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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESTRICTED BULLETIN

END-ZONE WATER INJECTION AS A MEANS OF SUPPRESSING KNOCK IN A SPARK-IGNITION ENGINE

By Rinaldo J. Brun, H. Lowell Olsen, and Cearcy D. Miller

SUMMARY

An investigation has been made of the effectiveness of water injection into the combustion end zone of a spark-ignition engine cylinder for the suppression of knock. Pressure-time records obtained show that injection of water at 60° B.T.C. on the compression stroke at a water-fuel ratio of 0.3 rendered M-3 fuel as good as S-3 fuel from an antiknock consideration. The optimum crank angle for injection of water into the end zone was found to be critical. As the injection angle was increased beyond the optimum, the quantity of water required to suppress knock increased to 3.6 water-fuel ratio at 132° B.T.C. The water quantity could not be increased beyond 3.6 water-fuel ratio because of injection-pump limitations; however, a further increase in the injection angle up to the earliest angle obtainable, which was 20° A.T.C. on the intake stroke, continuously increased the knock intensity.

The engine operating conditions of the tests did not simulate those encountered in flight, especially with regard to the operating speed of 570 rpm. For this reason the results should only be regarded as of theoretical importance until further investigation has been made.

INTRODUCTION

The investigation herein described was suggested by observation of high-speed photographs of combustion in a spark-ignition engine cylinder taken with the NACA high-speed camera at the rate of 40,000 frames per second (reference 1). These photographs confirmed the prevailing opinion that the combustion end zone involved in the knock reaction includes only a small fraction of the mass of the total cylinder charge. The photographs also indicated that this small fraction of the mass of the total charge is compressed into an extremely small and well-defined volume before knock occurs.

A study of the photographs suggested that a great saving in antiknock additive might be effected by injecting the additive exclusively into the end zone, presumably the only region in which it is needed.

Introduction of water into the combustion chamber of the internal-combustion engine for the purpose of suppressing knock or cooling of the engine parts is very old. In 1913 Hopkinson (reference 2) reported successful results of extensive tests with large gas engines with which the cooling was entirely by water spray on the inner surfaces of the combustion chamber. In 1921 Clerk (reference 3) indicated that he had used water to suppress extremely violent knock in the year 1880.

More recent investigations of the effect of water and other liquids introduced into the fuel-air mixture before admission into the cylinder on knock-limited and temperature-limited power output are described in references 4 and 5. The water or other liquids used in this manner are termed "internal coolant."

The object of the tests reported herein was to determine the value of injection of water into the end zone as an antiknock agent. The engine used in these tests could not be supercharged and the inlet-air temperature could not be raised above room temperature; therefore, the effectiveness of the water was determined by lowering the antiknock value of the fuel. The engine operating speed was far below the speeds used in flight. The results should be considered only on a theoretical basis until further investigations have been made more closely approaching the operating conditions of flight. This warning is particularly important because difficulty may be experienced in applying the method to high-speed engine operation.

The tests were performed at the Aircraft Engine Research Laboratory of the National Advisory Committee for Aeronautics during late 1943 and early 1944.

APPARATUS AND PROCEDURE

The engine used in the present tests was the NACA combustion apparatus described in reference 6. An injection valve was installed in one of the cylinder openings to spray water into the last part of the charge to burn. Photographs were taken with the NACA high-speed camera to observe the exact end-zone position and the shape and the extent of the region permeated by the water spray.

The engine was fired for one cycle only for each test run. An electric motor kept the engine speed constant until the firing cycle occurred. A single-cycle clutch was engaged at the beginning of the firing cycle between the engine crankshaft and an accessory shaft to inject a single charge of fuel into the cylinder on the intake stroke, ignite the charge at the proper time, and inject water at the predetermined injection angle. The cylinder temperature was maintained by circulating heated glycerin through the engine jackets. Three spark plugs were used to bring the end zone into the desired position in front of the water-injection nozzle. The ignition timing was so set that the completion of burning with S-3 fuel occurred near top center. The water used for injection into the cylinder was deaerated in order to avoid the formation of gas bubbles in the injection valve. The fuel-air ratio was set slightly richer than that required for maximum knock with S-3 fuel. Two valves were used, each serving for both intake and exhaust. Pressure-time records were obtained by photographing an oscilloscope screen. The input to the vertical plates of the oscilloscope was produced by a piezoelectric pressure pickup installed in the engine.

Engine conditions held constant were:

Engine speed, rpm	570
Fuel injection (intake stroke), degrees A.T.C.	20
Fuel-air ratio (approximate)	0.072
Cylinder temperature, °F	242±2
Compression ratio	7.1
Intake pressure	atmospheric
Exhaust pressure	atmospheric
Intake temperature, °F	65-70 (room temperature)
Spark timing, degrees B.T.C.:	
Earliest plug	30±1
Later plugs	26±1

RESULTS AND DISCUSSION

A photograph of about one-half the combustion chamber at the time all the water spray had entered into the chamber is shown in figure 1. The dashed circle shows the combustion-chamber outline as viewed from the top. The letter G in the figure indicates the position of the earliest-fired spark plug, E and F the positions of the later-fired spark plugs; J indicates the position of the water-injection nozzle, H the position of the fuel-injection nozzle, and I the position of the piezoelectric pressure pickup.

A photograph of the end zone a few engine crank-angle degrees before the end of combustion is shown in figure 2. The end zone as seen in figure 2 is somewhat larger than the knocking end zone under the most severe conditions imposed in the tests. The photographs in figures 1 and 2 are single frames from two series of pictures taken at 40,000 frames per second with the NACA high-speed camera and show the development of the water spray from the nozzle and the burning of the charge in the chamber, respectively. In figure 2, the water-spray outline obtained from figure 1 has been drawn in to show its location with respect to the end zone.

Pressure-time records of firing cycles are shown in figures 3 to 5. The lowest trace in each figure is a motoring trace taken just before the firing cycles.

The traces of two consecutive firing cycles superimposed on the same film are shown in figure 3. The trace with the violent knock, designated "unquenched M-3" in the figure, was taken with M-3 fuel without water injection. The trace with incipient knock and larger area under the trace, designated "quenched M-3" in the figure, was taken with M-3 fuel with injection of water at 59° B.T.C. on the compression stroke. The weight of water injected was three-tenths of the fuel weight. All of the operating conditions of the engine and oscilloscope were the same for the two runs of figure 3 except the water injection. The amplitude of the vibrations registered on the quenched trace was considered to be indicative of incipient knock because a lower amplitude of vibrations was not readily detected visually on the oscilloscope. The water-fuel ratio of 0.3 with injection at the optimum crank angle consistently gave incipient knock or no knock. The 0.3 water-fuel ratio was the lowest obtainable with the water-injection system; therefore, the smallest water quantity necessary to quench the knock was not determined in this investigation.

High-speed motion pictures of the quenched combustion of M-3 fuel indicated that the knock did not occur in that part of the end zone permeated by the water, but that the incipient knock such as registered on the quenched trace in figure 3 came from a very small fraction of the charge located on either side of the water spray near the cylinder wall. If the small pockets of gas near the water-injection nozzle alongside the cylinder wall could have been sprayed with water, possibly all traces of knock would have been removed.

The power loss resulting from severe knock is shown in figure 3. The two traces are nearly identical approximately to the point where knock occurred in the unquenched trace. The loss of energy with heavy knock cannot be accounted for as being involved

in the energy of vibration of the gases, because even after the vibrations have been nearly damped out the unquenched pressure-time trace remains about the same distance below the quenched trace. Some of the energy may be lost in the higher heat transfer through the cylinder walls with heavy knock because of the greater scrubbing action of the gases on the chamber walls, as suggested by Withrow and Rassweiler (reference 7). The greatest portion of the energy loss might be accountable in the form of unreleased energy in unburned carbon. During every violent knocking run made in these tests, the engine released a large quantity of black smoke on the exhaust stroke. When the knock was reduced to the incipient level, either by quenching or by increasing the antiknock value of the fuel, no traces of smoke were noted. MacCoull (reference 8) has presented measurements of power loss with heavy knock.

The traces of two firing cycles were superimposed in figure 4 to show that quenched M-3 fuel produces as much power as unquenched S-3 fuel. The octane ratings of M-3 and S-3 fuels, as obtained from the A.S.T.M. (Motor) Method, are about 20 and 100, respectively. The quenched trace in figure 4 has a sharp rise approximately at the point where knock would occur in an unquenched cycle. The sudden rise in pressure at that point is characteristic of all quenched M-3 runs. Motion pictures of these runs, however, do not show the characteristic vibrations in the burned gases which accompany knock. The trace for unquenched S-3 fuel in figure 4 shows about the same amplitude of knocking vibrations as does the trace in the same figure for quenched M-3 fuel.

The traces shown in figures 3 and 4 are representative of more than 50 traces taken under the same test conditions. The reproducibility of the test data was very good; furthermore, the order of taking the two traces on the cards was reversed many times and identical results were obtained.

The optimum angle for start of water injection with respect to knock was found to be critical; under the conditions of the tests, the optimum angle was from 50° to 60° B.T.C. on the compression stroke. The total time required for injection of water, as indicated by the high-speed photographs, was 8° to 10° of crank angle. Start of injection even as late as 48° B.T.C. did not give good results regardless of the quantity of water injected up to the capacity of the water-injection system, which was 3.6 times the fuel quantity, or 12 times the water used at the optimum angle. The large time lapse between knock and injection (50° minimum angle) is not encouraging from the consideration of applying the method to the conditions of flight. If the minimum time between water injection and completion of burning remains constant for different engine speeds, the minimum angle of injection for good results will increase from 50° at

570 rpm to 245° at 2800 rpm. The problem of injecting water when the piston is near bottom center in such manner that it will be concentrated in the end zone when the piston is at top center will be difficult.

With injection of water between 60° and 132° B.T.C., the quantity of water required to prevent the M-3 fuel from exceeding the incipient knock limit increased rapidly from 0.3 to 3.6 water-fuel ratio. As the injection angle was advanced beyond 132° B.T.C. on the compression stroke to 20° A.T.C. on the intake stroke, the knock intensity continuously increased at a constant water-fuel ratio of 3.6; also, the flame speed decreased and knock occurred later in the cycle. The slower rate of burning lowered the cycle efficiency considerably. Furthermore, some cycles were drowned out with the 3.6 water-fuel ratio injected at 20° A.T.C. on the intake stroke.

Injection earlier than 20° A.T.C. on the intake stroke was not possible because of mechanical limitations. Injection at this angle was as nearly comparable with introducing the coolant into the manifold near the intake valve as possible with the apparatus used. In other engines, depending on the operating conditions, introducing the coolant into the manifold near the intake valve will require different water quantities for the same effective knock reduction. The 3.6 water-fuel ratio used on this apparatus, therefore, should not be used in making comparisons with other engines.

In order to assure as thorough a mixing of the water and the fuel-air charge as possible, the plain valves used in the runs of figures 3 and 4 were replaced by shrouded valves for the run of figure 5. The shrouded valves increased the turbulence, particularly during the air intake. Figure 5 is a pressure-time trace taken with M-3 fuel, 3.6 water-fuel ratio, water injection at 20° A.T.C. on the intake stroke, and all other conditions the same as for the other runs. The knock intensity was not reduced appreciably from that produced by unquenched M-3 fuel, as shown in figure 3. The rate of pressure rise during combustion was appreciably reduced as compared with the pressure rise at the optimum injection angle (figs. 3 and 4), particularly during the earlier stages of combustion. With shrouded valves, the rate of pressure rise was considerably greater than with plain valves at the earliest injection angle and the largest quantity of water.

SUMMARY OF RESULTS

The following results were obtained from limited water-injection tests conducted on the NACA combustion apparatus at an engine operating speed of 570 rpm:

1. Injecting water into the end zone with a water-fuel ratio of 0.3 reduced the knock intensity of M-3 fuel to that of S-3 fuel without water.

2. The considerable power loss associated with violent knock was prevented in the cycles in which the knock was quenched by end-zone water injection.

3. The optimum angle of water injection was critical.

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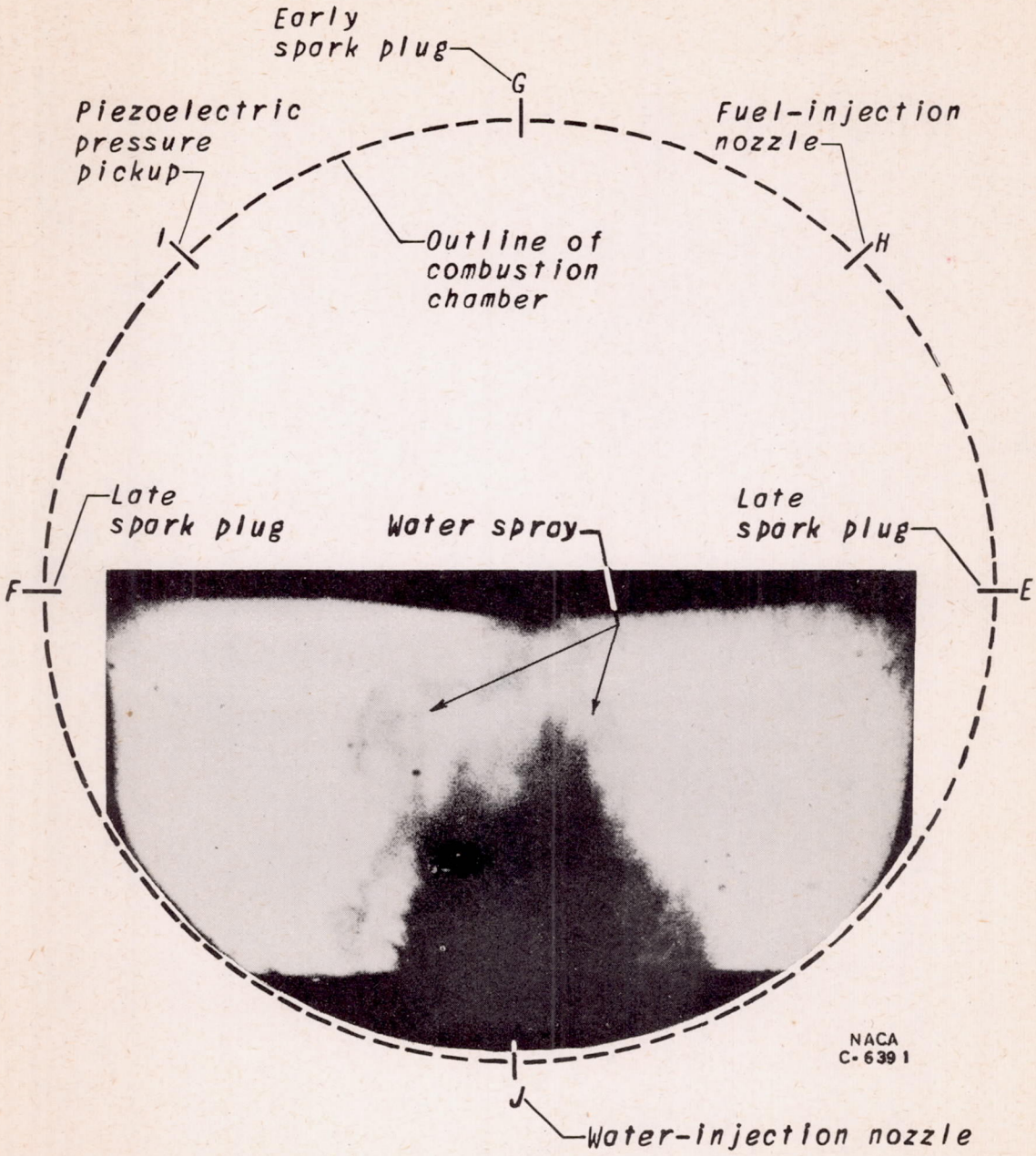

Figure 1. - Photograph of water spray in combustion chamber after water injection was complete. Combustion has not taken place. Exposure time, 25 microseconds.

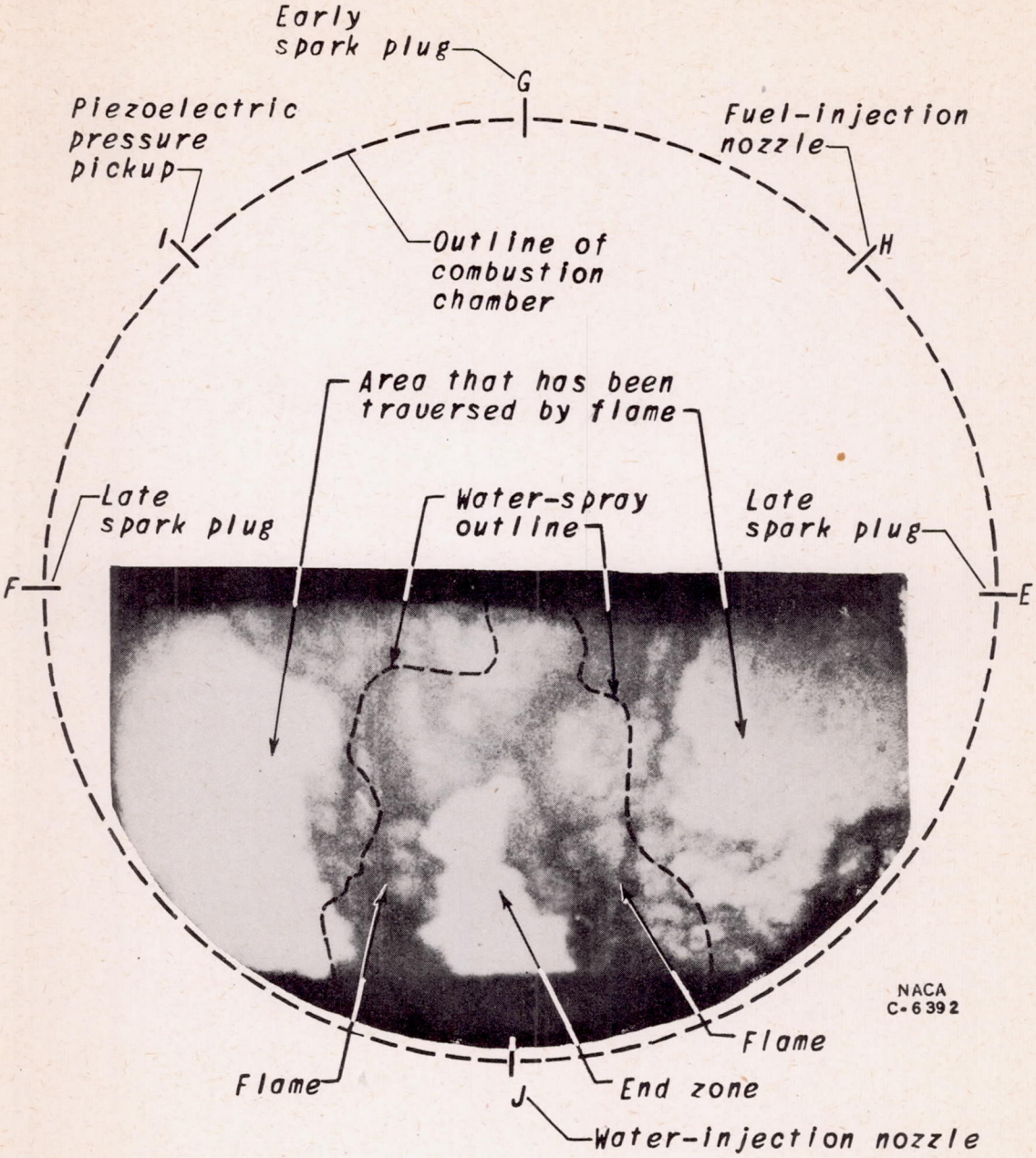

Figure 2. - Location and shape of end zone a few engine crank-angle degrees before completion of burning. Exposure time, 25 microseconds; relative position of water spray, shown by dotted lines, was obtained from figure 1.

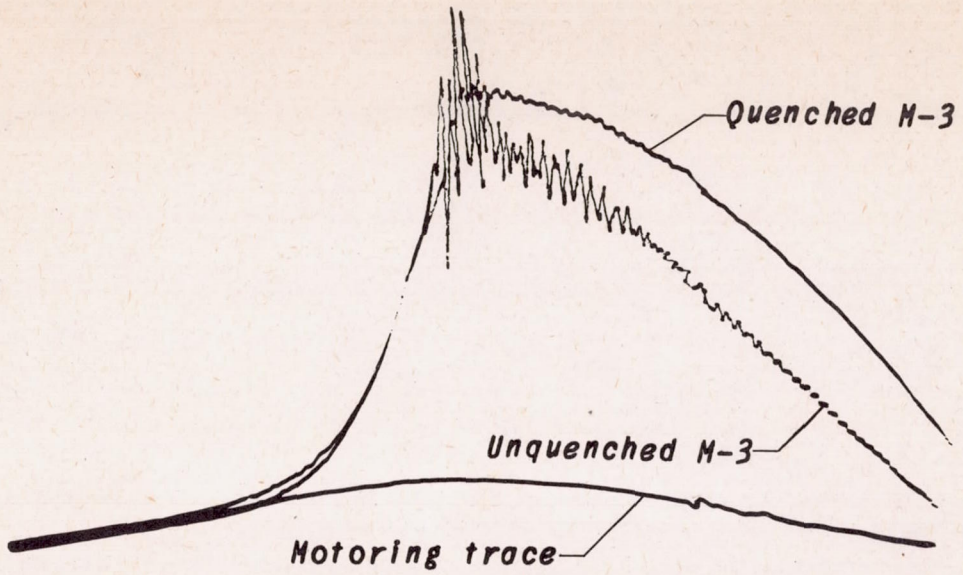

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Figure 3. - Pressure-time traces showing effect of end-zone water injection on knock. Quenched run: fuel, M-3; water-fuel ratio, 0.3; water-injection angle (compression stroke), 59° B.T.C. Unquenched run: fuel, M-3; no water.

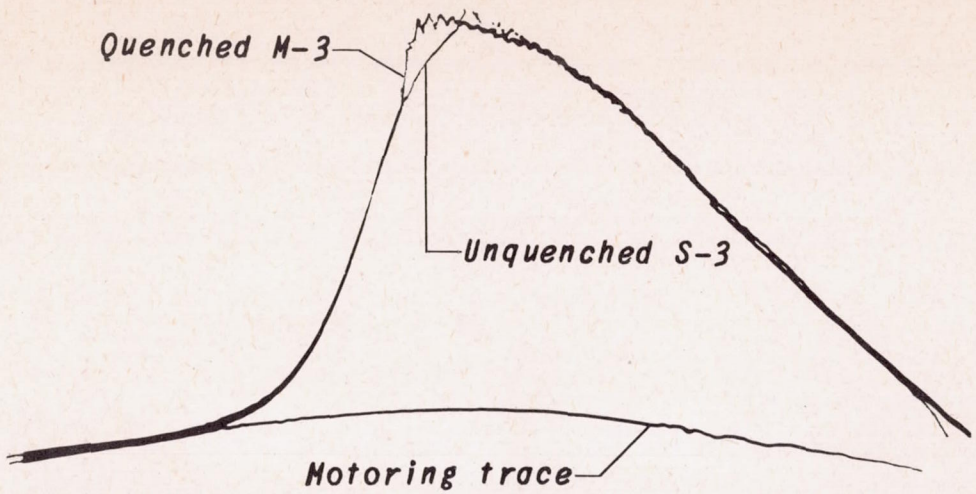

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Figure 4. - Pressure-time traces comparing quenched M-3 fuel with unquenched S-3 fuel. Quenched run: fuel, M-3; water-fuel ratio, 0.3; water-injection angle (compression stroke), 55° B.T.C. Unquenched run: fuel, S-3; no water.

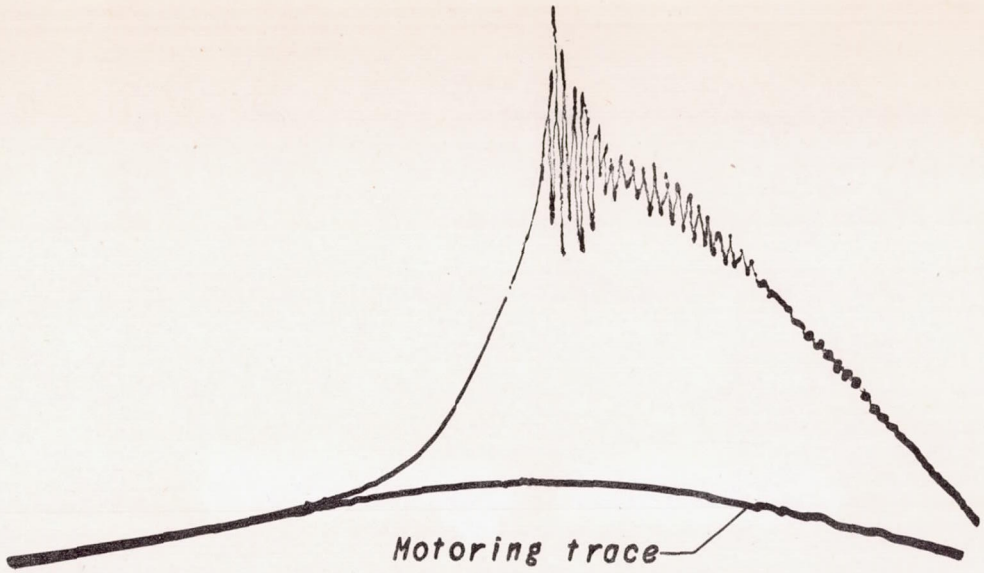

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Figure 5. - Pressure-time trace showing a firing cycle at a very early water-injection angle. Fuel, M-3; water-fuel ratio, 3.6; water-injection angle (intake stroke), 20° A.T.C.