DEVELOPMENT OF AN ENGINE TEST PROCEDURE FOR DETERMINING THE PREIGNITION CHARACTERISTICS OF MOTOR FUELS

by

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TABLE OF CONTENTS

FIGURES

TABLE OF CONTENTS - Continued

TABLES

TABLE OF CONTENTS - Continued

DEVELOPMENT OF AN ENGINE TEST PROCEDURE FOR DETERMINING THE PREIGNITION CHARACTERISTICS OF MOTOR FUELS

I. INTRODUCTION

Gasoline consists of various hydrocarbons belonging mainly to the paraffin, olefin, diolefin, naphthene, or aromatic families. The compounds in a gasoline vary with the method of manufacture and the source of the base stock. It is a well established fact that the character of the fuel used has considerable influence on the operation of an internal combustion engine, particularly as regards the output, efficiency, fuel consumption, reliability, and durability (15, p 158)*. The significant properties affecting the operating characteristics of a motor fuel are (1) the detonation characteristics, (2) volatility, which controls ease of starting, vapor lock, acceleration, and crankcase dilution, (3) gum and varnish deposits, and (4) sulphur content and corrosion. Federal specifications have been established which specify the method and conditions under which each of the above mentioned characteristics may be determined for a liquid fuel (5). From the results of these standard tests it is possible to design internal combustion engines that will efficiently burn a particular fuel, or to specify a certain fuel for use in an

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*Numbers in parenthesis refer to bibliography.

existing engine.

The phenomenon of detonation was given increased attention as efforts were made to raise the power and efficiency of spark ignition engines by raising the compression ratio. It was soon realized that the compression ratio at which an engine could be operated was limited by detonation. Considerable research along this line resulted in the use of additives to the fuel and the blending in of more aromatic hydrocarbons which resist detonation (13, p 60). From the standpoint of detonation, the best fuel is the one with the highest octane number.

Streeter and Lichty reported that attempts to increase the power and efficiency of an engine by appreciably increasing the compression ratio resulted in detonation, preignition, and overheating in the order mentioned (14, p 160). The term preignition may be defined as ignition of the charge before electrical spark occurs, but is interpreted to include post-ignition and ignition at the same time that spark occurs where the ignition initiates at a hot spot other than the spark plug. Preignition may occur with any fuel, whereas detonation occurs only with the somewhat volatile liquid fuels (8, p 156).

In 1941 cases of preignition were called to the attention of the Ethyl Gasoline Corporation laboratories in which automotive engines would preignite on fuels so high in antiknock value that, in the absence of preignition, there was no audible knock (4, p 1). This indicated that preignition was not dependent on detonation for its origin and, in fact, indicated that it probably was controlled by different intermediates (6, p 337). Whereas detonation is a gaseous phenomenon dependent on the density and the temperature of the end gas within the combustion chamber, preignition is probably a surface phenomenon resulting from the contact of the combustible charge with a hot surface (13, p 59). Detonation will usually stop when the spark is cut off, but preignition, if severe, continues for some time after the spark is cut off (10, p 21).

Inasmuch as the present trend in spark ignition engines is toward higher compression ratios with accompanying higher temperatures, the preignition characteristics of motor fuels should be considered separately from the detonation characteristics. A preignition rating, together with the existing ratings mentioned previously, would permit a better understanding of the operating characteristics of motor fuels in high compression ratio engines. It was therefore decided to undertake the development of a preignition test procedure utilizing a CFR knock test engine by which the preignition characteristics of motor fuels could be determined at representative operating conditions.

II EFFECTS OF PREIGNITION

Preignition results in an increase in the temperature of the combustion chamber parts, an increase in the work of compression, a decrease in the work of the cycle, and higher pressures (14, p 182-183). The effects of preignition on the pressure and work may be analyzed from the P-V diagram in Figure 1.

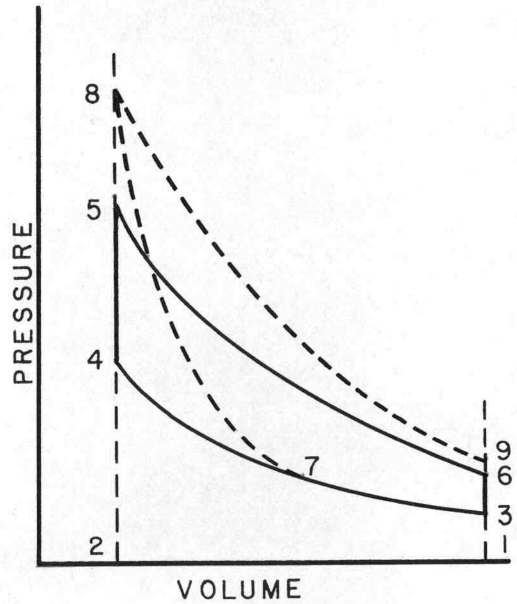


Figure 1.

Without preignition the work of compression is represented by the area 1243. The energy at 4 is equal to the energy at 3 plus the work done.

$$U_4 = U_3 + pdV$$

With preignition occurring during the compression stroke, the pressure at the end of compression will be at 8, because the heat of combustion has been liberated.

$$U_8 = U_3 + pdV + dQ$$

The work of compression, pdV, is larger than without preignition by the area 748. The pressure at the beginning of the expansion stroke will be greater with preignition due mainly to the increase in compression pressure. As the work done on the charge during compression increases, the net work of the cycle decreases. The net work is a minimum when preignition initiates very early in the compression stroke.

III PURPOSE OF THE INVESTIGATION

The purpose of this investigation was to establish an accurate, practical, and reproducible engine test method for evaluating the preignition characteristics of motor fuels. More specifically, it included the determination of (1) the engine operating conditions for the test, (2) the selection of suitable reference fuels, (3) a method of inducing preignition, together with suitable preigniter filament materials, and (4) a method of detecting preignition.

IV METHOD USED TO STUDY PREIGNITION

It has been stated previously that preignition is a surface phenomenon in that it results from contact of the combustible charge with a hot surface within the combustion chamber. Therefore in establishing a test procedure to determine the preignition characteristics of a motor fuel, a hot surface must be produced in the combustion chamber. Since it is absolutely necessary to be able to control the degree of preignition, the filament temperature must be controlled externally. The term "degree of preignition" refers to the time preignition occurs with respect to spark ignition. External control of the filament temperature was accomplished by an electric circuit, the detail of which is explained in Part VI of this thesis.

The second phase of the work involved the detection of preignition once it occurred. This was done by connecting an electronic circuit to a platinum-10%rhodium ionization pick-up wire projecting into the combustion chamber near the preigniter filament. At the time the flame front reached the ionization pick-up wire, the electronic circuit would send a high potential impulse to a protractor on the crankshaft and show the occurrence of ionization in crank angle degrees. The principle of operation and design of the electronic circuit are explained in Part VII.

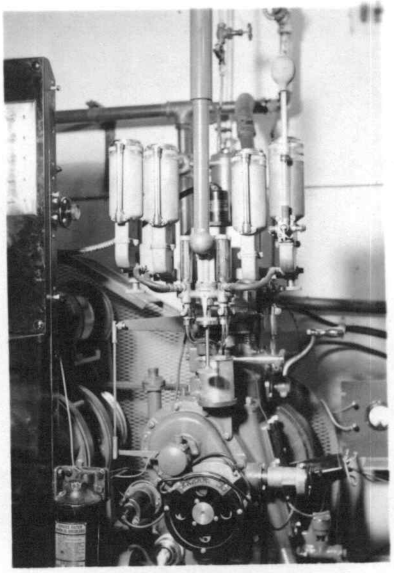
Mention is made here of the fact that the phenomena of preignition and detonation may occur simultaneously or separately. It is possible for preignition to result from the occurrence of detonation in the previous cycle. Inasmuch as a preignition test should indicate principally the relative tendency of a fuel to preignite, regardless of the effect of detonation, the test should be made at a comparatively low compression ratio where the knock, if any, is light. With the filament at a higher temperature than any other surface in the combustion chamber, due to the electrical energy supplied to the filament, preignition will originate from the filament. The pick-up wire is diametrically across the combustion chamber from the spark plug and located near the preigniter filament. This means that during normal combustion the ionization spark will lag the electrical spark by the time required for the flame to progress across the combustion chamber; however, when preignition occurs, it originates near the pick-up wire and this flash will lead the spark ignition flash on the timing rings.

V ENGINE USED FOR TEST

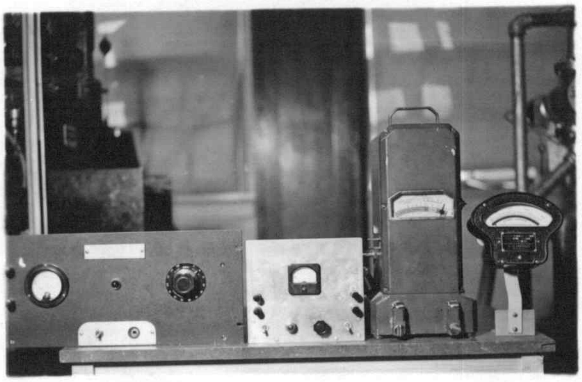
In order to devise a standard method for determining the preignition characteristics of motor fuels in an engine under more or less representative operating conditions, it was decided to use the same engine, slightly modified, as is used in the determination of octane ratings. This engine is standard equipment with all fuels testing laboratories and was developed by the Cooperative Fuel Research committee, composed of representatives of the Society of Automotive Engineers, American Petroleum Institute, National Automobile Chamber of Commerce, and the U. S. Bureau of Standards.

This engine, shown in Figures 2 to 4, shall conform to the requirements given in the Federal Specifications (5, p 138-140). It consists of a continuously variable compression, one cylinder, four-cycle, valve in head engine, together with suitable loading and accessory equipment. The engine has the following dimensions:

Bore, inches	3.25
Stroke, inches	4.50
Displacement, cubic inches	37.4
Valve diameter, inches clear	1.1875
Connecting-rod bearing:	
Diameter, inches	2.25
Length, inches	1.625



(a) CFR Engine



(b) Electric Filament Supply, Electronic Circuit, Air-Fuel Ratio Meter, & Pyrometer.

Figure 2. CFR Engine with Accessory Equipment

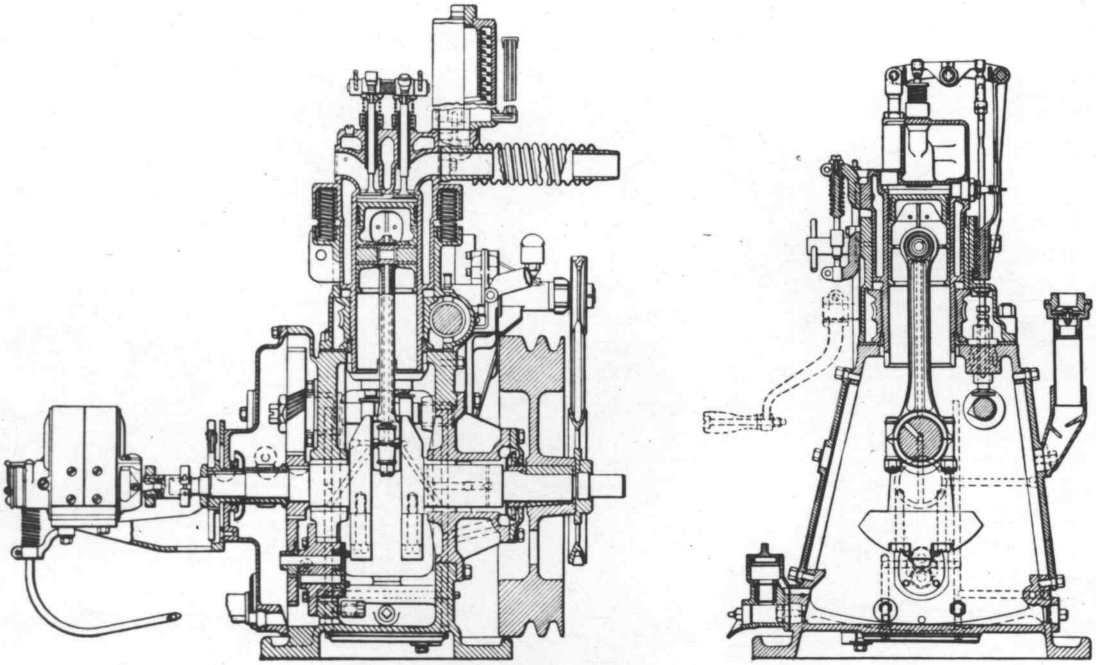


FIG. 79.—C.F.R. knock-testing engine.

Figure 3. Cutaway View of CFR Engine

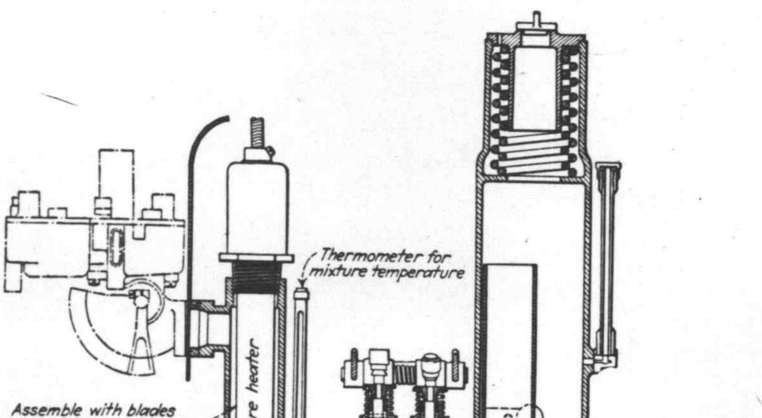


Figure 4. CFR Engine Cylinder Head.

Front main bearing:	
Diameter, inches	2.25
Length, inches	2.00
Rear main bearing:	
Diameter, inches	2.25
Length, inches	4.25
Piston pin, floating, diam., inches	1.25
Connecting rod, center to center, inches	10.00
Timing gear face, inches	1.00
Piston rings, number	5
Exhaust pipe, diameter, inches	1.25
Spark plug, size, millimeters	18.00

The engine is connected by V-type belts to an electric generator. This is an induction motor with synchronous characteristics and is used, first to start the engine, and then secondly to hold the engine at a constant speed.

The only modification necessary to make preignition ratings with this unit is the replacement of the bouncing pin with the preigniter assembly. Some care is essential in removing the bouncing pin in order that its calibration will not be changed.

VI EQUIPMENT TO INDUCE PREIGNITION

Preigniter

The preigniter shown in Figure 5 is one loaned to the author by the Ethyl Gasoline Corporation research laboratories who conducted an extensive investigation of preigniter design. After trying preigniters of various forms, they arrived at this as the most effective type (4, p 1). This preigniter consists of the following parts:

1 Steel shell

1 Steel packing nut

1 Insulator

2 Insulator gaskets

1 Nickel electrode

1 Terminal block

2 Terminal block nuts

1 Platinum-10%rhodium, 0.04 inch diameter filament

1 Platinum thermocouple lead

1 Platinum-10%rhodium thermocouple lead

1 Ionization pick-up wire

3 Brass binding posts

Sauereisen cement-used to seal the openings where the thermocouple, filament and ionization pick-up leads enter the insulator.

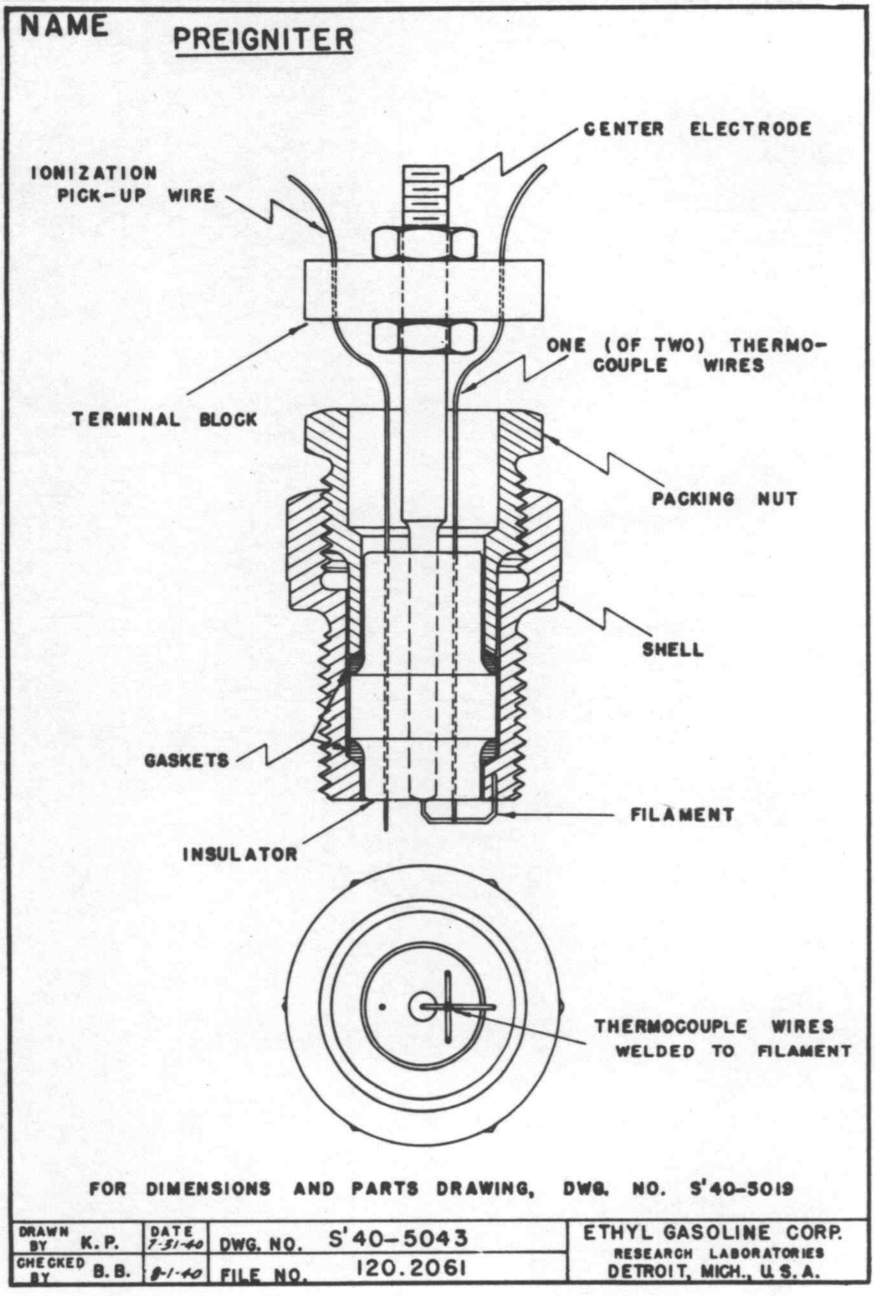


Figure 5. Preigniter.

The center electrode-filament assembly was made by welding the platinum-rhodium tip to the nickel shank. This work was done by Baker and Co., Inc., Newark, New Jersey. The two thermocouple wires were welded to the filament so that the filament temperature could be observed. Although the ionization pick-up wire is a part of the equipment to detect preignition, it is mentioned here due to the fact that it is incorporated in the preigniter. This was done primarily to facilitate projecting the end of the wire into the combustion chamber.

It was found that the filament temperature necessary to cause preignition of several fuels was approximately 1000 C (1800 F). Inasmuch as the filament must remain at a temperature near 1800 F for considerable time in an oxidizing atmosphere within the combustion chamber, the type of material that can be used in the filament is very limited.

Platinum-10%rhodium is rather expensive, but is the material least affected by the oxidizing atmosphere at the high temperatures. Platinum has a melting point of 1773.5 ± 1 C or 3224 F (16, p 16), but is affected somewhat by an oxidizing atmosphere. Rhodium has a melting point of 1966 ± 3 C (16, p 16), and as with platinum, there is a slight loss of weight in the presence of oxygen. This loss on heating in air is associated with the formation of a

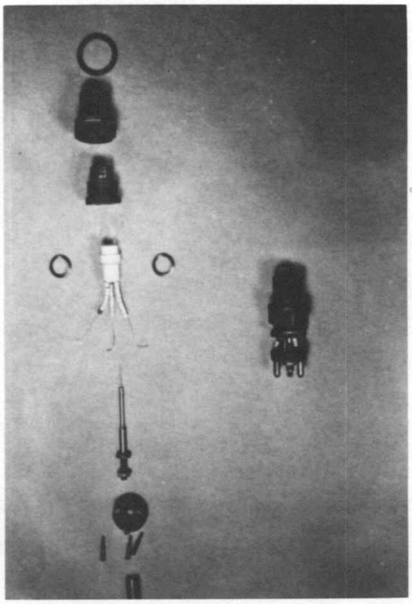


Figure 6. Ethyl Corporation Preigniter.

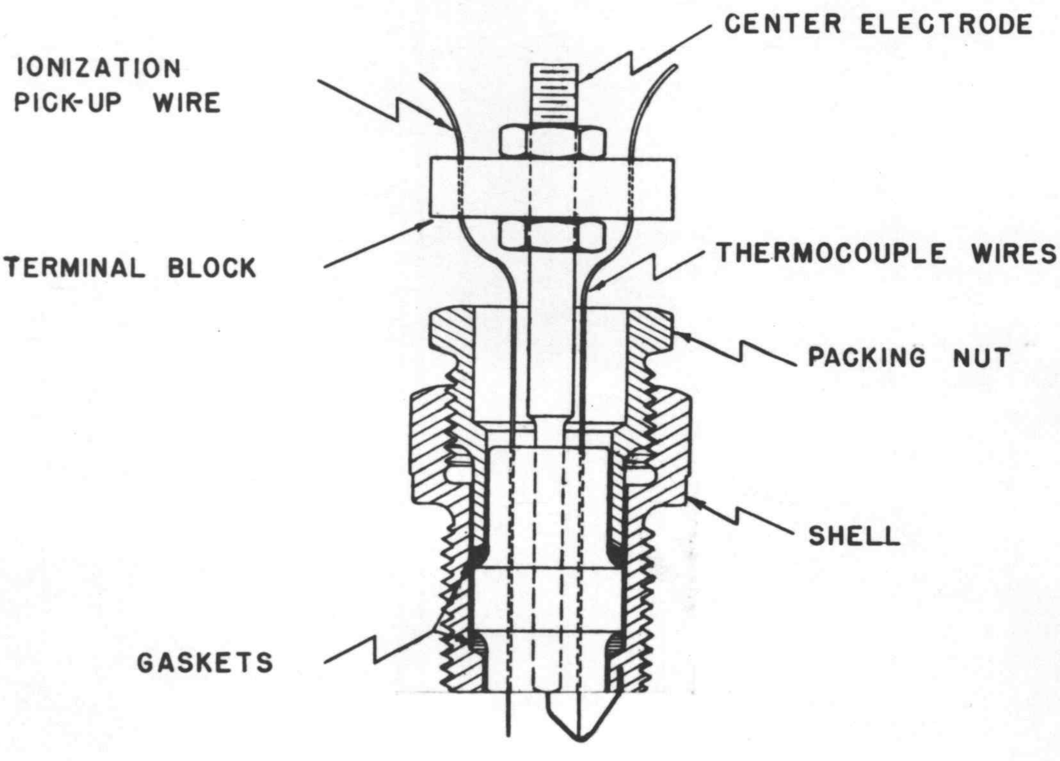


Figure 7 Preigniter with V - Type Filament Wire

volatile oxide. The corrosion resistance of rhodium is exceptionally high and improves the corrosion resistance of platinum. Other advantages of rhodium are that it moderately hardens platinum, increases the solidus temperature, and decreases grain growth at elevated temperatures (16, p 49).

Two other less noble metals, tungsten, with a melting point of 6098 F, and molybdenum, with a melting point of 4748 F, were considered (1, p 80). However, neither was tried since it was found that both could be expected to deteriorate rapidly in an oxidizing atmosphere.

The deterioration of the filament is disadvantageous in that the filaments must be replaced occasionally. They do not deteriorate to such an extent during one test, however, that the accuracy is affected. A properly constructed filament should be satisfactory for 100 hours of operation. This deterioration should be considered as a disadvantage and not a limitation of the test. When a filament fails to pass sufficient current to raise its temperature high enough to cause incipient preignition of the reference fuels, the connection between the filament and the steel shell should be checked. If this is found to be satisfactory, the filament is failing internally and must be replaced.

The filament temperature required for preignition of a particular fuel is a function of the air-fuel ratio, the velocity of the mixture across the filament, the area of contact of the filament, the time of contact, the catalytic effect of the filament material, and the filament surface condition.

Electric Filament Supply:

This filament supply was constructed by the Ethyl Gasoline Corporation and loaned to the author. It is shown schematically in Figure 8 and consists of the following equipment:

1 Voltage stabilizer

1 Variac

1 Step down transformer

1 Current transformer

This unit is designed to supply a high current at low voltage to the preigniter filament. Incorporated in the chassis is a voltmeter to measure the voltage across the filament. The positive lead is connected to the center electrode of the preigniter and the negative lead is grounded to the engine near the preigniter. The current transformer permits the measurement of the large current with an ammeter having a 0-1 ampere range.

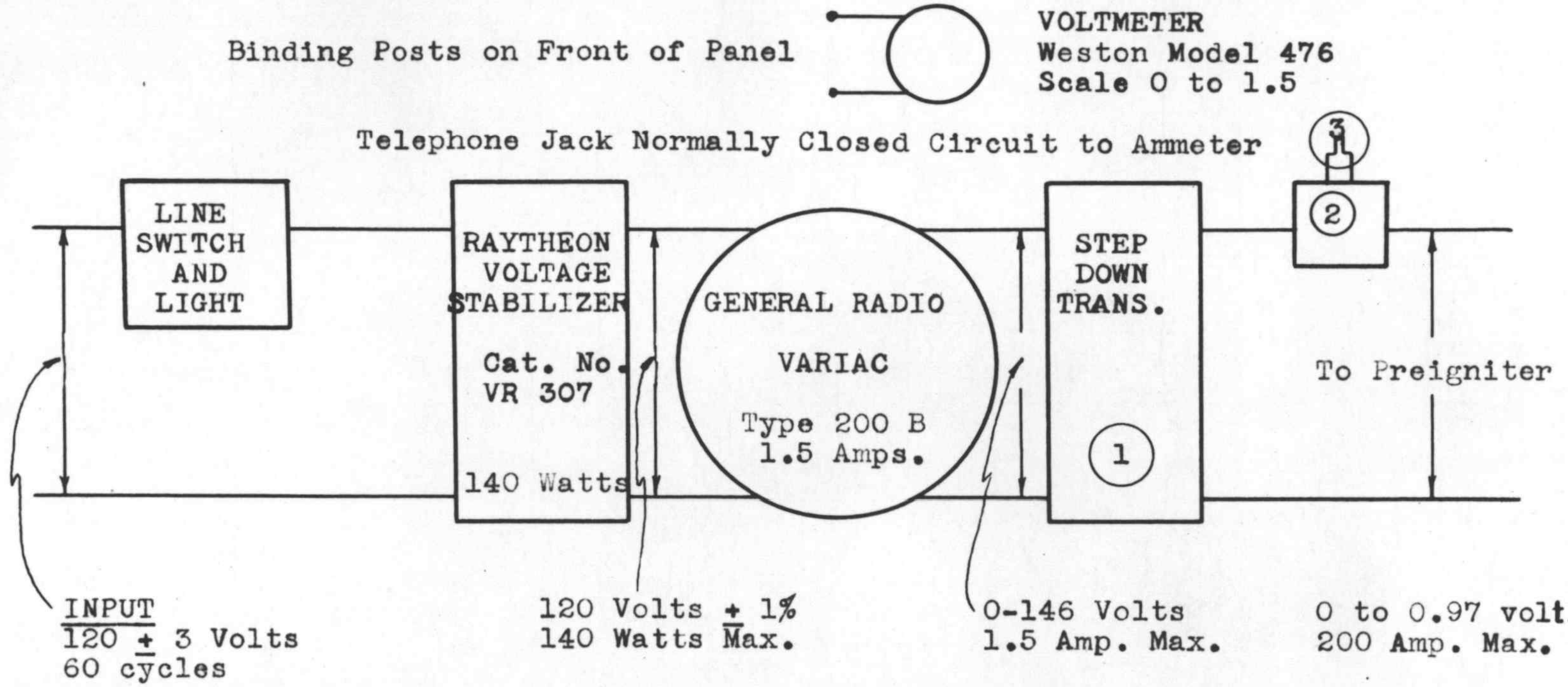


Figure 8. Preigniter Filament Supply Circuit
(Courtesy of Ethyl Gasoline Corp.)

1. Made to Order by the Osborn Transformer Company, Detroit.
   RATING: 0.7 volts, 200 amps.,120 volt input.

2. CURRENT TRANSFORMER made to order by the Osborn Transformer Company, Detroit.
   Ratio 1 to 100. There is no primary. The conductor in which current is to be measured passes through the transformer core opening.

VII EQUIPMENT TO DETECT PREIGNITION

Ionization Pick-up Wire:

This wire, which has been mentioned briefly in a previous section, is built into the preigniter assembly. Under preigniting conditions it is necessary to know the time in the cycle when preignition originates; therefore, it is desirable to have the ionization pick-up located near to the filament, for it must be realized that a lag will result according to the time it takes for the flame front to travel from the filament to the pick-up wire. The wire has a positive voltage impressed on it by an electronic circuit.

The principle of operation of the pick-up wire is based on the phenomenon of ionization. "Ions are created from neutral matter by detaching one or more electrons from a neutral atom. To do this, energy must be supplied to the atom. This energy can come from several sources, the most important being from an impact with another particle, from electromagnetic waves, from a chemical reaction, or from heat" (2, p 10). Therefore, as a result of the heat liberated at the flame front during combustion, ionization of the gas occurs. Two of the most important ions are the electron and the positive ion, and they are free to move independently (9, p 127). The ions produced make the gas an electrical conductor and establish a circuit momentarily between the ionization pick-up wire and the wall of the combustion chamber which is at ground potential.

Electronic Circuit:

The electronic circuit used to detect preignition is shown in Figure 9. Basically it is similar to the circuit shown in Figure 10 which was recommended by the Ethyl Gasoline Corporation research laboratories, but it was built of war surplus materials. For this reason, modifications were necessary to permit the use of materials which were available. The input of this unit is connected to the ionization pick-up wire in the combustion chamber, and the output is connected through an ignition coil to a spark protractor on the crankshaft. The ignition coil is not shown in Figure 9, since it was mounted externally to this circuit.

The design of this electronic circuit embodies the use of a Type-80 full wave rectifier, a Type-56 triode, and a General Radio Strobotron No. 631-Pl. Referring to Figure 9, the operation of this circuit may be explained as follows: The 110 volt-60 cycle input is rectified and filtered. Direct current flows from the anode to the cathode in the Type-56 tube with the grid being operated positive. When the flame front reaches the pick-up plug,

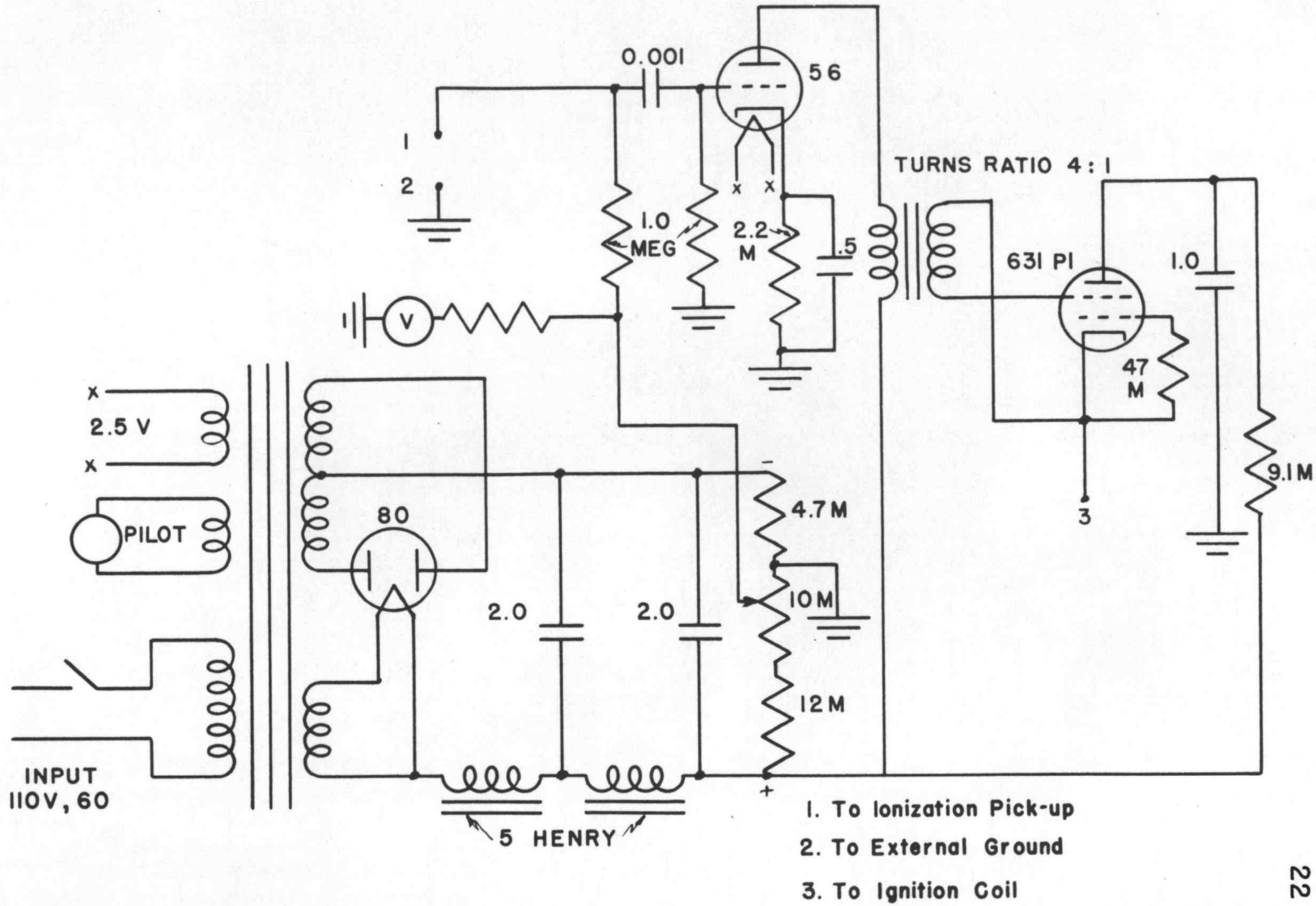


Figure 9. Ionization Pick-up Circuit Used

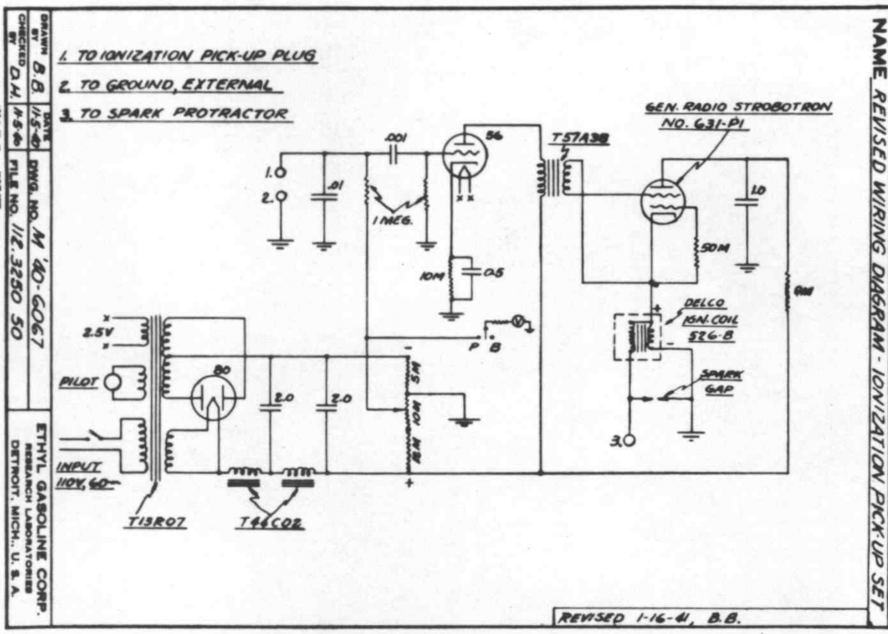


Figure 10. Recommended Ionization Pick-up Circuit.

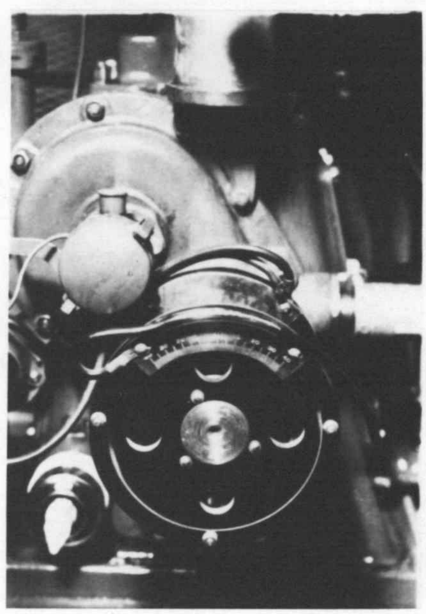


Figure 11. Spark Protractor.

ionization occurs and the grid potential decreases rapidly to the point where the Type-56 tube stops conducting. This stoppage of conduction creates a change in flux in the coupling transformer and results in a voltage being induced on the secondary of the transformer. This voltage drives the control grid of the strobotron positive and permits the tube to "fire" instantaneously. This sends a high potential impulse to the ignition coil where it is further increased and impressed on the spark protractor.

Spark Protractor:

In order to measure the time of ionization in crank-angle degrees, it was necessary to mount a second spark protractor on the crankshaft. This was done as shown in Figure 11. The author felt that having the two protractors in line would facilitate determining the occurrence of one spark with respect to the other. This particular mounting was accomplished by machining an extension to the crank-shaft. A bakelite rotor with a slot for a neon spark indicator was fastened to the crankshaft extension. This rotor was adjusted to rotate within a bakelite stator, which was fastened solidly to the engine. To the stator there was fastened an adjustable steel protractor scale to show the time of ionization. This protractor was connected through an ignition coil to the electronic circuit. A high potential impulse from the strobotron was sent through the ignition coil to the protractor plate from which it jumped to ground through the neon light, causing the light to flash instantaneously.

Filament Temperature Indicator:

The platinum to platinum-10%rhodium thermocouple built into the preigniter and welded to the filament had its cold junction on top of the preigniter assembly. A Wheelco Type-ST pyrometer, Serial No. 14, graduated in degrees Centigrade was connected to the thermocouple through compensating leads. The pyrometer indicated the average filament temperature; however, the thermocouple was not sensitive to cyclic changes in temperature, and, therefore, the maximum and minimum temperatures occurring during operation of the engine could not be determined exactly.

VIII SELECTION OF PREIGNITION REFERENCE FUELS

A separate investigation was made on various fuels to determine which would be suitable for use as preignition reference fuels. Since the primary reference fuels used for referee testing in octane ratings are costly, the secondary fuels are used for routine determinations. For this reason, this investigation was limited to several secondary reference fuels, and, in addition, commercially pure benzol, Stoddard solvent, and automotive diesel fuel.

In the selection of reference fuels, several factors must be taken into account. First, the characteristics of the fuels must be standard to permit reproducibility of tests. Next, they must be reasonably inexpensive. Lastly, they must be readily available. One of the reference fuels must resist preignition, and the other should preignite more readily than any of the fuels to be tested.

Table I gives the results averaged from three tests on six different fuels. The diesel fuel used was an automotive diesel with a specific gravity of 0.85. Considerable difficulty was encountered in causing the fuel to ignite even with manifold temperatures of 350 F, except at higher compression ratios. For this reason, diesel fuel cannot be considered as a preignition reference fuel. The cp benzol was furnished by California Research Corporation.

Their laboratory reports showed a sulphur content of 0.013 percent by the lamp method.

Fuel	Filament Temp at Normal Comb. Comp. Ratio 4:1 Deg F	Compression Ratio at Incipient Preignition	Filament Temp* at Incipient Preignition Deg F
A Reference	875	5.16	1920
C Reference	860	6.25	1920
F-5 Reference	840	9.50	2025
CP Benzol	910	4.60	1960
Stoddard Solvent	860	5.23	1940
Diesel	985	4.45	1920

* Variac set to give a filament temperature of 1830 F with engine not operating.

Table I. Preignition Characteristics of Various Fuels

Analyzing the data of Table I for the selection of reference fuels, F-5 resists preignition better than any of the others since it requires a compression ratio of 9.5 to 1 (for one setting of the variac) to cause it to preignite. Cp benzol, on the other extreme, requires a compression ratio of only 4.6 to 1 to cause it to preignite at the same variac setting. All of the other fuels fall in the range between these two, with the exception of the diesel fuel, and it was excluded as a reference fuel for the reason mentioned above. These facts are in agreement with the general belief that the aromatic fuels fail through preignition rather than detonation. The F-5 reference fuel, which is technical iso-octane, is a straight-run gasoline of the paraffin family.

It is of interest to note that cp benzol burns at higher temperatures than technical iso-octane (F-5) during normal combustion at a compression ratio of 4:1. This fact must be taken into consideration when determining the preignition characteristics, since the higher heat of combustion will raise the temperature of the combustion chamber parts. The filament temperature at incipient preignition of F-5 was 65 F above that for cp benzol. However, the filament temperature at incipient preignition of cp benzol was as much as 40 F higher than the temperature required for any of the other fuels tested. Although the actual temperature could be slightly in error, even though the thermocouple was calibrated, the difference in temperatures was reasonably accurate. Of more importance, perhaps, was the increased temperature of combustion accompanying an increase in the compression ratio. The increase for cp benzol was greater than any of the other fuels tested, and, therefore, it preignited at a lower compression ratio than any of the others.

IX OPERATING CONDITIONS FOR ENGINE

In the determination of the operating conditions for a preignition test, the fact was kept in mind that all variables would have to be kept within the limits allowed by the CFR engine. In general, where possible, the operating conditions specified herein are in conformance with those specified in the Federal Standard Stock Catalogue for the determination of octane ratings (5, p 141-142).

Engine Speed:

The engine speed should be 900 ± 3 revolutions per minute. The engine is belted to an induction motor with synchronous characteristics to hold the speed constant. The engine used in this investigation did not have accessory equipment to permit a variation of the speed. However, the Ethyl Gasoline Corporation laboratories reported that 900 rpm was the most satisfactory speed and that a change to 600 or 1200 rpm would have little effect on the results (4, p 1).

Jacket Temperature:

The jacket temperature should be constant within one degree F at a temperature between the limits of 205 F and 215 F. This temperature must be high enough to prevent the accumulation of carbon in the combustion chamber, around the valves, spark plug, preigniter, and piston head.

Cooling Liquid:

The cooling liquid can be either distilled water, rain water, or, where necessary at high altitude, ethylene-glycol solution.

Crankcase Lubricating Oil:

SAE 30 is the proper weight oil to use in the crankcase. The oil temperature should be between 135 F to 150 F.

Oil Pressure:

The oil pressure should be 25 to 30 pounds per square inch at operating conditions.

Valve Clearances:

The exhaust valve clearance should be 0.010 inch, cold. The intake valve clearance should be 0.008 inch, cold.

Spark Advance:

The spark advance is automatically changed with the compression ratio in accordance with the motor method knock test procedure.

In view of the fact that the two spark indicators were mounted in line, with the ionization indicator directly in front of the other, it was felt desirable to investigate the possibility of using a constant electric spark setting. A constant electric spark setting would eliminate the necessity of reading the electric spark indicator.

Realizing that preignition is a surface phenomenon, the engine should be operated to give the maximum normal combustion temperature for each fuel at maximum power. In order to study the effects of a varying spark advance, a test was made at a compression ratio of 6 to 1 with no preigniter filament current flowing. The spark was varied from 8 deg after top dead center to 40 deg before top dead center. The filament temperature during combustion and the time for the flame to progress from the spark plug to the ionization pick-up wire were measured. These data are presented in Table II. They show that the combustion temperature increases as the spark is advanced. The increase in temperature is due to the increased time during which the combustion chamber parts are exposed to burned gases (15, p 132). However, in this case, a spark setting in advance of 25 degrees before top dead center

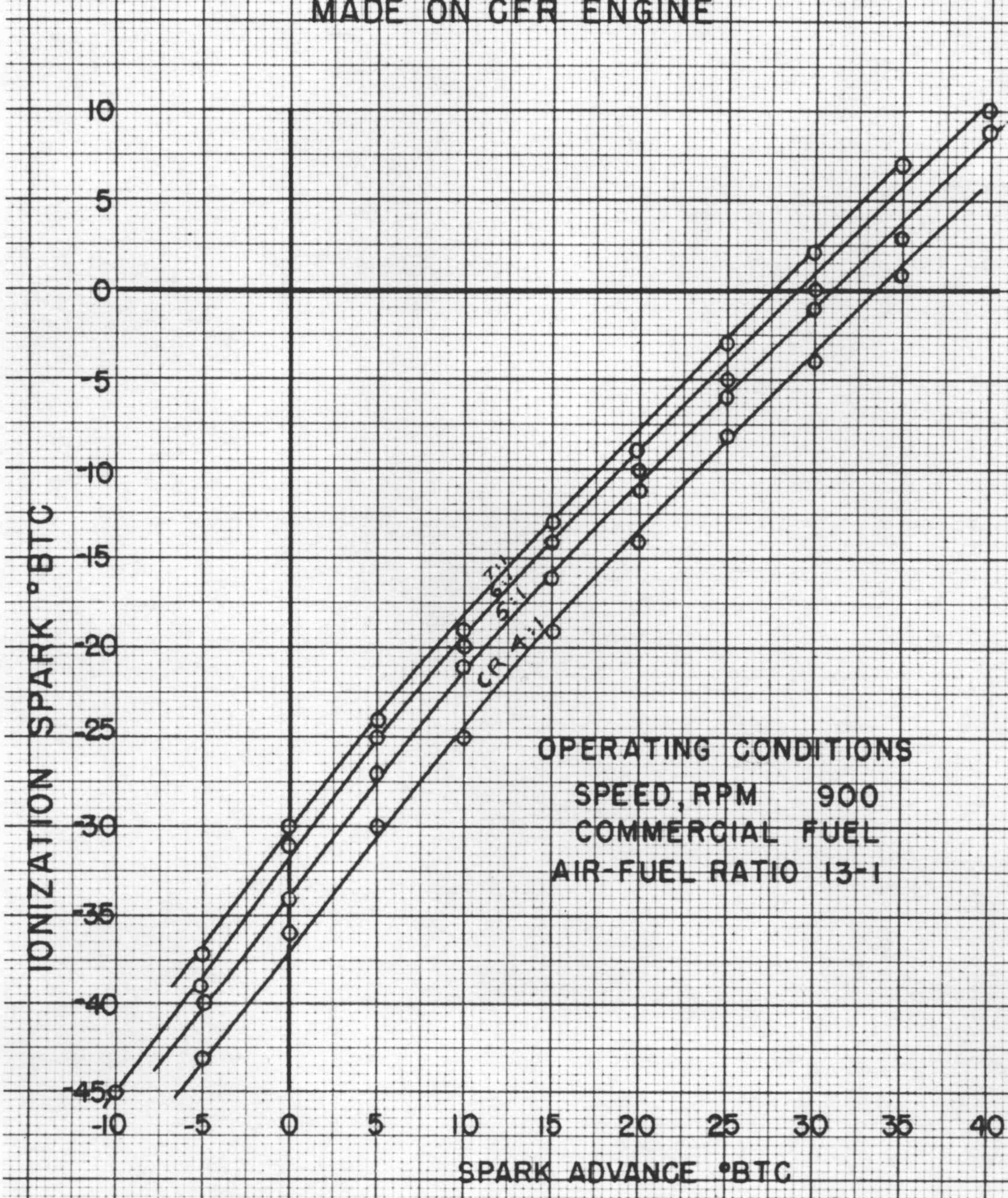


Figure 12. Effect of Compression Ratio on Flame Travel

would result in a loss of power since combustion is complete before the piston reaches top dead center, and maximum pressure would not occur near the beginning of the expansion stroke.

Spark Setting Deg BTDC	Ionization Indicator Deg BTDC	Crank-Angle for Flame to Progress From Spark Plug to Pick-up. Deg.	Filament Temperature During Comb. Deg F.
-8	-43	35	860
-5	-39	34	900
0	-32	32	930
5	-23	28	965
10	-17	27	980
15	-10	25	1000
20	- 4	24	1040
25	0	25	1070
30	5	25	1110
35	9	26	1160
40	13	27	1220

Table II. Effect of Spark Advance on Combustion Temperature and Time

The data presented in Figure 12 show that the flame travel varies, for a particular fuel, with the compression ratio. In order to get maximum pressure near top dead center, it was decided to specify that the test be made at maximum power by varying the spark setting with the compression ratio according to the motor method knock test procedure. This was accomplished automatically by a linkage arm connecting the manually adjusted engine head to the distributor arm.

Breaker Point Clearance:

For the battery system the breaker point clearance should be 0.015 inch, and for the magneto system it should be 0.020 inch.

Spark Plug:

The spark plug is a standard metric plug having the tolerance and thermal characteristics equal to the standard No. 8 spark plug manufactured by the Champion Spark Plug Company. The gap setting should be 0.025 inch.

Throttle Opening:

The throttle opening should be at the point of maximum volumetric efficiency.

Carburetor Adjustment:

The carburetor should be set to give the maximum pre-igniter filament temperature; this is, also, the mixture for maximum power (7, p 280). The fuel will have the greatest tendency to preignite at this condition, and the compression ratio will not have to be increased as much as with leaner or richer mixtures to cause preignition. This fact is verified by the curve shown in Figure 13. This curve represents the compression ratio necessary to cause

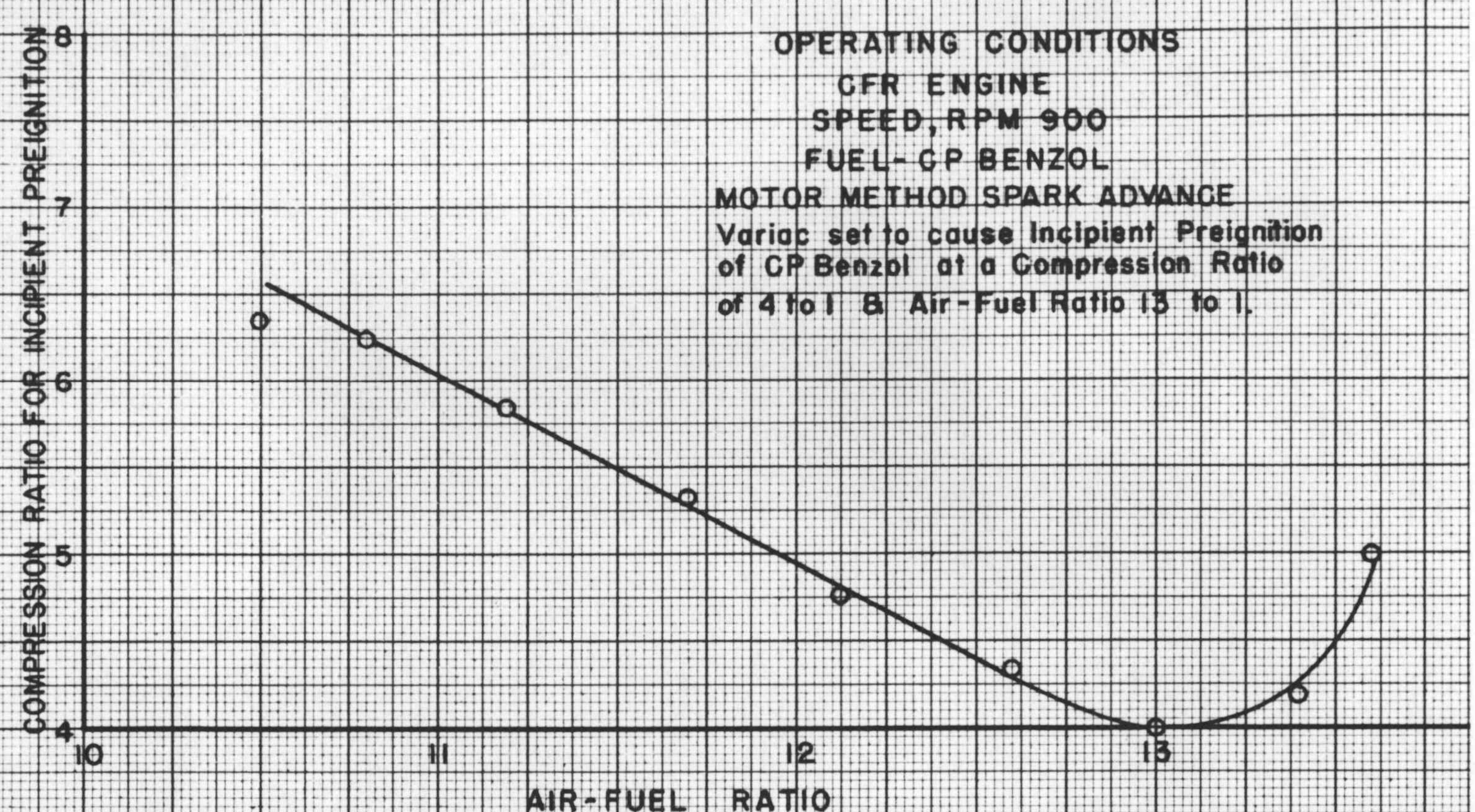


Figure 13. Effect of Air-Fuel Ratio on Compression Ratio
For Incipient Preignition

incipient preignition of cp benzol for different settings of the air-fuel ratio, and indicates that there is a critical value of the air-fuel ratio at which the fuel has the greatest tendency to preignite. This point is at the air-fuel ratio where the heat of combustion is greatest, and varies slightly for different fuels. Changes of the air-fuel ratio can have almost as much effect on the preignition rating of a fuel as the compression ratio itself. It is, therefore, extremely important to set the carburetor accurately when rating fuels for their preignition characteristics.

A portable Ranarex air-fuel ratio indicator was connected to a sampling tube in the exhaust line. A test showing the effect of air-fuel ratio on the preigniter filament temperature was made at a compression ratio of 4 to 1. The air-fuel ratio was varied in the range of the

Air-Fuel Ratio	Preigniter Filament Temperature Deg F
11.2	800
11.5	810
11.7	820
12.0	830
13.0	840
13.2	820
13.5	785

Table III. Effect of Air-Fuel Ratio on the Preigniter Filament Temperature mixture for maximum power, and the preigniter filament temperature recorded as a relative indication of the combustion temperature (Table III).

Exhaust Pipe:

This pipe must be $1\frac{1}{4}$ inches in diameter with a maximum of two ells. The pipe should not be over 20 feet long. A separate exhaust line is required for each engine.

Mixture Temperature:

This temperature should be maintained at 300 ± 2 F, according to the motor method knock test procedure. This temperature permits vaporization of most of the liquid fuel in the manifold. Raising the temperature of the unburned mixture by increasing the inlet manifold temperature does not noticeably increase the tendency of a fuel to preignite. The inlet air temperature has no appreciable effect on the preigniter filament temperature during combustion. This is due mainly to the fact that the thermocouple is not sensitive to very small and somewhat cyclic changes in the temperature.

X PROPOSED SPECIFICATIONS FOR TEST PROCEDURE

Starting and Stopping the Engine:

"While the engine is being turned over by the electric motor, the ignition shall be turned on and the carburetor set so as to draw fuel from one float bowl. To stop the engine the fuel and ignition switch shall be turned off, and then the motor shall be stopped by means of the push-button switch" (5, p 143).

Criterion for Incipient Preignition:

Incipient preignition shall be considered as occurring when the ionization pick-up spark flashes regularly 4 or 5 times in 15 seconds, lagging the electrical spark by 10 or 15 degrees.

Adjustment of the Carburetor for Fuels Being Tested:

Fill one float bowl with the fuel to be tested. Then adjust the float bowl level to give the maximum preigniter filament temperature (maximum power mixture) by raising and lowering the level of the float bowl and noting the pyrometer reading. The float bowl shall then be moved in the direction in which the temperature increases until the temperature passes through a maximum. This point shall be checked three times and the float bowl set at the position giving maximum preigniter filament temperature. It is important to let the pyrometer reach equilibrium after every change of the float bowl level. This same procedure shall be followed with each of the reference fuels used.

Adjustment of the Variac Setting:

Using cp benzol at a compression ratio of 4 to 1, the electric preigniter filament supply shall be turned on and the filament current increased by adjusting the variac until the point of incipient preignition is reached. The carburetor shall then be changed to the F-5 reference fuel and the compression ratio increased to the point of incipient preignition for F-5. If this point occurs at a compression ratio of 7.5 to 1, the variac setting shall be considered as being correct for the test. If either of the two reference fuels fails to preignite at the specified compression ratio, the variac setting shall be changed slightly, and the point of incipient preignition of the two reference fuels rechecked until they are in agreement with these values. When the proper variac setting has been established, it should not be changed during the rating of a fuel.

Outline of Procedure:

With a proper setting of the carburetor float bowl level and variac, and with the engine operating on the sample fuel at a compression ratio near 4 to 1, the compression ratio shall be increased until the point of incipient preignition of the sample is reached. The compression ratio necessary to cause incipient preignition shall be recorded. This shall be repeated three times and the compression ratio values averaged. The compression ratio required for incipient preignition of F-5 and cp benzol shall be rechecked to determine if the variac setting remained constant during the test. If it has changed, the results of the test shall be considered void and a new test made. The preignition rating of the unknown fuel is found by multiplying the average compression ratio required for incipient preignition of the sample by 10.

Preignition Number:

The preignition number of a motor fuel is the whole number nearest to the compression ratio required for incipient preignition, multiplied by ten. Using this test procedure, cp benzol will have a preignition number of 40, and the F-5 reference fuel will have a preignition number of 75.

The preignition number is based on an arbitrarily selected scale resulting from considerable research into the proper filament temperature at which to conduct preignition tests. The scale permits the rating of fuels superior to F-5 in preignition characteristics. Brief studies also indicate that this arbitrary scale should permit the reproducibility of ratings within 3 preignition numbers.

XI RESULTS AND CONCLUSIONS

The reference fuels were selected with the idea in mind that it would be absolutely essential to have one that resisted preignition and one that preignited more readily than any sample that might be tested. For this reason, F-5 and cp benzol were selected, the original plan being to give F-5 a preignition number of 100 and cp benzol a preignition number of 0. This method would have specified a constant variac setting in the determination of the compression ratio for incipient preignition of the sample. In addition, two blends of the reference fuels, one preigniting at a higher compression ratio and one at a lower compression ratio than the sample, would have had to be tested. The preignition number of the reference fuels would have been the percent of the F-5 reference fuel in cp benzol. The preignition number of the sample could then be found by interpolation between the reference fuels.

This method, initially tried, was disadvantageous in that considerable time was required to find two reference fuels with which to bracket the sample, and, secondly, the results of this type of test were not reproducible to the desired degree of accuracy, particularly at the higher preignition ratings. The lack of reproducibility is evident from the curve of Figure 14, which shows that the

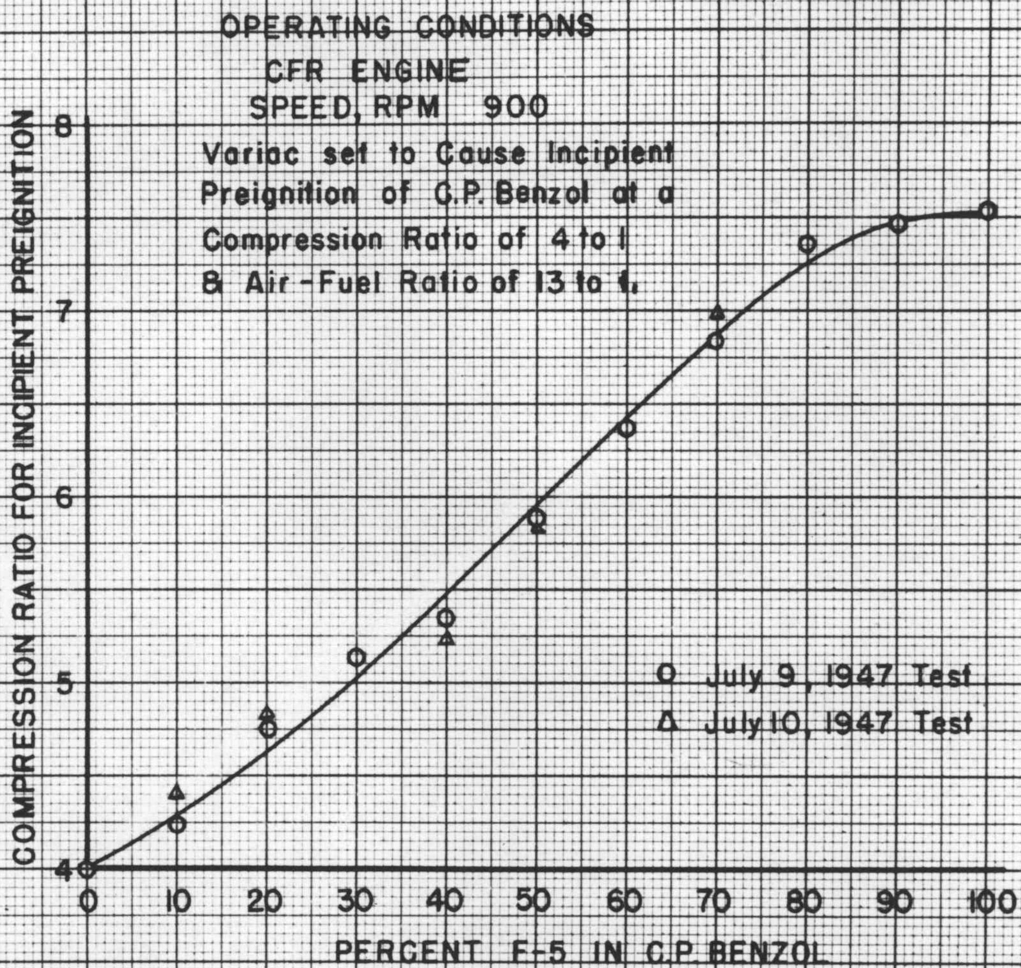


Figure 14. Compression Ratio for Incipient Preignition of Blends of F-5 in C.P. Benzol

compression ratio required for incipient preignition of blends of F-5 in cp benzol varies only slightly for percentages of F-5 between 80 and 100 in a blend with cp benzol.

The heat supplied to the preigniter filament, as measured by the thermocouple, comes from two sources. These are the heat of compression and combustion of the fuel and the electric energy supplied which is converted to heat by the resistance of the filament. An investigation was made to determine exactly how the filament temperature was affected by the electrical energy and the heat of combustion. A commercial grade fuel was used at compression ratios of 4, 5, and 6 to 1 with two settings of the spark advance. It should be mentioned that the results cannot be exactly duplicated due, primarily, to slow deterioration of the filament. In other words, the filament current at a particular voltage decreases as the time in service of the filament increases.

The filament temperature is plotted as a function of the filament current in Figure 15. The filament temperature appears to be directly proportional to the filament current without the engine operating. With the engine running, the filament temperatures are higher because the filament is heated by the electric energy plus the effective heat of the cycle. The filament temperature

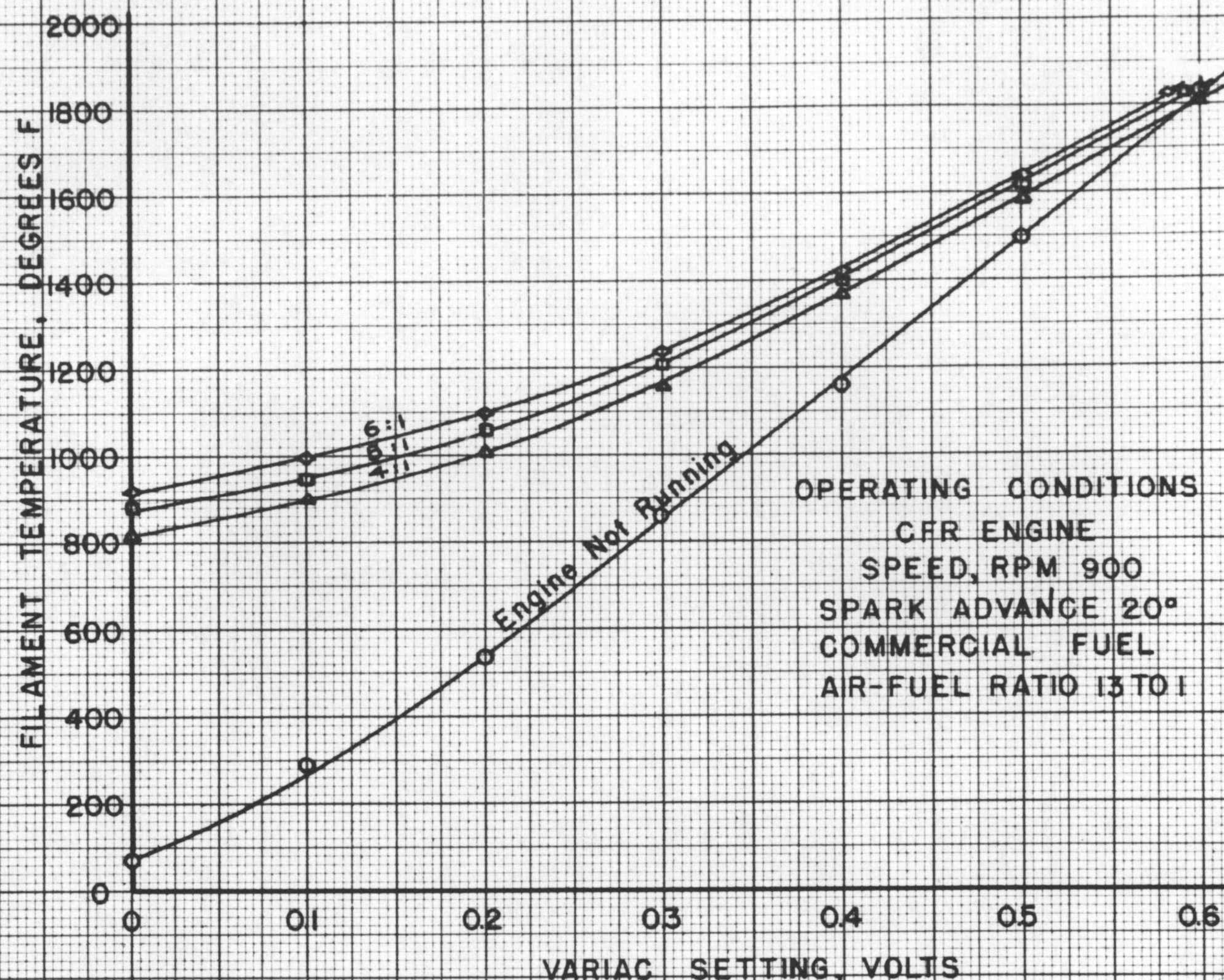


Figure 15. Effect of the Filament Current and Heat of Combustion on the Filament Temperature

indicated by the pyrometer is, therefore, more or less an average value between the temperature representing the "effective heat" and the temperature due to the electric energy supplied to the filament.

It was observed that above a critical value of filament current, at a compression ratio of 4 to 1, the filament temperature was lower with the engine operating than it was without the engine operating (at a constant variac setting). This meant that the "effective heat" was lower than the heat from the electric energy and that the "effective heat" of the cycle was actually cooling the filament. The intersection of the two curves represents the point at which the temperature due to the electric energy equals the temperature due to the "effective heat".

The filament temperature shows only the average temperature of the filament, and the thermocouple is not responsive enough to indicate the fluctuations that occur during one cycle. The filament is cooled during the suction stroke, heated during the compression stroke, further heated by the combustion of the gases, and cooled somewhat during the expansion stroke. This condition must be kept in mind when analyzing the filament temperature, particularly as it is affected by other variables of the cycle.

The filament temperature required for incipient preignition is believed to be constant for a particular fuel, regardless of the compression ratio. The results of a test conducted with a commercial gasoline are presented in Table IV. As the compression ratio was increased, more heat was liberated to the filament from the products of combustion and less electric energy was required to cause preignition as indicated by a decrease in the variac setting.

Compression Ratio	Filament Temp at Incipient Preignition Deg C.	Variac Setting Volts
4	1050	0.62
5	1050	0.61
6	1050	0.60
7	1050	0.58
8	1050	0.56
9	1050	0.54

Table IV. Effect of Compression Ratio on Filament Temperature Required for Preignition

During normal combustion without the presence of preignition, the hottest spot in the combustion chamber is presumed to be near the spark plug. "When the charge is completely inflamed, there is a temperature gradient along the length of the combustion space, the temperature at the spark plug end being as much as 600 F higher than at the opposite end" (11, p 125). However, with preignition occurring, it was believed that the preigniter filament would be the hottest spot in the combustion chamber. Tests showed that at the moment preignition occurred with a commercial grade of fuel, the filament temperature rose rapidly from 1050 C to 1240 C.

The thermocouple used in studying the preigniter filament temperature was calibrated against a Leeds and Northrup optical pyrometer to determine the accuracy of the thermocouple readings. This optical pyrometer was reasonably new and known to be accurate. The Wheelco pyrometer connected to the platinum-10%rhodium thermocouple never differed more than 60 F from the optical pyrometer.

The first two filaments used were of a U-type, as shown in Figure 5. It was observed that the thermocouple was not at the hottest point on the filament. The filament was the hottest near the ends and coolest near the center. This was due, in part, to the fact that the thermocouple conducted some of the heat away from the filament. Therefore, in later filaments a V-type design was used, as shown in Figure 7. The hottest part of this filament was at the point of the V, and, therefore, by welding the thermocouple to this point, the temperature indicated by the pyrometer is more nearly the filament temperature causing preignition.

The heat supplied to the filament by the electric energy was considerably greater than the heat supplied from combustion. For this reason, the variac setting must be very carefully controlled on the reference fuels if the results of the test are to be reproducible. A slight change in the variac setting will, therefore, have more effect on the results of the test than a slight change in the compression ratio. The heat supplied by the electric energy is the laboratory method of inducing preignition, whereas the heat necessary to cause failure of a fuel by preignition in an engine could come from a combustion chamber deposit, spark plug, or exhaust valve.

During preliminary test runs to check the electronic circuit, it was noticed that the ionization spark was cyclic over a range of approximately 20 degrees, rather than occurring at a particular point, as with the ignition spark. A separate investigation was conducted to determine if the electronic circuit contained a variable time lag that would have to be eliminated. This was done by using an eight inch disc rotating at 450 revolutions per minute. On the face of the disc a piece of white tape was mounted radially. The disc contained contact points that would close once per revolution. The contact points were connected to the electronic circuit input, and a 200 ohm resistor was connected across the output. The electronic circuit chassis was mounted so that the top of the strobotron tube faced the disc. With the disc rotating at 450 rpm, the strobotron tube fired 450 times per minute, and the image of the tape appeared to be stationary, which indicated that no significant time lag existed in the circuit.

Therefore, it was believed that the cyclic action was caused by an uneven rate of combustion. Investigation of existing literature disclosed that the flame front during combustion does not progress across the combustion chamber evenly. This was evident in studying pictures of flame propagation taken through a quartz cylinder head in a combustion chamber (12, p 34-35). Figure 16 shows a series of photographs of flame travel in a spark-ignition engine, and offers an explanation of the cyclic action of the ionization spark. Electric spark originates on the left side of the pictures, and the flame progresses toward the right side where the ionization pick-up wire projects vertically into the combustion chamber. When the flame front in the center of the combustion chamber leads, the difference between ignition and ionization spark is a minimum; but when the flame front on either side of the combustion chamber leads, more time is required for the flame to reach the pick-up wire, and, consequently, the difference between sparks is greater.

Mention was made previously, and an explanation given,

Figure 16. Flame Development in a Spark-Ignition Engine.

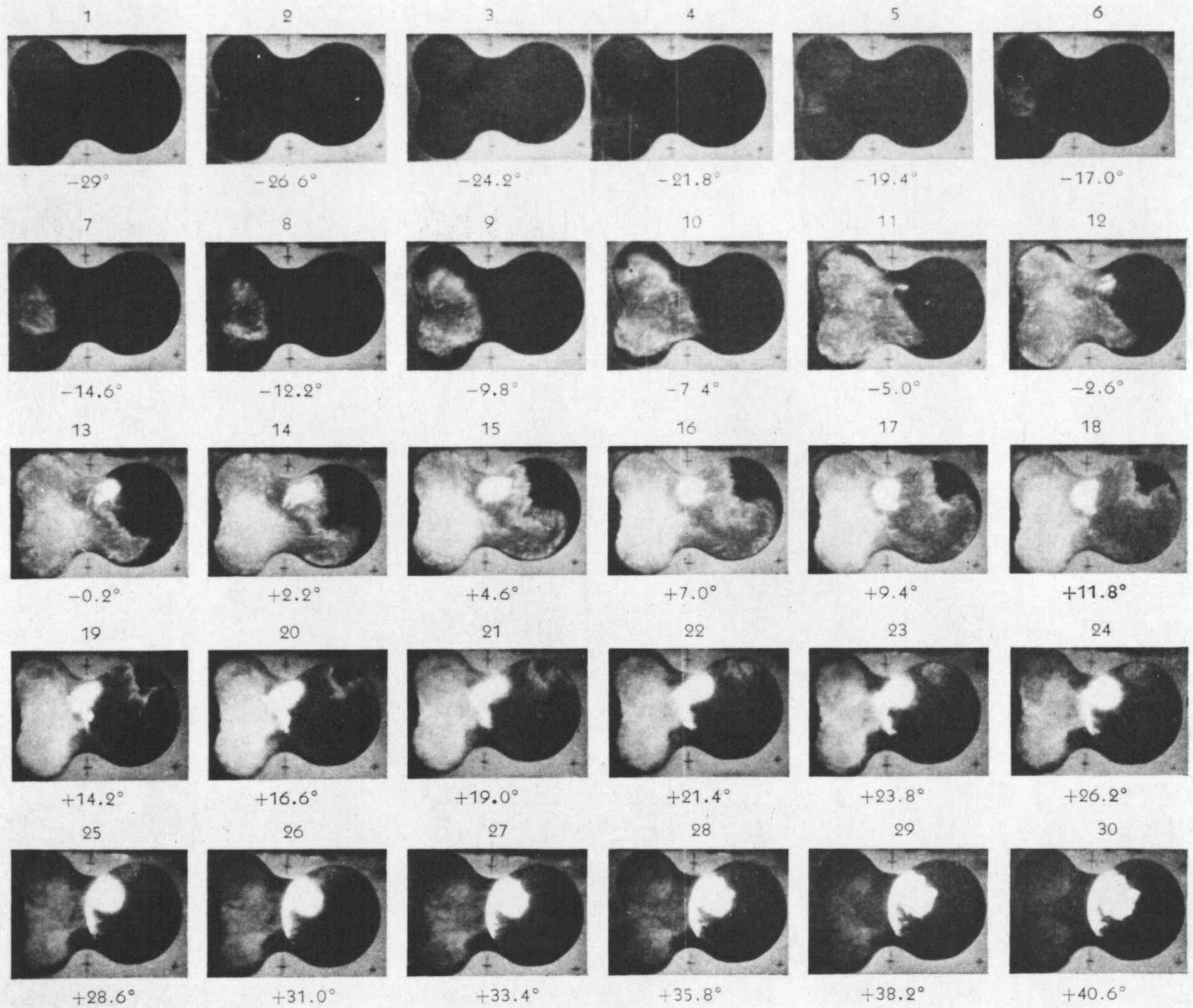


FIG. 34. High Speed Motion Pictures of Flame Development in a Spark-Ignition Engine, taken through a quartz-glass cylinder head by Withrow and Rassweiler (14.20). Duration of each picture 2.2 degrees of crank travel. Numbers indicate angle of the crank, after top center, at the end of each exposure.

of the fact that when preignition occurred, the filament temperature rose approximately 200 C. In conjunction with this rise in temperature, it was found that the point of preignition occurred earlier in the cycle as the temperature increased. The term "degree of preignition" was used to indicate ignition of the charge before spark occurred and was measured in crank angle degrees. It was noted that this angle could be either positive or negative. The preignition test procedure specified the determination of the point of incipient preignition in order to prevent the sudden rise in temperature. Originally, it was intended to define the occurrence of incipient preignition as two flashes of the ionization spark in advance of electric ignition, in 15 seconds. Subsequent tests, however, showed that the degree of preignition could not be controlled at this point, and that, actually, preignition was incipient approximately 15 degrees earlier. This fact was evident in that the engine would continue to fire intermittently at this point, with electric ignition turned off. At the point of incipient preignition the degree of preignition did not increase. This facilitated locating the point of incipient preignition for a fuel. As the filament temperature was increased further, preignition was regular and the degree of preignition increased. Under severe conditions, the degree of preignition could increase to the point where the charge would preignite while the intake valve was still open, and result in the engine backfiring through the intake manifold.

The fuels with a higher heat of combustion in the mixture as burned could be expected to have the greatest tendency to preignite, since they would raise the temperature of the combustion chamber surfaces higher than would fuels of lower heat liberation per unit of mixture volume. Those fuels with higher combustion temperatures should be derated on the preignition scale. This fact was taken into account in the test procedure prescribed, in that a lower compression ratio was required to furnish the heat necessary to cause preignition with this type of fuel. The preignition number is directly proportional to the compression ratio; consequently, fuels that require a low compression ratio to cause preignition will have a correspondingly low preignition number. The data of Table I show that the filament temperature required for incipient preignition of different fuels varies slightly. The maximum temperature difference between the fuels investigated was 105 F. The F-5 reference fuel required a temperature of 2025 F, and the "C" and "A" reference fuels required a temperature of 1920 F. The higher temperature required indicates that the fuel has a slightly greater resistance to preignition (neglecting the chemical structure) and is accounted for in the test procedure specified in that the compression ratio would have to be increased somewhat to cause a higher heat of combustion to overcome this resistance to preignition. The higher compression ratio would give the fuel a higher preignition number.

The engine was operated for a short time on a low octane fuel at a compression ratio where audible knock existed. The variac setting was then increased to cause preignition of the fuel at the filament. The point of incipient preignition was readily detected by the appearance of a sharp, more severe, knock. As the degree of preignition was increased so that the ionization spark occurred before electric spark, the knocking disappeared.

The problem of humidity has not been mentioned, as yet, in this study. It has been experimentally determined that the presence of water vapor in the fresh charge decreases the weight of air in a given volume of charge as a result of its diluent effect (3, p 141). Experience has shown that increased spark advance is required with an increase in humidity (15, p 70). Since this test procedure specified that the air-fuel ratio should be set for maximum combustion chamber temperature, the carburetor setting could be adjusted to partly offset the effect of the increase in humidity. It is reasonable to expect that the maximum filament temperature would be slightly lower at high humidity than at low humidity, due to the water vapor, and that the electric energy supplied to the filament would have to be increased. This would have to be done to cause the reference fuels, as well as the sample, to preignite, and, therefore, the effect of humidity would be compensated for.

The effect of lead tetraethyl on the tendency of a fuel to preignite is shown in Figure 17. This curve was obtained by blending lead tetraethyl in the F-5 reference fuel and determining the compression ratio required to cause incipient preignition of each blend. It was believed that any increase in the preignition number due to the addition of lead tetraethyl came either from the increased resistance of the fuel to detonate, or from an increased resistance of the mixture to preignite. Lead tetraethyl was blended with cp benzol, which fails by preignition without audible knock, and it was noted that the increase in the preignition number of the cp benzol was not as great as with the F-5 reference fuel. It was discovered that the filament had a deposit on it after several hours of operation with a mixture containing lead tetraethyl. This deposit apparently insulated the charge from the catalytic effect of the platinum filament, and required more heat supplied to the filament to cause preignition with this

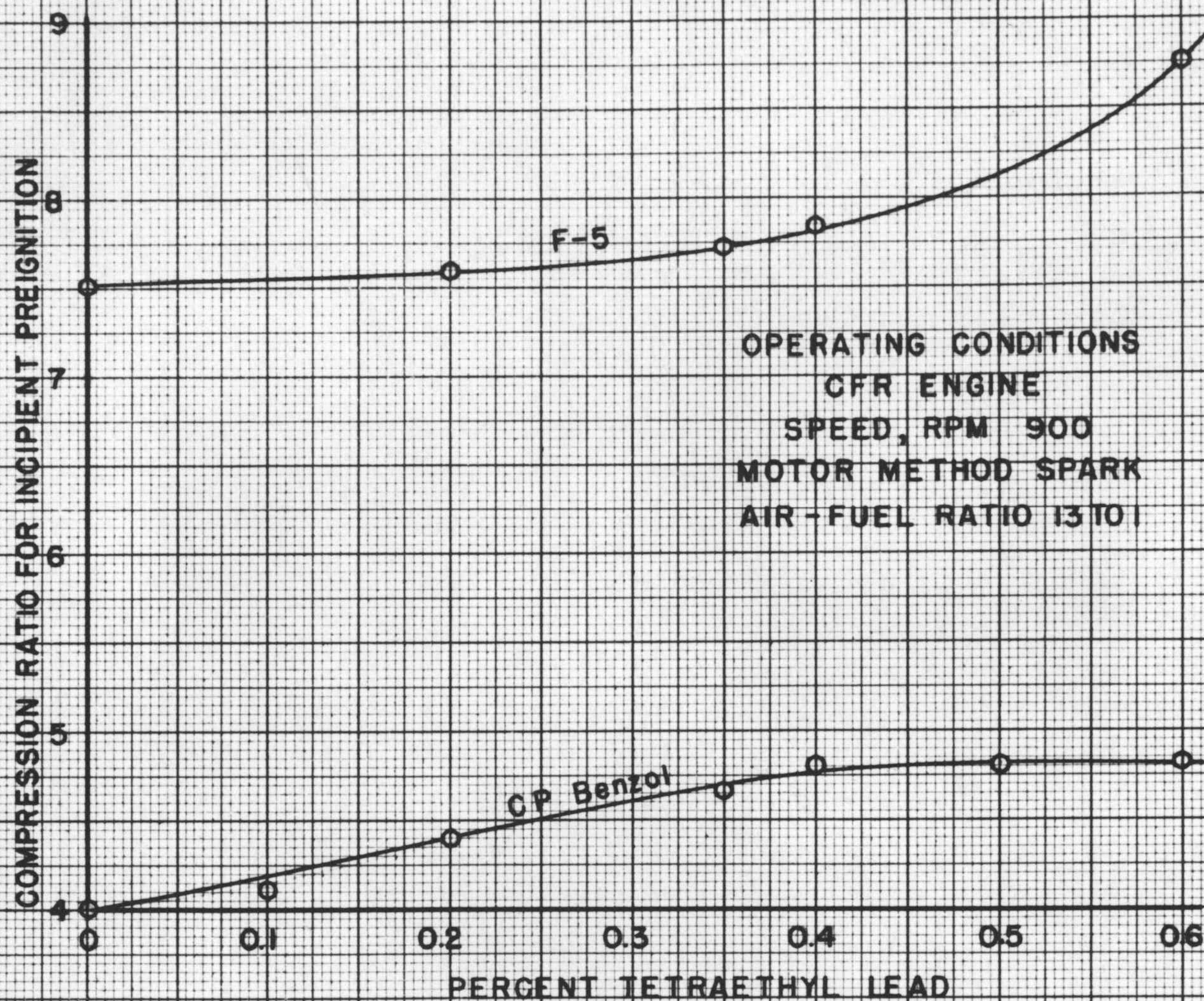


Figure 17. Effect of Lead Tetraethyl on the Compression Ratio Required for Preignition of F-5 & Benzol.

surface condition. When the deposit was removed from the filament, the variac setting was similar to its value before the deposit occurred.

No attempt was made in this investigation to determine whether or not preignition resulted in destruction of any of the engine parts. A test of this type would have required the running of the engine under preigniting conditions until failure occurred. Spare engine parts were not available for such a test, and, therefore, no attempt is made herein to cover such effects.

It was considered important to determine the pre-ignition rating of the "C" reference fuel, since this would facilitate setting or checking the variac adjustment. The preignition number of the "C" reference fuel was found to be 55 since it preignited at a compression ratio of 5.54. This fuel failed first by detonation, and preignition occurred immediately after the appearance of audible knock.

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