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# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 258

## SOME FACTORS AFFECTING THE REPRODUCIBILITY OF PENETRATION AND THE CUT-OFF OF OIL SPRAYS FOR FUEL-INJECTION ENGINES

By E. G. BEARDSLEY



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## AERONAUTICAL SYMBOLS

### 1. FUNDAMENTAL AND DERIVED UNITS

|             | Symbol   | Metric                      |        | English               |               |
|-------------|----------|-----------------------------|--------|-----------------------|---------------|
|             |          | Unit                        | Symbol | Unit                  | Symbol        |
| Length----- | <i>l</i> | meter-----                  | m      | foot (or mile)-----   | ft. (or mi.)  |
| Time-----   | <i>t</i> | second-----                 | sec    | second (or hour)----- | sec. (or hr.) |
| Force-----  | <i>F</i> | weight of one kilogram----- | kg     | weight of one pound   | lb.           |
| Power-----  | <i>P</i> | kg/m/sec-----               |        | horsepower-----       | HP.           |
| Speed-----  |          | km/hr-----                  |        | mi./hr-----           | M. P. H.      |
|             |          | m/sec-----                  |        | ft./sec-----          | f. p. s.      |

### 2. GENERAL SYMBOLS, ETC.

|  |  |
|--|--|
| <p><i>W</i>, Weight, = <math>mg</math></p> <p><i>g</i>, Standard acceleration of gravity = 9.80665 m/sec.<sup>2</sup> = 32.1740 ft./sec.<sup>2</sup></p> <p><i>m</i>, Mass, = <math>\frac{W}{g}</math></p> <p><math>\rho</math>, Density (mass per unit volume).<br/>Standard density of dry air, 0.12497 (kg-m<sup>-4</sup> sec.<sup>2</sup>) at 15° C and 760 mm = 0.002378 (lb.-ft.<sup>-4</sup> sec.<sup>2</sup>).</p> <p>Specific weight of "standard" air, 1.2255 kg/m<sup>3</sup> = 0.07651 lb./ft.<sup>3</sup></p> | <p><math>mk^2</math>, Moment of inertia (indicate axis of the radius of gyration, <i>k</i>, by proper subscript).</p> <p><i>S</i>, Area.</p> <p><i>S<sub>w</sub></i>, Wing area, etc.</p> <p><i>G</i>, Gap.</p> <p><i>b</i>, Span.</p> <p><i>c</i>, Chord length.</p> <p><i>b/c</i>, Aspect ratio.</p> <p><i>f</i>, Distance from <i>c. g.</i> to elevator hinge.</p> <p><math>\mu</math>, Coefficient of viscosity.</p> |
|--|--|

### 3. AERODYNAMICAL SYMBOLS

|  |  |
|--|--|
| <p><i>V</i>, True air speed.</p> <p><i>q</i>, Dynamic (or impact) pressure = <math>\frac{1}{2} \rho V^2</math></p> <p><i>L</i>, Lift, absolute coefficient <math>C_L = \frac{L}{qS}</math></p> <p><i>D</i>, Drag, absolute coefficient <math>C_D = \frac{D}{qS}</math></p> <p><i>C</i>, Cross-wind force, absolute coefficient<br/><math>C_C = \frac{C}{qS}</math></p> <p><i>R</i>, Resultant force. (Note that these coefficients are twice as large as the old coefficients <i>L<sub>C</sub></i>, <i>D<sub>C</sub></i>.)</p> <p><i>i<sub>w</sub></i>, Angle of setting of wings (relative to thrust line).</p> <p><i>i<sub>t</sub></i>, Angle of stabilizer setting with reference to thrust line.</p> | <p><math>\gamma</math>, Dihedral angle.</p> <p><math>\rho \frac{Vl}{\mu}</math>, Reynolds Number, where <i>l</i> is a linear dimension.<br/>e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, 0° C: 255,000 and at 15° C., 230,000;<br/>or for a model of 10 cm chord 40 m/sec, corresponding numbers are 299,000 and 270,000.</p> <p><i>C<sub>p</sub></i>, Center of pressure coefficient (ratio of distance of <i>C. P.</i> from leading edge to chord length).</p> <p><math>\beta</math>, Angle of stabilizer setting with reference to lower wing, = (<i>i<sub>t</sub></i> - <i>i<sub>w</sub></i>).</p> <p><math>\alpha</math>, Angle of attack.</p> <p><math>\epsilon</math>, Angle of downwash.</p> |
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**REPORT No. 258**

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**SOME FACTORS AFFECTING THE REPRODUCIBILITY  
OF PENETRATION AND THE CUT-OFF OF OIL SPRAYS  
FOR FUEL-INJECTION ENGINES**

**By E. G. BEARDSLEY**  
**Langley Memorial Aeronautical Laboratory**

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## NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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#### SUMMARY

*This investigation was undertaken at the Langley Memorial Aeronautical Laboratory at Langley Field, Virginia, in connection with a general research on fuel-injection engines for aircraft. The purpose of the investigation was to determine the factors controlling the reproducibility of spray penetration and secondary discharges after cut-off.*

*The development of single sprays from automatic injection valves was recorded by means of special high-speed photographic apparatus capable of taking 25 consecutive pictures of the moving spray at a rate of 4,000 per second. The effects of two types of injection valves, injection-valve tube length, initial pressure in the injection-valve tube, speed of the injection control mechanism, and time of spray cut-off, on the reproducibility of spray penetration, and on secondary discharges were investigated.*

*It was found that neither type of injection valve materially affected spray reproducibility. The initial pressure in the injection-valve tube controlled the reproducibility of spray penetrations. An increase in the initial pressure or in the length of the injection-valve tube slightly increased the spray penetration within the limits of this investigation. The speed of the injection-control mechanism did not affect the penetration.*

*Analysis of the results indicates that secondary discharges were caused in this apparatus by pressure waves initiated by the rapid opening of the cut-off valve. The secondary discharges were eliminated in this investigation by increasing the length of the injection-valve tube.*

#### INTRODUCTION

During an investigation of the characteristics and development of the sprays from several types of automatic fuel injection valves, designed for use in high-speed fuel-injection engines, considerable difficulty was experienced in obtaining the same spray penetrations, when using the same injection valve under seemingly similar conditions. Also spray discharges, of much smaller mass and at lower pressure than the main sprays, took place after cut-off. These small spray discharges will be referred to in this report as "secondary discharges." These and similar phenomena are undoubtedly present in many injection systems, but have generally remained undiscovered because there has been no apparatus available capable of recording them.

To obtain smooth operation in high-speed fuel-injection engines, running at constant speed and load, it is necessary that a constant quantity of fuel be injected each cycle, and that the sprays produced be alike in all respects. The spray cut-off must take place quickly and in most cases there must be no secondary discharges if the highest efficiency is to be obtained. The work presented in this report deals with the effects of two types of injection valve designs, injection-valve tube length, initial pressure in the injection-valve tube, speed of the injection control mechanism, and time of spray cut-off, on the reproducibility of spray penetration, and

on secondary discharges. Diesel engine fuel oil having a specific gravity of 0.85 at 80° F. was used in all tests. It was injected at 8,000 pounds per square inch pressure into a chamber containing nitrogen at pressures of 200 and 400 pounds per square inch.

### METHODS AND APPARATUS

The general method employed to study the reproducibility of spray penetration and secondary discharges was to record the development and cut-off of single sprays from automatic injection valves, by means of special high-speed photographic apparatus capable of taking 25 consecutive pictures at the rate of 4,000 per second. The spray photography apparatus used for this work was designed and developed for the investigation of fuel sprays for high-speed fuel-injection engines. Brief descriptions of this equipment have been given in annual reports of the National Advisory Committee for Aeronautics, and a more complete description has been given in Report No. 222, Spray Penetration with a Simple Fuel-Injection Nozzle. (Reference 1.)

The system for the production and control of the fuel sprays has, however, been changed and the present system was designed to permit the study of the characteristics of the sprays from automatic injection valves. It is provided with means for varying the duration of injection, the length and size of the injection-valve tube, the initial pressure in the injection-valve

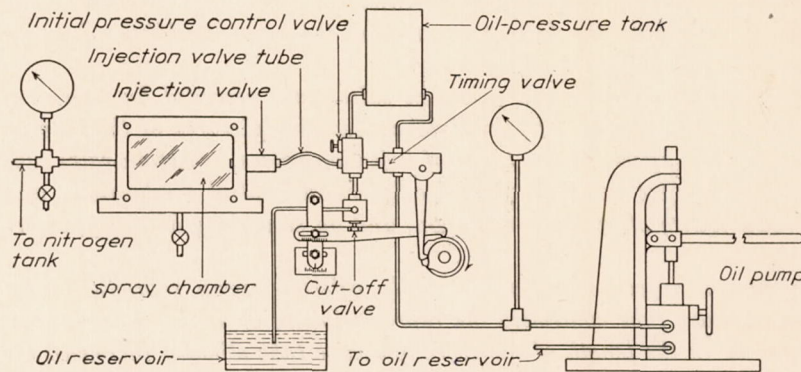


FIG. 1.—Diagrammatic arrangement of apparatus for production and control of spray.

was admitted to the automatic injection valve by a cam-operated timing valve. The cut-off mechanism consisted of a poppet valve lifted by a cam-operated lever. The duration of the injection was controlled by adjusting the lever along the cam so as to obtain earlier or later operation of the cut-off valve with respect to the timing valve. The mechanism was so designed that the amount and rate of lift of the valve was practically constant for all positions of the lever.

Two types of automatic injection valves were used, one being of the usual spring-loaded type valve, and the other being a diaphragm-type valve. In this latter valve, the stem was fixed and the nozzle was clamped between several steel diaphragms. The nozzle-diaphragm unit was deflected by the oil pressure which caused the nozzle to leave its seat on the stem and allowed the oil to pass through. In this type of valve inertia forces are greatly reduced, which tends to produce quick opening and closing of the valve. Spiral grooves having a 30° angle were used in this valve to break up the oil by centrifugal force.

### RESULTS

#### REPRODUCIBILITY OF SPRAY PENETRATION

The results for the investigation of the effects of the type of injection valve used, of the initial pressure in the injection-valve tube, and of the injection-valve tube length on the reproducibility of spray penetration are given in Figures 2, 3, and 4.

The results for the tests on the spring-loaded and diaphragm-type injection valves, in which the initial pressure in the injection-valve tube was not manually controlled, are shown

by the curves A and B in Figure 2. The divergence of the points from the mean curves indicates that the reproducibility of the sprays is not appreciably different for either of these two

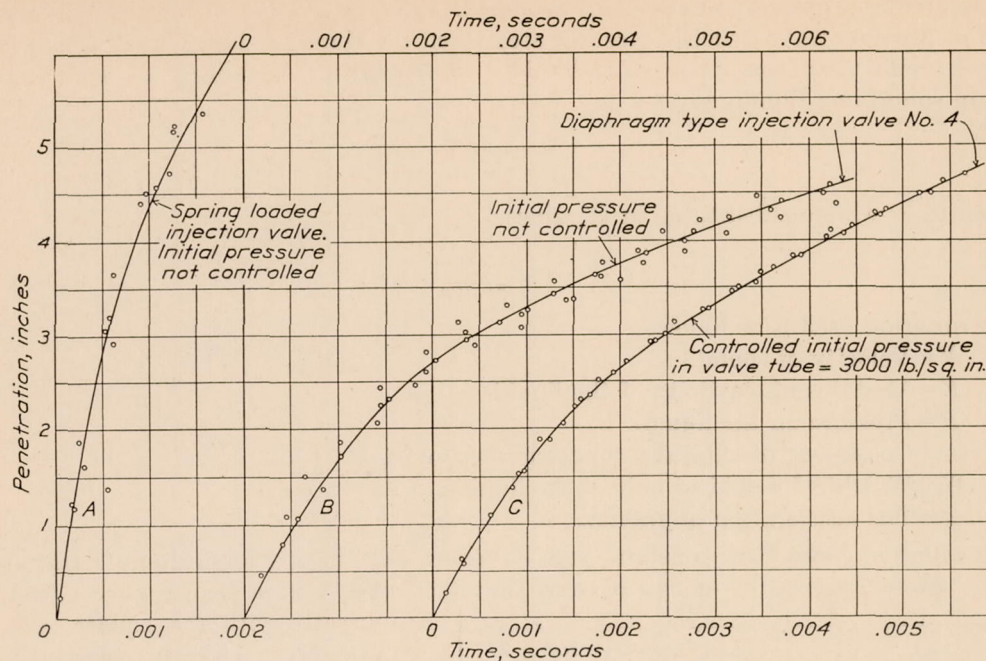


FIG. 2.—Effect of controlling initial pressure in injection-valve tube. Each curve is the result of four experiments. Injection pressure, 8,000 lb./sq. in.; chamber pressure, 400 lb./sq. in. No cut-off. Valve tube length, 7 inches.

types of injection valves. Difference in the design of the two valves caused the different penetration of the spray from one as compared with the other.

The effect of controlling the initial pressure in the injection-valve tube is shown, for the diaphragm-type injection valve, by curves B and C in Figure 2. These results indicate that when the initial pressure in the injection-valve tube is controlled to a definite value good reproducibility is obtained.

The initial pressure in the injection-valve tube may vary in successive tests if not controlled. The amount of this variation depends upon the pressure at which the injection valve closes after discharge, upon the rate of leakage in the system, and upon the time interval between tests. Accordingly, tests were made with several controlled initial pressures to determine their effect upon the spray penetration.

The results of these tests, in which the initial pressure was controlled to 1,000, 2,000, 3,000, and 4,000 pounds per square inch are shown in Figure 3. The penetration was found to increase about 3 per cent with each 1,000 pounds per square inch increase in the initial pressure.

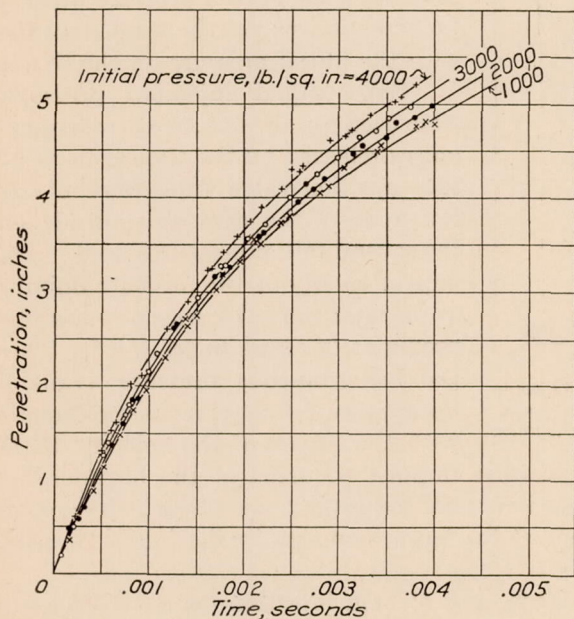


FIG. 3.—Effect of initial pressure in injection-valve tube. Each curve is the result of three experiments. Injection pressure, 8,000 lb./sq. in.; chamber pressure, 200 lb./sq. in. Injection valve No. 4. Injection valve tube length, 41 in. Cut-off after 0.003 seconds.

The initial pressure in the injection-valve tube acts directly against the end of the timing-valve needle. The effects of the intensity of this pressure upon the rate of opening of the timing

valve and the rate of pressure rise in the injection-valve tube have been considered in analyses of the results. Although these factors have some effect upon the penetration, a consideration of the characteristics of pressure waves seems to offer the best explanation of this phenomenon. The behavior of pressure waves, such as are initiated when the timing valve is opened, may be compared to the behavior of sound waves in a liquid. Merriman's *Hydraulics* (Reference 2) gives the velocity of sound in a liquid, as

$$V = \sqrt{\frac{Eg}{W}} \quad (1)$$

$E$  is equal to  $\frac{P}{\theta}$ , which, substituted in (1) gives

$$V = \sqrt{\frac{Pg}{W\theta}} \quad (2)$$

The notation used is as follows:

$V$  = Velocity of sound.

$E$  = Modulus of elasticity of the liquid.

$P$  = Pressure on the liquid.

$\theta$  = Coefficient of cubical compression of liquid.

$W$  = Weight of a cubical unit of the liquid.

$g$  = The acceleration of gravity.

The values of  $g$  and  $\theta$  are constant, and  $W$  varies only slightly for a liquid, with change in pressure. From formula (2) it can be seen that the velocity of a sound wave varies almost

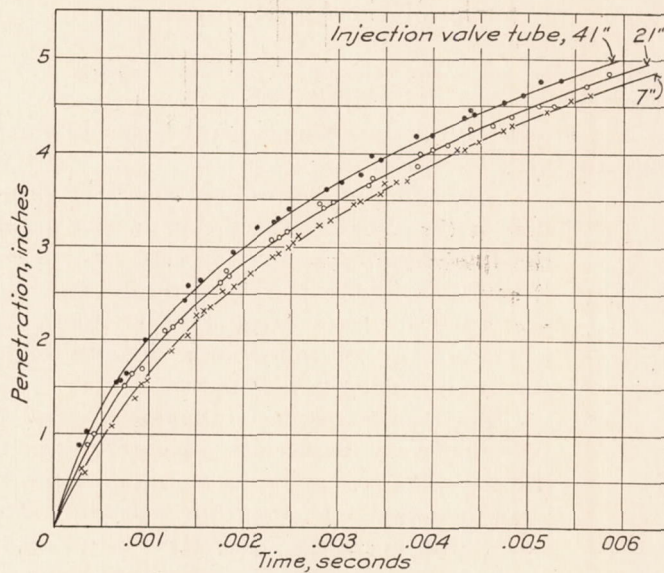


FIG. 4.—Effect of injection-valve tube length. Each curve is the result of three experiments. Injection pressure, 8,000 lb./sq. in. Chamber pressure, 400 lb./sq. in. Injection-valve No. 4. Cut-off after 0.003 seconds. Initial pressure, 3,000 lb./sq. in.

directly with the square root of the pressure. Thus the velocity of a sound wave in a liquid at 4,000 pounds per square inch pressure will be about twice the velocity for 1,000 pounds per square inch pressure. This analysis indicates that the velocity of a pressure wave in the injection-valve tube would increase with the initial pressure on the liquid.

Since equal injection pressures were used for all tests, the pressure impulses released by the timing valve to the injection-valve tube were of approximately the same magnitude for the several initial pressures used. The impact energy of the pressure impulse at the injection valve was, however, approximately equal to  $\frac{1}{2} MV^2$ . Thus the instantaneous pressure available for impulse discharge increased directly with the square of the velocity of the

pressure wave. The discharge caused by the pressure impulse occurred at the beginning of injection and was of very short duration in comparison with the total discharge, which explains why only slightly increased penetration was obtained for large increases in the initial pressure in the injection-valve tube.

The results for the tests with the 7-inch, 21-inch, and 41-inch injection-valve tube lengths are shown in Figure 4. The spray penetration was increased slightly, with increase in the injection-valve tube length, within the limits investigated.

Experiments have been made relating to the behavior of pressure waves in air contained in small tubes by the Aeronautical Research Committee of Great Britain, the results of which are given in their reports and memoranda No. 957. (Reference 3.) The results of these tests



show that in some cases the pressures, recorded at the far end of a closed tube, increased considerably as the length of the tube was increased. An effect similar to that indicated by these results might well have existed in the injection system and produced the greater spray penetrations recorded.

In order to determine the effect of the rate of opening of the timing valve on the spray penetration, tests were made with cam-shaft speeds of 550, 750, 900, and 1,100 revolutions per minute. The results of these tests show that the spray penetration was the same for the four rates of opening of the timing valve investigated. The rate of pressure rise in the injection-valve tube was not controlled, therefore, by the rate of opening of the timing valve in these tests. This indicates that the maximum rate of pressure rise at the injection valve was obtained with the slowest cam-shaft speed.

#### SECONDARY DISCHARGES

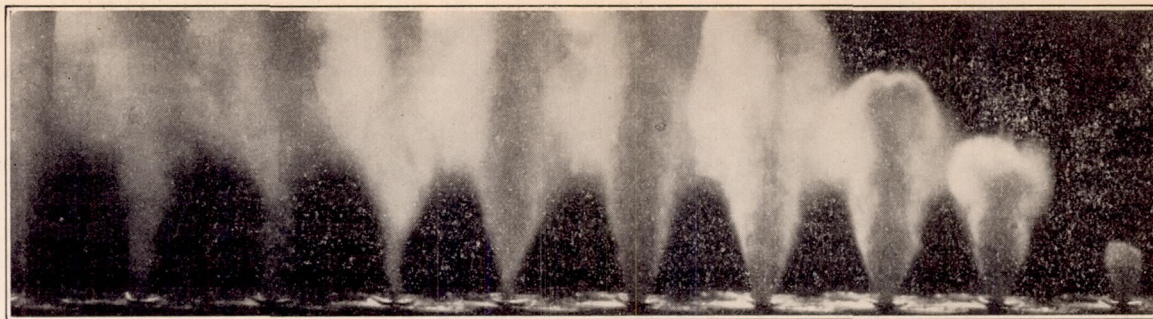
The results for the investigation of the effect of the type of injection valve used, the time of cut-off, and injection-valve tube length on the occurrence of secondary discharges and the time at which they appeared are shown in Table I. The results in Table I are given to the nearest hundred-thousandth second. By measurement to a hundredth of an inch on the film records, time computations can be made to 0.000003 second, so it can be seen that the results given in the table are within the limit of accuracy. Spray pictures taken during the investigation are shown in Figures 5 and 6. Figure 5 shows two sprays with typical secondary discharges, and Figure 6 two similar sprays with no secondary discharges. The secondary discharges may be seen to have their start in the third or fourth spray from the left in both pictures of Figure 5. Although a series of 25 pictures were taken of each spray, it was not thought necessary to show all of them in this report. The sprays are one-third actual size.

The start of the cut-off of the spray and of the secondary discharges are not always recorded by the films, since these events often occur in the time interval between consecutive illuminations. The variation in the time of the spray reappearance after cut-off as given in Table I is probably caused by the necessity for estimating the exact beginning of the cut-off, and of the secondary discharge by extrapolating slightly, curves plotted from measurements of the film.

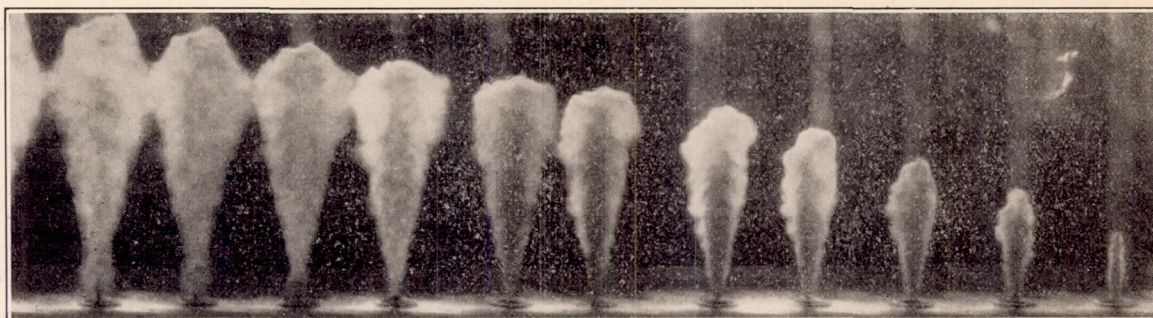
The results of the tests with the spring-loaded and diaphragm-type injection valves show that similar secondary discharges were obtained with both valves. Also the time of appearance of the secondary discharges after cut-off of the spray was approximately the same.

Tests were made with cut-off approximately 0.0018, 0.0034, and 0.0048 second after the start of the spray, using an injection-valve tube 7 inches long. The results of the tests with cut-off after 0.0018 and 0.0034 second show that the secondary discharges took place at approximately the same time interval after spray cut-off. This indicates that these secondary discharges were controlled by the cut-off valve and not by the timing valve. No secondary discharge appeared with cut-off after 0.0048 second. In this case the timing valve was nearly closed and the pressure impulse of any oil which passed through it was too low to open the automatic injection valve.

Bouncing of the moving parts of the injection valves after their impact at cut-off has been considered in analyses of the secondary discharge phenomena. For example, the nozzle-diaphragm unit of the diaphragm-type injection valve might vibrate according to its natural period, or might rebound because of its impact upon the fixed stem. However, the results of the investigation show that no secondary discharge appeared when a 41-inch injection valve tube was used in place of the 7-inch tube. It is probable that the length of the injection-valve tube would have little effect upon the vibration of the moving parts of the injection valve. If bouncing of the moving parts caused secondary discharges, the discharges would undoubtedly have taken place at different time intervals after cut-off for the two types of valve used. Table I shows, however, that the intervals were approximately the same for both valves. For these reasons, the results indicate that bouncing of the moving parts did not cause secondary discharges.

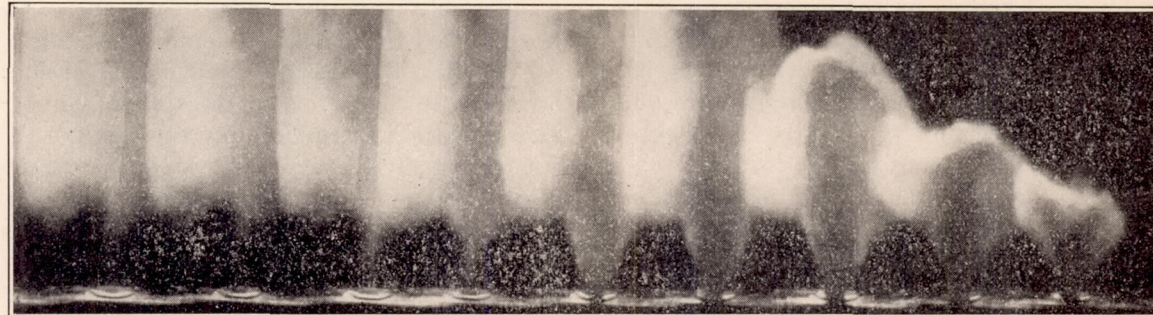


Injection pressure, 8,000 lb./sq. in., chamber pressure, atoms.

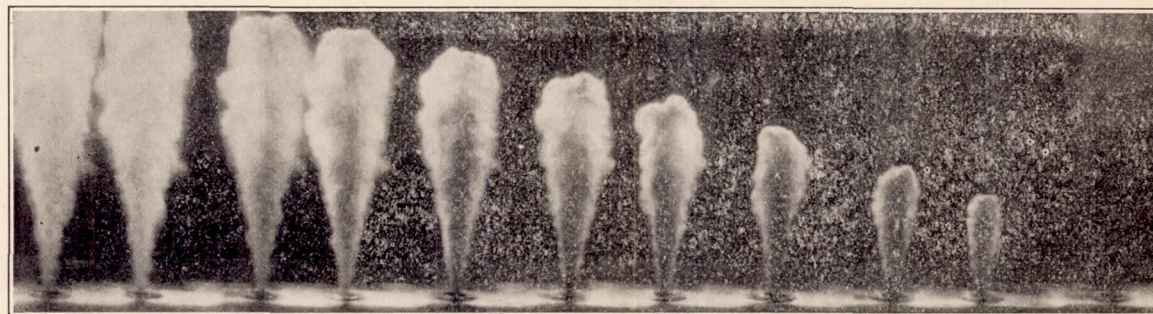


Injection pressure, 8,000 lb./sq. in., chamber pressure, 400 lb./sq. in.

FIG. 5.—Oil spray with secondary discharge.



Injection pressure, 8,000 lb./sq. in., chamber pressure, atoms.



Injection pressure, 8,000 lb./sq. in., chamber pressure, 400 lb./sq. in.

FIG. 6.—Oil spray without secondary discharge.

A brief analysis of pressure wave phenomena and of the operation of the apparatus in relation to the secondary discharge phenomena has been made. When the cut-off valve was opened, the pressure in the injection-valve tube was released so that the injection valve closed and cut off the spray. It is probable that the pressure on the oil in the injection-valve tube was so rapidly released that although the timing valve was still open the inertia of the oil in the supply system made increased flow through the timing valve impossible for an instant. When increased flow through the timing valve took place, its impact on the oil in the injection-valve tube, which was directly in line with the timing valve, may have created a pressure wave which caused a small spray to discharge from the injection valve.

No secondary discharges appeared in any of the tests with the 41-inch injection-valve tube length. In this case it is probable that the pressure wave was damped out by the resistance of the long tube, or absorbed by the compression of the oil and expansion of the tube. The pressures which caused the secondary discharges were never much above the opening pressure of the injection valve. It would not, therefore, have taken much resistance to damp out the pressure waves sufficiently to have prevented them from opening the valve and causing secondary discharges.

Although the secondary discharges were controlled in this investigation by increasing the length of the injection-valve tube, there are undoubtedly other ways to control these phenomena. Thus, rearrangement of the injection-control apparatus, change in the relative size and shape of various parts, or the use of other injection pressures, might govern secondary discharges.

#### CONCLUSIONS

The results of these experiments indicate that the initial pressure in the injection-valve tube must be controlled to obtain spray reproducibility. The spray penetration is slightly increased by increasing the length of, or the initial pressure in, the injection-valve tube.

Secondary discharges may be caused by pressure waves in the injection system during and after spray cut-off. Though secondary discharges were eliminated in this investigation by increasing the length of the injection-valve tube, they could probably be controlled by changing the location or size of various parts of the spray production and control apparatus, and by using different injection pressures.

TABLE I.—Effect of cut-off, injection valve tube length, and type of valve on secondary discharges

| Test No. | Valve No. | Valve type    | Angle of spiral grooves | Orifice diameter | Valve tube length | Cut-off time  | Spray reappearance time | Reappearance time after cut-off |
|----------|-----------|---------------|-------------------------|------------------|-------------------|---------------|-------------------------|---------------------------------|
|          |           |               | <i>Degrees</i>          | <i>Inches</i>    | <i>Inches</i>     | <i>Second</i> | <i>Second</i>           | <i>Second</i>                   |
| 1        | 4         | Diaphragm     | 30                      | 0.022            | 7                 | 0.00178       | 0.00213                 | 0.00035                         |
| 1        | 4         | do            | 30                      | .022             | 7                 | .00190        | .00220                  | .00030                          |
| 1        | 4         | do            | 30                      | .022             | 7                 | .00180        | .00219                  | .00039                          |
| 2        | 4         | do            | 30                      | .022             | 7                 | .00336        | .00375                  | .00039                          |
| 2        | 4         | do            | 30                      | .022             | 7                 | .00345        | .00377                  | .00034                          |
| 2        | 4         | do            | 30                      | .022             | 7                 | .00337        | .00367                  | .00030                          |
| 3        | 4         | do            | 30                      | .022             | 7                 | .00490        | None.                   | -----                           |
| 3        | 4         | do            | 30                      | .022             | 7                 | .00485        | None.                   | -----                           |
| 3        | 4         | do            | 30                      | .022             | 7                 | .00480        | None.                   | -----                           |
| 4        | 4         | do            | 30                      | .022             | 41                | .00199        | None.                   | -----                           |
| 4        | 4         | do            | 30                      | .022             | 41                | .00180        | None.                   | -----                           |
| 4        | 4         | do            | 30                      | .022             | 41                | .00184        | None.                   | -----                           |
| 5        | 3a        | Spring loaded | 23                      | .029             | 7                 | .00275        | .00312                  | .00037                          |
| 5        | 3a        | do            | 23                      | .029             | 7                 | .00275        | .00310                  | .00035                          |
| 5        | 3a        | do            | 23                      | .029             | 7                 | .00272        | .00307                  | .00035                          |

The effect of time of cut-off is shown by tests 1, 2, and 3.  
The effect of injection-valve tube length is shown by tests 1 and 4.  
The effect of type of valve is shown by tests 2 and 5.

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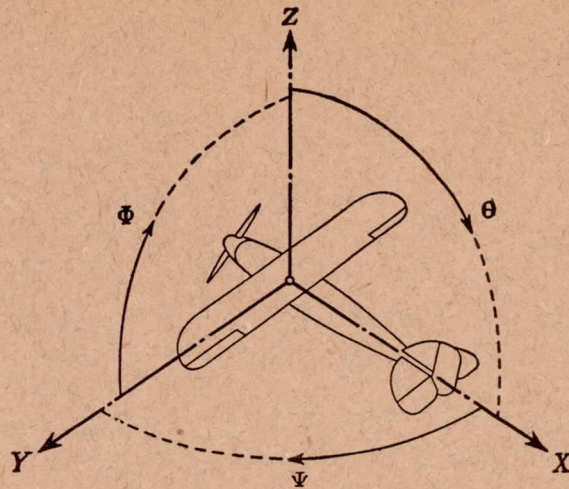
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▽



Positive directions of axes and angles (forces and moments) are shown by arrows

| Axis         |             | Force<br>(parallel<br>to axis)<br>symbol | Moment about axis |             |                       | Angle            |             | Velocities                               |         |
|--------------|-------------|--|-------------------|-------------|-----------------------|------------------|-------------|--|---------|
| Designation  | Sym-<br>bol |  | Designa-<br>tion  | Sym-<br>bol | Positive<br>direction | Designa-<br>tion | Sym-<br>bol | Linear<br>(compo-<br>nent along<br>axis) | Angular |
| Longitudinal | X           | X  | rolling           | L           | Y → Z                 | roll             | Φ           | u  | p       |
| Lateral      | Y           | Y  | pitching          | M           | Z → X                 | pitch            | Θ           | v  | q       |
| Normal       | Z           | Z  | yawing            | N           | X → Y                 | yaw              | Ψ           | w  | r       |

Absolute coefficients of moment

$$C_L = \frac{L}{qbS} \quad C_M = \frac{M}{qcS} \quad C_N = \frac{N}{qfS}$$

Angle of set of control surface (relative to neutral position),  $\delta$ . (Indicate surface by proper subscript.)

#### 4. PROPELLER SYMBOLS

$D$ , Diameter.  
 $p_e$ , Effective pitch  
 $p_g$ , Mean geometric pitch.  
 $p_s$ , Standard pitch.  
 $p_v$ , Zero thrust.  
 $p_a$ , Zero torque.  
 $p/D$ , Pitch ratio.  
 $V'$ , Inflow velocity.  
 $V_s$ , Slip stream velocity.

$T$ , Thrust.  
 $Q$ , Torque.  
 $P$ , Power.

(If "coefficients" are introduced all units used must be consistent.)

$\eta$ , Efficiency =  $T V/P$ .  
 $n$ , Revolutions per sec., r. p. s.  
 $N$ , Revolutions per minute., R. P. M.  
 $\Phi$ , Effective helix angle =  $\tan^{-1} \left( \frac{V}{2\pi r n} \right)$

#### 5. NUMERICAL RELATIONS

1 HP = 76.04 kg/m/sec. = 550 lb./ft./sec.  
 1 kg/m/sec. = 0.01315 HP.  
 1 mi./hr. = 0.44704 m/sec.  
 1 m/sec. = 2.23693 mi./hr.

1 lb. = 0.4535924277 kg.  
 1 kg = 2.2046224 lb.  
 1 mi. = 1609.35 m = 5280 ft.  
 1 m = 3.2808333 ft.