Some Fuel Injection Problems

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The paper deals with certain fuel injection problems which have engaged the attention of the British Internal Combustion Engine Research Association and describes the manner in which some of these problems have been solved.

A study of secondary injection led to the introduction of a form of pump delivery valve which, by acting as a dash pot, eliminates this troublesome effect.

From time to time cases occur of external corrosion of fuel injection nozzles. A particularly serious case, in which such corrosion rapidly led to failure of several engines, was investigated. Combustion studies in progress in the laboratory indicated that the corrosion might be due to overcooling of the nozzles and this was proved by tests in which similar corrosion was produced artificially. Other types of nozzle attack are also discussed.

In the course of work on the turbo-charging of engines, difficulties arose at high rates of injection as a result of the heavy impulsive loading of the mechanical drive of the injection system in use. These were overcome by the adoption of a new hydro-pneumatic driving system, the construction, characteristics and advantages of which are described. The system is considered to be very suitable for large engines.

INTRODUCTION

As the development of the oil engine proceeds and its applications are further extended, new problems of great variety arise. Among the most interesting at the present stage are those connected with torsional, bending and axial vibration of crankshafts, noise, problems arising in high-pressure turbo-charging, crankcase explosions and the many problems associated with the use of lower grade fuels.

The fuel injection equipment of the oil engine produces its full share of the problems as might be expected in view of the exacting requirements it is called upon to fulfil. The object of the present paper is to give an account of some of the fuel injection problems which have engaged the attention of The British Internal Combustion Engine Research Association during the past few years. It is hoped that the discussion will throw further light on some of these, and perhaps other problems worthy of attention will be brought to light.

In this paper consideration is confined, for the most part, to one commonly employed type of injection system. In this system the pump plunger has a helical groove in its side controlling the opening of a port through which fuel is spilled at the end of the effective stroke, the fuel quantity passed to the delivery pipe being varied by rotation of the plunger, and the injection nozzle is controlled by a spring-loaded needle valve. Nevertheless the information given has also a bearing in most cases on other types of system.

SECONDARY INJECTION

Under certain conditions the normal injection of fuel into the combustion chamber is followed by a re-opening of the needle valve and a further injection of fuel. This secondary injection usually occurs too late and at too low a fuel pressure for satisfactory combustion and hence results in a serious loss of thermal efficiency. It is frequently encountered in engine development work and also occurs in service when the characteristics of a system initially free of the defect are changed by the partial blocking of the nozzle holes by carbon. It is certain that the effect has occurred in many cases without being recognized since its existence is not apparent unless some means of indicating the movement of the nozzle needle is in use.

The needle movement diagrams on the left-hand sides of Figs. 1 to 6 show secondary injection encountered in a number of engines and fuel injection rigs in the laboratory. The diagrams of Figs. 1 and 2 were recorded during an investigation of the sources of noise in a fuel injection system. It was found that the pressure oscillations associated with the secondary injection were making a major contribution to the noise. As the system was equipped with instruments for the noise investigation, an excellent opportunity of finding the cause of secondary injection presented itself. It was quickly established that the pressure wave causing the second opening of the nozzle valve was produced at the pump end of the injection pipe, following the spilling of the pump and the sudden closing of the delivery valve, and that this wave arrived at the nozzle several degrees later. In the type of injection system under consideration, the stem of the pump delivery valve is provided with a cylindrical portion fitting the valve guide bore, which results in an unloading effect whereby the pipe pressure is rapidly reduced, after the pump commences to spill, to a pressure well below the closing pressure of the needle valve. This provision is necessary to avoid dribble at the end of injection. Before the pump spills, the discharge system beyond the pump delivery valve has been raised to a very high pressure, causing appreciable expansion of the passage and compression of the fuel so that a considerable amount of strain energy is stored in the system. As the spill port is rapidly uncovered, the delivery valve and the fuel at the pump end of the pipe are accelerated to a high velocity. The value of the unloading capacity of the valve must be such that the valve reaches

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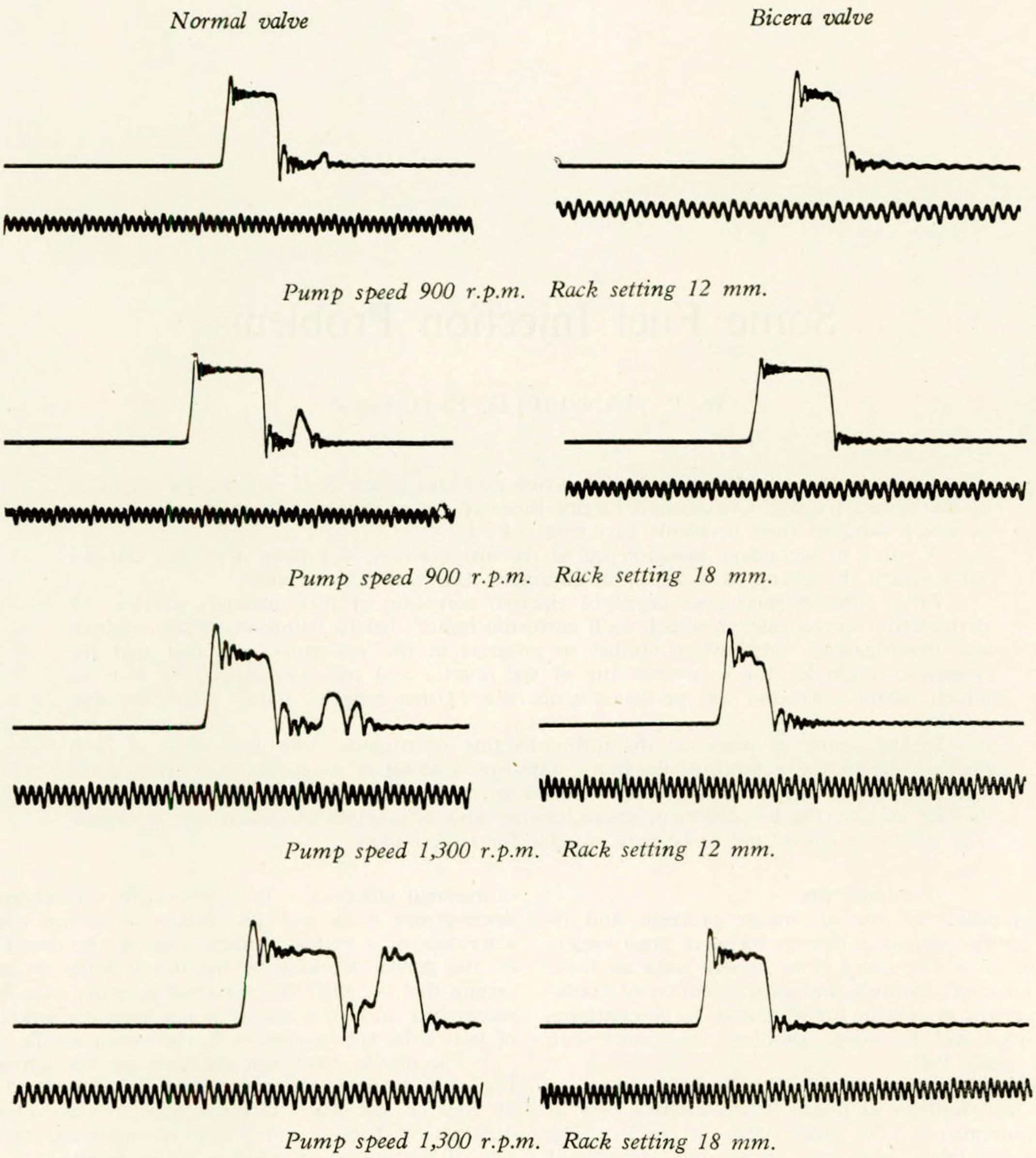
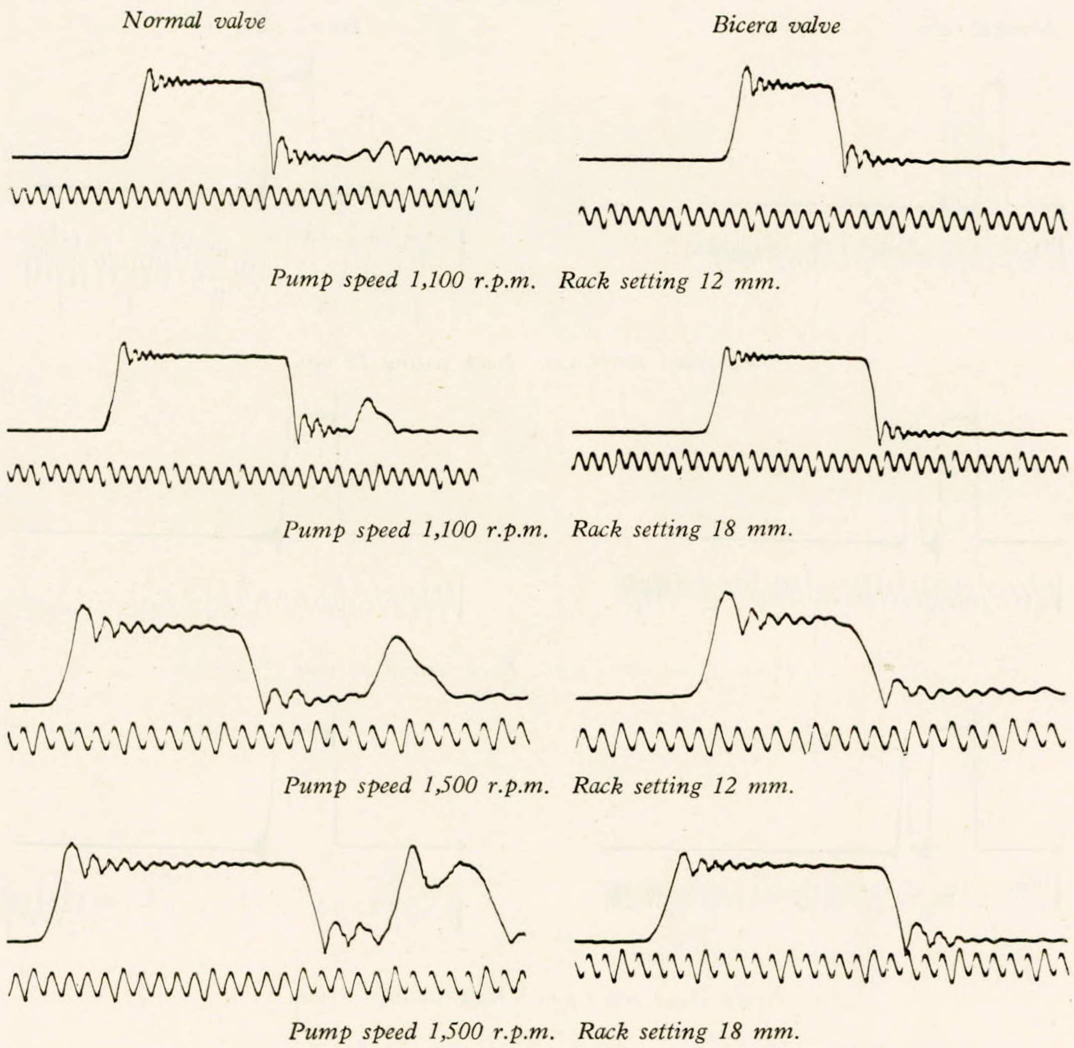


Note: Distance between peaks of degree scales represents 2 degrees pump shaft rotation

FIG. 1—*System No. 1: needle movement diagrams from system on test rig*

its seat before the high velocity flow ceases, since it is necessary to maintain a suitable residual pressure. Hence the valve strikes its seat at high velocity and the flow of fuel behind it is abruptly arrested. The kinetic energy of the fuel is converted to pressure energy in the fuel at the pump end of the pipe and the pressure wave thus formed travels to the injection nozzle. If the action is of sufficient intensity, the nozzle needle valve is lifted again and secondary injection occurs. This finding led to proposals by three members of the staff for providing various forms of dash pot to introduce a large amount of damping into the system and thus dissipate the stored energy harmlessly. Dash pots of many different forms were considered, some involving additional moving parts. In the most attractive designs the existing pump delivery valve was modified to form a dash pot. The simplest of these designs was tested and found very effective. This design is shown in Fig. 7, from which it will be seen that the only additional feature is a cylindrical wall round the head of the mitre valve. This extension is made integral with the valve seat and may be of the same outside diameter as the smaller part of the valve seat. A small radial clearance c is provided between the bore D and the valve head. When the valve head enters the large bore, a quantity of fuel is trapped in the chamber formed between the conical face of the valve head, the end of the unloading portion of the valve and the surrounding wall. Further movement of the valve is controlled by the discharge of fuel through the narrow annulus formed by the clearance round the valve head. The arrangement thus acts as a dash pot. Suitable values for the lengths s and u and the radial clearance c were determined by trial.

The needle movement diagrams on the right-hand side of Figs. 1 to 6 were recorded with Bicera dash pot delivery valves fitted and show that in every case the device completely suppressed secondary injections. For the present purpose the high frequency oscillations which follow those portions of the diagram showing the opening and closing movements of the needle valve may be ignored as they do not correspond to movements of the valve.



Note: Distance between peaks of degree scales represents 2 degrees pump shaft rotation

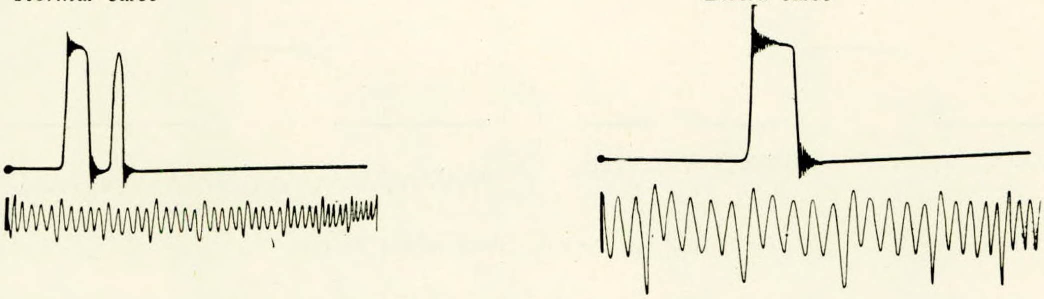
FIG. 2—*System No. 2: needle movement diagrams from system on test rig*

Before the dash pot valve was applied to System No. 1, attempts were made to suppress the secondary injections by varying the normal factors in the system. The nozzle release pressure was varied between 25 and 225 atmospheres in steps of 50 atmospheres, a nozzle holder spring of 4 mm. diameter wire was fitted in place of the 3 mm. diameter wire spring, pipes of length 6, 12, 72 and 132 inches were tested in place of the original 33-in. pipe and a delivery valve of 54 $mm.^3$ unloading volume was used in place of the original 33 $mm.^3$ unloading volume. Marked secondary injections were obtained in every case. A special valve with an unloading volume of 100 $mm.^3$ was next fitted. This stopped secondary injection but gave otherwise unsatisfactory needle lift diagrams. This was attributed to cavitation in the line produced by the excessive unloading. The use of a delivery valve with no unloading also eliminated the secondary injection but, as expected, produced dribbling at the end of the injection period. Secondary injection can be removed by reducing the pump discharge rate or by increasing the nozzle hole area, since both these changes reduce the fuel line pressure and hence the energy stored. However, such changes may mean the rejection of a system which, but for secondary injection, would produce a better engine performance, since with many combustion chambers the best performance is obtained with comparatively small nozzle holes and a high rate of injection requiring high pressures. Thus in a recent case a member company found during the development of a new engine that, of two types of nozzle tested, that with the smaller hole area gave a lower fuel consumption and a cleaner exhaust at part load. As the load was increased, however, the performance deteriorated rapidly, and at full load was very much worse than with the larger area nozzles. Needle movement diagrams showed that severe secondary injection was occurring in the upper part of the load range. Dash pot delivery valves were fitted and the improvement in performance was then obtained throughout the whole load range and the smoke limit extended.

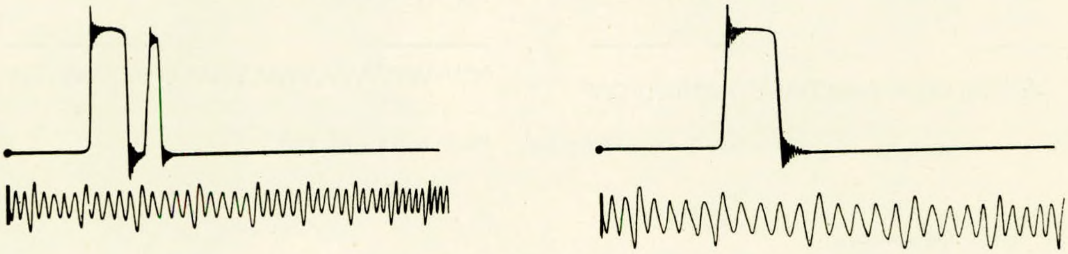
This example makes it evident that in the past the presence of secondary injection, recognized or unrecognized, may in many cases have determined the choice of injection rates and nozzle hole areas, and that without this limitation better engine performance might have been obtained.

The sudden closure of the normal pump delivery valve and the formation and propagation of the pressure wave to which secondary injection has been attributed above, represent only a part of the complicated conditions present in an injection system during the last stage of the injection period. Moreover, a variety of effects occurs according to the combinations of dimensions used in various systems. Nevertheless, the fact that the Bicera delivery valve has eliminated secondary injection in all of the many diverse systems to which it has been applied, shows that the sudden closure of the normal delivery valve is usually the cause of the trouble.

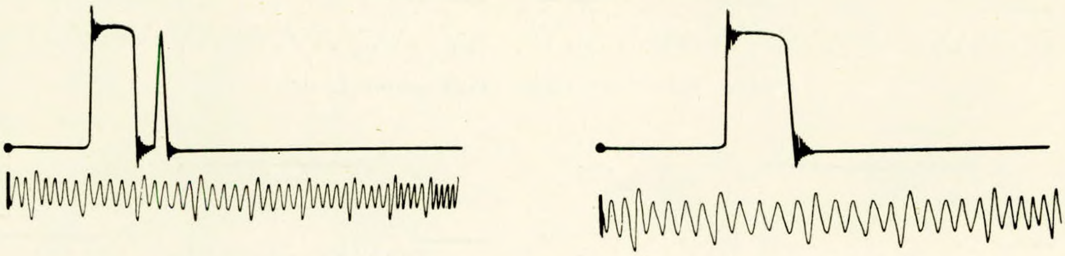
Normal valve *Bicera valve*



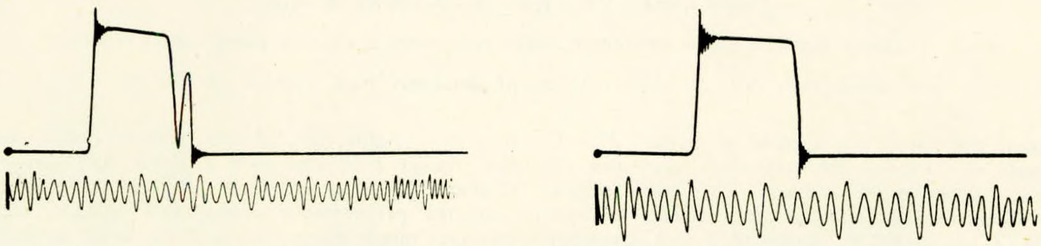
Pump speed 400 r.p.m. Rack setting 18 mm.



Pump speed 400 r.p.m. Rack setting 20 mm.



Pump speed 400 r.p.m. Rack setting 22 mm.

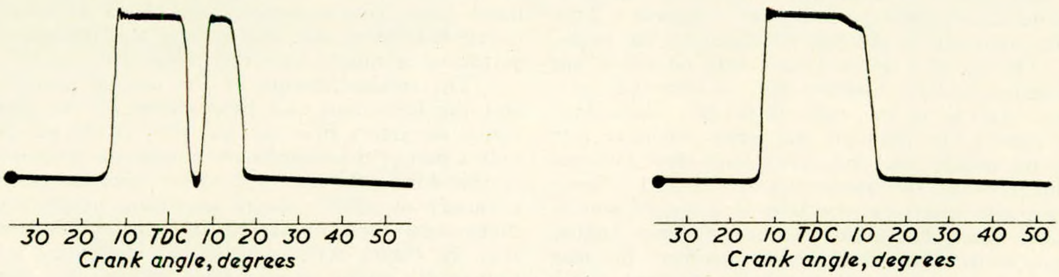


Pump speed 400 r.p.m. Rack setting 25 mm.

Note: Distance between peaks of degree scales represents 2 degrees pump shaft rotation

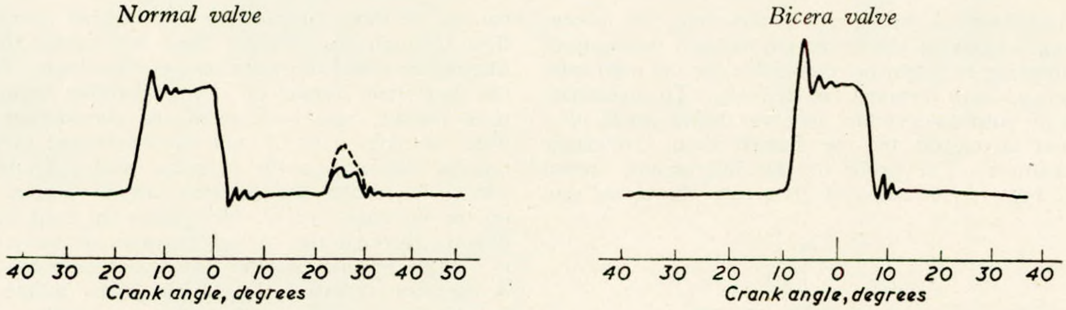
FIG. 3—*System No. 3: needle movement diagrams from system on test rig*

Normal valve *Bicera valve*

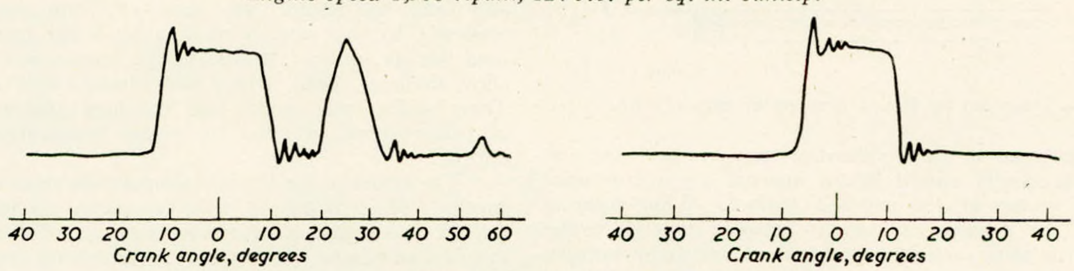


Engine speed 1,000 r.p.m., 75lb. per sq. in. b.m.e.p.

FIG. 4—*System No. 4: needle movement diagrams from two-stroke cycle engine*

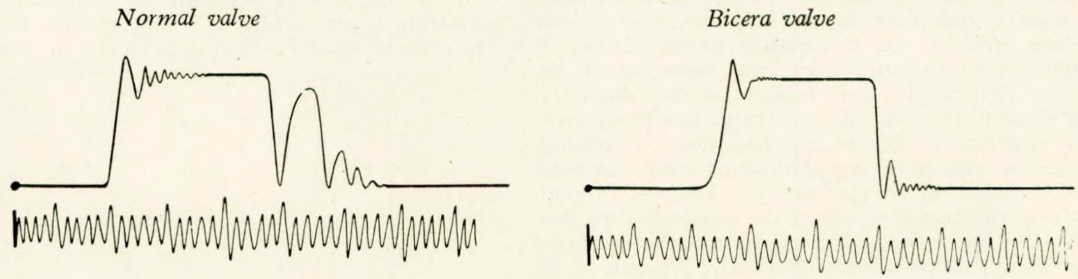


Engine speed 1,500 r.p.m., 124·5lb. per sq. in. b.m.e.p.



Engine speed 1,500 r.p.m., 186·5lb. per sq. in. b.m.e.p.

FIG. 5—*System No. 5: needle movement diagrams from two-stroke cycle engine*



Engine speed 750 r.p.m., 120lb. per sq. in. b.m.e.p.

Note: Distance between peaks of degree scales represents 2 degrees crankshaft rotation

FIG. 6—*System No. 6: needle movement diagrams from four-stroke cycle engine*

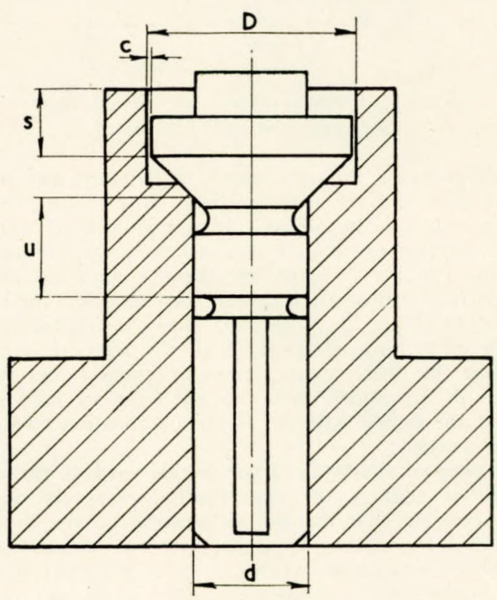


FIG. 7—*Bicera delivery valve*

CORROSION OF NOZZLES

The laboratory received a request for assistance from a member company which was confronted with a serious problem in connexion with engines of a modified design. A considerable number of these engines had been sold mainly to overseas customers. After they had been in service a short time, reports were received of rapid nozzle failure due to loss of metal from the wall of the nozzle body, resulting in many cases in discharge of fuel through the nozzle wall. Most of the affected engines were operating on Class A fuels. Fig. 8 (Plate 1) shows three examples of the nozzles which were returned to the engine makers for examination.

Nozzle A, returned from Portugal, had failed three months after installation of the engine. When the nozzle was tested, it was found that the fuel discharged through the side wall.

Nozzle B, returned from Syria, had also discharged through the side. It had been welded in an attempt to effect a repair, as this was sometimes found to be successful. Later, brazing was found to give better results.

Nozzle C, another of a number returned from Syria, was the only example seen by the engine makers in which the attack had extended beyond the shoulder of the nozzle to the large diameter portion housed inside the cap nut.

The exact numbers of hours of service completed by the above nozzles are not known, but in general failure had been found to occur in about 300 hours and sometimes much less.

At the time when this problem was presented, the laboratory was making a study of the formation of such products of oil engine combustion as might be responsible for the high rates of wear experienced with certain Class B fuels. To investigate the formation of sulphur-trioxide, use was being made of a dew-point meter developed by the British Coal Utilization Research Association. The probe of this instrument, shown in principle in Fig. 9, consists of a glass tube the closed end

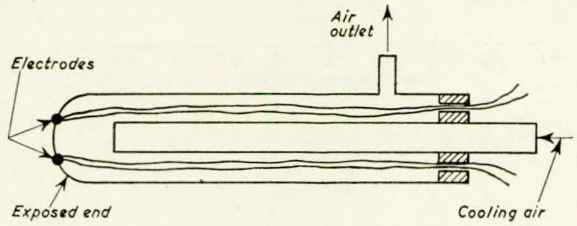


FIG. 9—*Diagram of Bcura dew-point meter probe*

of which is exposed to the combustion gases under examination and progressively cooled by an internal air stream until condensation occurs at the exposed surface. This point is indicated by the passage of current between two electrodes embedded in the glass surface, both of which are thermocouples and indicate the temperature at which condensation occurs. When the gases tested contain sulphur-trioxide the condensate is sulphuric acid. The use of this instrument and study of Bcura's work on corrosion of watertube boiler plant had focused attention on the fact that combustion gases containing sulphur-trioxide and steam deposit sulphuric acid on any adjacent surface provided the temperature of the surface is sufficiently low. Consequently, when two examples of the affected fuel injection nozzles were received at the laboratory, attention was given to the possibility of the surface being overcooled. The surfaces of the nozzles had many interesting features, as can be seen from the photographs, but the most significant was judged to be the complete absence, in both cases, of attack at the discharge end of the nozzles. This end, being subjected directly to the heat produced in the combustion chamber, is at a high temperature while the end adjacent to the cap nut is shielded from the heat and cooled via a short heat-flow path. It was considered very probable that the attack was due to the temperature of the nozzle surface remote from the combustion chamber being too low and it was therefore suspected that the nozzles were being cooled more effectively than usual.

On enquiry it was learned that the engines, which were arranged horizontally, were cooled by water from large tanks which took some hours to warm up. The water entered the lower side of the cylinder block and passed almost directly to the lower side of the cylinder head where the injector was situated. The external part of the injector was quite cold to the touch. During discussions with the makers of the fuel injection equipment, it was learned that the trouble had been experienced in varying degrees by many engine makers, but had not previously reached quite such serious proportions as in the present case.

To test the low temperature theory further, the various cases which had come to the fuel injection equipment maker's attention were reviewed and the cooling system considered in each case. The great majority of these cases had occurred in coastal districts and most were with marine engines. Hence it had been thought that a salt-laden atmosphere might be the cause. The many marine engines concerned were sea-water cooled directly and hence had low nozzle temperatures. The other engines employed in coastal districts which had given the trouble were vehicle engines. In these engines the cooling water was passed to the cylinder head first, where a full flow was maintained, while only a part of the water passed, under the control of a thermostat, through the cylinder jackets. In certain other vehicle engines in which the trouble was almost unknown, though the nozzles used were taken from the same batches as those supplied to the member company, the water flow through the cylinder head was under the control of a thermostat which kept the temperature high. In another case, the short-stem nozzles of a swirl chamber engine were situated in a passage well back from the combustion chamber, and were cooled by a jet of cool water arranged to impinge on the injector housing in the cylinder head. Another instance in which the trouble had occurred was in engines used in barges on the Venetian canals. Here again the cold water was passed directly through the cooling passages of the engines.

More recently another interesting case has come to light. A member company found the same action occurring on nozzles fitted in one of the company's engines installed in the works power house. The nozzles were replaced by new ones and later the engine was removed from service for other reasons. In this case, normal jacket water temperatures were used but an unusual feature of the engine was an aluminium alloy cylinder head which was being used experimentally. There seems little doubt that the high thermal conductivity of this material resulted in nozzle temperatures lower than normal.

The evidence for the low-temperature theory was thus very strong. Nevertheless, it was considered desirable to obtain definite proof that temperature is the controlling factor. To this end an engine was chosen in which long-stem nozzles were used but which was entirely free from the trouble, and an attempt was made to produce the nozzle attack by simply lowering the nozzle temperature. In place of the normal washer, two copper washers of smaller outside diameter were fitted in front of the cap nut, leaving an annular space of section measuring 3 mm. axially by 5 mm. radially below the cap nut. The cylinder head was drilled, as shown in principle in Fig. 10,

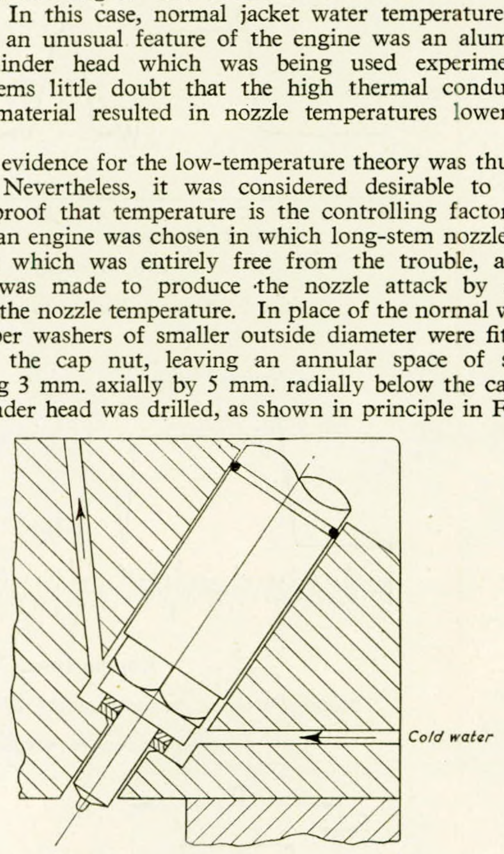


FIG. 10—*Arrangement for producing excessive nozzle cooling*

to provide passages through which cold water was passed at high velocity round the annular space, thus cooling the nozzle cap nut and hence the nozzle. In addition, cold water from the mains supply was passed through the cylinder head. The engine was run for 9 hours 20 minutes on Pool gas oil at two-thirds full load and the nozzle then removed for examination. Fig. 11 (Plate 1) (Nozzle D) shows its appearance. The same type of etching observed in all the affected nozzles was present and the characteristic irregular grooves had started to form even in this short time. As with the service specimens, the end of the nozzle adjacent to the combustion chamber was free from attack.

The external diameter of the nozzle used in this test had been reduced slightly for experimental purposes and as it appeared possible that the partial removal of the casing may have affected the result, a further test was made, using the same cooling arrangements, but with a standard nozzle not modified in any way. This particular nozzle had previously been used for over 500 hours in the same engine without any effect on its surface. Examination after 9 hours 20 minutes showed that the attack was occurring but at a somewhat lower rate than in the previous case. Running was therefore continued to a total of 20 hours 30 minutes. Fig. 11 (Plate 1) (Nozzle E) shows the appearance of the nozzle on removal and after cleaning. The characteristic features were again present. The grooving had reached a depth of 0·36 mm., i.e. 18 per cent of the nozzle wall thickness, so that complete penetration of the wall could be expected in a total of 114 hours' running. The nozzle cap nut which had been used in both tests was also found to have been heavily attacked, as shown in Fig. 12 (Plate 2).

The nozzles used in these tests were made by a different manufacturer from those which had suffered in service. This, together with the corrosion of the cap nut, is evidence that the trouble was not connected with nozzle material or heat treatment.

This brief investigation sufficed to show that this type of nozzle corrosion can be eliminated simply by a suitable increase in nozzle temperature. Raising the cooling water temperature is normally an effective method of achieving this. Where the use of cold water cannot be avoided, the cylinder head should be designed to ensure that a moderate nozzle temperature is attained shortly after starting the engine. On the other hand it is well known that there is also an upper limit to the range of satisfactory nozzle temperature.

There was a curious sequel to this investigation. As the attack was attributed to the presence of sulphur in the fuel, it was thought likely that a Class B fuel having a higher sulphur content would produce an even more rapid attack. When this was tested, however, no measurable loss of weight occurred. The clearance space adjacent to the combustion chamber was tightly filled with very hard carbon. It was concluded that this carbon had protected the over-cooled surfaces from the combustion gases.

Fig. 13 (Plate 2) shows a nozzle which has been attacked in a different manner, metal being removed from the surface of the nozzle facing the combustion chamber. The reason for this type of damage has not yet been established definitely. In view of the position of the attack it was first thought likely that the phenomenon was associated with a high nozzle temperature, and that it might be due to erosion by high temperature combustion gases moving in and out of the annular clearance between the nozzle and the holder. Very few cases of this type of attack have been reported and the effect has not caused any difficulty. It appeared possible that in these few cases nozzle temperatures were above normal, as a result of the scaling of the water spaces of the cylinder heads of the two-stroke cycle engine concerned. However, consideration of another case suggested an alternative theory.

Fig. 14 (Plate 2) shows a nozzle which, like the previous one, has been attacked on the face directly exposed to the combustion chamber. Metal has been removed in such a way as to form a depression which is symmetrically disposed about a diameter. The shape and position of this depression suggest that the fuel spray from the central hole plays some part in the action. The portion of the nozzle farther from the combustion chamber is heavily corroded. It thus appears likely that the nozzle was used at a low temperature and one possible explanation of the attack on the face is that the fringe of the fuel spray reached this part and produced a sufficient reduction in temperature locally to permit acid formation during light load running. If such an action can occur it may also have produced the attack on the conical nozzle of Fig. 13 (Plate 2). It is understood that there is a possibility that the affected nozzles of this type were overcooled. There is very little sign of attack on the cylindrical surfaces of the nozzles, but these may have been protected by carbon filling the annular spaces round these portions. Unfortunately in both these latter cases very little information is available regarding the conditions under which the nozzles operated. Further examples of this type of phenomenon would be welcomed, as the additional evidence thus obtained might enable the cause to be established. Unless the effect is understood and controlled it may sooner or later recur in a more serious manner.

DRIVING SYSTEMS FOR FUEL INJECTION PUMPS

In work on turbo-charging engines to high outputs, certain objectionable features of the mechanical drive commonly used for jerk type injection pumps were brought to notice in a forcible manner. As the output of the test engine was increased progressively, larger elements were fitted to the fuel injection pumps to prevent the fuel injection period from becoming excessive. It was found desirable to retain the original period of 30 crankshaft degrees used in the atmospherically-charged engine in order to limit maximum cylinder pressures, but with the largest elements which the existing C-type pumps could accommodate the injection period was no less than 47 deg. at 230lb. per sq. in. b.m.e.p. The fitting of larger elements had failed to give the expected increase in injection rate and

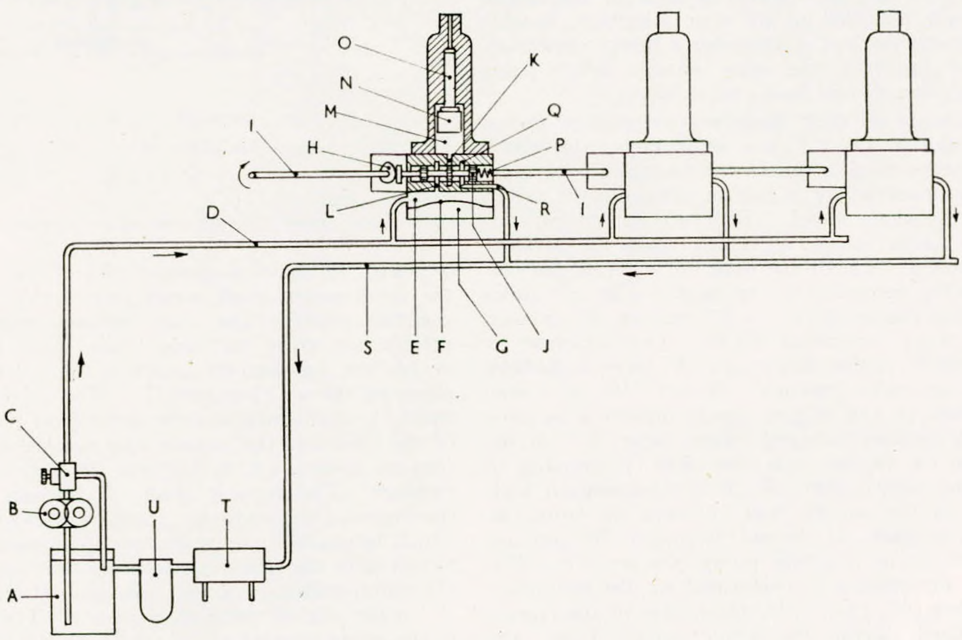


FIG. 15—*Diagram of servo-operated fuel injection system*

this was found to be due to marked increases in the strain in the driving gear. The pump plunger was found to be lagging no less than 1 millimetre behind its unloaded position when the full discharge pressure was reached. This reduced the maximum plunger velocity by 30 per cent.

It was clear that the whole injection system required redesigning to suit the increased loading. An order was placed for pumps of a new design which aimed at accommodating considerably larger elements with the minimum possible increase in external dimensions. The existing pumps were driven by cams midway between air valve and exhaust valve cams on a common camshaft. This simple arrangement was not acceptable with the larger pumps since it would have involved the use of a very massive shaft to withstand the increased bending moment. In the new design, the pumps were arranged close together on a platform projecting from the side of the engine and were driven by a short stiff shaft, connected by heavy gear wheels to the engine crankshaft. This arrangement, however, was never used: the need to provide such high torques in order merely to inject fuel drew attention to a fundamental objection to the mechanical method of driving jerk-type pumps. For approximately 350 degrees of revolution of the camshaft the cam of each pump is only very lightly loaded and performs no useful work. Then when the pump plunger closes the spill port, a sudden heavy load is applied to the whole drive comprising pump plunger, tappet, pin and roller, lever and fulcrum bearing if used, cam and shaft, shaft bearings, and driving gears and bearings. This mechanism performs its useful work during the following 10 degrees of camshaft rotation approximately, the process being repeated as many times per camshaft revolution as the number of engine cylinders. Every one of the components in the drive must be made strong enough to withstand these repeated sudden loadings. The rapid rise in pressure at the injection nozzle which is so desirable as an injection characteristic has a most undesirable effect on the driving gear, which in many cases is tortured also by torsional vibration of the crankshaft. An inevitable concomitant of this impact loading of the driving system is excessive noise.

It was realized that it would be much more satisfactory to take the power necessary for fuel injection from the engine crankshaft continuously, since the torque required would then be only a small fraction of that for which the conventional drive must be designed and the impact loading would be eliminated. It was considered, however, that the jerk-type fuel injection pump should be retained in view of the several good features which have led to its wide adoption, notably the positive and reliable method of achieving a sharp commencement and end of injection, the only serious defect being secondary injection, which had been overcome.

The system chosen to meet these requirements is shown diagrammatically in Fig. 15. (*A*) is a small tank from which fuel oil used as a servo-fluid is drawn continuously by a gear-type pump (*B*) mounted where it can be conveniently driven at several times crankshaft speed. The fuel oil leaving this pump passes to a control valve (*C*) which limits the pressure of the oil to a selected value of the order of 1,000lb. per. sq. in., surplus oil being returned to the tank. The oil under pressure passes via a manifold (*D*) to a chamber (*E*) in each of the injection pump operating units. This chamber is separated by a synthetic rubber diaphragm (*F*) from a chamber (*G*) charged with air under pressure. A cam (*H*) on a very light shaft (*I*) driven at half engine speed imparts a reciprocating motion to a pressure-balanced piston valve (*J*). At the appropriate time in the engine cycle, the valve (*J*), moving to the right, places the central port (*K*) in communication with the chamber (*E*) via the supply port (*L*) and oil from the chamber flows to the space (*M*) below the piston (*N*), moving the piston and with it the injection pump plunger (*O*). The work involved in this process is performed by the expansion of the air in chamber (*G*), that is, by the release of the energy gradually accumulated during the whole cycle. Later, the piston valve (*J*) moves to the left under the action of a return spring (*P*), placing the central port (*K*) in communication with the discharge port (*Q*). Oil from the space (*M*) then flows via a restriction at (*R*) to the discharge manifold (*S*), allowing the piston (*N*) to return gently under the action of a normal return spring. The discharged oil returns via a small cooler (*T*) and filter (*U*) to the tank (*A*).

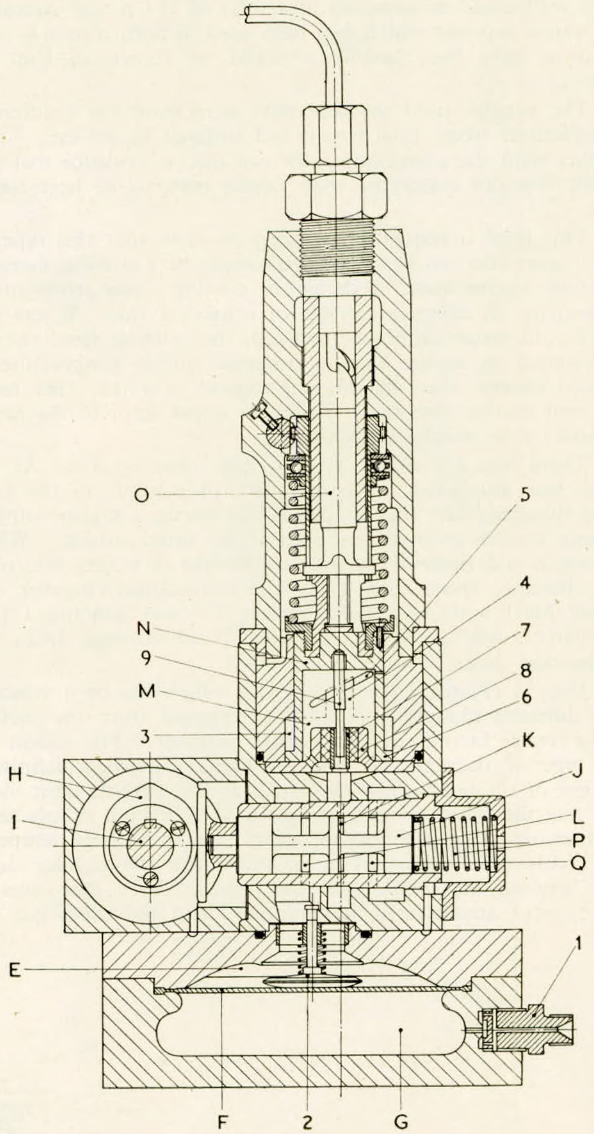


FIG. 16—*Cross-section of servo-operated pump unit*

Fig. 16 shows a cross-section of the pump unit used for the development work which embodied a conventional C-type injection pump. The chief features, which are easily recognizable, are given the same letters as in Fig. 15. Additional details are indicated by numbers. A valve (*1*) is provided for charging the air chamber (*G*). The valve (*2*) closes when the engine is shut down and the servo-fluid pressure falls, the head of the valve and the surrounding surface forming a single continuous surface which supports the diaphragm against the air pressure. The annular space (*3*) between the piston (*N*) and the surrounding cylinder forms the chamber of a dash pot which brings the piston and pump plunger assembly smoothly to rest after the effective stroke has been completed. The space (*3*) communicates, via two passages (*4*) with two helical ports (*5*) in the side of the hollow piston. The piston is connected to the pump plunger and rotates with it when the pump control rack is moved. The port (*5*) is so arranged in relation to the

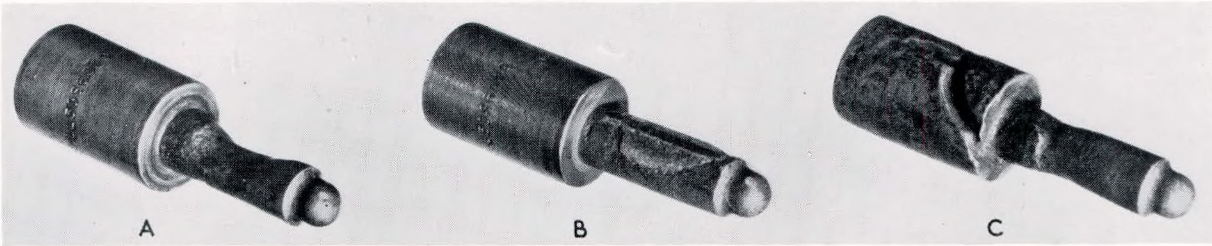


FIG. 8—*Fuel injection nozzles corroded in service*

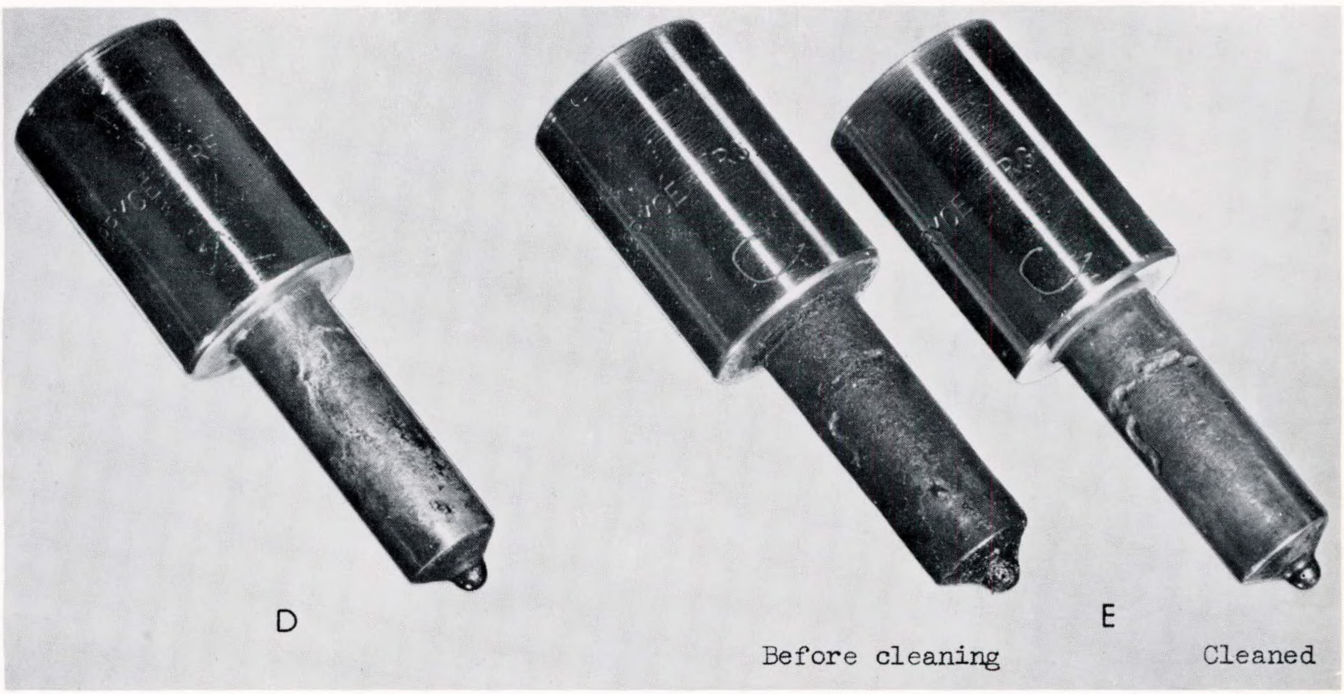


FIG. 11—*Nozzles corroded artificially*

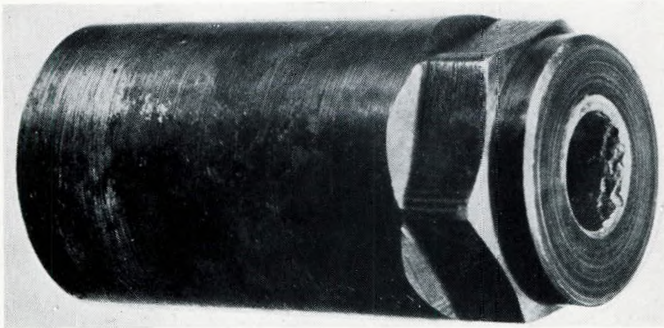


FIG. 12—*Cap nut corroded artificially*

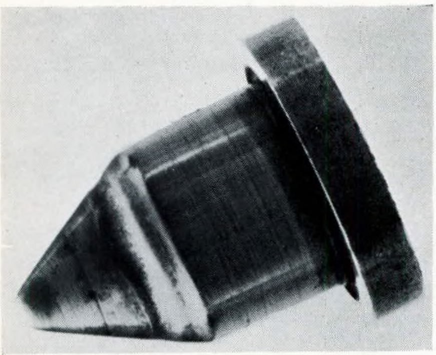


FIG. 13—*Nozzle attacked on conical combustion face*

FIG. 14—*Nozzle attacked on flat combustion face*

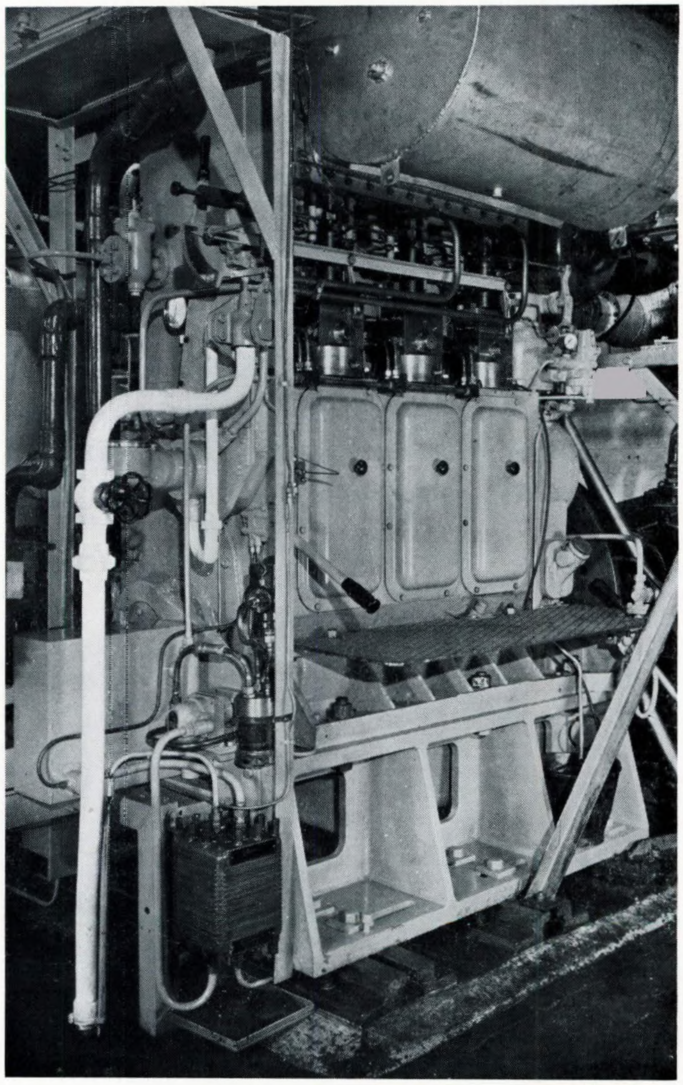


FIG. 19—*Servo system arranged on experimental turbo-charged engine*

helix and spill port of the injection pump that, whatever the pump rack setting, the port (*5*) is closed as soon as an ample spill port area has been uncovered. Further discharge of oil from the space (*3*) can then occur only through a small clearance round the flange (*6*) on the piston and thus the piston-plunger assembly is smoothly decelerated. The insulated sleeve (*7*) supported in plate (*8*) and the rod (*9*) attached to the piston (*N*) are not normally required. They formed a variable condenser which was used in conjunction with an oscillograph and a suitable circuit to indicate the movement of the piston-plunger assembly during development work.

At first the pump unit was found to be rather noisy in spite of the provision of the dash pot. To determine the reason, simultaneous oscillograms of the piston movement and the output of a microphone were recorded with the result shown in Fig. 17. The oscillograms showed clearly that the disturbance was produced not at the end but at the beginning of the stroke and could be attributed to the very sudden initial acceleration of the piston-plunger assembly. The cam form was then modified from the original design to that shown in Fig. 16, giving an initial rate of opening of the port (*K*) of one-tenth only of its original value. The effect of this change on the piston movement diagram is shown in Fig. 18, from which it will be seen that with the modified cam a smooth acceleration occurred during the first part of the piston movement before the pump port was closed, and that there was no loss of velocity during the effective part of the stroke. The change produced a great reduction in noise which was then much less than that of a mechanically driven pump performing the same duty.

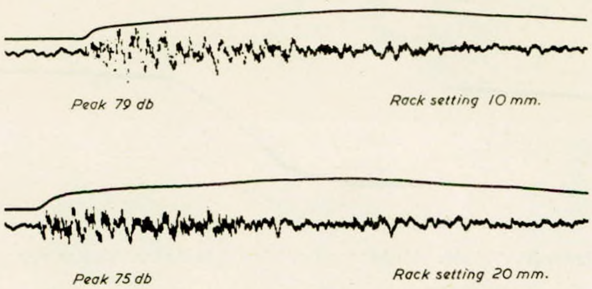


FIG. 17—*Oscillograms of piston movement and microphone output*

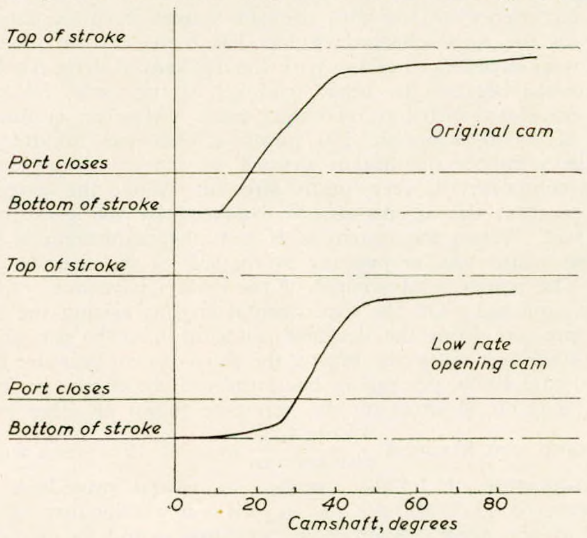


FIG. 18—*Piston movement diagrams with original and low-rate cams*

Fig. 19 (Plate 2) shows the system applied to the experimental four-stroke cycle turbo-charged engine at the laboratory using three pump units of the prototype design, which incorporated standard C-type pumps. An integral design permits the much more compact arrangement shown in Fig. 20.

Fig. 21 shows the diagrams of nozzle needle movement, fuel line pressure and pump plunger movement obtained at various pump rack settings. One interesting feature is the almost constant maximum value of the fuel line pressure. In this case the pressure of the oil in the servo system was 1,000lb. per sq. in. and the ratio $\frac{\text{area of piston}}{\text{area of plunger}}$ was 6, so that a pressure of 6,000 approximately would be expected in the line during the injection period. This value corresponds closely

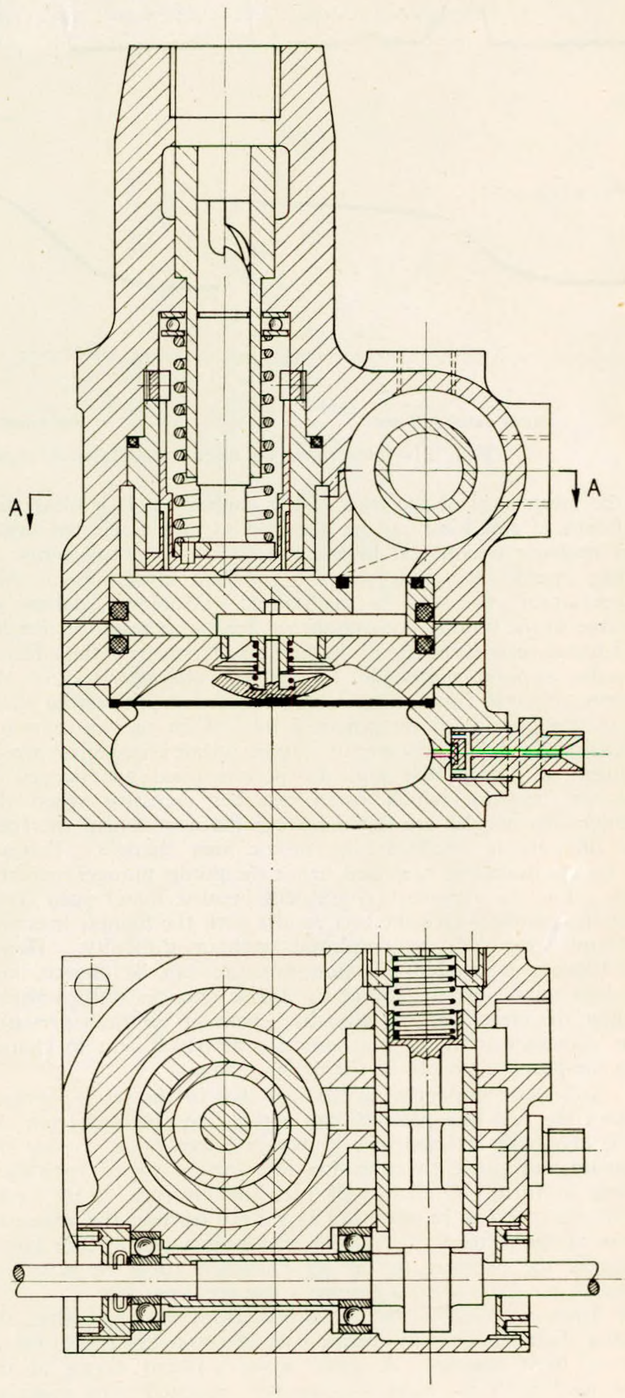


FIG. 20—*Integral design of pump unit*

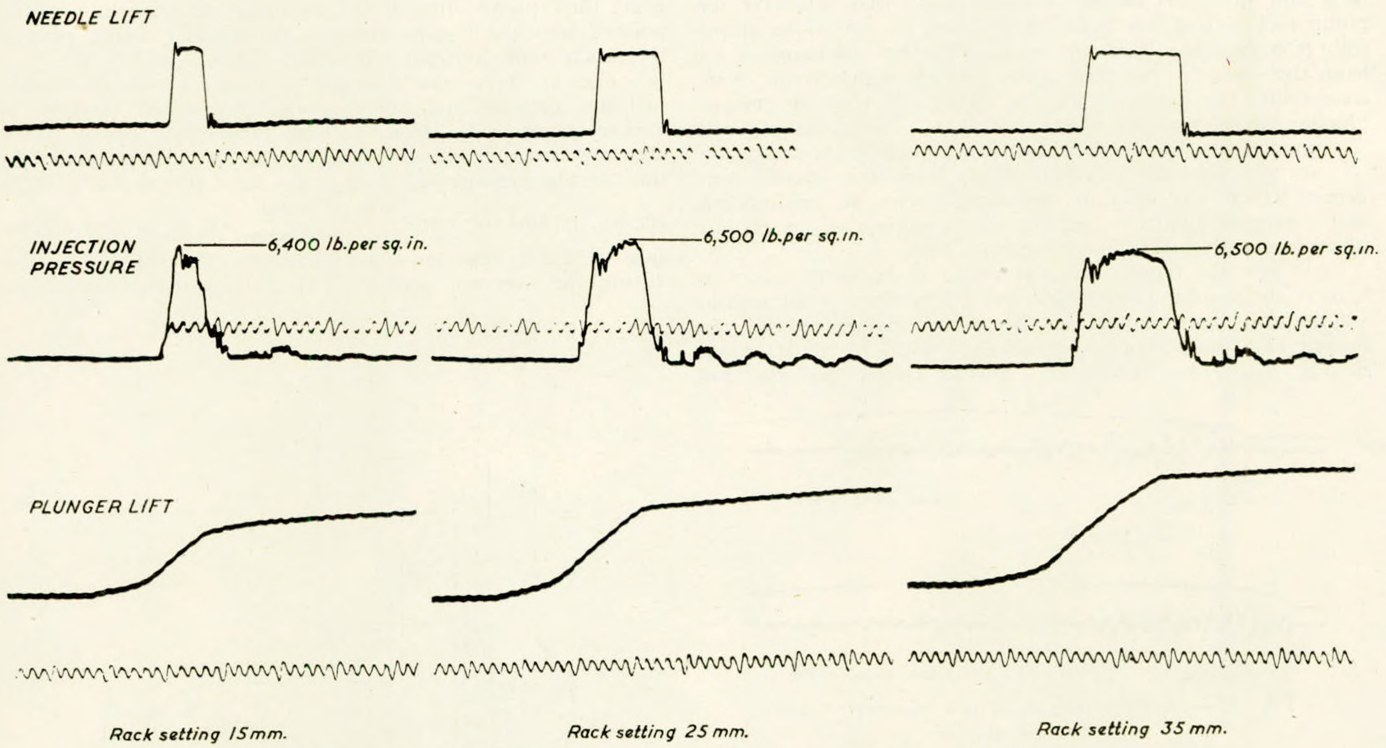


FIG. 21—*Diagrams of nozzle needle movement, fuel line pressure and pump plunger movement*

to the mean level of the tops of the diagrams. It is clear that a system of this kind can be designed to give a selected injection pressure which will be maintained over the full range of engine speed and load, so that the best condition of fuel "atomization" can also be maintained. Moreover, danger of damage to the pumps, connexions or drive as a result of nozzle-hole blockage is eliminated. Reduction of power in the affected cylinder appears preferable. This new characteristic of the system, constant fuel line pressure, has also an interesting effect on the progress of development work. With the conventional mechanically driven jerk-pump system, nozzle changes involving changes of nozzle hole area are accompanied by changes of fuel-line pressure which often becomes excessive when the smaller area nozzles are tested. With the new system the fuel-line pressure is unaffected by nozzle area changes. Instead, the nozzle discharge rate, and hence the pump plunger velocity, vary. This is often very convenient because many open combustion chambers give the best results with the highest injection pressures that can be employed without difficulty. Hence the highest acceptable injection pressure can be chosen, and the best nozzle can be found by nozzle changes only, whereas to give the larger area nozzles the benefit of the high pressure, it is necessary with the mechanically driven system to change also the pump elements or the driving cams.

Still more important is the fact that in the servo-operated system the fuel-line pressure can rapidly be changed from the value originally selected to a higher or lower value, so that the pressure and hence the injection rate can be varied with each nozzle in turn. A change of fuel-line pressure of the order of 30 per cent can be obtained by simply turning the adjusting screw of the control valve at the gear-pump outlet. For larger changes, the pressure in the air chambers must be raised or lowered, an operation occupying a few minutes only.

Another valuable facility arises from the fact that the timing shaft has only to operate balanced-pressure piston valves against light springs. A small advance-retard device of the type used with mechanically-operated enclosed type injection pumps of small engines can be fitted in the timing shaft of a large engine so that the timing can be varied at will while the engine is running. This has proved very useful in development work at the laboratory, and could be controlled to provide the best timing for every condition of operation of the engine. To reset the injection timing of a reversing engine, either the above device or a simple lost motion arrangement could be employed, together with changeover valves at the gear-type pump.

Experience to date with the new system, both on test rigs and on the turbo-charged engine, has been very satisfactory. The wear experienced earlier with the mechanical drive has been eliminated because the heavy loadings of the cams, followers and associated bearings no longer exist. After an endurance test of 1,000 hours at 350 pump strokes per minute, the synthetic rubber diaphragm showed no sign of deterioration. This component is very lightly stressed. While the system is in operation the air pressure is balanced by the pressure of the fuel. When the system is at rest, the diaphragm is supported against the air pressure by the side of the chamber.

The potential advantages of the system have not yet been fully exploited. On the experimental engine, raising the fuel-line pressure from the designed value of 6,000lb. per sq. in. to 8,400lb. per sq. in. by raising the servo-system pressure from 1,000 to 1,400lb. per sq. in. has improved the engine performance without ill effect on the gear-type pump or other parts. A pump unit having a $\frac{\text{piston area}}{\text{plunger area}}$ ratio of 10:1 used with a servo-pressure of 1,500lb. per sq. in. would provide a line pressure of 15,000lb. per sq. in. without overloading of any part of the drive. Such high pressures would facilitate the use of high viscosity fuels. The separate light timing drive to the pump units gives freedom in the choice of the position of these units, which may be placed very close to the injectors or even combined with the injectors.

The system has been used very successfully on the three-cylinder $8\frac{1}{2}$-in. bore, $12\frac{3}{4}$-in. stroke turbo-charged four-stroke cycle engine running at 600 r.p.m., with fuel quantities up to 1·4 cc. per pump stroke. Rig tests have shown that the same system operates well at all injection frequencies up to at least double those used on the engine. Hence with smaller pump elements the frequencies of operation required for small high-speed engines should be easily obtainable. However, the most attractive applications of the system are to pressure-charged medium-size engines and to large engines. In the latter case the system may well prove less costly than most existing systems as well as being more compact and more effective.

CONCLUSION

This paper has touched upon a few of the many problems associated with the fuel injection equipment of oil engines. The other departments of the engine all produce their own collection of intriguing conundrums. The conclusion to be drawn is not that the oil engine is a particularly troublesome form of prime mover, but that in spite of its past and present achievements it still offers great scope for improvement. It will handsomely repay the effort expended in further research and development.

ACKNOWLEDGEMENT

The author wishes to thank the British Internal Combustion Engine Research Association for permission to present this paper.

ADDITION TO PAPER

In presenting the paper the author added that, since the paper was written, another interesting example had been received of corrosion of the conical design of nozzle. In this example, shown in Fig. 22, the attack on the nozzle face was coupled with attack of the cylindrical portion as in the example shown in Fig. 14. Moreover there was clear evidence in the new example that the fuel spray played a part in the action, since, as could be seen from Fig. 22, the edge of the groove produced by the corrosion consisted of a series of arcs having the nozzle holes as centres. Since the corrosion of the cylindrical surfaces in these two cases was evidence of overcooling and the effect of the spray might well be to bring below the critical temperature the surfaces it brushed, it appeared that overcooling was responsible for all the observed effects.

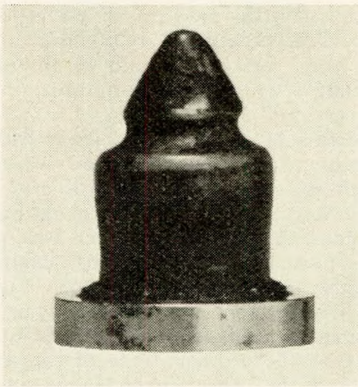


FIG. 22

Discussion

MR. J. CALDERWOOD, M.Sc. (Vice-President) said he would like personally to congratulate the author on a very excellent paper. No doubt most of the members who were present would feel that it was a most interesting collection of information that he had put before them.

In saying this, he must add—and this was a point to be noted during the discussion—that Dr. Mansfield might be a little handicapped in replying to questions. He was an officer of a research association and he could not give information which was still confidential to the members of that association. If he was unable to answer some of the questions put to him without prior reference to his research committee he might perhaps be forgiven.

It would be realized that the points discussed in the paper were only a small part of a much larger research programme. At the present stage, it was perhaps too much to say that the valve to which he had referred was a complete answer to the problem. It was true he had shown that in a number of cases where secondary injection had occurred it had been cured by this valve. In most cases, no doubt, it was a cure. But was there, as yet, any proof that this valve might not give worse results in an engine working with the normal valve without secondary injection?

From one aspect, one wanted the valve to close gently in order to stop secondary injection; but from another aspect one wanted it to close as promptly as possible, so that the end of the injection was perfectly clean. Had there been any converse test—the testing of performance with the valve in an engine which was running perfectly without it? Incidentally, although it had been developed primarily for the smaller and higher-speed engine, the same problem occurred from time to time in every type and size of engine.

Nozzle corrosion was a most interesting problem, but it was not of particular interest to the members of the Institute. It was obviously a difficulty that applied mainly to the smaller engines. In the larger engines, the nozzle was not usually cold enough for trouble to develop in this way. At the same time, it did give a guide as to other problems which arose in all sizes of engine. Whether the corrosive material was SO_3 or not, he did not know, and he doubted whether anyone could prove it, but undoubtedly under certain conditions one could condense, out of the combustion gases, some very corrosive products which almost certainly accounted for some of the other troubles arising from time to time in other parts of the engine, particularly when it was burning the worst grades of fuel.

His reason for suggesting that it might not be SO_3 was that the incidence of these troubles did not seem to be directly related to the amount of sulphur in the fuel. He was under the impression that the corrosion trouble illustrated in the paper occurred with fuel which was relatively low in sulphur.

DR. MANSFIELD agreed.

MR. CALDERWOOD, continuing, said that information was badly wanted on the real influence of sulphur and whether it varied with other characteristics of the fuel.

He considered the really important part of the paper to be the section relating to the pressure operated pump. His first criticism in this connexion would be that they should not have used a standard type fuel pump. In other words, they should have designed an element to suit the pressure operating system. He was aware that the whole of this development arose out of the old saying that necessity is the mother of invention. In the middle of a high-pressure pressure charging programme, the point was reached when the fuel pumps could not get the fuel injected in time to obtain reasonable combustion, and it was necessary to find some way of getting it there quickly. To have used a standard fuel pump would have entailed entirely rebuilding the engine. The camshaft, he believed, was already twisting through some degrees with a pump which still would not get the fuel in quickly enough. Substantially to increase the camshaft diameter would have required the rebuilding of the engine and would have delayed the work for six months or perhaps even a year.

They got down to the problem with a view to getting out of immediate troubles as quickly as possible, and new pumps were made up from parts that could be found quickly. He had seen the pumps working on a number of occasions and they did work very well.

On the question of noise, he had never had great faith in instrument measurement. His own view was that the Bicera pump was much less noisy than the ordinary injection pump on the same engine running at its normal rating, and approximately three times the amount of fuel was going into the cylinder as was normally burned in that engine.

If these pumps were eventually to come into commercial service, further development was needed. This was only one of several possible methods of getting fuel into the cylinder as an alternative to the ordinary type of cam-operated pump. But both this and the other methods had the advantage of greater flexibility than the straight camshaft driven unit.

He had not attempted to make a comparison of all of them, but the Bicera system seemed to him to be particularly valuable in that it allowed—when one made a change in an engine, either by way of development or even, say, by way of altering speed as between one and another engine that was sold—for the adjustment of the injection characteristics very simply and quickly to suit conditions without the need to fit a new camshaft or to make some other radical modification.

He hoped that the Association would continue this work. They might not have found the final answer, but they seemed to have a very promising development among the various fuel pump developments that were going on outside in various parts of the world.

MR. J. GAMBLE noted that Dr. Mansfield expressed the hope that the discussion would bring to light problems worthy of attention and that further light would also be thrown on some of the problems upon which Bicera had reported.

In his own capacity as engine designer of a member firm, he was aware of the work that was being done at the Bicera laboratories. To the best of his knowledge, during all the engine running they had done, there had been no undue wear of the helix type fuel pumps, no matter what grade of Diesel oil was used in the test engines. The same could be said of the engines of his own company which employed helix pumps everywhere, except for one country, namely Iraq.

Prior to 1934, they regularly fitted their own make of fuel pumps with plain plungers to their horizontal engines; but from that date, they gradually changed over to the proprietary helix pumps. Among the plain plungered fuel pump engines supplied to Iraq before the war, many were still working, and no undue wear of the fuel pump plungers and barrels had been reported.

In the Baghdad area a very cheap waxy fuel was, and had been available for many years. Medium-speed post-war engines

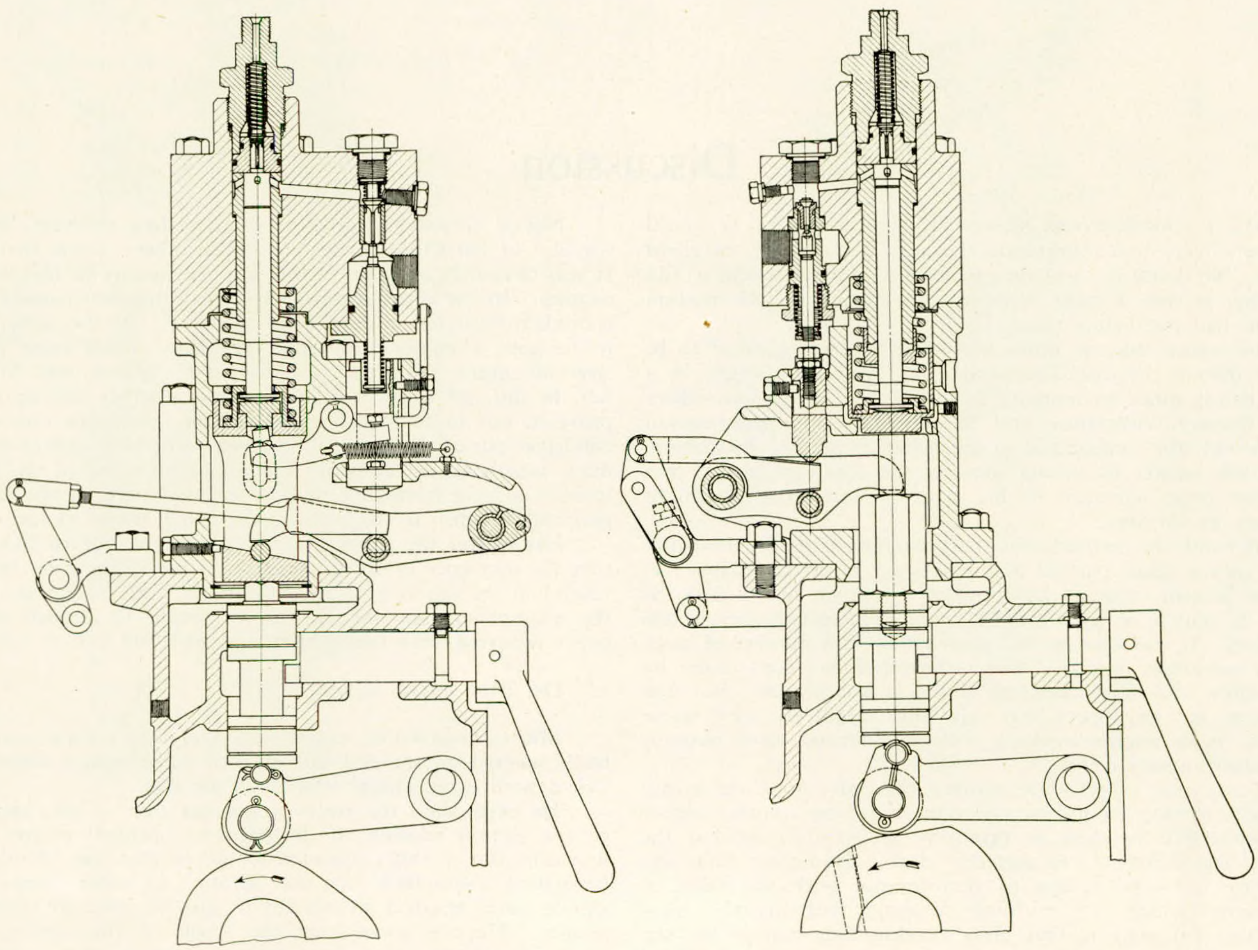


FIG. 23

were expected to run on this fuel without undue fuel pump wear, as did the pre-1934 engines. Owing to the grit that too often found its way into the fuel after leaving the refinery, however, the portion above the helix of the plunger soon wore, and the user was too often put to the expense of a replace pump element. He naturally complained of this, seeing that such a quick replacement was not required with the fuel pumps of plain plunger type.

The company's supplier of helix pumps had been requested to supply non-helix types to meet the market, but as yet no delivery had been made. Meanwhile, to meet this market, his company now found themselves again manufacturing fuel injection pumps for current production engines after a lapse of twenty years.

To avoid changing the mountings for carrying the fuel pumps, they had designed the pump casings with the same mounting centres as were used on the proprietary helix type fuel pumps.

Two types of plain plungered pumps had been evolved to meet this situation. One design was operated by a cam identical with that operating the helix type pump that it replaced for this market. This type worked on the same principle as the replaced pump. That was to say, after the fuel pump plunger had risen a certain number of millimetres—depending upon the size of the fuel pump—fuel injection to engine began. The mechanism controlling this was the subject of a patent.

The other design worked on the same principle as the pre-1934 fuel pump, that was to say, delivery of fuel to engine began as soon as the fuel pump plunger began to rise. To meet local demands, a packing gland was also incorporated to combat leakage when wear eventually took place.

Fig. 23 showed sections through the two fuel pumps. The first fuel pump shown, on the left, worked from the same cam as the helix type pump. As the first few millimeters of the plunger rose, fuel passed back to the suction side of the pump. The reason for this was that the rocker was holding up a spill valve from seating. One end of the rocker rose with the main plunger. As this end of the rocker rose so the other end fell, and the spill valve seated. When it was seated, the further rise of the plunger sent the fuel to the engine until such time as the wedge gear operated by a governor came into contact with a tappet and so lifted the spill valve from its seat.

On the right of Fig. 23 was a simple version of the plain plungered pump, and it also had been designed to fit on the same fuel pump casing as the proprietary fuel pump that it replaced, but was operated by a different cam. As soon as the plunger began to rise, injection of the fuel to the engine began. The quantity was controlled by the wedge gear. The users in Iraq had asked for the packing which could be seen around the plunger.

The company looked forward to the marketing of a series of proprietary fuel pumps designed to run on these abrasive-carrying waxy fuels at a reasonable price.

To talk of adequate filtering got one nowhere and it must be borne in mind that the fuel had a high pour point and required preheating. This was done from the engine exhaust, the engine being first started up on gas oil.

If Bicera could obtain a bulk supply of this fuel, preferably from the service tanks of the engine users—and thereby in the contaminated state—useful data might be obtained by running it in an engine. There was no need for any change of fuel pumps for high-speed engines, as these regularly ran on the much more expensive gas oil.

With regard to secondary injection, he would like Dr. Mansfield to give a figure for the loss of thermal efficiency due to not using the Bicera delivery valve and thereby justifying the adjective "serious". Such a valve was tried on one engine, and no difference was found in either fuel consumption or noise level or anything else as compared with the normal delivery valve.

He had no complaint about the use of the words "serious problem" in the opening sentence under "Corrosion of Nozzles". The corrosion failure of nozzles showed the value to a manufacturing firm of a research laboratory, such as Bicera. The full happenings during the ten weeks from its being reported and the solution to the trouble would be a paper in itself.

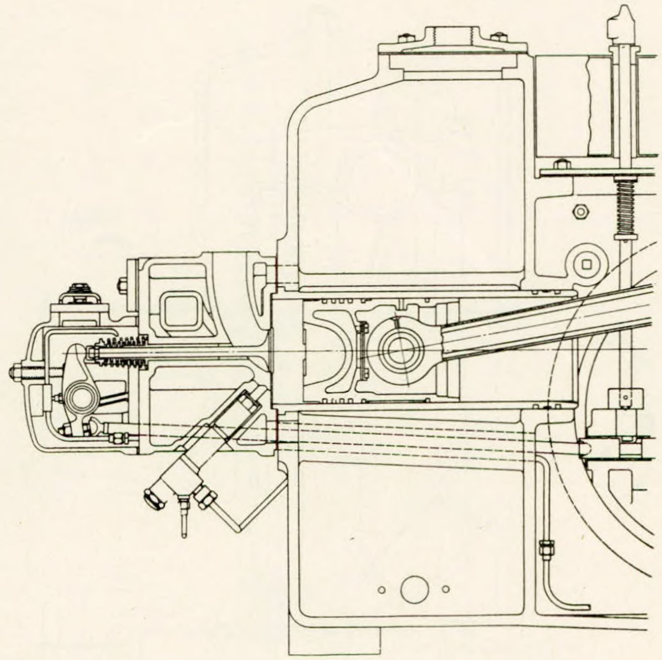


FIG. 24

Prior to the sale of any of these engines, the prototypes ran thousands of hours without any breakdown through nozzle corrosion; in fact, the company had never had an engine nozzle corrode right through on any engine during running at the works; and this included an engine which had been in a sub-power station for seven years. There were slight traces of corrosion on two of these engine nozzles, but a magnifying glass was necessary to see the corrosion: one had to know what to look for.

During their own investigation of the trouble, his company noticed that the nozzle-holder was always cold and that a sticky black substance sometimes collected on the end of the nozzle-holder. When this occurred, slight traces of corrosion were found by the aid of a magnifying glass, inasmuch as the tool marks on the nozzle stems had disappeared in places.

Fig. 24 showed a section through a horizontal engine of the series in which some nozzles were corroded. It was possible when the engine was on full load to put the hand anywhere just up to the centre line. From the centre line upwards it was too hot to bear. A rusty iron washer was temporarily

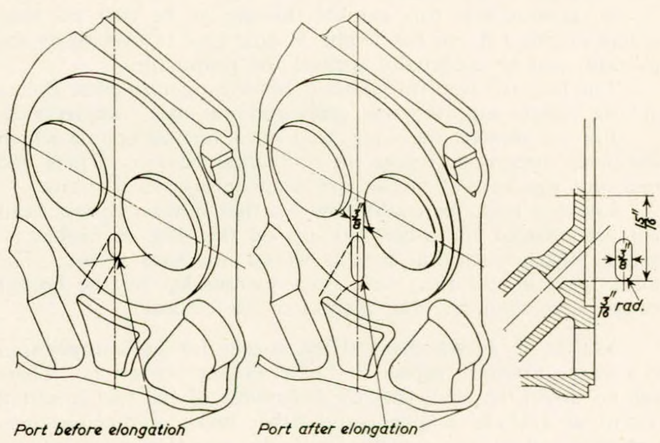


FIG. 25

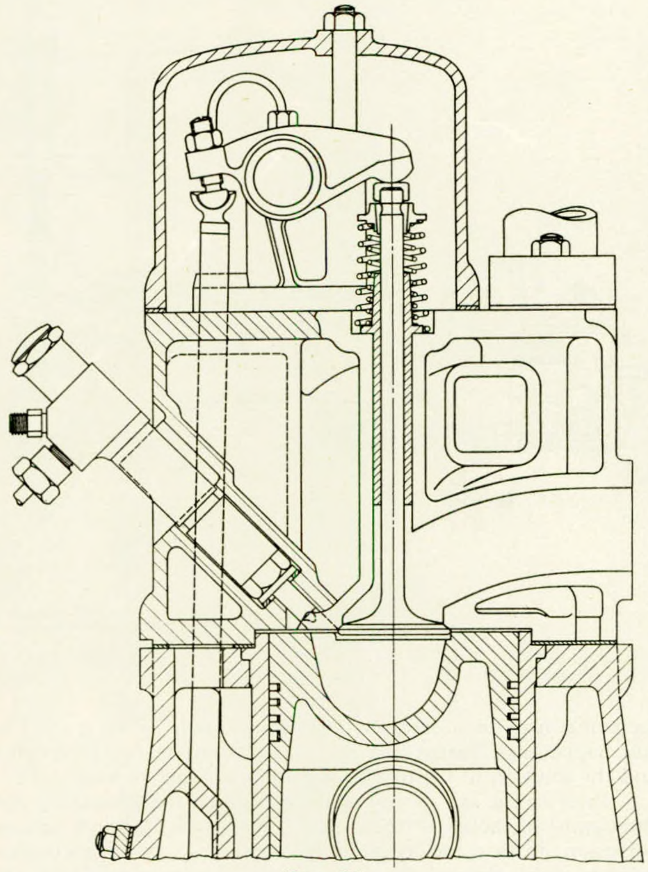


Fig. 26

fitted as a joint in an engine at the works so that hot gases could leak past this joint and thus warm up the nozzle holder. No sticky black was then found and there was no sign of corrosion. The nozzle port was therefore elongated to allow the heat of combustion to reach almost the full length of the nozzle stem, and there had been no more reports of trouble. Whether or not the company's agents had experienced this trouble, they were all circularized and given a drawing showing how to safeguard the nozzle from corrosion attack by the application of a ¼-in. round file.

Fig. 25 showed the modification of the nozzle port. The nozzle in position could be seen before the file was applied. There was a round hole drilled on the angle and it was eventually elongated by filing. A part section through the cylinder head could be seen showing the port through which the heat then went on to the nozzle.

So serious was this trouble thought to be that his firm had an engineer flown out to the Middle East to investigate the problem, and he eventually applied the round file.

The help received throughout the investigation from Bicera and the nozzle suppliers was great and was much appreciated.

Fig. 26 showed the same head on a vertical engine which was made three years before the horizontal version. There had been only one case of nozzle corrosion on a vertical engine.

Looking back, he could now see that if the cylinder head had been placed the other way up on this size of horizontal engine, nozzle corrosion trouble would not have arisen. The nozzle port would then have been surrounded by the hottest water in the cylinder head instead of the coldest.

Mr. L. E. Lowe thanked the author for his contribution to a very important aspect of Diesel engine operation. There was no doubt, he said, that the behaviour of the fuel injection system in a Diesel engine could either make or mar the performance and all too often the faults, because they were difficult to detect, were not fully realized.

Any simplification of the fuel injection system which could reduce the possibilities of secondary injections occurring must always be welcomed; and the Bicera unloading valve, with its dashpot effect, could be used to reduce the reflected waves which travelled along the fuel pipe and brought about secondary injection. It could be shown that these pipe-line pressure waves would sometimes cause pre-injection as well as after-injection and in any case they were a frequent cause of dribbling at the injector. This was usually the beginning of carbon formation on the nozzle, either starting the blocking of holes or the beginning of carbon trumpet formation.

An engine having any defect of this type in its injection system would not give a great deal of trouble if it was run on a distillate fuel, but if heavier grades, such as marine Diesel fuel or boiler fuel were used, then the after-injection or dribbling of fuel tended to carbonize much more rapidly. Any deposition of carbon in injector holes would tend to restrict the fuel spray and set up secondary injection conditions so that sooner or later a secondary opening of the needle valve would take place. Any fuel injected under these conditions would not be able to find the requisite amount of oxygen in the cylinder and, therefore, would not burn completely. This contaminated the lubricating oil on the cylinder wall and tended to start port blocking in two-stroke engines and exhaust valve deposits in four-stroke engines. These troubles were all too common nowadays and had become more pronounced during the past year or so with the use of heavy fuels by many engine operators.

Carbonizing at the nozzle could be reduced by adequate cooling, and there were many well-known instances where intense cooling of the nozzle tip without any other alteration to the injection system had stopped carbon formation, purely by reducing tip temperature.

The cooling of injector nozzles was, therefore, of great importance; but as the author had pointed out, there were dangers of overcooling which should be avoided to prevent the risk of corrosion. The external surface of the injector should be kept above the dewpoint of sulphur oxides, some of which, as Mr. Calderwood had said, might be not sulphur trioxide but in a state of transition from sulphur dioxide to sulphur trioxide. As the overcooling of such sulphur oxides brought them below the dewpoint, they might attack the metal and cause a risk of corrosion. There was no doubt that the example they had been shown that evening was a case of external corrosion from sulphur oxide from fuel. The fuel used in the instance where bad corrosion took place was not a normally recommended Diesel grade. It was a grade of fuel which was rather cheap in the area in question. It was distributed by Arab merchants, and it was not likely to be particularly clean. Apart from that, it was higher in sulphur content than any normal Diesel fuel.

On the other hand, the internal temperature of the injector required closer study. If it were allowed to rise too high and the fuel exceeded a temperature of 135 deg. C. during its passage through the injector, there was a risk of the incipient formation of deposits on the injector needle. Such deposits could start injector sticking, which again caused a sluggish return of the needle to its seat. This could be just as troublesome as secondary injection. This clearly called for much better control of injector tip temperatures than existed today on many engines. It was of interest that some Continental makers used stainless steel for injector nozzle tips, mainly to prevent corrosion which sometimes occurred underneath the carbon deposits. This practice was likely to spread with the increasing use of heavier fuels.

With regard to the servo-operated fuel injection system, he would like to congratulate the author on his useful contribution to the present problem of giving a shorter injection period without the necessity for overstressing the fuel-pump driving mechanism. In a number of instances which had been examined in engines of 10-in. bore and upwards run on boiler fuel, trouble had been diagnosed as being due to "too long" and "too slow" an injection. In some instances, the fitting of larger pump plungers and faster rate fuel pump cams had improved engine performance, but this was usually accompanied by an increase in combustion pressure. It was generally this increase in maximum cylinder pressure (although it gave a lower exhaust temperature and a slight improvement in thermal efficiency) which caused misgivings in the engine makers.

Had the author any indicator diagrams taken on the three-cylinder engine mentioned in the paper as using the servo-operated fuel pump, to show whether the combustion pressure was materially increased and whether this was likely to be a stumbling block with the use of higher injection rates? It would appear that the provision of an injection timing control would be helpful in this respect, as it would provide means of limiting the maximum pressures. It would, however, be helpful to see cylinder pressure diagrams as an indication of the degree of control which was given by this new system.

From some of the cylinder pressure diagrams which have been studied from engines using boiler fuel, it would appear that the engine makers should give some thought to abandoning the Diesel cycle and endeavour to adapt their engines to follow the Otto cycle in order to burn heavy fuels with greater efficiency.

MR. G. R. GREEN, who expressed appreciation of Dr. Mansfield's paper, said it contained much information which was of general value throughout the engine industry. So frequently in industry one could only grapple with the bare bones of a problem. Dr. Mansfield had provided the meat and gravy and had given much food for thought.

In connexion with the Bicera delivery valve, Dr. Mansfield had stolen the thunder by suggesting that the right way to deal with secondary injections was to remodel the injection system so that they did not exist. He himself heartily subscribed to that view. However, Dr. Mansfield had suggested that he had evidence that in certain cases where the Bicera delivery valve had been used to suppress secondary injections there had also been improved engine performance which could not have been achieved by an alteration of another kind to the injection system.

Had he done any work using constant-pressure unloading valves? In certain cases, they seemed to present a solution to pipe-line problems, and this type of valve seemed to be easier to manage than the Bicera valve, merely from the manufacturing point of view. With the Bicera valve, there would seem to be some difficulty in matching valves in large numbers. When a valve wore on the unloading collar, as it invariably would, there seemed to be some danger of its unloading on the damping collar instead.

His own firm had come into contact some years ago with the corrosion of nozzle shanks. As so often happened, they had to guess at half the solution, but it was gratifying to find afterwards that they had at least guessed correctly why the trouble had occurred. It had not been possible to offer the same solution to the problem as Dr. Mansfield had been able to put forward.

The hydraulic operation of fuel injection pumps obviously presented great potentialities, especially on big engines. It opened up a completely new field of thought, particularly as one could now set down beforehand the mean pressure in the pipe line for a fuel injection system and work back from that. This was a new conception, and it was interesting to note that the mean pressures were substantially lower than one would expect to find in the pipe lines of such an engine. It meant that one could study the distribution of the fuel in the combustion chamber as the prime requirement and work the whole injection system back from that stage.

This was the first opportunity he had had to see inside the fuel pump, although he had had the opportunity of seeing one running at Slough. He was surprised at the way the construction had gone, and there were many questions he would like to ask as to the reason why things were made in a certain way. However, he did not propose to take up much time on questions of that kind.

He would like to touch very briefly on Mr. Gamble's point regarding pumps with helix control. There was no doubt in anyone's mind that spill valve type pumps were capable of handling much dirtier fuels than helix-controlled pumps; but it did appear that the occasions on which the necessity arose for that kind of pump were so few that it was not an economic proposition so far for any manufacturer to go into large-scale production. Mr. Gamble had doubtless found the best solution, which was to manufacture a pump which was entirely interchangeable with the proprietary pump and could be fitted to engines expected to work under these conditions.

MR. D. ROYLE, B.Sc.(Eng.), said that the author and his colleagues at the British Internal Combustion Engine Research Association had performed a very useful service in investigating from a new angle some of the problems which tended to retard the development of the oil engine as a prime mover. The paper dealt with three of these problems and finished on a note of expectation that there were many more problems awaiting the attention of research workers.

From a study of Fig. 1 through to Fig. 6, it was obvious that the duration of secondary injection usually increased with increasing speed of the engine and also at greater fuel pump rack settings. The maximum speed referred to in Figs. 1 to 6 was 1,500 r.p.m. It would be very interesting to study needle movement diagrams for the higher-speed type of Diesel engine using similar injection equipment. On first reading the paper, he thought the speeds given in these diagrams were engine speeds. They now seemed to him after hearing the author's presentation to be pump speeds in every case, which corresponded to engine speeds of 3,000 r.p.m. in some instances.

He assumed that as secondary injection resulted in a loss of thermal efficiency, there would also be a corresponding increase in the amount of exhaust smoking, particularly at high engine speeds and power outputs. It would, therefore, be interesting to compare, at constant engine speed, curves of exhaust smoke density measured as per cent smoke or exhaust smoke density against the power output of the engine for the two injection systems. A graph of this nature would enable the reader to assess quickly the advantages to be obtained from using the Bicera delivery valve.

Had any tests been made with fuels of differing viscosities? Presumably variations of fuel viscosity would have some bearing on the dimensions chosen for lengths s and u and the radial clearance c of the delivery valve as shown in Fig. 7.

With regard to the section on the corrosion of nozzles, he would like to suggest that more information be given about the fuel and engine conditions used in the tests designed by the author to promote corrosion similar to that found on the nozzles returned from the field. "Pool gas oil" was an out-of-date term, and some inspection data on the fuel used, such as its sulphur content, would be very useful.

The test using a Class B fuel brought in other factors besides sulphur content of the fuel. If his recollection were correct, the Class B fuel used by the author contained a residual component and, therefore, the carbon-forming tendencies of this fuel were enhanced. The sequel to this investigation would probably have been different if the second fuel, while having a higher sulphur content, had a similar Conradson carbon content. The investigation did give some definite guidance, however, as to how engine manufacturers and operators who were faced with nozzle and possibly liner corrosion might overcome their difficulties.

The section on driving systems for fuel injection pumps dealt with a problem which would come more to the fore as supercharging of oil engines became common practice. He would like to know the reasons for using fuel oil, which contained many undesirable features, as a servo fluid. If it were desirable to use a fuel as the servo fluid, would not a distillate of the gas oil variety be more suitable for this purpose, even though the engine might be burning a residual type of fuel?

MR. W. S. HARVEY said he thought that Dr. Mansfield had made a very important point in his paper when he said that secondary injection often occurred without being recognized. He might have elaborated by saying that a secondary pressure wave, with or without secondary injection, could often occur without being recognized.

The fact that there was a secondary pressure wave could be important. To lift the fuel valve, the secondary pressure wave must, of course, be appreciably greater than the fuel valve opening pressure. If it approaches this pressure, the fuel valve would not lift, but where the fuel valve had been in service for some time, the increase in line pressure might cause fuel to leak across the nozzle valve seat. This leakage would cause carbon formation, and it was one reason for some of the carbon found on fuel valves.

He had intended to make a few comments on nozzle corrosion but Mr. Gamble had already covered the points in a very interesting contribution.

He was not clear as to the precise action of the rubber diaphragm in the servo-operated fuel pump. Was its function to act as a shock absorber? If so, could not some form of spring-loaded piston be used instead? Dr. Mansfield had referred to the arrangement being used on marine engines, but air at 1,000lb. per sq. in. to maintain a pressure on the rubber diaphragm, was not a commodity one came across in a ship.

A point which had not been touched upon was that a number of Diesel-engined ships were now in service with the fuel pumps operated by the gas pressure in the engine cylinder. This was another version of the servo-operated fuel pump. The arrangement was originally applied to blast air engines to convert them to solid injection. It was now used in a modified form in a number of new main engines. The arrangement was described in a paper* read before the Institute in 1953. He believed it had been very successful indeed in practice.

MR. A. F. EVANS (Member) said that the fitting of a dashpot to a Van Amstell valve was a practical way of eliminating an outstanding fault in this element—this fuel-pump rectifier—which was itself a considerable advance when it was introduced.

With regard to nozzle corrosion, would not the employment of a closed circuit, using distilled or treated water maintained at a constant temperature, be the answer to this trouble? This should be independently circulated, preheated for starting, and should have a temperature of perhaps 140 deg. F. on entry, leaving at 170 deg. F. This might eliminate the trouble: it cured many ills.

His first glance at the hydraulic-pneumatic fuel pump gave him an appreciable thrill. He thought that at long last a new fuel pump had arrived. However, it soon became obvious that it was a new way of actuating the old inadequate pump.

The author pointed out some of the disabilities of the usual cam operation and the excessive loads imparted to the camshaft causing, among other things, the distortion of the injection timing. In large engines, this was a problem; and in one large marine two-stroke engine of which he knew, the camshaft for the pumps was eight inches in diameter.

The new hydraulic servo system shown in Figs. 15, 16 and so on would appear to be practical, if somewhat complex in detail, but like the pump itself it relied on hydrostatics. With the pump the hydrostatics could, and were, distorted by sonics. This servo would not suffer in this manner; the rubber diaphragm and compressed air capacity *G* would look after this. Without that item the whole scheme would be out of the question.

The light loading of the timing shaft and the ease of all the adjustments was of great value. The live-line system had some of these characteristics.

When it came to the pump itself, Fig. 21 told a different story. The top line showed the opening of the differential valve of the injector. The injector was not only a nozzle holder; it was a rectifier that had to be used with the pump to make it workable. The needle-lift diagrams in this case were excellent and while the injection pressure recordings were a great improvement on what was usually seen, they were far from correct. For instance, the full load card showed a delay of four degrees in the pressure rise and six in the fall to zero. The author had explained that the fault lay with the pump, the timing of the spill port being out of adjustment.

To get the best out of an engine, one required a high vertical pressure rise and a quick fall to the normal pressure, while to eliminate the pre-generation of smoke there must be an immediate or vertical fall to zero.

The squiggles that terminated each card were, of course, taken care of by the differential injector needle valve. That was what it was for, but they could be taken as evidence against the fuel pump.

This led to another point—the elimination of the fuel delivery pipe. To know exactly how detrimental this was, one required a recording of the actual delivery of oil to the cylinder. This was what the engine wanted to know.

One knew what was happening in the system up to the rectifier, the injector. One was given no information at all as to what happened after this either by the author or by anyone else. Might he ask the author why this was not done? Was it that those concerned were afraid to disclose the true state of affairs?

ING. E. R. GRÖSCHEL said this was indeed a very interesting paper and as it came from such an expert source as Bicera, there was little if anything to question. It would, however, be interesting to know *how* "it was quickly established that the pressure wave causing the second opening of the nozzle valve was produced at the pump end of the injection pipe, following the spilling of the pump and the sudden closing of the delivery valve".

There was another question in his mind; this was in connexion with a new development in fuel injection pumps. He was thinking of a fuel pump plunger being operated by a multi-lobed cam which supplied fuel to a distributing device. It was quite feasible to have a six-lobed cam running at 1,500 r.p.m. (supplying a 3,000 r.p.m. four-stroke engine).

Assuming that the reflected pressure wave maintained its intensity over the speed range and the delivery valve settled down on its seat with a constant velocity over the speed range (because damping conditions of the valve remain unchanged) then the closing period of the valve, expressed in degrees of cam angle, must increase proportional to the speed. In orthodox pumps this might not matter but in the aforementioned distributor pump it might interfere with the cycle. He was, however, a believer in the virtues of the Bicera damped valve and as the proof of the pudding was in the eating he would try it at the next opportunity.

Regarding the ingenious pneumatic hydraulic pump operating mechanism, might he ask what kind of diaphragm was used; was it a laminated one or one of homogencon cross section, e.g. injection pressure moulded? He remembered considerable trouble being caused by laminated moulded diaphragms which were used in a pneumatic hydraulic accumulator; in fairness it must be stated that the pressures were much higher (maximum 4,500lb. per sq. in.).

He remembered a manufacturer of large Diesel engines using those accumulators in a fuel injection system, where they failed after a few hours' running. The pressure there was indeed very high—as far as he could remember in the region of 6,000lb. per sq. in.

Finally, cases were known where such accumulators exploded for unknown reasons; he himself inspected such as accumulator shortly after explosion. He could assure Dr. Mansfield that it was very substantially constructed, the picture left in his mind was as devastating as the result of the explosion. The presence of a comparatively large quantity of oil and high

* Arnold, A. G. 1953. "The Burning of Boiler Oil in Two- and Four-stroke Cycle Diesel Engines and the Development of Fuel Injection Equipment". Trans.I.Mar.E., Vol. 65, p. 57.

compressed air, a breaking diaphragm and perhaps a discharge of static electricity either caused by the disintegration of the diaphragm or other suitable conditions set the thing off; as far as he knew this accumulator was now being charged with nitrogen, thus eliminating this danger entirely. Shipowners, being cautious people, might resent the presence of a number of charged "bombs" in the engine room of their vessel.

MR. W. MCCLIMONT, B.Sc (Member) said that his interest in the problems contained in the paper was mainly with the corrosion of nozzles. Reinforced by the remarks of earlier speakers, he would like to make one or two observations on the effect of sulphur in fuel oil and its influence on corrosion.

Normally less than 5 per cent of the sulphur oxides in fuel appeared as sulphur trioxide (SO_3) in the products of combustion, although this percentage might be higher in a few cases where combustion chamber walls were cooler for a temporary period and the degree of turbulence in the combustion chamber was low. The condition of equilibrium between sulphur dioxide (SO_2) and SO_3 in combustion products was dependent on the temperature of the combustion products; that was to say, less SO_3 could be present in combustion products at high temperature than at lower temperature. However, the concentration of SO_3—which was the dangerous factor—could be increased or decreased by catalytic action after combustion. The most important of these effects in the present context was that carbon had been shown to have a marked effect in reducing the SO_3 content of combustion products, which would appear to be relevant in the experience of the author in what he described as the "curious sequel" to his investigations on cooling nozzles, namely, the relative immunity of the nozzles in the tests with Class B fuel and also on the nozzles of the type shown in Fig. 14. Perhaps the author could say whether the corroded nozzles in Fig. 8 came originally from very clean engines, as this might be a relevant consideration.

Much consideration had been given at different times to the effect of vanadium as a catalyst for the production of SO_3. Maximum conversion of SO_2 to SO_3 by a vanadium catalyst occurred when the combustion products contained about 7 per cent SO_2, which was fifty to one hundred times greater than was found in the combustion process; and though the effect of vanadium as a catalyst should not be precluded, experimental work did not lend much support to its being of practical significance.

The dewpoint temperature of the combustion products would determine the range of temperature over which corrosion would occur, but the severity of the attack would depend on the rate of deposition of acid. The rate of deposition was independent of the water vapour content of the combustion products and reached a peak at about 50 deg. F. below the dewpoint, the magnitude of this peak increasing with increasing dewpoint. This effect arose from consideration of the size of the mist particles diffusing to the metal surface, and it was quite critical. It was not always necessarily an extreme degree of undercooling, therefore, which might cause the most serious effect. The most serious corrosive effect was probably due to the cooling of the surfaces, such as the nozzle or any other surface in the cylinder, to about 50 degrees below the dewpoint of the combustion products.

Finally, with reference particularly to Mr. Calderwood's remarks, although the dewpoint of combustion products generally increased with an increase in the sulphur content of the fuel, it did not do so to the extent that would be expected, since conversion of SO_2 to SO_3 fell off as the sulphur content increased. From the angle of the corrosion outlined by the author, therefore, the prospect of increasing sulphur content of fuels was not so serious as superficial consideration might suggest. In fact, the catalytic action of the increased ash and smoke in lower grade fuels in reducing SO_3 to SO_2 might offset the effect of increased sulphur commonly found in these fuels.

ADMIRAL(E) W. G. COWLAND, C.B.(ret.) (Member) thanked the author for his paper and said he had only one question—an elementary bit of arithmetic. The diaphragm in the drawing looked about three inches in diameter; if so its area was about seven square inches. The author said there was a difference of about 100lb. per sq. in. pressure between the air and the oil. That would be 700lb. difference of load on the two sides of the diaphragm. He wondered how it worked and perhaps the author would tell him.

Correspondence

MR. E. DAVIES (Member) wrote that the author was to be congratulated on having brought to the notice of the members some rather unusual fuel injection problems and the methods by which these were overcome.

As a member of the Research Committee of Bicera he had had the opportunity of following Dr. Mansfield's investigations into these problems and could, therefore, confirm the improved performance which had been effected to many fuel injection systems by the adoption of the Bicera delivery valve.

With regard to nozzle corrosion, this investigation led to quite definite conclusions as to the cause and he had noticed this phenomenon occurring occasionally in large Diesel engine spray valve nozzles. In one case nozzle cooling was abandoned and whilst it cured the corrosion trouble it led to nozzle end failures which were finally only overcome by change of material. This was due to the increased operating temperature of the nozzle by elimination of cooling, bringing the material into a zone of extremely low Izod values and as the valve seat was heavily loaded this led to failure. By changing over to a steel with an acceptable Izod value at the operating temperature, the failure of the nozzle ends was eliminated.

The servo-operated fuel injection system, to meet the injection requirements for highly supercharged engines, was a very neat solution to the problem and, as Dr. Mansfield said, enabled research to be carried out at different fuel injection rates without altering other characteristics.

He had seen and heard the gear in operation and it was most impressive. Undoubtedly it possessed many desirable features for application to high-speed highly supercharged engines but he felt that it would require to be demonstrated that the performance of the gear type pump supplying the servo fluid was capable of maintaining a reliable performance over long periods without mechanical trouble or loss of efficiency, before the gear could be said to be applicable to production engines.

MR. W. A. GREEN, B.Sc., was much interested in the author's remarks on erosion, since he had a similar case to deal with shortly before the war. In his case he found that excessive cooling of the nozzle alone was not sufficient to produce erosion. After running the engine light for long periods with a cooling water outlet at 80 to 90 deg. F. without effect, a nick was formed in the copper joint below the nozzle nut so that blowing took place to such an extent that it was difficult to start the engine. This, however, was ineffective until the clearance between the nozzle and the cylinder head was increased to 0·040 inch on the diameter. Under these conditions erosion was produced similar to that shown by Dr. Mansfield.

From these results and Dr. Mansfield's it seemed likely that erosion could be prevented providing the clearance between the nozzle and cylinder head was kept small enough. There was a certain difficulty in doing so, however, since it was most important that it should be impossible to cant the injector so as to cause the nozzle to bind on the sides of the hole. It was therefore suggested that the right procedure was to give the nozzle holder body the minimum possible clearance in the cylinder head and then to keep the clearance of the nozzle down to the minimum figure which would just prevent binding when the injector was canted to the maximum amount allowed by the clearance.

With regard to the ingenious hydraulic drive for fuel injection pumps, there are two points on which the writer would like to comment. The first was the need for a supply of compressed air at a pressure of about 1,000lb. per sq. in. He realized that the amount was small, but it seemed a retrograde step to have to return to the use of air at such a pressure since one of the main points of the modern Diesel engine was the elimination of blast air by the solid injection system.

The system described by Dr. Mansfield amounted, in effect, to a form of spring injection. It was well known that this could give good results on engines running at a fixed speed, but it was generally unsatisfactory for engines working over a large speed range unless provision was made for varying the injection pressure. If such provision were made automatic, as would be necessary in many cases, it would result in a somewhat complicated system.

Author's Reply

The author wrote in reply that the discussion had proved very gratifying to himself and his colleagues because it had produced a great deal of further valuable information regarding the problems in question, and because the interest shown in these problems greatly encouraged further efforts.

Thanks were due to Mr. Calderwood for explaining that some reservations might be required in replying. Probably as a result of this, contributors to the discussion had made comparatively few demands for further information and the questions raised could be answered readily.

Mr. Calderwood had asked whether dash pot delivery valves had been tested in an engine which was running perfectly without them. A set of the valves had been fitted on one occasion to an engine in which the makers thought secondary injection might be occurring. Subsequent indication of nozzle needle movement showed that no secondary injection was occurring even with the standard valves. No change of performance resulted from changing to the dash pot valves. In two cases, dash pot valves had been fitted in the erroneous belief that they were expected to improve performance even when no secondary injection was originally present. No loss of performance had resulted in these cases. The reason why the valve did not produce a dribbling end of injection in spite of the gentler seating action was that the valve was normally arranged to provide a certain amount of unloading before the dash pot was closed off. Moreover, the dash pot had little effect until the annular escape path had become of considerable length. The result was that ample unloading to produce a sharp needle closure occurred before the valve decelerated near to its seat. No case of a dribbling end of injection had ever been reported with these valves.

The question of nozzle corrosion should be of interest to members of the Institute. Arising from the paper, two cases in large marine engines had been reported verbally, and Mr. E. Davies in a written contribution to the discussion had referred to others. The use of intense nozzle cooling to prevent carbon formation could lead to corrosion, as pointed out by Mr. Lowe.

Regarding the part played by sulphur oxides, the work of BCURA studied in conjunction with that of Shell, left little doubt that sulphur was responsible for the corrosion which occurred on cold surfaces. The Class A fuel used in the Bicera tests contained 0·8 per cent of sulphur which would be quite sufficient to produce the observed effects. The presence of carbon might modify the effect, physically by protecting the surface, as suggested in the paper, or chemically as pointed out by Mr. McClimont. At normal engine temperatures other constituents of the fuel might be of greater importance than sulphur in producing the ill effects experienced with some lower grade fuels and, as Mr. Calderwood had pointed out, more information on this subject was badly needed.

Mr. Gamble's experiences of the use of a waxy fuel containing a considerable amount of grit were of great interest and importance, and his solution of the problem would be difficult to better. There was much to be said for designing fuel pumps and other parts of the engine so that a certain amount of dirt could be accepted and a reasonable engine life was not conditional on the maintenance of fine filtration of air, fuel and lubricant.

Mr. Gamble had asked for a figure for the loss of thermal efficiency due to not using a Bicera delivery valve. There was no loss of efficiency and hence no gain in applying the valve if the injection system in use were free of secondary injection, as was probably the case in the engine referred to. At the other extreme, a case was known in which the development of secondary injection reduced the output of the engine by some 60 per cent, which figure represented, in this case, the loss of efficiency due to not using dash pot valves.

The further information provided by Mr. Gamble on the subject of nozzle corrosion was of special interest as it showed the simple and ingenious method by which the Laboratory finding was applied in the field.

Mr. Lowe had referred to the special importance of secondary pipe line pressure waves when heavier grades of fuel were employed, in that with such fuels the resultant dribbling and secondary injection led to carbon-trumpet formation and nozzle hole blocking. It might be added that nozzle hole blocking increased the amplitude of the secondary pressure waves and it was sometimes difficult to determine whether hole blocking or secondary injection was the first defect to occur. In either case the suppression of the secondary waves would effect an improvement.

Mr. Lowe had stated that the fuel used in the instance where bad nozzle corrosion took place was not a normally recommended Diesel grade. The makers of the engines concerned, however, had stated that most of the affected engines were operating on Class A fuels. Moreover, the Laboratory tests in which heavy corrosion had occurred in a very short time were made with a Class A fuel, and in most of the cases reported by the fuel injection equipment maker, Class A fuel was used.

Mr. Lowe had asked whether the maximum cylinder pressures were increased as the result of the higher rates of injection of which the servo-operated fuel injection system was capable. In the experimental engine to which the system was applied there was no increase, partly because the optimum injection rate was not much higher than the highest obtainable with difficulty with the mechanically operated pumps, and partly because special means were employed in this engine to limit the maximum pressure. It was true that increase of injection rate was normally accompanied by increase of maximum cylinder pressure. The problem of obtaining the best combustion conditions with a limited maximum cylinder pressure was of great importance and was being studied by Bicera.

It appeared from Mr. Green's contribution that the statement that secondary injection could be removed by reducing the pump discharge rate or by increasing the nozzle hole area had been misunderstood. It was not suggested that this was the right way to deal with secondary injection. It was only satisfactory when the high rate or small nozzle hole area had been used without justification. As pointed out in the paper, with many combustion chambers the best performance was obtained with comparatively small nozzle holes and high rates of injection. It was in this type of engine that secondary injection was therefore naturally encountered and to stop it by using larger holes or lower injection rates was to accept a poorer performance than the engine could give. This had undoubtedly been the normal procedure in the past, in the absence of any real solution of the problem.

Bicera had not carried out any work on constant pressure unloading valves. The dynamic behaviour of such valves appeared to be rather unpredictable and as far as was known there had been no reports of the successful use of constant pressure unloading valves under the violent conditions tending to produce secondary injection.

Mr. Green, who had much experience of the manufacture of fuel injection equipment, thought there might be special difficulties in matching Bicera valves in large numbers. This question had recently been thoroughly examined and it had been found that a six-element pump fitted with Bicera valves could be balanced as readily as the same pump with normal valves, even when there were considerable variations in the dash pot clearances. The fit of the unloading collar was important but it would require not only wear but considerable differences in the wear rates of the several valves to upset the balance seriously.

As pointed out by Mr. Royle, the captions of Figs. 1 to 6 in the advance copy of the paper left some doubt regarding the meaning of the figures quoted for speeds. The captions had now been amended in this respect. The highest pump speed tested was 1,500 r.p.m. which was used in one rig test (Fig. 2) and a two-stroke cycle engine test (Fig. 5).

In these tests no smoke-meter readings were taken. They would rarely be necessary in order to assess the desirability of suppressing secondary injection when present, since the fuel consumption was affected and nozzle troubles were likely to develop even in the mildest cases.

The Bicera valve had been used so far only with fuels of low viscosity. A larger dash pot clearance would be used with high-viscosity fuels. A given valve would operate satisfactorily with a reasonable range of viscosities, since with a given fuel the dash pot clearance could be varied considerably without spoiling the performance of the valve.

The additional data requested by Mr. Royle in connexion with the test designed to promote corrosion of nozzles were:—

Engine running condition

Speed	1,200 r.p.m.
Load	52·0lb. per sq in. b.m.e.p.

Fuel

Supplier's designation ...	Pool gas oil
Specific gravity	0·85
Viscosity, Redwood No. 1, 100 deg. F., seconds...	34
Sulphur, per cent... ...	0·7
Carbon residue (Conradson)	0·05

In giving this information it had to be emphasized that the data for this particular fuel were not considered to be of any special significance in connexion with nozzle corrosion since the effect was known to have occurred with a variety of Class A fuels.

The expression "fuel oil" used in the paper to describe the fluid used in the servo-system was intended to mean the oil used as fuel, as distinct from the "lubricating oil" which is the oil used as lubricant, the latter having also been considered for the purpose. The particular fuel used was to the Class A specification. The Glossary of Petroleum Terms issued by the Institute of Petroleum gave as a first definition of fuel oil "A general term applied to an oil used for the production of power or heat". It seemed desirable to use a term such as "burner oil" or "boiler oil" when a restricted meaning was intended.

Mr. Harvey had made a most useful contribution by pointing out that with a fuel valve which had been in service for some time, a secondary wave too small to lift the valve could produce a harmful effect, namely carbon formation. Another reason for suppressing secondary pressure waves which did not cause a re-opening of the valve was that they added considerably to the noise produced by the fuel injection system.

It was apparent from the questions put by Mr. Harvey and a later question by Admiral Cowland that the paper had not made clear the action of the diaphragm. In the particular example of the system described, the air vessel *G* (Fig. 16) was charged to 850lb. per sq. in. During this process the diaphragm *F* lay against the surface of the servo-fluid chamber *E* and against the head of the closed valve (*2*). When the engine started and the servo-fluid pressure built up to its working value, 1,000lb. per sq. in. in this case, the air was thereby further compressed to 1,000lb. per sq. in. The initial air charging pressure 850lb. per sq. in. was calculated so that the further compression to 1,000lb. per sq. in. brought the diaphragm to its mean working position shown in Fig. 16. During operation the diaphragm moved a distance of approximately 1/16th inch only, on both sides of this position, the pressure on the two sides of the diaphragm remaining equal.

The use of air at pressures of the order of 1,000lb. per sq. in. presented no supply problem since the leakage occurring in six months' use had been found barely measurable, and if necessary the whole charging operation could be performed in a few minutes by a small hand-operated lever-type air pump.

Mr. Harvey had referred to the use of injection pumps operated by cylinder gases. Because of the inherent difficulties in this system many years of development work had been devoted to it, and even some of the latest designs gave trouble. In contrast, the first prototype pump of the type described in the paper performed well on its first test and only minor modifications, chiefly to make a further reduction of noise, were made. This comparison reflected the relative merits of the media chosen as servo-fluid in the two cases, namely high-temperature gases contaminated by combustion products on the one hand and cool liquid on the other. The maintenance requirements of the two types of system could be expected to show corresponding differences.

The closed circuit cooling system described by Mr. Evans would undoubtedly ensure freedom from nozzle corrosion but, in the case discussed, the engine makers had to employ a method of raising the nozzle temperature which did not involve alterations to the existing simple cooling systems.

The injection characteristic advocated by Mr. Evans might well be very good for certain combustion systems, but since there was not a great deal of information available regarding the performance of various combustion systems when various injection characteristics were employed in each, it was perhaps too early to draw general conclusions. Mr. Evans asked why no recording of the actual delivery of oil from the injector was taken, and he appeared to suggest that such a record would reveal an unsatisfactory state of affairs. It was difficult to see why this was suspected. In the past, good correlation had been found at the Laboratory between pressure diagrams of the type presented, and the discharge from the nozzle as determined both by an injection rate analyser (which measured the quantity discharged in each 0·83 degrees of rotation of the pump-shaft) and by recording the varying force exerted by the spray upon the diaphragm of a pick-up. In the present case the needle movement diagrams, which Mr. Evans agreed were excellent, showed that the needle was rapidly forced against its stop at the commencement of injection and remained there till it closed very rapidly at the end of injection. Thus, for practically the whole of the injection period the passage past the valve seat was of fixed dimensions and, therefore, the nozzle hole velocity would be roughly proportional to the square root of the pressures shown by the pressure diagrams up to the point of valve closure. Thus, the discharge could hardly show any major additional features.

The answers to Mr. Gröschel's questions were as follows:—

The origin of the secondary pressure wave causing secondary injection was established by studying delivery valve movement diagrams and pipe pressure diagrams taken at both ends of the pipe. These showed a rapid rise of pressure at the pump end of the pipe immediately after the normal delivery valve struck its seat, and a rise of pressure at the nozzle end of the pipe several degrees of pumpshaft rotation later, which re-opened the nozzle needle.

The delivery valve movement diagrams also showed that the dash pot valve took only a few degrees of pumpshaft rotation at 1,500 r.p.m. to reach its seat so that it could easily operate with a six-lobe cam.

The diaphragm used in the servo-system was a simple disc cut from a sheet of Neoprene, and as stated earlier had given no trouble.

The suggestion that the accumulators used in the servo-system might explode did not accord with general experience of the behaviour of air in contact with fuel when the air was at a temperature in the region of 60 deg. C. only and at a pressure less than 1,500lb. per sq. in. Special effects could occur at the much higher pressures, 6,000lb. per sq. in. or more used in the case mentioned by Mr. Gröschel. However, in view of the importance of this question it had been decided to put the matter to the test.

Attempts had accordingly been made to rupture the diaphragm by arranging a knife-edge in the air vessel to cut the diaphragm when the oil pressure was built up by a hand-operated pump after charging the vessel with air. This proved much more difficult than expected but was eventually achieved by employing a piece of razor blade as the knife edge. Twelve tests were made with the accumulator immersed in water at 95 deg. C. in a vessel at the bottom of a pit, a new diaphragm being fitted for each test. The air vessel was charged to give various pressures at rupture ranging between 1,200lb. per sq. in. and 1,500lb. per sq. in., the latter being the highest pressure contemplated for use in the system. In every test the oil pressure was repeatedly raised and lowered until the diaphragm ruptured but in no case was there any explosion. When it was further considered that the chances of the tough lightly-loaded diaphragm breaking in service were very small, it must be concluded that the chance of an explosion was negligible. If the slightest anxiety persisted in the mind of the user it could, of course, be allayed by using nitrogen.

Mr. McClimont had given some interesting information on the factors affecting the concentration of sulphur tri-oxide. The reduction of the sulphur tri-oxide content by carbon might be of considerable importance in connexion with the low temperature corrosion produced by different fuels. In the experiments described in the paper, however, the particular Class B fuel used formed carbonaceous deposits so rapidly that the annular space round the nozzle was quickly filled completely with very hard material which must have prevented access of the combustion gases to the cooler surfaces of the nozzle. Thus, while on the one hand the influence of the carbon on the behaviour of the sulphur was important, the influence of the sulphur on the nature of the carbonaceous deposits formed was also of importance in this connexion.

Mr. W. A. Green's account of his experience of nozzle corrosion was very interesting. It might well be that the use of a very small clearance made the cooler surfaces of the nozzle less accessible to the combustion gases and also facilitated the filling of the annular clearance space with carbon. Since it had now been shown that an increase in nozzle temperature was all that was required to prevent corrosion, this method appeared preferable to the use of very small clearances which, apart from the difficulties mentioned by Mr. Green, might not be effective with fuels which form the least carbon. The best way of raising the temperature was to maintain the water temperature at a reasonable level, since the use of cold water could also produce rapid cylinder bore wear and other troubles. If the use of cold water was unavoidable, the nozzle temperature should be raised by some simple design change such as that described by Mr. Gamble, which was found completely successful.

The question of charging the air chambers of the accumulators had been dealt with earlier in the author's reply.

With regard to the behaviour of the servo-operated fuel injection system over a large speed range, the results on the experimental engine had been very satisfactory. Without any adjustment of the pressure regulator, the injection conditions suited the engine at all speeds up to the maximum engine speed of 750 r.p.m. There was a noticeable improvement in the idling, which was quieter and more regular. This was attributed to better atomization and more regular nozzle movement resulting from the higher pressure.

The account given by Mr. Davies of nozzle corrosion in a large engine would be of special interest to the Institute and revealed yet another aspect of the question.

With regard to the reliability of the gear-type pump supplying the servo-fluid, it should be explained that the type of pump used had been employed successfully for many years in a wide range of applications, and had been generally adopted for the hydraulic operation of agricultural tractor equipment. Experience at the Laboratory using Diesel fuel in these pumps had indicated the importance of filtration but the pumps used throughout the rig and engine work were still performing well.