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No. 352

# EFFECT OF ORIFICE LENGTH-DIAMETER RATIO ON SPRAY CHARACTERISTICS

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# EFFECT OF ORIFICE LENGTH-DIAMETER RATIO ON SPRAY CHARACTERISTICS.

By A. G. Gellales.

## Summary

The effect of variations of orifice length to diameter ratio on spray characteristics was determined for a 0.014-inch and a 0.040-inch orifice for ratios of 0.5 to 4.0. The nozzles containing the orifices were mounted in an injection valve and tested with a plain stem and with a helically grooved stem. The injection pressure was varied from 4000 to 8000 pounds per square inch. The air density into which the fuel was sprayed was varied from the density obtained with a pressure of 60 pounds per square inch to the density obtained with a pressure of 250 pounds per square inch at room temperature. The tests showed that increasing the orifice length to diameter ratio with a plain stem in the injection valve causes the spray tip penetration first to decrease, reaching a minimum between a ratio of 1.5 and 2.5, and then to increase, reaching a maximum at a ratio greater than 3.5. The spray cone-angle showed little change with variation of the ratio. With a helically grooved stem and a small ratio of orifice area to groove area, the penetration at first shows little tendency towards a minimum; but,

as the time of injection is increased to 0.004 second, the penetration becomes a minimum at a ratio between 0.5 and 2.0. As the ratio of orifice to groove area is increased, there is less tendency for a minimum penetration to occur between the ratios of orifice length to diameter of 0.5 and 4.0 up to 0.004 second after the start of injection.

## Introduction

One of the important factors influencing the penetration and the distribution of the fuel spray in the combustion chamber of a fuel-injection engine is the ratio of the length to the diameter of the discharge orifice. The results published on researches to determine the effect of the orifice length-diameter ratio on the fuel spray are meager. Joachim and Beardsley (Reference 1) found that, with an injection valve employing a helically grooved stem, a ratio of 1.5 gave the greatest spray tip penetration during the time available for injection in compression-ignition engines. They also found that the spray cone-angle increased slightly with an increase in the ratio. McKechnie, as quoted by Buchner (Reference 2), concluded that to obtain the greatest ultimate penetration, the length of the orifice should be made as long as possible, and to obtain the greatest fineness of atomization the length should be made as short as possible. The length of the orifice cannot be increased indefinitely, however, without reaching a length beyond which the

penetration begins to decrease because of friction losses in the orifice throat.

The tests reported herein represent a part of an investigation being conducted at the Langley Memorial Aeronautical Laboratory at Langley Field, Virginia, to determine the effect of the orifice length-diamater ratio on fuel spray characteristics for a series of orifices covering sizes suitable for aircraft compression-ignition engines.

## Methods and Apparatus

High-speed motion pictures were taken, by means of the N.A.C.A. spray photography equipment, of individual fuel sprays discharged from the orifices into air at various densities and at room temperature. The apparatus, which is capable of taking photographs at the rate of 4000 per second, has been described in detail in Reference 3.

The injection nozzles containing the discharge orifices were the same as employed by the author in the investigation on coefficients of discharge of orifices (Reference 4). The results of these tests showed that orifices geometrically similar to that shown in Figure 1 had a discharge coefficient of 0.94, and that the coefficient was not affected by the back pressure into which the discharge took place.

A nozzle with a single 0.014-inch diameter orifice and one with a 0.040-inch diameter orifice were used in the tests re-

ported herein. The orifice length to diameter ratio was varied from 0.5 to 4.0. The nozzles were assembled in an automatic injection valve shown in Figure 1. A plain injection valve stem and one with four grooves, having a helix angle of 30 degrees were tested in conjunction with the nozzles. The combined area of the grooves was equivalent to a 0.022-inch diameter orifice, making the ratio of orifice area to groove area 0.4 and 3.3 for the 0.014- and 0.040-inch orifices, respectively.

The injection pressures were varied from 4000 to 8000 pounds per square inch, and the chamber air densities were varied from the density obtained with pressures of 60 pounds per square inch to the density obtained with pressures of 250 pounds per square inch at room temperature. The fuel was a high-grade Diesel oil with a specific gravity of 0.86 and a viscosity of 0.048 poises at 80 degrees Fahrenheit.

A record of the development of a single fuel spray is shown in Figure 2. The spray penetration in a given time after the start of injection is taken as the distance the spray tip has penetrated. The lines drawn on the photograph show how the spray penetration and spray cone-angle were measured. The maximum penetration which the apparatus could record was 5 inches. Where greater penetrations are shown they were obtained by extrapolating the curve beyond this point. Under these conditions the spray penetration curve up to 5 inches was so nearly a straight line that the extrapolation was permissible without in-

troducing an appreciable error.

## Results and Discussion

Noncentrifugal Fuel Sprays.- Figure 3 shows the spray penetration with the 0.014-inch diameter orifice 0.001 second after the start of injection with the plain stem in the injection valve. The curves show little variation in the penetration for orifice length to diameter ratios from 0.5 to 1.0. However, as the ratio was increased the penetration decreased, reaching a minimum at a ratio between 2.0 and 2.5. The penetration then increased, and the curves show a decided rate of increase at the ratio of 4.0, the largest tested. The rate of change of the penetration with orifice length to diameter ratio decreased as the chamber density into which the fuel was sprayed was increased.

Figure 4 shows the penetration after 0.001 second with the 0.040-inch diameter orifice. A comparison of this set of curves with those shown in Figure 3 shows that the curves for the larger orifice are similar to those for the smaller orifice, but have been shifted toward the origin. The penetration shows a decrease as the orifice length to diameter ratio is increased from 0.5 to 1.0. The minimum occurs between the ratios of 1.0 and 1.5. As the ratio is further increased, the penetration increases. After the ratio of 3.0 has been reached, however, the rate of increase of penetration starts to decrease; so that, for the high injection pressure and low chamber densities, a maximum pene-

tration is reached between the ratio of 3.0 and 4.0. The curves which do not show a maximum indicate that a maximum would have been reached had the orifice length to diameter ratio been extended to values greater than 4.0.

The explanation of the shape of the curves is found in an analysis of the flow through the injection nozzle. The jet contracts as it enters the throat of the orifice from the upstream side of the nozzle. The amount of contraction depends on the pressure head, the viscosity and density of the fuel, and the entering edges of the nozzle. Following the contraction, the jet re-expands and tends to fill the orifice throat. If the length of the throat is sufficient, the expanded jet is redirected along the axis of the orifice, increasing the velocity component of the fuel in this direction. The result is to increase the initial velocity of the spray, parallel to the axis of the throat. When the orifice length is not sufficient to permit complete re-expansion within the orifice throat, the flow conditions cannot be completely determined. The results show that the spray penetration decreased reaching a minimum at an orifice length to diameter ratio varying from 1.0 to 2.5, depending on the conditions. After the minimum was reached the spray penetration again increased. However, due to skin friction and internal friction, the energy losses within an orifice throat also increase as the orifice length is increased. Hence, a ratio is

reached where the penetration reaches a maximum, and any further increase in the orifice length results in decreasing the penetration. This condition is observed in Figure 4. The coefficients of discharge for the orifices (Figure 5) show that the coefficient is the same for the 0.014-inch orifice for length to diameter ratios from 1.0 to 3.0 and for injection pressures from 1000 to 4000 pounds per square inch; but that for a ratio of 0.5 the coefficient decreased as the pressure was increased. It can be concluded from Figures 3 and 5 that, with the 0.014-inch orifice, the initial axial velocity of the fuel spray varied considerably. It can also be concluded that, although with a ratio of 0.5 the rate of fuel discharge was less than with a ratio of 1.0, the axial velocity of the jet was sufficient to cause the jet to penetrate as far as for the ratio of 1.0.

Centrifugal Fuel Sprays.- Figures 6 and 7 show the spray tip penetration using the 0.014-inch diameter orifice at 0.002 and 0.004 second after the start of injection, with the helically grooved stem in the injection valve. At 0.002 second minima or maxima occurred in some cases with 8000 pounds per square inch injection pressure. With 4000 and 6000 pounds per square inch injection pressure the rate of change of penetration varied with the orifice length to diameter ratio, but not sufficiently to cause either a minimum or a maximum. In all the curves the penetration is increasing at the ratio 4.0. At 0.004 second minimum

penetration occurred in every case between the ratios of 1.0 and 2.0. As was the case with the plain stem, the rate of increase of penetration decreased as the chamber density into which the fuel was sprayed was increased.

The spray penetration at 0.002 and 0.004 second with the 0.040-inch orifice (Figure 8) shows much the same shape of curves as are shown in Figure 7. While minima did not occur in every case, there was a tendency for them to occur between the orifice length to diameter ratios of 1.0 and 2.0 in the case of the 4000 pounds per square inch injection pressure at 0.002 second.

A comparison of Figures 6, 7, and 8 with Figures 3 and 4, shows that the penetration with the centrifugal sprays was considerably less than with the plain sprays. This is due both to the velocity components of the spray, which are not parallel to the axis of the spray, and to the loss in energy caused by the fuel passing through the helical grooves. In passing through the grooves the fuel was given a velocity component tangential, as well as axial, to the cross section of the injection valve stem. Following this, the fuel was forced to converge and pass through the orifice, where the axial component was increased and the tangential component was partially damped out. The amount of this damping depended on the orifice length to diameter ratio and on the orifice area to groove area ratio. As the orifice length was increased, the tangential velocity components were decreased and the axial components increased, resulting in an in-

crease in the penetration, although there was some interference to the re-expansion of the jet in the orifice throat, as is shown in Figure 7. As the ratio of orifice area to groove area was increased, the tangential velocity components were increased, because the velocity through the helical grooves was increased, making the spray from the 0.040-inch orifice have less penetration than the spray from the 0.014-inch orifice.

In Figure 5 the extent of the energy loss with the helically grooved stem is indicated by the coefficients of discharge. It is seen that with the 0.040-inch orifice, in which the tangential velocity components were high, the coefficient of discharge was extremely low. While there was considerable energy loss with the 0.014-inch orifice and the centrifugal stem (compare curves (b) and (c)), the coefficient of discharge was approximately 2.8 times as great as with the 0.040-inch orifice.

Joachim and Beardsley concluded from their experiments that, for a helix angle of 40 degrees, the greatest penetration at 0.003 second was obtained with an orifice length to diameter ratio of 1.5. They used an 0.022-inch orifice and a stem with six helical grooves, giving a ratio of orifice area to groove area of 0.63. The injection pressure was 8000 pounds per square inch and the chamber density corresponded to a pressure of 200 pounds per square inch. In Figure 6 of this report it is seen that a maximum penetration occurred at 0.002 second, with 8000 pounds per square inch injection pressure and 250 pounds per

square inch chamber pressure at an orifice length to diameter ratio of 2.3. However, at 0.004 second (Figure 7), no maximum occurred between ratios of 0.5 and 4.0. The present work shows that, while a maximum penetration may occur at a low orifice length to diameter ratio, the penetration decreases after this maximum, and then increases again, so that a second maximum is reached which is greater than the first.

Spray Cone-Angle.- In Figure 9 are given the spray cone-angles of the sprays at 0.003 second after the start of injection, when the spray was fully developed. With the 0.014-inch orifice the spray cone-angle was independent of chamber pressure. With the helically grooved stem in the injection valve, there was a slight decrease in the angle as the orifice length to diameter ratio was increased. With the plain stem, a maximum angle occurred at a ratio of 2.6. With the 0.040-inch orifice and the helically grooved stem, the spray angle was considerably greater than with the 0.014-inch orifice, because of the larger tangential velocity components of the spray. The higher chamber densities decreased the spray cone-angle. With the plain stem and the 0.040-inch orifice, the angle was nearly the same as with the 0.014-inch orifice; but no maximum occurred. Joachim and Beardsley (Reference 1) also showed the spray angle to decrease with an increase in the orifice length to diameter ratio.

## Conclusions

The conclusions drawn from the experimental data are as follows.

1. With a plain stem in the injection valve -

   a) Increasing the orifice length to diameter ratio causes: first, a decrease in the spray tip penetration, so that a minimum penetration is reached at a ratio between 1.0 and 2.5; and, second, an increase in penetration, so that a maximum is reached at a ratio of 3.5 or greater.

   b) As the air density into which the fuel is sprayed is increased, the rate of change of penetration with orifice length to diameter ratio is decreased.

   c) The spray cone-angle is little affected by the orifice length to diameter ratio.

2. With a helically grooved stem in the injection valve -

   a) Increasing the orifice length to diameter ratio causes at first an increase in the penetration. However, as the time is increased, a minimum penetration occurs at a ratio between 0.5 and 2.0 with a .014-inch orifice.

b) As the ratio of orifice area to groove area is increased by enlarging the orifice diameter, the tendency for a minimum penetration to occur is lessened.

c) As the air density into which the fuel is sprayed is increased, the rate of change in penetration decreases.

d) The spray cone-angle is decreased as the orifice length to diameter ratio is increased.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., October 1, 1930.

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| | | | |
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| Reference 2. | Buchner, Dr. | : | The Fundamental Principles of High-Speed Semi-Diesel Engines. Part I: A General Discussion of the Subject of Fuel Injection in Diesel Engines and Detailed Descriptions of Many Types of Injection Nozzles. (Translation from Jahrbuch der Brennkrafttechnischen Gesellschaft, Vol. V, 1924.) N.A.C.A. Technical Memorandum No. 356, 1926. |
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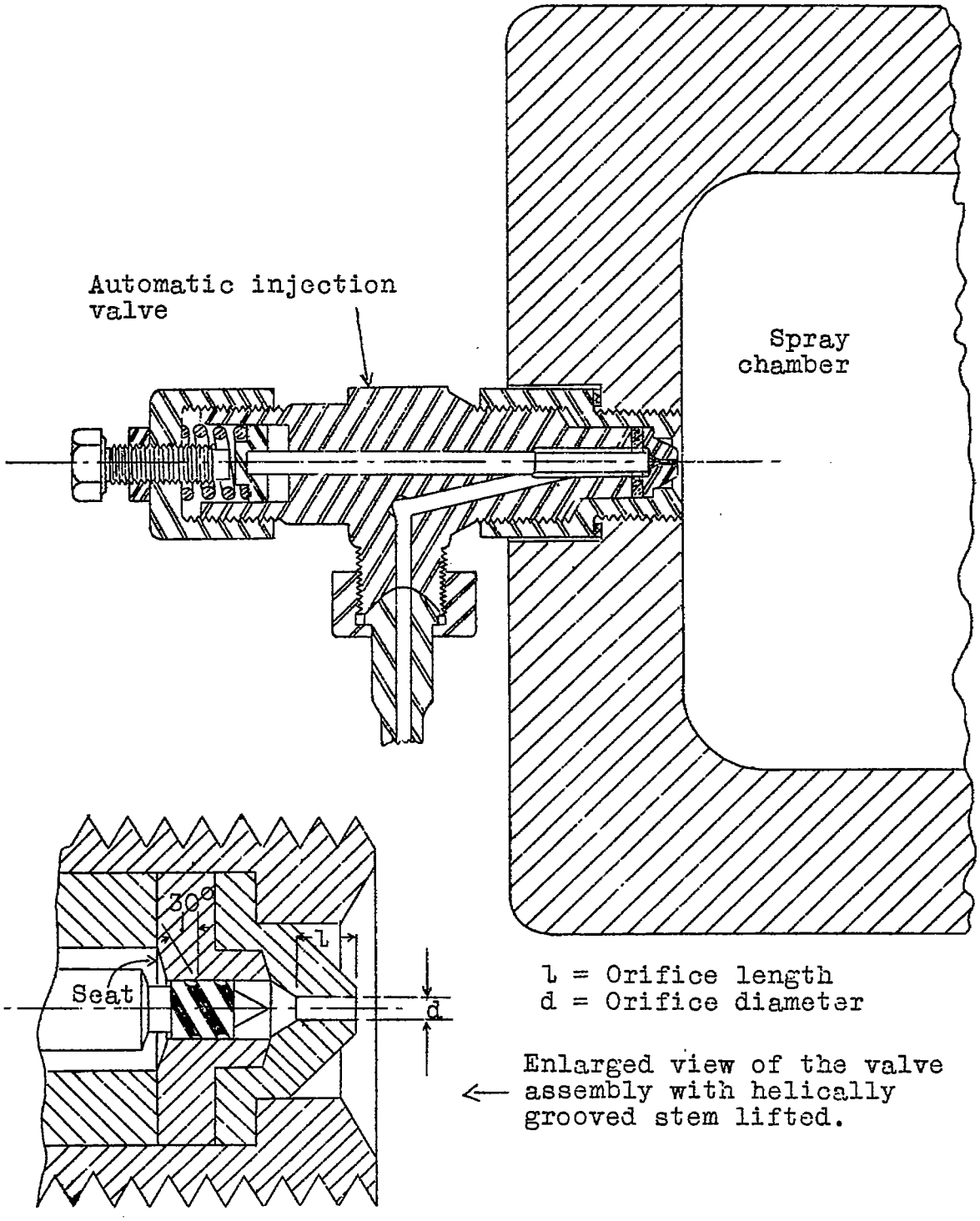



Fig.1 Injection valve assemblies and spray chamber.

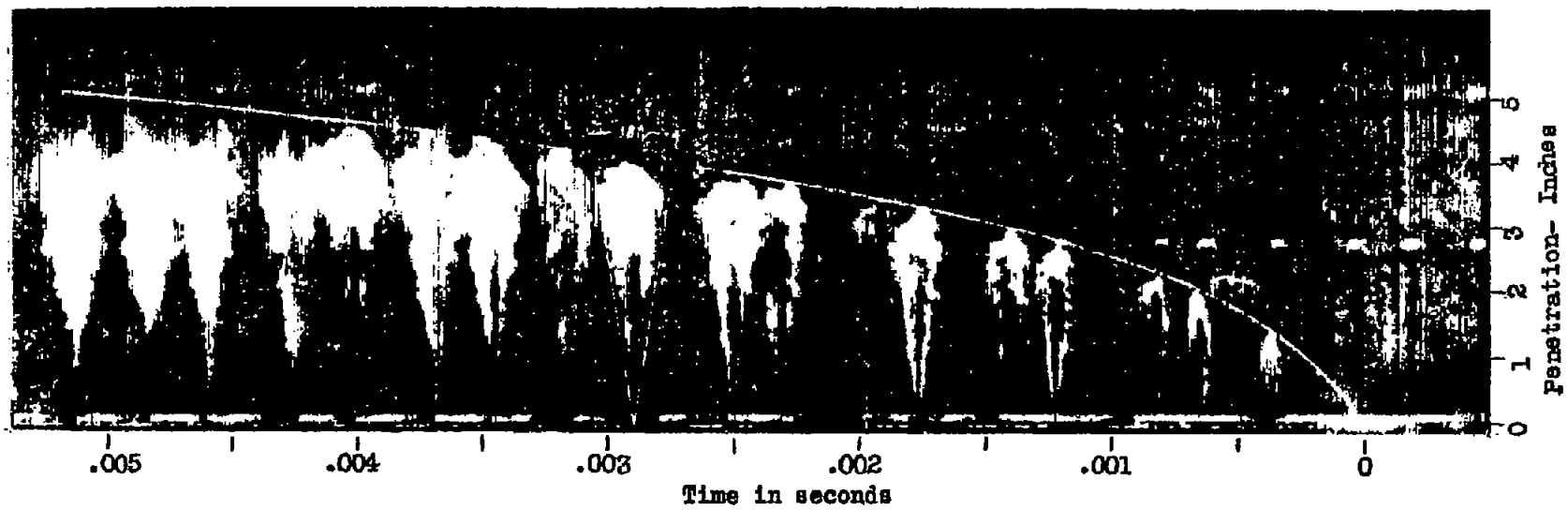
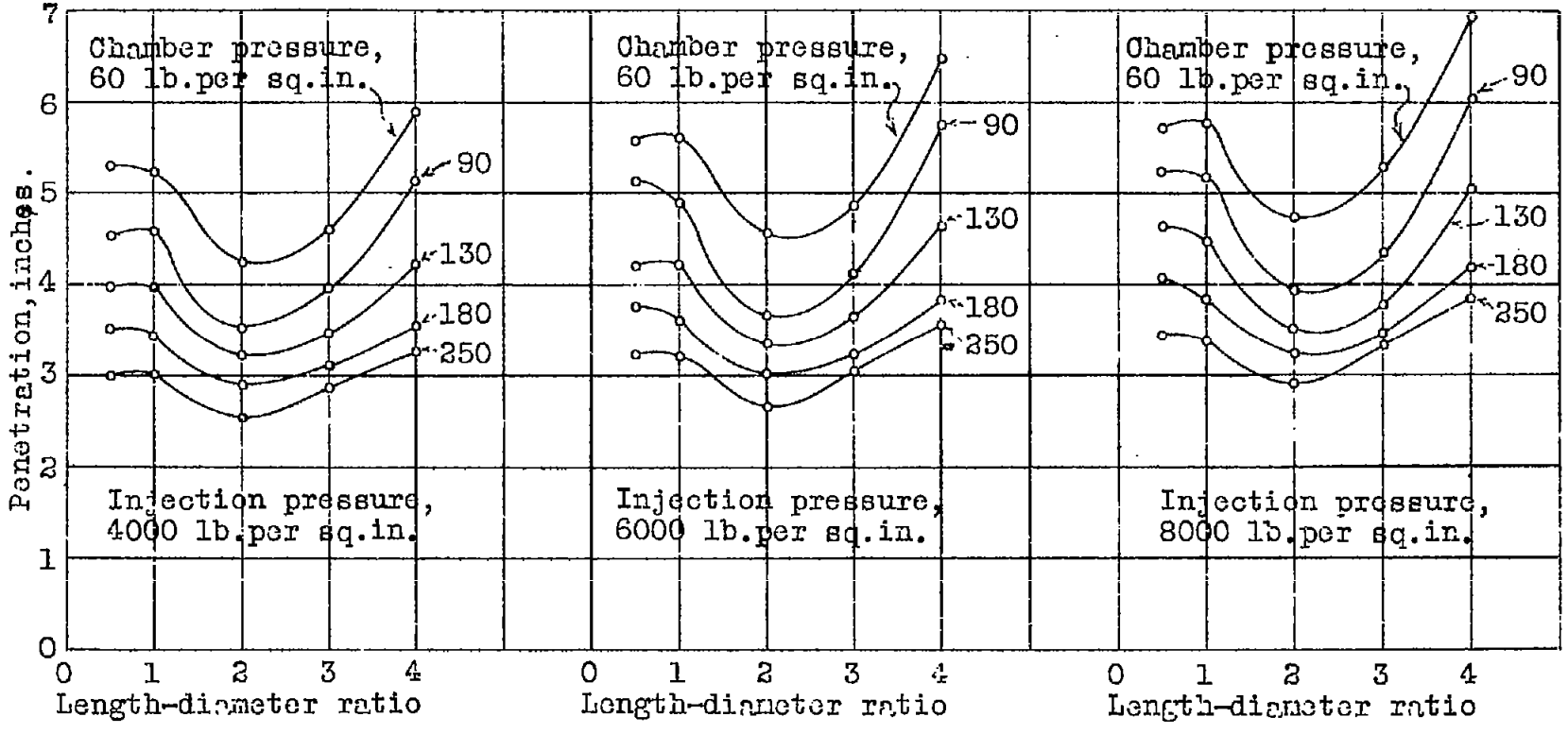


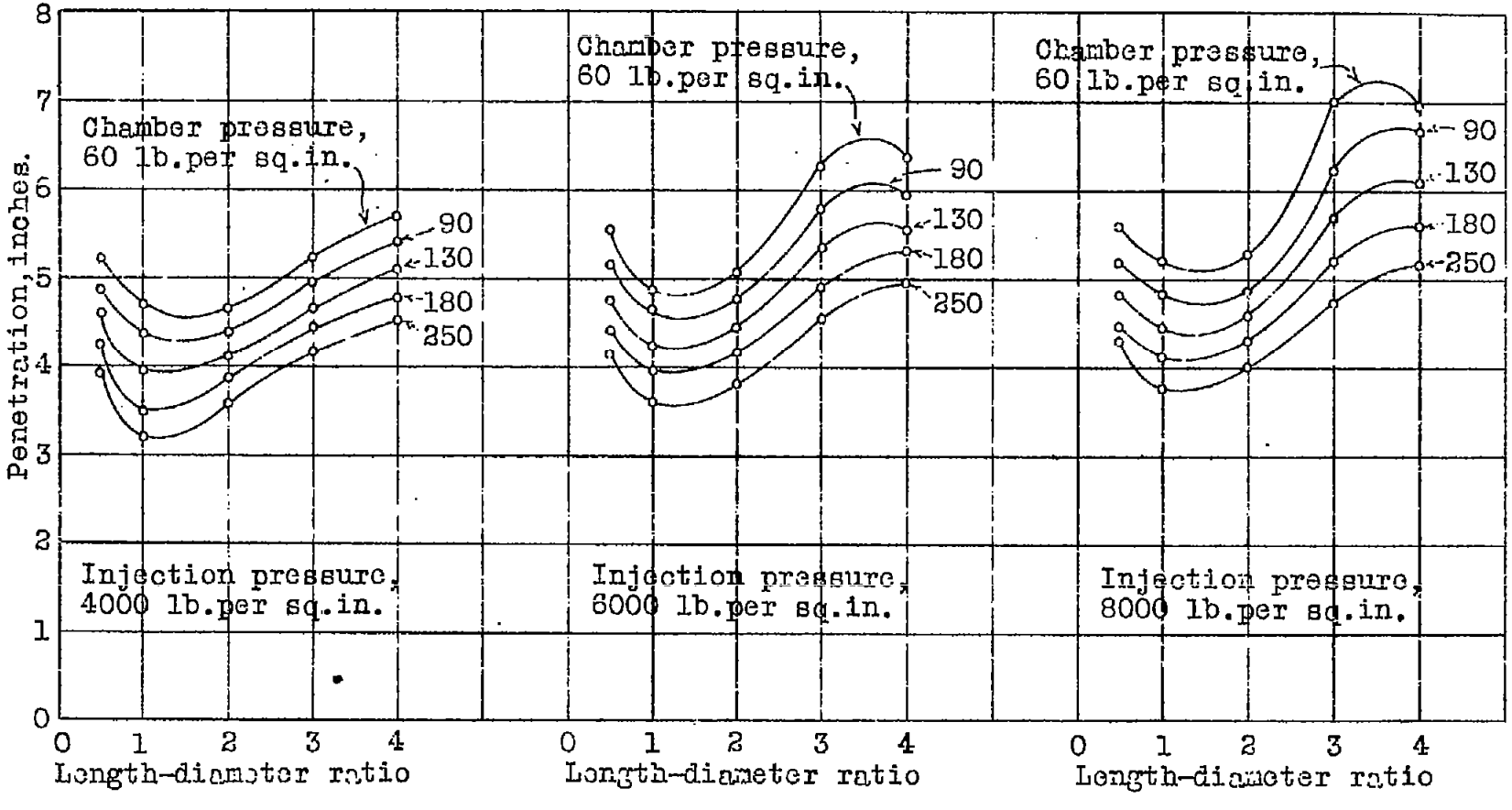

Fig.2 Spray photography with lines drawn to show spray-tip penetration and spray cone angle. Orifice diameter 0.014 inch, orifice length 0.056 inch, injection pressure 2000 lb. per sq. in. plain stem. Chamber pressure 250 lb.per sq.in.




Penetration 0.001 second after the start of injection.
Orifice diameter 0.014 inch.

Spray tip penetration of plain stem at varying orifice length-diameter ratio.

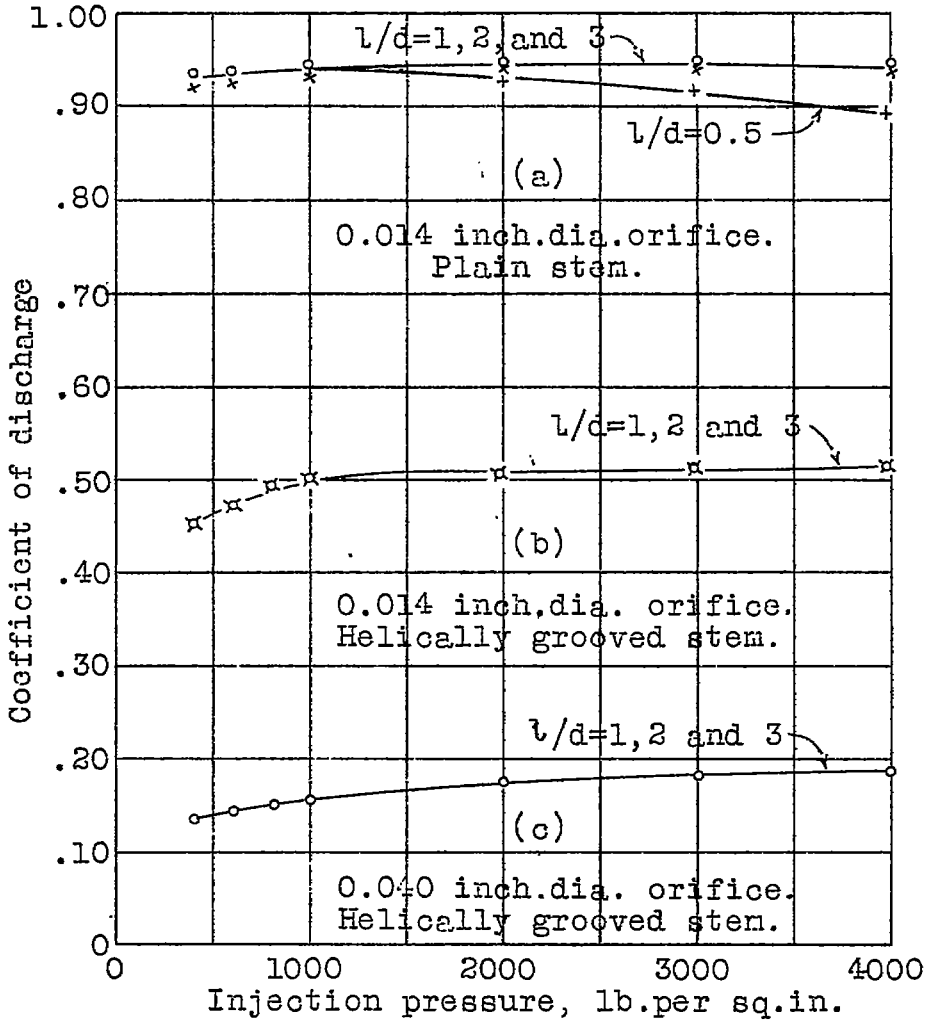
Fig. 3




Penetration 0.001 second after start of injection.
Orifice diameter 0.040 inch.

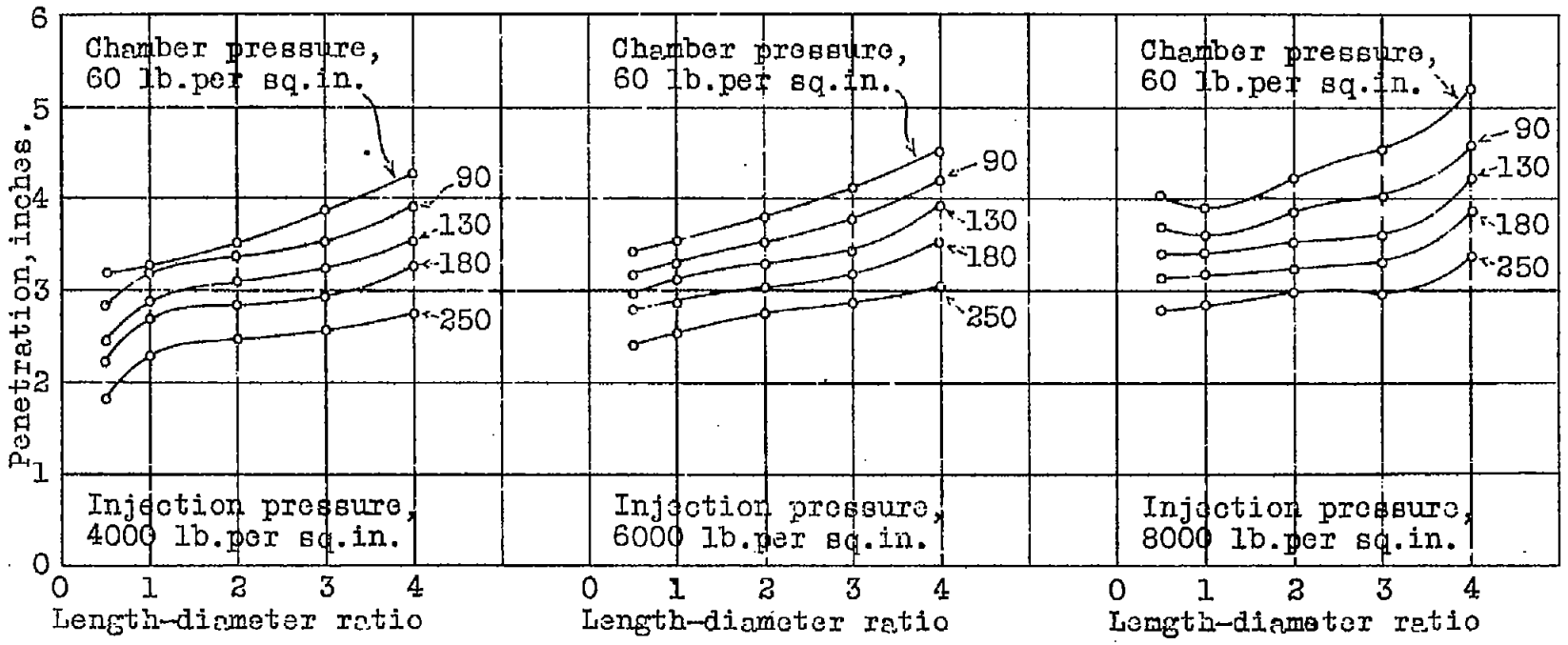
Spray tip penetration of plain stem at varying orifice length-diameter ratio

Fig. 4




Discharge into atmospheric back pressure.
l, orifice length. d, orifice diameter.

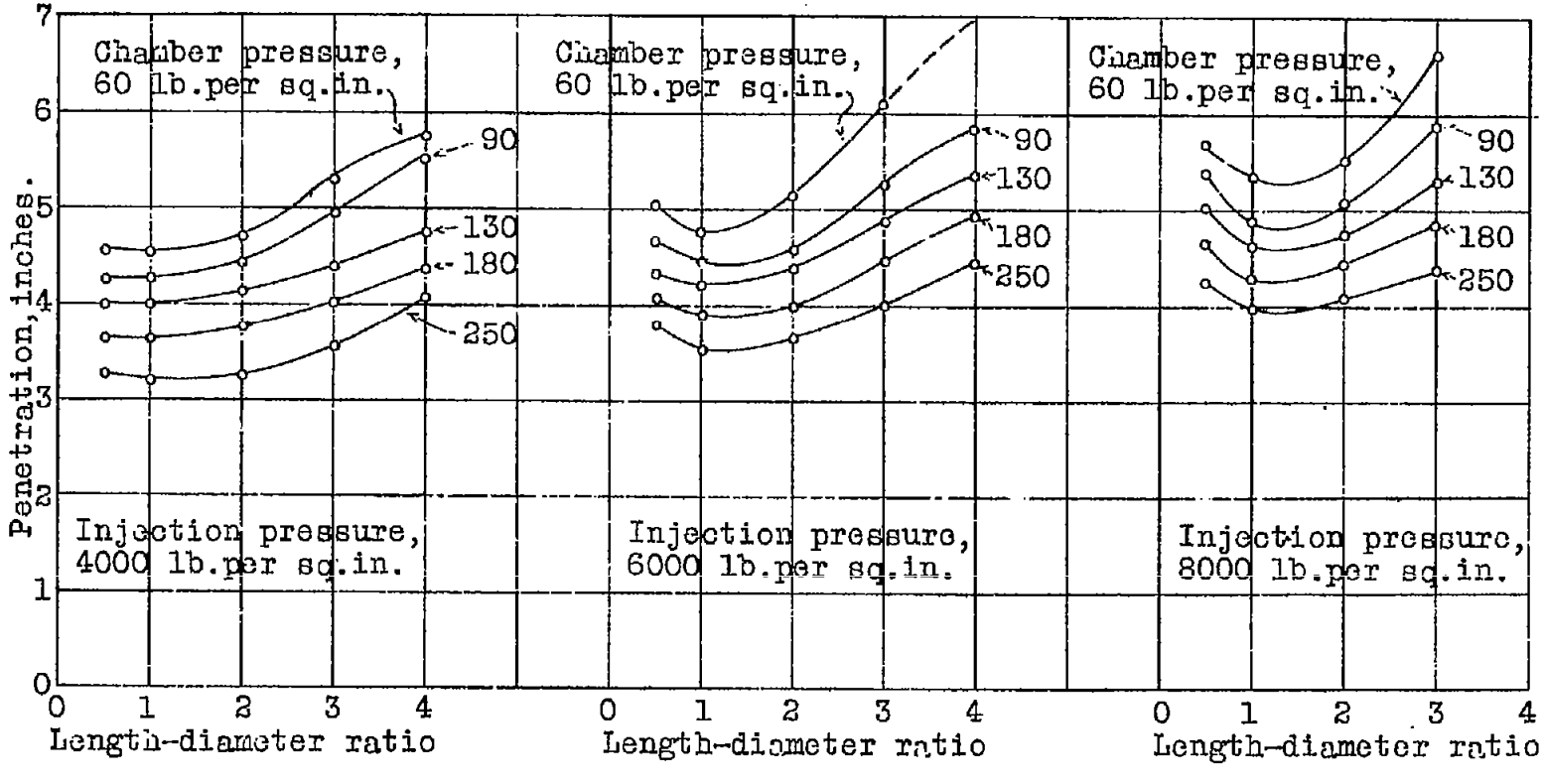
Fig.5 Coefficient of discharge at varying injection pressures and different length-diameter ratios of orifice and types of stem used.




Penetration at 0.002 second after the start of injection.
Orifice diameter 0.014 inch.

Spray tip penetration of helically grooved stem at varying orifice length-diameter ratios

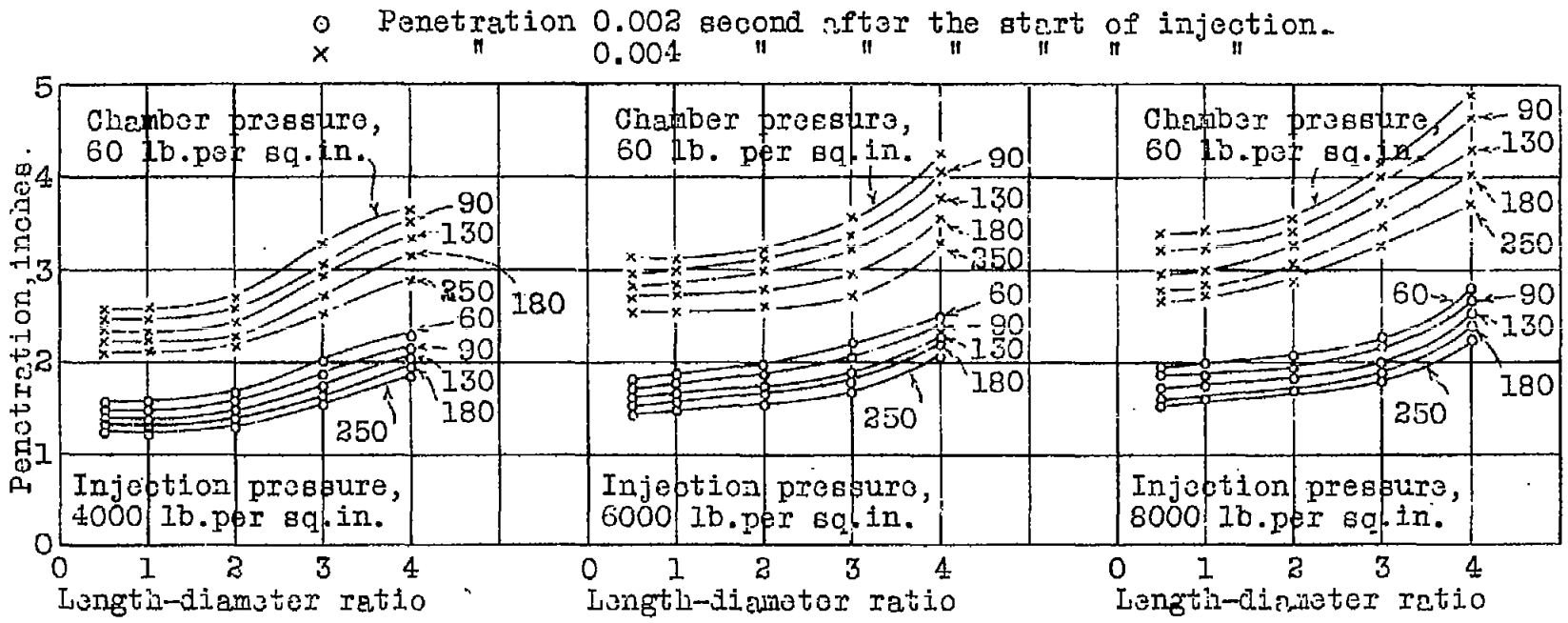
Fig. 6




Penetration at 0.004 second after the start of the injection.
Orifice diameter, 0.014 inch.

Spray tip penetration of helically grooved stem at varying orifice length-diameter ratio.

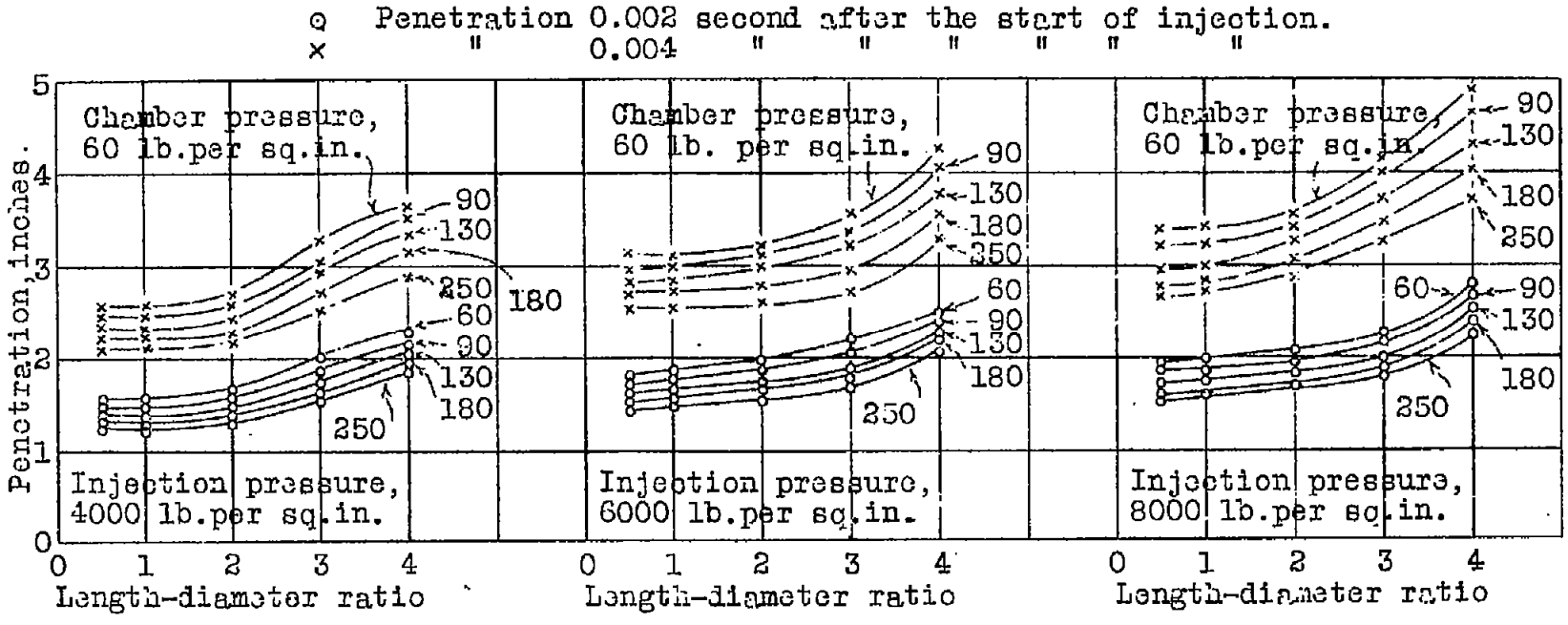
Fig. 7




Penetration at 0.002 and 0.004 second after the start of injection.
Orifice diameter 0.040 inch.

Spray tip penetration of helically grooved stem at varying orifice length-diameter ratio.

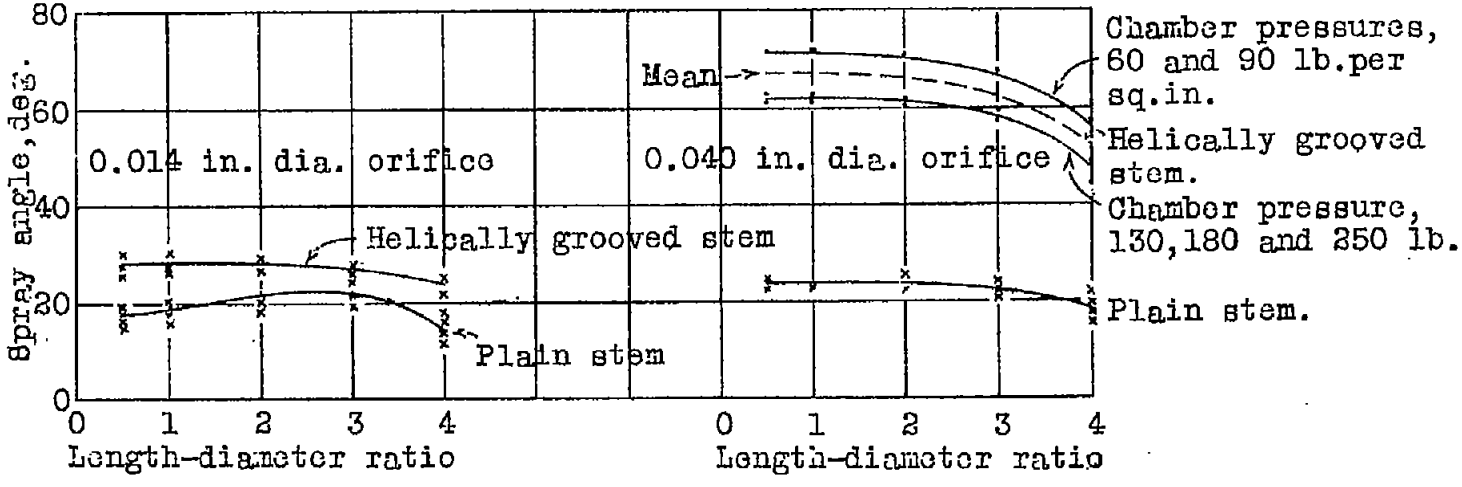
Fig. 8




Penetration at 0.002 and 0.004 second after the start of injection.
Orifice diameter 0.040 inch.

Spray tip penetration of helically grooved stem at varying orifice length-diameter ratio.

Fig. 8




Injection pressure, 4000, 6000 and 8000 lb.per sq.in.
Chamber pressure, 60, 90, 130, 180 and 250 lb.per sq.in., except as noted.

Spray angle at varying orifice length-diameter ratio.

Fig. 9