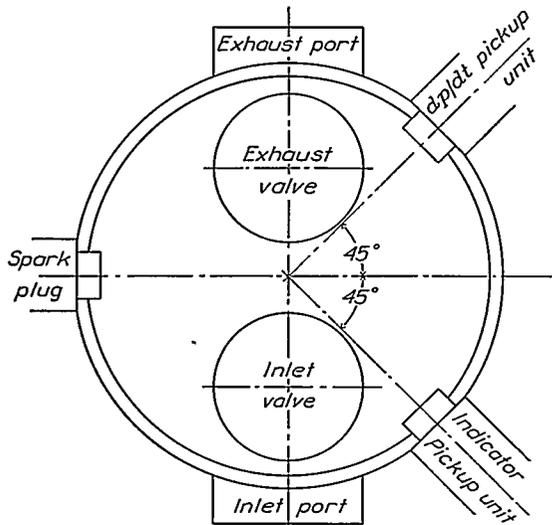


FIGURE 5.—Arrangement of pick-up units in cylinder head.

jacket was maintained at all times above this temperature so that no droplets or puddles might form on the sides or bottom, with consequent error of the mixture ratio.

The tank was also equipped with a safety valve, a baffle plate, and a water manometer. A check valve was placed between the tank and the heater to prevent injury to the drying tower and the air meter in case of a backfire.

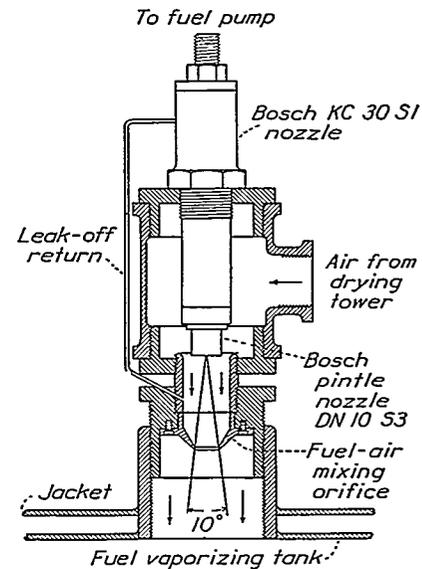


FIGURE 6.—Sectional view of fuel-air mixing system.

The pipe from the mixing tank to the engine was 1½ inches in diameter, 8 inches long, practically straight, and smooth inside. The reading of a mercury thermometer inserted in this pipe, clear of cylinder radiations, was taken as the mixture inlet temperature. The pipe was lagged with a magnesia covering.

This inlet system was found to result in unusual uniformity of combustion, as shown by the fine combustion line on the indicator diagram (fig. 7). Detonation was also unusually uniform as judged by ear.

#### EXHAUST SYSTEM

After leaving the engine cylinder, the exhaust gases were passed through a 5-inch length of 1½-inch pipe to a surge tank of about 5 gallons capacity, thence to the laboratory exhaust main. Pressure in the tank was increased by closing a gate valve in the exit from the tank or decreased by diminishing the pressure in the exhaust mains by means of the laboratory suction pump. An alcohol manometer and a Cambridge exhaust-gas analyzer were attached to the tank. For the sake of the comfort of the operators, the tank was fitted with a jacket through which cold water was continuously circulated.

#### MEASURING INSTRUMENTS

The dynamometer was of the conventional electric cradle type. The engine speed was set as nearly as possible at 1,200 rpm by means of a tachometer and was then accurately adjusted and maintained by observing the engine coupling illuminated by a Strobotac operating on a 60-cycle frequency. An M. I. T. balanced-pressure indicator (references 4 and 5) was used for obtaining pressure-crank angle diagrams in conjunction with M. I. T. diaphragm and "flapper-valve" type pressure units.

The visual cathode-ray oscillograph had a 5-inch tube. The Draper recording oscillograph (reference 6) was used in taking the rate-of-change-of-pressure ( $dp/dt$ ) records. This oscillograph consists of a high-speed camera and two cathode-ray tubes with specially designed amplifiers for giving a linear response over the range of frequencies associated with the pressure waves accompanying detonation. Only one of the tubes (No. 2) was used in the tests. The film was an ultraspeed panchromatic and was run through the camera at a speed of 49.6 inches per second.

The detonation pick-up unit was a Draper flat-diaphragm type (reference 6) having a natural fre-

quency of about 95,000 cycles per second. It was screwed into the side of the cylinder head with its diaphragm directly exposed to the cylinder pressures. It was located as near the exhaust valve as practicable and about  $135^\circ$  from the spark plug. The arrangement is shown in figure 5.

When an engine is detonating, the  $dp/dt$  wave, as shown in figure 8, is characterized by a "ragged" appearance to the right of the peak; whereas, when the engine is not detonating, the appearance of the wave form is as shown in figure 9.

In order to arrive at incipient detonation, the engine was run under conditions of no detonation while one of the variables affecting detonation, such as compression ratio, was varied until the part of the wave form to the right of the peak began to show the first signs of raggedness, as shown in figures 10 to 17. This adjustment was rather critical and the point could be detected with surprising accuracy.

Runs were made to determine the personal equation of the observer. The observer was asked to define the state of incipient detonation for a given set of operating conditions. All of the conditions were then maintained constant except the compression ratio,

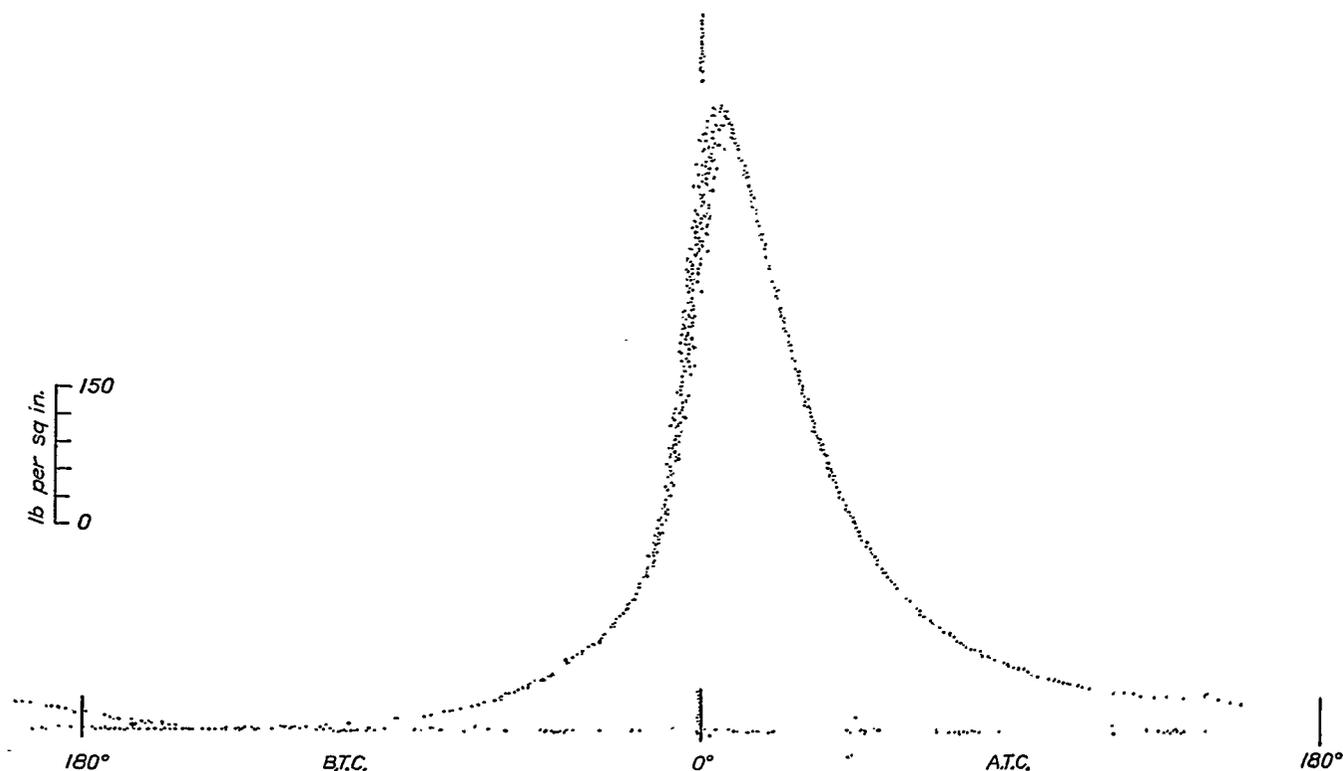


FIGURE 7.—Specimen heavy spring M. I. T. indicator diagram for point 1.

quency of about 95,000 cycles per second. It was screwed into the side of the cylinder head with its diaphragm directly exposed to the cylinder pressures. It was located as near the exhaust valve as practicable and about  $135^\circ$  from the spark plug. The arrangement is shown in figure 5.

The fuel-air ratio was computed by measuring the time required to empty a fuel burette of 42.2 cubic centimeter capacity while at the same time counting the revolutions of the air meter, all other factors being held constant. The fuel-air ratio was varied by means of a micrometer screw adjustment on the fuel pump.

## PROCEDURE

### METHOD USED TO MEASURE DETONATION

No one generally accepted standard of detonation intensity is prevalent today; hence, individual experi-

ments set their own standards and the comparison of results is unsatisfactory. Probably most experimenters judge the intensity of detonation by the characteristic knocking sound accompanying it. The accuracy of this method suffers not only from the personal equation of the observer but also from the general noise level around the engine.

When an engine is detonating, the  $dp/dt$  wave, as shown in figure 8, is characterized by a "ragged" appearance to the right of the peak; whereas, when the engine is not detonating, the appearance of the wave form is as shown in figure 9.

In order to arrive at incipient detonation, the engine was run under conditions of no detonation while one of the variables affecting detonation, such as compression ratio, was varied until the part of the wave form to the right of the peak began to show the first signs of raggedness, as shown in figures 10 to 17. This adjustment was rather critical and the point could be detected with surprising accuracy.

Runs were made to determine the personal equation of the observer. The observer was asked to define the state of incipient detonation for a given set of operating conditions. All of the conditions were then maintained constant except the compression ratio,

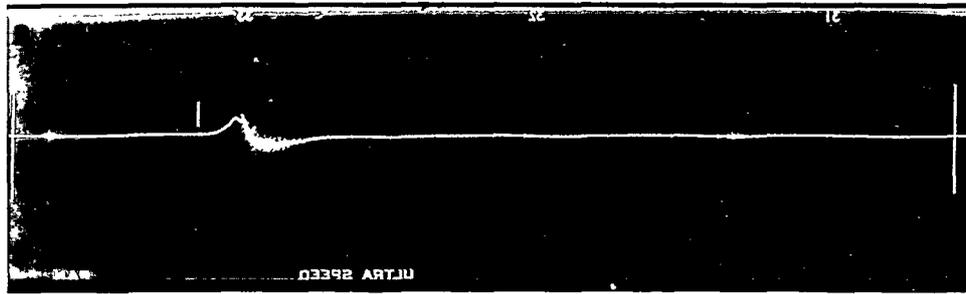


FIGURE 8.—Specimen rate-of-change-of-pressure record for detonating combustion.

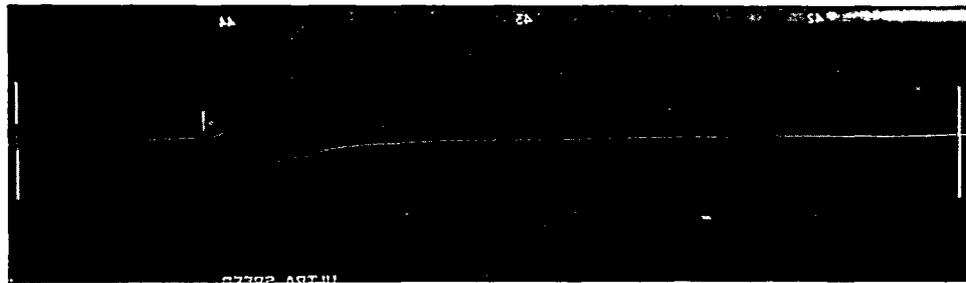


FIGURE 9.—Specimen rate-of-change-of-pressure record for nondetonating combustion.

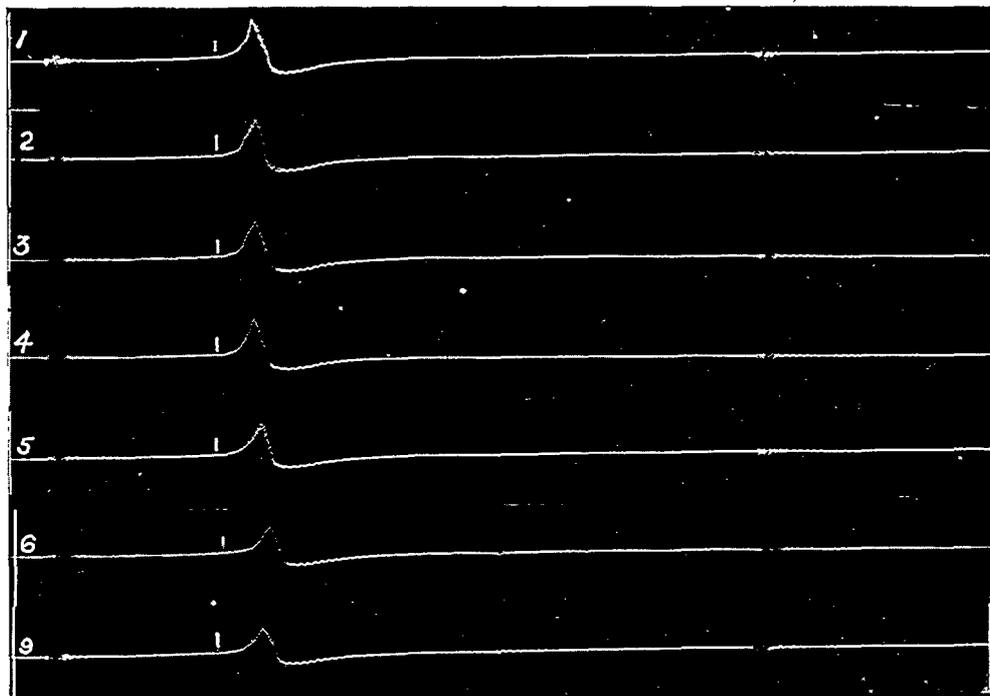


FIGURE 10.—Rate-of-change-of-pressure records for constant incipient detonation. Inlet-mixture temperature, 200° F; fuel-air ratio and compression ratio, variable; all other factors constant.

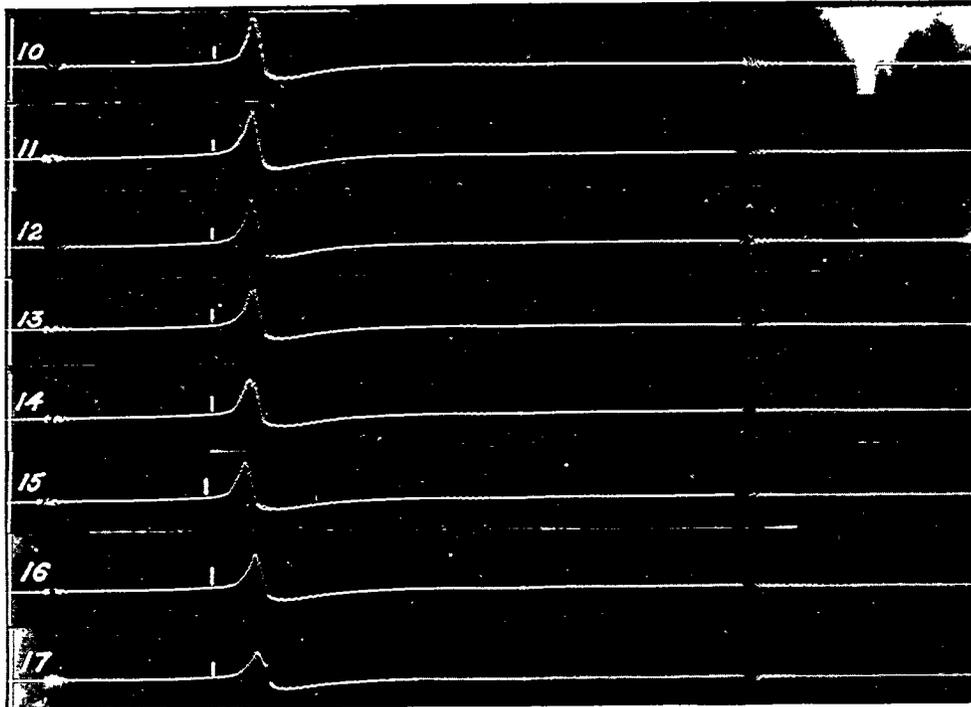


FIGURE 11.—Rate-of-change-of-pressure records for constant incipient detonation. Inlet-mixture temperature, 180° F; fuel-air ratio and compression ratio variable; all other factors constant.

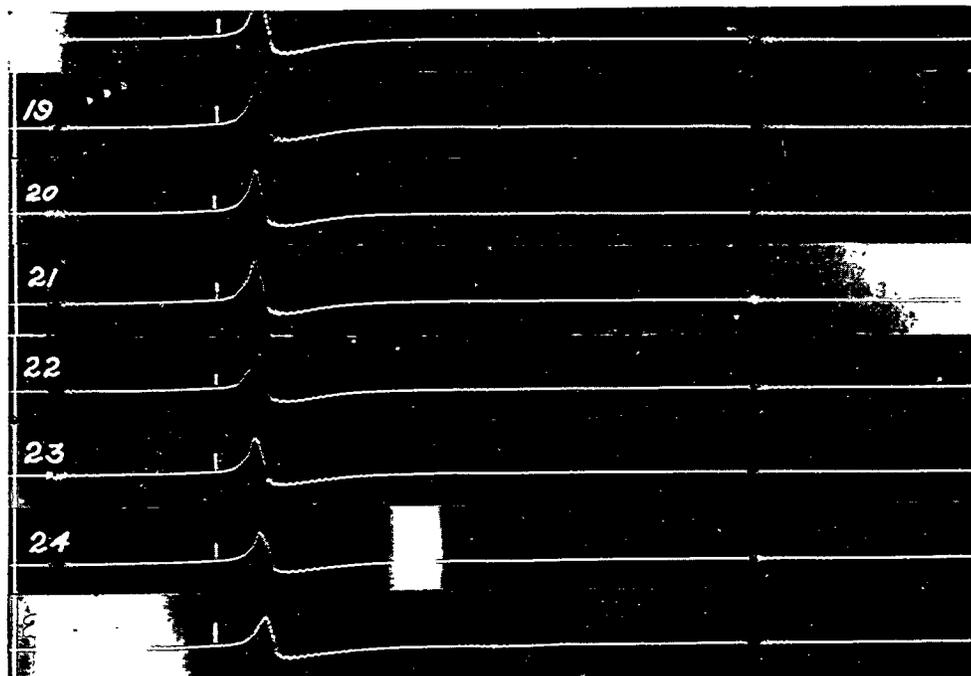


FIGURE 12.—Rate-of-change-of-pressure records for constant incipient detonation. Inlet-mixture temperature, 160° F; fuel-air ratio and compression ratio, variable; all other factors constant.

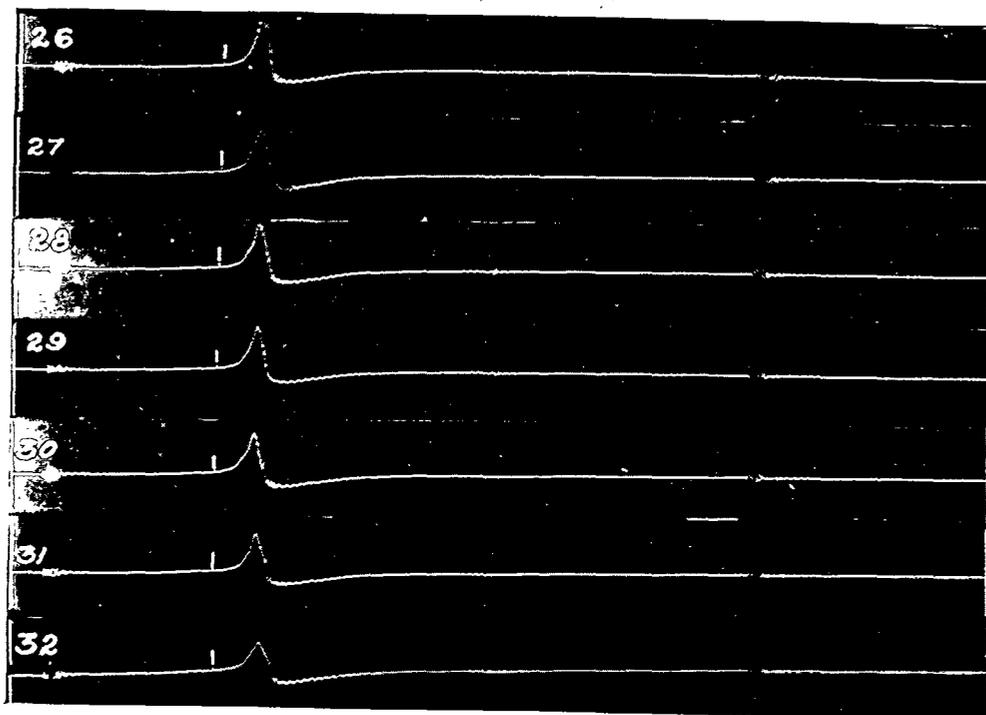


FIGURE 13.—Rate-of-change-of-pressure records for constant incipient detonation. Inlet-mixture temperature, 140° F; fuel-air ratio and compression ratio, variable; all other factors constant.

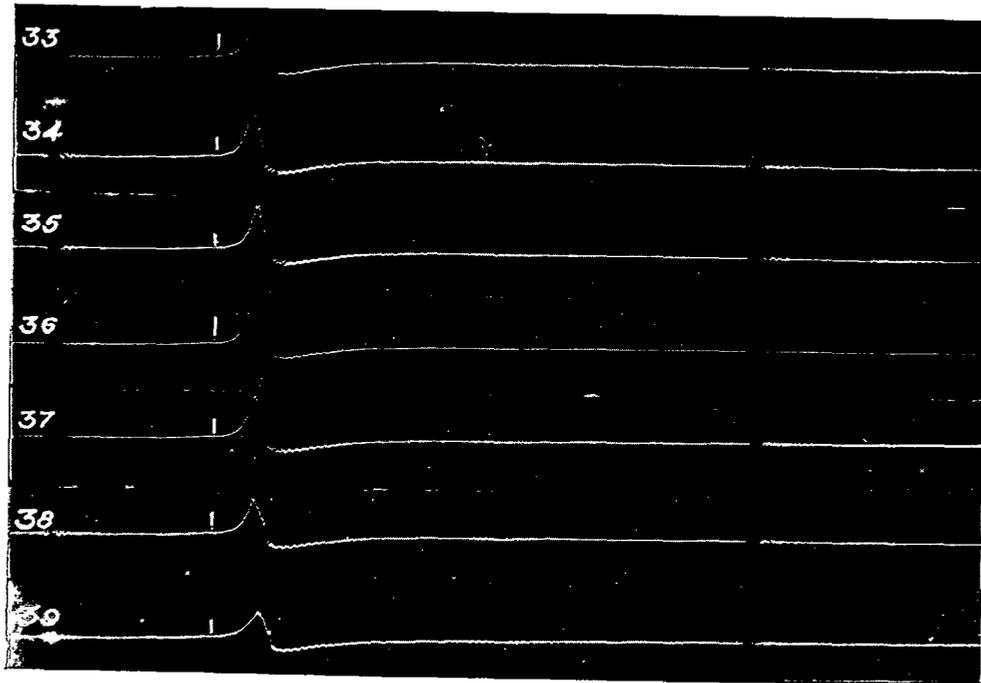


FIGURE 14 —Rate-of-change-of-pressure records for constant incipient detonation. Inlet-mixture temperature, 120° F; fuel-air ratio and compression ratio, variable; all other factors constant.

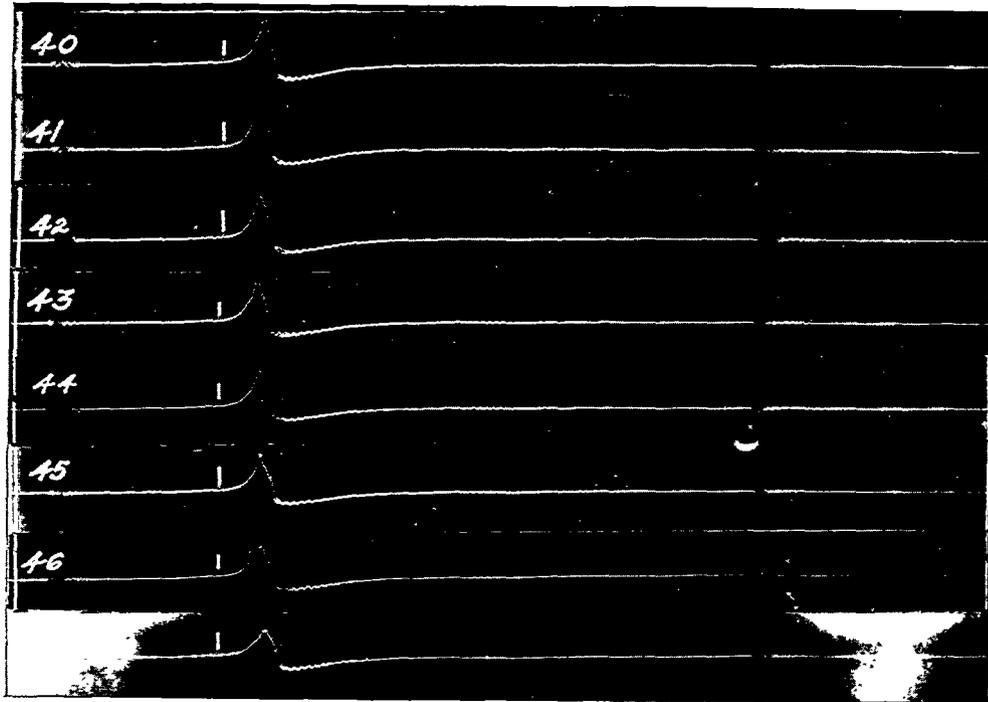


FIGURE 15.—Rate-of-change-of-pressure records for constant incipient detonation. Inlet-mixture temperature, 100° F; fuel-air ratio and compression ratio, variable; all other factors constant.

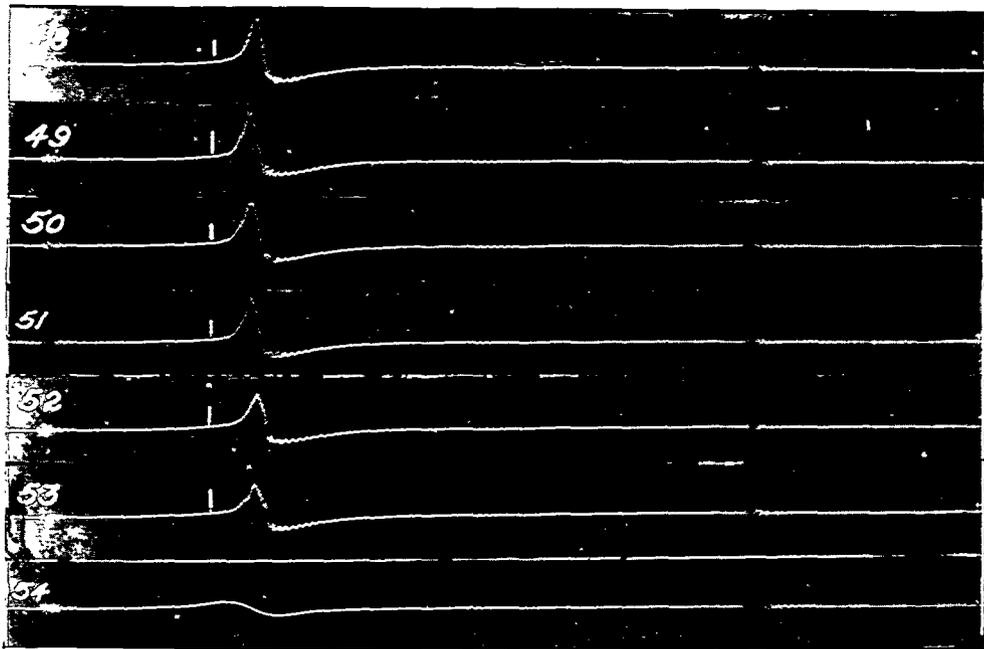


FIGURE 16.—Rate of-change-of-pressure records for constant incipient detonation. Inlet-mixture temperature, 80° F; fuel-air ratio and compression ratio, variable; all other factors constant. No. 54 is a calibration record.

which was varied by an assistant with a resulting change in the wave form shown on the oscillograph. The observer was then asked to direct the assistant which way to change the compression ratio to bring back the characteristic wave form of incipient detonation and to let the assistant know when the point was arrived at. Results of the test appear in table I and are compared

server in defining standard incipient detonation in the actual experiment was no more than 1 percent. In the following discussion, the expression "incipient detonation" will be used to mean "standard incipient detonation" as just defined. There is nothing absolute about this definition. Because it depends largely on judgment, the standard would vary somewhat with

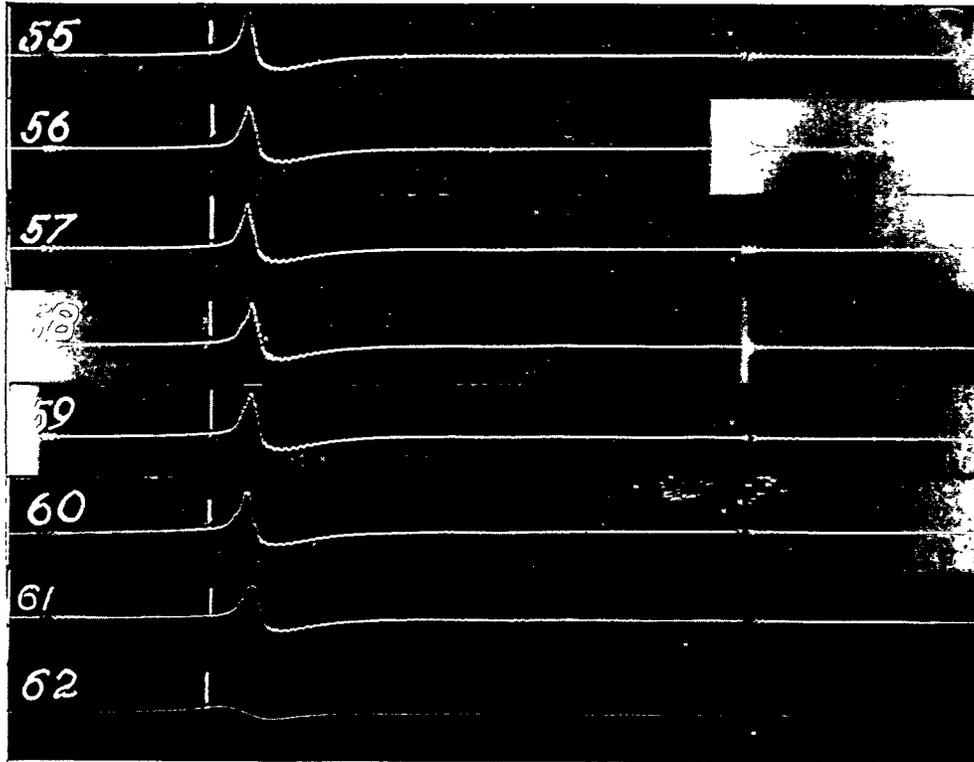


FIGURE 17.—Rate-of-change-of-pressure records for constant incipient detonation. Exhaust back pressure and compression ratio, variable; all other factors constant. No. 62 is a calibration record.

with a similar test where the detonation intensity was judged by ear.<sup>1</sup>

TABLE I.—THE CONSISTENCY OF THE OBSERVER IN DETECTING STANDARD INCIPIENT DETONATION

| Trial  | Compression ratio named by observer |        |
|--------|-------------------------------------|--------|
|        | By oscillograph                     | By ear |
| 1..... | 7.11                                | 7.01   |
| 2..... | 7.12                                | 7.02   |
| 3..... | 7.11                                | 7.12   |
| 4..... | 7.09                                | 6.99   |
| 5..... | 7.12                                | 7.02   |
| 6..... | 7.11                                | 6.98   |

Tests such as the foregoing could be repeated with about the same results. The maximum variation in table I for the oscillograph method is  $\frac{1}{4}$  percent and for the ear method is 2 percent; hence, it is reasonable to assume that the compression-ratio error of the ob-

<sup>1</sup> The compression ratios determined by ear and by oscillograph cannot be directly compared because the two tests were run at different times under slightly different conditions. Only the variation is significant.

different observers and would also depend on the sensitivity of the pick-up unit used. These objections are unimportant here because all the observations were made by the same observer and pick-up unit.

Records of what the observer judged to be incipient detonation are shown in figures 10 to 17. Some of the fine detail present on the negatives of these records was lost in reproduction but, in general, they present very well what the observer saw in the oscillograph. A record was taken for every point on the curves of figure 18 and is numbered to correspond.

The interval between the two vertical white lines, drawn at the extremities of the records shown in figures 10 to 17, represents the events in the cylinder from bottom center at the start of the compression stroke to the same point two revolutions later. All these records should be exactly the same length, 4.96 inches, and are so in the negatives; it was difficult to control the warping of the paper in printing and they appear to vary somewhat.

The disturbance to the extreme left is caused by the vibrations set up in the cylinder when the inlet valve

closes, and that farthest to the right is due to the exhaust valve closing. The low-frequency vibrations that appear in the trough are probably due to mechanical vibrations of the cylinder because their amplitudes could be increased by loosening the clamp on the cylinder. This effect is clearly shown in figure 9. All these factors are of no interest here.

The small vertical line just before the peak indicates the time at which the spark occurred. This mark was automatically recorded but, since it showed up only faintly, a heavier line was drawn for convenience.

It will be noticed that the detonation disturbances to the right of the peaks are reasonably constant for all the records. Records corresponding to high compres-

The engine and accessories were thoroughly cleaned and overhauled before making the runs.

First series.—The following variables that affect detonation were held constant at the values indicated:

Inlet-air humidity---- less than 0.12 grain per pound dry air.  
 Inlet-mixture pressure\_ 28.7 in. (730 mm) Hg.  
 Exhaust back pressure\_ 30.7 in. (780 mm) Hg.  
 Coolant temperature\_ 211° F.  
 Spark advance----- 30°.  
 Engine speed----- 1,200 rpm.  
 Fuel----- C. F. R. reference fuel S-1 (iso-octane).

The inlet-mixture pressure was taken as the pressure in the vaporizing tank and the exhaust back pressure, as the pressure in the exhaust surge tank. The pres-

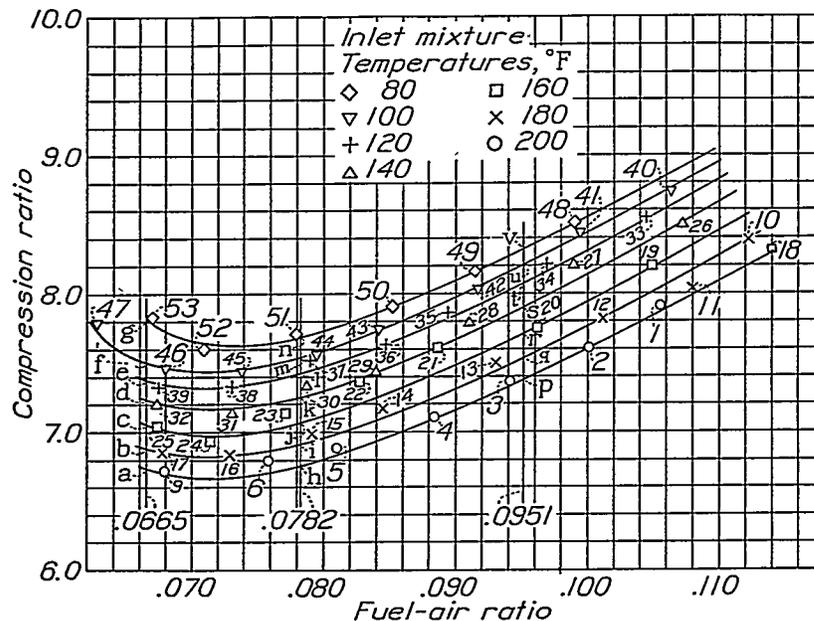


FIGURE 18.—Effect of fuel-air ratio on compression ratio for constant incipient detonation. C. F. R. engine; 1,200 rpm; spark advance, 30°; inlet-mixture pressure, 28.7 inches of mercury; exhaust back pressure, 30.7 inches of mercury; fuel, iso-octane; coolant temperature, 211° F.

sion ratios appear at the top of each set and decrease progressively to the lower values at the bottom. The heights of the peaks decrease as the compression ratio is lowered. For high compression ratios, incipient detonation is first detected by the entire right-hand side of the wave becoming ruffled; whereas, for low compression ratios, it is first detected by the appearance of only a small discontinuity. Records 54 and 62 are calibration records taken with the engine motoring at 1,200 rpm and with the compression ratio set at 10.0.

#### EXPERIMENTAL TESTS

The experimental work consisted principally of one continuous series of runs of about 17 hours duration in which the various combinations of inlet temperature, compression ratio, and fuel-air ratio for constant detonation were determined. A secondary series of runs was made at a later date, in which the effect of exhaust-gas dilution was investigated.

sure in the vaporizing tank was maintained at 28.7 inches Hg so as to be always below the barometer and hence controllable by throttling. Similarly, the exhaust surge-tank pressure was kept at 30.7 inches Hg so as to be always above the barometer and hence controllable by restricting the flow of exhaust gases to the exhaust mains. This procedure was also desirable for the better operation of the exhaust-gas analyzer.

The engine was allowed to warm up for about 2 hours under the foregoing fixed conditions with an inlet temperature near 200° F, a compression ratio about 6.0, and a fuel-air ratio approximately 0.080. At the end of the warm-up period, the apparatus was in thermal equilibrium. The inlet temperature was then carefully adjusted to 200° F. The fuel-air ratio was adjusted until the fuel-air meter read 0.1005. The compression ratio was increased until incipient detonation appeared on the visual cathode-ray oscillograph. The observer then threw a switch that removed the input from the visual oscillograph and transferred it to the Draper

recording oscillograph where a photographic record of the wave form was made by an assistant.

Simultaneous readings were taken of the air-meter speed and the time for consumption of 42.2 cubic centimeters of fuel. At the same time, an assistant took an indicator diagram with the M. I. T. balanced-pressure indicator using a spring having a rate of 150 pounds per square inch per inch and a diaphragm-type pick-up unit. A reproduction of this diagram (point 1) is shown in figure 7.

This procedure was repeated using successively leaner fuel-air ratios but maintaining inlet temperature and detonation intensity constant. At least 10 min-

of 80° F. The consistency of the dynamometer readings was noted as a check on possible preignition. The ignition switch was cut from time to time, but no evidence of preignition was observed. The oil pressure remained at 28 pounds per square inch; the oil temperature, at 147° F; and the coolant temperature, at 211° F throughout the runs. All the experimental data are given in table II.

Second series.—The effect of residual gas pressure on the compression ratio for incipient detonation was obtained by varying the pressure in the exhaust surge tank and determining the corresponding change in compression ratio required to maintain the detonation

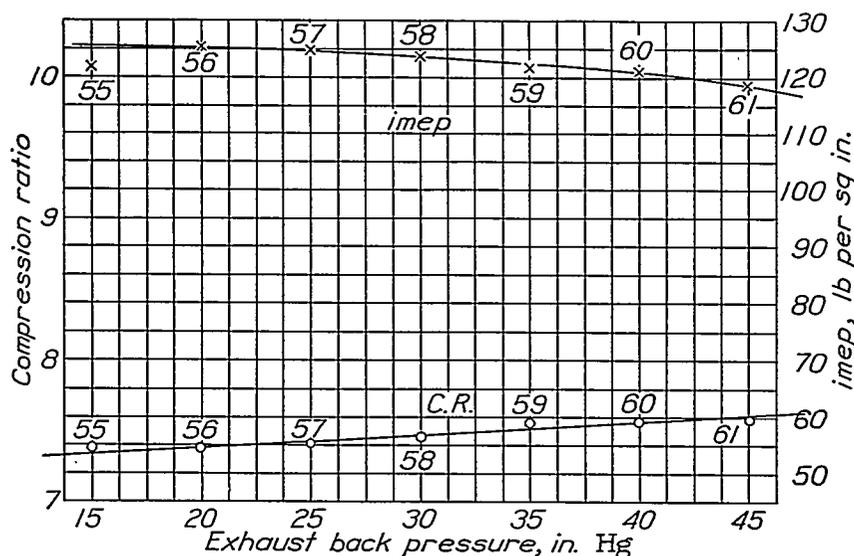


FIGURE 19.—Effect of exhaust back pressure on compression ratio and indicated mean effective pressure for constant incipient detonation. C. F. R. engine; 1,200 rpm; inlet mixture temperature, 120° F; inlet-mixture pressure, 28.7 inches of mercury; fuel-air ratio, 0.0782; spark advance, 30°; fuel, iso-octane; coolant temperature, 211° F.

utes was allowed between each change to insure mixture equilibrium in the vaporizing tank. As the fuel-air ratio approached a value of approximately 0.065, the engine commenced to misfire occasionally and the  $dp/dt$  curve became erratic and difficult to judge. When either of these conditions obtained, the investigation at this inlet temperature was discontinued and a new one, at 20° F lower temperature, was started. In this way the "isothermal" lines of figure 18 and the records of figures 10 to 17 were obtained. About 20 minutes was allowed for the apparatus to come to thermal equilibrium for each change of inlet temperature.

Extreme caution was used throughout to insure reliability of results. The speed was maintained at exactly 1,200 rpm by means of the Strobotac. A careful check was kept on the barometer and the room temperature and any changes were allowed for in the calculation of air consumption. The humidity of the inlet air was constantly checked for any significant variations. The vaporizing tank was checked from time to time for the presence of condensate but was found to be dry at all times even at the lowest inlet temperature

constant while all other variables were held constant. The values of the variables held constant were:

|                                |   |
|--------------------------------|---|
| Inlet air humidity.....        | less than 0.12 grain per pound dry air.   |
| Inlet-mixture pressure.....    | 28.7 in. (730 mm.) Hg.                    |
| Inlet-mixture temperature..... | 120° F.                                   |
| Fuel-air ratio.....            | 0.0782.                                   |
| Coolant temperature.....       | 211° F.                                   |
| Spark advance.....             | 30°.                                      |
| Engine speed.....              | 1,200 rpm.                                |
| Fuel.....                      | C. F. R. reference fuel S-1 (iso-octane). |

The values of the inlet-mixture temperature and the fuel-air ratio chosen represented approximate mean values for the first series.

The pressure in the exhaust surge tank was first reduced to 15 inches Hg absolute and the compression ratio was set to give incipient detonation. A  $dp/dt$  record and an indicator diagram were then taken as in the first series.

The pressure in the exhaust surge tank was then gradually increased, by 5-inch Hg increments, to 45 inches Hg absolute and the corresponding compression ratios were determined. No evidence of preignition or

afterfiring was observed during the run either from the brake readings or by cutting the ignition switch but, when the run was finished and the ignition shut off, the engine fired a few times just before coming to rest.

Results of this series are tabulated in table III and plotted in figure 19 as compression ratio and indicated mean effective pressure against exhaust back pressure.

For the calculations of the temperature of the last part of the charge to burn, it was found convenient to use as a reference the point on the compression stroke at which the pressure in the cylinder was atmospheric. This point was determined by making a short run in which some light-spring diagrams were taken. The

#### ESTIMATE OF TEMPERATURE OF THE END GAS

A general description of the method used in the first series is given here and a detailed calculation, using actual values, is carried out in appendix B.

Data obtained from the experiment and used in computation appear in table II. Each point is numbered and gives all the data pertaining to incipient detonation for a given setting of inlet temperature, compression ratio, and fuel-air ratio. The data are plotted in figure 18 as points on constant temperature curves with compression ratio as ordinate and fuel-air ratio as abscissa.

The procedure used in calculating the weight of

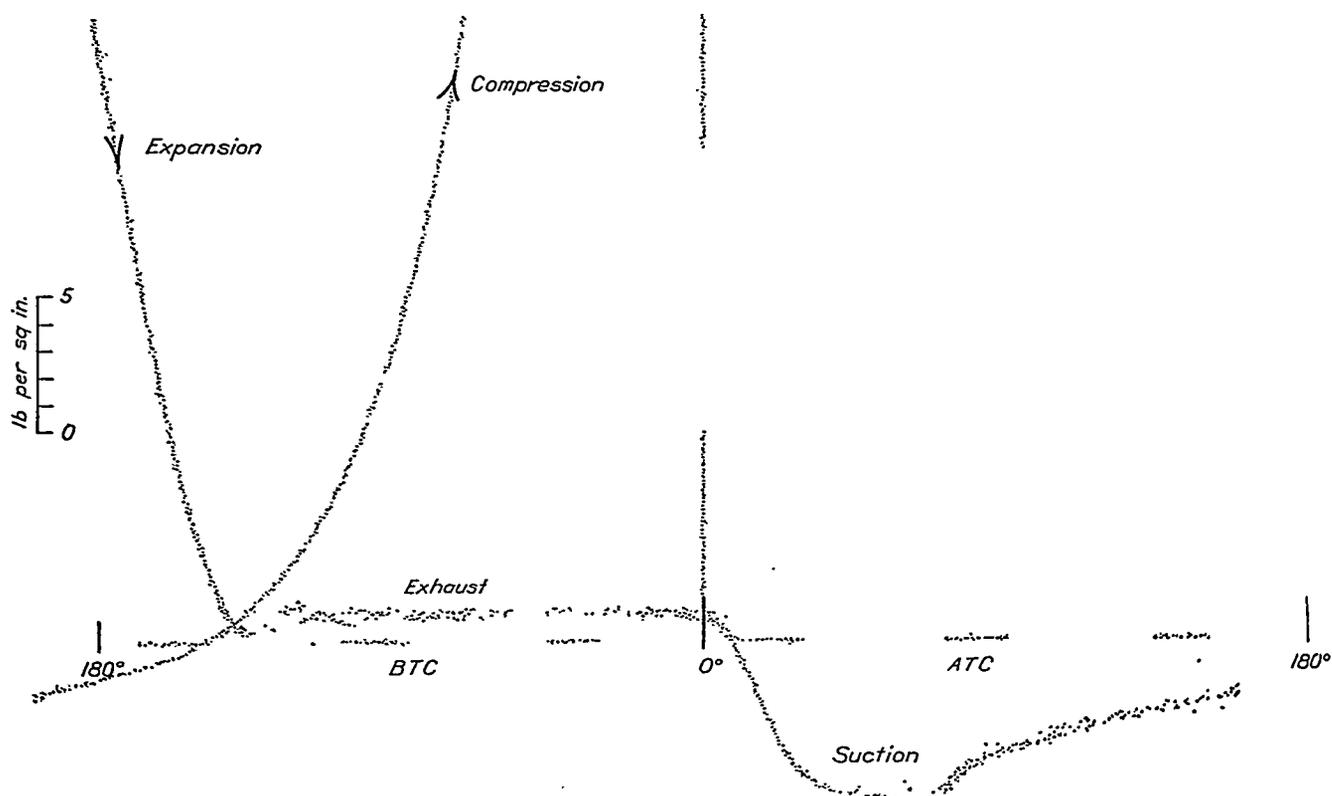


FIGURE 20.—Specimen light-spring M. I. T. indicator diagram. C. F. R. engine; incipient detonation; 1,200 rpm; inlet-mixture temperature, 120° F; inlet-mixture pressure, 28.7 inches of mercury; exhaust back pressure, 30.7 inches of mercury; compression ratio, 7.45; spark advance, 30°; fuel, iso-octane; barometer, 30.0 inches of mercury.

intersection of the compression and the atmospheric lines on these diagrams gave the desired point, which was located at 146° before top center. The variation of this point with different operating conditions proved to be negligible under the conditions of this experiment.

A spring having a rate of 5 pounds per square inch per inch was used on the indicator and the diaphragm unit was replaced by the "flapper valve" type. (See reference 5.) A small surge tank, placed in the line between the cylinder unit and the indicator, allowed a more uniform control of the indicator pump and resulted in well-defined diagrams. A specimen light-spring diagram is shown in figure 20.

charge in the cylinder was as follows: The number of pounds of air and the number of pounds of fuel admitted to the cylinder each stroke were computed from air and fuel measurements. An estimate was then made of the weight of residual gas and the three values were added to give estimated pounds of charge per stroke. This value was then used to recompute the percentage of residual gas as follows: A point was taken arbitrarily on the expansion stroke where combustion was considered complete. The specific volume was computed by dividing the cylinder volume at that point by the estimated weight of charge. The pressure at the point was determined from the indicator diagram.

The characteristics of the charge were considered to be given by the thermodynamic charts published in reference 7. If the chart for the products of combustion was entered with this specific volume (modified as explained in appendix B) and pressure, and the gas was considered to expand adiabatically (and at constant entropy) to the exhaust-tank pressure, a point was located that corresponded to the specific volume of the residual gases. The clearance volume divided by this specific volume gave a new estimate of the weight of residual gas per stroke from which the percentage of residual was computed. The process was repeated again using the new percentage and a still better approximation obtained. One or two trials usually sufficed.

With the percentage residual carefully determined, the total weight of charge per stroke was accurately known. With this value and the maximum pressure from the indicator diagram, the maximum end-gas temperature was computed, using thermodynamic characteristics of the fresh charge as given in appendix C. This procedure was as follows: A point was chosen on the compression stroke and the specific volume  $V_0$  of the charge was computed. This point was taken at  $146^\circ \text{B. T. C.}$  ( $8^\circ$  after inlet valve closing) at which point the pressure  $P_0$  in the cylinder was atmospheric. (See figure 20.) The temperature  $T_0$  at this point was determined by the relation

$$T_0 = \frac{P_0 \times V_0}{B} \quad (1)$$

where  $B$  is the gas constant and varies with the fuel-air ratio according to the relation

$$B = \frac{1544}{m_c} \quad (2)$$

where  $m_c$  is the molecular weight of the charge.

The last part of the charge to burn was considered as an infinitesimal volume that was adiabatically compressed from this point by the upward motion of the piston and was further compressed by the expanding gases behind the flame front. Its temperature  $T_3$  was calculated from the equation given on page 278 of reference 8:

$$\log T_3 = \log T_0 + \frac{B}{\left(a + \frac{B}{J}\right)J} \log \frac{P_3}{P_0} - \frac{b}{2.30\left(a + \frac{B}{J}\right)} (T_3 - T_0) \quad (3)$$

where

$J$  mechanical equivalent of heat, 778 ft-lb/Btu.

$a$  first coefficient in the specific-heat equation at constant volume for the charge.

$b$  second coefficient in the specific-heat equation at constant volume for the charge.

The specific-heat equations are given in appendix B. The results of the calculations are plotted in figure 21 as  $P_3$  against  $T_3$ . The detailed procedure arranged in a form suitable for computation appears in table IV of appendix B.

The method used for calculating the temperature and the pressure of the last part of the charge to burn for

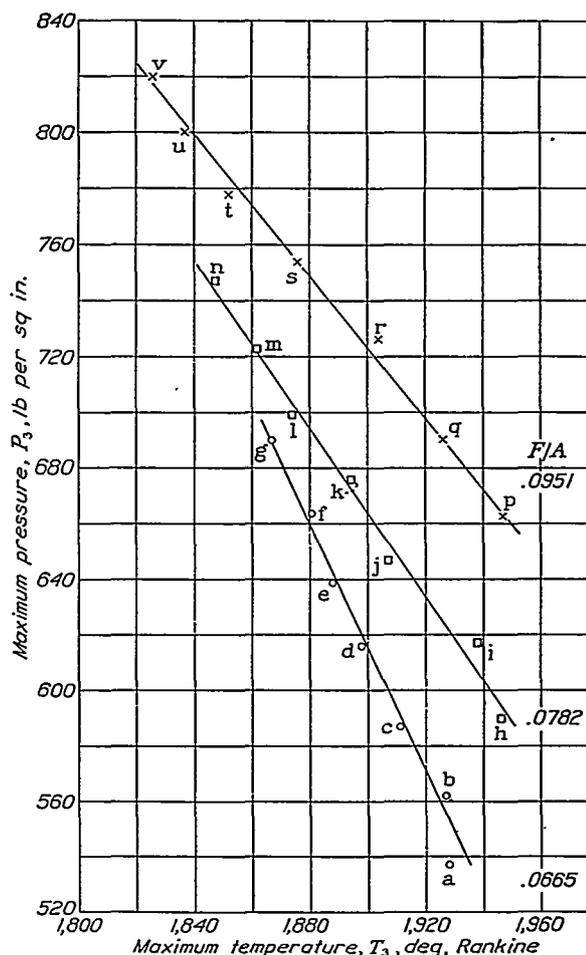


FIGURE 21.—Effect of end-gas temperature on maximum permissible end-gas pressure for constant incipient detonation at various fuel air ratios. C. F. R. engine; 1,200 rpm; inlet-mixture pressure, 28.7 inches of mercury; exhaust back pressure, 30.7 inches of mercury; spark advance,  $30^\circ$ ; fuel, iso-octane.

the runs in which residual gas pressure was the independent variable (second series) was identical with the method used in the first series. The computation form is given in table V of appendix B and the results of the computations are plotted in figure 22 as  $P_3$  and  $T_3$  against percentage residual. The curve of compression ratio against percentage residual is also included in this figure.

The value of  $T_3$  could also have been obtained by means of the thermodynamic charts with much less effort than that involved in the use of equation (3) but, unfortunately, some of the results were outside of the range of the charts.

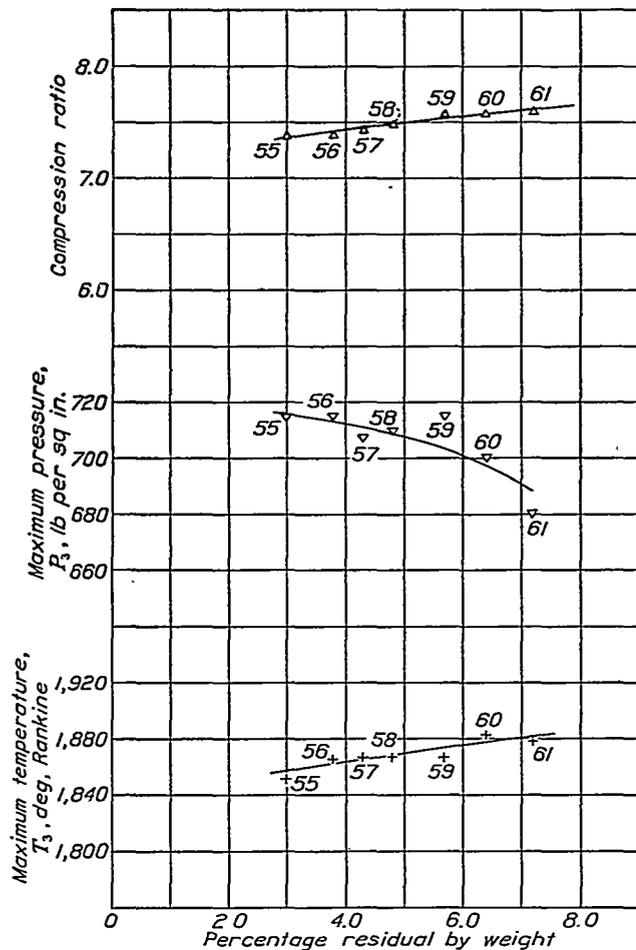


FIGURE 22.—Effect of percentage residual gas on maximum permissible end-gas temperature and pressure and maximum permissible compression ratio for constant incipient detonation. C. F. R. engine; 1,200 rpm; inlet-mixture temperature, 120° F; inlet mixture pressure, 28.7 inches of mercury; fuel-air ratio, 0.0782; spark advance, 30°; fuel, iso-octane.

PRECISION OF THE RESULTS

Measurements of air consumed and of pressure in the cylinder made it possible to compute the end-gas temperature with the following assumptions:

1. Expansion of the residual gas in the cylinder is isentropic from a point slightly before exhaust valve opening to the pressure in the exhaust surge tank.
2. The cylinder contents after combustion have thermodynamic characteristics as given by the charts of reference 7.
3. Compression of the end gas is isentropic from the point of inlet closing to maximum pressure.

Assumptions (1) and (2) affect only the residual gas content and hence contribute little error to the final result.

The third assumption may be the source of some error due to heat transfer to and from the cylinder walls and from the burned to the unburned portion of the charge. Heat transfer during the compression stroke is small because the average charge temperature is not far from the cylinder-wall temperature. During combustion

there are high temperature differences between the burned and the unburned portions of the charge and between the unburned portion of the charge and the cylinder walls; but, owing to the rapidity of the combustion process, there is probably very little heat energy transferred by conduction and convection. There is undoubtedly some energy transfer by radiation to the unburned charge, most of which must come from the burned charge due to selective absorption by the unburned portion. Radiant energy thus transferred does not necessarily appear in the form of heat energy. It has been suspected that excitation by radiation of the unburned charge has an appreciable effect on the detonation process if not upon the temperature of the unburned charge; the magnitude of the effect has yet to be shown.

The temperature and the pressure of the end gas were taken as the criterion of detonation rather than the temperature and the density because the pressures could be directly measured. Density factors seemed not to present any particular advantages.

An estimate of  $\pm 3$  percent is believed to be a safe value for the over-all experimental precision. Errors due to variations in speed, spark timing, humidity, chemical composition of mixture, inlet pressure, exhaust pressure, and coolant temperature were negligible. Errors in determining compression ratios for incipient detonation are estimated to be less than 1 percent. (See table I.) Measurements of inlet-mixture temperatures were probably good to within  $\pm 2$  percent

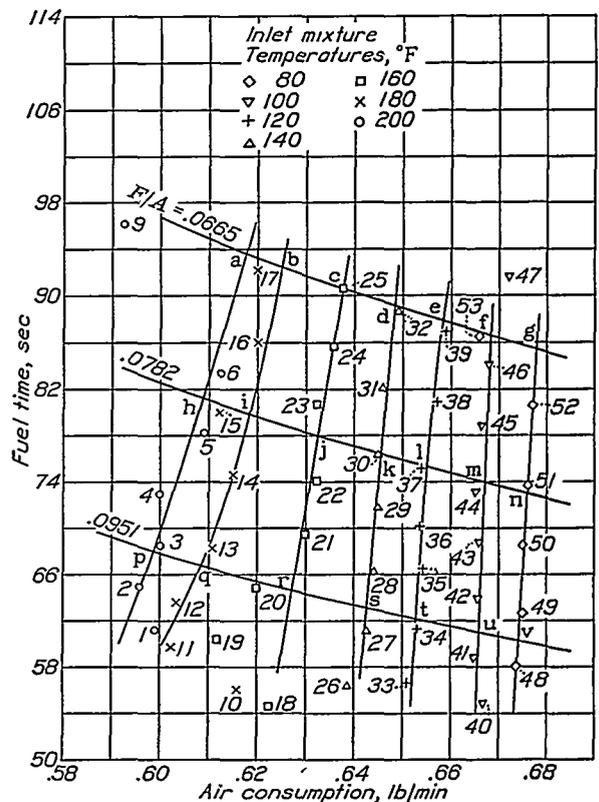


FIGURE 23.—Interpolation curves for determining air consumption for end-gas calculations.

because all the fuel was completely vaporized before coming in contact with the thermometer bulb and there was no possibility that the bulb became wet. Time was allowed for the thermometer to come to equilibrium after a temperature change. Determinations of fuel-air ratio were probably the greatest source of error owing to the difficulty in measuring air consumption precisely. Reference to figure 23 shows that, at the low inlet-mixture temperatures, the air measurements are consistent but, at the two highest temperatures, they are erratic. The reason for this lack of agreement is not clearly understood.

On the basis of these measurements, the fuel-air ratio is estimated to be in error by no more than 1 percent for inlet-mixture temperatures between 80° and 160° F and probably not more than 3 percent for inlet-mixture temperatures between 180° and 200° F.

#### COMPARISON OF RESULTS WITH THOSE OF REFERENCE 2

It is interesting to compare the results of this report with those of reference 2 where a somewhat simpler, although probably less accurate, method was used to compute the end-gas conditions.

The principal differences in the two methods are as follows: In the present report, pressures were determined by measurement with a balanced-pressure indicator; whereas, in reference 2, pressures were computed and the assumption was made that maximum pressure occurred at top center. In reference 2, the process of induction was assumed to be adiabatic. This assumption was unnecessary in the present report. The authors of reference 2 also assumed that the burned and the unburned charge had the characteristics of perfect gases. In the present report, due allowance was made for the thermodynamic characteristics of both media in accordance with the best available data. In reference 2 it was assumed that combustion is equivalent to the addition of a certain amount of sensible heat to the assumed perfect gas medium. This assumption was also unnecessary with the present method of calculation.

In view of the differences in the assumptions, it is not surprising to find certain differences in a direct comparison of results.

The density and the temperature of the end gas were determined in reference 2 according to the following equations:

$$K\rho_3 = \frac{RP_1}{T_1} \left( 1 + \frac{H}{c_v T_1 R^{\gamma-1}} \right)^{\frac{1}{\gamma}} \quad (4)$$

$$T_3 = T_1 R^{\gamma-1} \left( 1 + \frac{H}{c_v T_1 R^{\gamma-1}} \right)^{\frac{\gamma-1}{\gamma}} \quad (5)$$

where

$K$  a constant.

$\rho_3$  density of end gas.

$R$  compression ratio.

407300°—41—29

$P_1$  inlet-air pressure.

$T_1$  inlet-air temperature.

$c_v$  specific heat, 0.25.

$\gamma$  adiabatic coefficient, 1.29.

$T_3$  temperature of end gas.

$$H = \frac{E_{com} \times 18000 \times F/A}{1 + F/A}$$

$E_{com}$  is the combustion efficiency and varies with the fuel-air ratio according to the curve of figure 4 of reference 9.

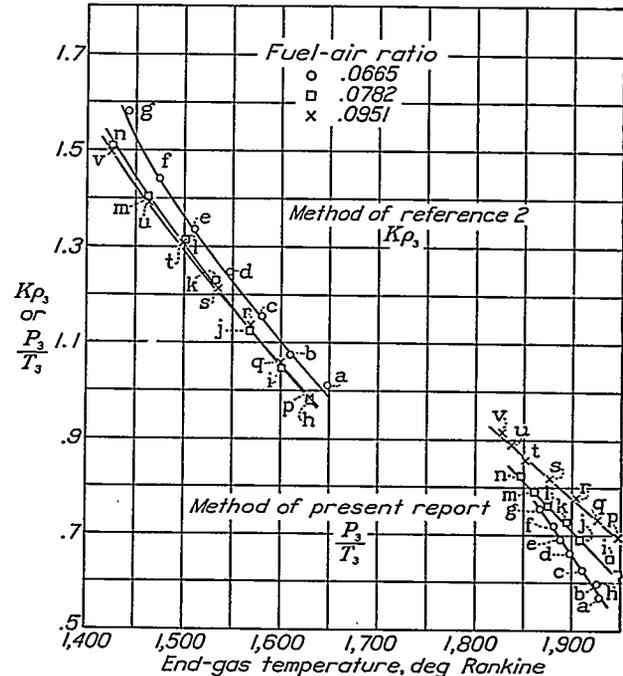


FIGURE 24.—Comparison of effect of end-gas temperature on maximum permissible end-gas density as determined by the methods of reference 2 and the present report.

Values of  $K\rho_3$  and  $T_3$  have been computed using values  $R$ ,  $P_1$ , and  $T_1$  from the data of the present report. Values of the inlet-mixture temperature were used for  $T_1$ , expressed in degrees Rankine, and  $P_1$  was expressed in inches of Hg. The results are plotted in figure 24. It will be noticed that the maximum permissible end-gas density at any given end-gas temperature decreases as the fuel-air ratio is increased, which is in accordance with the results given in reference 2.

Values of end-gas density were also computed from the temperature and the pressure of the end gas, as determined by the method of the present report. The density was expressed as  $P_3/T_3$ , in which  $P_3$  was converted to inches of mercury, which differs from the  $K\rho_3$  of reference 2 by the value of  $K$  only, which is immaterial here. The results are also plotted in figure 24. Here the maximum permissible end-gas density at any given temperature increases as the fuel-air ratio is increased, which is contrary to the results of reference 2.

As a further illustration, the temperature  $T_3$ , as computed from equation (3), is plotted in figure 25 against  $T_3$  as computed from equation (5). The scatter of the

points, the different temperature ranges, and the deviation of the general slope of the points from a 45° line shows clearly the disagreement of the two methods of computing end-gas temperatures. In the same figure, values of  $P_3/T_3$  are also plotted against  $Kp_3$ , as computed from equation (4), for the same set of data and appear as three distinct curves. If both methods took proper account of the influence of fuel-air ratio, the points should lie on a single curve.

Additional analysis by Rothrock of the experimental data of reference 2 indicates that the apparent reversal of the effect of fuel-air ratio is principally due to the difference between the measured maximum pressure used in the present report and the computed maximum

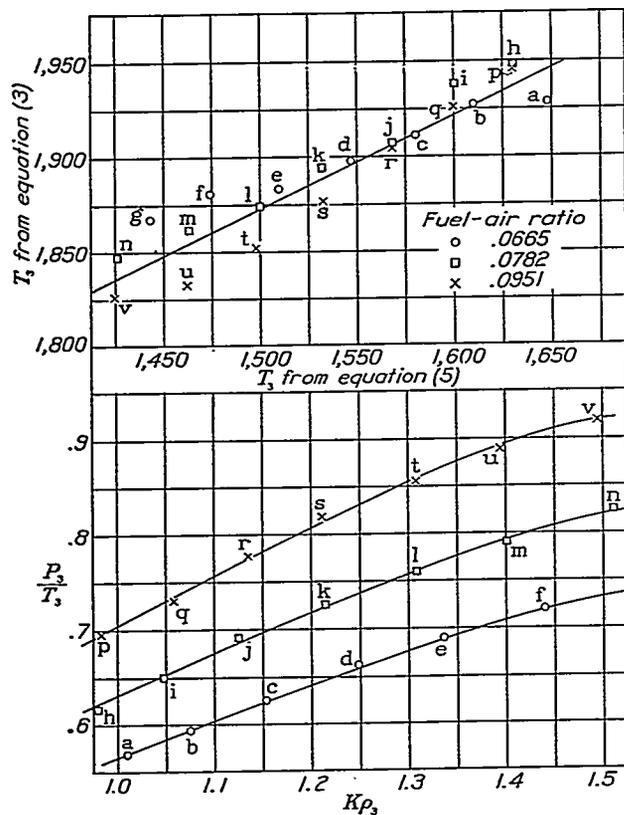


FIGURE 25.—Comparison of end-gas temperatures and density factors calculated by the methods of reference 2 and the present report.

pressure used in reference 2. When the experimental results of reference 2 are used in connection with maximum pressures that were measured but not presented in this reference, the trends agree with those shown in the present report. Apparently the method of computation of maximum pressure used in reference 2 should not be used when a high degree of accuracy is required.

Rothrock also shows that equations (4) and (5) can be modified to give results consistent with those of the present report by a correction of the values of  $H$  or  $R$ , or both, when it is required to determine the effect of fuel-air ratio on end-gas conditions. This effect is small; an error of 2 percent in computing end-gas temperatures is sufficient to mask the effect completely.

Such small margins seem to preclude the feasibility of approximate analysis, at least in the present state of the knowledge of the phenomena, and there seems to be no shorter method than to make a painstaking accounting of all the factors that can be measured, in order that these effects can be noticed at all.

It was mentioned in reference 2 that the simplified density factor,  $RP_1/T_1$ , was affected by compression ratio to a negligible extent in engines of large bore but, for the C. F. R. engine, this statement was not true. As a matter of interest in this connection, values of  $RP_1/T_1$  against compression ratio are plotted in figure 26. The curves bear out the exception made for the C. F. R. engine.

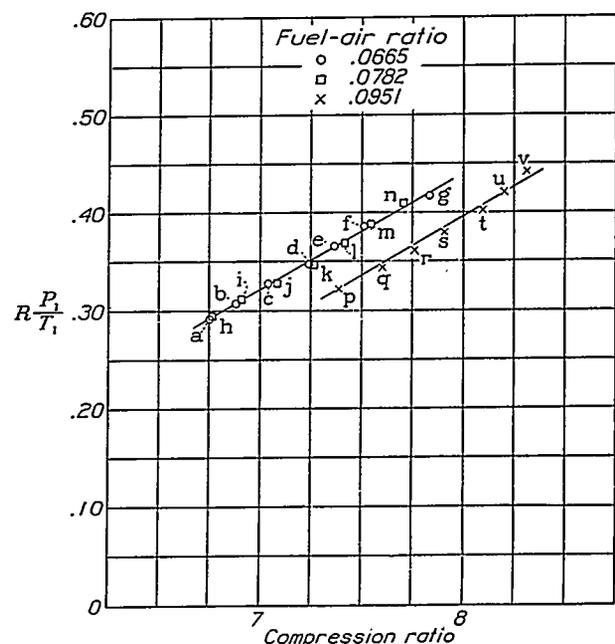


FIGURE 26.—Variation of  $RP_1/T_1$  with compression ratio for various fuel-air ratios. C. F. R. engine.

**SUGGESTION FOR FURTHER STUDY**

The present study was made at constant engine speed and therefore did not cover the question of the effect of time or combustion rate on detonation. As a topic for further study, an investigation of the effect of pressure-time and temperature-time relations in the end gas is suggested in order to try either to eliminate the time variable or to establish its importance.

**CONCLUSIONS**

1. Rich mixtures showed higher maximum end-gas temperatures for incipient detonation, in contrast to the results of reference 2.
2. Fuel-air ratio for maximum detonation was found to be 0.072. This ratio may be compared with the value 0.080 given in reference 2, using 85 percent iso-octane.
3. Increasing the residual gas content by increasing back pressure and maintaining inlet pressure constant slightly reduced the tendency to detonate.

4. A technique has been devised that provides unusual cyclic reproducibility and, to a fair degree of precision, makes possible the determination of the state of the end gas at any instant.
5. A method of computing end-gas conditions has been developed that is more accurate than the method of reference 2.
6. Different fuel-air ratios gave different relations of maximum end-gas pressure to maximum end-gas temperature. Whether the difference is due to difference in the pressure-time relationships that accompanies a change in charge composition cannot be stated without further investigation.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY,  
CAMBRIDGE MASS., November 15, 1939.

#### APPENDIX A HUMIDITY CONTROL DEHUMIDIFIER

The air supply to the engine was dehumidified by means of a drying tower (fig. 27), consisting of an outer cylindrical shell in which was placed a removable cylinder containing the drying agent. Air from the surge tank was led into the tower so as to pass through the drying tower from the bottom upward. Considerable care was taken in selecting the drier best suited for the purpose, and after experimenting with Silica Gel, calcium chloride, anhydrous calcium sulphate, and activated alumina, it was decided that activated alumina was most satisfactory as regards cost, efficiency, and durability. About 70 pounds of number 2 and 4 mesh alumina were used and the dimensions of the bed were 9 inches diameter by 40 inches long. This quantity was found sufficient to dry the air at high efficiency for about 25 hours of engine operation. Air from the drying tower was found to have a dew point of about  $-64^{\circ}$  F. Activated alumina heats up while absorbing moisture and, if this heat is not removed, the drying efficiency falls. This difficulty was overcome by imbedding a cooling coil, consisting of about 50 feet of  $\frac{3}{8}$ -inch copper tubing, in the tower and allowing cold water to run through it while in use.

When the drying agent was exhausted, it was reactivated by blowing hot air through it overnight. A small vacuum-cleaner blower and a 5,000-watt electrical resistance heater were found useful for this purpose. The whole tower was covered outside with magnesia pipe covering  $1\frac{1}{2}$  inches thick to prevent heat losses during reactivation. The cooling coil was arranged so that steam or cold water could be passed through it and, at the start of reactivation, the steam was turned on to help bring the tower and the bed to temperature. After about an hour, the steam was turned off and the

reactivation was carried on by only the blower and the heater.

The temperature of the reactivating air was maintained at  $575^{\circ}$  F and, from a comparison of the entering and exit temperatures of the bed, a good indication of the degree of reactivation could be obtained. The air leaving the bed at the start was about room temperature but gradually rose until it approached about  $480^{\circ}$  F. at which temperature it remained constant. This

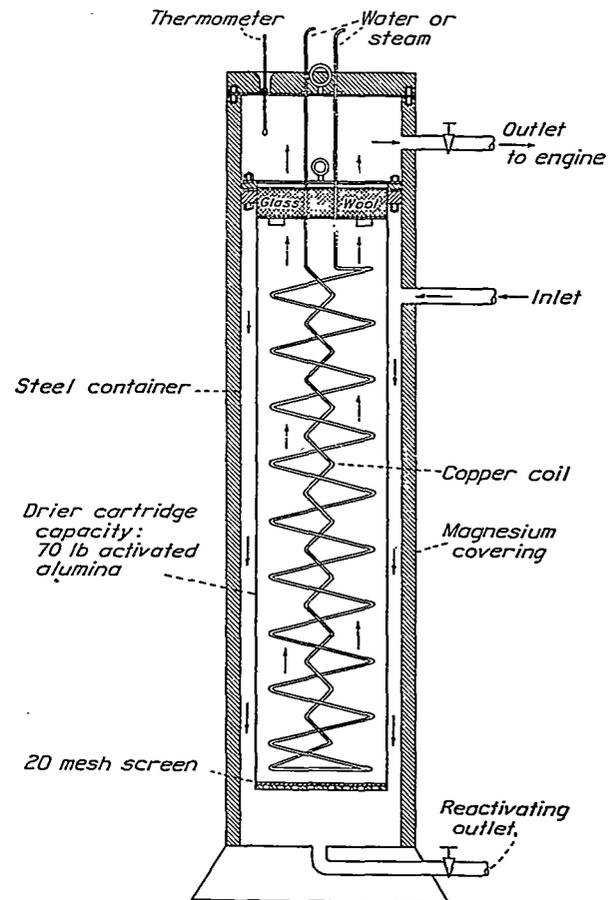


FIGURE 27.—Sectional view of drying tower.

result was taken as an indication of complete reactivation, the temperature difference being the drop across the tower.

A layer of glass wool was placed at the top of the tower to prevent any alumina dust from entering the air stream.

#### DEW-POINT HYGROMETER

As a check on the efficiency of the drying tower a small amount of dried air was drawn from the line by means of small sampling tubes and passed through an airtight brass box with a glass front. Here its dew point could be determined and then passed back into the line. The box contained two thin-walled brass tubes of square cross section, which were chrome plated and highly polished. One of the tubes was a dummy for comparison purposes and the other was cooled to low temperatures by passing a stream of cold ether

through it. The ether was cooled by mixing it with solid carbon dioxide (commercial dry ice) in an airtight cylinder, and the pressure evolved when the carbon dioxide sublimed was used to force the cold liquid through the dew-point tube. A low-temperature toluene thermometer was fixed in this tube. With this arrangement, temperatures as low as  $-100^{\circ}\text{F}$  were easily obtained. Details of the system are shown in figure 28.

In use, air from the line was drawn into the airtight box and passed across the face of the tube. The temperature of the solution in the tube was gradually lowered by increasing the pressure in the carbon diox-

The pounds of air per minute,  $A$ , is given by

$$A = 0.180 \times n \times 0.0524 \times \frac{P}{T} \quad (7)$$

where:

- 0.180 cubic foot per revolution for the air meter.
- $n$  revolutions per minute of the air meter.
- 0.0524 a conversion factor.
- $P$  room pressure in millimeters of Hg.
- $T$  room temperature,  $^{\circ}\text{R}$ , ( $460 + ^{\circ}\text{F}$ ).

Atmospheric conditions in the laboratory were such that the vapor-pressure correction for air measurements was never greater than  $\frac{1}{2}$  percent and was neglected.

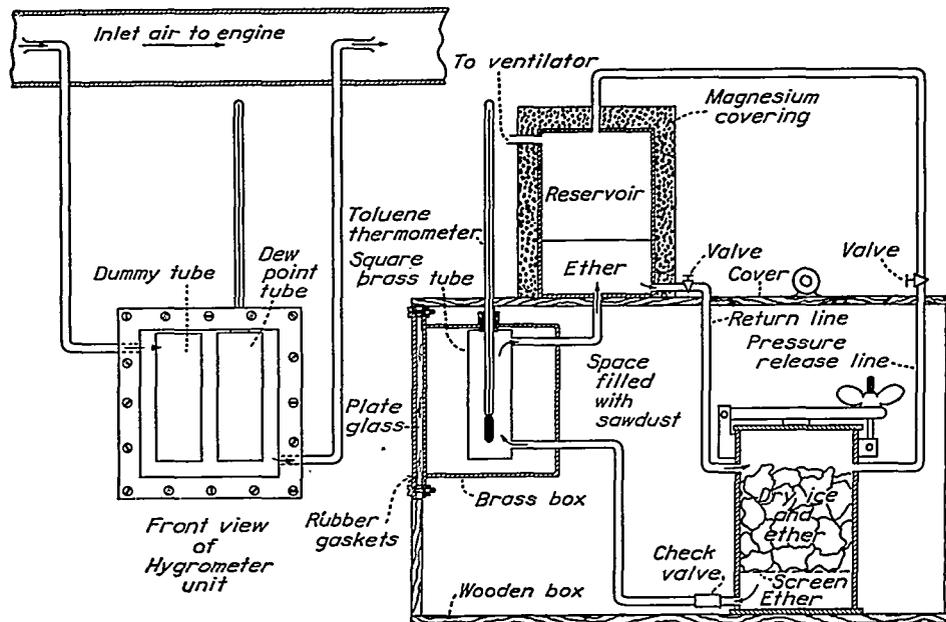


FIGURE 28.—Schematic diagram of dew-point hydrometer.

ide-ether chamber and hence increasing the flow of ether through the tube. At the first sign of mist or frost on the face of the tube, the temperature was read and taken as the dew point of the air.

A pound of dry ice was found to be sufficient to operate the device continuously for about 2 hours and the ether lost through evaporation at such low temperatures was small; hence, there was little or no disagreeable odor attending its use.

## APPENDIX B

### DETAILED CALCULATION OF THE TEMPERATURE OF THE END GAS

The following section gives a detailed description of how the temperature of the last part of the charge to burn was computed:

The fuel-air ratio was calculated from the definition:

$$\frac{F}{A} = \frac{\text{pounds of fuel per minute}}{\text{pounds of air per minute}} \quad (6)$$

The pounds of fuel per minute,  $F$ , is given by

$$F = 5.585 \times \frac{\text{S.G.}}{t} \quad (8)$$

where

- 5.585 a conversion factor.
- S.G. the specific gravity of the fuel = 0.692.
- $t$  fuel time, or time in seconds to empty a 42.2 cubic centimeter burette.

Combining (6), (7), and (8) the fuel-air ratio is

$$\frac{F}{A} = \frac{592.5(T \times \text{S.G.})}{t \times n \times P} \quad (9)$$

It will be noted in table II that the computed fuel-air ratios are from 3 to 5 percent greater than the fuel-air ratios indicated by the exhaust-gas analyzer, but this difference is of no consequence inasmuch as the meter was used only as a convenience and a rough check on computed values.

The compression ratios were calculated from the formula:

$$r = 1 + \frac{37.4}{4.16 + 8.29 \times h} \quad (10)$$

where

$r$  compression ratio.

37.4 piston displacement, cubic inches.

4.16 clearance volume at  $r=10.0$ .

8.29 piston area, square inches.

$h$  number of inches the cylinder head was raised above the setting for  $r=10.0$ .

All other values in table II were directly obtained and are self-explanatory.

As mentioned before, thermodynamic charts (reference 7) were used in making these calculations. These charts were available in four fuel-air ratios: 0.0605, 0.0665, 0.0782, and 0.0951. Satisfactory engine performance, in this experiment, could not be realized at the fuel-air ratio of 0.0605 but the other three values gave a fair range for computation purposes. It was found convenient to draw lines of constant fuel-air ratio for these last three values across the isothermal lines of figure 18. These points of intersection were marked a, b, c, etc. and all further calculations were based on values obtained from these points.

Selecting one of these points, say k, the fuel-air ratio is 0.0782, the inlet temperature is 140° F, and the corresponding compression ratio is 7.26.

The weight of fuel and air per minute cannot be obtained from table II as point k does not coincide with any of the numbered points of figure 18. This statement is true for practically all of the other "lettered" points; hence, an interpolation is necessary. This interpolation is effected by computing values of the pounds of air per minute for each of the numbered points of table II by means of equation (7) and plotting them as abscissas against the corresponding fuel times as ordinates. Isothermal lines are then drawn through the points from which is read the fuel-time and the air-quantity relationships for any intermediate point such as k. These curves are shown in figure 23. For the most part, the points fall regularly so that a smooth curve can be passed through them. Lines of constant fuel-air ratio for the three values, 0.0665, 0.0782, and 0.0951, are then superimposed on the plot, thus definitely locating any point lying on one of the isothermals and having one of the foregoing fuel-air ratios. The constant fuel-air line for k is computed from equations (6) and (8) by writing

$$\frac{F}{A} = 0.0782 = \frac{5.585 \times \text{S.G.} / t}{A}$$

and solving for

$$A = \frac{71.4 \times \text{S.G.}}{t} \quad (11)$$

Values of  $A$  are thus computed for various values of  $t$  and a smooth curve is drawn through the points.

The intersection of the 140° F isothermal and the 0.0782 constant fuel-air line gives for k, a value of 0.645 pound of air per minute.

The weight of air per stroke at 1,200 rpm is

$$\frac{0.645}{1/2 \times 1200} = 0.001075 \text{ pound}$$

The weight of fuel per stroke is

$$F = 0.0782 \times 0.001075 = 0.0000840$$

and the weight of fuel and air mixture is

$$0.001075 + 0.0000840 = 0.001159 \text{ pound}$$

A guess is then made as to the residual gas content. If this quantity is defined fractionally as

$$f_r = \frac{\text{weight of residual}}{\text{weight fuel-air mixture} + \text{weight residual}} = \frac{\text{weight of residual}}{\text{weight of charge}} \quad (12)$$

and  $f_r$  is estimated to be, say, 0.052, the approximate weight of charge per stroke is

$$\frac{0.001159}{1 - f_r} = \frac{0.001159}{0.948} = 0.00122 \text{ pound}$$

and the approximate weight of residual is

$$0.00122 \times 0.052 = 0.0000634 \text{ pound per stroke}$$

A check on this assumed value of the residual is then made by means of the thermodynamic charts. This checking is done by considering the charge as compressed and burnt and existing only as products of combustion. A point on the expansion stroke before exhaust-valve opening is arbitrarily chosen, say 120° A. T. C., for computing the specific volume. The cylinder volume at this point is computed from the formula

$$V = \frac{1}{1728} \left[ \frac{\pi d^2}{4} a \left( 1 - \cos \alpha + \frac{a \sin^2 \alpha}{2l} \right) + \frac{37.4}{r-1} \right] \quad (13)$$

where

$V$  volume above the piston, cubic feet.

$d$  cylinder diameter, 3.25 inches.

$a$  crank radius, 2.25 inches.

$\alpha$  crank angle from T.C., 120°.

$l$  length of connecting rod, 10 inches.

$r$  compression ratio, 7.26.

37.4 piston displacement for complete stroke, cubic inches.

which gives for point k,

$$V = 0.02058 \text{ cubic feet}$$

The specific volume is then found by dividing this volume by the weight of the burned charge,

$$\frac{0.02058}{0.00122} = 16.9 \text{ cubic feet/pound}$$

The thermodynamic charts are based on  $1 + F/A$  pounds of charge so that chart volumes are expressed

as cubic feet per  $(1+F/A)$  pounds of charge. Hence, the value 16.9 must be multiplied by 1.0782, giving 18.1 as the specific volume for chart use.

The pressure in the cylinder at 120° A. T. C. is measured from the indicator diagram nearest to point k giving 66 pounds per square inch. It is unnecessary to draw interpolation graphs for determining the values of the lettered points from the numbered points as the variations in pressure in this region are small and introduce a negligible error in the calculation of the residual.

The gases from this point on are considered to expand isentropically to the exhaust tank pressure of 15.1 pounds per square inch. Hence entering the thermodynamic chart with a pressure of 66 and a volume of 18.1 and following a line of constant entropy to a pressure of 15.1, the corresponding chart specific volume of the residual is found to be 58.5 cubic feet per  $(1+F/A)$  pounds. This volume is then divided by 1.0782 which

and, since this value is practically the same as the assumed weight, the first guess is correct and no further trials are necessary.

As previously explained, a fresh charge, with its attendant residual, is then considered at 146° B. T. C.

The cylinder volume is computed from equation (13) and gives 0.0237 cubic foot for point k. The specific volume is

$$\frac{0.0237}{0.00122} = 19.4 \text{ cubic feet per pound}$$

and the temperature, from (1), is

$$T_0 = \frac{14.8 \times 144 \times 19.4}{50.8} = 813^\circ \text{ Rankine}$$

The next step is to calculate the final temperature  $T_3$ , using formula (3). The final pressure  $P_3$  is obtained from the indicator diagrams; but there being a sizable variation from diagram to diagram, an interpo-

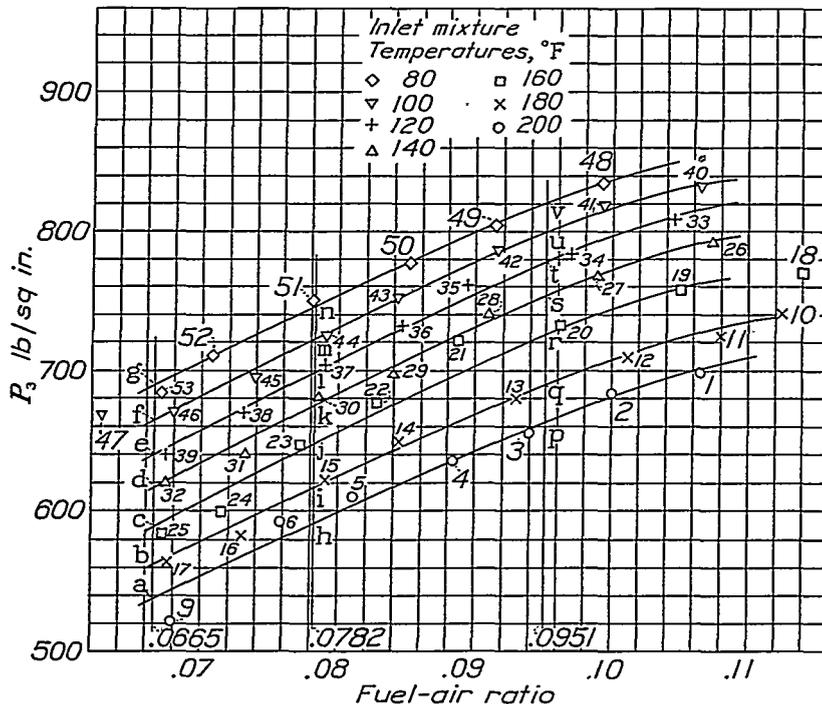


FIGURE 29.—Interpolation curves for determining peak pressures for end-gas calculations.

gives 54.4 as the volume of the residual in cubic feet per pound.

The clearance volume is determined from the formula

$$V_c = \frac{1}{1728} \times \frac{37.4}{r-1} \tag{14}$$

where

$V_c$  is the clearance volume in cubic feet

Substituting  $r=7.26$  for the point k,

$$V_c = 0.00346$$

The weight of residual per stroke is then

$$\frac{0.00346}{54.4} = 0.0000636 \text{ pound}$$

lation plot must be constructed similar to the one for air consumption. Values of  $P_3$  as measured directly from the diagrams for the numbered points are plotted against the corresponding computed fuel-air ratios obtained from table II. Through these points smooth curves are drawn giving a set of isothermal lines. Lines of constant fuel-air ratio corresponding to the values 0.0665, 0.0782, and 0.0951 are drawn and the intersections with the isothermals are given the proper designations a, b, c, etc. The graph is shown in figure 29 and gives 676 pounds per square inch for point k.

The constants  $a$  and  $b$  in equation (3) are taken from the specific-heat equation of the charge, which is

$$c_p = 0.151 + 6.16 \times 10^{-5} T$$

This equation is derived in appendix C. Hence with

$$\begin{aligned} a &= 0.151 \\ b &= 6.16 \times 10^{-5} \\ T_0 &= 813 \\ P_0 &= 14.8 \\ B &= 50.8 \\ J &= 778 \\ P_3 &= 676 \end{aligned}$$

Equation (3) becomes

$$\log T_3 = 3.4112 - 0.000124(T_3 - 813)$$

This equation must be solved by trial. The value of  $T_3$  that satisfies the equation is

$$T_3 = 1,894^\circ \text{ R.}$$

The computation form for all "lettered" points is given in table IV.

This procedure was used in calculating the temperature of the last part of the charge to burn for all runs. In the runs with varying residual-gas content, no interpolation plots were necessary. This computation form is given table V.

### APPENDIX C

#### DERIVATION OF PHYSICAL DATA FOR THE UNBURNED CHARGE

The component gases in the unburned charge are  $\text{N}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{H}_2$ ,  $\text{CH}_4$ ,  $\text{O}_2$ , Air, and  $\text{C}_3\text{H}_{18}$ . The specific-heat equations of these gases, according to the latest available data, are given in table VI.

TABLE VI.—THE SPECIFIC HEAT EQUATIONS FOR THE GASES IN THE UNBURNED CHARGE

| Gas                             | Molecular weight | Specific heat at constant pressure, $c_p$ (Btu/lb/°R) | Maximum deviation from experimental data (percent) | Reference                                |
|---------------------------------|------------------|---|--|--|
| $\text{N}_2$ .....              | 28.02            | $0.227 + 0.0000292 T$                                 | < 1  | 11.                                      |
| $\text{H}_2\text{O}$ .....      | 18.02            | $.433 + .0000166 T$                                   | < 3  | 10.                                      |
| $\text{CO}_2$ .....             | 44.00            | $.186 + .0000625 T$                                   | < 1  | 12.                                      |
| $\text{CO}$ .....               | 28.00            | $.226 + .0000321 T$                                   | < 1  | 11.                                      |
| $\text{H}_2$ .....              | 2.03             | $3.35 + .000114 T$                                    | < 1  | 13.                                      |
| $\text{CH}_4$ .....             | 16.03            | $.208 + .000561 T$                                    | < 1  | 8.                                       |
| $\text{O}_2$ .....              | 32.00            | $.200 + .0000353 T$                                   | < 1  | 14.                                      |
| Air.....                        | 28.85            | $.220 + .0000306 T$                                   | < 1  |  |
| $\text{C}_3\text{H}_{18}$ ..... | 114.14           | $.105 + .0000486 T$                                   |  | Private communication from H. C. Hottel. |

Most of the references give tabulated values of the heat capacities and, from these values the foregoing values of  $c_p$  were derived. They hold for the range  $720^\circ$  to  $1,900^\circ$  R to within the percentage error indicated. The equations for  $\text{H}_2\text{O}$ ,  $\text{CH}_4$ , and  $\text{C}_3\text{H}_{18}$  were given directly. The equation for  $\text{H}_2\text{O}$  in reference 10 contained a second-degree term that is negligible in computing the specific heat of the charge. The equation for air was derived from the equations for  $\text{N}_2$  and  $\text{O}_2$ .

The equation for the specific heat at constant pressure of the charge is given by

$$c_{p(\text{charge})} = \frac{\sum w c_p}{\sum w} \text{ Btu/lb/}^\circ\text{R} \quad (15)$$

where  $w$  is the weight of each constituent in pounds. The specific heat at constant volume of the charge is given by

$$c_{v(\text{charge})} = c_{p(\text{charge})} - B/J \quad (16)$$

A convenient graphical analysis of the unburned charge, arranged by G. B. Wood, of the M. I. T. Automotive Laboratory, is given in figure 30. Referring to this figure, the number of pounds of air per pound of charge is

$$\frac{1}{\left(1 + \frac{F}{A}\right)} (1 - f_r)$$

|        | Fresh                                       | Residual                              | Charge               |
|--------|---|---------------------------------------|----------------------|
| Air    | $(1 - f_r) lb$                              | $f_r lb$                              | $1 lb$               |
| Fuel   | $(1 - f_r) \frac{F}{A} lb$                  | $f_r \frac{F}{A} lb$                  | $\frac{F}{A} lb$     |
| Charge | $(1 - f_r) \left(1 + \frac{F}{A}\right) lb$ | $f_r \left(1 + \frac{F}{A}\right) lb$ | $1 + \frac{F}{A} lb$ |

FIGURE 30.—The composition of  $1 + \frac{F}{A}$  pounds charge before ignition.

where

$F/A$  fuel-air ratio.

$f_r$  weight fraction of residual.

The number of pounds of fuel per pound of charge is

$$\frac{1}{\left(1 + \frac{F}{A}\right)} (1 - f_r) \frac{F}{A}$$

The number of pounds of each constituent of the residual per pound of charge is obtained as follows:

Let  $x$  be the volume percentage of residual for any constituent (from fig. 31).

$m_x$ , molecular weight of the constituent.

$m_r$ , average molecular weight of the residual.

Then

$$\frac{0.01 \times m_x}{m_r} = \text{pounds constituent per pound of residual}$$

Since there are  $f_r$  pounds of residual per pound of charge, the weight of each constituent in the residual per pound of charge is

$$f_r \frac{0.01 \times m_x}{m_r} \text{ pounds}$$

The volume of 1 pound of any constituent in the charge under standard conditions is

$$\frac{358.7}{m_x} \text{ cubic feet}$$

where the constant 358.7 is the volume of 1 pound-mole of gas under standard conditions. Therefore, the volume of any constituent in 1 pound of charge is

$$w \times \frac{358.7}{m_x} \text{ cubic feet}$$

The volume of 1 pound of charge is

$$358.7 \sum \frac{w}{m_x} \text{ cubic feet}$$

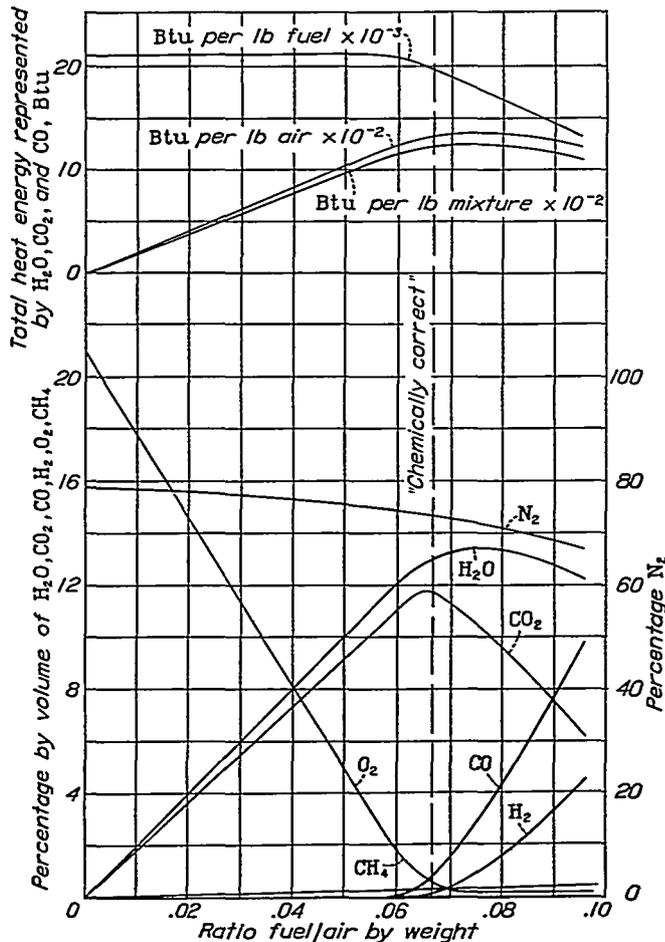


FIGURE 31.—Analysis of exhaust gases from a spark-ignition engine and heat energy from the formation of the  $\text{CO}_2$ ,  $\text{CO}$ , and  $\text{H}_2\text{O}$  contained therein. (From reference 15.)

and the average molecular weight of the charge is

$$m_c = \frac{358.7}{358.7 \sum \frac{w}{m_x}} = \frac{1}{\sum \frac{w}{m_x}} \quad (17)$$

The value of  $B$  in the equation  $PV=BT$  is equal to  $R/m_c$ , where  $R$  is the universal gas constant and is equal to 1,544 when  $P$  is measured in pounds per square foot,  $V$  in cubic feet, and  $T$  in  $^\circ\text{R}$ .

From the foregoing relations, table VII is constructed.

#### REFERENCES

1. Serruys, Max: La Combustion détonante dans les moteurs à explosion. Pub. No. 103, Pub. Sci. et Tech. du Ministère de l'Air, 1937.
2. Rothrock, A. M., and Biermann, Arnold E.: The Knocking Characteristics of Fuels in Relation to Maximum Permissible Performance of Aircraft Engines. T. R. No. 655, N. A. C. A., 1939.
3. Biermann, Arnold E.: Effect of Spark-Timing Regularity on the Knock Limitations of Engine Performance. T. N. No. 651, N. A. C. A., 1938.
4. Taylor, E. S., and Draper, C. S.: A New High-Speed Engine Indicator. Mech. Eng., vol. 55, no. 3, March 1933, pp. 169-171.
5. Reynolds, Blake, Schecter, Harry, and Taylor, E. S.: The Charging Process in a High-Speed, Single-Cylinder, Four-Stroke Engine. T. N. No. 675, N. A. C. A., 1939.
6. Draper, C. S.: Pressure Waves Accompanying Detonation in the Internal Combustion Engine. Jour. Aero. Sci., vol. 5, no. 6, April 1938, pp. 219-226.
7. Hershey, R. L., Eberhardt, J. E., and Hottel, H. C.: Thermodynamic Properties of the Working Fluid in Internal-Combustion Engines. S. A. E. Trans., vol. 39, no. 4, Oct. 1936, pp. 409-424.
8. Goodenough, G. A.: Principles of Thermodynamics. 4th ed., Henry Holt and Co., 1931.
9. Gerrish, H. C., and Voss, Fred: Mixture Distribution in a Single-Row Radial Engine. T. N. No. 583, N. A. C. A., 1936.
10. Marks, Lionel S.: Mechanical Engineers' Handbook. 3d ed., McGraw-Hill Book Co., Inc., 1930, p. 384.
11. Johnston, Herrick L., and Davis, Clyde O.: Heat Capacity of Nitrogen and Carbon Monoxide. Jour. Am. Chem. Soc., vol. 56, no. 2, Feb. 1934, pp. 271-276.
12. Kassel, Louis S.: Thermodynamic Functions of Nitrous Oxide and Carbon Dioxide. Jour. Am. Chem. Soc., vol. 56, no. 9, Sept. 1934, pp. 1838-1842.
13. Davis, Clyde O., and Johnston, Herrick L.: Heat Capacity Curves of the Simpler Gases. V. The Heat Capacity of Hydrogen at High Temperatures. The Entropy and Total Energy. A Corrected Table of the Free Energy above 2000°. Jour. Am. Chem. Soc., vol. 56, no. 5, May 1934, pp. 1045-1047.
14. Lewis, Bernard, and von Elbe, Guenther: The Specific Heat of Oxygen at High Temperatures from Ozone Explosions and the Energy of the  $^1\Delta$  Level of the Neutral Oxygen Molecule. Jour. Am. Chem. Soc., vol. 55, no. 504, Feb. 1933, pp. 511-519.
15. D'Alleve, B. A., and Lovell, W. G.: Relation of Exhaust Gas Composition to Air-Fuel Ratio. S. A. E. Jour., vol. 38, no. 3, March 1936, pp. 90-98, 116.

TABLE II.—RUNS TO DETERMINE THE EFFECT OF INLET TEMPERATURE, COMPRESSION RATIO, AND FUEL-AIR RATIO ON DETONATION (FIRST SERIES)

Engine, C. F. R.; bore, 3.25 in.; stroke, 4.5 in.; spark advance, 30°; speed, 1,200 rpm; fuel, iso-octane; specific gravity, 0.692; inlet pressure, 28.7 in. Hg absolute; exhaust back pressure, 30.7 in. Hg absolute; coolant temperature, 211° F; oil pressure, 28 lb per sq in.; oil temperature, 147° F; air-meter constant, 0.180 cu ft per revolution]

| Time  | Point | Brake load (lb)   | Fuel time (sec) | Computed $F/A$ | Fuel-air meter | Air meter (rpm) | Compression ratio | Inlet temperature (°F) | Vaporizing-tank jacket temperature (°F) | Room temperature (°F) | Corrected barometer (in. Hg) | Inlet-air dew point (°F) |
|-------|-------|---|-----------------|----------------|----------------|-----------------|-------------------|------------------------|---|-----------------------|------------------------------|--------------------------|
| a. m. |       |   |                 |                |                |                 |                   |                        |   |                       |                              |                          |
| 8:30  | 1     | 16.8  | 61.1            | 0.1055         | 0.1005         | 43.8            | 7.91              | 200                    | 180                                     | 69                    | 30.15                        | -58                      |
| 8:40  | 2     | 16.9  | 64.9            | .1000          | .0950          | 43.6            | 7.60              | 200                    | 173                                     | 69                    | 30.15                        | -60                      |
| 8:55  | 3     | 17.0  | 68.5            | .0941          | .0897          | 44.0            | 7.36              | 200                    | 161                                     | 70                    | 30.15                        | -62                      |
| 9:10  | 4     | 17.0  | 72.9            | .0884          | .0835          | 44.1            | 7.10              | 200                    | 165                                     | 71                    | 30.15                        | -60                      |
| 9:25  | 5     | 17.3  | 78.2            | .0811          | .0780          | 44.8            | 6.88              | 200                    | 160                                     | 71                    | 30.15                        | -64                      |
| 9:40  | 6     | 17.3  | 83.4            | .0758          | .0729          | 45.0            | 6.79              | 200                    | 163                                     | 71                    | 30.15                        | -62                      |
| 11:45 | 9     | 16.0  | 96.2            | .0679          | -----          | 43.9            | 6.71              | 200                    | 160                                     | 75                    | 30.15                        | -60                      |
| p. m. |       |   |                 |                |                |                 |                   |                        |   |                       |                              |                          |
| 1:15  | 10    | 17.2  | 56.0            | .1125          | .1050          | 45.5            | 8.37              | 180                    | 146                                     | 76                    | 30.10                        | -60                      |
| 1:25  | 11    | 16.9  | 59.8            | .1080          | .0990          | 44.4            | 8.03              | 180                    | 144                                     | 76                    | 30.10                        | -64                      |
| 1:40  | 12    | 17.5  | 63.6            | .1012          | .0940          | 44.6            | 7.82              | 180                    | 142                                     | 76                    | 30.10                        | -65                      |
| 1:55  | 13    | 17.3  | 68.4            | .0930          | .0872          | 45.1            | 7.50              | 180                    | 140                                     | 76                    | 30.10                        | -64                      |
| 2:05  | 14    | 17.5  | 74.7            | .0845          | .0800          | 45.4            | 7.16              | 180                    | 140                                     | 75                    | 30.10                        | -63                      |
| 2:15  | 15    | 17.8  | 80.1            | .0791          | .0750          | 45.3            | 6.98              | 180                    | 138                                     | 75                    | 30.10                        | -62                      |
| 2:30  | 16    | 17.9  | 85.9            | .0729          | .0705          | 45.8            | 6.82              | 180                    | 136                                     | 75                    | 30.10                        | -65                      |
| 2:45  | 17    | 17.1  | 92.5            | .0677          | -----          | 45.8            | 6.85              | 180                    | 136                                     | 75                    | 30.10                        | -64                      |
| 3:05  | 18    | 17.6  | 54.5            | .1140          | .1040          | 46.2            | 8.31              | 160                    | 138                                     | 75                    | 30.10                        | -67                      |
| 3:15  | 19    | 17.8  | 60.4            | .1050          | .0962          | 45.2            | 8.19              | 160                    | 136                                     | 75                    | 30.10                        | -67                      |
| 3:30  | 20    | 17.9  | 65.1            | .0962          | .0898          | 45.8            | 7.85              | 160                    | 133                                     | 75                    | 30.10                        | -67                      |
| 3:40  | 21    | 17.9  | 69.6            | .0886          | .0848          | 46.5            | 7.61              | 160                    | 139                                     | 75                    | 30.10                        | -58                      |
| 3:50  | 22    | 18.1  | 74.1            | .0828          | .0793          | 46.7            | 7.36              | 160                    | 135                                     | 75                    | 30.10                        | -58                      |
| 4:00  | 23    | 18.3  | 79.5            | .0771          | .0742          | 46.7            | 7.12              | 160                    | 133                                     | 75                    | 30.10                        | -64                      |
| 4:10  | 24    | 18.3  | 85.7            | .0714          | .0702          | 46.9            | 6.92              | 160                    | 142                                     | 75                    | 30.10                        | -64                      |
| 4:20  | 25    | 18.1  | 90.2            | .0673          | -----          | 47.2            | 7.03              | 160                    | 148                                     | 75                    | 30.10                        | -58                      |
| 4:40  | 26    | 18.4  | 56.5            | .1073          | .1054          | 47.2            | 8.50              | 140                    | 142                                     | 75                    | 30.10                        | -58                      |
| 4:55  | 27    | 18.4  | 61.2            | .0990          | .0970          | 47.4            | 8.20              | 140                    | 141                                     | 75                    | 30.10                        | -58                      |
| 5:05  | 28    | 18.6  | 66.3            | .0910          | .0891          | 47.5            | 7.79              | 140                    | 137                                     | 75                    | 30.10                        | -58                      |
| 5:15  | 29    | 18.7  | 71.8            | .0840          | .0812          | 47.6            | 7.44              | 140                    | 138                                     | 75                    | 30.10                        | -65                      |
| 5:25  | 30    | 18.9  | 76.5            | .0787          | .0757          | 47.6            | 7.33              | 140                    | 144                                     | 75                    | 30.10                        | -65                      |
| 5:35  | 31    | 18.2  | 82.2            | .0731          | .0698          | 47.7            | 7.13              | 140                    | 136                                     | 75                    | 30.10                        | -65                      |
| 5:45  | 32    | 18.7  | 88.6            | .0674          | -----          | 47.9            | 7.20              | 140                    | 144                                     | 75                    | 30.10                        | -67                      |
| 6:20  | 33    | 19.0  | 56.9            | .1045          | .1028          | 48.1            | 8.55              | 120                    | 130                                     | 75                    | 30.10                        | -64                      |
| 6:30  | 34    | 18.9  | 61.2            | .0970          | .0945          | 48.2            | 8.21              | 120                    | 125                                     | 75                    | 30.10                        | -58                      |
| 6:40  | 35    | 19.0  | 66.5            | .0894          | .0871          | 48.3            | 7.86              | 120                    | 129                                     | 75                    | 30.10                        | -58                      |
| 6:50  | 36    | 19.3  | 70.2            | .0847          | .0819          | 48.3            | 7.63              | 120                    | 131                                     | 75                    | 30.10                        | -64                      |
| 7:00  | 37    | 19.6  | 75.2            | .0790          | .0758          | 48.3            | 7.51              | 120                    | 127                                     | 75                    | 30.10                        | -67                      |
| 7:15  | 38    | 19.9  | 80.9            | .0730          | .0700          | 48.5            | 7.32              | 120                    | 126                                     | 74                    | 30.10                        | -67                      |
| 7:25  | 39    | 19.2  | 87.0            | .0675          | -----          | 48.6            | 7.31              | 120                    | 127                                     | 74                    | 30.10                        | -64                      |
| 8:00  | 40    | 19.7  | 54.8            | .1065          | .1058          | 48.9            | 8.74              | 100                    | 116                                     | 72                    | 30.13                        | -64                      |
| 8:10  | 41    | 19.8  | 58.7            | .0995          | .0972          | 48.8            | 8.45              | 100                    | 115                                     | 72                    | 30.13                        | -64                      |
| 8:25  | 42    | 19.8  | 63.8            | .0916          | .0890          | 48.9            | 8.04              | 100                    | 118                                     | 71                    | 30.13                        | -64                      |
| 8:35  | 43    | 20.3  | 68.9            | .0843          | .0814          | 48.9            | 7.76              | 100                    | 117                                     | 71                    | 30.13                        | -64                      |
| 8:45  | 44    | 20.3  | 73.3            | .0795          | .0759          | 48.8            | 7.56              | 100                    | 116                                     | 71                    | 30.13                        | -64                      |
| 8:55  | 45    | 20.5  | 78.9            | .0738          | .0702          | 48.9            | 7.44              | 100                    | 119                                     | 71                    | 30.14                        | -64                      |
| 9:10  | 46    | 19.9  | 85.1            | .0680          | -----          | 49.1            | 7.45              | 100                    | 115                                     | 71                    | 30.14                        | -67                      |
| 9:25  | 47    | 18.6  | 91.6            | .0628          | -----          | 46.4            | 7.79              | 100                    | 118                                     | 70                    | 30.14                        | -70                      |
| 10:05 | 48    | 20.2  | 58.0            | .0992          | .0983          | 49.3            | 8.50              | 80                     | 108                                     | 70                    | 30.14                        | -70                      |
| 10:15 | 49    | 20.2  | 62.5            | .0915          | .0895          | 49.4            | 8.15              | 80                     | 111                                     | 69                    | 30.14                        | -68                      |
| 10:25 | 50    | 20.4  | 67.5            | .0852          | .0818          | 49.4            | 7.89              | 80                     | 114                                     | 69                    | 30.14                        | -68                      |
| 10:35 | 51    | 21.0  | 73.5            | .0779          | .0742          | 49.5            | 7.70              | 80                     | 105                                     | 69                    | 30.14                        | -65                      |
| 10:45 | 52    | 20.9  | 80.6            | .0709          | -----          | 49.6            | 7.60              | 80                     | 104                                     | 69                    | 30.13                        | -65                      |
| 10:55 | 53    | 20.1  | 86.6            | .0670          | -----          | 48.7            | 7.82              | 80                     | 122                                     | 69                    | 30.13                        | -65                      |
| 11:10 | 54    | Calibration run: Compression ratio, 10.0; engine motoring at 1,200 rpm; indicator constant, 100 lb/sq in./in. |                 |                |                |                 |                   |                        |   |                       |                              |                          |

TABLE III.—RUNS TO DETERMINE THE EFFECT OF RESIDUAL GAS PRESSURE ON DETONATION (SECOND SERIES)

Engine, C. F. R.; bore, 3.25 in.; stroke, 4.5 in.; spark advance, 30°; speed, 1,200 rpm; fuel, iso-octane; specific gravity, 0.692; inlet pressure, 28.7 in. Hg absolute; coolant temperature, 211° F; oil pressure, 28 lb per sq in.; oil temperature, 147° F; air-meter constant, 0.180 cu ft per revolution]

| Time  | Point | Brakeload (lb)  | Fuel time (sec) | Computed $F/A$ | Air meter (rpm) | Compression ratio | Exhaust back pressure (in. Hg abs.) | Vaporizing-tank jacket temperature (°F) | Room temperature (°F) | Corrected barometer (in. Hg) | Inlet-air dew point (°F) |  |
|-------|-------|---|-----------------|----------------|-----------------|-------------------|-------------------------------------|---|-----------------------|------------------------------|--------------------------|--|
| p. m. |       |   |                 |                |                 |                   |                                     |   |                       |                              |                          |  |
| 1:15  | 55    | 21.1  | 71.6            | 0.0782         | 51.5            | 7.38              | 15.0                                | 122                                     | 81                    | 30.0                         | -58                      |  |
| 1:55  | 56    | 20.8  | 72.2            | .0783          | 51.0            | 7.38              | 20.0                                | 126                                     | 81                    | 30.0                         | -63                      |  |
| 2:15  | 57    | 20.4  | 73.1            | .0780          | 50.4            | 7.41              | 25.0                                | 127                                     | 82                    | 30.0                         | -67                      |  |
| 2:45  | 58    | 20.0  | 73.8            | .0782          | 50.0            | 7.47              | 30.0                                | 128                                     | 82                    | 30.0                         | -60                      |  |
| 3:15  | 59    | 19.6  | 74.6            | .0783          | 49.4            | 7.56              | 35.0                                | 126                                     | 82                    | 30.0                         | -60                      |  |
| 4:00  | 60    | 19.0  | 77.6            | .0783          | 47.5            | 7.57              | 40.0                                | 128                                     | 81                    | 30.0                         | -63                      |  |
| 4:30  | 61    | 18.2  | 80.3            | .0781          | 46.0            | 7.59              | 45.0                                | 127                                     | 81                    | 30.0                         | -63                      |  |
| 4:55  | 62    | Calibration run: Compression ratio, 10.0; engine motoring at 1,200 rpm; indicator constant, 100 lb/sq in./in. |                 |                |                 |                   |                                     |   |                       |                              |                          |  |

TABLE IV.—DATA FOR COMPUTATION OF TEMPERATURE OF LAST PART OF CHARGE TO BURN (FIRST SERIES)

[Pounds charge per stroke =  $\frac{\text{lb mixture}}{1-f}$ ; pounds residual per stroke = lb charge per stroke  $\times f$ ; displacement volume at 146° B. T. C. = 0.0202 cu ft; atmospheric pressure = 14.821 lb per sq in.; exhaust back pressure = 15.1 lb per sq in.]

| F/A=0.0665 B=51.15                                    |           |           |           |           |           |           |           |
|---|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
|   | a         | b         | c         | d         | e         | f         | g         |
| Point (from fig. 18)                                  | 200       | 180       | 160       | 140       | 120       | 100       | 80        |
| Inlet temperature, $T_1$ (°F)                         | 6.75      | 6.87      | 7.04      | 7.24      | 7.37      | 7.51      | 7.83      |
| Compression ratio (from fig. 18)                      | 0.618     | 0.625     | 0.638     | 0.648     | 0.658     | 0.668     | 0.6775    |
| Air per minute (lb)                                   | 0.00103   | 0.001041  | 0.001062  | 0.001095  | 0.001112  | 0.001129  | 0.001129  |
| Air per stroke (lb)                                   | 0.000685  | 0.000693  | 0.000707  | 0.000719  | 0.000730  | 0.000740  | 0.000751  |
| Fuel per stroke (lb)                                  | 0.0010985 | 0.001103  | 0.0011327 | 0.0011519 | 0.0011680 | 0.001180  | 0.001204  |
| Mixture per stroke (lb)                               | 6.2       | 5.5       | 5.2       | 5.3       | 5.1       | 5.2       | 5.0       |
| Assumed percentage of residual by weight              | 0.00117   | 0.001175  | 0.001195  | 0.001217  | 0.00123   | 0.00125   | 0.00127   |
| Approximate weight of charge per stroke (lb)          | 0.0000725 | 0.0000646 | 0.0000624 | 0.0000644 | 0.0000628 | 0.0000650 | 0.0000634 |
| Approximate weight of residual per stroke (lb)        | 0.02087   | 0.02081   | 0.02070   | 0.02058   | 0.02052   | 0.02044   | 0.02030   |
| Cylinder volume at 120° A. T. C. (cu ft)              | 17.87     | 17.7      | 17.3      | 16.9      | 16.7      | 16.3      | 16.0      |
| Approximate specific volume of charge (cu ft/lb)      | 60        | 66        | 65        | 66        | 66        | 69        | 69        |
| Pressure at 120° A. T. C. (lb/sq in.)                 | 53.5      | 54.5      | 54.5      | 53.5      | 51.5      | 52.5      | 53.5      |
| Specific volume of residual (cu ft/lb)                | 0.00375   | 0.00369   | 0.00358   | 0.00346   | 0.00340   | 0.00332   | 0.00318   |
| Clearance volume (cu ft)                              | 0.0000701 | 0.0000678 | 0.0000657 | 0.0000647 | 0.0000659 | 0.0000632 | 0.0000650 |
| Weight of residual (lb)                               | 0.001169  | 0.0011781 | 0.001198  | 0.001217  | 0.001234  | 0.001249  | 0.001263  |
| Actual weight of charge (lb)                          | 6.0       | 5.7       | 5.5       | 5.3       | 5.3       | 5.1       | 4.7       |
| Actual percentage of residual by weight               | 0.02395   | 0.02389   | 0.02378   | 0.02366   | 0.02360   | 0.02352   | 0.02338   |
| Cylinder volume at 146° B. T. C. (cu ft)              | 20.50     | 20.28     | 19.84     | 19.43     | 19.13     | 18.86     | 18.51     |
| Specific volume of charge at 146° B. T. C. (cu ft/lb) | 856       | 828       | 828       | 811       | 798       | 787       | 772       |
| Temperature of charge at 146° B. T. C., $T_0$ (°R)    | 537       | 562       | 587       | 616       | 639       | 664       | 690       |
| Maximum pressure (lb/sq in.)                          | 1,928     | 1,927     | 1,911     | 1,898     | 1,888     | 1,881     | 1,867     |
| Maximum temperature, $T_3$ (°R)                       |           |           |           |           |           |           |           |

| F/A=0.0782 B=50.8                                     |          |          |          |          |          |          |          |
|---|----------|----------|----------|----------|----------|----------|----------|
|   | h        | i        | j        | k        | l        | m        | n        |
| Point (from fig. 18)                                  | 200      | 180      | 160      | 140      | 120      | 100      | 80       |
| Inlet temperature, $T_1$ (°F)                         | 6.76     | 6.92     | 7.08     | 7.26     | 7.42     | 7.54     | 7.70     |
| Compression ratio (from fig. 18)                      | 0.609    | 0.618    | 0.633    | 0.645    | 0.655    | 0.665    | 0.676    |
| Air per minute (lb)                                   | 0.001014 | 0.00103  | 0.001055 | 0.001075 | 0.001092 | 0.00111  | 0.001128 |
| Air per stroke (lb)                                   | 0.000794 | 0.000805 | 0.000825 | 0.000840 | 0.000855 | 0.000868 | 0.000880 |
| Fuel per stroke (lb)                                  | 0.001093 | 0.001105 | 0.001138 | 0.001159 | 0.001178 | 0.001197 | 0.001216 |
| Mixture per stroke (lb)                               | 5.7      | 5.5      | 5.2      | 5.2      | 5.0      | 5.0      | 5.0      |
| Assumed percentage of residual by weight              | 0.00116  | 0.00117  | 0.00120  | 0.00122  | 0.00124  | 0.00126  | 0.00128  |
| Approximate weight of charge per stroke (lb)          | 0.000662 | 0.000642 | 0.000624 | 0.000634 | 0.000620 | 0.000629 | 0.000639 |
| Approximate weight of residual per stroke (lb)        | 0.02087  | 0.02078  | 0.02068  | 0.02058  | 0.02049  | 0.02043  | 0.02035  |
| Cylinder volume at 120° A. T. C. (cu ft)              | 18.0     | 17.8     | 17.3     | 16.9     | 16.5     | 16.3     | 15.9     |
| Approximate specific volume of charge (cu ft/lb)      | 63       | 63       | 65       | 66       | 66       | 67       | 69       |
| Pressure at 120° A. T. C. (lb/sq in.)                 | 57.5     | 54.8     | 54.9     | 54.4     | 52.5     | 52.5     | 52.0     |
| Specific volume of residual (cu ft/lb)                | 0.00375  | 0.00366  | 0.00356  | 0.00346  | 0.00337  | 0.00331  | 0.00323  |
| Clearance volume (cu ft)                              | 0.000651 | 0.000668 | 0.000650 | 0.000636 | 0.000641 | 0.000630 | 0.000611 |
| Weight of residual (lb)                               | 0.001158 | 0.001172 | 0.001203 | 0.001223 | 0.001242 | 0.001260 | 0.001277 |
| Actual weight of charge (lb)                          | 5.6      | 5.7      | 5.4      | 5.2      | 5.1      | 5.0      | 4.8      |
| Actual percentage of residual by weight               | 0.0240   | 0.0239   | 0.02377  | 0.0237   | 0.02357  | 0.02350  | 0.0234   |
| Cylinder volume at 146° B. T. C. (cu ft)              | 20.72    | 20.40    | 19.75    | 19.38    | 18.96    | 18.66    | 18.33    |
| Specific volume of charge at 146° B. T. C. (cu ft/lb) | 870      | 856      | 829      | 813      | 796      | 783      | 769      |
| Temperature of charge at 146° B. T. C., $T_0$ (°R)    | 590      | 617      | 647      | 676      | 699      | 723      | 747      |
| Maximum pressure (lb/sq in.)                          | 1,946    | 1,938    | 1,907    | 1,894    | 1,874    | 1,862    | 1,847    |
| Maximum temperature, $T_3$ (°R)                       |          |          |          |          |          |          |          |

| F/A=0.0951 B=50.5                                     |          |          |          |          |          |          |          |
|---|----------|----------|----------|----------|----------|----------|----------|
|   | p        | q        | r        | s        | t        | u        | v        |
| Point (from fig. 18)                                  | 200      | 180      | 160      | 140      | 120      | 100      | 80       |
| Inlet temperature, $T_1$ (°F)                         | 7.38     | 7.54     | 7.71     | 7.92     | 8.10     | 8.20     | 8.32     |
| Compression ratio (from fig. 18)                      | 0.598    | 0.609    | 0.625    | 0.643    | 0.653    | 0.666    | 0.674    |
| Air per minute (lb)                                   | 0.000997 | 0.001015 | 0.00104  | 0.00107  | 0.00109  | 0.00111  | 0.001125 |
| Air per stroke (lb)                                   | 0.000948 | 0.000966 | 0.000990 | 0.001018 | 0.001038 | 0.001056 | 0.001070 |
| Fuel per stroke (lb)                                  | 0.001092 | 0.001112 | 0.001139 | 0.001172 | 0.001194 | 0.001216 | 0.001232 |
| Mixture per stroke (lb)                               | 5.6      | 5.3      | 5.2      | 5.3      | 5.1      | 5.1      | 5.1      |
| Assumed percentage of residual by weight              | 0.001158 | 0.001174 | 0.00120  | 0.001238 | 0.001260 | 0.001282 | 0.001300 |
| Approximate weight of charge per stroke (lb)          | 0.000649 | 0.000622 | 0.000625 | 0.000643 | 0.000643 | 0.000655 | 0.000663 |
| Approximate weight of residual per stroke (lb)        | 0.02051  | 0.02040  | 0.02032  | 0.02025  | 0.02017  | 0.02013  | 0.02008  |
| Cylinder volume at 120° A. T. C. (cu ft)              | 17.7     | 17.4     | 16.9     | 16.4     | 16.0     | 15.7     | 15.4     |
| Approximate specific volume of charge (cu ft/lb)      | 63       | 64       | 62       | 64       | 61       | 64       | 64       |
| Pressure at 120° A. T. C. (lb/sq in.)                 | 53.8     | 52.0     | 49.2     | 48.4     | 45.2     | 46.5     | 45.0     |
| Specific volume of residual (cu ft/lb)                | 0.00339  | 0.00331  | 0.00323  | 0.00313  | 0.00305  | 0.00301  | 0.00296  |
| Clearance volume (cu ft)                              | 0.000630 | 0.000636 | 0.000656 | 0.000665 | 0.000667 | 0.000666 | 0.000665 |
| Weight of residual (lb)                               | 0.001155 | 0.001176 | 0.001205 | 0.001237 | 0.001261 | 0.001282 | 0.001297 |
| Actual weight of charge (lb)                          | 5.5      | 5.4      | 5.4      | 5.2      | 5.3      | 5.2      | 5.0      |
| Actual percentage of residual by weight               | 0.02359  | 0.02348  | 0.02340  | 0.02333  | 0.02325  | 0.02321  | 0.02310  |
| Cylinder volume at 146° B. T. C. (cu ft)              | 20.42    | 19.95    | 19.42    | 18.87    | 18.44    | 18.11    | 17.60    |
| Specific volume of charge at 146° B. T. C. (cu ft/lb) | 862      | 842      | 820      | 797      | 778      | 765      | 754      |
| Temperature of charge at 146° B. T. C., $T_0$ (°R)    | 663      | 690      | 726      | 754      | 778      | 800      | 820      |
| Maximum pressure (lb/sq in.)                          | 1,947    | 1,926    | 1,904    | 1,876    | 1,852    | 1,837    | 1,820    |
| Maximum temperature, $T_3$ (°R)                       |          |          |          |          |          |          |          |

TABLE V.—DATA FOR COMPUTATION OF TEMPERATURE OF LAST PART OF THE CHARGE TO BURN (SECOND SERIES)

[Variable exhaust back pressure; displacement volume at 146° B. T. C.=0.0202 cu ft; atmospheric pressure=14.78 lb. per sq in.]

|  | F/A=0.0782 B=50.8 |          |          |          |          |          |          |
|--|-------------------|----------|----------|----------|----------|----------|----------|
| Reference point (from table III).....                            | 55                | 56       | 57       | 58       | 59       | 60       | 61       |
| Inlet temperature, T <sub>1</sub> (°F).....                      | 120               | 120      | 120      | 120      | 120      | 120      | 120      |
| Compression ratio.....   | 7.38              | 7.38     | 7.41     | 7.47     | 7.56     | 7.57     | 7.59     |
| Air per minute (lb).....   | 0.634             | 0.676    | 0.669    | 0.662    | 0.654    | 0.642    | 0.632    |
| Air per stroke (lb).....   | 0.00114           | 0.00125  | 0.001115 | 0.00110  | 0.00109  | 0.00107  | 0.001055 |
| Fuel per stroke (lb).....  | 0.000802          | 0.000880 | 0.000872 | 0.000860 | 0.000852 | 0.000838 | 0.000825 |
| Mixture per stroke (lb).....                                     | 0.00123           | 0.00121  | 0.00120  | 0.00119  | 0.00118  | 0.001164 | 0.001138 |
| Assumed percentage of residual by weight.....                    | 2.8               | 3.8      | 4.0      | 4.8      | 5.7      | 6.3      | 7.1      |
| Approximate weight of charge per stroke (lb).....                | 0.00127           | 0.00126  | 0.001250 | 0.001250 | 0.00125  | 0.001230 | 0.00122  |
| Approximate weight of residual per stroke (lb).....              | 0.000035          | 0.000048 | 0.000050 | 0.000050 | 0.000071 | 0.000078 | 0.000087 |
| Cylinder volume at 120° A. T. C. (cu ft).....                    | 0.02052           | 0.02052  | 0.02049  | 0.02046  | 0.02042  | 0.02041  | 0.02040  |
| Approximate specific volume of charge (cu ft/lb).....            | 16.2              | 16.3     | 16.4     | 16.4     | 16.4     | 16.6     | 16.7     |
| Pressure at 120° A. T. C. (lb/sq in).....                        | 66                | 65       | 63       | 60       | 67       | 66       | 61       |
| Exhaust back pressure (lb/sq in) absolute.....                   | 7.41              | 9.87     | 12.3     | 14.8     | 17.2     | 19.8     | 22.2     |
| Specific volume of residual (cu ft/lb).....                      | 95                | 71       | 62       | 56       | 47       | 42       | 37       |
| Clearance volume (cu ft).....                                    | 0.00340           | 0.00340  | 0.00337  | 0.00334  | 0.00330  | 0.00329  | 0.00328  |
| Weight of residual (lb).....                                     | 0.000039          | 0.000049 | 0.000054 | 0.000060 | 0.000071 | 0.000079 | 0.000088 |
| Actual weight of charge (lb).....                                | 0.001269          | 0.001259 | 0.001254 | 0.001250 | 0.001251 | 0.001233 | 0.001227 |
| Actual percentage of residual by weight.....                     | 3.0               | 3.8      | 4.3      | 4.8      | 5.7      | 6.4      | 7.2      |
| Cylinder volume at 146° B. T. C. (cu ft).....                    | 0.0236            | 0.0236   | 0.0235   | 0.0235   | 0.0235   | 0.0235   | 0.0235   |
| Specific volume of charge (cu ft/lb).....                        | 18.00             | 18.75    | 18.83    | 18.81    | 18.79    | 19.06    | 19.16    |
| Temperature of charge at 146° B. T. C., T <sub>2</sub> (°R)..... | 780               | 787      | 790      | 789      | 788      | 800      | 804      |
| Maximum pressure (lb/sq in).....                                 | 715               | 715      | 707      | 710      | 715      | 700      | 680      |
| Maximum temperature, T <sub>3</sub> (°R).....                    | 1,852             | 1,865    | 1,866    | 1,867    | 1,867    | 1,882    | 1,878    |

TABLE VII.—PHYSICAL DATA FOR THE UNBURNED CHARGE

[Base, 1-lb charge; temperature range, 720° to 1,900° R; m<sub>c</sub>=average molecular weight of charge; c<sub>p</sub>=specific heat of gas at constant pressure (Btu/lb/° R); c<sub>v</sub>=specific heat of gas at constant volume (Btu/lb/° R)=c<sub>p</sub>-B/J; w=weight of each constituent of charge (lb/lb charge); B=gas constant (ft° R); 858.7=volume in cu ft occupied by 1-lb mole of gas under standard conditions; T=temperature (°R); F/A=fuel-air ratio; f<sub>r</sub>=weight fraction of residual in charge; x=volume of any constituent in residual (percent); m<sub>r</sub>=molecular weight of any constituent in charge; m<sub>r</sub>=average molecular weight of residual]

| Gas                                  | m <sub>c</sub> | f <sub>r</sub> | F/A=0.0665            |                    |        |  |   | F/A=0.0782            |                    |        |  |   | F/A=0.0951            |                    |        |                  |  |  |
|--------------------------------------|----------------|----------------|-----------------------|--------------------|--------|--|---|-----------------------|--------------------|--------|--|---|-----------------------|--------------------|--------|------------------|--|--|
|                                      |                |                | x                     | $\frac{xm_c}{100}$ | w      | w/m <sub>c</sub>   | wc <sub>p</sub>                                     | x                     | $\frac{xm_c}{100}$ | w      | w/m <sub>c</sub>   | wc <sub>p</sub>                                     | x                     | $\frac{xm_c}{100}$ | w      | w/m <sub>c</sub> | wc <sub>p</sub>                                      |  |
| Residual:                            |                |                |                       |                    |        |  |   |                       |                    |        |  |   |                       |                    |        |                  |  |  |
| N <sub>2</sub> .....                 | 28.01          | 0.07           | 73.0                  | 20.4               | 0.0505 | 0.00180  | 1,160×10 <sup>-3</sup> +147×10 <sup>-3</sup> T      | 71.0                  | 19.9               | 0.0501 | 0.00179  | 1,140×10 <sup>-3</sup> +146×10 <sup>-3</sup> T      | 67.0                  | 18.8               | 0.0493 | 0.00176          | 1,120×10 <sup>-3</sup> +144×10 <sup>-3</sup> T       |  |
| H <sub>2</sub> O.....                | 18.01          | 0.07           | 12.9                  | 2.32               | .0057  | .0003  | 247×10 <sup>-3</sup> +9.5×10 <sup>-3</sup> T        | 13.4                  | 2.41               | .00606 | .000336  | 262×10 <sup>-3</sup> +10.1×10 <sup>-3</sup> T       | 12.2                  | 2.20               | .00577 | .00032           | 250×10 <sup>-3</sup> +9.5×10 <sup>-3</sup> T         |  |
| CO <sub>2</sub> .....                | 44.0           | 0.07           | 11.8                  | 5.19               | .0128  | .000291  | 238×10 <sup>-3</sup> +80.0×10 <sup>-3</sup> T       | 9.8                   | 4.31               | .01085 | .000270  | 202×10 <sup>-3</sup> +67.8×10 <sup>-3</sup> T       | 6.3                   | 2.77               | .00762 | .000165          | 135×10 <sup>-3</sup> +454×10 <sup>-3</sup> T         |  |
| CO.....                              | 28.0           | 0.07           | 7                     | .196               | .0005  | .000018  | 11.3×10 <sup>-3</sup> +1.6×10 <sup>-3</sup> T       | 3.7                   | 1.04               | .00262 | .000091  | 59.2×10 <sup>-3</sup> +8.4×10 <sup>-3</sup> T       | 9.5                   | 2.66               | .00698 | .000249          | 158×10 <sup>-3</sup> +224×10 <sup>-3</sup> T         |  |
| H <sub>2</sub> .....                 | 2.02           | 0.07           | 1                     | .002               | .0000  | .0000  | 0.0 + 0.0×10 <sup>-3</sup> T                        | 1.3                   | .026               | .00007 | .000033  | 22×10 <sup>-3</sup> + .7×10 <sup>-3</sup> T         | 4.3                   | .09                | .00024 | .000119          | 80.4×10 <sup>-3</sup> +27.4×10 <sup>-3</sup> T       |  |
| OH.....                              | 16.03          | 0.07           | 3                     | .048               | .0001  | .000006  | 2.1×10 <sup>-3</sup> +5.6×10 <sup>-3</sup> T        | .4                    | .064               | .00016 | .000010  | 3×10 <sup>-3</sup> +9.0×10 <sup>-3</sup> T          | .5                    | .03                | .00021 | .000013          | 4.37×10 <sup>-3</sup> +118×10 <sup>-3</sup> T        |  |
| O <sub>2</sub> .....                 | 32.0           | 0.07           | 5                     | .16                | .0003  | .000094  | 6.0×10 <sup>-3</sup> +1.1×10 <sup>-3</sup> T        | .2                    | .064               | .00016 | .000005  | 3×10 <sup>-3</sup> + .6×10 <sup>-3</sup> T          | .2                    | .06                | .00016 | .000005          | 3.2×10 <sup>-3</sup> +5.65×10 <sup>-3</sup> T        |  |
|                                      |                |                | m <sub>r</sub> =28.32 |                    |        |  |   | m <sub>r</sub> =27.81 |                    |        |  |   | m <sub>r</sub> =26.66 |                    |        |                  |  |  |
| Fresh mixture:                       |                |                |                       |                    |        |  |   |                       |                    |        |  |   |                       |                    |        |                  |  |  |
| Air.....                             | 28.85          |                |                       |                    | .872   | .0302  | 19,200×10 <sup>-3</sup> +2,670×10 <sup>-3</sup> T   |                       |                    | .863   | .0299  | 19,000×10 <sup>-3</sup> +2,640×10 <sup>-3</sup> T   |                       |                    | .849   | .0294            | 18,700×10 <sup>-3</sup> +26,000×10 <sup>-3</sup> T   |  |
| C <sub>8</sub> H <sub>18</sub> ..... | 114.1          |                |                       |                    | .0580  | .000508  | 609×10 <sup>-3</sup> +2,820×10 <sup>-3</sup> T      |                       |                    | .0675  | .000592  | 709×10 <sup>-3</sup> +3,280×10 <sup>-3</sup> T      |                       |                    | .0807  | .000708          | 847×10 <sup>-3</sup> +30,200×10 <sup>-3</sup> T      |  |
|                                      |                |                |                       |                    | Σ=1    | Σ=.033217  | Σ=21,463×10 <sup>-3</sup> +5,735×10 <sup>-3</sup> T |                       |                    | Σ=1    | Σ=.033030  | Σ=21,400×10 <sup>-3</sup> +6,160×10 <sup>-3</sup> T |                       |                    | Σ=1    | Σ=.032739        | Σ=21,298×10 <sup>-3</sup> +67,600×10 <sup>-3</sup> T |  |
| Specific heat of charge...           |                |                |                       |                    |        | c <sub>p</sub> =0.215+5.74×10 <sup>-3</sup> T<br>c <sub>v</sub> =0.149+5.74×10 <sup>-3</sup> T |   |                       |                    |        | c <sub>p</sub> =0.214+6.16×10 <sup>-3</sup> T<br>c <sub>v</sub> =0.149+6.16×10 <sup>-3</sup> T |   |                       |                    |        |                  |  | c <sub>p</sub> =0.213+6.76×10 <sup>-3</sup> T<br>c <sub>v</sub> =0.148+6.76×10 <sup>-3</sup> T |
| Molecular weight of charge.....      |                |                |                       |                    |        | m <sub>c</sub> = $\frac{1}{0.0332}$ =30.2  |   |                       |                    |        | m <sub>c</sub> = $\frac{1}{0.0330}$ =30.4  |   |                       |                    |        |                  |  | m <sub>c</sub> = $\frac{1}{0.0327}$ =30.6  |
| Gas constant of charge...            |                |                |                       |                    |        | B=1544/30.2=51.15  |   |                       |                    |        | B=1544/30.4=50.8   |   |                       |                    |        |                  |  | B=1544/30.6=50.5   |

EFFECT OF FUEL-AIR RATIO, INLET TEMPERATURE, AND EXHAUST PRESSURE