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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 565

# INFLUENCE OF FUEL-OIL TEMPERATURE ON THE COMBUSTION IN A PRECHAMBER COMPRESSION-IGNITION ENGINE

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Washington
April 1936

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# INFLUENCE OF FUEL-OIL TEMPERATURE ON THE COMBUSTION IN A PRECHAMBER COMPRESSION-IGNITION ENGINE

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## SUMMARY

The influence of fuel-oil temperature on combustion was investigated by injecting the fuel into the prechamber of a single-cylinder, 4-stroke-cycle, water-cooled, compression-ignition engine operating at 1,500 r.p.m. and at a compression ratio of 13.5. Indicator cards, exhaust-gas samples, and engine-performance data were obtained for changes in fuel temperature from 124° to 750° F. The injection characteristics of the fuel system and the appearance of the fuel spray were studied by injecting the fuel into the atmosphere. A common-rail fuel-injection system was used with a hydraulically controlled fuel-injection valve operating at a pressure of 8,800 pounds per square inch. The fuel was heated by passing it through an electric heater inserted between the pump and the injection valve.

The results showed that heating the fuel oil to 750° F. increased the injection period, changed the rate of injection, and eliminated the spray core. Engine tests showed that the ignition lag, rate of pressure rise, and maximum cylinder pressure were reduced. The indicated mean effective pressure, the fuel economy, and the thermal efficiency were slightly increased. Operation of the engine when the fuel was heated to 750° F. was smoother, the exhaust clearer, and the carbon formation in the combustion chamber considerably less than when the fuel was heated to 124° F.

## INTRODUCTION

The present methods of proportioning the fuel to air and the utilization of air flow in combustion chambers to mix the fuel with the air have resulted in some improvement in the combustion process, but the fuel still burns throughout a large portion of the power stroke. No great improvement in the engine performance can be expected as long as the fuel is burned late in the cycle.

Attempts to increase the thermal efficiency by injecting the fuel during the earlier part of the compression stroke and thus to obtain a more uniform mixture throughout the combustion chamber have not been satisfactory. The early injection resulted in the accumulation of a considerable quantity of fuel in the combustion chamber and, upon ignition, high cylinder pressures were developed, knocking occurred, and the engine operation was rough.

A theoretical analysis shows that, for the same maximum cylinder pressure, an engine operating on the constant-pressure combustion cycle is more efficient than one operating on the constant-volume cycle. A method of obtaining the constant-pressure combustion cycle is to reduce the ignition lag to zero so that the rate of injection will control the rate of burning, to inject the fuel at such a rate that constant pressure may be maintained, and to insure that the necessary air for combustion is available at the proper time.

It should be possible to reduce the ignition lag by reducing the time required in the engine cylinder to heat the fuel to its ignition temperature. Various methods of raising the temperature of the fuel have been proposed (references 1 and 2). Methods of heating the fuel directly have utilized the heat of the exhaust gases as well as part of the heat developed during combustion. Hawkes (reference 3) preheated the fuel by passing it through an oil heater in the exhaust stack of the engine.

The object of this investigation was to determine the effect of raising the fuel-oil temperature prior to injection on the injection characteristics, the ignition lag, the combustion, and the engine performance.

## APPARATUS

The single-cylinder, 4-stroke-cycle, water-cooled test engine used in this investigation is shown in figure 1. The N.A.C.A. universal test-engine base and cylinder were used with the cylinder head included in figure 2.

The following table gives the special characteristics of the engine, the test conditions, and the fuel used.

| | |
|---|---|
| Engine | 5-inch bore, 7-inch stroke. |
| Combustion chamber --- | Disk, prechamber, 2-3/4 inches in diameter and 1 inch thick containing 50 percent of the clearance volume. Chamber connected to cylinder by a 9/16-inch-diameter passage flared at both ends. |
| Engine speed ---------- | 1,500 r.p.m. |
| Compression ratio ---- | 13.5. |
| Start of injection --- | Top center (1 crankshaft degree late for 750° F. fuel temperature). |
| Fuel ------------------ | Auto Diesel fuel, 41 seconds Saybolt universal viscosity at 80° F. Distillation curve (A.S.T.M.) shown in figure 3. |
| Fuel quantity -------- | 0.0003 pound per cycle, 4 percent excess air. |
| Fuel-injection pressure ---------------- | 8,800 pounds per square inch. |
| Fuel nozzle ----------- | Single round-hole orifice, 0.060-inch diameter, length-diameter ratio, 4. |

Previous tests with heated fuel using a displacement-type fuel pump and an automatic fuel-injection valve indicated the necessity of reducing the injection period and maintaining an accurate control of the start of injection. Other factors encountered were warping of the valve parts and excessive leakage of fuel past the lapped portion of the valve stem at the higher fuel temperatures.

The fuel system used in these tests is shown mounted on the test engine in figure 1 and diagrammatically in figure 2. It consists of a modified commercial fuel-injection pump, a suitable injection valve, and an electric heater. The fuel-injection system has a low- and a high-pressure fuel-oil circuit. The low-pressure circuit has two small gear pumps: the primary pump that supplies oil to three uniformly phased high-pressure plunger pumps and the sump pump that returns any fuel oil passing through the various pressure seals to the primary fuel supply. The fuel supplied to the high-pressure plungers is maintained under pressure by a regulating valve in the pump body. Excess oil from the primary pump and the oil collected by the sump pump is bypassed through the crankcase of the fuel pump for lubricating purposes and through an oil cooler to the oil reservoir on the fuel-weighing stand.

The high-pressure oil circuit consists of three uniformly phased plunger pumps, which supply oil to the maximum-fuel-pressure regulating valve, the injection-control valve, and the injection valve. Pressure is maintained in this circuit by the maximum-fuel-pressure regulating valve. Excess oil passes through this valve and the oil cooler to the reservoir on the fuel stand. The oil to be injected passes through the safety check valve, the electric heater, the auxiliary control valve, and into the injection valve. The oil used to control injection maintains pressure on the injection-valve stem between injections and replaces that quantity of oil released by the operation of the injection-control valve.

The injection-control valve shown diagrammatically in figure 2 consists of a lapped spindle rotating in a valve body. The spindle has a set of ports located on its circumference, which at the proper time uncover a port in the valve body connected to the injection-control tube. The pressure on top of the injection-valve stem is released when port 2 sufficiently overlaps port 3. The high-pressure fuel oil acting on a small differential annular area at the nozzle end of the valve stem raises the valve stem and discharges fuel into the combustion chamber. This discharge of fuel continues until port 2 sufficiently overlaps the high-pressure fuel-oil supply in port 4, which produces a pressure wave that returns the injection-valve stem to its seat and stops the injection. The quantity of fuel discharged is controlled by manually adjusting the interval between ports 3 and 4.

The maximum-fuel-pressure regulating valve shown in figure 2 is the usual spring-loaded automatic injection valve with a single round-hole orifice nozzle. The injection pressure can be adjusted during operation to any desired value by varying the spring tension.

The injection valve shown in figure 4 was designed to operate at an injection pressure of 10,000 pounds per square inch and at a fuel temperature of 1,000° F.; it has the usual lapped clearance between the valve stem and the sleeve. In order to maintain the lapped clearance, the heated fuel, in its passage through the valve, transmitted heat to the stem through the sleeve. This method maintains a positive clearance between the stem and sleeve at all times during the heating process. A special key, clamped between the valve body and the nozzle, allowed the stem and sleeve to expand but prevented the sleeve from turning in the body. The high operating stress caused by the injection pressure together with the high fuel temperature necessitated the construction of the injection-valve stem, sleeve, nozzle, and stem-stop of steel having a high tungsten content. This steel had sufficient hardness at the high fuel temperature to prevent galling the stem with the sleeve or peening the stem at the seat and the stem-stop.

The electric heater is shown in figure 5 with part of the insulation removed. It was composed of 10 feet of seamless carbon steel tubing, 1/4-inch outside diameter and 1/8-inch bore, wound in the form of a close-coiled helical spring, 4-1/2 inches in diameter. The consecutive coils were lightly tack-welded together at intervals to prevent any springing of the unit caused by pulsating high-pressure fuel oil. The heating element was made of No. 15 B & S gage nichrome IV wire wound in a small helix and wrapped around the tubing. The wire was insulated from the tubing by porcelain insulators and alundum cement. The heating element was placed in a sheet-iron container and the intervening space filled with mineral wool.

## METHOD

The effect of fuel temperature on the start of injection was determined by mounting the injection system on the engine, allowing the fuel valve to discharge into the exhaust system, and observing the development of the fuel spray with the Stroborama. The engine was motored at the test speed of 1,500 r.p.m. and the spray characteristics were obtained for several changes in fuel temperature from 124° to 600° F. An injection pressure of 8,800 pounds per square inch was found necessary with the present valve design to insure regular injection at all fuel temperatures.

Engine tests were made with the injection valve in the top hole of the precombustion chamber. (See fig. 2.) As soon as test conditions became stabilized, the usual engine data, temperatures of the fuel system, exhaust temperature, indicator cards, and samples of the exhaust gases were obtained. As no trouble was encountered with the injection system for fuel temperatures up to 600° F., the temperature of the fuel was increased to 750° F. and the data previously mentioned were obtained.

In order to obtain the necessary correction to the injection advance angle for the 750° F. fuel, the injection valve was removed from the combustion chamber and allowed to discharge fuel into the exhaust system. The start of injection for this fuel temperature was determined but with a slightly larger fuel quantity than that used in the engine tests. The heating unit failed, however, and therefore the start of injection obtained at the larger fuel quantity was considered to be the actual start of injection which, according to other data, is not critical with fuel quantity.

The heat input to the electric heater was measured by a voltmeter and an ammeter. The quantity of heat was controlled by water-cooled rheostats. As the heat losses from the heater were excessive, the voltmeter and ammeter readings were used only as a guide for regulating the temperature at the injection valve.

Exhaust-gas samples taken through a 1/4-inch steel tube inserted in the center of the exhaust stack approximately 1 inch from the exhaust valve were completely analyzed by means of a modified Bureau of Mines gas-analysis apparatus (reference 4).

The start of injection, the spray development, the stop of injection, and the location of the top center lines on the indicator cards were determined by means of a Stroborama. A modified Farnboro indicator (references 5 and 6) was used to record the variations of pressure in the precombustion chamber. (See fig. 2 for valve location.) The maximum explosion pressure in this chamber was determined from the indicator cards; the maximum cylinder pressure was recorded by means of a Farnboro-type valve in the cylinder head. (See fig. 2.)

Various attempts to measure the actual temperature of the fuel oil at the high temperature and pressure used were unsatisfactory, and the temperature of the injection tube close to the injection valve as indicated by a thermocouple T (fig. 2) was considered to be the temperature of the fuel. This method of indicating the fuel temperature was satisfactory for these tests but was not considered sufficiently accurate to correct the engine-performance data for the increase in thermal energy of the fuel.

## EFFECT OF FUEL-OIL TEMPERATURE ON INJECTION CHARACTERISTICS

The preliminary tests with this fuel-injection system indicated the necessity for cooling the injection-control tube. Without the water jacket the start of injection was retarded 30 crankshaft degrees at an engine speed of 1,500 r.p.m. when the fuel was heated to 800° F. When the water jacket was used, this interval was reduced to 3 crankshaft degrees. The change in the start of injection was caused by the large increase in the compressibility of the fuel oil, which affected the velocity of the pressure wave through the injection-control tube. The increasing temperature in the control tube was caused by the conduction of heat from the injection valve and not by the alternate compression and expansion of the fuel oil in the tube.

The action of the injection-valve stem for the test conditions further indicates the compressibility effect. With the 124° F. fuel the valve stem did not lift the 0.030 inch allowed by the stem stop, as indicated by the lack of markings on the top of the stem. Apparently the orifice was sufficiently large to keep the restricting point at the seat for this fuel-injection process. With the 750° F. fuel, however, definite markings appeared on the top of the stem, in addition to an increase in the injection period of 3 crankshaft degrees, indicating a large change in the specific volume of fuel passing through the orifice for similar pressure conditions.

The effect of temperature on the compressibility of the oil was further shown in the development of the fuel spray. The 124° F. fuel-spray envelope had a cone angle of less than 10°, within which was a concentrated core; the spray envelope at a fuel temperature of 750° F. had a cone angle of approximately 30° with no perceptible core, the entire spray being a well-defined billowy cloud. A definite increase in the spray cone angle occurred with the increase of the fuel temperature to above 400° F.

During the preliminary tests with a spring-loaded automatic injection valve operating at an injection pressure of 3,500 pounds per square inch and a fuel temperature of 670° F., the spray issued from the valve as a blue haze, leaving the nozzle dry. A few inches from the nozzle, the haze gradually formed a fleecy white cloud. This condition was not attained in the tests using the hydraulic-injection system because of the much higher injection pressures.

The start and stop of injection with 124° F. fuel was characterized by a slight dribbling of oil; whereas with the fuel heated to temperatures above 400° F. the start and stop were well defined. At the highest fuel temperature with the fuel injecting into the atmosphere, the start was characterized by a sharp crack, and the fuel expanded from the 0.060-inch orifice to approximately 1/4-inch diameter instantly at the orifice.

## EFFECT OF FUEL-OIL TEMPERATURE ON THE EFFECTIVE IGNITION LAG

Effective ignition lag was determined by the method used in reference 7 and is defined as the period between the start of injection, and the time when $4.0 \times 10^{-6}$ pounds of fuel has been effectively burned, as determined from the analysis of the indicator card. The effective-ignition-lag curve shown in figure 6 shows that the lag increased up to a fuel temperature of 300° F. and then decreased with an increase in the fuel temperature. It is believed that the increase in ignition lag is caused by the progressively finer atomization of a larger portion of the fuel spray, which results from the decreasing viscosity and surface tension of the fuel oil. The increase in the surface-volume ratio of the drops also produces a local decrease in temperature greater than that normally occurring with the 124° F. fuel. As soon as the fuel oil is sufficiently heated to offset this cooling, the ignition lag starts to decrease. It is significant that the fuel-spray envelope begins to show change at this time. The decrease with fuel temperatures greater than 300° F. is believed to be principally due to either the decreased difference between the fuel temperature at injection and its auto-ignition temperature, to the finer atomization and dispersion of the fuel, which increases the surface-volume ratio of the drops and their rate of heat absorption, or to both these factors.

## EFFECT OF FUEL-OIL TEMPERATURE ON COMBUSTION

The effects of heating fuel oil from 124° to 750° F. on the shapes of the indicator cards are shown in figure 7. Heating the fuel oil did not affect the dispersion of the points that form the diagrams. The cards show that heating the fuel causes the breakaway of the combustion from the compression to occur nearer top center and the pressure rise and the maximum pressure to be less.

The difference in the injection period and in the combustion of the fuel for the two conditions is quite marked (fig. 8). Although the start of injection is nearly the same for both fuel temperatures, the stop of injection is different. For the 124° F. fuel the injection is practically complete before breakaway occurs, while for the 750° F. fuel it continues into the region of maximum pressure. The development of the initial pressure rise for the 750° F. fuel is more desirable than that for the 124° F. fuel since the average rate of pressure rise from ignition to maximum explosion pressure is only 30 pounds per square inch per degree, whereas with the 124° F. fuel it is 50 pounds per square inch per degree.

A thermodynamic analysis of the indicator cards was made to obtain information on the evolution of heat when fuel oil heated to 124° and to 750° F. was used. Figure 9 shows the amount of fuel effectively burned. By "effectively burned" is meant the amount of fuel required to produce the change in enthalpy indicated by the pressure-time cards.

Although the start of the injection of the 750° F. fuel was later than that of the 124° F. fuel by 1 crankshaft degree, the former fuel started to burn approximately 3 crankshaft degrees earlier and combustion had proceeded to a large extent before the completion of the injection.

With the latter fuel, combustion had just started at the end of injection. The late start of combustion with the 124° F. fuel results in the formation of a large amount of combustible mixture in the engine and, upon ignition, causes high maximum cylinder pressures accompanied by a heavy metallic knock. The early combustion of the 750° F. fuel maintains lower rates of pressure rise with less intense knock and leads to a more desirable form of indicator card.

The total effective fuel burned up to the position of maximum explosion pressure was approximately the same with the 750° F. fuel as with the 124° F. fuel, but the maximum explosion pressure as determined from the indicator cards was approximately 70 pounds per square inch less with the 750° F. fuel. Although the maximum pressure was lower, the energy released early in the power stroke resulted in a slight improvement in the performance of the engine.

It was expected that the high residual air flow in the prechamber together with the 750° F. fuel would materially reduce the quantity of fuel burned late in the stroke, but figure 9 shows that the quantity burned after maximum pressure was approximately the same as that with the 124° F. fuel. Apparently the heating of the fuel had the greatest effect during the first part of the combustion period in this particular combustion chamber. It is not known whether the 750° F. fuel would have a greater effect on combustion late in the stroke if it had been injected into all instead of less than half the combustion air. It seems that the time utilized in forming the excessively rich mixture in the prechamber could have been advantageously used to mix the fuel with the air, since the tremendous volume of the heated fuel spray would assist the mixing process much better than could a spray with a central core.

Additional information on the combustion of the 750° F. fuel was obtained by examining the combustion chamber after several hours of engine operation. No appreciable amount of carbon was found in the combustion chamber. The deposit on the piston crown was so thin that it did not obscure the polish on the exposed surface. In the case of the 124° F. fuel, the carbon formation was very pronounced even after a much shorter period of operation. The cause of the lack of carbon deposit when using the 750° F. fuel is not apparent, inasmuch as chemical analysis of the exhaust gases showed practically no difference in composition, which indicates that the same amount of carbon was burned in both cases.

It is not definitely known whether the high temperature had any effect on the composition of the fuel because the heater failed before a sample of the fuel could be obtained for analysis. It is believed, however, that no change in the composition of the fuel occurred because of the small amount of time that the fuel was exposed to the high temperature, approximately 12 seconds, and because of the high pressure maintained on the fuel at all times. An examination of the inside of the injection tube, after 14 hours of operation with fuel above a temperature of 300° F. and 9 hours above a temperature of 700° F., showed no carbon deposits on the walls.

## EFFECT OF FUEL-OIL TEMPERATURE ON ENGINE PERFORMANCE

Figure 6 shows the effect of heating fuel on the performance of the engine. Only a slight improvement in the power and economy is indicated. Since only one size of connecting passage between the combustion chamber and the cylinder and one form and size of prechamber was used in this investigation, it is not known whether some other combination of these factors would have shown a greater improvement. As the investigation was primarily concerned with the control of the initial combustion, the various combinations were not studied.

Heating the fuel oil improved the operation of the engine. The combustion knock was perceptibly less and the exhaust showed less flame than that obtained with 124° F. fuel. Smoke was present in the exhaust under all conditions as would be expected with only 4 percent of excess air but, as the fuel temperature was increased, the amount of smoke became less and intermittently there were clear periods. The tendency of the knock to decrease with increasing fuel temperature was probably caused by the changing rate of injection, which was indicated by the increase of the injection period and by the change in the rate during this period as previously explained. The decreased smoke and flame in the exhaust indicated a change in the combustion process with increased fuel temperature. Because of the limited nature of these tests, this phase of the problem was not investigated.

Hawkes (reference 3) reported a decrease in engine performance with an increase in fuel temperature up to 400° F. This decrease in engine performance was probably due to the retarded injection accompanying the preheated fuel because the authors found, during some preliminary experiments with heated fuel and a displacement-type fuel-injection system, that injection was materially retarded with an increase in fuel temperature if the injection timing was not advanced to compensate for the increased compressibility of the fuel.

## CONCLUSIONS

From the preliminary tests of a prechamber compression-ignition engine using heated fuel oil and a nozzle with a 0.060-inch-diameter orifice, it was found that with increasing fuel temperatures:

1. The injection period was increased, the average rate of injection of the fuel was decreased, the spray core was eliminated, and the entire spray was a white cloud.

2. The ignition lag, rate of pressure rise, and cylinder pressures were reduced.

3. The mean effective pressure and the thermal efficiency were slightly improved.

4. The operation of the engine was smoother, the exhaust was clearer, and the carbon formation in the combustion chamber was considerably less.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 26, 1936.

## REFERENCES

1. Richardson, Edward Adams: Heating Fuels for Injection Engines. Tech. Bull. No. 16, Penn. State Coll., 1933, pp. 3-17.

2. Groff, Joseph C.: Heating Fuels for Injection Engines, Discussion. Tech. Bull. No. 16, Penn. State Coll., 1933, pp. 17-20.

3. Hawkes, C. J.: Some Experiments in Connection with the Injection and Combustion of Fuel Oil in Diesel Engines. Paper read before the N.E. Coast Inst. of Eng. and Shipbuilders (London), 1921.

4. Gerrish, Harold C., and Tessmann, Arthur M.: Relation of Hydrogen and Methane to Carbon Monoxide in Exhaust Gases from Internal-Combustion Engines. T.R. No. 476, N.A.C.A., 1933.

5. Collins, John H., Jr.: Alterations and Tests of the "Farnboro" Engine Indicator. T.N. No. 348, N.A.C.A., 1930.

6. Hemmeter, George T.: New Recording Method for Electric Engine Indicator Gives Positive Card Directly. Auto. Indus., Feb. 9, 1935, pp. 177-178.

7. Gerrish, Harold C., and Voss, Fred: Influence of Several Factors on Ignition Lag in a Compression-Ignition Engine. T.N. No. 434, N.A.C.A., 1932.

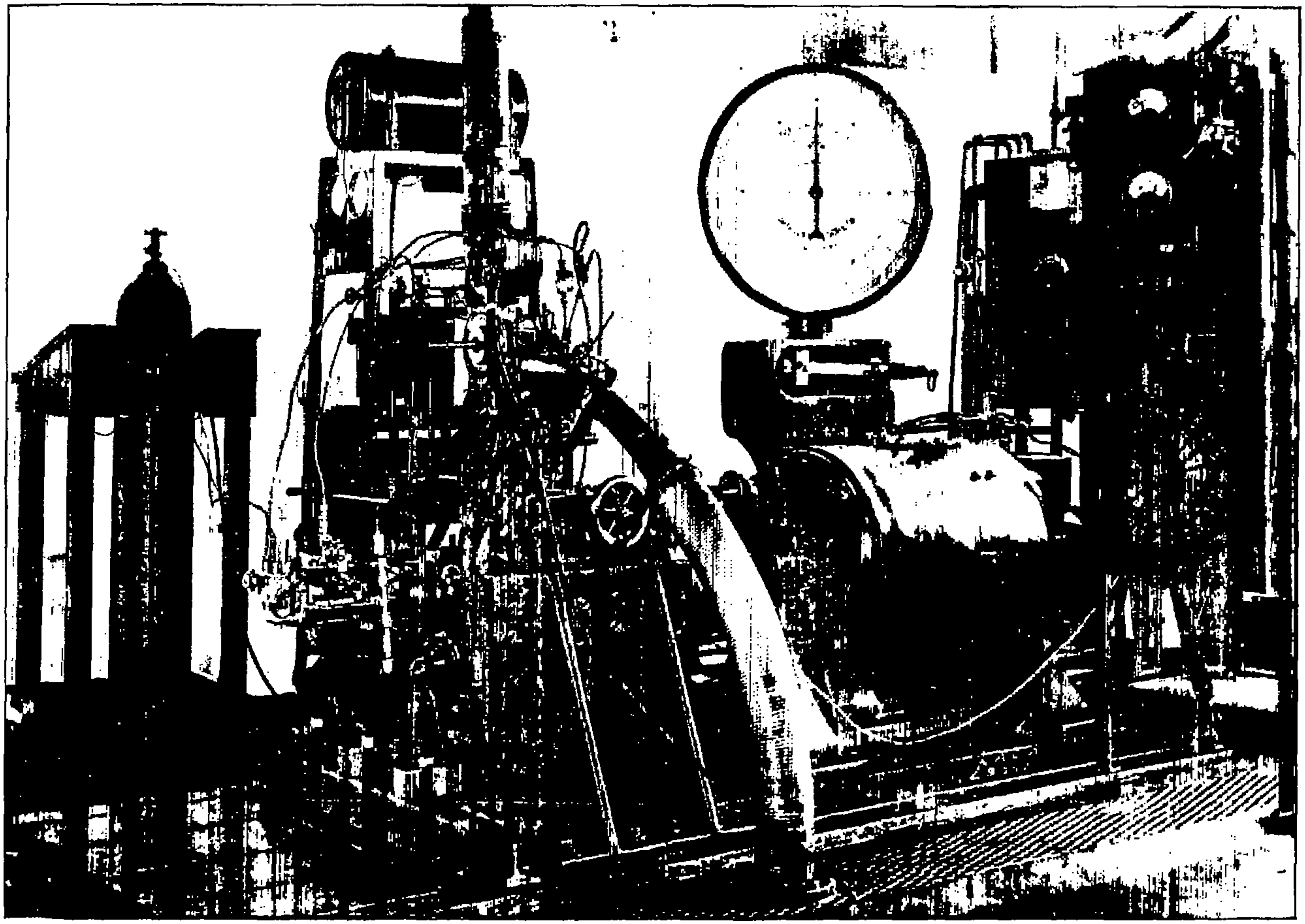

Figure 1. Single-cylinder engine and equipment.

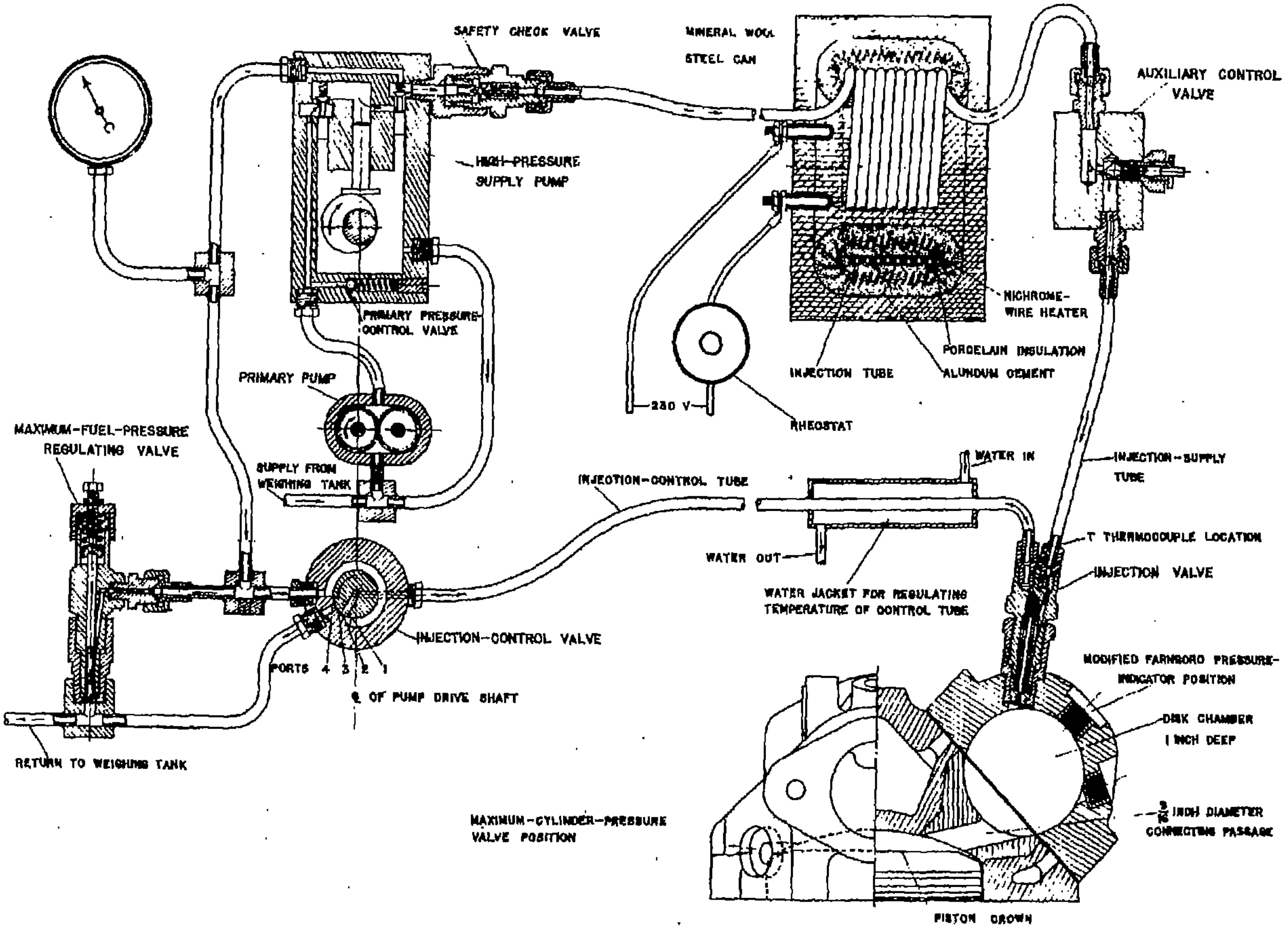

FIGURE 2. DIAGRAMMATIC SKETCH OF FUEL SYSTEM AND COMBUSTION CHAMBER

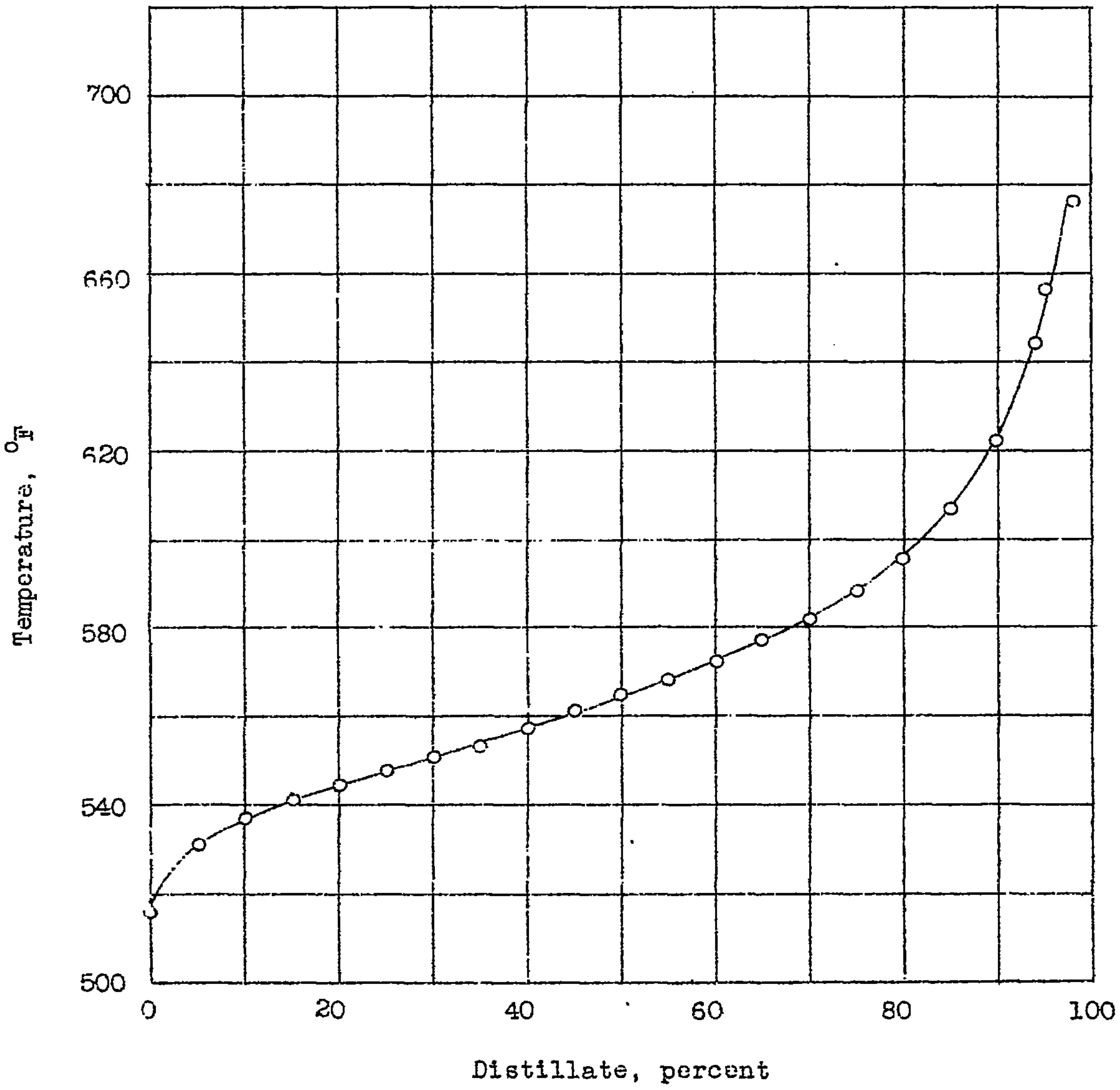

Figure 3.- Auto Diesel fuel oil distillation curve (A.S.T.M.).

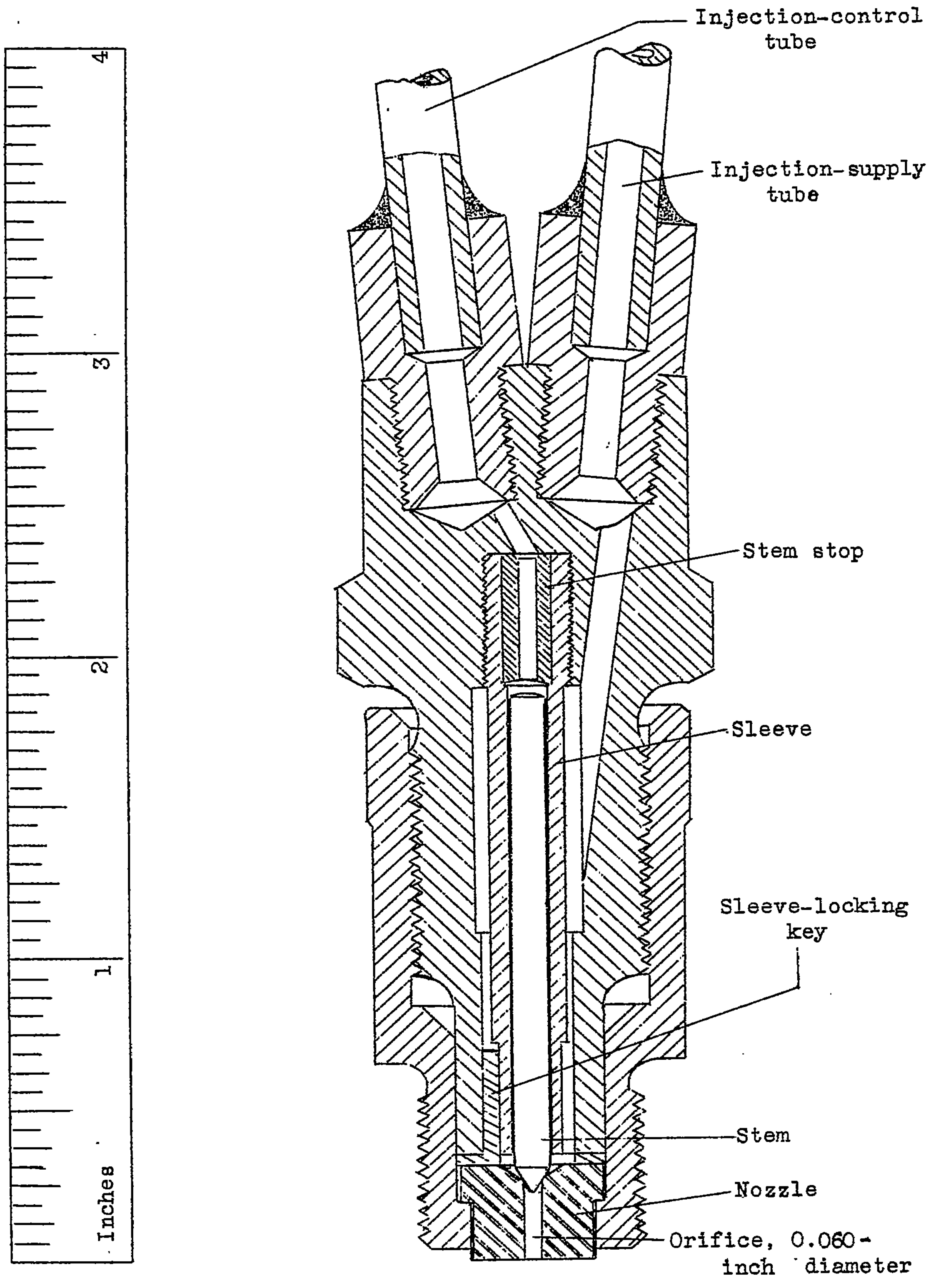

Figure 4.- Fuel-injection-valve assembly

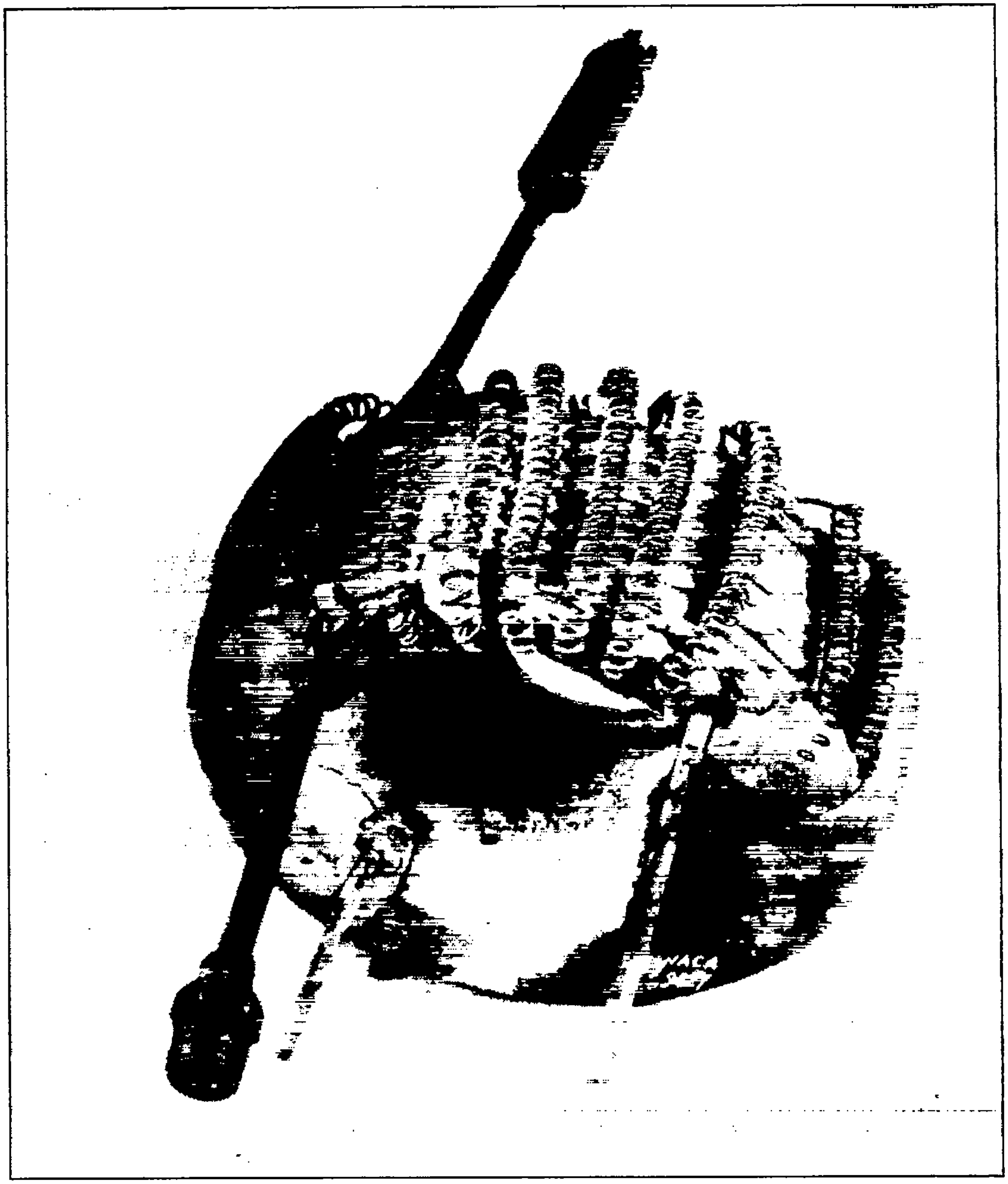

Figure 5.- Fuel heater construction.

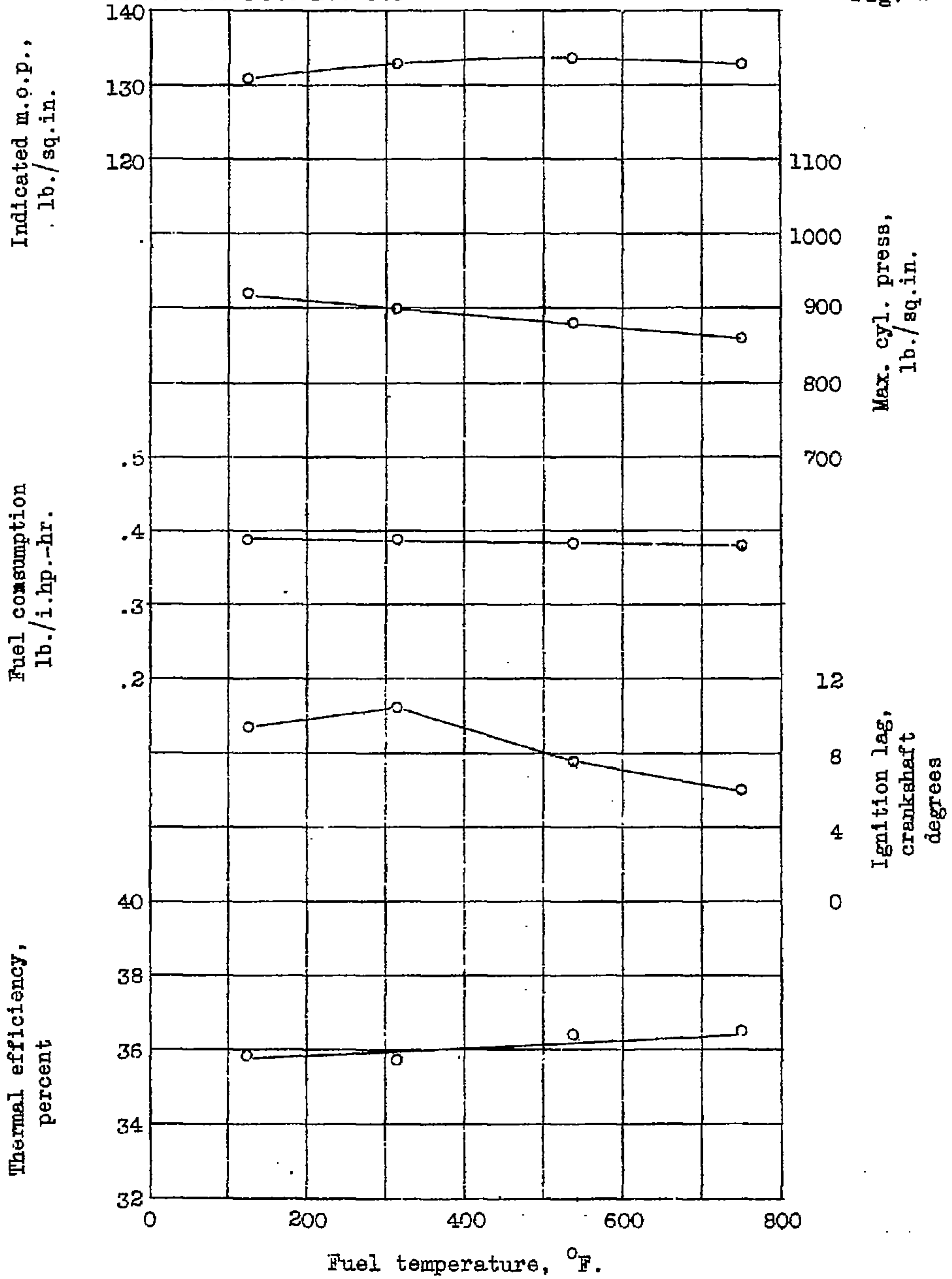

Figure 6.- Effect of fuel temperature on engine performance.

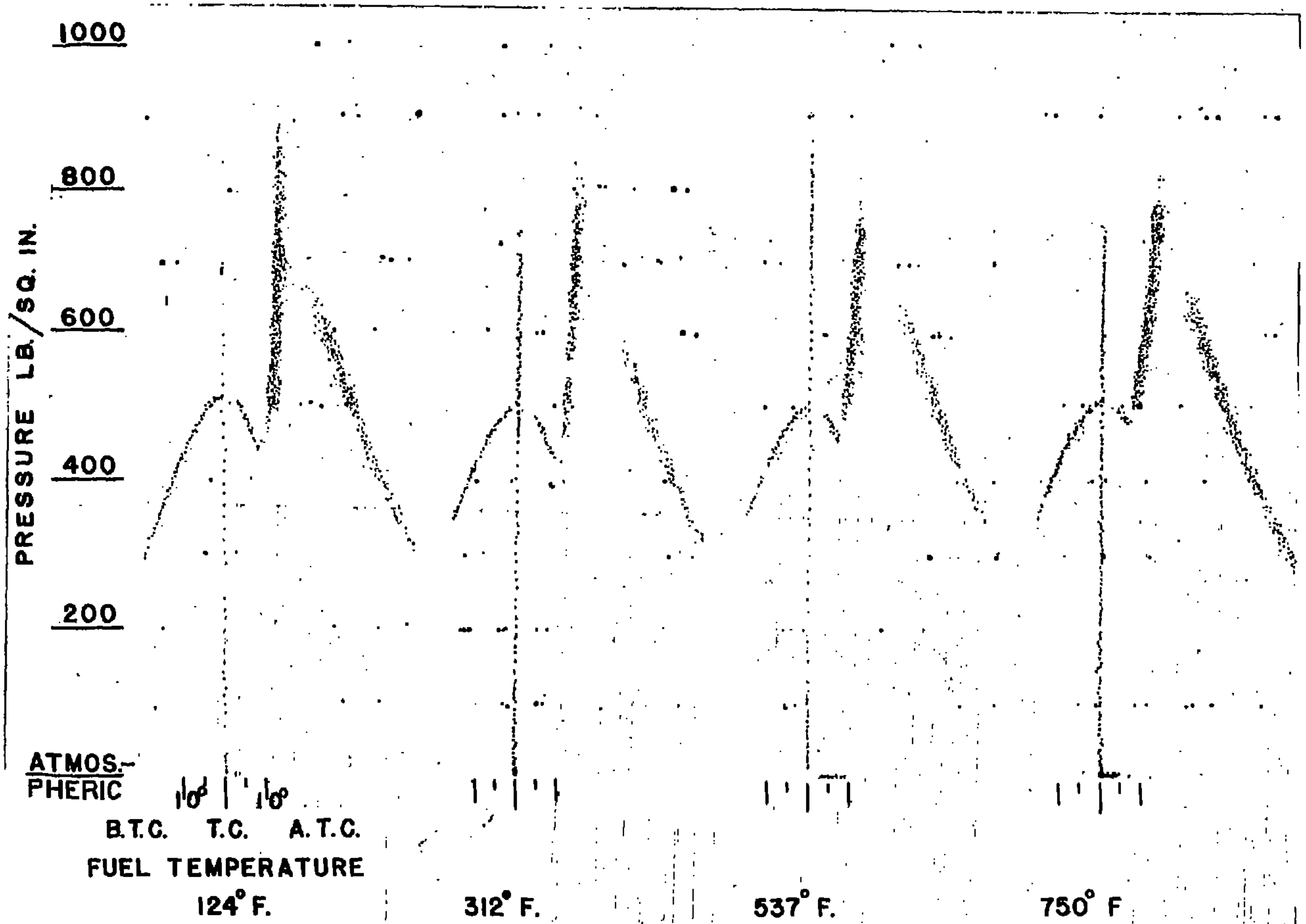

Figure 7.- Indicator cards obtained at different fuel temperatures.

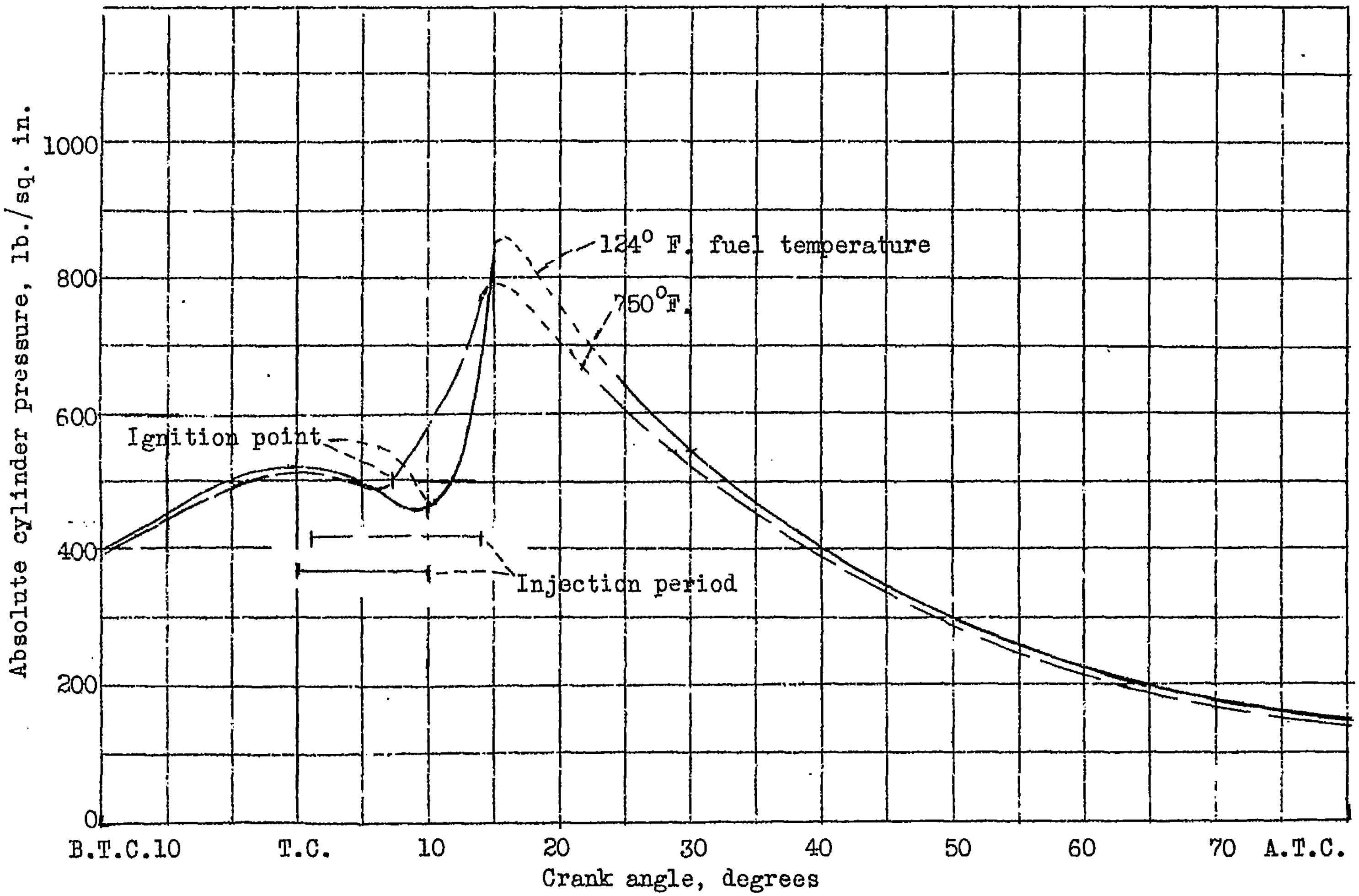

Figure 8.- Comparison of indicator cards obtained with heated fuel.

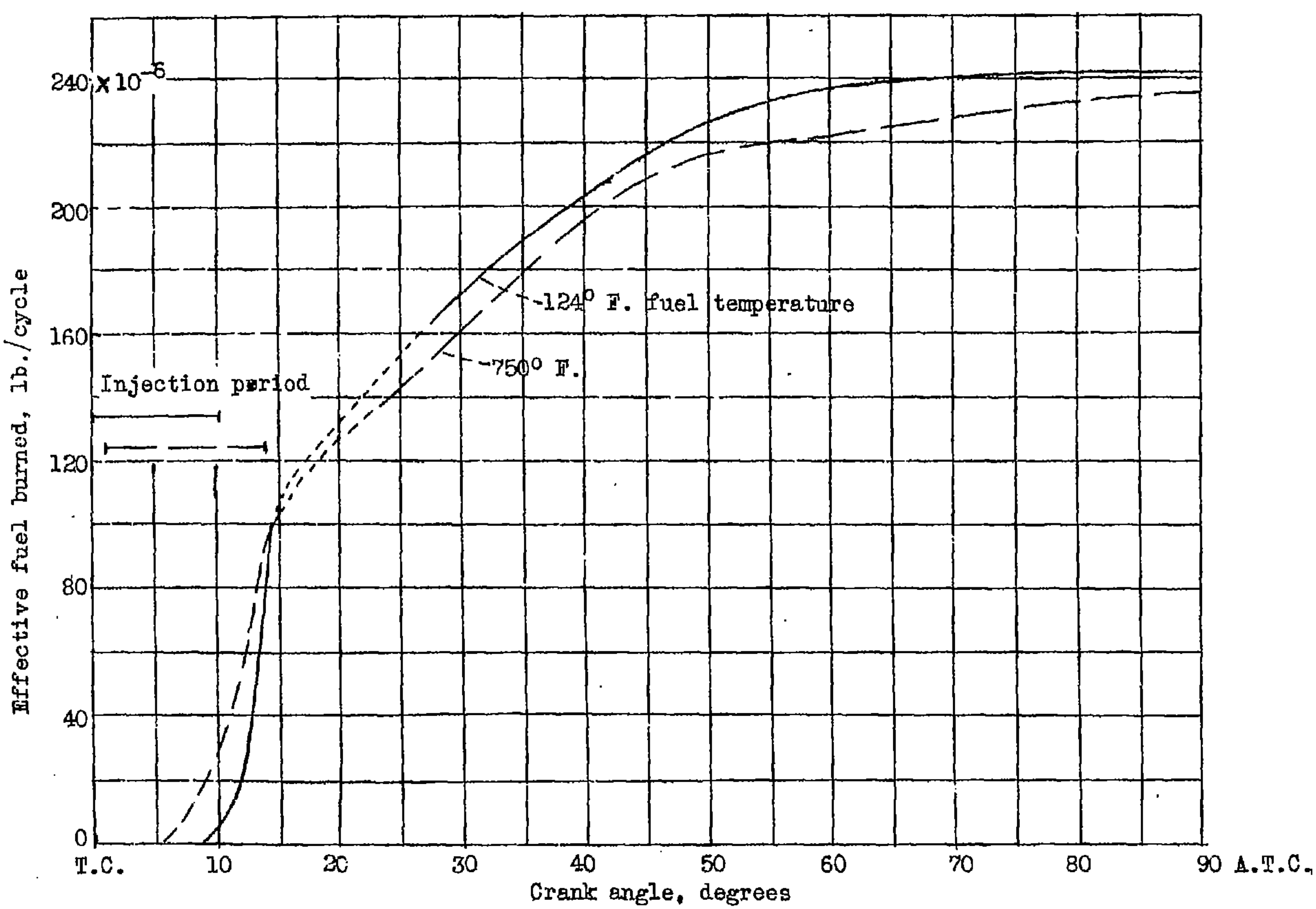

Figure 9.- Effect of fuel temperature on combustion.